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GEOLOGICAL SURVEY OF JAPAN

# METALLOGENY OF ASIA, 1980

Edited by

S. Ishihara and A. Sasaki

GEOLOGICAL SURVEY OF JAPAN

Higashi 1-1-3, Yatabe-machi, Tsukuba-gun, Ibaraki-ken, 305 Japan

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Hiroshi ISOMI, Director

# METALLOGENY OF ASIA, 1980

Proceedings of an International Symposium on Metallogeny of Asia, held at Tsukuba and Tokyo, January 1980.

Edited by

Shunso ISHIHARA and Akira SASAKI

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# FOREWORD

The metallic mineral resources of Asia have become increasingly important during the past two decades in the context of world mineral resources. Important new deposits have been discovered and new mines have become operational and the world ratio of production, reserves, and potential of the region have increased significantly.

This trend is expected to continue for many metals and thus metallogeny of this part of the world is important not only for the countries of the region, but it also has world-wide significance both scientifically and economically.

The international symposium on Metallogeny of Asia was held as a part of the International Research and Development Co-operation Programme of the Agency of Industrial Science and Technology at the Geological Survey of Japan in Tsukuba Science City from January 22 to 28, 1980. One of the objectives was to discuss and guidance for future studies and for exploration. The Geological Survey of Japan is responsible for compiling the Metallogenic Map of Asia and Professor K. KANEHIRA is coordinating the work done by the national institutions of the countries of the region. The map is in the final stage of preparation and another important objective of this symposium was to discuss and decide with the participants the metallogenic epochs and provinces and the background geologic information of the map. Geo-scientists from seven Asian countries and Japan participated in the discussions and, we believe, achieved the above objectives.

All the papers presented at the Symposium are published in this Proceedings. These papers will provide new and important information and data on the metallic mineral resources of Asia and we believe that they constitute a significant contribution to the understanding of the metallogeny of Asia.

March, 1981

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# Some Thoughts on Geodynamics of Asia*

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## Extended Abstract

Plate tectonics has given answers to many basic questions of global geodynamics. However, it is also true that there are still unsolved problems. In particular, problems related to the tectonic developments of continental regions largely remain unanswered.

Asia, of which large fraction is continental, has an extremely complicated geologic structure and history. Present plate tectonics appears incapable of explaining them.

The most fundamental process occurring today in the continental Asia is the collision of India and Eurasia. The collision appears to have such a profound and far-reaching effect upon the Cenozoic Asian tectonics, that not only Himalayas but entire eastern Asia is under its influence (MOLNAR and TAPPONIER, 1975). For the more ancient evolutionary history of Asia, consisting of a mosaic of numerous cratons and sub-cratons, the author is unaware of a clear-cut explanation (DICKINSON, 1973).

The eastern margin of Asia is fringed by a series of trench-arc-back arc basin systems, where the subduction of the Pacific plate is underway.

The southeastern margin of Asia, on the other hand, is a region where the three mega-plates of Asia, Pacific and Austral-India are entangled in a complicated manner (HAMILTON, 1979).

### Subduction

Among the above three major regions, the subduction plate boundaries in the eastern Asian margin are the simplest, because subduction is one of the two fundamental processes in the framework of plate tectonics: the generation of oceanic plate at spreading mid-oceanic ridges and its destruction at ocean trenches. In this paper, the author points out that even in the case of simple subduction process, very basic problems are unsolved (UYEDA, 1977; 1979).

It is widely accepted that subduction is playing an essential role in the actualistic tectonic processes in the arc-trench-back arc systems (MATSUDA and UYEDA, 1971). Formation of trench itself and the occurrence of shallow-interplate seismicity and deep seismicity are the notable examples that are explained as a result of subduction. On top of these, the origin of arc magmatism, distribution of heat flow (high in the arc and back-arc and low in the trench and forearc), and the formation of back-arc basins are also suspected to be related to subduction.

However, the detailed physical mechanism producing these phenomena are unknown: how are the arc magma and high heat flow produced by subduction of cold slab of plate?: how is an extensional tectonic stress regime brought about where plates are converging?

* Presented at the international symposium on Metallogeny of Asia, held at Tsukuba, January 1980.

*Report of Geological Survey of Japan, No. 261, p. 1–6, 1981*

## Two Types of Subduction

To help solving these basic problems, it may be worth noting that there are two different modes in subduction (UYEDA and KANAMORI, 1979). One mode of subduction is associated with active spreading of back-arc basin (called Mariana-type subduction) and the other is not (called Chilean-type subduction). This difference is apparently caused by the corresponding difference in the degree of mechanical coupling or the interaction of the slab and the over-riding plate, as evidenced by the differences in various features, such as the seismic energy out-put of interplate thrust earthquakes. Various possible causes may be considered for the different degrees of plate interaction (KANAMORI, 1977; CHASE, 1978; MOLNAR and ATWATER, 1978; UYEDA and KANAMORI, 1979).

Table 1 and Figure 1 (both from UYEDA, 1979) summarize the classification of subduction zones.

Table 1 Classification of arcs (UYEDA, 1979)

| | CLASSIFICATION | | | STRESS REGIME | TYPICAL EXAMPLES |
|---|---|---|---|---|---|
| Arc | Continental arc (without back-arc basins) | | | Compressive (or neutral) | Peru-Chile, Alaska |
| | Island arc (with back-arc basin) | Back-arc inactive | Back-arc inactivated | Compressive (or neutral) | Kuril, Japan Shikoku, Parece Vela Basins |
| | | | Back-arc trapped | Compressive (or neutral) | Bering Sea |
| | | Back-arc active | Back-arc spreading | Tensional | Mariana Trough, Scotia Sea, Lau Basin |
| | | | Leaky transform | Tensional with shear | Andaman Sea |

As noted in the table, the mode of subduction can change from one type to another at one subduction zone. For instance, Japanese arc has a back-arc basin (the Japan Sea) that was formed in some geologic past but now the spreading is not active, corresponding to the change of the mode of subduction from the Mariana-type to the Chilean-type. The change probably took place during Pliocene time (NAKAMURA and UYADA, 1980).

## Porphyry Copper versus Massive Sulphide

The difference in the mode of subduction is best reflected in the stress regimes in the over-riding plates: more compressive in the Chilean-type and more tensional in the Mariana-type. As a possible manifestation of the different stress regimes, non-uniform distribution of porphyry copper-type and massive sulphide-type copper deposits in the arcs (Fig. 2, a, b) was pointed out (UYEDA and NISHIWAKI, 1980). Porphyry copper-type deposits are favored by the compressive stress regime of the Chilean-type subduction zones and the massive sulphides (kuroko-type) by the tensional regime of the Mariana-type subduction zones.

The long-noted absence of porphyry copper and presence of kuroko in Japan can be explained by noting that Japan was Mariana-type in the Tertiary period when kuroko was formed.

Moreover, the recent discovery of hydrothermal activity in the bottom of the

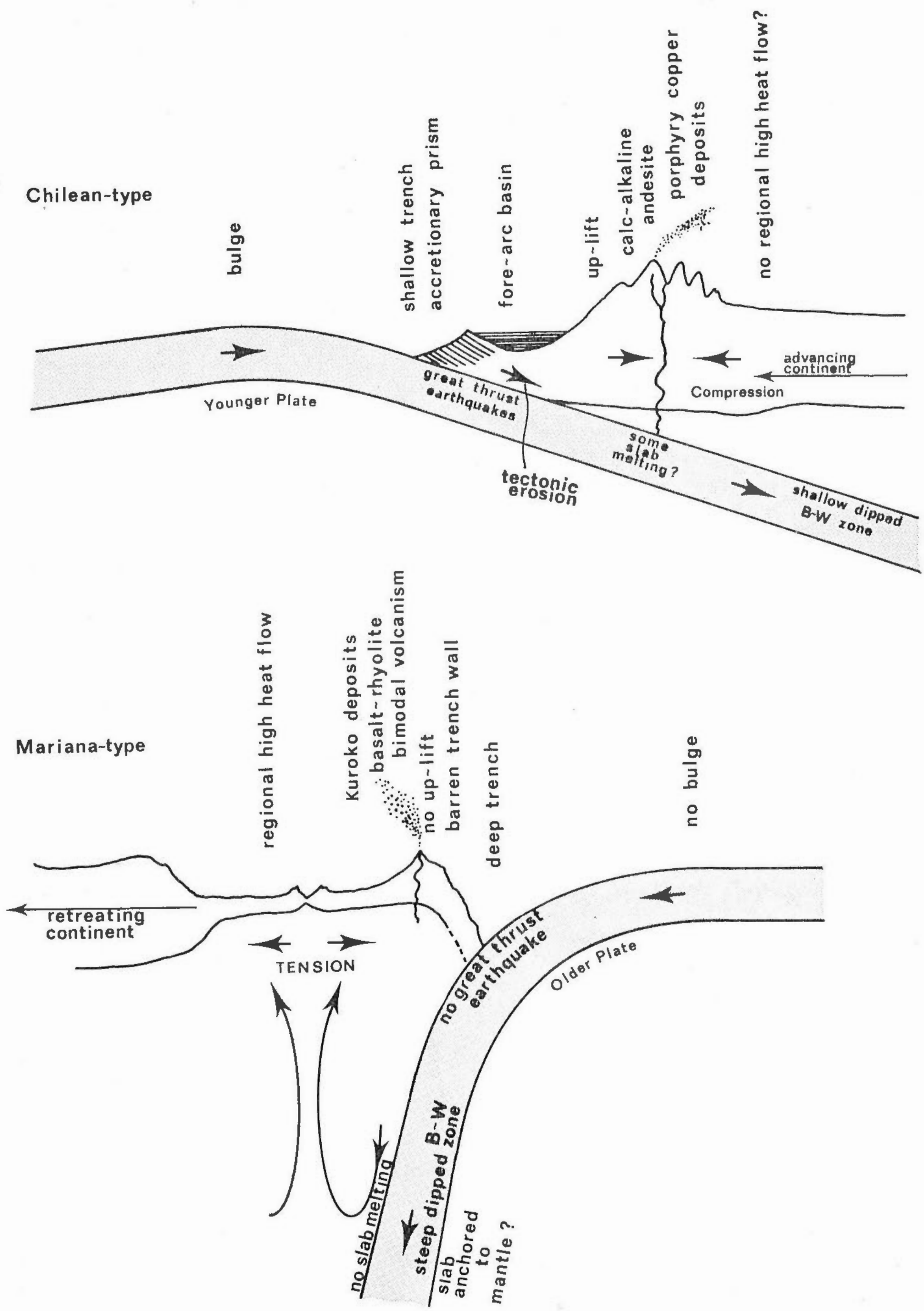


Fig. 1. Two modes of subduction with possible tectonic implications and causes (not to scale) (UYEDA, 1979)

currently spreading Mariana Trough (ANDERSON *et al.*, 1981), when considered together with the spectacular findings of hydrothermal mineralization on the active spreading centers in the East Pacific (National Geographic Magazine, 1979), strongly

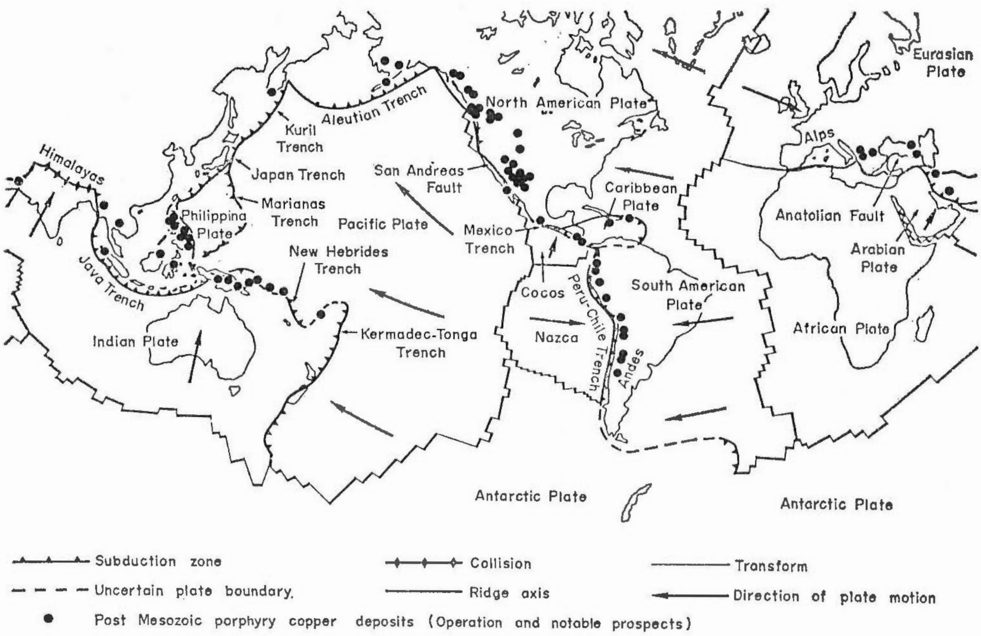


Fig. 2a Distribution of young porphyry copper deposits (UYEDA and NISHIWAKI, 1980)

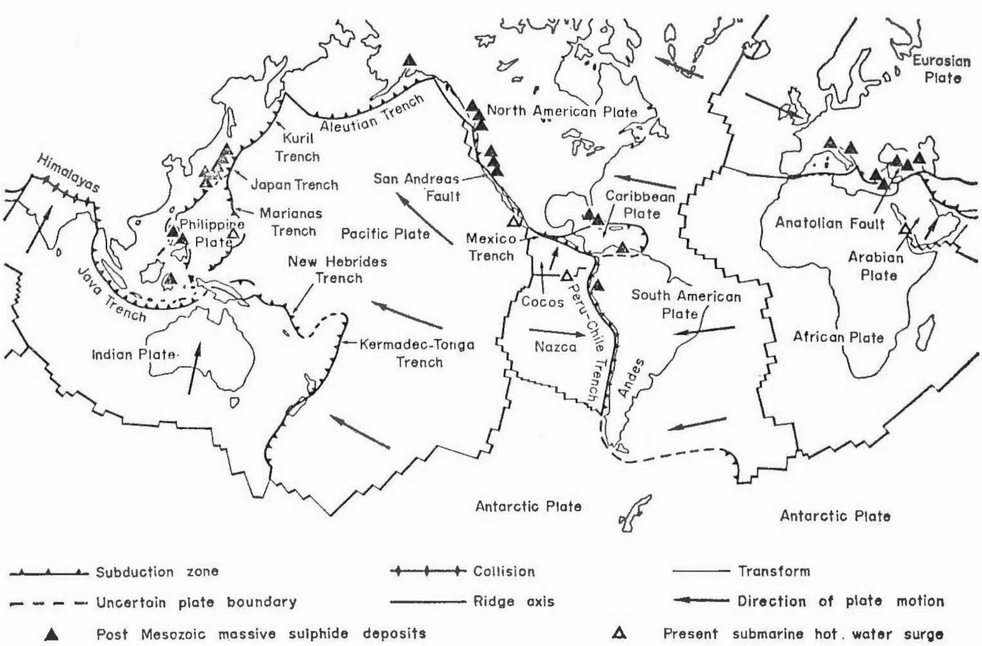


Fig. 2b Distribution of young massive sulphide deposits (UYEDA and NISHIWAKI, 1980)

suggests that ore genesis similar to kuroko formation may be underway in the Mariana Trough today.

In Figure 2a, it is notable that porphyry copper deposits are frequently found in the southwestern Pacific margin also, in particular in such areas as the Philippines, New Guinea, and Solomons. The Philippine and Melanesian zones are certainly not typically Chilean-type in the mode of subduction, so that some explanation is needed to account for the occurrence of porphyry copper.

UYEDA and NISHIWAKI (1980) suggested that the stress regimes in these Philippine and Melanesian zones may be highly compressive because these regions represent the zones of collision (BALCE *et al.*, 1981; HAMILTON, 1979).

## Collision versus Subduction

In addition to the two processes (plate generation and plate consumption), collision is another basic process in plate tectonics. Namely, if the plates continue to move, collision of buoyant features on the sea floor, such as seamounts, islands, oceanic plateaus and continental fragments, with the island arcs and/or continental arcs, is inevitable. In fact, recent study shows that Dai-ichi Kashima Seamount is in an actual collision at the Japan Trench (MOGI, 1980). Sooner or later, all the uplifted features in the present Pacific Ocean, such as the Shatsky Rise and the Hawaiian islands, will collide with the Asian margin.

The most spectacular of the collision, of course, is the collision of India against Eurasia to form the Himalayas as cited already.

It is then a very natural conjecture that similar collisions have taken place in the geologic past also. The so-called Wilson cycle (JACOBS *et al.*, 1974) is an expanded version of the concept.

Noting the recently accumulating pieces of evidence that much of the Circum-Pacific areas are composed of exotic elements (KERR, 1980), NUR and BEN-AVRAHAM (1977) proposed the idea of the lost Pacifica continent. The validity of this idea is yet to be tested but its general concept appears to the author quite sound. Even in Japan, some supporting evidence for the exotic nature of some terranes is being put forward (HATTORI and HIROOKA, 1979; SASAJIMA, 1980; Y. SAITO and M. HASHIMOTO, private communication).

Apart from the factual details to be tested, the notion of Pacifica contains, at least, three important conceptual aspects. One is that this concept provides a mechanism for the initiation of sea-floor spreading in the present Pacific Ocean (HILDE *et al.*, 1977) as starting in the middle of the continent. Thermal blanketing due to the continental lithosphere is the proposed cause of the initiation of a rift.

The second is a general speculation that all the large scale mountain building or orogeny may be associated with a collision process. If this speculation is right, the current notion on the Andean or Pacific-type orogeny would need serious reconsideration as to its reality. This problem is undoubtedly of enormous impact on the basic thinking in geodynamics.

The third point is that the concept of the Pacifica or similar nature would open a new approach to the understanding of the tectonic development of the continental Asia, since many, if not all, of the cratons and sub-cratons in Asia may also be the accreted landmasses travelled from afar.

Finally, the author would like remark that this is an extended abstract of the paper given orally at the International Symposium of Metallogeny of Asia, January 22, 1980 at the Geological Survey of Japan and also that the number of references cited is minimized.

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# Geology of Southeast Asia, a Review*

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## ABSTRACT

Five major structural elements of different ages are discerned in Southeast Asia. These are: Precambrian stable landmasses (Khorat plateau or Kontum massif and Sula Spur), Pre-Mesozoic orogenic belts (Annamitic Cordillera and Indochinese Variscides), Mesozoic orogenic belts (Southwest Japan, Mindoro-Palawan arc, Burmese-Malayan belt), Cenozoic geosynclinal basins (Northwest Borneo geosyncline, Taiwan Foothills zone) and Cenozoic-Recent island arcs (Northeast Japan, Philippines, Indonesia). These structural elements have their proper internal constitution, and can be considered as the orogenic belts created in different ages. The elements are not disposed in regular fashion but rather complexly superimposed to each other. In the superposed part of the orogenic belts of different ages, the older structure was profoundly deformed by the later orogenic movement, whereas the younger structure is also more or less influenced by the preexisting structures. The best examples of the intersection of two successive orogenic movements are central Japan and the Philippines, where the Mesozoic orogenic belts are distorted and fragmented by the genesis of the Cenozoic island arc systems. This kind of the superposition of different orogenies should be taken into account for the full understanding of the geological structure of Southeast Asia.

## INTRODUCTION

The geological structure is one of the fundamental information for the mineral exploration of a given area. The first step to analyse the structure is to establish an appropriate structural classification and to individualize the structural units. This has been attempted repeatedly for every countries of Southeast Asia by various authors. Synthetic works for whole Southeast Asia are, however, much less advanced mostly because of uneven level of the available information.

The geological framework of Southeast Asia is very complicated as the results of successive orogenic movements occurred many times through the geological time. The Eurasian continent has grown not simply from the nucleus to the outer side, but sometimes orogenies take place repeatedly in the same places.

The island arcs of the present day in fact determine the outline of the continent, but they comprise within themselves parts of the older orogenic mountains. Consequently older orogenic belts are secondarily distorted and fragmented by overprinting of the later orogenic belts. Therefore the analyses of the geological structure

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in this region should commence with segregating the orogenic belts of different ages.

In this paper, the writer tried to present one point of view which seems to him somewhat neglected so far. Detailed descriptions of the geological structure of each country should be referred to other published documents.

## STRUCTURAL UNITS DISCERNIBLE IN SOUTHEAST ASIA

Southeast Asia consists geologically of five major structural elements each of which corresponds to an orogenic belt of different age: Precambrian stable land masses, orogenic belts of Precambrian to pre-Mesozoic, Mesozoic, and Cenozoic-Recent ages, in addition to Cenozoic geosynclinal basins with reverse polarity.

Aside from the nuclear shields of Eurasian and Gondwana continents, Precambrian blocks of relatively small size are the first unit, standing stably and surrounded by the later orogenic belts. The Khorat plateau in Northeast Thailand is an example of this element.

The second element is the Variscan or older orogenic belts, greatly fragmented into small blocks when not amalgamated into later orogenies. It plays the role of basement under many of the later orogenic belts. The Annamitic Cordillera of Indochina is an example.

The third is the Mesozoic orogenic belts, well individualized in Southeast and East Asia, taking part of the Circum-Pacific orogenic zones. Burmese-Malayan orogenic belt is one of the best known examples, as well as Southwest Japan arc system. This element is also more or less deformed secondarily by partly overlying Cenozoic orogenic belts.

The fourth is the Cenozoic geosynclinal basins, developed locally on the pre-existing orogenic belts. These are characterized by heavy geosynclinal sedimentation throughout the Early Cenozoic time and by tectonism occurred in Late Cenozoic. The Northwest Borneo geosyncline is the best example. This element is individualized by its reverse polarity.

The last one is the Cenozoic orogenic belts, or present island arc systems. The tectonic activity in most of these belts began in Tertiary time but continues up to present. The so-called Alpine mountain system belongs to this element. The Northeast Japan arc, Sunda and Banda arcs, or Himalayan mountains are representatives of this structural element.

These elements are, in general, not disposed parallel to each other. Parts of the older orogenic belts are in fact involved in the later orogenic belts. At the points of intersection, the geological structure of the older ones is greatly modified secondarily, and becomes much complicated. On the contrary, the pre-existing structures influenced to the new organization of the younger orogenic belts. The bending of the Southwest Japan arc in Fossa Magna in central Japan is one of the examples of this type of superposition of the deformations.

## STABLE BLOCKS AND PRE-MESOZOIC OROGENIC BELTS

Southeast Asia is located on the margins of the three major plates: Eurasian, Indo-Australian and Pacific (Fig. 1). Most of Southeast Asia lie on the margin of the Eurasian plate, except for parts of Molucca island group and New Guinea. Himalayan mountains are, in turn, on the northern edge of the Indian plate, while the Afghanistan-Pakistan overlie the boundary of both.

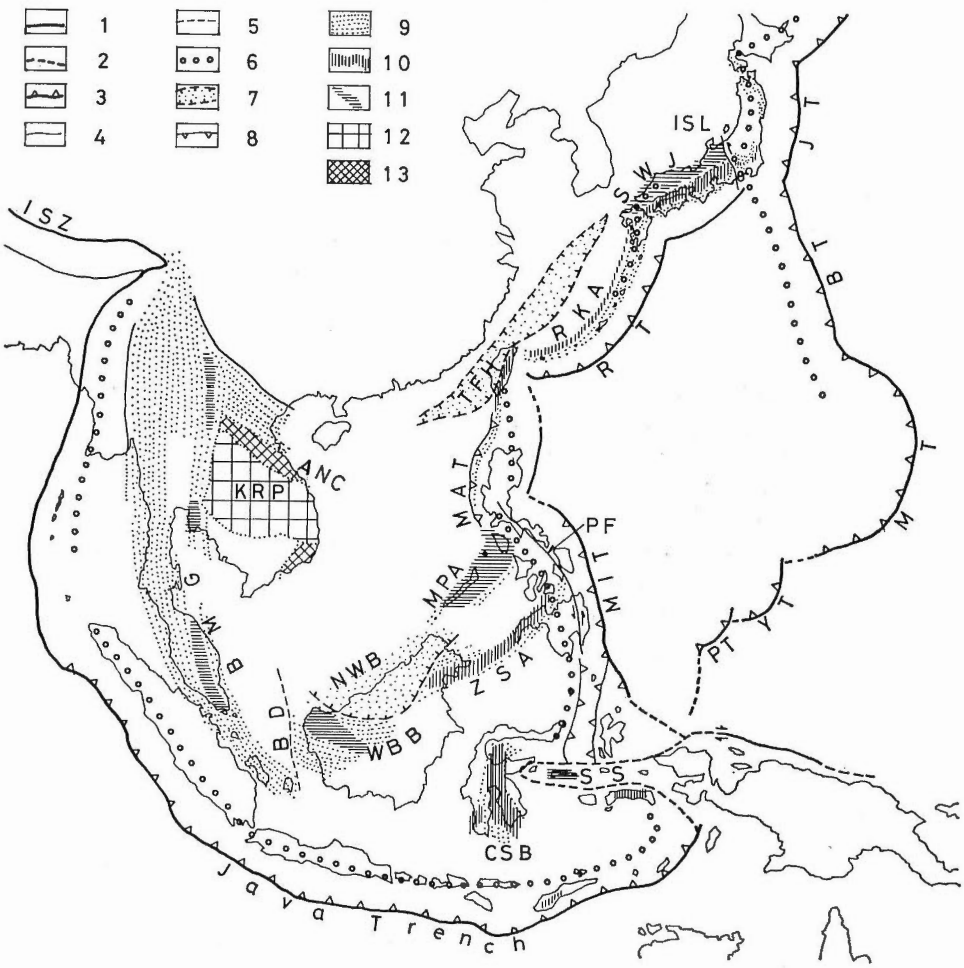


Fig. 1. Structural elements of Southeast Asia.

1. Plate boundaries, 2. Assumed plate boundaries, 3. Oceanic trenches located at the major plate boundaries, 4. Important faults, 5. Presumed faults, 6. Approximate axial traces of Quaternary volcanic belts, 7. Cenozoic geosynclinal basins of reverse polarity, 8. Oceanic trenches not related to the major plate boundaries, 9. Mesozoic orogenic belts, 10. Metamorphic axes of mostly Triassic age, 11. Metamorphic axes of mostly Cretaceous age, 12. Stable land mass, 13. Variscan orogenic belt.

Abbreviations: ANC, Annamitic Cordillera. BD, Billiton Depression. BMG, Burmese-Malayan geosynclinal belt. BT, Bonin trench. CSB, Central Sulawesi metamorphic belt. ISL, Itoigawa-Shizuoka Line. ISZ, Indus Suture Line. JT, Japan trench. KRP, Khorat plateau. MAT, Manila trench. MIT, Mindanao trench. MPA, Mindoro-Palawan arc. MT, Mariana trench. NWB, Northwest Borneo geosyncline. PF, Philippine Fault. PT, Palau trench. RKA, Ryukyu arc. RT, Ryukyu trench. S.S., Sula Spur. SWJ, Southwest Japan arc. TFH, Taiwan Foothills zone. WBB, West Borneo basement. YT, Yap trench. ZSA, Zamboanga Peninsula-Sulu arc.

The suture between the Pacific and Eurasian plates is represented by the line of oceanic trenches. Japan, Mariana, Yap and Palau trenches demarcate the western boundary of the Pacific plate. It becomes dormant in the north of Irian Jaya.

On the western margin of the Philippine plate, the topography is not very prominent in comparison with that of the Pacific plate boundary. Oceanic trenches develop in the southeastern side of the Ryukyu and Mindanao arcs, but only shallow depressions are present elsewhere. The Mindanao trench disappears in the eastern side of Halmahera, and is truncated by the translational plate boundary running in E-W direction, reflecting the westward protrusion of the Gondwana continental fragment (KATILI, 1975).

The suture between the Indian and Eurasian plates is clearly demarcated by the Java trench system which continues northwards to the concealed suture between Naga Hills and Shillong plateau in Upper Assam (STONELEY, 1974).

To the north of Himalayan mountains, the Indus suture line (GANSSER, 1974), with ophiolite sheets, limits the northern boundary of the Indian plate. It passes through Kashimir and converges to the western margin of the Axial zone of Pakistan-Afghanistan (STONELEY, 1974). It is further connected to the Zagros thrust zone (STÖCKLIN, 1968) in Iran, after a bent in the Gulf of Oman.

In the Eurasian plate, Precambrian masses remained stable during the Mesozoic and Cenozoic time. South China craton (Tectonic Map of Eurasia, 1966), englobing the North Vietnam Paraplatform (FONTAINE and WORKMAN, 1978), is a relatively large block of this kind, as well as Tibet block in the north of the Himalayan mountains.

The Indo-Australian plate is mostly composed of shields, except its oceanic part. It is believed to be a part of Gondwana land.

Beside these stable land masses of greater size, small but stable masses exist in Southeast Asia. The Khorat plateau in Northeast Thailand, together with Kontum massif in South Vietnam, acted as a nucleus of the continental accretion from which the later orogenic belts developed outwards. The belt of Variscan orogeny is added at the northeastern and southern sides of the Khorat plateau. The Annamitic Cordillera (FROMAGET, 1941) is comparatively well preserved in the northeastern side of this block.

These Variscan belts could have much greater extension than now, but parts of these belts have been amalgamated into the Mesozoic orogenic belts described below. It appears from the preserved parts that the belts encircle the Khorat plateau. FONTAINE and WORKMAN's (1978) North-Central, Southeastern and Southwestern Variscides correspond to the preserved parts.

## MESOZOIC OROGENIC BELTS

The Mesozoic fold belts in Southeast Asia are generally better preserved than the Variscan and older fold belts. It is more or less difficult, however, to reconstruct the whole tract of the orogens, because of the secondary deformations due to the involvement in later orogenic movements.

Unlike the present island arcs, geophysical information about the Mesozoic orogenic belts cannot be obtained. Moreover, the data on the geological structures and ages of tectonic activities are much poorer in quality and quantity. Thus the reconstruction of the whole figure of the belts is always somewhat uncertain.

Metamorphic rocks are generally good criteria for the purpose of reconstruction of the orogenic belts, because the nature and age of these rocks are relatively well known, beside the rocks are easy to recognize in field. Therefore, in this paper, the metamorphic rocks are used as the indicators of the existence of the relevant orogenic belt.

## Southwest Japan

Two pairs of metamorphic belts of contrasting nature are present in Southwest Japan (MIYASHIRO, 1973). One pair, in continental side, composed of low pressure type (Hida metamorphic belt) and high pressure type (Sangun metamorphic belt) metamorphic belts, is of Late Permian-Jurassic age. Another, in Pacific side, comprises a belt of low pressure type (Ryoke metamorphic belt) and that of high pressure type (Sanbagawa metamorphic belt) and is dated Jurassic-Cretaceous in age. These metamorphisms occurred within the Chichibu geosyncline (KOBAYASHI, 1941), suggesting the ocean-ward migration of tectonic activity (SATO, 1979). These pairs of metamorphic belts form the axial parts of the Mesozoic orogenic belt of Southwest Japan.

In the northeastern side of the Itoigawa-Shizuoka Line, which borders the Fossa Magna in central Japan, equivalents of these axes are secondarily deformed and fragmented into blocks by the superposition of Cenozoic Northeast Japan arc system (SATO, 1980).

The Mesozoic orogenic belt of Southwest Japan continues southwestwards to the Ryukyu arc, after a rather pronounced bent in Kyushu. Nearly the same structural disposition can be followed there, though largely submerged. The older pair of the metamorphic belts of Late Permian-Jurassic age is unknown, as it is entirely under the East China Sea. The younger pair is, in turn, known in some of the islets belonging to the arc (KONISHI, 1963). In this segment, Tertiary and Recent tectonic activity occurs roughly parallel to the Mesozoic belts, thus the latter escaped from the later modifications to some degree.

## Taiwan

The Central Range (BIQ, 1974) which forms the cordillera of Taiwan, consists of the crystalline basement overlain by Cretaceous to Miocene clastics. As the glaucophane schist is included in the crystalline basement and the latter is unconformably covered by Cretaceous, the basement complex has the equivalent of the Sanbagawa metamorphic belt of Southwest Japan in its interior. The original structure, before the involvement into the Cenozoic orogeny, is entirely unknown, because it was reorganized by the later deformations.

It is not easy to follow the southward extension of this belt. It might continue to the submarine ridge in Luzon strait to reach probably the submarine ridge between the Manila trench and the West Luzon trough (IDOE, 1974), to the west of Luzon island. It can not be connected directly to Luzon, because the geology of the volcanic Batan island group, topographically connecting Taiwan to Luzon, is different from that of the Central Range, as discussed later.

## Philippines

A metamorphic belt of pre-Jurassic age reappears in Mindoro-Palawan arc, to the southwest of the Philippine Fault, which longitudinally cuts the Cenozoic Philippine arc. The said belt is composed of metamorphic rocks of high pressure type, which is unconformably overlain by Middle-Upper Jurassic ammonite-bearing formations (ANDAL *et al.*, 1968; SATO and SEKI, 1972). The metamorphic rocks are exposed in Lubang, Mindoro and North Palawan, forming a structural belt (HASHIMOTO and SATO, 1973). Judging from the age and nature of metamorphism, this belt can be correlated to the Sangun belt of inner pair of the metamorphic belts of Southwest Japan. This is considerably deformed and fragmented as a whole, though overall structure remains perceptible.

This metamorphic belt is the remnant of the Mesozoic orogenic belt, escaped from the absorption in the Cenozoic orogenic belt. Together with the Zamboanga Peninsula-Sulu arc which is not fully studied yet, an orogenic belt of the Mesozoic age can be assumed in southwestern part of the archipelago, in NE-SW direction. The northeastward extension of the orogen is cut obliquely by the left-lateral Philippine Fault, just like Southwest Japan cut obliquely by the Itoigawa-Shizuoka Line. This particular geologic setting will be discussed later.

The southwestward extension of this Mesozoic orogenic belt is hard to establish. It disappears under the South China Sea. The relation between this arc and northern Borneo is obscure, though it seems to be linked to the crystalline basement in Sabah.

## Sulawesi

Upper Cretaceous pair of metamorphic belts are also present in the central part of Sulawesi. A zone of metamorphic rocks of low pressure type runs in N-S direction on the continental side, whereas another belt of high pressure type on the oceanic side (MIYASHIRO, 1973). The outward extension of this pair cannot be evidenced at present. Both northern and southern extremities are in fact masked by the Cenozoic belt or submerged under the sea. Probably later deformations have obliterated completely the original structures.

There is a block of Triassic crystalline rocks in Sula islands to the east. There is probably no relation between this metamorphic pair and Sula island metamorphics, the latter of which belong to the continental mass of Gondwana land.

## Burma-Malaya-Borneo

Encircling the Khorat plateau and its annex in Thailand and South Vietnam, the Mesozoic orogenic belts develop in diverging directions. On the west side of the Khorat plateau mass, the Burmese-Malayan geosyncline (KOBAYASHI, 1964; or Yunnan-Malaya geosyncline, BURTON, 1967) runs in N-S direction, covering most of Thailand, Shan plateau of Burma and Malay Peninsula, parallel to the Cenozoic Indo-Burman range. The internal organization of this geosyncline is variously classified (see for instance TJIA, 1978; BURTON, 1970). BURTON distinguished eu- and mio-geosynclinal furrows in Malaya and Peninsular Thailand. His eugeosynclinal furrow corresponds to the Central Belt of Malaya (RAJAH and YIN, 1980). The materials of this furrow are metamorphosed (up to amphibolite facies) and cleaved. As non-marine molassic sediments of Jurassic and Cretaceous age cover unconformably deformed sediments, the orogenic event has to have occurred before the Jurassic. BURTON's miogeosynclinal furrow received the sediments from Cambrian to Triassic, which are folded but not metamorphosed, as far as the exposed parts are concerned. Therefore, the geosyncline in question formed an orogenic belt in Mesozoic time.

The southward extension of this belt is difficult to follow. The orogen can be recognized as far south as in tin islands off Singapore. The connection to West Borneo is frequently suggested (for instance see GOBBETT and HUTCHISON, 1973). There is however a weak offset between the southern end of the Peninsular Malaya and West Borneo, probably displaced along the submerged zone of Billiton Depression (BEN-AVRAHAM and EMERY, 1973). The West Borneo basement (HAILE, 1974) of the Northwest Borneo geosyncline comprises the crystalline schist of pre-Jurassic age. This can therefore be the extension of the Burmese-Malayan orogenic belt.

If this tract of the Burmese-Malayan orogen is acceptable, the Cenozoic Indonesian orogenic belt is disposed slightly oblique to the former belt. In fact, the crystalline basement of probably Variscan age is known from South Sumatra, suggesting the overlapping of two successive belts at the south of Malay Peninsula.

The tongue-like termination of the belt in the central part of Borneo (suggested by VAN BEMMELEN, 1949, and adopted by GOBBETT and HUTCHISON, 1973) seems to be very improbable, though not definitively denied because of the lack of exposure. The connection between West Borneo and Sabah under the Cenozoic cover can also be suggested. If so, this belt continues to the Mindoro-Palawan arc.

Toward the north, the Burmese-Malayan orogenic belt seems to continue to western Yunnan. The eastern and central belts of the Malay Peninsula are connected by the Paklay-Petchabun fold belt (WORKMAN, 1975) in Northeast Thailand, of which the metamorphic axis is exposed in Chantaburi region of eastern Thailand. Thai-Burmese frontier belt is undoubtedly the northward extension of the miogeosynclinal zone of Malaya, although the exposed crystalline basement in the Main Western Range (BUNOPAS and VELLA, 1978) might be Precambrian in age.

### North Vietnam and Laos

Another essentially Mesozoic orogenic belt is known in North Vietnam and Laos. It is oriented in NW-SE direction (FONTAINE and WORKMAN, 1978), bounded on its northeastern limit by the Red River rift from the southwestern border of North Vietnam Paraplatform.

It is likely to be truncated obliquely by the Petchabun-Paklay belt in North Laos and converges to the latter. Its southeastward extension is unknown.

The Burmese-Malayan orogenic belt of Mesozoic age seems to extend in West Yunnan and central and southern Tibet, to the north of the Himalayan mountains (ACHARAYYA, 1978).

There is no reason to consider that a given orogenic belt or geosyncline continues infinitely to lateral direction. However, the Mesozoic belt of mobility in Southeast Asia is likely to encircle completely the old continental mass of Eurasia. It incorporated the older terrain within itself as seen in North Vietnam where the Mesozoic belt amalgamated the part of Variscan Annamitic Cordillera. On the other hand it is involved in the Cenozoic-Recent orogenic zones, and is rather considerably distorted and fragmented, as in the case of Southwest Japan and Mindoro-Palawan arc. The present state of the Mesozoic orogenic belts is therefore very fragmentary.

## MOSTLY CENOZOIC GEOSYNCLINAL BELTS

In Cenozoic time, new geosynclinal and orogenic belts commenced to be formed in whole Southeast Asia. These are the island arc systems now developed in the western margin of the Pacific and Indian oceans. Beside these, two peculiar geosynclinal furrows were born in the interior of the Mesozoic orogenic belts.

Thick sedimentation of geosynclinal nature occurred in Northwest Borneo and Taiwan, entirely on the continental crust, or within the already tectonized part. These geosynclinal furrows are characterized by the reverse polarity.

## Northwest Borneo Geosyncline

Beginning with the Cretaceous sedimentation, the Northwest Borneo geosyncline began to receive the Tertiary geosynclinal sediments. Two geosynclinal troughs are discriminated within it (HAILE, 1963). Eugeosynclinal furrow or Sibu zone (HAILE, 1974) is located in the oceanic side (south and southeast). Eugeosynclinal sediments including chert and ophiolite of Lower Tertiary accumulated in it. The southern border of the geosyncline corresponds to a part of the Burmese-Malayan orogenic belt. Miogeosynclinal furrow, or Miri zone (HAILE, 1974) is located in the South China Sea side (north and northwest), and is characterized by the Tertiary flysch and molasse sediments. The geosyncline was orogenized in Eocene-Oligocene, and the Sibu zone was slightly metamorphosed.

The orogenic movement occurred therefore in this area in Tertiary time. It is noteworthy that the organizational pattern is similar to the classical geosynclinal model, but the tectonic polarity is not oceanward, but continentward. This is quite exceptional as the Mesozoic and Cenezoic-Recent orogenic belts having the polarity directed to the oceanic side in whole Southeast Asia.

The outward extension of this geosyncline is not precisely known. Its both extremities are completely submerged in South China Sea basin. Its counterpart is nowhere observable in Asiatic continent.

## Taiwan Foothills Zone

The Foothills zone of Taiwan (BIQ, 1974) presents the similar organization. This is the zone of subsidence since Miocene. The sediments were brought from the east. In fact, its oceanic side is bounded by the Central Range, in which the Mesozoic crystalline schists form the basement. Folding and thrusting occurred in Pleistocene. The tectonic polarity is toward the west, or toward the Chinese continent, as demonstrated clearly by the vergence of folds and east dipping thrust faults. Therefore, this zone can be compared to the Northwest Borneo geosyncline by its reverse polarity, though the exposed part is much more reduced in comparison to the Borneo example.

This zone will extend under the East China Sea. The so-called Taiwan basin (WAGEMAN *et al.*, 1970), stretching roughly in NE-SW direction, seems to be the underwater extension of this zone. However, this does not extend farther, restricted in somewhat short belt, unlike the Mesozoic orogenic belts.

# CENOZOIC-RECENT OROGENIC BELTS

The present geological structure of Southeast Asia is defined fundamentally by the island arc systems, which are generally formed on the plate boundaries. These systems are not necessarily parallel to the general trend of the pre-existing structures, as emphasized many times. The older structures are frequently destroyed or amalgamated in new structures.

In the interior of the plates, tectonic activity takes place as well, but it is considerably different in nature from that of the arc-trench systems. It gives, in fact, less effect to alter the already established geological structures.

The internal constitutions of each island arc system in Southeast Asia is well documented already. Therefore the structural classification of individual area will not be discussed in detail here. Instead, the lateral connection between adjacent areas will be focused in this paper.

One of the most important features of island arcs is the combination of trench and volcanic arc. This will be used as a marker to follow the arc system in neighbouring area, because they are easy to recognize and give the clue to the correlation. The volcanic arcs, located in some distance from the consuming plate boundaries, are clearly traceable in Southeast Asia. The alignment of this arc gives the general configuration of the Cenozoic-Recent orogenic belts.

## Northeast Japan

The volcanic arc of Northeast Japan arc system is disposed parallel to the trench system. This is a composite arc, made of Kurile, northern Honshu, and Izu-Bonin arcs, each of which is joined with cusp-shaped linkage to the neighbour. Its oceanic side is flanked by non-volcanic arc. Seismic and other geophysical phenomena are prominent in this arc-trench system (see for instance SUGIMURA and UYEDA, 1973).

## Taiwan

The volcanic activity in Taiwan is confined to the Volcanic Inner Arc (BIQ, 1974) at the Pacific coast of South Taiwan. This volcanic arc is disposed slightly obliquely to the general trend of the geological structure of mainland. It extends southwards to the Luzon island, passing through Batan island group in Luzon Strait.

The relation of this volcanic belt with that of the Ryukyu arc is obscured by the presumed right-lateral fault running in N-S direction between Taiwan and the south end of the Ryukyu island group.

The Cenozoic orogenic belt of Taiwan is therefore not directly connected to the Ryukyu arc. There is some tectonic complication at the junction of two arcs.

## Philippines

Active volcanoes in the Philippines are aligned along the Cenozoic Philippine arc. It is parallel to the Mindanao trench system. The Cenozoic-Recent orogenic belt of the Philippines, englobing the volcanic arc, is overprinted on the NE-SW trending Mesozoic orogen, as discussed later in full detail, obliquely to the latter. The belt is therefore the southward extension of the Taiwan-Luzon arc.

## Northern Molucca Region

The volcanic belt of the Philippines continues southwards to Sangihe island group and north arm of Sulawesi. Another volcanic belt runs parallel to this along the west coast of the Halmahera island group. Therefore there are two rows of volcanic arcs in the northern Molucca region, probably reflecting the existence of a pair of two opposite dipping Wadati-Benioff zones (FITCH and MOLNAR, 1970). The structure is much complicated in this region, as this feature shows. Furthermore, the volcanic arcs mentioned are abruptly terminated at the Sorong Fault zone. The westward advancement of the Sula Spur is one of the available interpretation of this particular configuration (KATILI, 1975; HAMILTON, 1979).

## Indonesia

The geological structure of Indonesian archipelago is recently summarized by HAMILTON (1979). Active volcanoes are aligned on the line connecting the volcanic inner arc (KATILI, 1974; AUDLEY-CHARLES, 1974; HAMILTON, 1979). This volcanic arc is continuous through whole of the Sunda arc, and attains Barat Daja island chain bordering the eastern margin of the Banda Sea basin.

Its northward extension can be traced along the volcanic islands in Andaman Sea. It is parallel to the Andaman-Nicobar outer arc. It still extends northwards to the Central Burma Molasse bain (BRUNNSCHWEILER, 1974), where active volcanoes exist though discontinuously.

As this volcanic arc shows, Indonesian Cenozoic-Recent island arc system is disposed with various angles with the Mesozoic orogenic belt. It is slightly oblique to the Burmese-Malayan orogen in Sumatra, roughly parallel in Andaman-Nicobar segment, and nearly perpendicular in Sulawesi.

The Himalayan mountains are the Cenozoic belt, but this belt will not be treated in this paper.

## MODIFICATION OF THE OLDER STRUCTURES

As discussed briefly already, central Japan and the Philippines present much analogous tectonic settings. These are the examples of the oblique intersection of two successive orogenic belts of different ages. The older structures are more or less modified and partly disappear within the new orogenic belts (Fig. 2). It is worthy studying separately.

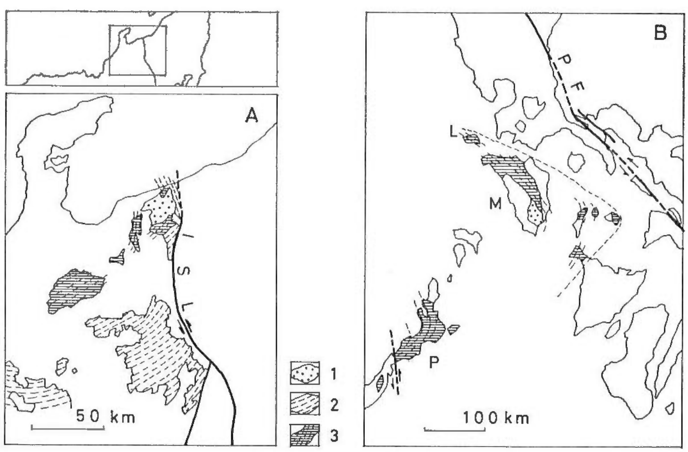


Fig. 2. Comparison of the geologic settings of central Japan and central Philippines.
A: Relation of the structural trend of the Paleozoic and Lower Mesozoic fold belts to the left-lateral Itoigawa-Shizuoka Line.
B: Relation of the Mindoro-Palawan arc to the left-lateral Philippine Fault. L. Lubang island, M. Mindoro P. Palawan island, PF. Philippine Fault.
1. Jurassic molasse basins. 2. Structural trend of the Paleozoic-Lower Mesozoic fold belts. 3. Exposures of the metamorphic rocks of pre-Jurassic age. Broken lines indicate the structural trends.

In both regions, prominent left-lateral faults cut the older structure. In Japan, it is the Itoigawa-Shizuoka Line which bounds the western margin of the Fossa Magna. In the Philippines, the Philippine Fault runs longitudinally through the Cenozoic island arc. Both are left-lateral faults, and oblique to the pre-existing orogenic belts.

The Sangun-Yamaguchi zone of Southwest Japan forms the arcuate belt of which the covex side is toward southeast. It appears that this curvature was resulted from the sinistral motion along the Itoigawa-Shizuoka Line, but this interpretation is misleading. In fact, the belt runs in NE-SW direction in the main part of Southwest Japan, but becomes parallel in the north, finally in NW-SE direction at the extreme north. The Itoigawa-Shizuoka Line cuts consequently its eastern flank of this arcuate belt.

This situation is also visible in the Mindoro-Palawan arc. The general trend of the arc is in NE-SW direction in Palawan and Mindoro segments, but it is bent in North Mindoro and finally takes the NW-SE direction in Lubang island. The Philippine Fault is therefore in similar fashion with respect to the relative disposition of the Itoigawa-Shizuoka Line and bent segment of the Sangun-Yamaguchi zone in Southwest Japan.

This particular situation cannot be explained by the drag effect of the sinistral faulting. It should be assumed that the bending of the pre-existing structures occurred earlier than the formation of the left-lateral faulting.

The metamorphic rocks consisting the bent belts of Mesozoic age are of high pressure type in both regions (SATO and SEKI, 1972). These are unconformably covered by the Lower Jurassic in Japan (KOBAYASHI *et al.*, 1957) and the Middle-Upper Jurassic in Mindoro (ANDAL *et al.*, 1968). The overlying sediments are of molassic nature, thus the ages of the tectonic activity are roughly correlatable.

On the northeastern side of the bounding faults in both regions, the volcanics and sedimentaries of Tertiary age were thickly accumulated. This sedimentation represents the geosynclinal sinking in Tertiary time. The Cenozoic orogenic belts are thus obliquely disposed to the Mesozoic ones in both regions (SATO, 1979). The interpretation of this particular geologic setting is not available at present. But this kind of superposition of successive orogenies should be stressed in the structural analysis of Southeast Asia. This is the reason why the necessity of the discrimination of the orogenic belts of different ages was emphasized in this paper.

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# Granitoids and Ore Genesis in East Asia*

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Extended Abstract

Magmatic-hydrothermal metallogenesis in East Asia can be explained by the magnetite-series/ilmenite-series petrogenesis of granitoids (ISHIHARA, 1981). Here, the metallogenesis is briefly reviewed in several areas in East Asia, dividing the metallogenic provinces into three tectonic settings. Emphasis is placed on the magnetite-series mineralization, in particular of porphyry type, along the eastern coast of East Asia.

## Island Arcs

Cenozoic magmatism occurs from Kamchatka peninsula to Sunda arc, passing through Japanese and Philippine islands which comprise typical island arc systems. Among these island arcs, most intense mineralization is known to occur in the East Japan arc and the Philippine arc. These arcs are composed mainly of the magnetite-series magmatism with some sporadic distribution of the ilmenite-series granitoids at the oceanic side (i.e., Hidaka belt in the East Japan arc and weakly magnetic magnetite-series in the Sierra Madre in Luzon island). These non-magnetic and weakly magnetic granitoids are associated with practically no mineralization.

The main sulfide mineralization is seen in much interior of the marginal sea side, a zone called Green Tuff belt in Japan. Vein and kuroko are major types. The vein types contain various metals that are combined with sulfur, but each metal is separated generally, as copper vein, lead-zinc vein, rhodochrosite vein and gold-silver vein. On the other hand, the kuroko types are polymetallic in a single orebody containing these metals mixed together. Ratio of the metals in the whole Green Tuff belt is more or less similar to those of crustal abundance, and the intensity of mineralization may be expressed as $n \times 10^4$ tons/km along the volcanic front (Table 1), which is one of the highest concentrations in common orogenic belts.

The same order of intense mineralization is seen in the Philippine mobile belt. This mineralization is predominated by copper that occurs mostly in porphyry types

Table 1 Ore metal produced per kilometer of volcanic front in the most productive magmatic arcs in East Asia

| Arc | Cu(t) | Pb(t) | Zn(t) | Ag(t) | Au(kg) |
|---|---|---|---|---|---|
| East Japan Arc | 3,400 | 2,100 | 6,600 | 8 | 270 |
| Philippines | 15,000 | 130 | 270 | tr | 450 |

Data for the Philippines are taken from BALCE *et al.*, this volume.
tr, trace

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(BALCE *et al.*, this volume). The porphyry copper deposits have high gold contents, whose Cu/Au reaches into 5,500 at Santo Tomas (MOTEGI, 1977). Besides the porphyry type, gold occurs in veins with various sulfides, sulfosalts and tellurides. Kuroko- and Cyprus-type massive sulfide deposits are present in minor extent.

## Continental Margins

Mesozoic volcano-plutonic belts along the eastern margin of East Asia can be considered as a typical example for this tectonic setting. In Sikhote Alin, South Korea and southern China, the magmatism is quite different from that occurs in the island arcs. Age of the magmatism becomes younger toward the marginal sea side (KIM, 1971; WANG *et al.*, 1980), and content of magnetite and ratio of volcanic rocks/plutonic rocks increase toward the same direction; thus forming magnetite-series volcano-plutonic belt along the coast and ilmenite-series plutonic belt behind the coastal belt.

Mineralization in the coastal magnetite-series belt is generally weak. In Sikhote Alin, some lead-zinc and slightly polymetallic, tin deposits are known (RADKEVICH, 1977). In South Korea, abundant small-size and medium-size tungsten-molybdenum deposits are associated with Cretaceous magmatism in Gyeongsang basin (PARK, this volume). Intense mineralization, such as scheelite and lead-zinc skarns at Sangdong and Yeonwha mines, respectively, is seen in an area to the north of the basin, related to Cretaceous granitoids (FARRAR *et al.*, 1978; YUN and SILBERMAN, 1979) of possibly magnetite-series.

The ilmenite-series belt is a zone of Triassic-Jurassic granitoids associated essentially with tungsten-tin deposits (Fig. 1). The ore deposits are generally vein type associated with or without greisenization. Some exogranitic ones are somehow polymetallic (e.g., Dachang, Guangsi province).

Late Mesozoic Southwest Japan has similarity in many ways to the geology of the continental margin. However, the paired belt of the magnetite-series rocks/ilmenite-series rocks and the lateral variation of the formation age suggest that this arc belongs to the island arc category. Here, tungsten-tin deposits are distributed in the ilmenite-series belt and molybdenum (lead-zinc) deposits are present in the magnetite-series belt.

## Continental Interior

The magnetite-series/ilmenite-series paired belt along the eastern coast of East Asia is most fundamentally controlled by northeast lineament called Sinian direction. In much interior of the ilmenite-series belt (Fig. 1), Mesozoic magmatism of possibly the magnetite-series occurs in tectonic framework with east-west and north-northeast lineaments (Chinese Academy of Geological Sciences, 1971). Volcanism and plutonism are seen in limited extent in an-orogenic environment. They are often associated with intense mineralizations.

Along the east-west Yangtze River folded belt, massive magnetite ores called "porphyrite iron ore" (Research Group of Porphyrite Iron Ore of the Middle-lower Yangtze Valley, 1977), occur in close association with intermediate, relatively alkaline porphyries in faulted-block basins. Several porphyry copper deposits, and skarn-type magnetite and lead-zinc deposits are also known to occur in this belt. The largest copper deposit at Dexing, Jiangxi Province (8.5 million tons copper metal), is a low temperature prophyry type, characterized by no potassic alteration but wide-spread phyllic alteration (YAN and HU, 1980).

Porphyry-type tungsten deposit which has been recently discovered at Yangchuling, Jiangxi province, is unique one occurring around tops of granodiorite porphyry and explosive breccia pipes (YAN *et al.*, 1980). In association with potassic and phyllic alterations, Mo-scheelite and molybdenite mineralization in disseminated and veinlet manner occurs controlled by boundary of these intrusive bodies.

Porphyry copper-molybdenum and porphyry-type and skarn-type molybdenum deposits appear to be present in the continental interior of northern China. These are associated with highly differentiated granite of the magnetite-series (FENG and ZHU,

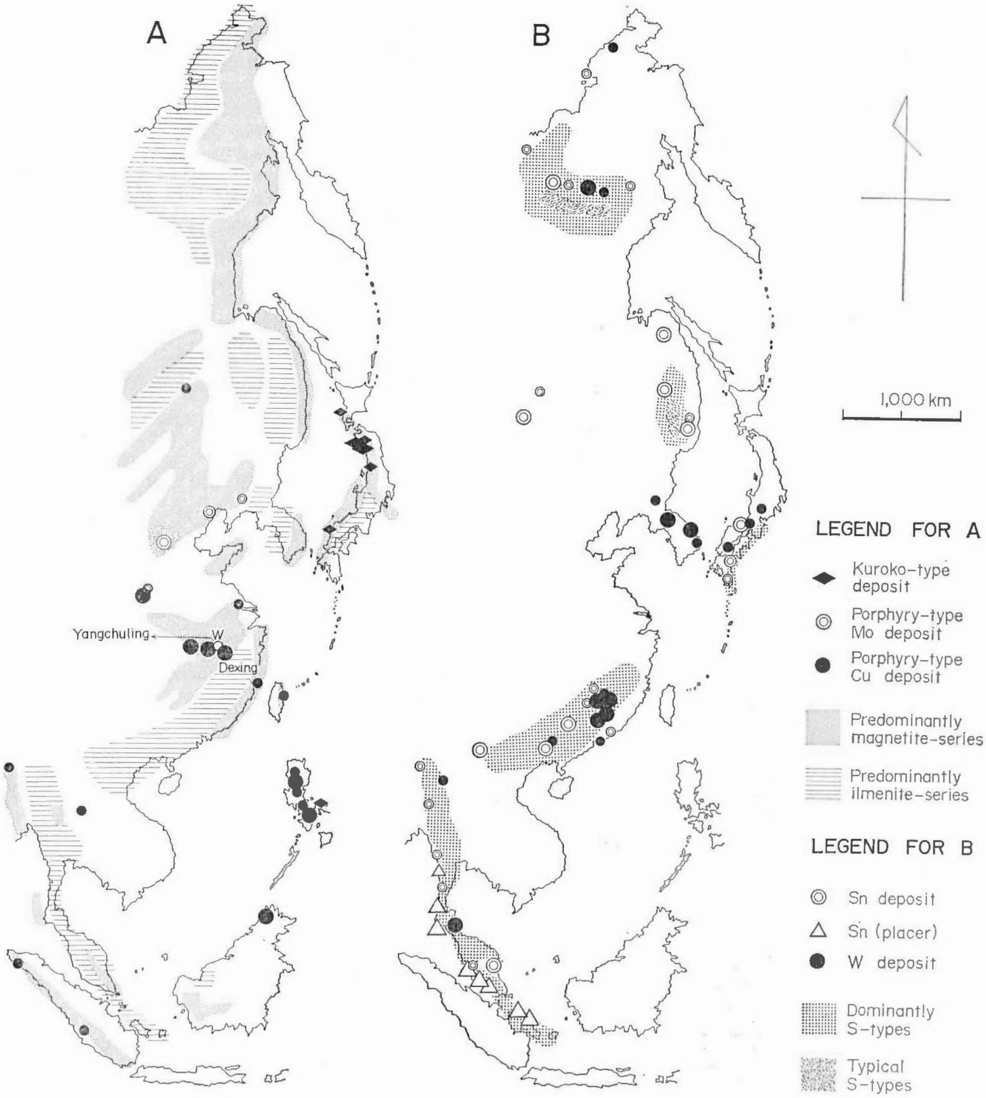


Fig. 1. Distribution of tin, tungsten and molybdenum deposits associated generally with the ilmenite-series granitoids, and porphyry-type copper, molybdenum and tungsten and kuroko-type deposits associated with the magnetite-series granitoids in East and Southeast Asia. For the granitoids classification, see TAKAHASHI *et al.* (1980). Relative size and distribution of the ore deposits are mainly taken from TATARINOV (1970).

1978; ISHIHARA and SHIBATA, 1980). The granites have petrographic similarlity to those associated with the rift-related porphyry molybdenum deposits in North America (SILLITOE, 1980a).

## Discussion and Conclusions

Granitic activities in Mesozoic-Cenozoic East Asia can be divided into three tectonic settings: island arc, continental interior and continental margin. The magmatism is most intense in the first two settings. The island arc magmatism is characterized by a paired magnetite-series/ilmenite-series belt parallel to the island arc structure, and the continental margin magmatism also shows a linear, northeast trend but has a reversed pair, i.e., the magnetite-series along the coast and the ilmenite-series in the interior. The continental interior magmatism is scattered through a wide area in anorogenic environment.

Mesozoic magmatism of the entire region cannot be explained by the simple subduction model of UYEDA and MIYASHIRO (1974); the oceanward migration of the magmatism across the continental margin contradicts particularly to this model. The island arc magmatism could have been caused by major subduction of oceanic lithosphere. Magnetite-series magmatism of the continental margin may have been developed by rifting and opening of the marginal basins, because the magmatism is preceded by formation of sedimentary basins. Genesis of the ilmenite-series magmatism of the continental margin is still unclear; a collision hypothesis may have one possibility. Magnetite-series magmatism of the continental interior that occurs in the complexed tectonic frameworks may have been born with rifting within the continental plates.

Sulfide mineralization is generally intense in magnetite-series terrains of the island arc setting and to some degree of the continental interior setting. Most of porphyry copper and molybdenum deposits are known to occur in these terrains. On the contrary, the continental margin magnetite-series belt is poorly mineralized. Only a few prospects of porphyry-type mineralization have been reported from Zhejiang-Guangdong and Gyeongsang volcano-plutonic basins. Cauldron subsidence may have developed dominantly in these terrains, an oldest one of which may be a Jurassic one in Fujian province (20 × 30 km, CHEN *et al.*, 1980). Lack of large porphyry-type deposits may be explained by the caldera-forming style of magmatism (SILLITOE, 1980b). However, general paucity of sulfide deposits may indicate inadequate supply of sulfur and chlorine into this magmatism that has been originated in opening of marginal basins (ISHIHARA, 1981).

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# Metallogenesis in the Precambrians of India*

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## ABSTRACT

The Precambrians of India are the principal sources of iron and manganese, basemetal, gold and alloy metal ore deposits. A spectacular lineament divides the Indian Peninsular Shield into two contrasted segments. The southern segment is girdled by an Archean granulite belt. Inwards, gneisses and two distinct greenstone-banded iron sequences span the Lower Proterozoic time and perhaps the Middle Proterozoic too. Upper Proterozoic platform cover rests unconformably on them in separate basins. In the northern segment the greenstone belts are not so distinct, and the Middle Proterozoic has a better development. Upper Proterozic platform cover is more widespread.

The younger greenstone belts of the southern segment are the major sources of iron and manganese ores. The associated ultramafics provide chromite, alloy metal ores and nickel. The overlying supracrustals in the southern belt and the Lower-Middle Proterozoic sequences of the northern segment contain the major basemetal ore deposits. Gold is confined to the older greenstone belt of the southern segment.

The Himalayan basement is essentially Upper Proterozoic though the base might be even older. These Precambrians occupy the cores of the mountain belt. Sporadic basemetal mineralisations occur in the lower part of the basement.

## INTRODUCTION

The Precambrians of India provide the major sources of metalliferous ore deposits as well as a host of other industrial minerals and rocks which are currently being exploited in the country. The major ore minerals comprise those of iron, manganese, gold, basemetals (copper, lead and zinc) chromium and nickel. A brief summary of the main characteristics of the Precambrians of Indian peninsula and the Himalaya and their metallogenic characteristics are given in the following text.

## GEOLOGY OF THE PRECAMBRIANS OF INDIA

The peninsula is a huge Precambrian shield, broadly triangular in shape with two northern promonotories, one extending northwestwards into Rajasthan from northern central India and the other northeastwards into the northeastern corner of India. In

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the latter area a prominent inlier of Precambrians is exposed in the Meghalaya upland. This segment is isolated from the northeastern edge of the shield but the gap is narrow. Along the coast, the peninsular shield has a variable fringe of Mesozoic-Cenozoic platform cover in faulted terrace as well as shelves in the immediate vicinity of the littoral area. In the northwestern part, Upper Proterozoic platform cover flanks the crystallines and are progressively over-lapped perhaps by still younger sediments till the Potwar plateau is reached. In the northcentral part, a broad valley of young sediments marks the edge of the shield, and the sedimentary trough of this Ganga alluvial country is very young and terminates in the foothills belt of the Cenozoic molasse flanking the Himalayan mountains. The alluvial trough becomes narrow between the Himalaya and the edges of the shield as one proceeds eastwards. In the northeastern sector sedimentary piles of Cenozoic troughs are thrust against the shield elements.

From geological and structural considerations the Indian shield appears to be divided into two contrasted segments by an ENE-WSW linear defile along the courses of the Narmada and the Son rivers. This linear element, generally referred to as the Narmada-Son lineament is an enigmatic zone of suspected activity even from Precambrian times.

The shield element to the north is in a major part a platform with Upper Proterozoic platform cover, the underlying crystallines rising up in the west and east in a spectacular amphitheatre.

To the south the shield is over a major part composed of crystallines with areally separate basins of Upper Proterozoic sedimentary cover showing only mild or no deformation. Three major regional grabens or half grabens split this shield into segments; and these grabens are providing channels to major rivers like the Godavari, the Mahanadi and the Damodar (with tributaries). The Godavari and Mahanadi grabens have sedimentary fills ranging in age from Upper Proterozoic to Mesozoic, but with a large stratigraphic gap corresponding to Lower Paleozoic. The Damodar graben is filled mainly with Upper Paleozoic and Mesozoic sediments. These three grabens radiate to southwest, from the Narmada-Son lineament zone.

Classification of the Precambrian formations of the Indian shield by detailed lithological and structural mapping is going through a developing stage. Controversies are many, and inter-regional correlation is still debated. For the sake of convenience of discussion the shield elements referred to earlier can be described separately, namely, South Indian Shield, Central Indian Shield (between Godavari and Mahanadi grabens), East Indian Shield (between Mahanadi graben and Bengal basin), the Meghalaya Wedge (or NE Wedge) and the North Indian Shield or Vindhyan platform (Fig. 1).

The major lithostratigraphic units of the Precambrians of India are listed in Table 1 showing a tentative correlation. The distinctive features of the Vindhyan platform as contrasted from the segment lying to the south of the Narmada-Son lineament are quite obvious. The southern segment has a peripheral Archean granulite belt. From Archean-Lower Proterozoic time the greenstone-granite diapir type evolution has been repeated at least twice before the Upper Proterozoic. Middle Proterozoic separation is not clearly discernible except in central and eastern sectors.

The greenstone-granite diapir process of evolution is not clearly discernible in the North Indian Shield, which also exposes a more complete Middle Proterozoic sequence as well as more widespread Upper Proterozoics. Further north in the core of the Himalaya, Middle-Upper Proterozoic development reached the climax with great

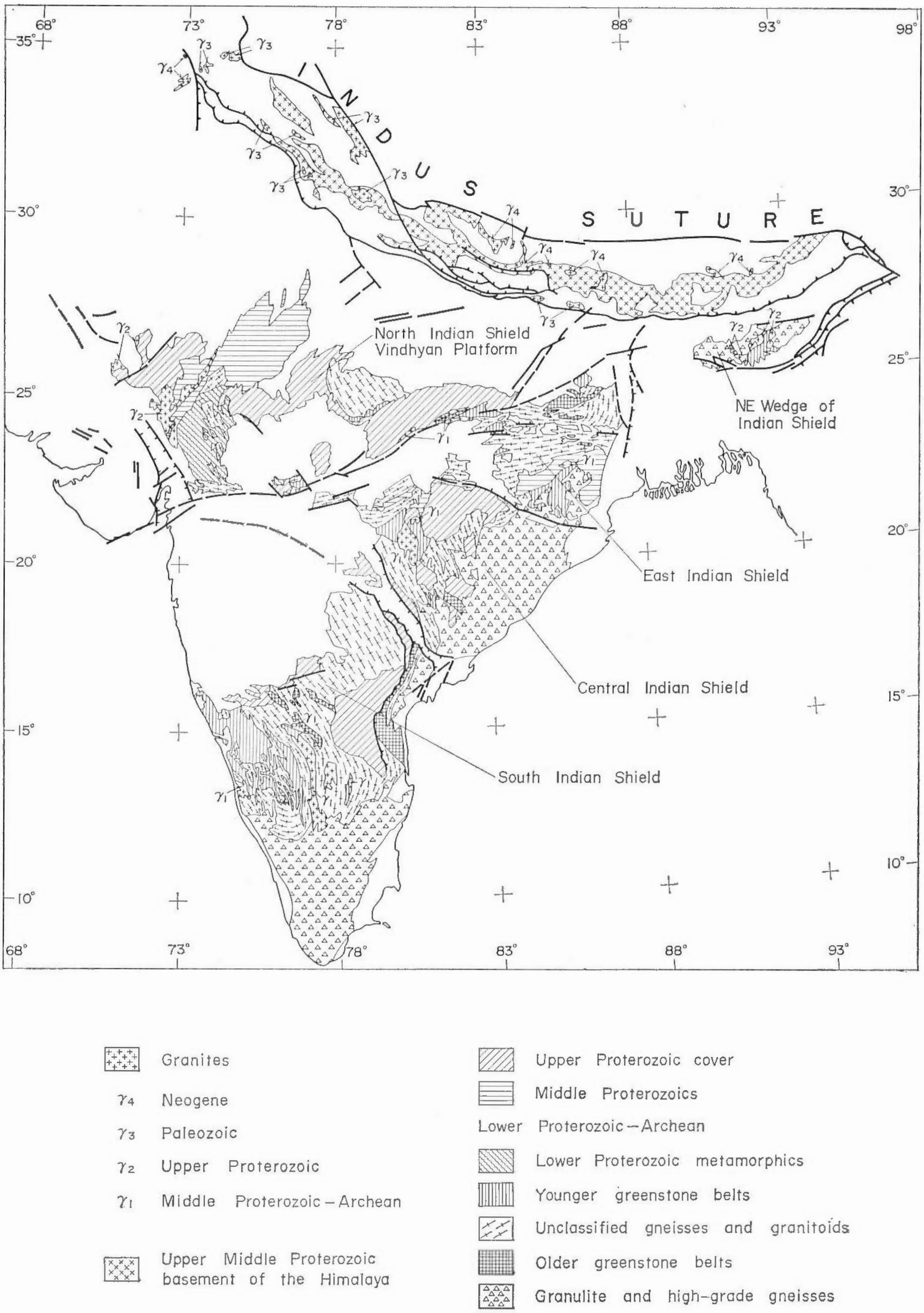


Fig. 1. Principal elements of the Indian shield and Precambrians of Himalaya.

Table 1 Precambrian stratigraphy

| Age (Ma) | South Indian Shield | | Central Indian Shield |
|---|---|---|---|
| 600 | Bhima, Kurnool and Palnad Groups; Sullavai-Penganga Group, Godavari Graben | | Jungel Fm, Chattisgarh Group, Indravati Group, Sukma Group |
| Upper Proterozoic | Pakhal-Alabaka Groups, Kuddapah and Kaladgi Groups | | Narainpur and Khairagarh Groups |
| 1,600 | | | |
| Middle Proterozoic | —— ? —— | | Chilpi Group |
| 2,000<br>Lower Proterozoic | Dharwar Super Group (Younger greenstone) | Closepet granite | Sausar Group (?) Dongargarh granite Sakoli-Bailadila-Upper Mahakoshal Groups (Younger greenstones) |
| 2,600 Archean | Peninsular gneisses, Kanara granites | | Amgaon-Sakoli-Bengpal Groups Tirodi Gneisses, Malanjkhand granite, Rampur granite |
| 3,000 Archean | Sargur schist complex (Older greenstones) | | Bengpal-Amgaon-Lower Mahakoshal Groups (Older greenstones) |
| 3,500 Archean | Eastern Ghats granulite complex | | |

Table 2 Characteristics of the Precambrians

| Age (Ma) | Stratigraphic group | | Lithology |
|---|---|---|---|
| 600 | Bhima, Kurnool and Palnad Groups | | Limestone-dolomite, shale, quartzite |
| | Kaladgi and Cuddapah Groups | | Quartzite, slates, limestone-dolomite, hematite schists, ultrabasic rocks in diatremes |
| 1,600 | | Ranibennur Group | Mangan-phyllites, ankeritic limestones, greywackes, chlorite phyllites |
| 2,000 | Dharwar Supergroup | Chitradurga Group | Agglomerates, tuffs, ultrabasics, pillow lavas, ferruginous-manganiferous cherts, dolomites-limestones, phyllites, orthoquartzites, conglomerates |
| | Closepet granite | Bababudan Group | Banded iron formation, argillites, mafic lavas, orthoquartzites |
| 2,600 | Peninsular gneiss | | Granites, granodiorites, migmatites, tonalites |
| 3,000 | Sargur schist complex | | Magnetite quartzites, graphitic schists, fuchsite quartzites, kyanite-staurolite schists, cordierite granulites, crystalline limestone and dolomites, mafic and ultramafic flows, anorthosite pods |
| 3,500 | Granulite complex of Eastern Ghats | | Nepheline syenites, anorthosites, carbonatites, pink and grey granites, migmatites, leptynites, leptites, two-pyroxene granulites, enderbites, hypersthene granites, garnet-sillimanite-cordierite gneisses, diopside granulites |

of Indian Shield and the Himalaya

| East Indian Shield | Vindhyan Platform | NE Wedge | Himalaya |
|---|---|---|---|
| Kolhan Form | Malani volcanics and granite | | Vaikrita-Haimanta-Garbyang Groups; Jaunsar, Bomdila, |
| Pegmatites of Bihar | Vindhyan Super Group, Pegmatites of Rajasthan, Erinpura granite | Mylliem granite | Shali-Krol-infra Krol-Garhwal Groups, Upper Proterozoic of Lohit, Salkhala-Dogra-Simla-Daling-Tanawal-Sela Groups. |
| Gangpur Group | Delhi-Gwalior Groups (greenstones ?) | | Jutogh-Chail-Almora-Dudatoli Groups, Paro Group, Central Himalayan gneisses |
| Dhanjori-Simplipal-Dalma-Noamundi Groups (Younger greenstones) | Aravalli Group Bijawar-Champaner Groups (Greenstones ?) | Shillong Group (Younger greenstones) | |
| Singhbhum granite, Chhotanagpur gneisses | Banded gneissic complex, Bundelkhand granite, Berach granite | Shillong Mikir gneiss | |
| Gorumahisani-Sukinda Group and Gaya-Hazaribagh schist belt (Older greenstones) | Pre-Aravalli schist complex | Older schist complex (Older greenstones) | |
| | Isolated granulites | Isolated granulite facies assemblages | |

of the South Indian Shield

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| Mild/no deformation and metamorphism | Cu (hypothermal) syngenetic sulphides, limestone-dolomite, diamonds |
| Mild deformation and metamorphism | Basemetal sulphides (syngenetic), limestone-dolomite, baryte, diamond |
| Mild deformation, feeble metamorphism | Fe, Mn |
| Tight folding, greenschist facies assemblages | Placer Au, Cr, basemetals, banded iron ore, Mn, limestone-dolomites |
| Open folds, greenschist-amphitolite facies assemblages | Fe, Au |
| Complex deformation, amphibolite facies assemblage | |
| Tight folds, multiple deformation, amphibolite-granulite facies assemblages | Au, W, Cr, Ti-Fe, V, baryte, limestone dolomite, mica |
| Multiple deformation, granulite facies assemblages, retrogression | Rare earths, radioactive minerals, Mn, basemetal sulphides, baryte, graphite, magnesite |

Table 3 Characteristics of the Precambrians of

| Age (Ma) | Stratigraphic group | Lithology |
|---|---|---|
| 600 | Jungel Fm, Chhattisgarh-Indravati-Sukma Groups | Orthoquartzite-carbonates (and shales) and tuffs |
| | Sullavai-Penganga Groups | |
| | Narainpur-Khairagarh, Alabaka-Pakhal Groups | Sandstone-tuff-basic-intermediate lavas (greenstones), quartzite-slates |
| 1,600 | Chilpi Group | Sandstone-shale-sub-greywackes, arkose |
| | Sauser Group (?) (may be older) than Sakoli Group | Impure calc-magnesian sediments, pelitic-quartzo-feldspathic sediments, metamorphosed greenstones, Fe-Mn sediments |
| 2,000 | Dongargarh granite | Granite, granodiorite, rhyolite (granite diapir) |
| | Sakoli-Bailadila-Upper Mahakoshal Groups | Pelitic and quartzo-feldspathic sediments, limestone, banded iron formations, Mn-sediments, greenstones, rhyolites |
| 2,600 | Bengpal gneisses, Amgaon gneisses, Tirodi gneisses, Malanjkhand granite, Rampur granite | Granite, granodiorite gneisses, migmatites, gregarious batholiths (granite diapir) |
| 3,000 | Bengpal-Amgaon-Lower Mahakoshal Groups | Greenstones, komatiites, ultrabasic plutons, fuchsite quartzites, pelitic quartzofeldspathic sediments, cordierite gneiss, magnetite-grunerite rocks |
| 3,500 | Granulites of Kondagaon-Kalahandi (Eastern Ghats) | Garnet-sillimanite-cordierite-graphite gneisses, two-pyroxene granulites, enderbites, hypersthene granites, calc-silicates, leptynites, leptites, anorthosites, gabbros, kinzigites |

Table 4 Characteristics of the Precambrian

| Age (Ma) | Stratigraphic group | Lithology |
|---|---|---|
| 600 | Kolhan Fm. | Shale-limestone-sandstone |
| | Pegmatites of Bihar | Mica-pegmatites |
| 1,600 | Gangpur Group | Pelitic schists, marble-dolomite, manganese-sediments |
| 2,000 | Gabbros, ultrabasics, Bonai granite | |
| | Dhanjori-Simlipal-Dalma-Noamundi Group | Manganese-shales, banded iron formation, quartzites, greywackes |
| 2,600 | Romapahari granites | |
| | Ultrabasics, gabbro | |
| | Singhbhum granite, Chhotanagpur gneisses | Granites and gneisses, diorites |
| 3,000 | Gorumahisani-Sukinda Group and Gaya-Hazaribagh schist belt | Banded iron formation, Fe-shales, limestone-dolomites, carbon-phyllites, schists, meta-greenstones, meta-ultramafics, fuchsite quartzites |
| 3,500 | Granulite complex | Garnet-sillimanite gneisses and pyroxene granulites, anorthosites |

Central Indian Shield (including Godavari graben)

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| Mild deformation, no metamorphism | Mn, limestone, dolomites, phosphates |
| *ditto.* Locally intense deformation, moderate metamorphism | Rare Au, pyrite-chalcopyrite |
| Moderate deformation, feeble metamorphism | |
| Intense deformation, amphibolite-granulite facies assemblages in part | Mn, limestone-dolomites, W |
| | Rare pyrite-chalcopyrite, fluorite |
| Multiple deformation, greenschist facies assemblages | Fe-Mn, basemetal sulphides |
| Complex deformation, amphibolite facies assemblages | Cu (hydrothermal) |
| Multiple deformation, amphibolite-granulite facies assemblages | Fe, baryte, Cr, Ni, andalusite-sillimanite (?), basemetal sulphides |
| Complex deformation, granulite facies assemblages, retrogressions | Sillimanite, doubtful basemetal sulphides |

of the East Indian Shield

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| Mild/no deformation, feeble metamorphism | Limestone |
| | Mica, Cb, W |
| Multiple deformation, greenschist facies assemblages | Mn, limestone |
| Multiple deformation, greenschist facies assemblages | Cr, Ni, Au, Fe-Mn, basemetal sulphides, apatite-magnetite-uraninite |
| Complex deformation, amphibolite facies assemblages in enclaves | |
| Multiple deformation, amphibolite facies assemblages | Fe, Cr, Ni, Sn |
| Multiple deformation, granulite facies assemblages | V, Ti, Fe, W |

Table 5 Characteristics of the

| Age (Ma) | Stratigraphic group | Lithology |
|---|---|---|
| 600 | Malani volcanics and granites | Rhyolite, granite |
| | Kimberlites | Kimberlites |
| | Vindhyan Super-group | Orthoquartzite-shale-carbonate |
| 1,600 | Pegmatites of Rajasthan, | Pegmatites, granites |
| | Erinpura Chhapoli granite | Alkaline complex, |
| | Nepheline syenite | granite |
| | Bairat granite | |
| | Delhi-Gwalior Groups | Orthoquartzite, carbonate, pelites, conglomerates, impure calcareous rocks, basic lavas |
| | Sarara granite | Granite |
| 2,000 | Gavaliya migmatite, Dadikar granite | |
| | Aravalli Group | Conglomerate, quartzite, greywacke, sulphidic sapropelites, phosphorite-dolomite-carbon-phyllite, basic and ultrabasic rocks |
| | Bijawar-Champaner Group | Orthoquartzite, carbonate, greenstones, banded iron formation, impure limestones, Fe-Mn sediments, phosphorites, greenstone |
| 2,600 | Banded gneissic complex, Bundelkhand granite, Berach granite | Granodiorite gneiss, granites, paragneisses |
| 3,000 | Pre-Aravalli schist complex | Quartzites, garnet-granulites, high grade aluminous schists, marbles, basic rocks |
| 3,500 | Isolated granulite enclaves | Diverse granulites, enderbites (rare) |

Table 6 Characteristics of the Precambrians

| Age (Ma) | Stratigraphic group | Lithology |
|---|---|---|
| 600 | Mylliem granite | Granite |
| 1,600 | | |
| 2,000 | Shillong Group | Quartzites, shale, slate, mica schists, metamorphosed greenstones, banded iron formation |
| 2,600 | Shillong-Mikir gneisses | Granitic gneisses |
| 3,000 | Older schist complex | Biotite-sillimanite-corundum-cordierite rock, banded magnetite quartzite |
| 3,500 | Isolated granulites | Hornblende-pyroxene granulites |

Table 7 Characteristics of the

| Age (Ma) | Stratigraphic group | Lithology |
|---|---|---|
| 600 | Vaikrita-Haimanta-Garbyang Groups, Jaunsar Group, Shali-Krol, Infra-Krol-Garhwal Groups, Bomdila Group, Upper Proterozoics of Lohit | Quartzite-phyllite, limestone, dolomite |
| | Salkhala-Dogra-Simla-Tanawal-Daling-Sela Groups | Carbon-slates, graphitic phyllites, limestone, quartzites, high grade schists, banded iron formation |
| | Jutogh-Chail-Almora-Dudatoli Groups, Paro Group, Central Himalayan gneisses | Quartzite, carbon-phyllites and limestones, mica-schists, para- and ortho-gneisses, basic rocks |

Precambrian of Vindhyan Platform

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| No deformation | |
| Feeble or no deformation in Lower Vindhyan, feeble or no metamorphism | Diamond, limestone, syngenetic sulphides (pyrite-pyrrhotite), mica, rare earths |
| Multiple deformation, amphibolite facies assemblage | Basemetal sulphides, pyrite-pyrrhotite |
| Multiple deformation, amphibolite-facies assemblages | Pb-Zn sulphides, phosphates, W |
| | Fe-Mn, phosphates |
| Multiple deformation, amphibolite-granulite facies assemblages | |
| Complex deformation, granulite facies assemblages | |

of the North Eastern Wedge of Shield

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| Moderate to intense deformation, greenschist facies-amphibolite facies assemblages | Fe, basemetal sulphides |
| Intense deformation, amphibolite-granulite facies, pyroxene hornfels facies assemblages | Sillimanite, corundum, Fe |
| Intense deformation, granulite facies assemblages | |

Precambrians of the Himalaya

| Structure and metamorphism | Metallogenic characteristics |
|---|---|
| Complex structure, greenschists facies assemblages | Syngenetic sulphides, limestone, hematite-chert |
| Complex structures, amphibolite facies assemblages | Basemetal sulphides, Fe |
| Complex structure, amphibolite facies metamorphism | Fe |

diversities in facies and structure.

It would be further evident from Tables 2–7, detailing the lithological, structural, metamorphic and metallogenic characteristics of each sector of the shield, that the older and younger greenstone belts are the main sources of iron, manganese and gold (confined to the older greenstone sequences). The supracrustals in the younger greenstone belt contain basemetal sulphides, variously mobilised by deformation and metamorphism, but the occurrences are not many. On the contrary better developments of basemetal sulphides are witnessed between Lower Proterozoic and Middle Proterozoic in thicker clastic sequences atop the younger greenstones. The ultrabasic rocks of the older greenstones provide the major sources of chromium, nickel, vanadium and barytes, though the base of Upper Proterozoic in the South Indian Shield contains abundant barytes again. Whatever little tin and columbium-tantalum mineralisation is reported and has been explored/exploited to a limited extent, they are from the older greenstone belts, being confined to the later pegmatites in them. Mica deposits are entirely restricted to the 700 Ma–1,000 Ma old pegmatites traversing the greenstone belts of both the segments of the shield. Middle and Upper Proterozoic sedimentary blankets are the principal sources of limestones-dolomites. These calcareous assemblages also contain significant disseminations of syngenetic sulphides.

The Precambrians in the core of the Himalaya, involved in multiple deformations, show a wider development of the Upper Proterozoic sequences with carbonate-sequences dominating the top and pelipsammitic sequences dominating the base. Dating of the basal sequences is far from certain, and it is quite likely that they extend well beyond 1,600 Ma. It is also significant that basemetal occurrences are reported from the older sequence of the Himalayan Upper Proterozoics, while the younger Upper Proterozoics provide the limestones.

The information on South Indian Shield is derived partly from the paper by Radhakrishna and Vasudev (1977), while those on the Vindhyan Platform and East Indian Shield are mostly after Raja Rao *et al.* (1971), Iyengar and Banerjee (1972) and Mazumdar (1978). The summarised data on the Himalaya are from a previous publication of the writer (Ray, 1975), and the data on Central Indian Shield are based on recent unpublished work of the writer. In the absence of any recent documentation on the NE Wedge, the information has been collected from the work of Pascoe (1973), modified by the writer on the basis of personal communications from geologists active in the area.

## METALLOGENIC CHARACTERISTICS

### South Indian Shield

It will be evident from Table 2 that the banded iron formations of the Lower Proterozoics are the major sources of stratabound sedimentary metamorphic deposits of iron and manganese. The older greenstone belt (Archean) also contains such banded iron formations which are predominently metamorphosed to magnetite quartzites. The ultramafics associated with the greenstone belts are sources of early magmatic chromite and vanadiferous-titaniferous magnetites. Late granite intrusions in the Archean granulite belt and shear zones filled up by reefs contain hydrothermal basemetal suphides; but more promising sedimentary-syngenetic basemetal mineralisations are associated with carbonate-bearing supracrustals in the greenstone belts, which have subsequently been remobilised by metamorphism and/or igneous activity.

Sedimentary syngenetic sulphides are common in the carbonate facies of the Upper Proterozoic cover as well. Gold mineralisation is entirely restricted to the older greenstone belt.

## Central Indian Shield

In the granulite terrain of Central Indian Shield quartz reefs traversing shear zones contain sporadic basemetal mineralisation of hydrothermal origin. Banded iron formation of the two greenstone sequences are both sources of sedimentary metamorphic iron ore deposits. As in the South Indian Shield, the sedimentary metamorphic manganese deposits are associated with the younger greenstone belt. The banded iron formation of the older greenstone belt is more metamorphosed and amphibole/magnetite spinel bearing. The granite diapirs in the older greenstone belt contain hydrothermal copper which may be remobilisations from supracrustals. Hydrothermal fluorite is common in the granites penetrating the younger greenstone belt. The Middle Proterozoic carbonate facies is associated with sedimentary metamorphic manganese deposits which are metamorphosed to varying degrees. In the Upper Proterozoic cover the greenstone lavas contain rare gold and hydrothermal sulphides. The Upper Proterozoic carbonate facies is occasionally associated with sedimentary manganese and phosphatic lenses (Table 3).

## East Indian Shield

The iron-manganese metallogeny in East Indian Shield resembles that of the South Indian Shield. The iron-manganese association in the younger greenstone belt is also similar. The ultramafics associated with the greenstone belt contain magnetic segregations of chromite and vanadiferous/titaniferous magnetites. Presence of nickel in the oxide and silicate lattice is also recorded. The Lower-Middle Proterozoic supracrustals contain basemetal mineralisation (sedimentary-syngenetic) in various forms of remobilisation, due to metamorphism and igneous activity, the latter being also responsible for apatite, magnetite and uranium mineralisations. The Middle Proterozoic carbonate facies, as in the Central Indian Shield, contains sedimentary metamorphic manganese. The Upper Proterozic pegmatites are the major sources of mica and rare earth mineralisations (Table 4).

## Vidhyan Platform

The Lower Proterozoic greenstone belt does contain banded iron-managenese formations with sedimentary metamorphic deposits. In the chert facies there are phosphates too. In the overlying supracrustals there are sulphidic sapropelites and phosphate-dolomite carbon shales which contain the most important lead-zinc mineralisation (sedimentary-syngenetic) of the country. In the Upper Proterozoic pegmatites micas are common with rare earth minerals. The cover sequence reveals kimberlitic diatremes with diamond. The basal sequence of the cover is rich in syngenetic sulphide mineralisation (Table 5). The contrast in the history of metallogenic evolution as compared to the Southern Shield is quite evident.

## North Eastern Wedge

The Archean metamorphics of the wedge contain important mineralisations of aluminous refractories, perhaps in enclaves of aluminous resistates or kinzigites. The Lower Proterozoic (?) supracrustals with some greenstones and banded iron formations (which can also be components of the enclaves in Archean gneisses) contain stray basemetal sulphide mineralisations. The banded iron formation contains sedimentary iron ore deposits of poor potentials (Table 6).

### Precambrians of Himalaya

Syngenetic sulphide mineralisations are common in the carbonate facies of the upper part of Upper Proterozoic folded cover on Himalayan basement. None of the mineralisations are persistent. Syngenetic basemetal sulphide mineralisations are also common in the dark shale sequences underlying the carbonate facies. In the highly metamorphic basement occasional sedimentary metamorphic iron mineralisation is found. Correlation with the peninsular shield segments is not possible; but some similarities with the Vindhyan platform are evident.

## MINERALISATIONS

### Iron-Manganese

There are great similarities in the nature, mode of occurrence and genesis of the iron-managenese ore deposits of the younger greenstone belts of the South, Central and East Indian Shield sectors. The iron ores containing hematite and alteration products are associated with shales/phyllites and banded hematite quartzite/jasper. The iron ore occurs at the top of shale/banded iron member, and the manganese ore, wherever present, occurs at the lower part of the shale. These shales overlie the greenstones.

This iron-manganese association is not observed in the Bailadila-Rowghat deposits of the Central Indian Shield, but along its northern fringe the association reappears in the Upper Mahakoshals. In South Indian Shield also, in the younger greenstone belt, the basal formations are devoid of such an association. This particular feature has been one of the criteria of a sub-division of the younger greenstone sequence into a lower Fe-bearing and an upper Fe-Mn bearing formation.

Genetically, the greenstones are widely thought to be the source of iron and manganese, though, however, the geochemical sequence as seen in the stratigraphic record does not seem to confirm the experimental data. The alternative sedimentary model is attractive, but studies have just begun on the validity of this model for Indian occurrences. The genesis of the workable deposits of iron ore may be due to processes like (i) leaching and replacement of banded-hematite-quartzite, (ii) replacement of shales or (iii) primary sedimentation. The studied deposits in the country show that the orebodies are co-deformed with the associated banded iron formation, having shale intercalations with sharp boundaries and the ore bands appear to be nothing but thickened layers of hematite in the banded iron formation. Traces of leaching and replacement are yet to be recorded. Obviously, leaching-replacement of banded iron formation or shales does not seem to have been operative, and the sedimentary process provides a more plausible solution (GHOSH, 1972).

Primary sedimentary origin is widely favoured for the lenticular reef like manganese orebodies which occur in the shales. Remobilisation of manganese from the smaller and near surface bodies by the agencies of weathering has been responsible for developing lateritic manganese orebodies in East India and South Indian Shield, and the central part of Central Indian Shield (GHOSH, 1972).

Manganese orebodies associated with the Middle Proterozoic and Archean granulites provide a slightly different mode of genesis, and are discussed later.

The banded iron members of the older greenstone sequences are not commercially significant except in East Indian Shield.

The iron-ore deposits are in a long linear belt in the Singhbhum-Keonjhar-Bonai belt. The most well known occurrences are those of Gorumahisani, Sulaipat and Badampahar. In Gorumahisani rich hematite ore with more than 60% Fe occurs in high relief in three distinct bands. In Badampahar, the ore occurring in a similar set up, is inferior in grade. High grade massive hematite deposits occur in Barabil, Noamundi, Kurband and Joruri along the border of Orissa and Bihar. In the same Keonjhar district important deposits were located at Kiriburu, Meghahatuburu, Malangtoli and Daiteri.

The lateritoid manganese ore deposits associated with greenstone-banded iron formation–shale sequences, occur in areas adjacent to the iron ore belt of Singhbhum-Keonjhar. In Keonjhar important deposits are in the Jamda-Koira valley while the Chaibasa area of Singhbhum is also equally important. In these deposits, conformable tabular lenses of ores are in intimate association with folded shales and phyllites. The ores result from lateritoid concentrations; and principally consist of pyrolusite, cryptomelane-psilomelane. Several million tons of reserves are estimated and the deposits are worked at many places.

Commercial iron ore deposits associated with banded iron formations are restricted to outcrop areas of the Bailadila Group of metasediments, which occupy sinuous belts in Bailadila and Rowghat-Rajhara areas of Central Indian Shield. Along the Narmada-Son lineaments the Upper Mahakoshals (greenstone-banded iron formation) also contain iron and lateritoid manganese deposits which are of local importance only. Significantly, the Bailadila type iron ore occurrences are devoid of manganese associations.

In Bailadila the ore is considered to have originated from leaching of silica from banded hematite quartzite. The major deposits are in synforms often thickened near fold closures. The deposits contain mainly massive and laminated ores, which soften downwards. Powdery ore and blue dust form the lower parts of the orebodies. The ore occurs as capping on both ferruginous shale and banded hematite quartzite, and contains intercalations of shales as well (GHOSH, 1972).

North of Bailadila, iron ore was located in almost similar set up in the Rowghat Range. Alternate synforms contain the deposits between banded iron formations and lateritic cover. Shale partings do occur. In Rajhara iron ore deposit, the geological set up and structure are similar.

In South Indian Shield the iron ore deposits are derived from the younger greenstone-banded iron formations; and major deposits are found in Goa, North Kanara, Sandur, Bababudan and Ratnagiri. In Goa, the iron and manganese deposits are closely associated with pink phyllite along a 9 km × 95 km belt, and overlies quartz-chlorite schist and greywacke. Banded hematite-magnetite-chert and limestones are included in the pink phyllite horizon. Manganiferous quartzites are also present.

In North Kanara, the geological set-up of the manganese and hematite ore deposits are similar to those of Goa. The manganese ore deposits occur in laterites formed due to alteration of phyllitic rocks and banded iron formation. In some deposits dolomitic limestones contain bands of Mn-shale.

In Sandur, the iron and manganese deposits are associated with a thick shale horizon. The manganese orebodies occur within the 400 m wide grey basal shale, while the iron orebody occurs at the top of the shale. The orebodies are deformed into an isoclinal synform. The ore consisting of hematite and martite is laminated, lateritised at top and friable and powdery at depth.

In Babudan range, the detached orebodies are set within pinkish shale. Banded and massive hematite-quartzites occur as irregular small lenses within the shale. These deposits are free from manganese.

## Manganese

Extensive manganese deposits occur in the southern segments of the shield. A few deposits also occur in the northern segment. Both syngenetic and supergene epigenetic deposits are present, of which the syngenetic deposits are more numerous. The epigenetic deposits of South and Central Indian Shield have already been referred to above.

The syngenetic deposits occur mostly in the North Indian Shield and Central Indian Shield.

The syngenetic manganese ore deposits generally occur as distinct lithological units associated with pelitic and impure calc-magnesian sediments. The rock typically associated with the manganese oxide-silicate bodies is called a gondite, quartz-manganogarnet-apatite rock. The occurrences in the Middle Proterozoic Sausar-Gangpur-Champaner Groups are gonditic. In the Eastern Ghats granulite belt occurrences of the manganese orebodies are associated with the 'Khondalites'—garnet-sillimanite-graphite gneisses. The lithological horizon is called Kodurite, which is a K-feldspar-manganogarnet-apatite-manganopyroxene-quartz rock. The syngenetic manganese ore deposits of the Central Indian Shield were initially laid down as higher oxides, and show on increasing metamorphism a reaction sequence characterised by the progressive reduction of manganese. The progressive reactions yielded assemblages characterised by braunite-bixbyite-hollandite-jacobsite-hausmannite-vredenburgite (Roy, 1973).

## Basemetal Ore Deposits

Following Banerjee and Ghosh (1972), the basemetal deposits of the Precambrians are discussed according to the following classification of the geological framework:

(1) Occurrences in the Eastern Ghats granulite belt,

(2) Occurrences in the greenstone belts of the two segments of the Shield (Lower Proterozoic),

(3) Occurrences in the Middle Proterozoics of North Indian Shield and the Southern Shield,

(4) Occurrences in the NE Shield Wedge,

(5) Ore deposits of the Upper Proterozoics of North and South Indian Shields, and

(6) Ore deposits in the Precambrian of the Himalaya.

### 1. Occurrences in the Eastern Ghats granulite belt

All these occurrences are poor in grade and small in dimension. The pyrite-pyrrhotite-chalcopyrite-galena specks and disseminations in charnockitic rocks of Central Indian Shield, pyrrhotite specks in pyroxene granulites, pyrite-chalcopyrite-pyrrhotite disseminations in hornblende-biotite-gneisses, pyrite-chalcopyrite-pyrrhotite disseminations and stringers and galena-barytes veinlets in the charnockite tract of the South Indian Shield are representative examples.

### 2. Ore deposits in the Lower Proterozoic greenstone belts

(a) Northern Shield—Aravalli Group

The Dariba-Rajpura lead-zinc deposits is the most noteworthy one. It is associated with epidote-amphibolite to amphibolite facies metapelites, calc-silicate rocks, graphite schists and quartzites. The sulphide bodies are localised within graphite schist and along the contact with tremolite marble. The most abundant ore minerals are sphalerite, galena, pyrite and pyrrhotite. The source of this mesothermal assemblage is uncertain. Sedimentary structures strongly suggest a syngenetic origin.

Other examples in this belt include the chalcopyrite-pyrite-pyrrhotite-galena mineralisation along fold closures within calc-silicate rocks and biotite schists extending over a strike length of 25 km between Pur and Banera and the galena-sphalerite-pyrrhotite-chalcopyrite disseminations, fracture-fillings and replacements in the limestone of Sawar area.

Basemetal mineralisation in the Aravalli Group is best reflected in the Zawar Pb-Zn belt. The country rocks are folded steeply dipping quartzites, dolomites and pelitic rocks including greywacke in green schist facies assemblages. The chief ore bearing prospect extends over a cumulative strike length of 10.4 km, of which the Mochia-Balaria segment extending over 6.4 km is the most productive sector. The host rock is a fine-grained dolomite. The most abundant sulphide minerals are galena, sphalerite and pyrite. The sulphide assemblages are frequently characterised by crystalloblastic fabric. The sulphides occur in three types of structural domains: (i) concordant to bedding, (ii) ill-defined shoots following the plunge of the fold axis, and (iii) replacement and fracture fillings along sub-parallel strain-slip cleavages and other shear planes constituting well defined shear zones. The concordant types carry perfectly preserved sedimentary structures, and thus hint to the sedimentary syngenetic origin.

(b) South and Central Indian Shield

Most of the basemetal sulphide occurrences within Lower Proterozoic greenstone belts are sub-economic in grade and dimension. Of the medium sized prospects those of Pular-Parsori (Maharashtra), Kalyadi, and Chitradurga belts, Mysore are noteworthy.

In Pular-Parsori belt veins and stringers of chalcopyrite-pyrite-pyrrhotite-sphalerite-cobaltite-scheelite occur in quartz-chlorite phyllite and quartz-sericite schists along zones of intense shearing and brecciation in association with silicification. Further southwards near Thanewasna, fracture fillings and disseminations of chalcopyrite and pyrite occur in shear zones in granite and metavolcanics. ESE of Thanewasna, at Mundatikra the mineralisation extends over 1.6 km.

Further southward in Andhra Pradesh, impersistent stringers and veins of chalcopyrite and pyrite associated with vein quartz and pegmatites occur sporadically in the older greenstone belt of Nellore at Garimanipenta. In the greenstone belt of Dharwar Group basemetal mineralisation is known from the Chitradurga schist belt. Here pyrite, chalcopyrite and galena occur intermittently in five sub-parallel zones trending N-S in the form of replacement or cavity fillings in quartz veins traversing agglomerates, volcanic tuff and chert over a length of 36 km. In the Kalyadi belt chalcopyrite-pyrite mineralisation occurs along the contact of quartzites and altered ultrabasic rocks.

Basemetal occurrences within the greenstone belt are generally associated with metavolcanics and genetic affinity is very apparent.

## 3. Ore deposits in the Middle Proterozoics

(a) Northern Shield—Delhi Group

Mineralisation in the Delhi Group is widespread and abundant. The best studied sector is the Khetri copper belt in Jhunjunu and Sikar districts. The country rocks are psammites and pelites belonging to the Alwar and Ajabgarh formations, thrown into doubly plunging asymmetric isoclinal synclines and anticlines, trending NE-SW. The bulk of the mineralisation is confined to the western limb, and the most prominent mineralised belt localised more or less along the sheared contact between the formations, extends NE-SW over a strike length of 65 km. The chief copper prospect extends over 15 km. The host rock of mineralisation progressively transgresses the stratigraphy upwards from NE to SW from carbon phyllites and andalusite phyllites to garnet-chlorite schists. The important sulphides are chalcopyrite, pyrite and pyrrhotite. The zone of oxidation extends to 60–90 m. The ore localisation is primarily controlled by fractures and shear zones related to the major strike faults. Within the tabloid zones of dispersed mineralisation, at places over 100 m in width, workable ore concentrations occur in the form of sporadic lenses, each of which in turn is made up of a bundle of ore shoots. Individual ore shoots averaging more than one percent copper hardly exceed 100 m.

A distinctive pattern of wall rock alteration characterises the belt. Iron-magnesium metasomatism is marked. The mineralisation is attributed to hydrothermal replacement. Remobilisation of syngenetic sulphides is probable.

The Delhi sedimentation reflects a prominent basemetal epoch.

(b) East Indian Shield

Gangpur-Singhbhum Shear Zone: The shear zone runs along the contact between two contrasted stratigraphic-tectonic provinces, the southern sector being that of the younger greenstones (Lower Proterozoics) and the northern sector being that of the psammo-pelitic pile of the Gangpur-Chaibasa formations. The shear zone dips steeply towards north and is an important locale of basemetal mineralisation.

In the eastern sector of about 160 km, sizeable copper deposits are confined to a belt of about 50 km, of which a 20 km belt is the most important and includes the prospects of Rakha, Roam-Siddheswar, Surda and the Mosaboni mines. Sulphide lodes occur within diverse types of rock—meta-volcanics, soda-granite, quartz schist and quartz-chlorite schist. The most abundant ore minerals are chalcopyrite, pyrite and pyrrhotite. The zone of oxidation is about 40 m. The deposits are of fissure vein type and ore is localised along brecciated zones. Individual orebodies are cymoidal in shape, and occur as solid, massive, braided and disseminated ores. The source of the ore is uncertain, and could either be the soda-granite or the sedimentary volcanic pile (Banerjee and Ghosh, 1972).

In the western sector also, the shear zone traces the boundary between the meta-argillite-psammite sequence of the south and the Gangpur formation to the north. Sizeable galena-chlacopyrite-pyrite bodies have been located in mica schists and phyllites of Sargipalli. Minor chalcopyrite-galena-pyrite mineralisation and stringers have also been found in the mica schists, north of Panposh.

The same zone of dislocation seems to be traceable into the Balaghat district (Malanjkhand) where large reserves of copper ore are estimated. The copper content is above 1%, and development work is in progress. The metamorphics (equivalent of Sausar Group) are located to the north while a zone of silicification (quartz reef) in the Malanjkhand granite (Lower Proterozoic) carry the mineralisation of chalcopyrite-pyrite.

## 4. Ore deposits in the NE Shield Wedges

Of the few occurrences in the Archean gneisses and granites of the Meghalaya plateau, the chalcopyrite-galena-sphalerite-pyrite-pyrrhotite mineralisation at Umpyrtha is noteworthy. Disseminations, stringers and fracture filling of sulphide occur in disconnected shoots in biotite gneiss. Moderately high temparature wall rock alteration is seen. Assessment of the potentials of this deposit is in progress.

**5. Ore deposits in the Upper Proterozoics of South and North Indian Shield**

(a) South Indian Shield

The thick pile of Upper Proterozoic intracratonic conglomerate-quartzite-phyllite-dolomite-megarhythms of the Cuddapah Group carries sporadic concentrations of basemetal sulphides in different lithostratigraphic levels. Majority of the deposits are located in the Cumbum phyllites and dolomites of Nallamalai formation, and the basic volcanics contain some minor deposits.

In the Cumbum formation the ores occur in quartzite, dolomites, chlorite phyllites, carbon phyllites, calcareous argillites etc. The orebodies are either concordant or occur as disseminations, stringers (in fold closures) or as disconnected masses of disseminations and pockets in dolomite, localised along axial plane shear zones as well as intersections of shear systems.

The chief ore bearing prospects are in Agnigundala area, having a cumulative strike length of about 6 km. The bodies are often arranged in overlapping fashion. In some orebodies there is a distinct separation between galena mineralisation at the upper levels and chalcopyrite mineralisation in the lower levels of a dolomite horizon. The Agnigundala Pb-Zn sulphide deposits are considered to be originally syngenetic, but later mobilised and localised in favourable structural zones by epigenetic process. The stratabound nature, predominance of older granites, lack of significant wall rock alteration and association of carbonate-metasapropelite sequence suggest the syngenetic origin.

Within the upper sequences of the Upper Proterozoics of the Cuddapah-Kurnool basins hypothermal sulphides of basemetal occur in association with basic sills and flows.

(b) Vindhyan Platform—North Indian Shield

There are syngenetic baryte-sphalerite veins and disseminations and galena-sphalerite disseminations in the Lower Vindhyan sequences. These are not significant.

**6. Ore deposits in the Precambrian of Himalaya**

They are of the nature of localised and sporadic concentrations, and form veins, lenses, pockets, clots, disseminations and networks associated with quartz veins in foliation/shear planes, tension gaps and fault zones (BANERJEE and GHOSH, 1972). The only producing prospect is in Rangpo (E. Himalaya) where mineralisation in garnetiferous chlorite schist consists of a pyrrhotite-chalcopyrite-sphalerite-galena assemblage. There is no zonal arrangement and the origin is not known.

In the Himalaya diverse types of assemblage are found. Nowhere the mineralisation is traceable from the Himalayan basements into the Phanerozoic cover. The structural fabric of the basements is also different. Thus the basemetal mineralisation in the Himalayan is pre-Himalaya orogeny in nature.

## Chromium and Nickel

Chromium and nickel bearing ultramafics are common in the Precambrians of Indian Shield and can be classified broadly into three groups (BANERJEE and HALDAR, 1972):

(1) Ultramafics of the granulite belt of Southern segment of Indian shield,
(2) Ultramafics associated with the greenstone belts and
(3) Ultramafics of Middle Proterozoic sequences.

**1. Granulite belt (Southern segment)**

In Sittampudi complex of anorthositic rocks with amphibolites and gabbros, economic deposits of chromite and corundum occur. There are discrete steeply dipping layers of chromitite. The chromite layers are due to magmatic segregation.

**2. Greenstone belts**

Economic mineral deposits related to ultramafic bodies of the greenstone belts are sporadically distributed in the Southern segment of the shield and rarely in the Northern Shield. Most of the ultramafics are pre/early tectonic with near contemporaneous basic magmatism (IYENGAR and BANEJEE, 1972). The chromite deposits are early magmatic with discordant attributes developing during reintrusion en masse. Important deposits are those at Jojohatu, Sukinda, Nausahi, Pauni and in Shimoga and Chitradurga belts of East, Central and Southern Indian Shield.

The ultrabasics of Jojohatu (dunite, harzburgite, lherzolite, pyroxenite) are concordant bodies in the greenstone group supracrustals. Chromite occurs as segregations lenticular masses and pods.

The Sukinda ultramafic complex is a chrome-nickel rich early montmorillonite-serpentine rock and a later chrome-nickel poor orthpyroxenite. Chromite deposits are in the form of tabular to lenticular bodies occurring as primary layers in the synclinally folded ultrabasic rock.

The Sukinda complex also contains large reserves of low grade nickel ore. These are associated with the hydrothermally altered ores. Nickel occurs in oxide/hydroxide state in limonitised rock while in the associated montmorillonite rich serpentinites the nickel is in the silicate lattice (BANERJEE and HALDAR, 1972).

The Nausahi ultramafic complex is composed of an earlier dunite-chromite pluton invaded by a later chrome-poor ultramafic. The chromite deposits are restricted to the earlier phase. The chromitite bodies are tabular in form and occur in six levels interlayered with dunite. The chromite deposits owe their origin to early magmatic differentiation.

The Pauni ultramafics are composed of dunite and steatised/silicified serpentinite emplaced in synclinal troughs in tightly folded Sakoli Group. Chromite occurs in concordant pods and thin layers shredded apart during regional deformation.

Shimoga and Chitradurga belts: Peridotites, pyroxenites and dunites occur as infolded bodies in the Shimoga and Chitradurga belts of greenstones. The ultrabasics occur in the metabasics and the supracrustals, and are deformed and invaded by granites. The ultramafics now occur as detached narrow lenticular bodies in NNW trending belts. The major chromite deposits are confined to the Sidhuvalli-Mysore belt in Mysore District and Nuggihalli belt in Hassan District. Chromite occurs as massive lenses and layered bands in serpentinites. Genetically these orebodies resemble those of E. Indian Shield.

North Indian Shield: Detached masses of talc-serpentine-chlorite rocks occur intermittently over a distance of more than 500 km commonly paralleling the regional trend of the Aravalli-Delhi Groups. The lenticular ultramafic bodies appear to be cofolded but are poor in chromite contents.

The well known Salem (South Indian Shield) dunite and related rock masses, mostly converted to magnesite steatite and asbestos, belong to the greenstone belt ultramafic rocks now occurring in the granulites.

## Diamond

The diamondiferous kimberlitic rocks are sporadically exposed in the Upper Proterozoic platform cover in the Vindhyan Platform and in the neighbourhood of basin edge in Cuddapah region of South Indian Shield (Wajrakarur).

Around Wajrakarur are four pipes of kimberlitic rocks. The diamond potentials, once historically famous, are now insignificant.

In Vindhyan Platform, around Majhgawan a pear shaped kimberlite diatreme pierces the Upper Vindhyan sequence. The rock is earthy green in colour and is composed of much serpentine and little phlogopite. Chemically the rock is analogous to those of South Africa.

## Gold

The gold bearing quartz veins are restricted to the older greenstone belt of the South Indian Shield. The arc shaped Sargur-Kolar-Ramgiri belt (Mysore and Andhra) around the younger greenstone belt contain the important prospects. Stray occurrences in East Indian Shield are known, but are insignificant.

The Kolar gold field currently under exploitation is located in the centre of the 80 km long Kolar schist belt. The schist belt is essentially composed of metamorphosed greenstones and banded iron formation, bordered on the east by the Champion gneiss. Post-tectonic granites intrude the belt at the terminal sectors. The lodes are localised along the contacts of massive and schistose amphibolites. Gold occurs in native form as fine disseminations and rarely as thin streaks, films, lenses and granular aggregates. Besides gold, other ore minerals include scheelite, magnetite and hematite and sparse sulphides. Payable shoots along the lodes are localised in en echelon pattern in areas of dilation in the vicinity of dextral and sinistral drag folds and associated faults.

In Hutti sector the host rocks are metamorphosed greenstones and supracrustals are intruded by granite, quartz porphyry, felsite, gabbro and dolerite. The regional structure is NNW plunging isoclinal synform. Auriferous quartz veins are disposed along the shear-fracture zones in greenstone and chlorite schists. Native gold is finely disseminated in quartz, sulphides and silicates. Rare sulphides are present.

The Ramagiri gold field is located in the Pennukonda-Pamdi schist belt extending N-S over 15 km. The host rocks are metamorphosed greenstones, banded iron formation and supracrustals, injected by gold-quartz veins. The host rocks are thrown in a south plunging anticlinal fold occupied by the Ramagiri granites followed in the east by a synclinal fold, the western limb of which contains the gold field. The quartz vein is replacement type with minor fracture fillings. Besides disseminations of gold, there are some sulphides.

The Gadag field is an analogous set up of meta-greenstones and supracrustals in gneisses and granites, the regional structure being a north plunging isoclinal synform. The gold bearing belt is located in the western limb. Most of the lodes are along a thin zone of greywackes, being stratigraphically controlled.

Auriferous quartz lodes occur as a series of subparallel moderate dipping quartz reefs in gneisses, high grade meta-basic rocks and granulites in Wynad. The lodes vary in width from 0.5–1.5 m and extend to 1.5 km in strike length. The quartz reefs carry gold with an outer rim of pyrite. In the Nilambur valley of Wynad, placer gold of good potentials has been located.

## Pyrite and Pyrrhotite

The Middle and Upper Proterozoics of the Vindhyan Platform—North India Shield provide the important deposits of these sulphides.

In Saladipura, Rajasthan, the mineralisation is confined to the peli-psammitic metamorphites of the Ajabgarh formation of Delhi Group. Pyrite and pyrrhotite occur as massive bodies, lenticular patches and as streaks and stringers in the country rock. Prominent gossan led to the discovery of the deposit. The mineralised zone extends over 7 km with a thickness of 5.5 m. The mineralisation is considered to be hydrothermal, but probably remobilised syngenetic.

In Amjhor, Mirzrapur Dt, the Bijaigarh shale member of the Lower Vindhyan sequence of the eastern edge of Vindhyan platform contains sedimentary syngenetic pyrite. It is a major pyrite deposit, concordant and stratabound. The prospect extends over nearly 25 sq.km.

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# Metallogenic Framework and Mineral Resources of Pakistan*

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## ABSTRACT

Six post-Paleozoic metallogenic environments are recognized in Pakistan. The Makran convergence zone of oceanic-continent lithospheric collision, the Himalayan convergence zone with continent to continent collision and the Chaman transform fault zone connecting these convergence zones dominate in the geology of Pakistan. Various stages of geodynamic evolution are reckoned for the development of the tectonic and related metallogenic environments.

Himalayan metallogeny is connected with magma generated by melting and remobilization of pre-existing rocks and consolidation at shallow depth without possessing subduction related subvolcanic and volcanic equivalents. Notwithstanding the association of kuroko-type massive sulphide of island-arc setting, the Chagai belt may represent an Andean type continental margin arc. Cretaceous calc-alkaline magmatism and mineralization were prior to collision of the Indian and Iran-Afghanistan plates, whereas the Saindak and other porphyry copper were generated during post collisional subduction. Neogene metallogenic environments were imposed in the Himalaya by the process of thrust progradation where renewed post Eocene northward motion of the Indian plate was taken up on a series of major, low-angle thrusts within its leading edge, with activity migrating progressively with time southwards from the Indus collisional suture. In Baluchistan post-collisional northward motion was taken up on the Chaman transform fault zone so that thrust progradation was relatively unimportant. However, the location of the trench related subduction shifted from north Raskoh in the Paleocene to Siahan in the late Eocene and was rejuvinated south of the Makran coast during middle Miocene.

The six discrete metallogenic environments possessing characteristic rock assemblages for mineral and hydrocarbon formation are: (1) the continental shelf of Indo-Pak plate, (2) the ophiolitic suture zone, (3) the calc-alkaline magmatic belt of Chagai, (4) Chaman transform fault zone, (5) Indus molasse basin and (6) metamorphic mineralization in Himalayan collision belt.

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## INTRODUCTION

The scenario for the metallic mineral potential in Pakistan has brightened up recently. Pakistan was considered earlier as a country possessing only industrial mineral reserves which could be exploited economically (HERON, 1954, AHMED, 1969). Although no major ore deposits with the possible exception of Saindak porphyry copper, have yet been proved in Pakistan, the variety of known and new occurrences clearly indicate that future potential exists.

Mineral sector was almost non-existent in Pakistan during independence in 1947. Only seven minerals were mined on a small scale. The inventory of mineral wealth of Pakistan today consists of 21 major items and 15 minor items. In early seventies, mineral commodities comprised 10 percent of total Pakistan's export value and about 20–25 percent of its import value. Slow growth in mineral sector against extremely large reserves could be discernible in Table 1.

Mineral exploration in Pakistan has been viewed in the past on the non-genetic model and as such the exploration efforts were conducted not according to the environments but according to the placement of intrusive bodies and volcanic rocks. It was realised only recently that a systematic approach to exploration together with a study of the known mineral prospects and search in well defined genetic areas could bring more successful and rewarding results.

Mineralization in Pakistan is now considered to be closely related to the geodynamic

Table 1 Ore reserves, production and level of important minerals in Pakistan

| S.No. | Minerals | Ore reserves (ton) | Production (ton) | | |
|---|---|---|---|---|---|
| | | | 1973–74 | 1975–80 | 1980–85 |
| 1. | Aggregate and buildg. stone | Very large | 449,565 | | |
| 2. | Limestone | Very large | 4,080,000 | 10,000,000 | 20,000,000 |
| 3. | Rock salt | Very large | 383,890 | | |
| 4. | Sea salt | Very large | 230,000 | 250,000 | 500,000 |
| 5. | Gypsum/anhydrite | Very large | 155,000 | 400,000 | 6,000,000 |
| 6. | Dolomite | Very large | 1,400 | 10,000 | 245,500 |
| 7. | Chromite | Fairly large | 17,678 | 30,000 | 60,000 |
| 8. | Fire clay | Over 1,000,000,000 | 43,756 | 75,000 | 120,000 |
| 9. | Fuller's earth | Fairly large | 13,059 | | |
| 10. | Marble/aragonite | Very large | 20,784 | | |
| 11. | Silica sand | Very large | 44,625 | 60,000 | 100,000 |
| 12. | Ocher | Not estimated | 375 | | |
| 13. | Radioactive minerals | Sufficient | Not available | | |
| 14. | Coal | 442,000,000 | 1,110,654 | 2,400,000 | 4,800,000 |
| 15. | Crude oil | 40,000,000 barrels | Not available | | |
| 16. | Natural Gas | 20 million million cft. | 126,309 (1971–72) | | |
| 17. | Barytes | 1,322,000 | 1,666 | | |
| 18. | Copper (Saindak) | 412,000,000 | Not yet opened up | | 4,500,000 |
| 19. | Iron ore | 446,100,000 | Not exploited | 670,000* | 3,000,000* |
| 20. | China clay | Over 698,000 | 1,074 | 7,709 | 20,000 |
| 21. | Rock phosphate | 23 million at 15 to 25% $P_2O_5$ | — | 260,000 | 500,000 |

* Imported ores.

evolution. Speculative papers on the relation between plate movements and ore formation for the Andean mineralization in Cordillera of South America (SILLITOE, 1976), tectonically controlled basin evolution and metallogenic evolution of a mountain belt in Pakistan (SILLITOE, 1978) proved to be a catalyst, stimulating on-going studies in Pakistan and spurring new directions of research.

A close inter-relationship between plate tectonics and metallogeny has been demonstrated with regard to the geological framework of Pakistan. The various plate tectonic divisions constitute distinct and discrete metallogenic provinces which possess characteristic rock assemblages and environments for mineral and hydrocarbon formation.

A unified presentation of these features has been attempted in the present report which is intrinsically based on the useful work done recently by the Geological Survey of Pakistan personnel partly in collaboration with foreign scientists. Of particular use and relevance are the studies made under the Geodynamic Project of Pakistan and the United States National Science Foundation (FARAH and DEJONG, 1979).

## GENERALIZED TECTONIC FRAMEWORK OF PAKISTAN

From a global tectonic point of view, Pakistan occupies a unique position as its landmass, now constituting the country, is composed of a number of continental fragments welded together along the 'suture' belts. Probably nowhere else in the world in such a compact piece of land with excellently exposed rock masses so many important features essential for a proper understanding of Plate Tectonics, are available for study. Pakistan's geodynamic evolution is characterized by the collision and coalescence of continental plates and microplates which were once separated by oceanic domains.

In the geological set-up of Pakistan, the plate boundaries are responsible for bringing together the obducted oceanic crust material—the ophiolites, the rock assemblages of the island arc, trench-arc-system, pelagic-platform sediments of continental slope-shelf-shield slope—in a complex present day configuration (GRAUHAR *et al.*, 1979). Each of these classes of tectonic mega features is typified by a characteristic structural behaviour, rock composition and ore mineral association.

In Pakistan, a thick sequence of sediments is piled up on the gently dipping northerly and northwesterly slope of the Precambrian Indo-Pakistan Shield. Classically and conventionally this region is known as the Indus Basin which occupies over half of the country on its eastern side. Rocks on the Shield slope dip gently where as those bordering the foreland and within the limit of convergence collisional zone are highly deformed, and constitute the Himalayan fold belt and northern metamorphic zone. Makran-Chagai region illustrates trench-arc and accretionary wedge on active subduction zone and represents an arc of ocean-continent lithospheric collision. Interaction between thrust and strike-slip fault systems is well detailed in Pakistan where the Chaman transform zone which forms the western boundary of Indo-Pakistan plate, connects the Makran and Himalayan convergence zone.

### Speculative Tectonic History of Pakistan and Surroundings

Plate-tectonic models involving impingement of Eurasia with India and Iran-Afghanistan with Afro-Arabic during Meso-Cenozoic have been presented for the Himalaya and Zagros, but no convincing geotectonic reconstruction is available for the intervening section of the collisional mountain belt in Pakistan and adjoining Afghanistan, although the region has been briefly referred to in recent discussions of Tethyan ophiolites (GANSSER, 1974, 1979; STONELEY, 1974, 1975) and Cenozoic tectonics (NOWROOZI, 1972, CRAWFORD, 1974a; STOCKLIN, 1977).

The tectonic history of Pakistan and surrounding region is modelled (POWELL, 1979) in terms of two major convergence zones; a northern one, the Alborz-Hindukush convergence bordering the southern edge of the stable Eurasian plate, and a southern one, the Zagros-Chitral convergence zone, lying at the southern part of a complex of microcontinents, island arcs and ocean-floored basins which is preserved at present as a wide orogenic belt in Iran-Afghanistan. Pakistan contains at least two major ophiolite belts, possibly the only remains of former extensive ocean. Three stages in the tectonic development of Pakistan are envisaged: (1) Rapid northward movement of India from late Cretaceous to early Eocene (2) Small counter clockwise rotation of India during Eocene and (3) Slower northward movement of India during Oligocene to the present.

## Mountain Belts and Geodynamic Evolution in Pakistan

Since the advent of plate tectonic theories of orogeny, the youthful Himalayan mountain system has become a type example for collisional orogeny. Arcs, oroclines and syntaxes characterize Pakistan's geology, as there is no other country where mountain belts bend so often and so severely.

### Metamorphic Zone and Fold Belts

Pre-orogenic minerals along with Jurassic to Cambrain sediments laid on the Indo-Pak shield-shelf slope has been subjected to earlier orogenic movements. The Platform sediments bordering of the Indo-Pak foreland had to withstand much compression during subsequent orogenic movements and northward motion of the Indo-Pak plate. Rocks within the convergence zone in northwest Himalaya is highly metamorphosed. The Pakistani fold belt is not a simple oroclinal bend of the Himalayan structure, but evolved as a consequence of the shape of the north-western corner of India. The Salt and Trans-Indus Salt Ranges, Sulaiman fold festoon structures may all be currently moving on shallow decollements thrusting on Cambrain salt beds (GANSSER, 1964 and POWELL, 1979) as the Indo-Pakistan Shield continues its northward convergence with Eurasia. The northern Himalayan convergence zone has its southern boundary at the thrust faults of the Salt and Trans-Indus Salt Ranges. The bent mountain belts of Pamir-Pakistan region are generated in terms of progressive convergence of the Indo-Pakistan block and other Eurasian blocks to the west and north of it. Under this tectonic framework, the resulting allocations, forming along the deformed margins and moving inward, faced tremendous space problems, which caused southward squeeze-outs of material from the northern parts. The Pamir-Himalayan Arc, the Nanga Parbat-Haramosh massif, the Hazara-Kashmir syntaxis, the Bannu-Potwar thrust sheet, the Salt Range composite orocline and the Sulaiman Arc are explained by the above reasoning. In the case of the Quetta syntaxis, obstruction by the uplifted great Sibi-Jacobabad trough rockwedge is considered. The Khuzdar knot and the Hyderabad Arc are possibly the results of rotational tectonics.

However, in the subsurface, the Indo-Pakistan Shield makes a few prominent highs which are mainly responsible for the division of the Indus Basin and for the formation of syntaxial bends and sinous features of the mountain ranges. The highs observed at Sargodha and Jacobabad acted as resistant buttresses during the Himalayan

Orogeny dividing the Indus Basin into three main provinces, that is, the Bannu-Kohat-Potwar province (or the Upper Indus Basin), the Sulaiman province (or the Middle Indus Basin) and the Kirthar province (or the Lower Indus Basin).

The syntaxes are produced when projections on approaching plates undergo collison before the intervening portions of plate margins (DEWEY and BURKE, 1974). The syntaxial bends are more highly tectonised than the intervening embayed lengths of suture. The main compression was radial to the Indian foreland, with folds and thrusts showing movement towards the foreland as predicted by the collisional hypothesis (DEWEY and BURKE, 1973). Folding was dominantly post-Oligocene in age thus indicating important development during the subsequent northward movement of India.

## Ophiolite Suture Zone

The ophiolites of axial belt originated from the southern Tethys which was formed between the Indo-Pakistan continent and Afghan-Eurasian block during the early Mesozoic. Sea-floor spreading was active in this ocean during the early Mesozoic prior to the main dispersal of Gondwanaland, as well as in the Cretaceous. The Indian plate separated from Gondwanaland probably in the early Cretaceous and moved northwards, particularly rapidly from 75 to 55 m.y. ago, under the influence of an ancestral Indian Ocean ridge system (MCKENZIE and SCLATER, 1971). As indicated by ages of magmatic rocks, northward subduction of the Tethys beneath Iran took place in late Jurassic, Cretaceous and much of the Cenozoic (FORSTER *et al.*, 1972; DEWEY *et al.*, 1973), beneath northwest Pakistani Baluchistan from Cretaceous to Quaternary and beneath southeast Afghanistan during the Cretaceous and Cenozoic (DE LAPPARENT, 1972). Collision of Iran-Afghanistan microcontinent, and further east the Eurasian plate with the Indo-Pakistan plate commenced in Pakistan and Afghanistan in the late Cretaceous-early Paleocene and in the Himalaya in pre-middle Eocene times (POWELL and CONAGHAN, 1973). Collision resulted in the closure of the eastern part of the Tethyan Ocean.

At the time of tectonic emplacement of the ophiolites and melange in Pakistan in pre-early Eocene times, no underthrusting of, or within, the Indian plate took place. Sea-floor spreading in the Indian Ocean which slowed down following collision, resumed once again about 35 m.y. ago in the lower Oligocene (MCKENZIE and SCLATER, 1971) and also documented by on-land palaeomagnetic studies (WENSINK, 1975).

Such motion induced underthrusting of the Indian plate beneath the southern margin of the Eurasian plate along the Himalaya resulting in continent-continent collision, southward nappe emplacement, crustal thickening and violent uplift (POWELL and CONAGHAN, 1973; DEWEY and BURKE, 1973; LE FORT, 1975). Juxtaposition of rocks of different domains, intense folding, faulting and metamorphism typify the geology of northwestern Himalaya.

## Chaman Transform Fault Zone

The main tectonism in Pakistan is Middle Miocene in age (KRISHNAN, 1960). The renewed motion of the Indian Plate was taken up by transform faulting on the Chaman and further south, Ornach-Nal systems in Afghanistan and Pakistan, which from at least the early Miocene onwards have formed the plate's western boundary. This zone absorbs the major left lateral displacement created by the relative northward motion of the Indo-Pak plate. The interaction between thrust and strike-slip fault systems is well detailed in Pakistan where the Chaman transform zone connects the Makran and Himalayan convergence zones (LAWRENCE and YEATS, 1979).

## Chagai Makran Arc-Trench

The Chagai-Makran region of Pakistan, Baluchistan, west of Chamman-Ornoch-Nal fault system, represents an area of ocean-continent lithospheric collision which is bounded on the east and west by zones which mark the contact with areas of continent-continent collision. The oceanic lithosphere of the Makran convergence zone is being subducted beneath the Lut and Afghan microplates. Unlike northern Himalayan areas, the rocks are not essentially metamorphosed in this region. Arc trench system is well illustrated in Chagai-Makran from north to south.

Various stages of geodynamic evolution are reckoned in the development of the Makran convergence zone (SILLITOE, 1976; LAWRENCE *et al.*, 1980). Extensive and vigorous andesitic arc activity occurred during rapid subduction as the Indian plate moved northward as much as 20 cm/yr (MCKENZIE and SCLATER, 1971; POWELL, 1979).

In the Chagai arc, submarine calc-alkaline volcanics associated with clastics and limestone were deposited during the Cretaceous. Sedimentation was predominant in the Eocene and Oligocene with only localized volcanic activity. Subaerial andesites were erupted during the remainder of the Cenozoic (Hunting Survey Corporation, 1960, AHMED *et al.*, 1972). Dioritic-to-granitic plutons and stocks are known to have been emplaced in the Cretaceous and also in the Miocene (SILLITOE and KHAN, 1977). In the northern Raskoh range, syenodioritic plutons of post middle Eocene age cut andesitic and basaltic rocks of Cretaceous age. A highly folded, thrust and cleaved Paleocene flysch succession cut by small fault-controlled ultrabasic bodies in Raskoh (AHMED, 1961; BAKR, 1963) may represent a forearc basin generated on the trench side of the magmatic arc.

This late Cretaceous to middle Eocene igneous episode is recorded in the Chagai Hills and Raskoh in Pakistan and along the eastern Afghan block (JONES, 1961; BAKR, 1963; AHMED, 1964). Trenches related to subduction during this time may have been located approximately along the northern Raskoh in the Paleocene and near the present Siahan fault in the late Eocene. This episode climaxed when the Indian plate first contacted Eurasia and the rate of sea floor spreading in the Indian ocean slowed or even stopped in late Paleocene to middle Eocene time (MCKENZIE and SCLATER, 1971; POWELL, 1979). Notwithstanding the common association of kuroko-type massive sulphide deposits with island-arc setting in western most part, the Chagai belt is believed to represent an Andean-type continental margin arc.

## Flysch and Molasses Basins

The Makran has been interpreted (WHITE and KLITGORD, 1976; FAROUDI and KRAIG, 1977; JACOB and QUITTMEYER, 1979) as an accretionary wedge forming on the hanging wall of a shallow slowly moving active subduction zone. Uplift consequent upon collision gave rise to extensive erosion and deep-marine flysch deposition commencing in late Eocene-Oligocene along the tectonic strike of plate margin especially in the Makran ranges where flysch deposition may have been directly on oceanic crust in remnant ocean basin (SILLITOE, 1979). During the period from late Eocene to early Miocene clastic sedimentation dominated in the region bodering the Afghan plate: a. The Khojak flysch accumulated towards the east and subsequently became a part of the Chaman transform zone; b. The Turbat group deposited simultaneously towards south and is now present in the central and northern Makran ranges.

In the middle Miocene more rapid sea floor spreading resumed and continental lithosphere of the Indian plate began to underthrust Eurasia. Subduction was rejuvinated south of the Makran coast. This renewal of tectonic activity is marked by the folding and thrust faulting of Pliocene and older rocks of the Raskoh and Dalbandin trough, Khojak flysch and Turbat group. The parallel east-west ridges of the Makran arc formed by a set of imbricate north dipping thrusts which are likely to be responsible for a crustal shortening of between 50 to 70% (White and Klitgord, 1976).

## Future Challenge

If the plate tectonic scenario for development of Bela-Quetta-Muslimbagh-Waziristan and Indus suture tectonic zone is correct, then Palaeozoic-Mesozoic sedimentary wedges from two or three continents-cum-microcontinents were involved (Talent, 1979). The process of unravelling the craze of fault-slices along this belt and determining which slivers belonged to which continental margin (Indo-Pak block vs. the block or blocks to the west) may be facilitated by careful and perceptive analysis of faunas. One would anticipate there having been substantial provincial contrasts between fossil remains in each sedimentary wedge and for this to have persisted until such time as the continental blocks had converged sufficiently to allow case of migration from shelf to shelf.

No one has yet synthesized the Cretaceous-Palaeogene data of south and central Pakistan in terms of plate-tectonically controlled basin evolution—the development, coalescence and amalgamations of basins on either side of the axial belt. Much of this sedimentary history, i.e., the massive influxes of clastics and the regressive tendencies, will substantially document events in the evolution of the Himalayas and Hindukush; for this exercise, precise palaeontological control is essential. The potential spin off for petroleum exploration from better understanding of the changing pattern of facies through time needs no further elaboration (Talent, 1979).

There remains a dearth of palaeontological and radiometric control on the stratigraphy and inferred igneous and tectonic events for the mountainous region of northern Pakistan.

## METALLOGENIC FRAMEWORK OF PAKISTAN

The first conceptual model of metallogeny as presented by Scheglov (1969) mainly related to an analysis in terms of geosynclinal theory. The Scheglov model gives detail of:

(1) Chromite ore belt of Baluchistan geosyncline,
(2) Mercury-antimony belt in the Pishin-Makran geosyncline trough; and
(3) Copper-molybdenum belt associated with the medium massif of Chagai District.

The occurrences of copper-molybdenum-gold porphyries at Saindak, manto-type copper at Talaruk and zinc-silver-kuroko deposit at Makki in Chagai and numerous other copper-molybdenum porphyry occurrences in the Chagai District studied by the Geological Survey of Pakistan are not reasonably explained by the geosynclinal model. Also these porphyries are not directly related to and are younger than the medium massif of Chagai. A close inter-relationship between plate tectonics and metallogeny exists with regard to the geological framework of Pakistan.

## Plate Tectonics and Metallogeny

In the present report a coherent assembly of many of the assorted ideas has been attempted primarily with a view to define the broad plate tectonic and metallogenic divisions of Pakistan.

"The metallogeny of collisional mountain belts is potentially more complex than that of Andean-type (Cordilleran or thermal) orogens since mineralization related to pre-, syn-, and post-collisional events can be juxtaposed. Like most aspects of metallogeny, it can best be understood by reference to post Palaezoic examples" (SILLITOE, 1978).

When the known mineral deposits and occurrences of Pakistan are viewed genetically in the light of the geotectonic model, six discrete metallogenic environments are recognized. Each of these classes of tectonic mega features is typified by a characteristic structural behaviour, rock composition and ore mineral association. A summarized description of the metallogenic environments are as follows (Fig. 1):

( i ) A Cretaceous ophiolitic suite generated at a site of sea-floor spreading within a Tethyan Ocean, and subsequently tectonically emplaced on continental crust during continental collision in the late Cretaceous-early Tertiary. Ore types include chromite deposits in serpentinized dunite, manganese-oxide deposits in Layer-1 sediments and a cupriferous massive sulphide occurrence in Layer-2 basalts generated within an ophiolite complex at a Tethyan oceanic spreading centre.

( ii ) A Jurassic shelf-carbonate succession developed on the continental shelf of Gondwanaland. Rifting preparatory to its dispersal is believed to have caused emplacement of barite, barite-lead-zinc and fluorite deposits of broadly Mississippi Valley-type.

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Fig. 1. Map showing mineral occurrences of Pakistan and location of ophiolite complexes, calc-alkaline intrusive and extrusive rocks, the Chaman and Ornach-nal transform fault zone, main boundary of thrust, Indus Suture zone and other tectonic elements in Pakistan and adjoining Afghanistan and Iran. Also marked are outcrop limits of Mesozoic rocks in axial belt of Pakistan, in Southeast Afghanistan and on the Indian Shield and Pleistocene stratovolcanoes at Koh-i-Taftan (I), Koh-i-Sultan (II) and Dasht-e-Nawar (III) and Miocene stratovlocanoes of Koh-i-Dalil (IV).

The following ore types and localities are depicted: Mississippi Valley-type deposits at Koh-i-Maran(A), Dilband(B), Khuzdar(C), Shekran(D), Monar Talar (E), Kudni(F) and Dahuddar(G); Calc-alkaline ore types at Saindak(H), Ziarat Pir Sultan(J), Maki Chah(K), Talaruk(L). Amuri(M), Kundi-Baluchap(N), Mashki Chah(O), Bandegan(P), Chilghazi(Q) and Pachin Koh(R); Ophiolitic ore types at Muslimbagh(S), Fort Sandeman(T), Waziristan(U), Las Bela(V), Ras Koh(W), Siro Dhoro(X), Kharrari(Y) and Ann Dhoro(Z); Tansform fault-related antimony at Qila Abdullah (a); and Molasse-basin uranium at Baghal Chur(B).

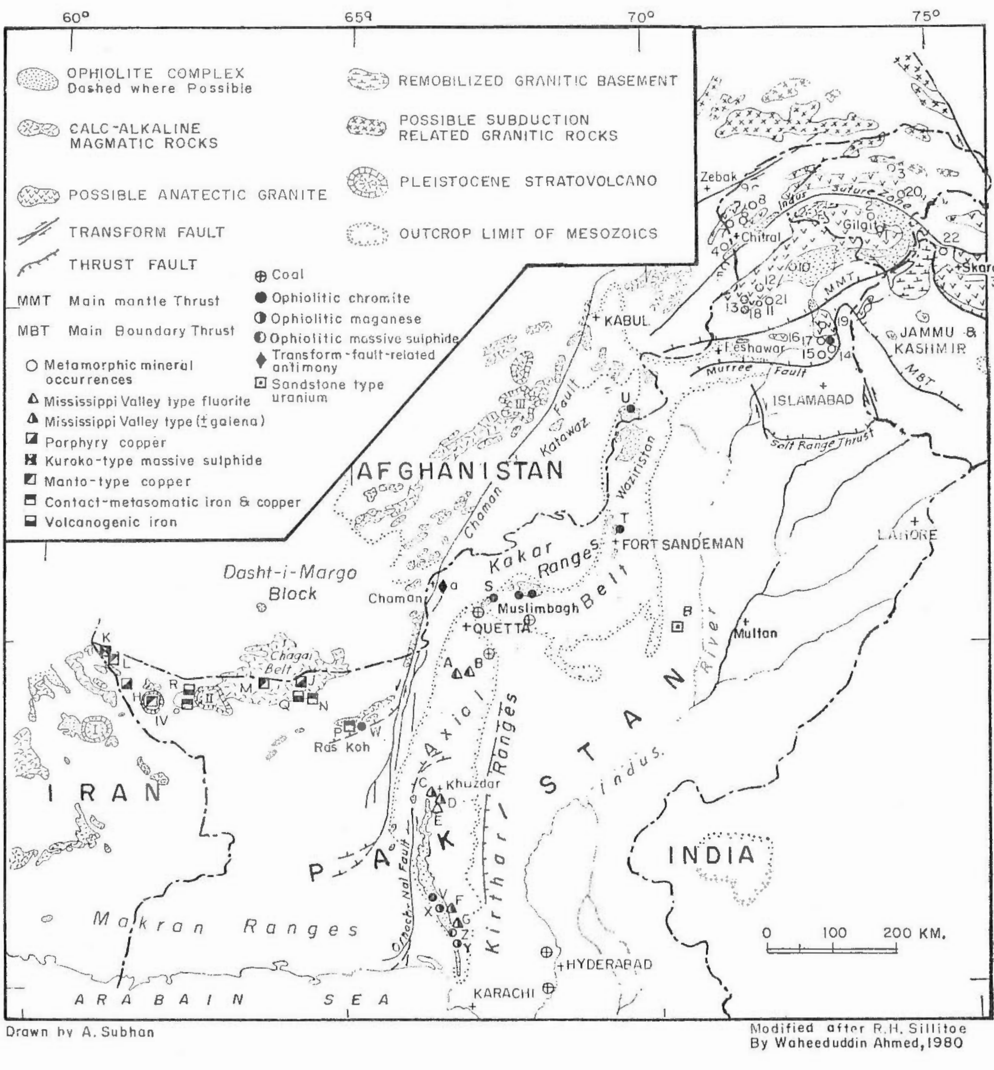
Metamorphic mineral occurrences include, 1. Hanzal copper, 2. Singal copper, 3. Chapursan arsenic, 4. Kaldam Gol copper, 5. Dammel Nissar iron, 6. Krinj antimony, 7. Awireth gold-lead-antimony, 8. Pakhturi lead-zinc-copper, 9. Aligot Nala arsenic, 10. Ushu lead-zinc, 11. Usheri copper, 12. Barwa-Kambat copper, 13. Kohala barite, 14. Faqir Mohammad barite, 15. Hal lead, 16. Mihal and Paswal lead, 17. Malakand-Mohmand chromite, 18. Oghi tungsten, 19. Hunza ruby, 20. Mingora emerald, 21. Dasu aquamarine, 22. The Chakdara fluorite is believed to be related to anatectic granites.

(iii) A calc-alkaline magmatic arc of Andean type generated by northward subduction, before (Cretaceous) and after (Cenozoic) continental collision. Porphyry copper-molybdenum, manto-type copper, kuroko-type massive sulphide, vein copper, contact-matasomatic copper and iron, and volcanogenic iron deposits generated in Cretaceous-Cenozoic times by intrusive and extrusive calc-alkaline magmatism.

(iv) The Chaman intracontinental transform-fault zone within which mid to late Cenozoic dynamothermal metamorphism has permitted emplacement of vein-type antimony mineralization.

(v) A late Cenozoic molasse basin produced at Middle Indus Basin as a result of erosion of the uplifting Himalayas. Sandstone type uranium prospects occur.

(vi) Metamorphic mineralization in the northern collisional belt of the Himalayas.




Drawn by A. Subhan

Modified after R.H. Sillitoe
By Waheeduddin Ahmed, 1980

Five discrete post-Palaeozoic metallogenic environments are recognized in Pakistani Baluchistan and adjoining region. None of these environments are well represented further to the northeast in the Himalayan region where ore types are considered as (1) epigenetic, polymetallic deposits generated by metamorphic fluids in low-grade metamorphic environments; and (2) minor flourite mineralization affiliated to anatectic granites. Both these Neogene metallogenic environments were imposed by the process of thrust progradation where renewed post-Eocene northward motion of the Indian plate was taken up on a series of major, low-angle thrusts within its leading edge, with activity migrating progressively with time southwards from the Indus collisional suture. In Baluchistan post-collisional northward motion of India was taken up on the Chaman transform fault zone so that thrust progradation was relatively unimportant.

## Description of Metallogenic Provinces

Geographic distribution, rock composition and mineral association for each of these metallogenic environments are described in the following pages.

### The Continental Shelf of Indian Plate

As described in earlier chapter, the 'Shield Slope Region' inclusive of the fold belt in the foredeep region is designated as the Indus Basin which occupies over half of the country on its eastern side. Generalized geology and mineral potential at the Indus Basin as described by GAUHAR and ASRARULLAH (1979) is repeated:

'The Indus Basin is a predominantly sedimentary region stretching from the Arabian Sea in the south and extending in a nearly north-south direction up to the outer Himalayas in the north covering over half of the total area of Pakistan. Shallow water carbonates, evaporites and clastic rocks constitute the bulk of the stratigraphic column. The clastic rocks generally have a dominant argillaceous facies, but in some Late Tertiary units, an increase in the arenaceous content of the sand/shale ratio is observable. These rocks range in age from Palaeozoic to Recent with maximum aggregate thickness generally exhibited by the Cainozoic formations. Small isolated protrusions of the Precambrian shield rocks are exposed in two widely separated areas; the one at Nagar Parkar in Tharparkar District, Sind and the other in Kirana-Sangla hills in Sargodha District, Punjab. In the rest of the Indus Basin, the basement shield rocks have a thick sedimentary cover.'

The highs observed at Sargodha and Jacobabad are the principal projections of the Indo-Pakistan Shield in the Indus Basin. These blocks acted as resistant buttresses during the Himalayan orogeny dividing the Indus Basin into three main provinces, that is, the Bannu-Kohat-Potwar Province (or the Upper Indus Basin), the Sulaiman Province (or the Middle Indus Basin) and the Kirthar Province (or the Lower Indus Basin).

The Upper Indus Basin also includes the Salt Range which is interpreted as the overthrusted block of presumably lowangle dip-slip fault. The thrusting occurred along the incompetent salt-bearing formation of the Precambrian age that outcrops at the base of the Salt Range and is supposed to rest on the shield basement. This typical decollement tectonics is probably related to the drastic difference in the strength of the rocks above and below the salt layer and its consequent decoupling effect. Geological evidences indicate that the Salt Range movement is relatively young as it affects the depositional pattern of the Siwalik (Miocene–Pleistocene) rocks only.

The entire oil production to date comes from the Potwar Province. The Sulaiman Province has small gas and condensate reserves in its central part in the foothills of the main Sulaiman Range while its southern extremity is the prolific gas producing region hosting the large gasfields of Sui and Mari and six other smaller fields. The Kirthar Province in the south has not yet yielded any major reserves of oil or natural gas. However, two small gasfields at Sari and Hundi near Karachi have been recently developed.

Based on a study of the geothermal data and the structural analysis of the Indus Basin as a whole, it appears that the prospects of liquid hydrocarbons generally decrease southward; from heavy crudes in the Potwar Province (Upper Indus Basin) to a gas-condensate association in the central part and gas proliferation in the south central part of the Sulaiman Province (Middle Indus Basin) to small gas occurrences only in the extreme south in the Kirthar Province (Lower Indus Basin).

Besides producing oil and natural gas, the Indus Basin is also the sole producer of coal in the country and in addition also hosts a large variety of industrial rocks and minerals. So far no metallic mineral has been found in commercial quantity in the Basin. The only possible prospects of metal mining in some distant future is that of the Kalabagh iron ores of Cretaceous age in the Upper Indus Basin. This ore is a complex admixture of carbonate-silicate-oxide iron minerals. In the current usage of geological terminalogy, this can more appropriately be called an "ironstone formation" rather than a conventional type of iron ore.

The coal occurrences in the Indus Basin extend over all the three listed subdivisions, i.e., the Upper, the Middle and the Lower Indus Basin. The coal in all these areas is of lignitic to sub-bituminous type and shows a quality relationship with its basinal distribution. The coal in the Upper Indus Basin is comparatively the best in terms of heating value and sulphur and ash contents followed by coal in the Middle Indus Basin and lastly by the coal in the Lower Indus Basin where its quality deteriorates to such an extent as to sometimes make it spontaneously combustible. An exception to this overall generalization is the coal of the Sharigh and adjoining areas in Baluchistan in the Middle Indus Basin. Here the coal is of better grade sub-bituminous type but its quality improvement is not because of any basinal feature. It is attributable to compact and close folding in the area which resulted in squeezing out the moisture and some of the other undesirable impurities thereby increasing the fixed carbon content.

## Mississippi valley-type deposits

A linear outcrop of Jurassic runs parallel to the east of the ophiolitic suture belt in Baluchistan and twists as a knot around Khuzdar region. It is mainly represented by a thick sequence of Jurassic limestones with some subordinate amounts of shale, sandstone and mudstone. Widespread indications of both vein-types and stratabound barite and fluorite have been reported from a narrow linear belt from near Quetta to Khuzdar and extending southwards up to Bela. Near Khuzdar indications of lead, zinc and silver have also been noted with a prominent limonitic iron oxide gossan formed due to the oxidation of sulphide minerals. Fluorite crystals in this zone often contain inclusion of liquid hydrocarbons, which is characteristic of some of the Mississippi Valley-type deposits in the southeastern United States.

Mineralization in Jurassic host rock is a precollisional feature and is related to connate brines expelled during incipient rifting of India from the Gondwanaland in late Jurassic—early Cretaceous times. This rifting would have probably been conductive for enhanced heat flow thereby facilitating the present pattern of mineralization.

At present this zone is producing significant quantity of barite while small production of fluorite is also obtained. The lead-zinc-silver occurrence near Khuzdar is being investigated by the Geological Survey of Pakistan. Geological indications in this zone are considered as fairly favourable to get an increase in the reserves position of the known minerals and to find new deposits through a programme of integerated exploration and basic geological research.

## Ophiolitic Suture Zone

The ophiolites in Pakistan occur in different tectonic environments. In Bela, Muslimbagh and Waziristan, they are fragments of oceanic crust materials which were obducted and emplaced upon the sediments on the margin of the Indo-Pak plate mostly in the early Tertiary period. In Ras Koh they occur in a zone with strongly deformed sediments dipping below the Chagai volcanic arc suggesting a subduction complex or forearc basin setting in the Ras Koh mountain range. The ophiolites in the northern part of Pakistan either occur in the suture zones between the Eurasian and the Indo-Pak plates or are associated with a major thrust zone.

The Muslimbagh ophiolites in Zhob District, Baluchistan are the best known ophiolites and the main supplier of chromite in the country. They consist of harzburgite ultramafic and mafic cumulates and a sheeted dyke complex. Pillow lavas are absent above the sheeted dykes but occur in the ophiolitic melange. The metamorphic foliation in the harzburgite and cumulate layering in overlying dunites, and gabbros were developed at the Tethyan spreading centre. Muslimbagh ophiolite is a tectonic slice obducted on the leading edge of the Indian plate. The hornblende-garnet schists, developed from sedimentary rock adjoining the ultrabasic mass (Bilgrami, 1964; Rossman in Ahmad, 1974), are equated with the dynamothermally metamorphosed rocks generated during obduction beneath the Bay of Islands Ophiolite complex of Newfoundland, as described by Williams and Smyth (1973). Middle Eocene sediments unconformably overlie the Muslimbagh complex and record completing of collision event.

Further to the northeast of Muslimbagh, large outcrops of ophiolites occur near Zhob town but have not yet been studied systematically. Here basalt flows are closely associated and often interlayered with sediments of Cretaceous age. Diorite, in small stocks, and dykes of dolerite intrude the ophiolitic rocks. A few small and scattered occurrences of chromite are known in the area but they show a higher alumina content than the deposits occurring in the vicinity of Muslimbagh.

Little is known about the ophiolite occurrences in Waziristan in N.W.F.P. because of the accessibility conditions. However, a few road traverses indicate that the ophiolitic assemblage in the area contains peridotite, pyroxenite, chromitite and mafic volcanic rocks emplaced upon Jurassic and Cretaceous sediments. There has been some small and sporadic chromite mining in the past. The area is now being regionally mapped by the Geological Survey of Pakistan.

Small and isolated outcrops of ophiolites are exposed in the Ras Koh range. The ophiolites consist of peridotite, serpentinite, norite, gabbro and diorite with a few other minor rock types. Chromite occurs as accessory grains in the ultramafic rocks and in small lenticular bodies.

The Dargai–Mohmand ophiolite complex in Malakand Division, N.W.F.P. is presumably underlain by Palaeozoic(?) carbonates and overlain by Precambrian–Cambrian schists. Both the upper and the lower contacts appear to be faulted. In this area a typical ophiolitic assemblage is present consisting of ultramafic tectonites, ultramafic cumulates and mafic cumulates. This area is becoming an important chromite producer after Muslimbagh.

The geological setting of ophiolites in the northern parts of Pakistan (Hazara, Swat, Dir, Chitral, Gilgit and Baltistan) is not well understood due to scarcity of adequate field data. In a general way two ophiolitic belts can be traced around Nanga Parbat and contiguous areas with numerous bifurcations. This asymmetrical distribution might have resulted from the incorporation of an island arc or most probably a micro-continent into the collisional zone or alternatively from a southward expulsion of an ophiolitic nappe from the suture zone, followed by erosion of its northern portion during uplift. Although a few occurrences of chromite and copper have been reported from this region but none has so far been proved to be of an economic value.

The Las Bela ophiolites, farthest south in Pakistan, occur in a north-south belt, which extends from Khuzdar to the coast of the Arabian Sea, west of Karachi. It linearly covers a distance of about 450 km. with an average width of about 10 km. In this region a huge slab with typical ophiolitic sequence of harzburgite, ultramafic and mafic cumulates, gabbro, plagiogranite, sheeted dykes and pillow lavas are mapped south of Wad. Mostly ophiolitic rock types occur in fragments without transition of one type into another. These fragments or slabs, sometimes of several kilometre size, are interspersed with a multitudes of melanges showing a chaotic mixture of various rock types.

Although the ophiolites of Las Bela have often been correlated with the famous Oman and Cyprus ophiolites, they cannot be so compared due to strikingly different structural and tectonic settings. Dismemberment of ophiolitic units into altogether separate slices and widespread association of melanges have reduced the metal prospects of the region to a considerable extent. This has been confirmed by recent exploration activities in the region by the Geological Survey of Pakistan. Several indications of massive type of copper sulphides, stratiform, replacement and vein-type manganese oxides and podiform chromite were investigated but all have so far failed to yield mineable reserves. Further geological studies and exploration are continuing.

As per description of SILLITOE (1979) the principal metallic mineral derived from the Axial belt is chromite, with annual and total production amounting to about 0.02 million tons. It is found chiefly in the Zhob valley area in serpentinized dunite members of the Muslimbagh ultrabasic complex. Where gabbro is present in the complex, chromite deposits occur in dunite of cumulate origin only a short distance below its base (cf. position of chromite in the Semail ophiolites of Oman). The major chromite deposits, however, appear to occur in basal parts of the cumulate sequence which have been down-folded into the subjacent harzburgite tectonite (MOORES, E. M., 1977, pers. com.). The chromite occurs as typical Alpine type deposits with podiform, chimney and layered varieties recognized (BILGRAMI, 1964, 1968). Minor chromite also occurs in the dunitic component of melange.

Chromite in smaller amounts also accompanies obducted ultrabasics in the Axial belt at Fort Sandeman, Las Bela and in Waziristan, and occurs in small amounts in serpentinized ultrabasics in a forearc-basin setting in the Ras Koh range. Chromite is also known from the ultrabasic members of the ophiolite complexes in southeast Afghanistan (DE LAPPARENT, 1972).

In the Las Bela region, lens-like, stratiform bodies of manganese oxides occur in iron and silica-rich horizons underlain by pillow basalts and overlain by red shales at Kharrari and elsewhere. Deposits are considered to be volcanogenic in origin (IQBAL ALI, 1971). Other manganese oxide deposits, as at Siro Dhoro, are present as replacements and veinlets in basalt and dolerite and presumably represent feeders to the syngenetic accumulations.

In view of the worldwide association of stratiform cupriferous massive sulphide deposits with Layer-2 basalts of ophiolite complexes (SILLITOE, 1972), a search for these deposits in basaltic terrains in the Las Bela region was instigated. A massive sulphide occurrence at a shale horizon intercalated in a succession of pillow basalts was quickly recognized at Ann Dhora. Here the feeder stockwork dominates, but several other gossans recognized by the writer during aerial reconnaissance could well cap stratiform massive sulphide lenses.

These three ophiolitic ore types are believed to have been generated in the Mesozoic at a spreading centre in the southern arm of Tethys. The chromite was generated as an integral part of ultrabasic Layer-3 beneath the spreading centre with evidence for a cumulate origin modified by later tectonism induced by lateral transport away from the spreading centre. In contrast, the massive sulphide and manganese deposits are syngenetic in origin and were generated on the ocean floor by hydrothermal activity related to ridge volcanism. The manganese-bearing sediments are equivalent to metalliferous horizons at the base of Layer-1 on the present ocean floors and in the Troodos ophiolite complex of Cyprus. They are precipitated from hydrothermal sea-water systems driven by the high heat flux at ridge crests. In the late Cretaceous-early Eocene interval the ore deposits were tectonically emplaced in the Axial belt during continental collision, following transport from ridge to trench by sea-floor spreading.

## Calc-alkaline Magmatic Belt of Chagai-Ras Koh

Covering about 40,000 sq. km. in the administrative district of Chagai in Baluchistan, the Chagai—Ras Koh calc-alkaline magmatic belt is convex towards south and extends for about 500 km. in an east-west direction and 150 km. in the north-south direction in the central part where maximum igneous activity appears to have taken place. Tectonically the Chagai belt is regarded as an arc-trench type subduction/convergence zone as evidenced by its structural and petrological characteristics.

Excellent synthesis on the metallogenic evolution of Chagai belt and its mineral deposits has been made by SILLITOE (1979) and his description is reproduced below:

Copper and iron are the principal metals encountered in the Chagai magmatic belt (including Ras Koh) and are found intimately related to both intrusive and extrusive activity. Several ore types are recognized by the writer.

1. A porphyry copper-molybdenum deposit at Saindak (SCHMIDT, 1968; AHMED *et al.*, 1972; SILLITOE and KHAN, 1977) and several other alteration zones with porphyry-type affinities. The Pleistocene native sulphur deposits close to the summit of the Koh-i-Sultan stratovolcano are believed to represent the effluent from a recently active porphyry copper system at depth. Travertine aprons and minor showings of manganese oxides accompany the waning volcanic activity. The Saindak deposits are composite in nature, related to typical zonal alteration patterns centred on three separate but related tonalite porphyry stocks of early Miocene age. Hydrothermal breccias are virtually absent but late-mineral veins and dykes are widespread. The deposits contain an aggregate 400 million tons of mineralized rock assaying from about 0.4–0.5 per cent Cu, with significant molybdenum and gold values. The Ziarat Pir Sultan porphyry prospect further east is centred on a small stock emplaced in the

roof zone of one of the Cretaceous plutons.

2. Minor vein deposits, mainly in the volcanic rocks, carry chalcopyrite and hypogene chalcocite. Copper and lead-bearing veins also constitute a halo around the Saindak porphyry copper deposit.

3. A manto-type copper occurrence at Talaruk comprises a stratabound accumulation of hypogene chalcocite disseminated in the uppermost 20 m of a dacite pyroclastic unit, lower portions of which are highly pyritic. Localized disseminations and pods of chalcocite in andesitic volcanics at Amuri are considered to be of the same type. The volcanics at Talaruk and Amuri are assignable to the Sinjrani Formation of submarine origin and Cretaceous age. Mineralization is believed to have been essentially syngenetic with the enclosing volcanic units and to have been generated by hydrothermal fluids, including an important sea-water component, circulating in the volcanic horizons during their submarine cooling and consolidation.

4. A kuroko-type massive sulphide deposit has been discovered at Maki Chah in the same dacitic volcanic unit as Talaruk, but 3 km. to the southeast. It consists of a pyritic stockwork transecting the dacitic volcanics, capped by a lens of massive sulphide-bearing hydrothermal gypsum. Bands of massive pyrite carrying sphalerite and chalcopyrite occur within the gypsum, with zinc becoming more important at the expense of copper upwards. Unlike the case of Talaruk, base metal at Maki Chah was deposited largely on the sea floor at the point of debouchment of a hydrothermal system instead of in the upper part of the volcanic unit.

5. Small magnetite and chalcopyrite deposits of contact-metasomatic type are found in Cretaceous limestone at the contact with dioritic and granodioritic intrusives at Kundi-Baluchap (AHMED, 1960) and Mashki Chah in the Chagai belt and in Cretaceous andesitic tuffs in contact with a syenodioritic intrusive at Bandegan in Ras Koh (AHMED, 1964). The last deposit is post-middle Eocene in age.

6.. Volcanogenic magnetite deposits containing a small amount of chalcopyrite occur as flows intercalated in submarine andesitic sequences of Cretaceous age at Chilghazi (FARUQUE and RAHMAN, 1970) and Pachin Koh (HUSSAIN and MEHDI, 1974). They could contain reserves of up to 5 million tons of high-grade ore. At Chilghazi, three magnetite flows are interbedded with andesitic flows, some containing magnetite globules ( ? products of liquid immiscibility), and tuffs, some containing magnetite fragments. At Pachin Koh, magnetite-actinolite plugs accompany two principal magnetite flows.

These ore types are those characteristic of magmatic arcs built on either continental or oceanic crust above subduction zones, as in the central Andes (SILLITOE, 1976). Notwithstanding the common association of kuroko-type massive sulphide deposits with island-arc settings, the Chagai belt is believed to represent an Andean-type continental-margin arc. It should be noted that the Cretaceous deposits were formed prior to collision of the Indian and Iran-Afghanistan plates whereas at least the Saindak porphyry copper and Bandegan contact-metasomatic deposits were generated during post-collisional subduction. The presence of contact-metasomatic copper deposits carrying some lead, zinc, tin and tungsten in western Afghanistan (CHMYRIOV *et al.*, 1973), landwards from the iron and copper deposits in the Chagai belt, may denote a shallow-dipping subduction zone (SILLITOE, 1976) during their probable period of emplacement in the early Tertiary.

**Chaman Transform Fault Zone**

This is a 900 km. long zone of an echelon faulting running north-south to the west of the suture zone and separates the shelf carbonate belt from the Chagai continental-margin arc system. It connects the Makran convergent margin in the south with the Himalayan convergence zone in the north through an internal convergence zone in the Zhob thrust block. It marks the western transform boundary of the Indo-Pakistan plate and covers approximately 10,000 sq. km. in Baluchistan. Part of this boundary zone extends into Afghanistan. The width of the transform zone varies markedly. In the south it is about 100 km. wide; it narrows to 30–40 km. between Khuzdar and Quetta; and in the Zhob thrust block it widens abruptly to over 300 km. and then again narrows gradually towards north.

In the Qila Abdullah area, small-tonnage deposits of calcite, fine-grained quartz and stibnite occur as long, en echelon bodies along parallel faults cutting an Oligo-Miocene flysch succession (AHMAD, 1969). The faults are offshoots of the Chaman transform system.

No intrusive rocks occur in the Qila Abdullah area so that the antimony deposits appear to be related to the Chaman fault system itself. Circulation of connate fluids in the flysch succession during dynamothermal metamorphism related directly to the faulting is proposed as an origin for the deposits. A zone some tens of kilometres wide, characterized by slaty cleavage, marks the trace of the fault system, including the Qila Abdullah area, and testifies to the associated metamorphism. Mineralization is most likely to be Miocene or later in age, the interval during which faulting is believed to have been most active.

## Indus Molasse Basin

Numerous, small sandstone-type uranium occurrences have recently been recognized in a 160 km. long belt along the eastern side of the Sulaiman Range bordering the Indus basin (MOGHAL, 1974). The principal occurrence at Baghal Chur has indicated reserves totalling several hundred tons of mineable ore (0.05–0.5 per cent $U_3O_8$). Uranium-bearing lenses or amoeba-shaped patches up to 3 m. thick are found in a fluvial sandstone horizon in the middle part of the Siwalik System. Limonitized plant remains, including logs, are present in the sandstone, and palaeochannels marked by conglomerates have also been recognized; both phenomena may have played a role in uranium fixation. The principal oxidized uranium mineral is the vanadate, tyuyamunite, whereas its hypogene counterparts are uraninite and coffinite (BASHAM and RICE, 1974).

It is concluded that uranium was precipitated from groundwater subsequent to sedimentation, as in all sandstone-type uranium deposits. The ultimate source for the uranium is probably the metamorphic and granitic terrain exposed during post-early Miocene uplift of the Himalaya, the northern source area for the Siwalik molasse sediments. Low-grade metamorphic rock fragments dominate in the mineralized sandstone, and uranium was probably contributed to the Indus basin as a component of detrital minerals, although this fails to explain the source of the vanadium (BASHAM and RICE, 1974).

## Metamorphic Mineralization of Northern Collisional Belt

Based largely on evidence from the northwest part, post-Palaeozoic mineralization in the Himalaya, including regions immediately north of the Indus suture, is believed to be dominated by minor polymetallic occurrences of Neogene age carrying mainly copper, lead, barite, gold, arsenic and antimony of metamorphic origin, and by gemstones, along with some fluorite and possibly rare-earths and minor base metals, generated by anatectic leucogranites. Metamorphic mineralization is attributed to precipitation in dilatent sites by fluids expelled from sedimentary rocks undergoing regional metamorphism, either during thrusting and/or during uplifting. The anatectic leucogranites are believed to be poorly mineralized compared with subduction-related intrusives because their source magmas, generated by partial melting of basement rocks during continental underthrusting, were water-saturated and therefore consolidated at depths of perhaps 10 km. without possessing subvolcanic or volcanic equivalents; the magmas also may have been intrinsically poor in metals.

It would appear that the metallogeny accompanying continental collision and its related later effects is on a small scale and that the major ore types, such as porphyry copper, epithermal precious-metal and kuroko-type massive sulphide deposits, found in Cordilleran or island-arc settings above subduction zones, are unlikely to be found. Exploration programmes should therefore perhaps concentrate on pre-Mesozoic ore types fortuitously incorporated in the mountain belt, relatively important examples of which are found at Rangpo, Sikkim and Askot, Uttar Pradesh.

## Mineral Occurrences of Pakistan

### Antimony

Mining of antimony ores, stibnite and boulangerite, has only been carried out in Lutkho area of Chitral State (Fig. 1). The oldest mine is at Krinj about 13 miles N of Chitral town where stibnite occurs in quartz veins in Palaeozoic slates between 150–300 feet below their contact with overlying Cretaceous limestone. The maximum thickness of the vein is 4 feet. The mineral is extracted by driving small inclines which follow the veins in the hills. The annual production ranges between 150–250 tons. The ore which, after hand sorting, contains about 20% Sb is converted into $Sb_2O_3$ in a small plant located close to the mine. The other locality, about 5 miles W of Krinj is Avirath Gol where veins of boulangerite up to 3 feet thick occur at the contact of Palaeozoic slates and Cretaceous limestone. The veins are irregular and only a few hundred tons of the mineral which contains up to 40 gms. of gold and 75 gms. of silver per ton of ore has been extracted. Reserves at both the localities put together may not exceed a few thousand tons though no estimates have been made.

Vein-type stibnite occurrence associated with quartz has been reported from Qila Abdullah (39°43′N : 66°38′E) (Fig. 1). The veins occur on the hanging wall side of the faults cutting slates of probably Oligo-Miocene age. About 50 tons of the mineral have been mined and reserves have not been estimated. Similar occurrences have been reported in the surrounding areas but detailed investigations have not been carried out.

### Barite

Only small scale mining of the mineral is being done in Pakistan and annual production during the past ten years has ranged between 2,000 and 16,500 tons. About a dozen occurrences of barite have been described in the published literature (Ahmed, 1969, p. 55–60) but only the major ones are being dealt with here.

Three deposits in close proximity of each other have been described from Khuzdar area. The Monar Talar deposit located about 3 miles SSE of Gunga village (26°46′N : 66°31′E) is exposed along the foot of Monar hills. The mineral occurs interbedded with limestone and is generally impure. The thickness varies from 10–20 feet at the southern end and to 50 feet at the northern end. The mineralized zone extends 4,000 feet. Reserves estimated to an arbitrary depth of 100′ are 850,000 tons (Hunting Surv. Corp., 1960, p. 409).

The second deposit in the area is at Shekhran hill about 12 miles west of Khuzdar and 1.5 miles NE of Shekhran hills in a locality noted for lead mining about a century ago. The mineral occurs as replacing a 2 feet bed of sandy Jurassic limestone along a strike length of 60 feet. The deposits exhibit characteristics which suggest them being possibly in the same beds as Monar Talar occurrence (Fig. 1).

KLINGER and AHMED (1967) have described Khuzdar deposits (27°44′30″N : 66°32′E) occurring in Zidi formation of Jurassic age. The ore occurs as a series of tabular lenses which are parallel and confined to the lower thinly bedded limestone. The footwall of the host rocks appears to have been leached, silicified and/or oxidized (KLINGER and AHMED, 1969, p. 10) and at places exceeds 100 feet in thickness the mineralized zone is 4,500 feet long and the layered barite lenses vary in thickness from 10–80 feet and 270 to 1,200 feet in length. The reserves are estimated to be about 1.3 million tons. Typical analyses are given in Table 2 (Nos. 1–2).

The Bankhri deposit (26°15′N : 66°30′E) is a vein 100 feet feet long and 3–9 feet wide occurring in a quartzitic vein of Jurassic age which occupies a shear zone striking 28°E. The mineral is being commercially exploited and more than 2,000 tons, the original estimate of reserves, has already been mined.

The Kundi barite deposits (26°24′N : 66°36′E) occurs as concordant replacement of repeatedly folded Jurassic fossiliferous limestone exposed for 1,800 feet, though barite is confined to western 1/3 of the structure. Five beds of limestone one to 5 feet thick partially replaced by barite are estimated to contain 30–98% of the mineral. According to KLINGER and RICHARDS (1967, p. 36) the available reserves to a depth of 25 feet are 14,000 tons.

In the north of Pakistan the most important barite deposit is that of Kohala (34°06′N : 73°27′E) occurring as dialation veins and lenses in Hazara slates of Precambrian age (?). The mineral occurs as coarse-grained aggregates of interlocking crystals and is quite pure. The deposits are estimated to contain 30,000 tons and are being commercially exploited. Typical analyses of the mineral are given in Table 2, Nos. PR–45, 47.

## Chromite

Alpine-type chromite deposits are widely distributed in Pakistan (Fig. 1). In the north lenses and at places veins of chromite associated with dunite, harzburgite and pyroxenite are found at several locations in Malakand district. The chromite here is of varying grades (Table 3, 31–34) but the deposits are mostly very small, none

Table 2 Selected analyses of barite (wt. %)

| Sample No. | $BaSO_4$ | $SiO_2$ | $Al_2O_3$ | $CaCO_3$ | $Fe_2O_3$ | MgO | Sp. Gr. |
|---|---|---|---|---|---|---|---|
| Ba–1 | 91.86 | 2.48 | 2.73 | 0.98 | 0.02 | 1.63 | — |
| Ba–2 | 95.92 | 1.84 | 0.02 | 0.49 | 0.03 | 0.67 | — |
| PR–45 | 88.42 | 2.55 | — | 5.78 | 0.15 | — | 4.21 |
| PR–47 | 92.76 | 1.91 | — | 2.64 | 0.09 | — | 4.35 |

Ba–1, Ba–2, Barite sample from Khuzdar area
PR–45, PR–47, Barite sample from Kohala area
Source: AHMED (1969), p. 57 and 59.

more than 3,000–4,000 tons. An interesting feature of the deposits is the range of chemical composition exhibited in these deposits where some of the ores are actually chromium magnetite ($Cr_2O_3$ as low as 8% and Cr/Fe .087). The second area in the north is that of Waziristan, where though large outcrops of ultramafics occur only small lenses of (up to a few hundred tons) high grade chromite ($Cr_2O_3$ 48% and Cr/Fe 3 : 1) have been found. Small lenses of refractory grade chromite have also been worked in areas 10–12 miles north of Fort Sandeman (now Zhob) but here again no significant deposit has been found. The chromite in this area is usually high in alumina (Table 3, Nos. 29–30).

The largest and best developed chromite deposits occur south of Muslimbagh

Table 3 Chemical composition of Pakistani chromites selected to show range of composition (wt. %)

| No. | 1 | 2 | 3 | 8 | 17 | 20 | 21 |
|---|---|---|---|---|---|---|---|
| $Cr_2O_3$ | 58.1 | 58.7 | 59.1 | 56.1 | 57.7 | 52.5 | 53.9 |
| $Al_2O_3$ | 11.8 | 11.8 | 10.2 | 12.7 | 10.7 | 14.9 | 15.1 |
| $Fe_2O_3$[1)] | 2.97 | 2.97 | 4.16 | 3.20 | 3.84 | 4.95 | 3.36 |
| $TiO_2$ | 0.37 | 0.30 | 0.26 | 0.21 | 0.22 | 0.30 | 0.43 |
| $V_2O_5$ | 0.06 | 0.08 | 0.07 | 0.06 | 0.05 | 0.08 | 0.12 |
| FeO | 11.4 | 11.53 | 10.46 | 13.60 | 13.35 | 12.10 | 13.19 |
| NiO | * | * | * | 0.16 | * | * | 0.10 |
| MgO | 14.6 | 14.5 | 15.2 | 13.9 | 13.0 | 14.50 | 13.80 |
| MnO | * | * | * | 0.18 | 0.09 | 0.19 | 0.02 |
| CaO | 0.06 | 0.05 | 0.05 | 0.07 | 0.08 | 0.08 | 0.08 |
| $SiO_2$ | 0.52 | 0.24 | 0.21 | 0.38 | 0.22 | 0.28 | 0.15 |
| Total | 99.88 | 100.17 | 99.71 | 100.56 | 99.25 | 99.88 | 100.43 |
| Cr/Fe | 3.44 | 3.45 | 3.47 | 2.84 | 2.86 | 2.65 | 2.77 |

| | 25 | 29 | 30 | 31 | 32 | 33 | 34 |
|---|---|---|---|---|---|---|---|
| $Cr_2O_3$ | 57.0 | 44.7 | 44.80 | 34.27 | 35.21 | 41.51 | 7.94 |
| $Al_2O_3$ | 11.2 | 21.0 | 21.30 | 10.32 | 24.08 | 12.67 | 5.38 |
| $Fe_2O_3$[1)] | 4.35 | 4.7 | 4.70 | 5.33 | 5.71 | 4.32 | 57.16 |
| $TiO_2$ | 0.29 | 0.23 | 0.23 | 0.12 | 0.07 | 0.10 | 0.29 |
| $V_2O_5$ | 0.10 | * | * | * | 0.06 | 0.04 | 0.01 |
| FeO | 13.60 | 13.1 | 13.30 | 13.38 | 13.03 | 14.93 | 24.22 |
| NiO | * | 0.18 | 0.22 | * | 0.10 | 0.11 | * |
| MgO | 13.10 | 15.3 | 14.80 | 34.78 | 21.51 | 25.01 | 3.61 |
| MnO | * | 0.19 | 0.18 | 0.05 | 0.03 | 0.05 | * |
| CaO | 0.24 | * | 0.08 | 0.96 | 0.17 | 0.79 | * |
| $SiO_2$ | 0.42 | 0.55 | 0.39 | * | * | * | 0.42 |
| Total | 100.30 | 99.95 | 100.00 | 99.21 | 99.81 | 99.53 | 99.03 |
| Cr/Fe | 2.71 | 2.15 | 2.13 | 1.57 | 1.62 | 1.84 | 0.087 |

1) Total iron determined as FeO
* Not determined
Nos. 1–30 Zhob Valley chromites, BILGRAMI (1968), Table 1, p. 142.
No. 31 Sample from quarries 1.3 and 1.5 miles.
No. 32 N.W. of Landi Raud Banda Harichand area.
No. 33 Sample from quarry 1.5 miles SW of Sakhakot, Harichand area.
No. 34 Sample from chromite dump at Takht-e-Bhai railway station.

(formerly Hindubagh) where chromite has been mined since 1903, with an annual production averaging 20,000 tons, the maximum being 39,000 tons a year. Since most of the chromite produced is exported, the production varies with the international demand and the current level is only about 10,000 tons a year. High grade metallurgical ore ($Cr_2O_3$ 48% and Cr/Fe 3 : 1) as well as medium grade ore ($Cr_2O_3$ 40–46% and Cr/Fe 2.6 : 1) is being produced (Table 3, Nos. 1–25). The mineral occurs in lenses, pods, veins and bands (Bilgrami, 1964, 1968; Ahmed, 1969) and is generally friable.

Smaller deposits of chromite mostly of high grade have also been worked at Khanozai about 35 miles NE of Quetta. The deposits are smaller in size than those of Muslimbagh area. Sporadic occurrences of chromite have been found in Chagai district, Kharan and Bela-Khuzdar areas though no substantial tonnage has been produced from these areas. Reserves at Kharan are estimated to be 20,000 tons.

Reserves of chrome ore in various areas have not been estimated to any degree of accuracy. An idea of reserves in Muslimbagh area can be obtained from the fact that during the last 75 years over 1.5 million tons of ore have been mined and Rossman (1970) considers that this is roughly 10% of the total expected reserves in the area.

## Coal

All Pakistani coals are lignitic to sub-bituminous and occur in the lower Tertiary sequence. Coal deposits of the Punjab and Baluchistan have been affected by orogenic movements and coal beds in these areas have been folded, faulted and at places squeezed into lenses. The seams range in thickness from a few inches to several feet. Most of Pakistani coals are non-coking, have high ash, volatile matter and sulphur content. They crumble to powder on drying and are liable to spontaneous combustion. There is a range of chemical composition exhibited by coals not only within the same coal field but also within the same coal seam from one area to another. Selected analysis from various coal fields are presented in Table 4. The major coal fields are briefly described below:

1. Lakhra Coal Fields (25°07′30″N : 68°08′E)

The coal field covers an area of over 150 sq. miles and has 3 lignitic coal beds of Paleocene age. The coal formations have been gently folded into an anticline with beds on the flanks dipping less than 10°. The main seam is 2.5 to 12 feet in thickness and extends up to 12 miles in length and 5 miles in width. It occurs 150 feet below the ground. The other two seams are much thinner (9″ to 2″) though the quality of coal is the same as the main seam. Reserves of all grades are estimated to be 240 million tons though proved reserves are only 60 million tons. The range of chemical composition of coal from this field is given in Table 4, No. 1.

2. Meting-Jhimpir Coal Field (25°03′N : 68°02′E) and (25°07′30″N : 68°08′E)

The coal field covers an area of over 35 sq. miles, has been subjected to minor faulting, has two coal seams varying in thickness from 9″ to 4′ which occur at 50–120 feet below the surface. The coal is lignitic, is of Eocene age and characterized at places by resin content which locally may be as high as 0.5%. The range of chemical composition of coals from this area is given in Table 4, No. 2. Reserves are estimated to be over 30 million tons.

3. Khost-Sharigh-Harnai Coal Field (Harnai–30°07′N : 67°55′E)

The coal field covers an area of over 300 sq. miles and has three workable seams ranging in thickness from a few inches to 8 feet. The coal formations trend NW-SE and intermittently crop out in a ridge about 35 miles long. The coal beds at places dip steeply and have been faulted at a number of localities. The coal which is bituminous is characterized by high volatile matter, has washable ash and possess coking properties. Reserves are estimated to be over 40 million tons (Table 4, No. 3).

4. Mach Coal Field (29°52′N : 67°20′E)

The coal field covers an area of 16 sq. miles. The coal is of Eocene age and three workable seams which are up to 4 feet in thickness are strongly folded and at places also faulted. The coal is inferior in quality to Quetta coal having intercalations of shale bands and also a high sulphur content. On drying it easily crumbles to powder and is liable to spontaneous combustion. Reserves are estimated to be 2 million tons up to a workable depth of 150 feet (Table 4, No. 4).

5. Sor Range-Degari Coal Fields

The coal field is located ten miles north of Quetta and covers an area of about 20 sq. miles. The coal is of Eocene age and the seams crop out on the western limits of syncline which has been cut by a fault of large displacement. The beds generally dip at angles higher than 45°. The coal is of sub-bituminous grade, has comparatively low ash and sulphur (Table 4, No. 5) and large size lumps can be extracted. Systematic development of this coal field has been undertaken by a number of private and public sector companies. Estimated proved reserves up to a dip depth of 2,000′ are over 20 million tons though the actual reserves may be several times that quantity.

6. Makerwal-Gullakhel Coal Field

The coal field covers an area of about 10 sq. miles and is located about 8 miles west of Kalabagh (32°55′N : 71°32′E). There is one coal seam in the area which occurs in an anticline which has been faulted at places. The western limit of the anticline is less disturbed and dips at an angle of 30°. In Gullakhel area this seam crops out along the higher slopes of the scrap. Mainly due to hard roof and floor conditions the coal is mined in large lumps and is consequently sold at a premium. It is high in volatile matter, ash and sulphur (Table 4, No. 6). Reserves of all categories are estimated to be about 20 million tons.

Table 4 Chemical composition of Pakistani coals (wt. %)
AHMED (1969), p. 173–176

| No. | Moisture | Volatile matter | Fixed carbon | Ash | Sulphur | Calorific value (Btu) |
|---|---|---|---|---|---|---|
| 1 | 31.8–35.7 | 28.0–30.9 | 26.8–30.0 | 7.4–10.5 | 3.3–6.0 | 7,010–7,660 |
| 2 | 15.4–29.8 | 29.8–39.8 | 31.0–36.3 | 8.2–14.6 | 3.4–7.4 | 7,400–9,800 |
| 3 | 4.0–11.4 | 34.8–45.3 | 25.3–43.6 | 9.3–34.8 | 5.0–7.1 | 8,500–12,400 |
| 4 | 7.1–12.1 | 34.5–39.4 | 32.4–41.5 | 9.6–20.3 | 3.2–7.4 | 9,200–10,300 |
| 5 | 15.9–18.7 | 33.5–39.6 | 35.0–42.0 | 3.0–13.0 | 0.5–5.6 | 9,000–11,000 |
| 6 | 4.2–6.8 | 37.1–44.9 | 36.0–46.0 | 7.0–21.0 | 4.0–5.6 | 9,500–11,850 |
| 7 | 3.2–7.6 | 26.3–38.8 | 29.8–44.8 | 12.3–37.7 | 3.5–10.7 | 7,100–11,100 |

1 Lakhra coal fields
2 Meting-Jhimpir coal field
3 Khost-Sharigh-Harnai coal field
4 Mach coal field
5 Sor Range Degari coal field
6 Makerwal coal field
7 Salt Range coal field
Btu British thermal unit

7. Salt Range Coal Field

The coal-bearing belt is about 100 sq. miles in area starting from 15 miles NE of Khewra (33°38′N : 73°00′E) to about 20 miles north of Khushab. Coal seams occur in a synclinal plateau of Patala shales (early Eocene) overlain by Sakesar limestone. Coal seam crops out on bold scraps facing Jhelum plains to the south.

Only one coal seam ranging in thickness from a few inches to 5 feet is being worked. The rapid lateral variation in thickness of the seam has been ascribed partly to conditions of deposition and partly to tectonic movements, the thickest parts of the seam being at the crest of the anticline. The coal is high volatile bituminous grade with high ash and sulphur contents and liable to spontaneous combustion. (Table 4, No. 7). Reserves are estimated at 100 million tons.

In addition to the above there are more than 15 other smaller coal fields being worked all over Pakistan. The interest in coal mining is limited due to small demand which is primarily from brick kilns. Efforts are being made by the government to set up a thermal power plant at Lakhra based on coal from that area.

**Copper**

Even though numerous copper deposits have been reported from all over the country the recently proved porphyry type deposits in the Saindak sulphide valley offer the best potential for development.

The sulphide valley is a shallow NNW trending depression delimited by latitudes 29°14′ and 29°18′N and longitudes 61°35′40″ and 61°37′E. This valley transects the line of northwest trending Mirjawa mountain range close to its junction with the sand covered desert plain which extends to the border with Afghanistan. The Saindak area is marked by volcanic activity which continued through Palaeocene to Oligocene and which is a prominent belt (Chagai belt) of calc-alkaline magma stocks extending to about 480 km. in E-W direction having a maximum width of 140 km. This belt hosts a number of porphyry copper prospects in Pakistan and Iran including the major Sar Chashmah copper deposits of Iran. The volcanic rocks in this zone are extensively epidotized and chloritized.

The volcanic and the locally found sedimentary rocks comprising mostly of marine shales, fluviatile or deltaic siltstone and sandstone are intruded by stocks of tonalite, granodiorite and adamellite. These intrusive bodies at Saindak belong to Miocene age.

The sulphide valley is traversed by the E-W trending Saindak fault. South of this fault an alteration zone near Saindak is developed mainly in siltstone and subordinate shale, sandstone and tuff of red-bed type Amalaf formation of Oligocene age. North of this fault the zone is marked by the volcanic agglomerate and tuff of lower part of Eocene Saindak formation. Minor cappings of volcanic rocks interpreted as an erosinal remnant of a stratovolcano that once overlay the Saindak alteration zone at the time of its formation. Much of this stratovolcano was removed probably in the Pleistocene resulting in the development of a pediment which overlies the Saindak alteration zone. This produced a subdued relief commonly called sulphide valley with sulphide free prominent ridge of rocks on the periphery.

The three mineralized zones of Saindak comprising the North, South and East copper orebodies are associated with three elongated stocks of tonalite porphyry (quartz diorite). These three stocks measure 1,000 × 200, 800 × 200, 1,000 × 400 meters respectively. Each of these stocks possesses a narrow dyke like connection with a 'parent' stock of porphyritic tonalite (grading to granodiorite) in the western part of the alteration zone.

The three mineralized stocks possess well defined oval to elongate forms and near vertical walls but their contacts are diversified by multiple offshoots that traverse the wall rocks. Swarms of near vertical dykes up to 12 m wide are seen in these alteration zones. The three orebodies have been hydrothermally altered and mineralized. The central greyish potassium silicate zone containing the main copper mineralization and is distinct from the whitish quartz-sericite zone.

Mostly in the north and south orebodies there is a superimposed gold and silver mineralization. The tourmaline veins which have cut the tonalite stocks have brought about gold mineralization. There is a halo of molybdenum mineralization around main copper zone. Besides copper, gold and molybdenum the orebodies also carry significant amounts of pyrite and magnetite. The proved reserves in the three orebodies are:

| Area | Cut-off grade % Cu | Average grade % | Ore reserves Million tons |
|---|---|---|---|
| North | 0.25 | 0.44 | 28 |
| South | 0.25 | 0.426 | 111 |
| East | 0.25 | 0.334 | 273 |
| Total | | | 412 |

In addition the South orebody contains recoverable values of gold, silver and molybdenum.

## Gypsum and Anhydrite

Pakistan possesses large reserves of gypsum and anhyrite (Table 1) and only a few most important occurrences are mentioned here.

One of the largest deposits occurs in Dera Ghazi Khan hills which form a part of Sulaiman Ranges. The mineral occurs in bands which are up to 25 feet thick and several miles long. Saidu Wali (32°12′N : 71°06′E) deposits though not being exploited at present are a part of 45–500 feet thick sequence of gypsum. Reserves are estimated to be at least 10 million tons.

Gypsum beds varying from 5–140 feet in thickness from a part of E-W trending linear ridges south of Kohat in a belt which is 20 miles wide. Gypsum beds usually overlie massive rock salt and are in turn overlain by red clays of Eocene age. Average of 20 analyses gave (in percent) CaO 30.0–33.2, $SO_3$ 38.0–46.0 and $H_2O$ 17.0–20.0. Reserves are estimated to be 5 billion tons.

Spin Tangi (29°55′N : 68°10′E) gypsum deposits in Sibi district of Baluchistan occur in beds up to 7 feet in thickness interbedded with green shales and nummulitic limestone of Eocene age. The range of chemical composition is the same as in Kohat area and reserves up to a depth of 50 feet are estimated to be 0.4 million tons.

The Chamalang gypsum deposit in Loralai district is located 7 miles SE of Chamalang village. Thirteen beds of gypsum up to 50 feet thick separated by shales and limestone have been mapped. Reserves up to a depth of 100 feet are estimated at 7 million tons.

White and grey gypsum associated with bituminous oil shales up to 200 feet as well as red coloured marl and rock salt beds (up to 800′ thick) occur in the Punjab saline series. The lower gypsum-dolomite stage of the series consists of anhydrite, dolomite, red verigated gypsiferous clays up to 750 feet thick. Reserves have been estimated at over 28 million tons.

Detailed geological investigations including drilling in Daudkhel area have proved gypsum and anhydrite reserves of over 55 million tons.

### Limestone and Dolomite

Pakistan has practically inexhaustible reserves of limestone and dolomite distributed all over the country. The estimated reserves above ground are at least 45,000 million tons. These deposits are, therefore, not described here.

### Magnesite

The best known, though not the largest, magnesite deposits are those of Nasai about 20 miles E of Muslimbagh in Zhob district. Cryptocrystalline, milky-white magnesite veins associated with serpentinized dunite occur in a vein about 500 yards long and up to 40′ in width. A number of small deposits of similar nature occur in close proximity of this deposit and the reserves are estimated to be 60,000 tons.

Analysis of typical magnesite gives (per cent) MgO 45.38, $SiO_2$ 0.38, CaO 1.72, $Fe_2O_3$ 1.4, loss on ignition 51.15. The mineral has formed as a result of alteration of ultramafic rocks whose fragments in various stages of alteration are common in large block of magnesite.

Another magnesite deposit is that of Sakhakot village (37°24′N : 71°56′E); the mineral occurs in irregular veins and lenses in grey dolomitic limestone of the Abbotabad formations. Steeply dipping veins of magnesite are supposed to have been formed by hydrothermal replacement of dolomite or dolomitic limestone. MgO content ranges from 44.9 to 46.7% probable and possible reserves have been estimated at 1.5 and over 11.0 million tons respectively.

### Marble

Pakistan possesses very large reserves of marble deposits which have been classified into three types (a) crystalline calcitic/dolomitic rocks (b) partially crystallized compact limestone—commercial marbles (c) travertine deposits, (AHMED, 1969, p. 117). Only the most important deposits are mentioned here (Fig. 1).

White, pink, grey and white banded marbles are being worked at Mullagori area of Khyber agency. The two deposits worked are located near Shahidmina (34°30′N : 71°17′30″E) and Kambela Khawai (34°08′N : 71°19′30″E) villages. The deposits are between 100–2,000 feet thick and the outcrops are over 2 miles long. The marble, though jointed, can be extracted in large blocks. Reserves are expected to be in excess of 200 million cubic feet.

High quality white marble is being worked at Ghundai Tarako (34°13′N : 72°25′E) in Swabi Tehsil. Reserves are estimated over 100 million cubic feet.

Pink marble with criss crossing veins of white calcite and brownish streaks of ferrogenous material occupying cracks is being worked at Nowshera village on the banks of river Kabul. Large size blocks can be extracted and reserves are estimated at several million cubic feet.

White marble of good quality is found in several hills of Bala Kot near Naran. The marble is not being worked due to high cost of transport but reserves are several thousand million cubic feet.

High quality light to dark green onyx marble is being mined extensively in Chagai district and being marketed under the trade names of aragonite and travertine. The best known localities are Zard Kan, Patkok, Juhlli, Butak, Tozghi, Zeh, Mushkichah, etc. (Ahmed, 1969, p. 120). Most deposits occur in small hills often forming terraces. A typical example is that of Juhlli (29°05′30″N : 63°21′30″E) where three terraces 900 × 100 × 15, 1,400 × 40 × 12 and 30 × 100 × 10 feet are being worked. Travertine is usually interbanded with volcanic ash. Light and dark green travertine mostly traversed by veins of ferrogenous material of brown or yellow colour are the common varieties. Rarely pale green travertine without any veins which is translucent in tiles up to 1/2″ thick is also found. The total reserves in the Chagai district have not been estimated though approximate studies indicate the reserves at several hundred million cubic feet.

## Rock Salt

Rock salt is one of the most important minerals of Pakistan which possesses probably the world's largest reserves of the mineral. Rock salt production during the past five years has varied between 358,000 to 600,000 tons a year (Table 1).

The salt occurrences of Pakistan are too numerous to be all dealt with here and, therefore, only the most important ones are briefly described.

The best known occurrence is that of Khewra area in the Salt Range which has been the subject of study for almost 100 years.

Khewra salt deposits occur in the Lower Saline Marl member (thickness 2,000′) of the Punjab Saline series. The salt deposits are part of an irregular dome which has been faulted at a number of places. A major N-S trending fault limits the westward working of the Khewra salt mines of lower Paleozoic age.

There are seven seams, three in upper and four in the lower group separated by a 100′ thick zone of thin salt seams and marl. The details of the seams are given below:

| | |
|---|---|
| Buggy | North Buggy salt seam 25′–50′ thick |
| Complex | Buggy seam 150′–600′ thick |
| of Seams | Sujjawal seam 60′–70′ thick |

At the western end of the present workings Buggy seam and Sujjawal seam become one with a thickness of 270 feet.
Zone of thin seams and salt marl:

| | |
|---|---|
| Pharwala | Upper Pharwala seam 35′–50′ thick |
| Complex | Middle Pharwala seam 60′ thick |
| of Seams | South Pharwala seam 45′ thick |
| | Low level tunnel seam 60′ thick |

The estimated reserves are in excess of 600 million tons. The other important salt producing area of the salt range is Warcha, near a village of that name in Sargodah division. There are five seams with an aggregate thickness of 93–154 feet. The seams are separated by beds of marl ranging in thickness from 6 inches to 30 feet. Reserves are estimated to be over 2 million tons.

Kalabagh deposits, also a part of Saline series, are the third most important salt deposits that have been developed. Individual seams up to 40 feet thick, are located on the right bank of Lun Wahan stream, a tributary of the Indus river. The seams are thinner than in Khewra, are contorted and lenticular dipping at steep angles. Reserves are in excess of one million tons.

Another extensive area (over 2,000 sq. miles) of salt deposits is Jatta-Bahadurkhel and Karak of Kohat district. Salt beds are confined to Salt Marl series (Lower Eocene) and are overlain by gypsum, selenite and bituminous shale. In Bahadur Khel area the exposed thickness of salt bed is 350 feet while in Jatta and Karak is over 100 feet. No estimates of reserves have been made but are expected to be over several hundred million tons.

### Vermiculite

The largest vermiculite deposit is that of Doki river area in Chagai district (Fig. 1). Vermiculite is considered to have formed by metamorphism of basaltic lavas by intruding Garrok-Sargahar-Osaphi stock and diorite, aplite dykes. Basalt has been altered to vermiculite schist, biotite-pyroxene schist and hornblende schist. The vermiculite has formed as an alteration product of biotite. (BAKR, 1962). A partial chemical analysis gave (per cent) $SiO_2$ 41.02; $Al_2O_3$ 19.05; MgO 10.30; $H_2O$ (at 105°C) 10.75. Exfoliation tests by Overseas Geological Survey, London, gave the following results:

| Temp. of test | Original thickness (inches) | Final thickness (inches) | Linear exfoliation (inches) |
|---|---|---|---|
| 775°C | 0.06–0.08 | 0.6–0.7 | ×9–10 |

Reserves of coarse-grained book (¾″ × 1½″ in diameter) are estimated at 11 million tons up to a depth of 100 feet only.

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# A General View to the Geology and Metallogeny of Iran*

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Extended Abstract

## Geology

Iran is tectonically divided from north to south and west to east briefly to the following zones:

Touran platform and Kopeh-Dagh ranges
Main volcanic-intrusive belt of Iran
Sanandaj-Sirjan zone
Zagros thrust zone
Zagros folded belt
Central and east Iran
Lut block (or central Iranian micro-continent) ophiolite zone
Arabian platform

A brief description of each zone is given below.

Touran platform is located in Tourkamanestan Republic of U.S.S.R. It is related to the Hercynian orogeny with Precambrian basement.

Alborz and Kopeh-Dagh ranges are located at north of Iran and south of the Caspian sea with approximate east-west trend. The oldest formation of this range is early Paleozoic. But the main sediments of this mountain are of Mesozoic. The southern part of this range consists of thick pyroclastic sequence of Eocene age, mainly green tuff with about 3,000 meters thickness at places. There are also several intrusive bodies in this range, mainly of Tertiary age. General trend of folding and faulting in this range is northwest-southeast, as well as west to east.

Main volcanic-intrusive belt of Iran trends from northwest to southeast of Iran. It continues to the northwest into Turkey and up to Bulgaria and Yugoslavia. To the southeast it continues all along the Chaghi district of Pakistan (northern part of Baluchistan).

In this zone there are volcanics of mainly andesitic composition being of Cretaceous to early Quaternary age and several intrusive bodies (acid to intermediate) of Mesozoic to Tertiary age.

Sanandaj-Sirjan zone trends parallel to the Zagros thrust zone. This zone is limited in north by the above mentioned volcanic intrusive belt, and at the south with the Zagros thrust zone. It consists mainly of Mesozoic sediments with some metamorphics of different ages and Paleozoic inliers.

Zagros thrust zone can be called also the Zagros crushed zone. It trends to

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northwest-southeast. It is rather a narrow zone located between the Sanandaj-Sirjan zone and the Zagros folded belt. This thrust zone consists of sediments of late Precambrian to Quaternary age, with many significant sedimentary gaps.

Zagros folded belt also trends to the NW-SE direction and is located at the southwestern part of the country. The sediments of this zone are mainly of Mesozoic and Tertiary ages. There are outcrops of Paleozoic as well as salt domes of Cambrian age. Many salt domes of this age are mainly located at the southeastern part of this zone.

Central and east Iran: In this vast part of Iran, there are formations from the probable upper Precambrian (metamorphic) to Tertiary. But the main part consists of Mesozoic to Tertiary. Volcanics and intrusives are predominant, but are less than the main volcanic-intrusive belt. A vast area in this part of the country is covered by Quaternary salt dump planes called Dasht-e-Kavir formation, which trends generally north-south.

Lut block is located at eastern central Iran. Its general trend is north-south. There are thick Mesozoic sediments gently folded at the western part of this block. But at the eastern part of the block there are more variety of Tertiary and younger volcanic rocks which are also gently folded. This part of Iran has been outcropped as a block from early Kimerian. This block is limited to the east and west by two main faults (Naiband and Nehbandan faults).

Because of ophiolite sequences and the especialities, this part of Iran can be called also a micro-continent or micro-plate.

Ophiolite zone (Coloured melange zone): A complex of ultramorphics and different sediments and volcanics occurs along the main fault zones of Iran. They are mainly located at southeast of Iran and around the Lut block (Fig. 1). Different ideas have been proposed about the age of this zone. But it is believed commonly that they are formed from Jurassic to early Cretaceous.

Arabian platform: A small part of this platform continues to the southwestern part of Iran (western part of Khozestan province).

## Metallogeney of Iran

Brief description about metallogeny of mineralized zones is as the followings:

### Alborz and Kopeh-Dagh ranges

There are phosphatic lenticular deposits in Devonian sediments of the Alborz range. The largest one is Shehshak stratiform phosphate deposit located about 30 km northeast of Tehran.

In the Permian calcareous sediments of Alborz, there occur several stratabound Pb-Zn deposits. The largest one is the Douna mine. Rather small Pb-Zn deposits have been found also in the calcareous Mesozoic sediments of Alborz. They are also believed as stratabound type related with the Alpine orogeny.

Several lenticular barite deposits occur in Eocene green tuff formation of the southern part of the Alborz range. They are all believed to be of hydrothermal type related with Alpine orogeny. Rather large altered zones have been known at the western part of this zone at the contact of granitic intrusives and tuffs.

### Main volcanic-intrusive belt of Iran

Several of metallic mineralization occur in this belt. This belt is a polymetallic zone. Copper is the main mineralization of this zone. Porphyry copper including the famous Sarcheshmeh deposit occurs in the acid intrusive bodies at several places of this zone. Other porphyry copper deposits near the Sarcheshmeh are Meidok, Neizar etc.

At the northwestern part of this zone there are several skarn-type copper deposits which contain also molybdenum and gold. They occur at contact of acid intrusive bodies and surrounding limestone formation.

At Songoun, Qarachilar, Anjert, Nazareh etc., contact of the same intrusive bodies with tuff is severely altered. This large altered zone contains alunite-kaolinite and silicified altered zones. In the other parts of this zone there are Nein type hydrothermal deposits of copper, manganese, barite, iron, lead, zinc etc.

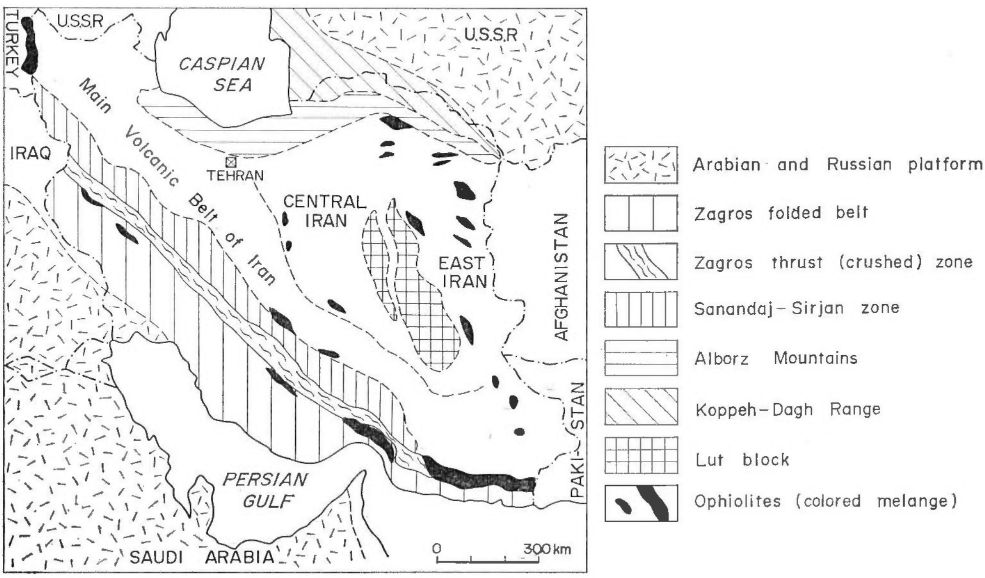


Fig. 1. Main structural units of Iran

## Sanandaj-Sirjan zone

There are many stratabound lead-zinc deposits occurring in this zone. The large ones are Badaghaleh, Lakan, Ahangaran, Anjired Tiran, Shakhouh and also Shamsabad hematite deposits which contain some lead and zinc.

At the central northwestern part of this zone there are several acid intrusive bodies which contain several medium-sized tungsten and gold deposits.

## Zagros thrust zone

There are several bauxite-clay deposits of Permo-Triassic age in this zone. The large ones are Semirom and Dopolan deposits. Origin of these deposits is believed to be sedimentary, followed by lateritic concentration.

Indications of copper and molybdenum have also been found in this zone.

## Zagros folded belt

The main deposit of this zone is oil. One of the most famous and large oil bearing area of the world is in this zone. But description about oil is beyond the scope of this paper.

Other than oil, a medium size lead-zinc deposit has been found in the Triassic sediments of this zone, which is a stratiform type. Several sulphur deposits also exist in this zone. The origin is believed to be the reaction of hydrocarbon gases in gypsiferous sediments. Hematite is also associated with the several salt domes in southeastern part of this zone.

**Central and east Iran**

Several large magnetite deposits are found in the probable upper Precambrian metamorphic formations of this part. Stratabound lead-zinc deposits are also present in the Paleozoics.

Copper and related mineralizations occur in the acid intrusives, diabasic sub-volcanics and tuffs as medium and small size, hydrothermal deposits. The famous turquoise deposits (Neishabour deposits) are formed by meteoric alteration in a low grade porphyry copper deposit of this zone.

**Lut block**

Medium and small size lead-zinc deposits have been known in the Mesozoic sediments of this part. Lead-zinc deposits as hydrothermal type are present in the Tertiary volcanics of this area.

**Ophiolite zone**

Chromite and related mineralizations such as asbestos in varying size, have been found in this zone. The most important one is located at southeastern part of Iran.

# Outline of Geology and Ore Deposits of Thailand*

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## ABSTRACT

The geology and some major mineral deposits were briefly reviewed. The economic significance of sedimentary and igneous rocks was also cited and examples were given. Among the metallic minerals, tin and tungsten are the most important economic minerals while fluorite used to be the leading non-metallic variety. Natural gas, lignite, oil shale, and potash and rock salt will become important non-metallic minerals in the future. A summary of major ore deposits and their relationship to geologic periods and rock types are also given.

## INTRODUCTION

The multiphases and periodic changes of geological evolution of Southeast Asia resulted in the complex geological framework, with various igneous activities and formation of many ore deposits which differ both in kinds and types of deposition. Thailand, a country in this region, situating on the mobile belt and at the junction of the plate boundaries can therefore be regarded as a most interesting site for geological investigation. It leads to the understanding of SE Asian geology and acts as a key area for the correlation to its neighbouring countries.

The size of the country covers an area of 518,000 square kilometres, bounded by Burma, Laos, Kampuchea and Malaysia. The country can be divided geographically into four regions: the mountainous highland in the north and northwest, the Khorat plateau in the northeast, the central Chao Phraya plain and the southern peninsula which are surrounded by Andaman and the South China Seas. These geographic expressions represent the imprints of the interaction as well as the subsequent movement of the three major plates: the continental Asian plate, the oceanic Pacific plate and the oceanic-continental Indo-Australian plate, which took place during the great orogenic movements in Cenozoic. The activity is being continued and can be noted by the present-day hot spring.

The geological framework of Thailand consists of rocks ranging from Precambrian to Quaternary age with periodically intervening between sequences which indicate sedimentation and erosion. This situation has been referred to earlier by KOBAYASHI (1976) as constructive and destructive stages, and he has classified these sequences into four stages.

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There is no confirmed evidence of geologic age for the inferred Precambrian stratigraphic unit, either by paleontological or radiometric data. Other stratigraphic units have at least some control of fossils or stratigraphic succession. Based on the sedimentary sequence, it indicates a long history of deposition from Cambrian to Early Carboniferous. There was apparently less igneous activity during this time. The igneous activity became more active and abundant in Upper Triassic-Jurassic and during Cretaceous to Tertiary, accounting for some important metallic mineral deposits.

Table 1 Summary of geological evolution of Thailand
(after SUENSILPONG *et al.*, 1978)

| ERA | Period | Stratigraphic Units | | Lithology | Igneous Activity | Orogenic Cycle |
|---|---|---|---|---|---|---|
| | | Group | Formation | | | |
| TERTIARY | Recent | | | Alluvium, colluvium, gravel, silt & clay | | |
| | Pleistocene | Krabi Group | Mae Taeng Fm. | Gravel beds & terrace deposits | Basalt | |
| | Pleiocene | | Mae Mo Fm. | Sandstone, conglomerate with inter-bedded lignite & oil shale | | |
| | Miocene | ? | Li Fm. | — do — | | |
| | Oligocene | | | | | |
| | Eocene | | | | | |
| | Palaeocene | | Salt Fm. | Rock salt, gypsum & conglomerate | Granite (50-70 m.y.) | *Tertiary Orogeny* |
| MESOZOIC | Cretaceous | Khorat Group | Ban Na Yo Fm.<br>Phu Phan Fm. | Sst., siltst., congl. & ls.<br>Sst., sh., conglomeratic sst. & congl. | Granite (110-135 m.y.) | |
| | Jurassic | | Phra Wihan Fm.<br>Phu Kradung Fm. | Congl. with ls. and rhyolite pebbles, gray sh/sst., ls. & congl. | Andesite, rhyolite, agglo.<br>Granite (190-210 m.y.) | *Mesozoic Orogeny (Indosinian)* |
| | Triassic | Lampang Group | Nam Phong Fm.<br>Marine Fm. | Marine sh/sst., red sst/sh., ls & volc. | Andesite & rhyolite<br>Granite (235-240 m.y.) | |
| PALAEOZOIC | Permian | Rat Buri Group | Sara Buri lm.<br>*Matsi fm. | Massive ls., sh., slaty sh., sst., rhyolite and andesite, tuff, agglo. & chert | Interm.-acid volc. rks., tuff | |
| | Carboniferous | Phuket Group | Kaeng Krachan fm. | Pebbly mudstone, turbidites and Laminated mudstone and sst. | Basic-Interm. volc. rks.<br>Granite ? | *Carboniferous Orogeny* |
| | Devonian | Satun Group | Kanchanaburi fm. | Black sh., slate, sst., qzite., green schist & phyllite | | |
| | Silurian | | | | | |
| | Ordovician | | Thung Song Ls. | Massive and bedded ls., slate, slaty phyllite, bedded ls. & sh. | | |
| | Cambrian | Tarutao Group | Nai Tak Fm.<br>Tarutao Fm. | Marine red sst., micaceous sst. & sh., qzite. & phyllite | | |
| | Precambrian | | | Paragneiss, amphibolite schist, qzite. marble & calc silicate | Granite ? | *Precambrian Orogeny* |

* New stratigraphic formation proposed by C.K. Burton

Sedimentation during Cambrian to Jurassic was confined mainly to the troughs with changing of sea levels. This was indicated by types of stratigraphic succession. Middle Jurassic was the time when the sedimentation took place in the shallow sea and mainly in the continental paralic condition of clastic sediments which are known as 'Khorat Group' (WARD and BUNNAG, 1964; IWAI *et al.*, 1966).

The Indosinian orogeny which may span the Late Permian to Early Jurassic (WORKMAN, 1975, 1977; SUENSILPONG *et al.*, 1978) has its peak of intensity in Upper Triassic-Lower Jurassic. This orogenic activity accounted for the intrusions of two phases of granites; in Lower Triassic and Upper Triassic-Lower Jurassic. The calc-alkali volcanics are found to be associated with the Upper Triassic activity. Cretaceous to Tertiary was another period of regional tectonic activity resulted for the regional uplift and the Khorat Plateau was formed. Most of the clastic rocks of 'Khorat Group' were tilted and folded at this time.

During the Tertiary the major sedimentation was found within the isolated intermontane basins throughout the country where hydrocarbons were accumulated, in the form of oil shale, lignite, oil and gas. Evaporites deposition took place in the closed basin on the Khorat Plateau forming salt beds and potash minerals, and also in certain part of the central plain, in the north as well as in the south, where gypsum was deposited.

Table 1 summarized the geological evolution of Thailand. Other accounts on the geological evolution and igneous activity were documented by SUENSILPONG *et al.* (1978) or elsewhere.

## GENERAL STRATIGRAPHY AND SOME ECONOMIC SIGNIFICANCE

### Precambrian

The inferred Precambrian strata is referred to the group of folded and contorted orthogneiss and paragneiss of calcareous and clastic metasediments which have been highly metamorphosed to amphibolite facies. The definite age of this rock unit is not known as mentioned earlier.

This rock unit is unconformably overlain by the Cambro-Ordovician formation. The best known areas are along Hot-Mae Sariang highway, southwest of Chiangmai (BAUM *et al.*, 1970) and west of Tak area along the Tak-Mae Sot highway (CAMPBELL, 1975). Many other inferred Precambrian gneisses, for instance, Cholburi and Hua Hin have been subsequently corrected to be of younger age as quoted by BECKINSALE (1979) and PUTTHAPIBAN and SUENSILPONG (1978). So far the mineralization in association with the inferred Precambrian strata is still unknown.

### Palaeozoic

There is a continuous record of sedimentary sequences throughout the Palaeozoic ranging from Cambrian to Permian.

**Cambrian** strata characterized by cross-bedded sandstone contain Upper Cambrian trilobites, *Pagodia* and *Saukiella.* This rock unit is better exposed in Tarutao Island and extends southward into Langawi Island of Malaysia. Other areas where Cambrian strata are recorded include an area at Satun, Nakhon Si Thammarat and some areas in northern Thailand. Apparently there is no mineral deposit associated with this rock unit.

**Ordovician** strata consist mainly of impure carbonate sediments designated as Thung Song limestone. This rock type is quite extensive in southern Thailand. In the north Ordovician strata are found to the west of Chiang Mai consisting of siltstone and sandstone intercalated with dolomitic limestone. Middle-Upper Ordovician fossils have been found. The Ordovician sequence in west of Kanchanaburi, central Thailand bears an economic significance containing stratabound lead and zinc deposits. This particular type of deposit is being taken into consideration and an attempt has been made to explore for similar occurrence in other parts of the country including northern Thailand. Most of the dolomitic limestones in this sequence are being exploited and used as raw materials in some industries.

**Silurian, Devonian and Carboniferous** sedimentary rocks can easily be described together as they form a continuous succession. In general it consists mainly of argillites with immatured arenites and subordinate amounts of carbonate rocks. This sequence is well developed in the western part of the country and in peninsular Thailand.

Two distinctive facies have been recognized, suggesting two different types of deposition within two major N-S trending troughs. The eastern facies which is associated with volcanic tuff along with an ophiolite suite is compatible to the eugeo-synclinal facies while the western belt corresponds to mio-geosynclinal facies.

No economic mineral deposit has been reported so far to be associated with these stratigraphic sequences.

**Permian** is well-known as Rat Buri limestone. This is probably due to the fact that the Permian sequence comprises more abundant limestone. However the Permian strata include some arenaceous sediments as well as chert bed and volcanic tuff. Fusulinid index fossils have been found by PITAKPAIVAN (1965) and other fauna have been intensively studied by many geoscientists such as WATERHOUSE and PIYASIN (1970) and BUNOPAS (1976).

The main economic significance of this rock unit is the utilization of limestone as construction material and in cement industries and the marble as paving stones.

## Mesozoic

The stratigraphic succession of the Mesozoic can be divided into two major groups, generally recognized as marine formation and Jurassic-Cretaceous Khorat Group which is a continental type of sedimentation.

Except the lowermost part of **Triassic** which consists of volcanic tuff and volcanic agglomerate, a continuous succession from Upper Permian, the marine sediments as recorded belong to Middle-Upper Triassic. This rock unit is composed of rock of flysch facies intercalated with minor amounts of limestone. These marine Triassic rocks have been termed as 'Lampang Group' by PIYASIN (1972).

No economic mineral has been found to be associated with this rock unit.

**Jurassic** and **Cretaceous** stratigraphy which is extensive in the northeastern part of the country covers the whole Khorat Plateau and is known as Khorat Group. Minor amounts of these rocks occur also both in the northern and southern parts of Thailand, particularly Nan Prae in the north and Krabi in the south.

Lithologically it consists of sandstone, shale, mudstone and conglomerate of red, pink and partly white in colours. This Khorat Group generally contains in the upper part, some salt, potash and gypsum beds which can be correlated to Tertiary age.

Recently, some uranium minerals have been discovered in the Phu Phan formation of the Khorat sandstone. The detailed exploration program has been carried out. This will certainly mark the economic importance associated with this rock formation. Activities for oil and gas exploration are being currently carried out by a petroleum company.

## Tertiary

Tertiary basins are quite extensive covering every part of the country even in the Gulf of Thailand. It can be regarded as the most important sedimentary type basin as far as economic minerals are concerned. Both oil and gas of commercial value have been discovered in the Tertiary basin in the Gulf of Thailand.

In northern Thailand, enormous volumes of lignite and oil shale have been found within several intermontane basins. Some of these deposits have already been developed, for instance, at Mae Moh and Li Basins. One of the important oil shale deposits is at Mae Sot. This Tertiary basin is very extensive covering an area of approximately 500 square kilometres and is believed to extend westward into Burma.

Crude oil is also detected and being developed at Fang Basin. Further activities for exploration are being carried out in Chiang Rai, Lampang and Chiang Mai Basins.

In central part, most of Tertiary basins contain thick layers of gypsum beds, some of which are being exploited. The well-known deposits are at Pichit and Nakhon Sawan. It is being used as raw material in cement industries. It is also hoped that oil and gas occurrences may be detected within the Tertiary basin of the Central Plain.

As mentioned earlier, the upper part of Khorat Plateau consists of some evaporite beds; these have been regarded as Tertiary formation by SUENSILPONG *et al.* (1978). Enormous quantities of rock salt and potash have been known to exist. Exploitation of these mineral deposits is now being planned.

In the southern part of the country Tertiary basins are also found, some of which are being developed for economic minerals such as gypsum at Surat Thani Basin and lignite at Krabi.

In addition to those economic minerals mentioned above, diatomite and bentonite are found within Lampang Basin, northern Thailand.

Lithologically, the sedimentary basin consists mainly of shale, sandstone and conglomerate with minor amount of limestone. The lithology is different from one basin to the others. Most basins in the north belong to the fresh water type whereas in the south, for instance, in Krabi both marine and non-marine strata are found. This stratigraphic unit has been termed as Krabi Group.

### Quaternary

The Quaternary geology in Thailand has not been intensively studied, although it is one of the most important parts of the geology in terms of mineral deposits. Most of placer tin, tungsten, monazite, columbite, tantalite, ilmenite, gold, gemstone, silica sand deposits and phosphate are associated with Quaternary beds. Most tin productions in Thailand are obtained from placer tin deposits both onland and offshore areas. Quaternary sequences are widespread and found in every part of the country. The most important areas are those basins in the north, the Central Plain, the topmost part of the Khorat Plateau and along the shorelines in the peninsula Thailand.

## IGNEOUS ROCKS

Most of igneous rocks in Thailand belong to the acidic magmatic composition in which granite and granodiorite are the most abundant intrusive rock and rhyolite as the volcanic derivative. The more basic type such as diorite, gabbro, and basalt are relatively less abundant. These igneous phases belong to different ages and can be correlated to different tectonic settings. SUENSILPONG and PUTTHAPIBAN (1979) have tried to illustrate with some radiometric data, the relationship between igneous intrusions and the regional geologic setting. They could reconstruct the palaeotectonic model as far back as Upper Permian-Lower Triassic and suggested that the granites with isotopic ages of 235–240 Ma and some acidic to intermediate volcanic rocks found in northern Thailand are related to a W-dipping subduction taken place in Permian time. The reconstruction of Permian history is not as clear as that of the Upper Triassic-Lower Jurassic period which is related to the Upper Triassic-Lower Jurassic granite. They also believe that this younger tectonic event was responsible for the calc-alkali volcanic belt, extending from northern to southern part of Thailand. This volcanic derivative may have played an important role in the genesis of base

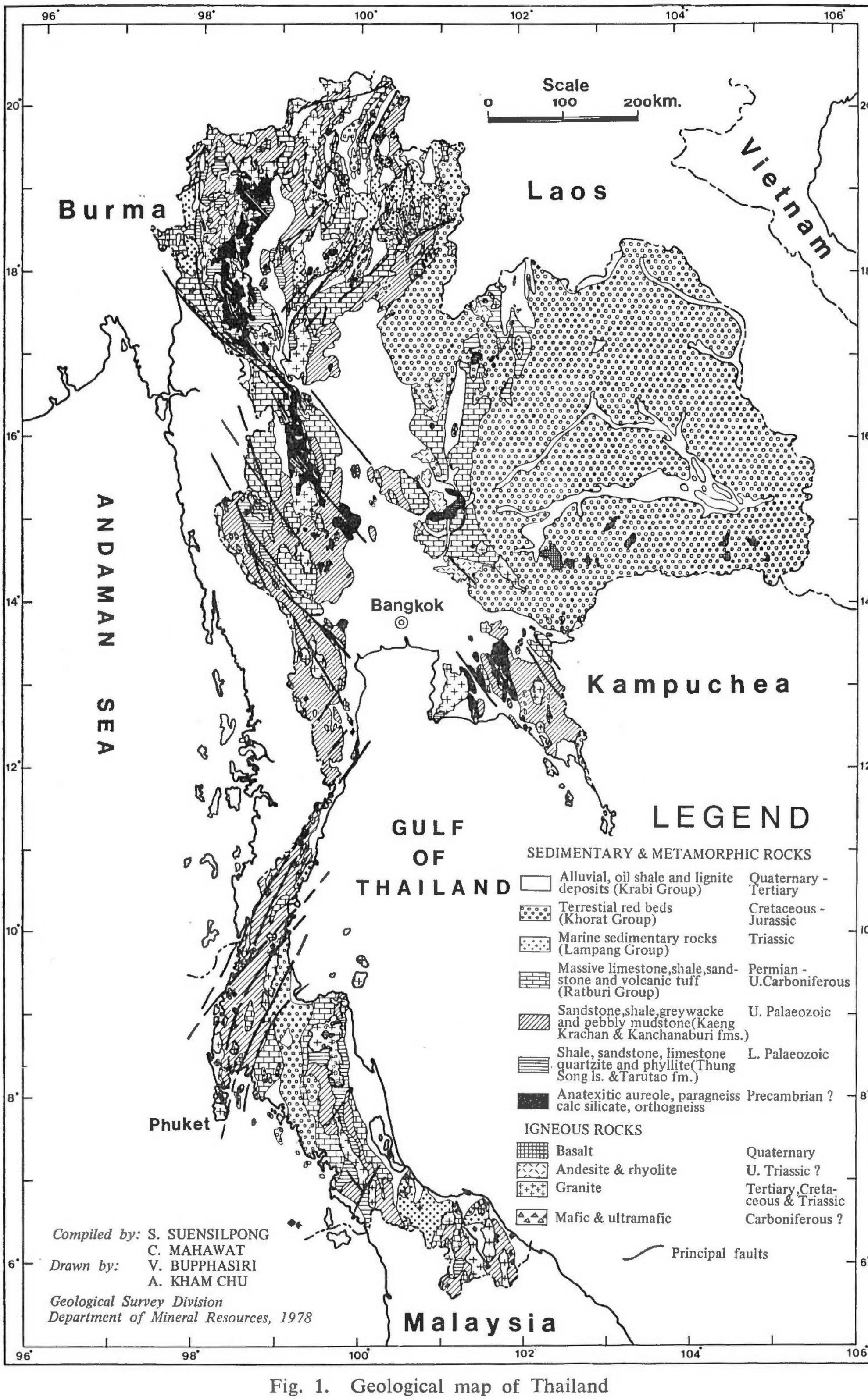


Fig. 1. Geological map of Thailand

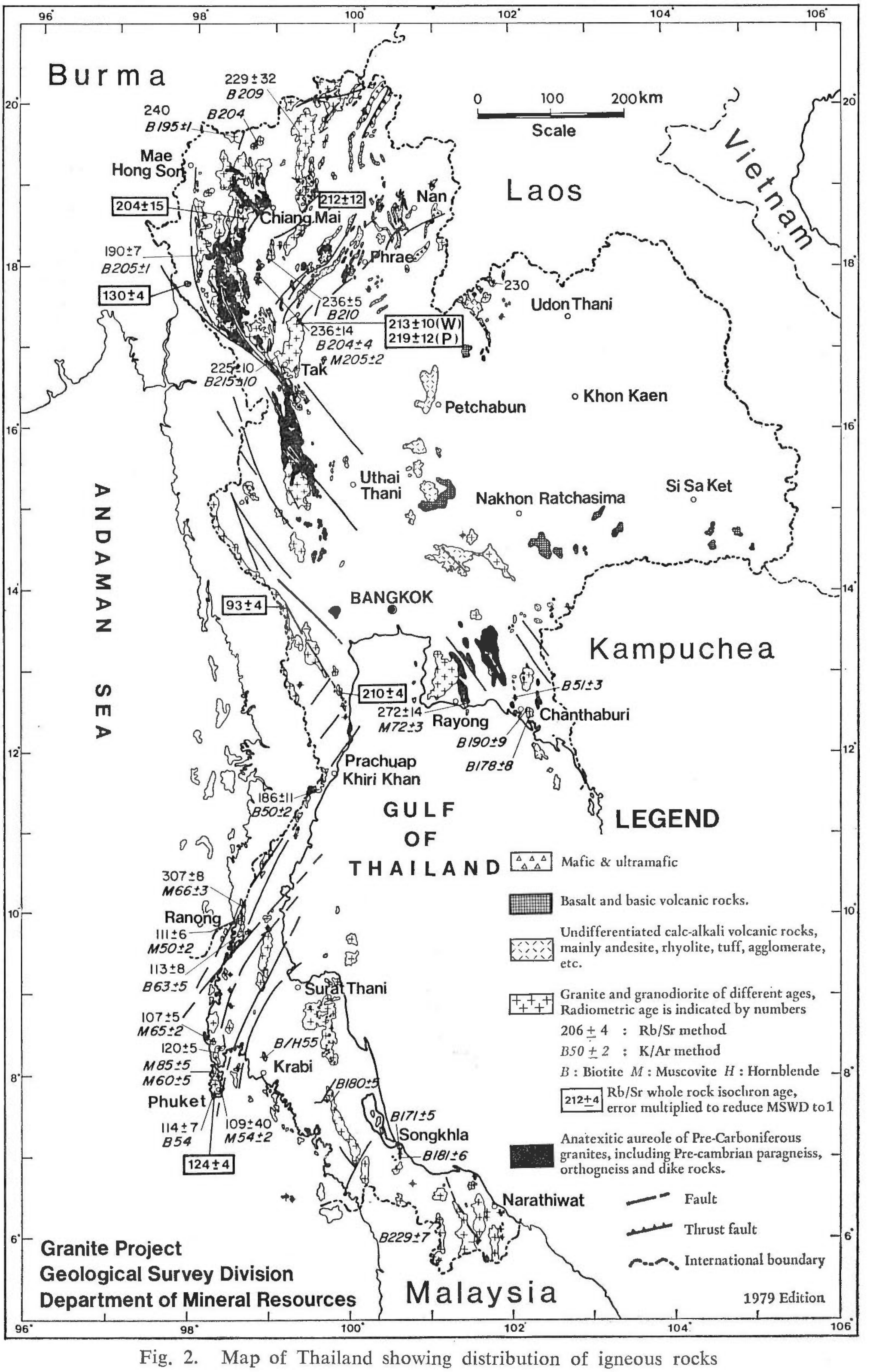


Fig. 2. Map of Thailand showing distribution of igneous rocks

metal deposits, including Cu, Pb, Zn, Ag, Sb and also barite. It is not yet fully understood, if it may be, that the sedimentary uranium deposit as found in sandstone of the 'Khorat Group' may have originated from these volcanic rocks.

Granite is the most abundant igneous rocks of the country as its belt extending in N-S direction with an approximate length of 1,700 kilometres. On the basis of geochronological data, it has been suggested that at least four different ages of granites are present. The oldest is the Upper Permian-Lower Triassic age with isotopic age ranging from 235–240 Ma. Granites of Upper Triassic-Lower Jurassic or with radiometric ages of 190–215 Ma can be regarded as the most predominant phase. There is a few confirmed data suggesting that this phase of granite is related to tin mineralization. Probably the granites which are responsible for tungsten mineralization as suggested by BECKINSALE (1979) and SUENSILPONG and PUTTHAPIBAN (1979), are of Lower Cretaceous age with isotopic age of 130 Ma. SUENSILPONG and PUTTHAPIBAN have also illustrated how this type of granite could have taken place. They have also distinguished it as an I-type granite as described by CHAPPELL and WHITE (1974). The youngest phase of granites which belongs to Upper Cretaceous to Lower Tertiary is probably the most important phase for tin mineralization. Generally it is always found intruded into granites of older age group. SUENSILPONG and PUTTHAPIBAN (1979) have shown that this younger phase of granites might have been derived from partial melting of the crustal materials, including some pre-existing granitic rocks. Hence it contains relatively higher concentration of tin metal.

Basalt is probably the most extensive basic volcanic rocks in this country. It is mostly found along the western and southern flanks of the Khorat Plateau, also in Chanthaburi, Trat, north of Kanchanaburi, Lampang and Prae. Apparently there is no basalt found in the southern peninsula. Stratigraphically these basalts belong to Quaternary age. The rocks can be subdivided into two groups, namely the corundum bearing and the corundum free basalts. Most of the sapphire and ruby found in Chanthaburi, Trat, Kanchanaburi, and Prae belong to corundum bearing basalt.

## MINERAL DEPOSITS

As summarized in Table 2, it is clearly seen that both sedimentary and igneous rocks in Thailand bear some economic significance. The distribution of most mineral deposits therefore is directly related to the distribution of each rock type. Tectonic activities which are in general responsible for folding and faulting are other important criteria for the setting of mineral or metallogenic provinces.

A number of non-metallic and metallic minerals have been found in Thailand. Some of these mineral deposits are being developed and exploited. Among them, tin, tungsten, niobium and tantalum are the most important metallic minerals in terms of value. While natural gas, lignite and probably oil shale, potash and rock salt will be the most important non-metallic minerals. Fluorite used to be the most leading non-metallic mineral for Thailand.

VEERABURUS (1978) has summarized a full account of metallogenic provinces together with metallogenic map which includes many countries in Southeast Asia. This work will be published by the Commission for Geological Map of the World (CGMW). TANTISUKRIT (1978) reviewed a number of metallic minerals while ASANACHINDA and PITRAGOOL (1978) outlined the non-metallic mineral deposits. It is the purpose of this paper to review some major mineral deposits in relation to their genesis.

Table 2 Summary of some major mineral deposits in Thailand in relation to geologic periods and rock types

| ERA | Period | Sedimentary rocks | Igneous rocks: Volcanic | Igneous rocks: Plutonic |
|---|---|---|---|---|
| QUATERNARY | Recent | placer tin, monazite, columbite, tantalite, ilmanite, gold, gemstone, phosphate, silica sand | gemstone | |
| | Pleistocene | | | |
| TERTIARY | Pleiocene | potash, rock salt, gypsum, lignite, oil & gas, oil shale, diatomite and bentonite | | |
| | Miocene | | | fluorite |
| | Oligocene | | | |
| | Eocene | | | |
| | Palaeocene | | | tin, monazite, columbite, tantalite |
| MESOZOIC | Cretaceous | | | |
| | Jurassic | uranium | | tungsten, molybdenum |
| | Triassic | phosphate ? | copper, lead, zinc, barite, antimony, silver, uranium ? | tin, gold, silver, iron, manganese, chromium, nickel, uranium ? |
| PALAEOZOIC | Permian | phosphate | | |
| | Carboniferous | | | |
| | Devonian | dolomite | | |
| | Silurian | | | |
| | Ordovician | stratabound lead, zinc | | |
| | Cambrian | | | |
| | Precambrian | U N | K N | O W N |

## Tin, Tungsten, Niobium, Tantalum and Molybdenum Deposits

These minerals are co-existing within the granite belt. On the basis of productions and export values, tin and tungsten can be regarded as the most important metallic minerals of this country. The amounts of foreign exchange equivalent to the export values of these two minerals boosted the mineral commodity to rank the third among the major export commodities. This metallogenic province is confined to the SE Asian tin-tungsten belt which is one of the most important tin fields in the world. The mineralization is essentially controlled by granite intrusives throughout the belt. This tin and tungsten province extends in the N-S direction covering most of the western part of the country and the peninsular Thailand, except the eastern part bounded by Kampuchea where tin deposits are also found. This particular area may represent the offset of the movement due to the subsequent transcurrent faulting. As stated earlier Suensilpong and Putthapiban have shown that tin and tungsten are related to different types of granite although they lie in the same trend.

Most of the tin deposits are of secondary alluvial type with minority of primary vein and disseminated type deposits. Veeraburus (1978) has subdivided this tin province into several submetallogenic provinces. Thailand as a whole forms a subprovince in the western part adjacent to Shan-Tenassarim subprovince of Eastern Burma. The most important tin mining district includes Phuket Island, Phang Nga, Takua Pa, Ranong, Nakhon Si Thammarat and Prachuap Khiri Khan in the southern peninsula; Kanchanaburi, Ratchaburi and Uthai Thani in the central part; and Tak, Chiang Mai and Chiang Rai in the northern part.

Niobium and tantalum minerals are commonly found in association with tin in the pegmatite. Certain parts of the country, for instance, Uthai Thani, have been reported to have a significantly high concentration of niobium and tantalum minerals up to 14% of the tin concentrate. Other areas, for instance, Phuket, columbite and tantalite are commonly found in the tin mines.

There are many kinds of tungsten deposits found in the country. The important tungsten minerals are wolframite, scheelite and ferberite. The well-known deposits include Doi Mok, Mae Lama mining district, Doi Ngoam in the north, Pilok mining district, western Kanchanaburi and Khao Soon in the southern peninsula. Huebnerite is also reported to occur as vein filling fractures at Khao Kratoon, Nakhon Si Thammarat.

In general molybdenum is found associated with tungsten in the tungsten-quartz veins, for instance, at Mae Lama Mines in northern Thailand. Probably the only reasonable size of molybdenum deposit is at Ban Nam Khun in Chanthaburi where molybdenite occurs as irregular scaly blebs ranging from a few to 20 mm in diametre in the contact zone of granite and metamorphic country rocks.

## Chromium and Nickel Deposits

The mineralization of Cr and Ni deposits are essentially controlled by basic and ultrabasic rocks which are usually characterized by serpentinite, pyroxenite or gabbro. This metallogenic province corresponds to the suture trend of the subduction as suggested by SUENSILPONG and PUTTHAPIBAN (1979). The age of these minerals has not been confirmed by radiometric dating but has been suggested on the basis of stratigraphic evidence as Upper Triassic-Lower Jurassic. Up to the present, there is no known Cr and Ni deposits that have been exploited.

## Copper, Lead, Zinc, Silver, Antimony and Barium Deposits

This metallogenic province which includes also barite deposits exists in the north passing through the western flank of the Khorat Plateau and the Central Plain, down to the south. It can probably be correlated to those deposits in the southern part of the country in Yala and Narathiwat areas. This belt corresponds to the calc-alkali volcanics represented mostly by andesite. This trend can be traced further northward into Laos as far as Luang Phra Bang. The age of mineralization has been considered as Upper Triassic-Lower Jurassic and belong to Indosinian orogenic activity (WORKMAN, 1977). According to SUENSILPONG and PUTTHAPIBAN (1979), this metallogenic province corresponds to the volcanic arc which took place during the process of west-dipping subduction in Upper Triassic-Lower Jurassic. Some of these deposits have been investigated and proved to be economical for exploitation. Presumably this metallogenic province continues southward to Malaysia.

## Iron and Manganese Deposits

Both stratabound and contact metasomatic type deposits have been reported for both metals. For iron, the important deposits are found at Phu Yang and Phu Ang in Loei province. The ore minerals are mainly hematite and magnetite. Phu Hin Lek Fai is considered to be a contact metasomatic deposit. Khao Thap Khwai, north of Lop Buri is the first iron mine in Thailand. Um Kruem in Kanchanaburi is probably the only large iron deposit in western Thailand. The proven reserves are 4.83 million tons of limonitic ore and 300,000 tons pyrrhotite. Another productive iron mine is Tha Sala. Besides there are many small deposits.

For manganese both battery and metallurgical grades are found. The major deposits are at Amphoe Li where the ore minerals are psilomelane and pyrolusite. At

Mae Taeng, Chiangmai, the metallurgical grade is found. About twelve manganese localities are reported to be found in Loei province.

## Fluorite Deposits

Most fluorite deposits in Thailand are found to belong to two major types, i.e., fracture filling vein and hydrothermal replacement, although there is suggestion of other geneses.

Most major fluorite deposits, for instance, at Ban Hong, Lam Phun and Amphoe Pai, Mae Hong Son, are situated on the major fault zone cutting through the contact of granite and calcareous sedimentary rocks. This geological phenomena suggest that the formation of fluorite may be related to the granite as the major source of fluorine. The amount of heat acquired for the formation may be derived from the younger fault movement. At the same time, the fault fractures will provide the channel way for the ascending of hydrothermal solution. The fluorine as naturally an active element will then react with the calcium provided by carbonate rocks and $CaF_2$ will be formed and deposited in the fracture zone. By this process quite a reasonable size of fluorite deposit may be formed.

Fluorite is also found disseminated in the granite or replaced in the calcareous sedimentary rocks. Other areas where important fluorite deposits are present are Doi Tao, Mae La Noi, Omkoi, Thoen, Mae Tha, Salak Phra, Chom Bueng, Khao Yoi and Cha-am.

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# Geology and Mineral Deposits of Korea*

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## ABSTRACT

South Korea is divided geologically into four provinces. The Kyonggi-Ryongnam massif is composed of Precambrian schists and gneisses. The Okchon geosynclinal zone in the Kyonggi-Ryongnam massif stretches from southwest to northeast diagonally across the peninsula in a direction known as the Sinian direction. Its northeastern part is composed of Paleozoic to early Mesozoic sedimentary formations and the southwestern part of the late Precambrian Okchon metamorphic series. The Kyongsang basin occupies southeast and southwest of the peninsula and is made up of a thick series of Cretaceous terrestrial sedimentary and andesitic rocks. A few small Tertiary basins are located in the eastern coastal area and Cheju island and are composed of marine sedimentary and basaltic rocks. Jurassic Daebo granite intruded the Kyonggi-Ryongnam massif and the Okchon zone in the Sininan direction whereas late Cretaceous Bulkuksa granites are scattered randomly in the Kyongsang basin.

Mineral deposits of Korea are divided into four metallogenic epochs and accompanied mineral commodities are as follows. 1) Precambrian: Sedimentary origin of hematite bearing quartz schist and crystalline graphite schist beds; also syngenetic, uranium and vanadium bearing black shale in late Precambrian age, magmatic segregation type of titaniferous magnetite deposits and nickel deposits of deuteric stage mineralization related to basic magma; finally several occurrences of low grade cassiterite bearing pegmatite deposits. 2) Paleozoic: Two hematite beds; one in Dongjom quartzite bed of Ordovician and the other in bed of Hongjom series of upper Carboniferous. Sedimentary limonite beds occur in the upper horizon of Sadong series of Permian age. 3) Jurassic to early Cretaceous: Hypothermal gold-silver veins related to Daebo granite are widly distributed and some occurrence of wolframite quartz veins are observed in and near the Daebo granite batholith. 4) Late Cretaceous to early Tertiary: Strong and various kinds of mineralization provided by Bulkuksa granite magmatism. Replacement type of copper, lead-zinc, tungsten, iron and flourspar deposits, and breccia or poppyry type of copper deposits, vein type of gold-silver, copper, lead-zinc and tungsten-molybdenum deposits were formed in this epoch.

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## GEOLOGICAL BACKGROUND AND PROVINCES

Geology of South Korea comprises all geological sequences from early Precambrian to Recent (Kobayashi, 1953; Cheong, 1956), except for the great break extending from late Ordovician to Early Carboniferous periods in which no sedimentary formation is known to be deposited in South Korea (Table 1). There are some debates as to the Precambrian geology (Cheong, 1970; O. J. Kim, 1973). However, geochronology and petrography of major rock units of Korea, Precambrian rocks and Mesozoic granites, are well established, thanks to intensive works of particularly O. J. Kim and his colleagues. Their works can be summarized as follows.

All the Precambrian geology except the Yonchon and Okchon (Ogcheon) systems have been collectively named "granite gneiss system" by all earlier workers. O. J. Kim has also differentiated the granite gneiss system into granite gneisses and many proper schist formations, and has tentatively correlated them as shown in the Table 1. In the Kyonggi massif, the Yonchon system is differentiated into three metamorphic complexes and the other two complexes, namely the Jangrak and Chungsong groups, have been newly established (1973). In the Ryongnam massif area the Ryongnam and Yulri systems are differentiated and tentatively correlated them to the metamorphic complexes in the Kyonggi massif, since no enough age dating on them has been made so as to correlate them exactly (1974). Lying uncomformably on the metamorphic complexes mentioned above is the Okchon system which streches along the Sinian direction diagonally in the southwestern parts of the Okchon geosynclinal zone.

The Okchon system is most controversial system as to its age and sequence. O. J. Kim has on the contrary concluded that the system is late Precambrian age (1968) and pointed out that the uppermost member of the system (Hwanggangri formation) is tillite origin (1969) which has been supported later by Reedman *et al.* (1973).

Mesozoic granites were known to be "Younger Granites" and thought to be Cretaceous age, and so described in all earlier articles up to 1970. O. J. Kim has differentiated the "Younger Granites" into Jurassic and Cretaceous granites, the former is named as the Daebo granite and the latter as the Bulkuksa granite (1971). He also pointed out that the Daebo granite is aligned in Sinian direction (NE to SW) across the Korean peninsula in the Precambrian terrains, whereas the Bulkuksa granite is distributed randomly in the Mesozoic Kyonsang sedimentary basin.

South Korea is divided geologically as well as tectonically into four provinces, namely the Ryongnam-Kyonggi massif, the Okchon geosynclinal zone, the Kyongsang sedimentary basin and Tertiary basin as shown in Figure 1. These provinces are briefly summarized below.

Kyonggi massif area: The Precambrian Yonchon system, Jangrak and Chunsong groups and granitic gneisses are widely distributed and the Daebo granite is widespread along the Sinian direction across the peninsula (Fig. 2).

Ryongnam massif area: The Precambrian Ryongnam and Yulri systems, granitic gneisses and Mesozoic Daebo granite are widespread. The Daebo granite is also aligned along the Sinian direction, but not so clear as in the Kyonggi massif area.

Okchon geosynclinal zone: Paleozoic to Mesozoic sedimentary formations are distributed in the northeastern Neogeosynclinal zone and the late Precambrian Okchon system in the southwestern Paleogeosynclinal zone. The Jurassic Daebo and Cretaceous Bulkuksa granites are scattered in both zones.

Kyongsang basin: Cretaceous terrestrial sedimentary formations and the associated

Table 1 Generalized geological sequence in South Korea (after O. J. KIM, 1975)

| Age | | C.H. CHEONG (1956) System | C.H. CHEONG (1956) Series | O.J. KIM (1973) System | O.J. KIM (1973) Series | |
|---|---|---|---|---|---|---|
| Cenozoic | | Quaternary | | Quaternary | Basalts | |
| | | Tertiary | Yonil | Tertiary | Yonil | |
| | | | Janggi | | Janggi | |
| | | | | | Granites (Bulkuksa granites) | |
| Mesozoic | Cretaceous | Kyongsang | Balkuksa (Granite & porphyry) | Kyongsang | Volcanics | |
| | | | intrusion | | | |
| | | | Silla | | Silla | |
| | | | Naktong | | Naktong | |
| | | | Granites | | Granites (Daebo granites) | |
| | Jurassic | Daedong | Ryukyong (in N. Korea) | Daedong | Undifferentiated in S. Korea | |
| | | | Sonhyon | | | |
| | | | | | Granite? | |
| | Triassic | Pyongan | Nokam | Pyongan | Nokam | |
| Paleozoic | Permian | | Kobangsan | | Kobangsan | |
| | | | Sadong | | Sadong | |
| | Carboniferous | | Hongjom | | Hongjom | |
| | | | | | Granite? | |
| | Devonian | | Chonsongri ? | | Lacking | |
| | Silurian | | | | | |
| | Ordovician | Chosun | Great limestone | Chosun | Great limestone | |
| | Cambrian | | Yangduk | | Yangduk | |
| | | | | | Granite? | |
| Proterozoic | | Sangwon | Kuhyon (in N. Korea) | Okchon (late) | Kunjasan | |
| | | | | | Hwanggangri | |
| | | | Sadangwu | | Changri | |
| | | | | | Munjuri | |
| | | | Jikhyon | | Hyangsanri | |
| | | | | | Kemyongsan | |
| | | | | | Granite gneiss | |
| | | Granite gneiss | | Yulri (middle) | Taebacksan | |
| | | | | | Kosonri | Chunchon: Chunsong |
| | | | | | Kakhwasa | Jangraksan |
| | | | | | granite gneiss | |
| Archeozoic | | Yonchon | | Ryongnam (early) | Wonnam | Yonchon: Yangpyong |
| | | | | | Kisong | Sihung |
| | | | | | Pyonghae | Puchon |

volcanics and tuffs are distributed, and the Cretaceous Bulkuksa granite intrudes randomly into the sediments in the basin.

Tertiary basin: The Neogene sedimentary formations and the associated basaltic flows are distributed in the small Tertiary basins and Cheju island off the peninsula. There also crop out granites but no dating has been done so as to designate them to the proper ages.

## TECTONISM AND RELATED GRANITES

In the Kyonggi massif area two great unconformities were recongnized (O. J. KIM, 1973) and three unconformities were also identified in the Ryongnam massif area (O. J. KIM *et al.*, 1963). The metamorphic rocks separated by these unconformities show a different attitude of deformation. Thus, the periods in which the metamorphism and deformation took place in these areas can be categorized into three periods

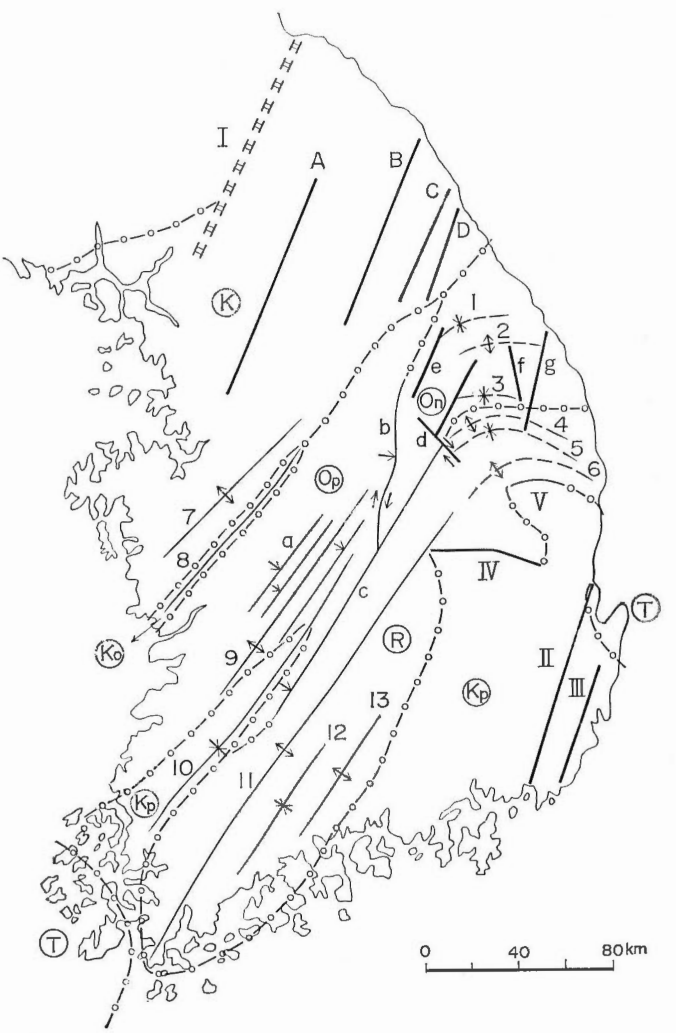


Fig. 1. Geological provinces and structural map of South Korea (after O. J. KIM *et al.*, 1977)

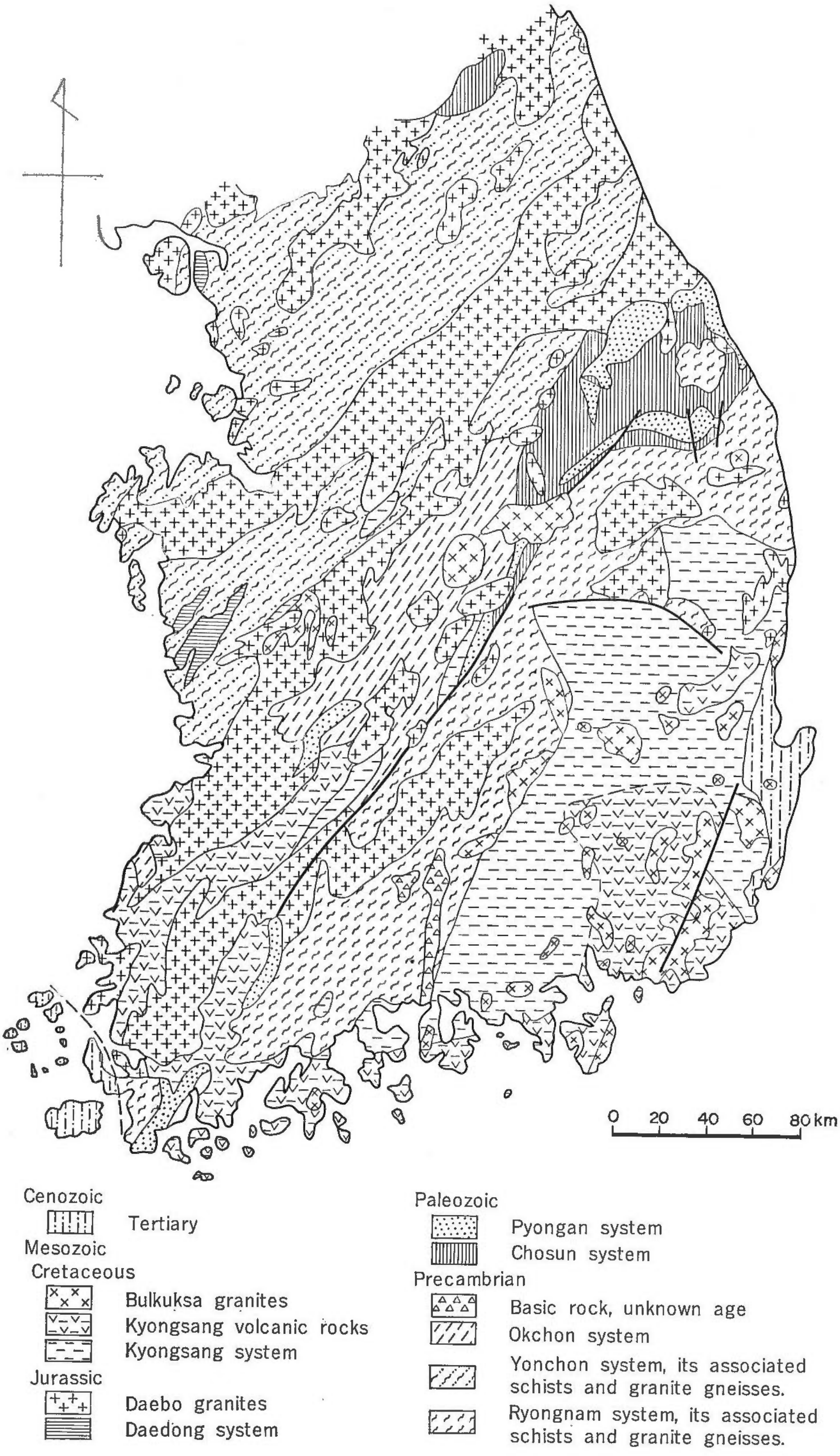


Fig. 2. Geological map of South Korea (after O. J. KIM, 1975)

(O. J. Kim, 1972). Nontheless, it is uncertain as to their exact ages of episodes and whether or not they could exactly be correlated each other in both Precambrian terrains. This is the reason why the geologic structure of both Precambrian terrains is grouped as Pre-Triassic in age. Structural breaks in Korea are definitely known to have occurred in the end of Triassic (Songrim Disturbance) and mid-Tertiary (Yonil Disturbance). The generalized structural pattern is shown in Figure 3 where the Tertiary structure is not shown because of insignificance.

## Pre-Triassic Deformation

In the Kyonggi massif, foliation of the metamorphic complex even within the same system as well as in the different systems bounded by unconformities is so diverse that generalization can not be drawn. However, the prevailing ones trend NNW-SSE direction in the western parts and NNE-SSW direction in the central to eastern pparts of the massif. Four major faults trend to NNE-SSW direction but are cut by the Daebo granite at the southwestern ends. There is no evidence that the foliation of the complex had been effected by the intrusion of the Daebo granite. In the Ryongnam massif the foliation is also very diverse, but changes to nearly NE-SW direction toward the southwestern parts and is cut slight-obliquely by the Jeomchon thrust.

## Triassic Deformation (Songrim Disturbance)

In the Okchon Neogeosynclinal zone at east-central region of South Korea, Paleozoic and Triassic sedimentary formations are folded and the axis of folds trends west-northwesterly. This deformation is thought to be caused by the Songrim disturbance at the end of Triassic period, since the Jurassic sediments in the area have not been affected by this deformational movement.

The western end of those folds are bent to the Sinian direction of Jurassic age. In the northeastern portion of the Ryongnam massif the trend of the Sobaeksan anticline, Yulri syncline and Andong anticline is WNW in general, but it is guessed that they were modified by the Triassic deformation although they might be originally Precambrian structures.

## Jurassic Deformation (Daebo Orogeny)

The Jurassic deformation caused by the Daebo orogeny had taken place and continued from early Jurassic to early Cretaceous (this was known from the age dating of the Daebo granites). This orogeny is most significant in Korea and some of the preceding formations were severely folded and faulted. The nature of the Daebo orogeny is manifested by the distribution of the Jurassic Daedong sedimentary formations and the alignment of the Daebo granites which are well cropped out along Sinian direction in the Okchon geosynclinal zone and its adjacent Precambrian terrains.

As shown in the tectonic map, four anticlinoriums and three synclinoriums run alternately from the southern border of the Kyonggi massif to the Ryongnam massif through the Okchon zone. The Okchon thrusts are in the Okchon zone, the Bonghwajae thrust bounds the Okchon Paleogeosynclinal zone and Neogeosynclinal zone, and the Jomchon thrust joined by the Bonghwajae thrust bounds the Okchon zone and the Ryongnam massif toward the southwest. These anticlinoriums constitute major mountain ranges and the younger sediments of Jurassic and Cretaceous periods scatter in the few isolated locations in the synclinorium areas.

## Late Cretaceous to Tertiary Deformation

Only minor folds are observed in the Cretaceous Kyongsang sedimentary basin although the sedimentary formations in the basin show holoclinal structure to the southeast in general. The fragmentation of the basin caused by the post-Bulkuksa disturbance resulted in forming of the upthrust at Andong and Ilwolsan, which bounds the Precambrian basement and the Cretaceous sediments. Along the Chugaryong rift valley extruded the Cenozoic basalt flows which cover the old river beds. High heat flows are checked along the Yangsan and Tongrae faults (CHANG, 1970).

## Mid-Tertiary Deformation (Yonil Disturbance)

The great unconformity has been known to exist between the lower and upper Miocene formations. The lower formations are wildly folded whereas the upper ones exhibit no sign of deformation. The disturbance of mid-Miocene is known as the Yonil disturbance.

Table 2 Orogenies and associated igneous rocks in South Korea (after O. J. KIM, 1975)

| Orogeny | Periods | Granites | Other igneous rocks |
|---|---|---|---|
| Yonil disturbance | Mid-Tertiary | Unknown | Basalt, rhyolite |
| Bulkuksa disturbance | Late Cretaceous-early Tertiary | Bulkuksa granites | Rhyolite, andesite, basalt |
| Daebo orogeny | Jurassic-early Cretaceous | Daebo granites | Hornblendite,andesite |
| Songrim disturbance | Late Triassic | Unknown | Unknown |
| Post-Chosun disturbance | Late Ordovician-early Carbonif. | Unknown | Unknown |
| Post-Sangwon disturbance | End of Precambrian | Unknown | Unknown |
| Taeback (Chunsong) disturbance | Early late-Precambrian (?) | Granite gneisses, | Amphibolite(?) |
| Ryongnam (Jongrak) orogeny | Early mid-Precambrian (?) | Granite gneisses | Serpentinite (?) |

## Associated Granites

Granites of various geologic time are closely associated with the orogenies in Korea. The ages and the occurrence of the Precambrian granites are not certain although their relative ages are estimated as shown in Table 1. The Jurassic Daebo granites, syntectonic plutons of the Daebo orogeny, intruded along the Sinian direction in the cores of the Okchon folded mountain belts and in the Kyonggi-Ryongnam Precambrian land mass (Fig. 2).

At the end of Cretaceous and probably extended into early Tertiary the Bulkuksa granites and the associated acidic intrusives intruded in the Kyongsang basin area and the adjacent Okchon zone as small stocks without any pronouncing deformation.

The granites of the post-Chosun (mid-Paleozoic) and the Songrim disturbance (late Triassic) are expected to exist. In fact the granites of these periods were reported in North Korea recently but not discovered in South Korea thus far. The granites of the Yonil disturbance (mid-Tertiary) are also expected to exist but no age dating has been done enough to find them. The relation of the plutons to various orogenies in South Korea is summarized in Table 2 and the distribution of the granites of

Jurassic and Cretaceous ages are shown in Figure 2.

## METALLOGENIC EPOCHS

Mineral deposits of Korea have been summarized by many workers (TSUCHIDA, 1944; BURKE, 1960; GALLAGHER, 1963; O. J. KIM, 1971; J. H. KIM, 1977). Metallogenesis of the mineral deposits can be treated in two folds: those related with igneous rocks and those of sedimentary and secondary origin. Metallogenesis of mineral deposits associated with igneous rocks is naturally related with igneous activities accompanied with orogenies and disturbances in Korea. Thus, metallogenic epochs that are certain in Korea so for are:

(1) Precambrian,
(2) Paleozoic,
(3) Jurassic to early Cretaceous,
(4) Late Cretaceous to early Tertiary.

Majority of hydrothermal deposits are embeded in Precambrian schist and gneisses as well as younger sedimentary formations up to Kyongsang formations. Nearly entire contact replacement deposits are in lenticular limestone layers in Precambrian formation as well as in Great limestone series of Cambro-Ordovician periods. Metallogenic epochs and accompanied mineral commodities are tabulated as follows.

| Metallogenic epochs | | Mineral commodities |
|---|---|---|
| A. Precambrian epoch | (1) | Iron (hematite) |
| | (2) | Graphite |
| | (3) | Talc, asbestos |
| | (4) | Tungsten (scheelite) |
| | (5) | Titaniferous magnetite |
| | (6) | Nickel |
| | (7) | Tin |
| | (8) | Uranium |
| B. Paleozoic epoch | (1) | Hematite |
| | (2) | Limonite |
| C. Jurassic-early Cretaceous epoch | (1) | Gold, silver |
| | (2) | Lead, zinc |
| | (3) | Molybdenum, tungsten |
| D. Late Cretaceous-Tertiary epoch | (1) | Gold, silver |
| | (2) | Lead, zinc |
| | (3) | Copper |
| | (4) | Tungsten, molybdenum |
| | (5) | Magnetite |
| | (6) | Maganese |
| | (7) | Fluorite |
| | (8) | Pyrophyllite |

## METALLOGENIC PROVINCES

### A. Precambrian Metallogenic Provinces

1) Iron (hematite)

Relatively low grade and sedimentary hematite deposits associated with quartzite are distributed in Chungju and Sosan areas, the former is being productive since the early 1950s, but the latter is active from the middle 1950s to present.

2) Crystalline graphite

Korea is one of the well-known graphite producing countries. The graphite is in graphite schists of Precambrian age and is distributed in many schist areas. The prominant areas are Gyonggi, Gongju, and Gure provinces, but only a couple of

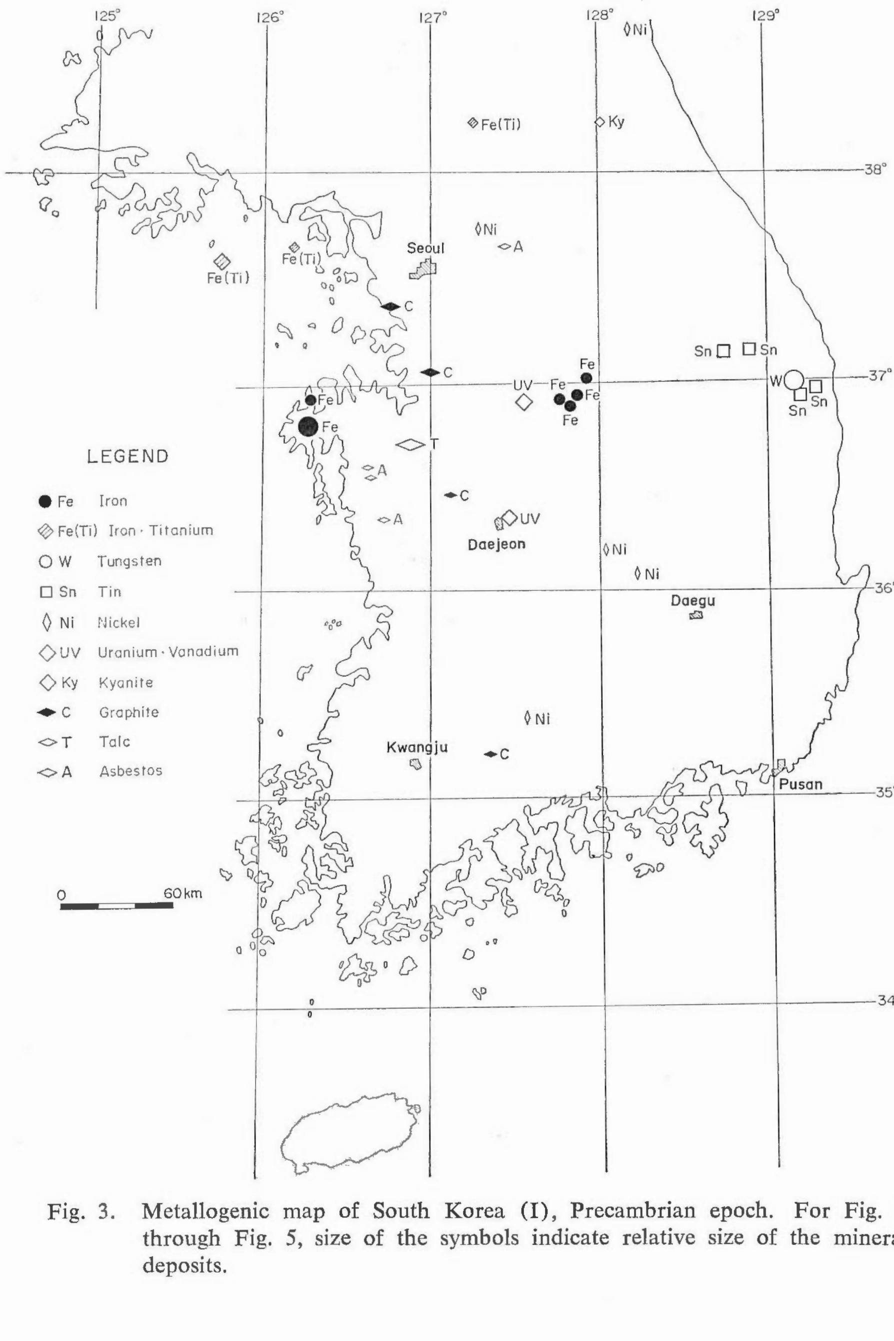


Fig. 3. Metallogenic map of South Korea (I), Precambrian epoch. For Fig. 3 through Fig. 5, size of the symbols indicate relative size of the mineral deposits.

mines in Kyonggi province are under operation.

3) Talc and Asbestos

Asbestos deposits are associated with Precambrian serpentinite in Kapyong and Kwanchon provinces, both of which extend NE-SW direction in general.

Talc is associated with Precambrian serpentinites. Talc of the Yugu belt (northeastern portion of Kwanchon province) occurs in serpentinite zone that extends NE-SW direction. Metallogenic epoch has been tentatively grouped into Precambrian epoch because of the fact that they are embedded in Precambrian formation although their mineralization age is strictly uncertain.

4) Tungsten

Precambrian amphibolite belt extends ENE direction in Ryongnam Precambrian area in which Okbang scheelite mine is a representative one. Metallogenic epoch of the deposit is thought to be Precambrian, because the deposit is of segregation type in amphibolite of probably Precambrian age.

5) Titaniferous magnetite

Several magmatogen magnetite-ilmenite deposits are emplaced in hornblende schist of the Archean crystalline schist complex at the north of Seoul and Soyeonpyeong, Bolum island, as fine exsolution intergrowth of magnetite and ilmenite.

6) Nickel

Nickel deposits in Korea are of pentlandite-bearing pyrrhotite deposits associated with Precambrian basic intrusives. Nickel deposits are distributed in Goseong, Kapyong, Gimcheon and Jirisan (Sannae) areas.

7) Tin

Low grade, cassiterite-bearing pegmatite deposits are distributed in southern part of Sangdong mine (Sungyeong mine) and east coastal area (Ulchin).

8) Uranium

Black slate in the Okchon sediments of the late Proterozoic time contains abnormally high values of heavy metal, including uranium and vanadium. The heavy elements in Okchon sea water were fixed by organic carbon under a reducing environment.

## B. Paleozoic Metallogenic Provinces

1) Hematite

Sedimentary hematite beds occur in two formations of Paleozoic age, one in Dongjom quartzite bed of Ordovician and the other in base of Hongjom series of upper Carboniferous. Hematite-magnetite bed in Dongjom is widely scattered in the east of Taebaeg Mountain Ranges, an E-W divide, which is named Samchok zone, and small scale mining is underway in some places.

Hematite bed in the base of Hongjom series crops out in Okgye area, east of the divide, and Yongwol area, west of the divide. Prospecting was done extensively.

2) Limonite

Sedimentary limonite bed occurs in the upper horizon of Sadong series of Permian age, the main anthracite coal measure in Korea. It is also known to occur in both west (Okdong area) and east (Yongdong area) of the divide and one mine in the eastern coastal area is under production.

## C. Jurassic to Early Cretaceous Metallogenic Provinces

1) Gold-Silver

Most of gold-silver deposits belong to Jurassic to early Cretaceous epoch. With few exceptions they are emplaced in Daebo granite or surrounding schists and para-gneisses, and aligned parallel to NE-SW Sinian direction. The gold-silver provinces are in order from north to south, Pochon, Chonan, Hongchon, Haemi, Sulchon and Hapchon. These deposits are mostly of hypothermal to mesothermal veins in Precambrian schists and para-gneisses or in granites.

2) Lead-Zinc

Lead-zinc provinces of this epoch are relatively small and show no definite trend. Deposits emplaced in Precambrian schists are mostly vein type and those in limestones of Precambrian or Cambro-Ordovician age are contact replacement type.

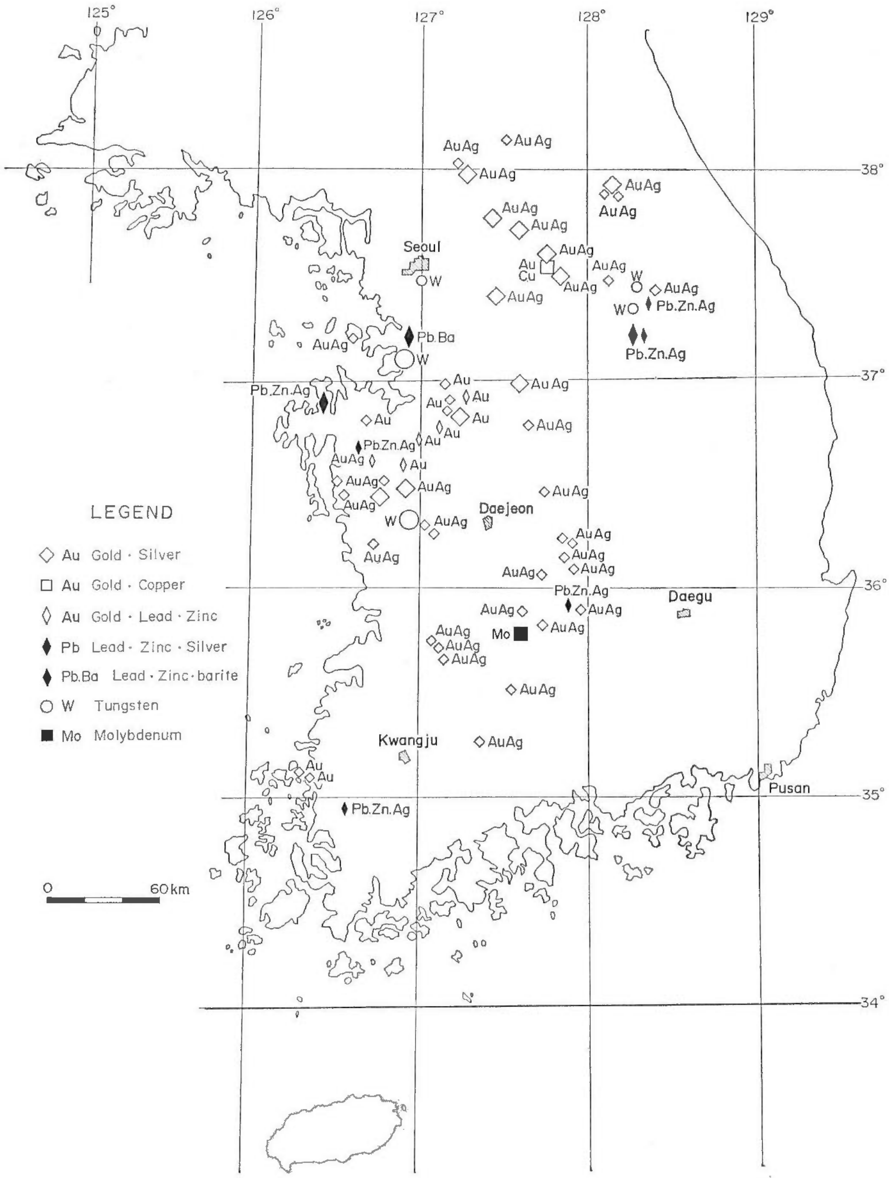


Fig. 4. Metallogenic map of South Korea (II), Jurassic-Early Cretaceous epoch.

Belonged to the former type are Kapyong and Muju zones, and to the latter type being Shihung and Doweonri, western margin of Taebaegsan mineralized area.

3) Tungsten-Molybdenum

Tungsten deposits related to Daebo granite in Korea are mainly wolframite-quartz veins occurring in Precambrian schist and Jurassic granite. This vein type of tungsten deposits associate with molybdenite. This kind of deposits is distributed in the Seoul, Cheongyang, Youngwol and Jangsu areas.

## D. Late Cretaceous to Early Tertinary Metallogenic Provinces

1) Gold-Silver

Gold-silver deposits of this epoch are rather scarce and are distributed in southernmost part and middle-eastern coast of Korean Peninsula. They are exclusively of fissure-filling veins in Cambro-Ordovician limestone and Cretaceous Kyongsang basin.

2) Lead-Zinc

Lead-zinc deposits of Korea are divided into two categories. First one is skarn and associated replacement type and second one is simple fissure filling vein type. The first type deposits are mostly distributed in Taebaegsan mineralized region and the second type of deposits in Kyongsang basin. Among them, the skarn replacement type is very important producer in Korea. It's production occupies 94% of total production. Famous ones are Yeonwha I, Yeonwha II, Ulchin mine etc. Most of fissure-filling type deposits are distributed in Kyongsang basin.

3) Copper

Chalcopyrite vein, breccia pipe, porphyry and alunite-pyrophyllite type deposits are formed in sedimentary formation and volcanic rocks and granite mainly in Kyongsang basin and along the southern coast. A few contact metasomatic deposits are emplaced in Paleozoic limestone, and native copper occurs in Cretaceous basalt in the nothern part of Kyongsang basin.

Veins are formed filling two main fissure systems, N-S and E-W, and consist of very simple mineral assemblage of chalcopyrite and minor galena and sphalerite, iron sulfides and arsenopyrite with quartz and calcite gangues.

Two collapse-type breccia pipes (Dalseong, Ilgwang) mineralized with chalcopyrite and tungsten are formed in Cretaceous andesite-porphyry and ganodiorite-quartz monzonite stock in Kyongsang basin.

Several low-grade porphyry copper and/or molybdenum type deposits are known in Kyongsang basin along southeast coast. Closely spaced fractures and veins in granodiorite stocks or andesite covers are mineralized with chalcopyrite, molybdenite and iron sulfides. Argillic and propylitic alterations are common.

4) Tungsten and Molybdenum

Korea is one of the main tungsten producers in the free world. Main production comes from the Sangdong deposits of contact metasomatic type. Generally tungsten is closely associated with molybdenum, and the deposits are classified into several types such as contact metasomatic scheelite deposits, wolframite-scheelite-molybdenite-quartz veins and breccia pipe.

High temperature veins of quartz-tungsten-molybdenum or quartz-molybdenum association in Precambrian gneiss and Mesozoic granite are common type of deposits.

5) Magnetite

Contact-metasomatic magnetite deposits are emplaced in Precambrian and Cambro-Ordovician limestones, and Cretaceous andesite. Those magnetite deposits are distributed in Yangyang, Hongcheon, Mungyeong and Mulgun areas. The ores, usually contain minor sulfides. A few iron deposits contain recoverable amount of copper (Geodo mine) or tungsten (Ulsan mine).

6) Manganese

Several small fissure-filling vein deposits are distributed in formation of various ages. Two economically important, replacement type deposits grade into contact-metasomatic lead-zinc deposits in depth (Yeonwha and Janggun mines).

7) Fluorite

Fluorite deposits are clustered in three districts, Hwacheon in the northern, and

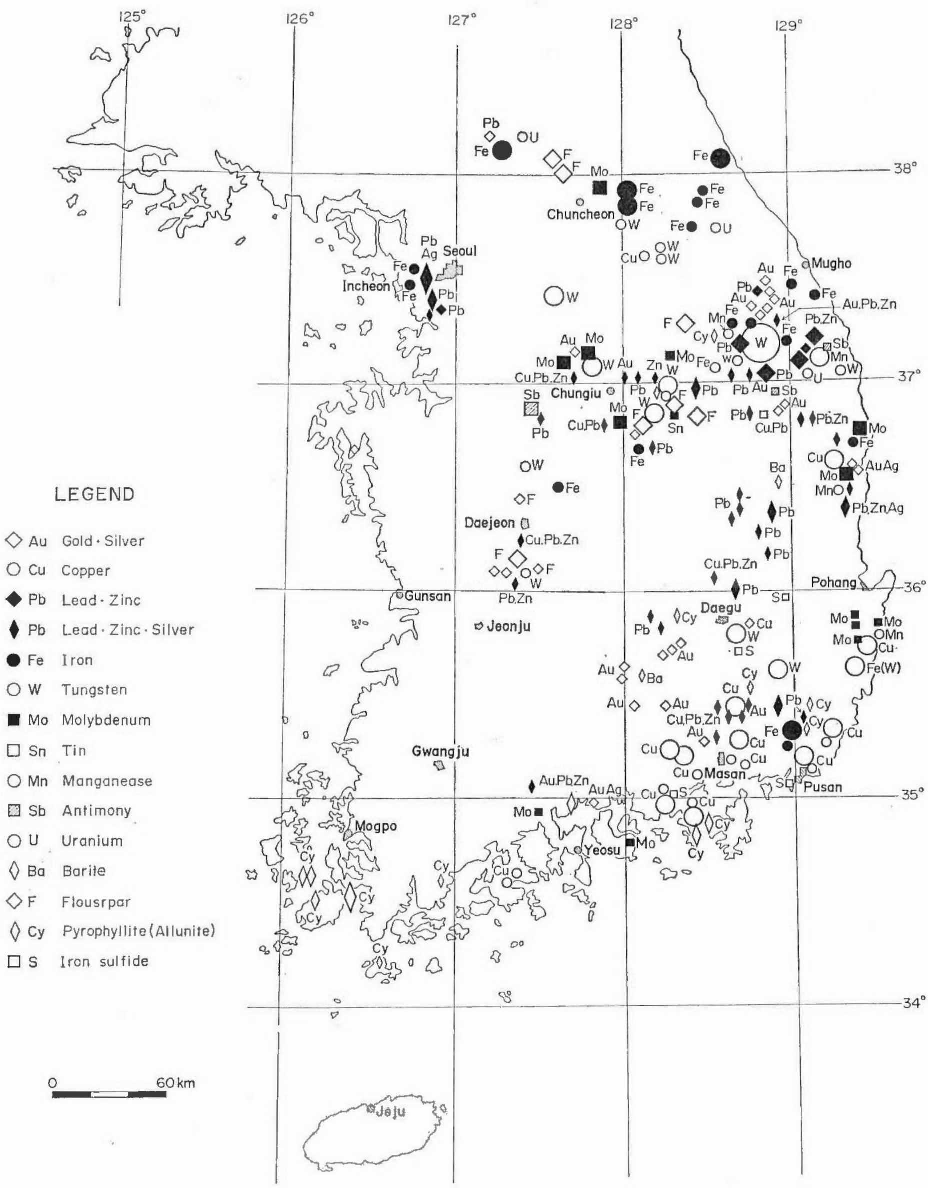


Fig. 5. Metallogenic map of South Korea (III), Cretaceous-Tertiary epoch.

Hwhangangri and Geumsan districts in the central Korea. Quartz-fluorite veins and calcite-fluorite replacement type deposits are formed.

In the Hwacheon zone, quartz-fluorite veins formed in Precambrian gneiss and Jurassic granite. In the central zone, both vein and replacement type deposits are emplaced in Cambro-Ordovician limestone and Cretaceous sediments. Some replacement type deposits contain scheelite.

8) Pyrophyllite

Majority of pyrophyllite deposits are distributed in Kyongsang basin area where Jukjang, Milyang, Tongrae and Jonnam provinces can be well defined. All deposits are emplaced in rhyolitic tuff or other acid volcanic rocks. In tectonic viewpoint, Milyang province is situated along Kimhae-Milyang fault zone, and Tongrae province along Tongrae-Ulsan graben area, both of which trend generally north-northeastward. No structural relation has been cleared in the rest of the provinces mentioned.

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# Metallic Mineral Deposits of Indonesia: A Metallogenic Approach*

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## ABSTRACT

The tectonic framework of Indonesia is complicated by interaction of the Eurasian continental, the Indian oceanic and the Australian continental as well as the Pacific-Philippine oceanic plates. During Late Palaeozoic-Early Cainozoic time, the region of western Indonesia (Kalimantan, Sumatra, Sulawesi, west and central Java) had been part of the Eurasian landmass. In Cainozoic time, this region formed the continental terrain bounding Eurasia on the southeast.

The region of western Indonesia may be grouped into four overlapped tectonic zones: (1) the Late Palaeozoic-Mesozoic tectonic zone, connecting Sumatra, Riauw-Bangka-Billiton islands, Anambas Natuna islands, west and central Kalimantan; (2) the Late Mesozoic-Early Tertiary tectonic zone, connecting southwestern Sumatra, west and central Java, southeast Kalimantan as well as Sulawesi (including Sumba continental fragment); (3) the Cainozoic tectonic zone of volcanic Sunda arc, connecting Sumatra, Java and the Lesser Sunda islands, and the volcanic belt of western and northern Sulawesi; (4) the tectonic zone of nonvolcanic Sunda arc comprising the Cainozoic subduction complex at west of Sumatra.

The tectonically separated unit of the tin-area (Sumatra, Riauw-Bangka-Billiton islands, and perhaps also Anambas islands) is presumably dominated by Late Palaeozoic-Mesozoic deformation and magmatism, underlain by pre-Late Palaeozoic (Precambrian ?) continental crust. Mineralization of tin is generally related to the intrusions of granite during diastrophic episodes of major geologic events, with the main periods of folding and igneous activity taken place in Late Palaeozoic, Mesozoic and Early Cainozoic time. The Late Palaeozoic granites are highly felsic and are characterized by the absence of hornblende. Their country rock consists of isoclinally folded dynamothermal greenschist facies metasediments; there is no hornfels thermal aureole. These granitic magmas evolved within the crust as a wet magma and resulted from anatexis of sialic rock in part of the pre-Late Palaeozoic rocks. The tin bearing Mesozoic-Early Tertiary granites intruded the country rocks and contain muscovite, biotite, tourmaline, garnet, alkali feldspar, sodic plagioclase, and traces of ilmenite. These tin granites do not show any foliation or any stressed features.

The principal metallic mineral areas of Sumatra, as well as west and central Kalimantan, and their association with Triassic-Jurassic, Jurassic-Cretaceous, and Cretaceous-Early Tertiary igneous and metamorphic activities, are characterized by precious, base, rare, and ferro-alloy metallic mineral deposits. Since Late Tertiary

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time more seasonal to semi-arid climates have facilitated the development of mechanical and chemical weathering on land; this has produced secondary mineral deposits, now present both on land and offshore.

The Cainozoic tectonic zone of volcanic Sunda arc may be grouped into two tectonically separated subzones: (1) the subzone of Sumatra, related to the ensialic basement or continental crust and (2) the subzone of Java, the Lesser Sunda islands, and the volcanic belt of western and northern Sulawesi related to the predominantly ensimatic or oceanic basement. The volcanic Sunda arc is generally connected with calc-alkaline volcanism. The Late Tertiary granites are probably responsible for the major precious and base metal mineralization within this arc. These granites contain hornblende, biotite, sphene, and traces of magnetite.

The tectonic zones of both volcanic and nonvolcanic Banda arcs in eastern Indonesia are complicated by change in the converging Indian oceanic and Australian continental plates. Plate tectonic explanations of this region have been made, but these are still unclear or speculative as there is at present insufficient knowledge on the various geologic-tectonic units and their relationships. From Sewu through Timor and Sermata to Seram islands, the nonvolcanic Banda arc contains imbricated units derived from the Australian foreland. They are believed to be underlain by continental crust. The Wetar strait to the north of Timor, the Weber deep and Sewu Sea are presumably underlain by oceanic crust. Alor, Wetar and Atauro islands and the volcanic area of the northern Banda arc system are considered to be a normal inactive volcanic belt that resulted from contamination of melting pelitic material at continental crustal depth. Parts of the leading edge of the Australian continental crust have been presumably involved in a subduction zone beneath the oceanic Banda Sea. In eastern Indonesia, ophiolites were emplaced and volcanic-plutonic rocks were erupted in Cainozoic time. Major geologic events occurred in Late Tertiary and Quaternary. Volcanism is predominantly calc-alkaline to high K-calc-alkaline, with minor tholeiite and shoshonite. The Late Tertiary volcano-plutonic activity is responsible for various types of important gold-silver and copper-lead-zinc as well as ferro-alloy metallic mineral deposits.

Since Precambrian time the southern region of Irian Jaya has been part of the Australian landmass. At the end of Early Tertiary or perhaps later, the region became a continental shelf bounding Australia on the north. About Late Tertiary, this region was compressed as imbricated thrust faults drove southward, and a foreland basin developed along the southern margin of the deformed terrain, receiving sediments from the newly uplifted region. The igneous rocks of Sula and Banggai islands are of about the same age as apparently is the magmatic belt of pre-Cainozoic rocks of Vogelkopf, Irian Jaya. These islands are obviously a sliver of continental crustal fragments torn from the Vogelkopf and transported westward along a strand of the Sorong fault system.

The region of Irian Jaya may be grouped into four tectonic zones: (1) the Precambrian-Palaeozoic (?) tectonic zone of Arafura platform (Sahul stable shelf); (2) the tectonic zone of Late Tertiary-Quaternary basins; (3) the pre-Tertiary tectonic zone of Central Mts. Range of Irian Jaya and (4) the tectonic zone of Northern Mts. Range of Irian Jaya (North Irian Jaya "geosyncline"). The principal metallic mineral areas of these tectonic zones and their relationships with Tertiary igneous and metamorphic activities are characterized by precious, base, rare and ferro-alloy metallic mineral deposits.

Six episodes of metallic mineralization are formulated on the basis of geologic

events, i.e., (1) the Late Palaeozoic to Early Mesozoic (Late Carboniferous to Late Triassic), (2) the Mesozoic (Mid-Triassic to Late Cretaceous), (3) the Late Mesozoic to Late Tertiary (Early Cretaceous to Mid-Miocene), (4) the Late Tertiary (Mid-Miocene to Pliocene), (5) the Late Tertiary to Early Quaternary (Late Miocene to Pleistocene) and (6) the Quaternary to Recent periods.

A geological classification is given of significant metallic mineral commodities and metalliferous indications of Indonesia, i.e., (1) skarn or greisen; (2) veins and shear zones; (3) placers; (4) irregular or concordant deposits in igneous rooks; (5) pegmatitic and aplitic deposits; (6) chemical sediments other than evaporites; (7) mineralized stocks, stockworks, pipes and deposits of irregular shape other than greisen; (8) porphyry-type deposits; (9) more or less strata-bound deposits within certain stratigraphic units other than placer; (10) more or less strata-bound massive deposits; (11) volcanic exhalative deposits and (12) lateritic, chemical, biochemical and residual deposits.

Grouping of typical metallic commodities and their geological classification appear to correspond to the six episodes of mineralization. These metallogenic elements are plotted on a geologic base-map at a scale of 1 to 10,000,000 compiled by the Geological Research and Development Centre, Geological Survey of Indonesia (1979).

## INTRODUCTION

The territory of the Republic of Indonesia, extends between main Asia and Australia. It posseses a vast land and sea areas, bordered by both Indian and Pacific oceans. It consists of 19 larger islands and many thousands of smaller ones, straddling the equator between 6° northern latitude to 11° southern latitude for about 5,000 kilometers. With a total land area of more than 1,900,000 square kilometers, the Republic of Indonesia is the third largest country in Asia, after mainland China and India.

Indonesia is rich in various metallic mineral deposits centering on precious, base, ferro-alloy, light and rare metals as a raw material for base-industry. The metallic mineral resources are very important in this country and the importance will become increasingly great in the future.

Since the appearance of the review of the metallic mineral deposits of Indonesia by Reksalegora and Djumhani (1973), considerable advances have been made in both geological mapping and mineral exploration. Some of these advances have been documented by Katili (1974) with paper on tectonic environment of the Indonesian mineral deposits. Sukamto and Suhanda (1977) inform some notes on magmatic activities which reflect different types of metallic mineral occurrences in northeastern Indonesia. Further information is contained in many published and unpublished reports available from Geological Survey and States as well as private companies.

The Distribution Map of Metallic Mineral Deposits in Indonesia on a scale of 1 to 10,000,000 is to supplement those prior publications and hopefully to provide a convenient picture of the group of metallic mineral deposits within principal mineral areas. The term principal mineral area used in this paper refers to a smaller region with a relatively high density of metallic mineral deposits with reference to their age of mineralization. In this paper the author introduces six episodes of metallic mineralization concerning one aspect of metallogeny.

The metallogenic symbols proposed by Phil. Guild in 1973 were slightly modified and plotted on a geologic base-map on a scale of 1 to 10,000,000 prepared by

Geological Research and Development Centre, Geological Survey of Indonesia (1979).*1) These symbols are organized into two tabular forms which correspond to mineral commodities and size of deposits in relation to geological environment, as well as geological classification of mineral deposits in relation to geological age of mineralization.

It is intention of the author that this paper will be revised in the future with gradual expansion of the subject coverage both in quality and quantity, whilst presenting here actual problems as well as theoretical hints of metallogeny for possible project of finding metallic mineral resources.

## TECTONIC OUTLINE

The tectonic history of the Southeast Asia region is dominated by Late Palaeozoic, Mesozoic and Cainozoic deformation and magmatism. Major Palaeozoic, Mesozoic and selected Cainozoic tectonic elements of the Southeast Asia region are shown schematically on Figure 1.

Based on plate tectonic concept, India was an island continent during Mesozoic time. In Early Tertiary the island continent sailed northward and then collided with Thethyan margin of Eurasia. Since then it has continued to move northward at a velocity of about 5 cm/yr., relative to the northern part of Eurasia (MOLNAR and TAPPONNIER, 1975). GANSSER (1966) has also recognized that the great Pakistan and Assam syntexes at west and east corners of the Indian plate, indicate northward motion of India relative to the Middle East to the west, and to Southeast Asia to the east. The continuing convergence of Indian and Eurasian plates has been accommodated by continental underthrusting, by crustal compression, and by the eastward motion of China, obliquely out of the way of the advancing southern continent, along a complex series of strike-slip faults and other structural features (TAPPONNIER and MOLNAR, 1976).

The continuous subduction zone trending south from the Assam syntexis and swinging southeastward to Sumatra requires that the Southeast Asia region and western Indonesia have a westward component of motion relative to the Indian Ocean. This westward component integrated with the active tectonic pattern north of India requires that the Southeast Asia region be rotating clockwise, pivoting near the Assam syntexis. Sumatra may have also rotated in the same direction during Late Tertiary time from an initially more east-west orientation to its present southeast trend (HAMILTON, 1979).

According to HAMILTON (1979), the broad arc defined by the terrains of Southeast Asia and Kalimantan may be an orocline, produced by the counter-clockwise rotation of Kalimantan as it advanced over the lithosphere of the then-larger South China Sea. The broadly curving Early Tertiary subduction system ended midway between Kalimantan and Indochina and records the subduction of oceanic lithosphere beneath northwestern Kalimantan. The Kalimantan end of the Southeast Asian subcontinent may have advanced over the South China Sea, whereas the Indochinese end did not. If the Cretaceous trends were initially straight, then southwest Kalimantan has rotated about 45° counter-clockwise relative to southernmost Malay Peninsula and about 135° relative to Indochina; northern Kalimantan has rotated almost 90°

*1) See Tables 2, 3 and Distribution Map of Metallic Mineral Deposits in Indonesia 1 : 10,000,000.

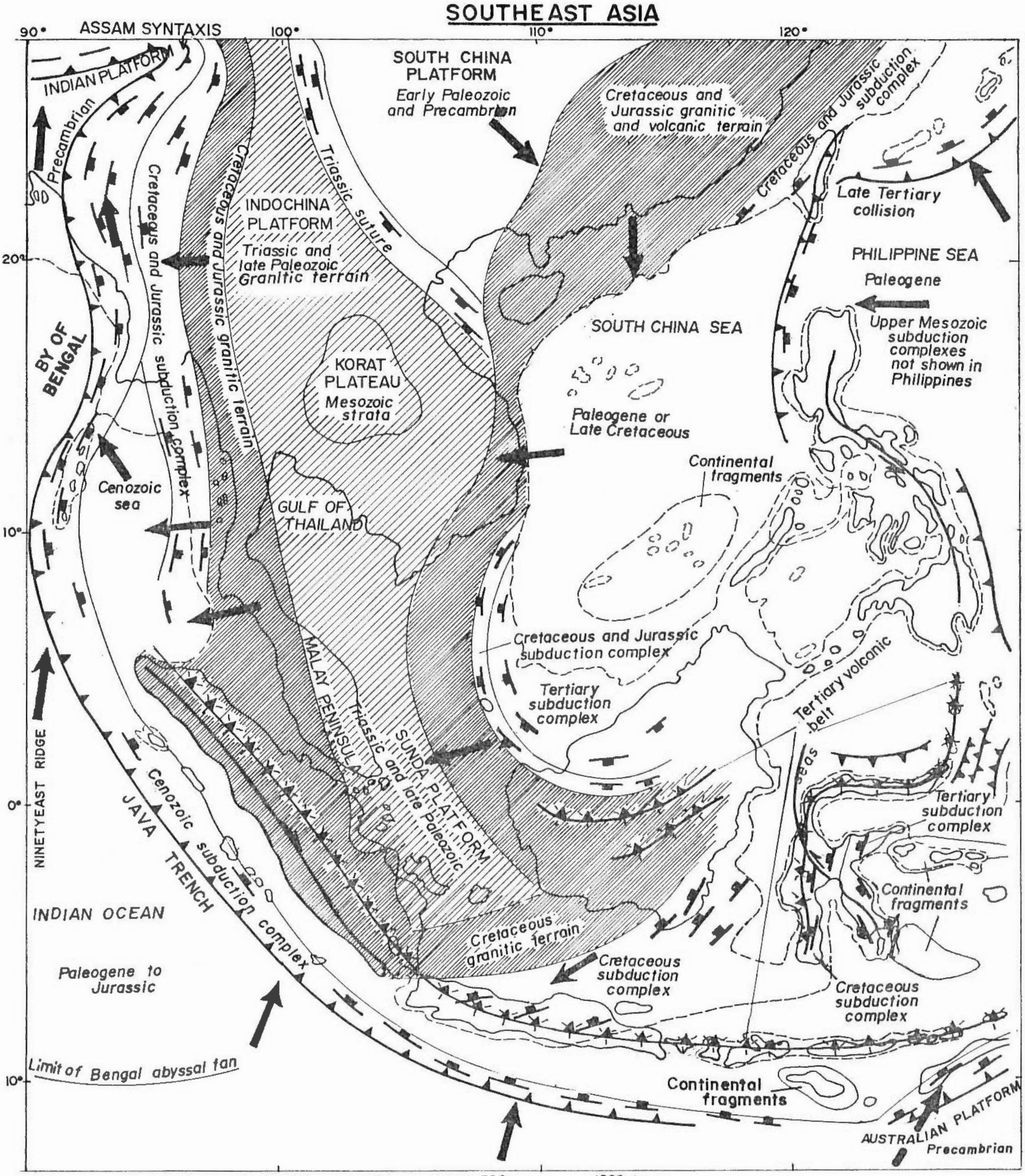



Fig. 1. Tectonic scheme of Southeast Asia and western Indonesia. Compiled and slightly modified from HAMILTON (1979). Arrows indicate direction of plate motion relative to northwestern Eurasia (not to vector scale).

more.

The dominant paleomagnetic declination of Upper Cretaceous crystalline rocks in southwest Kalimantan is northwest-southeast, suggesting a net rotation of about 45° counter-clockwise within the last 80 million years (HAILE *et al.*, 1977). The same paleomagnetic orientation characterizes a small suite of vaguely dated, post-Triassic basalts from southernmost Malay Peninsula (McELHINNY *et al.*, 1974). HAILE *et al.* (1977) assumed that Kalimantan and Malay Peninsula are of the same age and have not moved relative to one another. If they are correct, then Kalimantan and Malay Peninsula may have pivoted together, propeller fashion, subducting Bay of Bengal crust at west of Malay Peninsula, but South China Sea crust at north Kalimantan (HAMILTON, 1979).

Warren HAMILTON infers in his report that the Malay Peninsula-Sumatra-Tin islands and Australian-Irian Jaya-New Gunea terrains were continuous before Mesozoic continental rifting.

The volcano-plutonic belt of Late Palaeozoic-Early Mesozoic rocks of northeast Australia continues northward—as a bedrock high into the medial highlands of Irian Jaya-New Guinea where it ends against the east-west belt of Mid-Tertiary melange of the northern part of the highlands. It is an obvious inference that truncation of the magmatic-terrain represents a rifting of the continent, the terrain having been initially continuous along the east margin of a contiguous continental mass to the north which has since been removed. Mid- and Late Mesozoic sedimentary rocks were deposited in water that deepened northward toward medial New Guinea (SKWARKO, 1973), hence they likely postdate any rifting. Rocks as young as Mid-Mesozoic do not show clear evidence for a continental margin in medial New Guinea, so the rifting may have occurred within Early to Mid-Mesozoic time (HAMILTON, 1979).

The igneous rocks of Late Palaeozoic-Early Mesozoic terrain of Irian Jaya-New Guinea are of about the same age as those of the Sula-Banggai bedrock. Strong east-west trending submarine topographic lineaments, including the straight sides of the narrow Sula ridge, connect the Sula islands with the strike-slip Sorong fault system of northern Irian Jaya, as KRAUSE (1965) emphasized (Fig. 2). The various tectonic belts of the Vogelkopf (Bird's Head) of Irian Jaya—the large projection of Irian Jaya-New Guinea northward from the meridian of 135°E—trend northwestward to an oblique truncation against this fault system. The rocks along the south side of the fault in Vogelkopf are Mid-Palaeozoic rocks overlain by Late Palaeozoic, Mesozoic and Tertiary continental shelf strata. It is obvious inference that the Sula-Banggai ridge is a sliver of continental crust, torn from Vogelkopf and transported westward about 1,000 km along a strand of the Sorong fault system (HERMES, 1974).

Eastern and southeastern sections of Kalimantan sharing Late Mesozoic and Early Tertiary features with Sulawesi are suggestive that until Tertiary time, Sulawesi was a part of Kalimantan. Southeastern Kalimantan, the shelf to the east of it, and the south arm of Sulawesi all have bedrock highs of Late Mesozoic (Cretaceous) subduction complexes overlain by similar Tertiary shelf strata.

In both Kalimantan and Sulawesi, Early Tertiary quartzose clastic strata and coal are overlain by Mid-Tertiary limestone, which gives way northward to mostly clastic rocks. If Sulawesi has moved southeastward away from Kalimantan, the westward bulk of central Sulawesi having slid along the southeast-trending edge of the continental shelf off southeastern Kalimantan, then the limestone and underlying continental strata on both islands were initially continuous. Rifting may have begun in Tertiary (Palaeogene) time (HAMILTON, 1979); the eastward thickening of Mid-Tertiary (Oligo-Miocene) strata on the continental shelf of eastern Kalimantan might record the tensional thinning of the continental crust as rifting progressed, before the complete sundering of the crust in Mid- or perhaps Late Tertiary time.

In Tertiary time the development of the arcuate trench system was parallel or subparallel with the volcano-plutonic belt. The new spreading centre in the Indian Ocean generated an "Old Sunda arc" which stretched from Sumatra via Java, the Lesser Sunda islands, Timor, Tanimbar, Kai Seram to Buru.

In western Indonesia, the first plate collision in Early Tertiary time is responsible for the development of Late Palaeozoic-Mesozoic bedrock faulting in the continental crust and subsequent different vertical movement resulting into tectonic basin deeps and highs. Meanwhile this movement forms fault blocks in its periphery. A high rate of subsidence results into immediate marine transgression, while slower rate of subsidence in the adjacent uplifted blocks resulted into nonmarine environments greatly enhancing the possibility of coal deposition, limited to the center of the basin lake or swamps (KOESOEMADINATA and PULUNGGONO, 1974).

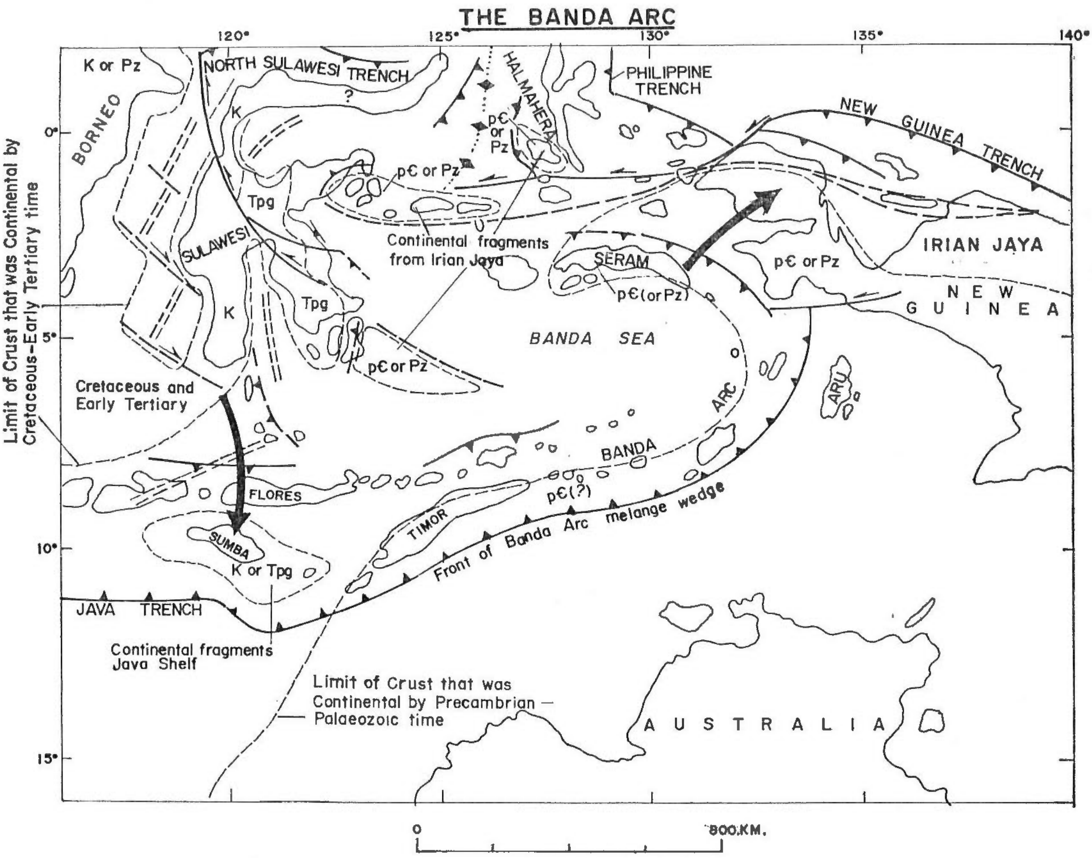



Fig. 2. Tectonic scheme of eastern Indonesia showing distribution of pre-Tertiary continental crusts. Time of the formations due to tectonic accretion related to subduction or to silicic magmatism is specified: p-C, Precambrian; Pz, Palaeozoic; K, Cretaceous; Tpg, Palaeogene (after HAMILTON, 1979).

The change in movement of the Pacific plate directing west-northwestward since Early Tertiary time, has coincided with the emergence of the Sulawesi-Philippine island arc system (BEN-AVRAHAM and UYEDA, 1973).

In Late Tertiary time the north-south trending Sulawesi Mindanau subduction zone migrated farther eastward-facing Halmahera island arc. This arc could not be developed further south as its growth was hampered by the northward-advancing Australian continent with Irian Jaya-New Guinea attached to its northern border (KATILI and HARTONO, 1979).

In Mid-Tertiary (Mid-Miocene) time, increased rate of plate collision resulted into the uplifting of the continental crust in the present volcanic island arc with accompanying magmatism and marine regression, while increased subsidence and down warping took place in the foreland (back deep basin) resulting into marine transgression.

In western Indonesia, an abrupt sea-level depression during the Late Mid-Miocene to around 1,000 m below present, is well correlated with an emergent "Sundaland continent." A major Mid-Late Miocene discontinuity in the Sundaland is parallel worldwide by contemporaneous unconformities or facies changes. Increased land/sea ratio since Late Miocene time has resulted in more seasonal semiarid climates facilitating development of lateritization (BATCHELOR, 1979).

During the Mid-Miocene time the initiation of the right lateral strike-slip movement along the Sumatran fault system is thought to have started (PAGE, 1978). Emplacement of the serpentinized ultramafic rock in northern Sumatra occurred at about the same time.

At the end of the Miocene time, subduction zone ceased and the nonvolcanic outer arc, Mentawai-Nias islands west of Sumatra, Timor, Tanimbar, Kei, Buru, Seram and Buton was really emerged.

Increased rate of collision in Plio-Pleistocene time resulted into uplifting of the volcanic inner arc and also increased rate of erosion and subsequent sedimentary basin infill of the backdeep through deltaic progradation towards the continental inland. The plate collision took place in Pliocene time is considered to be the most dramatic event in the geologic history of Indonesia (KATILI, 1975), when northward advancing Australian continent coupled with the counter-clockwise rotation of Irian Jaya-New Guinea and accompanied by the spear heading westward thrust of the Sorong fault system, caused the westward bending of the east-west trending Banda arc. In this time collision also took place between the western arc of Sulawesi and eastern Kalimantan, obducting ophiolites in the Meratus Range and slightly deforming the sediments in the eastern Kalimantan oil basins (KATILI, 1978).

The youngest subduction zones that formed northwest of Sulawesi, east of northern Sulawesi and west of Halmahera could be held responsible respectively for the formations of the active Una-Una volcano in the gulf of Gorontalo, the volcanoes in the Minahasa-Sangihe region and for the generation of the active volcanoes west of Halmahera (KATILI and HARTONO, 1979). Collision complex between the active Minahasa-Sangihe and Halmahera arc is thought to begin in Quaternary time.

On the HUTCHISON's (1979) map in reviewing of the volcanic arc, he defines that the Indian oceanic plate subducts with high obliquity beneath ensialic Sumatra and perpendicular incidence beneath predominantly ensimatic Java. It is supported by a good positive correlation between depth of the underlying Benioff zone and the contents of $K_2O$ and the Sr isotope ratio, indicating that magma is of mantle origin. In relation to subduction zone, there is a decreasing volume of partial melting with increasing depth. An eastward decrease of initial $^{87}Sr/^{86}Sr$ from 0.706 to 704 from west Java to Bali suggests a gradual transition from underlying ensialic to ensimatic bedrock.

In northeast of Sumatra there is no active Benioff zone or no seismicity deeper than about 200 km. This may be related to the significant wrench displacements along the active right-lateral Semangko fault system, which terminates in the Sunda strait between Sumatra and Java. Volcanoes are located on approximately east-west lineaments over major plutons which give rise to strong aeromagnetic anomalies. Active volcanoes occur at their intersection with the northwest-southeast-trending Semangko fault system (POSAVEC *et al.*, 1973). A seismic Benioff zone is observed in north of Java and eastward to the north of Wetar-Romang islands.

The trace of the outcrop of a subduction zone indicated by HAMILTON (1978) in the fore-deep of the westernmost part of the Sunda arc system can be interpreted as the front of upthrusts of imbricated melange-wedges which have been rifted outward. Eastward to the south of Java and the Lesser Sunda islands, the submarine nonvolcanic outer arc presumably consists of melange-wedges which hide the real trace of the passively subducted floor of the Indian Ocean. From Sewu through Timor to Sermata, the nonvolcanic outer arc contains imbricated units derived from the Australian foreland. This convergence between the southward migrating Sunda arc system and the Australian continental plate is very young. The age of the junction increases eastward to a maximum of five million years (BOWIN, 1978).

HAMILTON (1978) indicated the position of Sumba on his map as a continental micro-plate. BRUNN and BUROLLET (1979), however, characterize it as a northwestward directed horst-like promontory of the Australian foreland which is actively pushing and underthrusting into that direction.

The Timor trough situated between the Australian continent and Timor is underlain by continental crust. CHAMALAUN *et al.* (1976) suggest that the Timor is completely underlain by continental crust. There is no gap separating the continental crust of Australia from that of Timor but there may be a structural discontinuity in the neighborhood of the Timor trough.

The Permian to Cretaceous sequence of northwest Australian shelf is indeed analogous to those seen on the Timor (CROSTELLA and POWELL, 1976). Metamorphic rocks associated with deep to shallow water sedimentary sequences are interpreted either as overthrust masses or upthrust blocks.

The Wetar strait to the north of Timor, the Weber deep and Sewu Sea are presumbly underlain by oceanic crust.

Inactive volcanic island of the inner arc, north of Timor, Alor, Wetar and Atauro, are composed of normal island arc tholeiites but the more silicic volcanic rocks show high K contents and high initial $^{87}Sr/^{86}Sr$ ratio indicating contamination by pelitic sediment or continental crust (HUTCHISON, 1979).

The Banda arc system is considered to be a younger addition to the Sunda arc system (Sunda-Banda arcs system). Tanimbar-Kai parts of the Banda arc system are forming as a link betwen Timor (belonging to the Sunda arc system) and Seram.

The very young volcanic inner arc extends from Gunung Api by way of Damar to the Banda group of islets. It consists of volcanic cones which rise directly from the abyssal oceanic floor of the Banda basin. The Weber trough belongs structurally to the south Banda basin. Both have an oceanic crustal floor. The nonvolcanic arc extends from the Tanimbar islands by way of the Kai Group to Pulu Panjang and Pulu Gorong.

The inner volcanic arc of the northern Banda arc system is represented by cordierite-bearing dacite having high concentration of K, Rb, Cs and high initial $^{87}Sr/^{86}Sr$ ratios of approximately 0.715. This is considered to have been formed by melting of pelitic material at continental crustal depths. WHITFORD and JEZEK (1979) and also HUTCHISON (1979) believe that the source of the rocks is likely to be the margin of the Australian continent which has subducted beneath the Seram accretionary wedge along a Benioff zone which outcrops at the Seram trough, or in other words, that parts of the leading edge of the Australian continental crust have been involved in subduction zone beneath the oceanic Banda Sea.

The eastward migrating of the frontal sector of the Banda arc system is separated by an east-southeast trending right-lateral shear fault at its southern side, which might be traced from Gunung Api through the strait between Romang and Damar of the inner arc and the strait between Sermata and Babar Masela of the outer arc.

## EPISODES OF MINERALIZATION

The Late Palaeozoic-Mesozoic tectonic events were formed principally by a Carbo-Permian sequence, locally conformably overlain by Triassic sedimentary rocks, and extensive contemporaneous consanguineous magmatic masses. In some places, these rocks are unconformably underlain by pre-Late Carboniferous metamorphosed rocks of high-temperature type and overlain by Triassic-Cretaceous sedimentary rocks. Perhaps in Early Palaeozoic time, both shelf and deeper water sedimentary rocks were laid down contemporaneously. Some mafic and felsic plutonism probably occurred in Late Palaeozoic, but major geologic events occurred in Mesozoic time. These events are very pronounced in deformations of older rocks. Large granite masses characterize the metamorphosed country rocks of low P/T type.

The Late Palaeozoic Main Range granites of west coast belt of the Malay Peninsula (in Bintang and Klendang Ranges, Dindings area and Penang island; after BIGNELL and SNELLING, 1972) characterized by the absence of amphibole and alkaline nature as well as their country rock envelope of isoclinally folded, greenschist facies metasediments and absence of hornfels facies thermal aureole, indicate that the granites were evolved within the crust as a wet magma and had very poor capacity to rise. These are considered as typical distal and mesozonal or more truly granites (HUTCHISON, 1973).

Although not proven, the possibility must be believed that similar Late Palaeozoic distal and mesozonal granites may occur in the southeastwards extension of this trend, in northwestern part of Lingga Group (JONGMANS, 1950) and northeast Bangka (OSBERGER, 1965), where the pre-Carboniferous dynamometamorphic and unaltered rocks are found side by side.

The granitic magma which gave rise to the Main Range granite arc continuing southeastwards extension to the "Tin islands," resulted from anatexis of sialic rocks, in part of pre-Late Palaeozoic (Precambrian ?) rocks. The zones of high heat flow in the igneous arc supplied the necessary heat for anatexis at deeper levels, and for greenschist facies metamorphism of the sedimentary formations of the shallower levels (HUTCHISON, 1973).

The Mesozoic granites intruded into older rocks are dominantly granodiorite, quartz monzonite, and granite but include locally more mafic rocks (PRIEM *et al.*, 1975). There are two granite generations. The older one with trace of cassiterite contains sphene, hornblende, epidote and little magnetite. This granite is characterized by medium to coarse grained texture and shows some foliations. The younger one known as the tin-bearing granite contains, muscovite, tourmaline, garnets in addition to K-feldspar, plagioclase, biotite and trace ilmenite. This tin-bearing granite is characterized by fine to medium grained texture and does not show any foliation. All of the granites may be of Late Triassic age (JONES *et al.*, 1977; PRIEM *et al.*, 1975). SCHÜRMANN's age determination on two tin granites from the adjacent islands of Singkep and Billiton (SCHÜRMANN *et al.*, 1960) indicates the average age of these granites as 145 million years.

The initial ratio of $^{87}Sr/^{86}Sr$ of the Late Triassic granites (about 0.715) indicates incorporation of an old silicic crust in the magmas. The tin-bearing granites have high rare-earth contents and contain accessory fluorite, tourmaline, topaz and scheelite. Galena and other sulfides in tin ores in two mines on Billiton have highly radiogenic lead (JONES *et al.*, 1977; DOE and DELEVAUX, 1973) For a given value of $^{206}Pb/^{204}Pb$, the ratios of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are relatively high ($^{206}Pb$, $^{207}Pb$, and $^{208}Pb$ are the daughter products of $^{238}U$, and $^{235}U$, and $^{232}Th$, respectively, and $^{204}Pb$ is non-radiogenic), and those typical of cratonic continental regions. This indicates that old pre-Late Palaeozoic continental basement likely underlies the Tin islands and Sumatra, and that components from it have been incorporated in the ores and in the granites (HAMILTON, 1979).

The Late Mesozoic-Cainozoic tectonic events are characterized by Cretaceous plutonism (granite arcs mainly occurring in west Kalimantan). Major bursts of Late Tertiary and Quaternary volcanic rocks were formed in Sumatra, Java, the Lesser Sunda islands, western and northern Sulawesi, and western Halmahera.

The Mesozoic and Early Tertiary folding, faulting, thrusting and granodiorite intrusions mainly occurred in western Indonesia. In eastern Indonesia, however, these deformations and intrusions occurred in Late Tertiary time. The Plio-Pleistocene displacements were important along large transcurrent faults in Sumatra and northern Irian Jaya-Maluku and perhaps also affected the stable region of the Sundaland. Ophiolites in eastern Indonesia (Timor, Seram, eastern Sulawesi, eastern Halmahera and northern Irian Jaya) were emplaced in Eo-Oligocene and Mid-Miocene (TJOKROSAPUTRO and WIRYOSUJONO, 1978).

The tectonic history of the Indonesia has been outlined in terms of tectonic stages (HEHUWAT, 1976). These include geological formations and complexes bounded by major unconformities and distinguished by characteristic histories of sedimentation, structural evolution and configuration, magmatism, metamorphism and mineralization. Six main phases of orogenic events can be recognized, possibly seven if the so called "basement" of the island, the Sula-spur and the Lampung High, is considered a product of an older phase of events which eventually gave rise to metamorphism. Taking into account the "migratory character" of an orogeny in space as well as in time, HEHUWAT (1976) distinguished the following orogenic events, i.e. (1) The Palaeozoic event (at some locations probably starting in the Early Palaeozoic), ending at the Palaeozoic-Mesozoic boundary, (2) The Early Mesozoic event, starting at the Palaeozoic-Mesozoic boundary and lasting throughout the Triassic (at certain places there seems to be evidence that the event continued well into the Jurassic period), (3) The Late Cretaceous event (in some places this orogeny seems to have continued into the Palaeogene epoch), (4) The Palaeogene orogeny, (5) The Neogene event and (6) The Plio-Pleistocene orogeny (in some places it is still continuing at present).

There are six principal major unconformities in the sedimentary-volcanic sequence, which can be briefly described as follows:

(1) The Upper Palaeozoic unconformities between Devonian and Lower Carboniferous and between Lower and Upper Carboniferous: Although not exposed, they are indicated by the difference in style of folding in some places of Sumatra and Kalimantan. The geologic events apparently ended at the Permo-Triassic boundary. These events involved folding and magmatism, low grade metamorphism, pegmatitic-aplitic and pneumatolytic, pyrometasomatic and hydrothermal activities.

(2) The Mesozoic unconformities between Mid- and Upper Triassic, between Upper Triassic and Lower Jurassic, and between Mid- and Upper Jurassic: The geologic events started at the Lowest Mesozoic and lasting throughout the Triassic, but at some places of western Indonesia these events continued into the Jurassic time. Because extensive magmatism occurred in Jurassic and Cretaceous time, they are not clearly exposed near the intrusive rocks. The igneous events involved folding, faulting, magmatism, low grade metamorphism, and pegmatitic-aplitic and pneumatolytic, pyrometasomatic and hydrothermal activities.

(3) The unconformities between Mid- and Upper Cretaceous, and between Upper Cretaceous and Palaeocene: They have been assumed at some places throughout western Indonesia. Three geologic events possibly took place somewhere within Mid- and Late Cretaceous and Palaeocene. The Mid- and Late Cretaceous and Palaeocene events apparently involved folding, magmatism, low grade metamormism, pneumatolytic, pyrometasomatic, hydrothermal vein-replacement and dissemination and stratabound exhalative activities as well as "ortho-igneous" deposition. The Late Cretaceous event is marked by uplift, faulting and erosion of the older rocks. In north Sumatra, Natuna islands and northern West Kalimantan, and southeastern Kalimantnan, this event was accompanied by granitic and dioritic stocks and dykes. The Palaeocene event is indicated by uplift and perhaps felsic magmatism but no external volcanism.

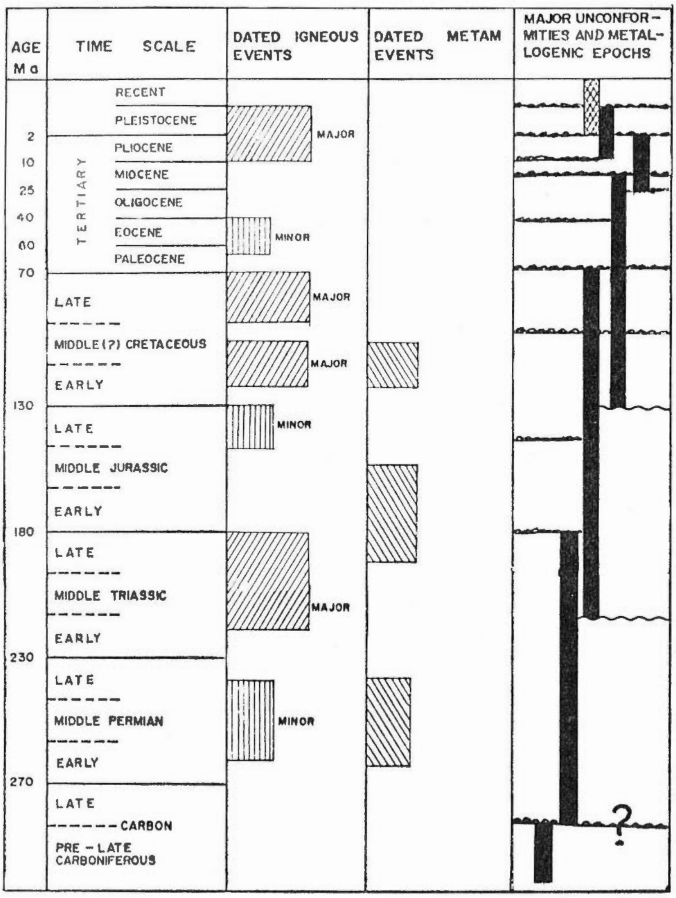
(4) The unconformities between Upper Palaeocene and Lower Eocene, somewhere within Mid-Eocene, and between Upper Eocene and Lower Oligocene and somewhere within Mid-Oligocene: The Eo-Oligocene event is marked by emplacement of ophiolites. Evidence of uplift in some places in the Sunda arc is found in Oligocene sedimentary-volcanic series.

(5) The unconformities between Upper Oligocene and Lower Miocene and somewhere within Mid-Miocene: In some places, they are characterized by a distinct hiatus within the Mid-Miocene succession and also by a marked angular unconformity which separates folded Palaeogene to Early Mid-Miocene rocks from generally low-dipping younger rocks. In western Indonesia, an abrupt sea-level depression during the Late Mid-Miocene to around 1,000 m below present, is related to the submergence of the Sundaland region. The Mid- and Late Miocene, Pliocene and Plio-Pleistocene events apparently involved folding, ophiolite emplacement, magmatism, metamorphism, faulting and the formation of primary mineral ore deposits. These deposits may be related to "ortho-igneous," pneumatolytic, contact metasomatic, hydrothermal vein-replacement and dissemination, stratabound exhalative and volcanogenic activities.

(6) The unconformities between Lower and Mid-Pleistocene and between Pleisto-

cene and Holocene or Recent, characterized by uplifting, faulting, erosion and sedimentation during Quaternary time.

Table 1 Tectonic evolution and metallogenic epochs of Indonesia. Endogeneous metallogenic epochs are shown in 6 solid columns and supergene metallogenic column in 1 shaded column.




Based on the geologic events obtained so far and the conclusions based on the study of metallogeny, an attempt can be made to correlate tectonics and metallogenic epochs (Table 1). Six episodes of metallic mineralization can be distinguished. These are: (1) the Late Palaeozoic to Early Mesozoic (Late Carboniferous to Late Triassic), (2) the Mesozoic (Mid-Triassic to Late Cretaceous), (3) the Late Mesozoic to Late Tertiary (Early Cretaceous to Mid-Miocene), (4) the Late Tertiary (Mid-Miocene to Pliocene), (5) the Late Tertiary to Early Quaternary (Late Miocene to Pleistocene) and (6) the Quaternary to Recent periods.

## METALLIC MINERALIZATION

The intimate genetic relation between phases of geologic events and formation of metallic mineral deposits seems to be reasonable in grouping principal metallic mineral areas in Indonesia (Fig. 3), because the most striking features of the country are the presence of distinguishable geologic events. Consequently, it is necessary to clarify the various types of metallic mineral deposits and their characteristics of mineralization in each phase of geologic events. The magmatic process accompanying various folding and subsequent uplifting, erosion and deposition, brought forth a wide range of metallic mineral deposits that include orthomagmatic, pegmatitic, pneumatolytic, contact-pyrometasomatic (skarn, greisen), hydrothermal (stockwork, pipe, vein, shear zone and deposits of irregular or indefinite shapes) and volcanogenic (exhalative) deposits and weathering-sedimentation or supergene enrichments (laterite, bog, beach, alluvials, placer and terraces).

## Metallic Mineralization in Late Carboniferous to Late Triassic Period

The oldest dated geologic event resulting in metamorphism of rocks which are accompanied by plutonism is known from Banggai and Sula islands, Vogelkopf-Irian Jaya, and Lampung, south Sumatra. The Early Palaeozoic or older rocks were intruded by Late Palaeozoic-Early Mesozoic granites and they are in turn metamorphosed into granite-gneisses.

Geological data on mineral deposits in this period are very scarce. The information presented in this paper comes from the quarterly reports, Arch. Sumatra Mineral Survey (G.S.I. unpubl. 1973). The molybdenite occurrence of Lampung, south Sumatra, associated with rare and other base metal minerals occur in aplite and veinlets. They are exposed in the Palaeozoic granite-gneiss as oxides and sulfides. They illustrate that mineralization was first developed as pneumatolytic or pyrometasomatic deposits which have been later modified by hydrothermal activity. Various types of precious, base and rare metal mineral deposits are found in connection with pneumatolytic, pyrometasomatic and hydrothermal processes in Palaeozoic or older rocks of Vogelkopf-Irian Jaya.

## Metallic Mineralization in Mid-Triassic to Late Cretaceous Period

Metallic mineral occurrences in this period are known in Sumatra, western part of Kalimantan, and the Tin islands. They are distinguished by Palaeozoic and Late Palaeozoic-Mesozoic history of repreated sedimentations and volcanisms which were affected by Trias-Jurassic and Jura-Cretaceous geologic events. The rocks mainly consist of quartzite, slate, shale, sandstone, limestone, lava flows and pyroclastic rocks ranging in composition from mafic to felsic. The Mesozoic granitoids are regarded to have been caused by plutonic activities intruded into the sedimentary and volcanic rocks.

The mineralization of this period includes important mineral resources such as tin and rare metal minerals in "Tin islands" (Riauw islands, Bangka and Billiton). It is characterized by the granitic plutonism belonging to the southeastern most part of "Southeast Asia tin province." The primary tin mineral (cassiterite) is commonly associated with scheelite, xenotime, columbite, monazite and fluorspar in the granitoids with relatively low cafemic alkali ratio. It is also regarded that plutonism was responsible for the pneumatolytic or pegmatitic, contact pyrometasomatic and hydrothermal alteration and metallic mineral deposition. The deposits occurred in the intrusive granodiorite and in the intruded country rocks. In general, the features of primary tin deposits may be grouped as follows:

( i ) Cassiterite with rare metal minerals (Nb-Ta-Zr) in pegmatite (Bangka, Billiton).

( ii ) Cassiterite with a little or without rare metal minerals in aplite (Bangka).

(iii) Cassiterite with magnetite, andradite and other gangue minerals of skarn rocks in contact pyrometasomatic zone (Billiton).

(iv) Cassiterite veinlets, stringers or vein swarms in greisen and in shear zones of hydrothermal origin (Bangka, Billiton).

(v) Cassiterite with base metal sulfides in lode or pipe of hydrothermal origin (Billiton).

(vi) Disseminated cassiterite (tin porphyry ?) in replacement body of the intrusive rocks of hydrothermal origin (Billiton).

(vii) Cassiterite veins in the intruded rocks of hydrothermal origin (Bangka).

Volcanic rocks of Mesozoic age in southern part of west Kalimantan may be contemporaneous and consanguineous with the granite and granodiorite. In some plutonic bodies and their surroundings, mineralization of iron and ferro-alloy, base and precious metallic minerals are known, and they are related to massive skarn rocks in contact pyrometasomatic zones and shear zone of hydrothermal environment.

## Metallic Mineralization in Early Cretaceous to Mid-Miocene Period

HEHUWAT (1976) is inclined to think that there are two separate phases of foldings in this period: The Late Cretaceous-Palaeocene folding which affected the Palaeozoic and Mesozoic rocks in Sumatra, west-central and south Kalimantan, southeast-central and east Sulawesi, and the Eo-Oligocene folding which made deformation of Late Triassic and Early Tertiary rocks in north and east Sulawesi. There are various kinds of sedimentery and metasedimentary rocks consisting slates, quartzites, limestones, hornstones and schists. In those areas, plutonic and volcanic rocks range from mafic to felsic were erupted and ophiolites were emplaced. The Cretaceous granites and granodiorites in Sumatra and Natuna island have been positively determined.

Primary metallic minerals, i.e. magnetite-hematite, molybdenite, pyrolusite, pyrite, pyrrhotite, chalcopyrite, gold, sphalerite and galena, connected with mafic to felsic intrusions in this period, generally occur as pyrometasomatic or skarn deposits. Iron and copper occurrences occur at many localities along fault-zones (from Alahan Panjang to Muaralabuh, Bukit Barisan, Sumatra). The resulting mineralization, however, is sporadic, in the form of oxide and sulfide impregnations in contact zones.

In Cretaceous-Mid-Miocene period, the mineralization of alkaline granites of west Kalimantan brings some molybdenum, manganese, mercury, iron, lead, zinc and other rare metallic minerals. These mineral occurrences are considered to belong to one complex paragenetic mineral zone, i.e., a zoned gold-copper-molybdenum-mercury and base metal mineral area of west Kalimantan. Several kinds of subvolcanic intrusions associated with mineral occurrences are known around the epithermal mineralization at Mandor, which is a type of deposit thought to be connected with Tertiary volcanic rocks (SUHANDA, 1978). The molybdenum mineral deposits of west Kalimantan (Benaul, Bawang Mts.) occur as sulfide veinlets within the granodiorite. The molybdenite is associated with chalcopyrite but no cassiterite. It is certain that these occurrences form a principal mineral area of their own, and the author is inclined to separate it from the "Natuna-Anambas tin area." Primary manganese mineral occurrences commonly occur in hydrothermal veins, but at some places, high-grade ores are impregnated in the zone of contact metamorphic rock (Jelatok).

In southeastern Kalimantan, two principal mineral areas are present in parallel each other. They are the southern part of south Kalimantan which includes Laut-Sebuku islands and Meratus Mts. On the first-mentioned islands, serpentinized peridotites occur. Minor chromite occurrences were developed in the marginal serpentinized zones. In the Meratus Mts., the Cretaceous (perhaps Early Tertiary) granodiorites contain iron and ferro-alloy, precious and base metal deposits of pyrometasomatic and hydrothermal types.

Similar chromite occurrences of Tertiary age are found in south and east Sulawesi, Timor, northern part of Irian Jaya and East Halmahera island. Massive copper occurrences in gabbroic and diabasic rocks are also found in Timor.

## Metallic Mineralization in Mid-Miocene to Pliocene Period

The mineralization of this period produced numerous kinds of metallic mineral occurrences (Au, Ag, Cu, Pb, Zn, Mo, Mn, Fe, Hg, As and Sb). These occurrences are found in Miocene rocks of Southern Mts. of west Java and perhaps also in the Bukit Barisan Ranges of Sumatra. The mineralization is thought to be related to Mio-Pliocene volcanism. Several kinds of volcanic and subvolcanic rocks are known, namely, rhyolite, dacite, trachy-andesite, quartz latite, quartz porphyry and basalt.

The Western Coastal Ranges of Sumatra with rocks of this period, are regarded to belong to the "precious and base metal mineral area of the southwestern Bukit Barisan"; however, the Southern Mts. of west Java is considered as another area, accompanied with a more simple geologic environment. Gold and silver associated with copper, lead and zinc on the Western Coastal Ranges of Sumatra are predominantly of epithermal vein type containing minor manganese with trace of tellurium, bismuth and selenium. On the other hand, in the Southern Mts. of west Java, they are characterized by minor arsenic sulfides of the epithermal vein type.

## Metallic Mineralization in Late Miocene to Pleistocene Period

Metallic mineralizations in this period are known in southern and northern Sulawesi, western Halmahera, central and northern Irian Jaya, and the Lesser Sunda islands. Primary chromite occurrences of Tertiary age are found in south and east Sulawesi, Timor and southeast Kalimantan. In central part of Irian Jaya, precious and base metal sulfides of meso-epithermal and telethermal veins are known. Very interesting are high-grade pyrometasomatic (skarn) copper-gold deposit of Tembagapura, Irian Jaya, and low grade porphyry copper deposits of Sassak and Tapadaa-Tambuililato, Sulawesi. Complex metallic minerals and also 'kuroko ores' are found in Sangkaropi, Sulawesi, and perhaps also in northern Irian Jaya and the Lesser Sunda islands. Manganese occurrences are widely scattered in Mio-Pliocene limestones and volcanic sedimentary rocks. Sizable but sporadic occurrences of pyrometasomatic iron ores are related to the Late Miocene-Pleistocene magmatism.

## Metallic Mineralization in Quaternary to Recent Period

The youngest dated phase of folding of this period, accompanied by andesitic and basaltic volcanism, is observed in Kalimantan, Sumatra, Java, the Lesser Sunda islands, Sulawesi, and perhaps also in northern Irian Jaya and northern Muluku. The mineralization of precious and base metal sulfides are of telethermal vein type. Weathering of rocks produces very important alluvial and elluvial deposits of tin and rare metal minerals (Bangka, Billiton and Riauw islands), bauxite (Riauw islands, western Kalimantan and perhaps also Irian Jaya), secondary chromites, gold placer and other precious fragments (Sumatra, Kalimantan, Sulawesi and Irian

Jaya), nickel as well as ferro-nickel laterites (southeastern Kalimantan, eastern and southeastern Sulawesi, eastern Halmahera and Irian Jaya). Valuable titaniferous iron sand deposits accur along the south coast of Java.

## CONCLUSIONS

There is an intimate relationship among metallic mineralizations and volcano-plutonic activities and ophiolite emplacements within tectonic zones. These zones are grouped into four overlapped tectonic zones in western Indonesia, one overlapped tectonic zone in northernmost part of Sulawesi-Halmahera region (Mayu Ridge collision complex), two sub-parallel tectonic zones in Banda region and four tectonic terrains in Irian Jaya.

Grouping of metallic mineral deposits of Indonesia into principal mineral areas according to six episodes of metallic mineralization seems to be practicable. More detail grouping, whenever possible, could be worked out, perhaps according to other principles. To make further grouping, however, would be a tremendous task, and a considerable amount of time would be required to analyse and interprete all geological, geophysical and geochemical as well as mineralogical data.

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# Metallogenesis in the Philippines: Explanatory Text for the CGMW Metallogenic Map of the Philippines*

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## INTRODUCTION

The accompanying metallogenic map follows the standard legend for the Metallogenic Map of Asia of the Commission for the Geological Map of the World (CGMW). Preparation started back in 1964, when the Working Party of Senior Geologists of the Economic Commission for Asia and the Far East (ECAFE) decided to compile the map. In 1974, the CGMW Subcommission for Asia took over the job and came up with the legend that is now being followed by the individual countries concerned.

This text aims to clarify the information depicted in the map and provide the geologic and tectonic base which could not be included in the map due to cartographic limitations. While the map legend required boxed capsules of commodity groupings, lithologic environment, genetic types and ages of mineralization that are generally adaptable to the region, this text presents the relevant aspects of metallogenesis in the light of specific Philippine conditions. The classification schemes herein presented do not therefore necessarily follow the legend.

## GEOLOGY

The Philippines is an archipelago of 7,100 islands, between 5 and 22 degrees north latitudes, in the southwest margin of the Pacific. It is divisible into four major physiographic provinces (Fig. 1). Eastern, central and western physiographic provinces comprise the seismically active "Philippine mobile belt," while Palawan physiographic province and Sulu Sea comprise the "stable or aseismic belt" (GERVASIO, 1966). The "Philippine mobile belt" is bounded on both sides by trenches while the Palawan physiographic province is bounded on the northwest by the Palawan Trench.

### Palawan Physiographic Province

Palawan physiographic province is divisible into two subprovinces. The northern, comprising the northern half of Palawan Island, Busuanga Island Group and Cuyo Island Group, is underlain by Early Jurassic basement composed of Carboniferous to Early Jurassic (?) geosynclinal sediments regionally metamorphosed to the low-pressure greenschist facies and deformed mainly during Early Jurassic (Fig. 2). This sequence is intruded by granitic plutons of unknown age represented by Kapoas granite in various portions of northern Palawan. In the Cuyo Island Group, the

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sequence is covered with the Cuyo volcanics of probable Pliocene age. Offshore, it is overlain unconformably by poorly deformed sediments ranging in age from Late Eocene to Recent. Middle Jurassic to Cretaceous continental sediments are probably present at the base of the poorly deformed cover (Fig. 2).

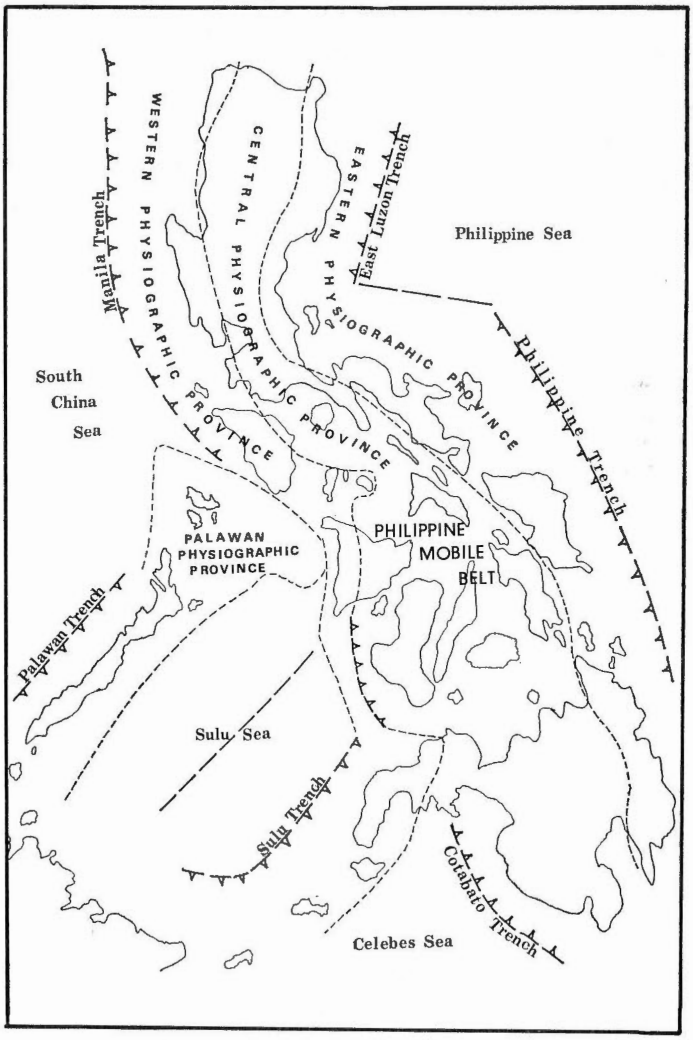


Fig. 1. Major physiographic elements in the Philippines

In great contrast to the northern sub-province, the southern sub-province of Palawan is composed mainly of a strongly deformed complex of ophiolite and Paleocene to Miocene marine to continental arkosic to quartzitic clastics and limestone. This complex is covered by thin undeformed Pliocene to Recent sediments.

## PHILIPPINE MOBILE BELT

### Western Physiographic Province

The western physiographic province constitutes the belt of mountain ranges in the western side of the mobile belt. The mountain ranges are Ilocos, Zambales, Mindoro,

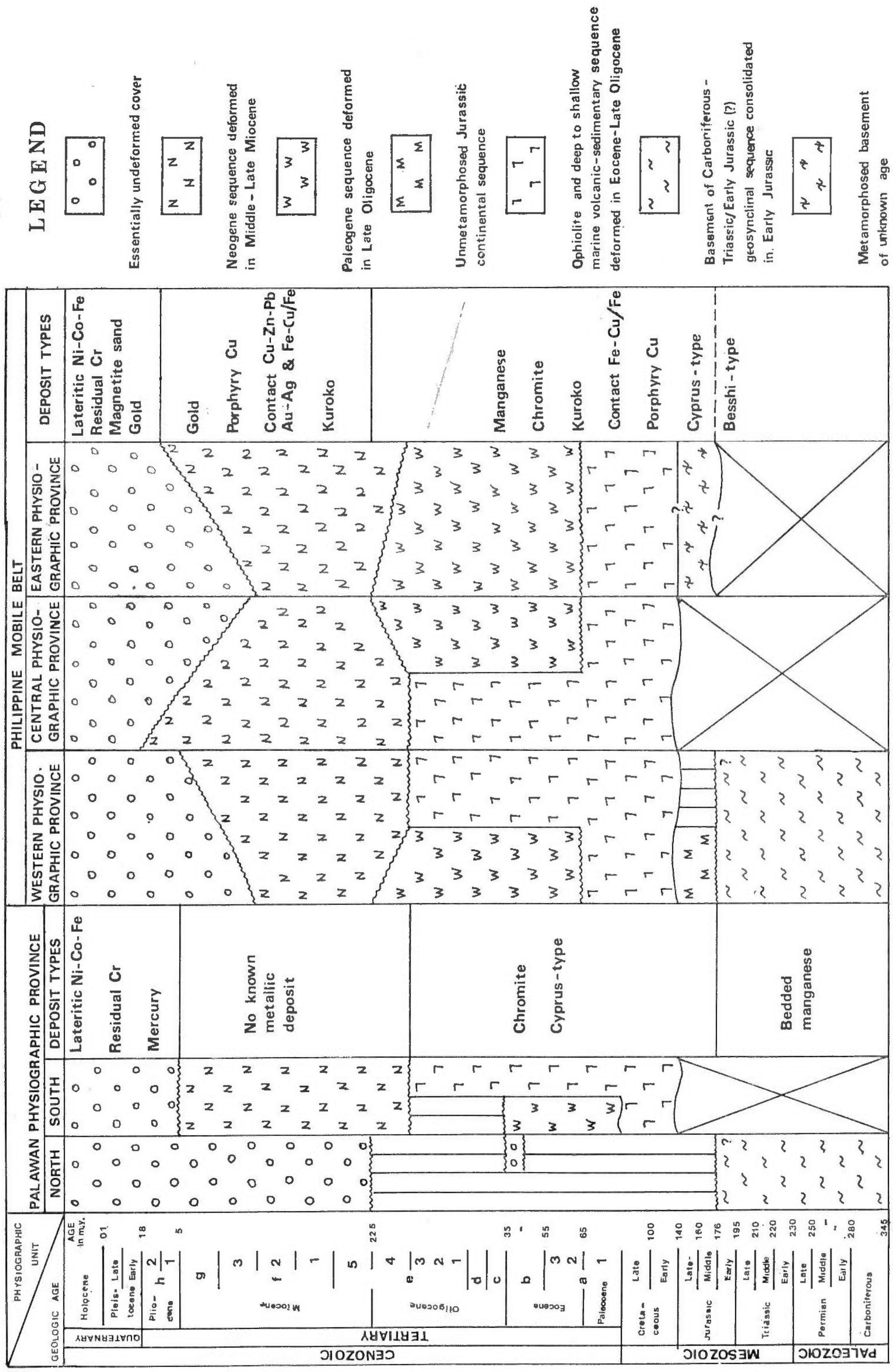


Fig. 2. Distribution of ore deposit types in the tectonostratigraphic column

western Panay and Zamboanga Peninsula.

Ilocos Range is composed of a highly deformed complex of ophiolite, Paleogene turbidites and Lower to Middle Miocene basaltic volcanics and sediments. East dipping thrust faults of late Middle Miocene age are very prominent. The undeformed cover ranges from Late Miocene to Recent.

Zambales Range exposes the biggest single mass of ultramafic-mafic rocks as well as the most complete ophiolite sequence in the Philippines. A series of diabase dike complex, back-arc basin-type tholeiitic pillow basalt (HAWKINS, 1979), and pelagic sediments (GARRISON *et al.*, 1979) lie over the ultramafic-mafic mass in the northwestern and eastern flanks of the range and constitute the upper part of the ophiolite sequence. The age of the uppermost part, the Aksitero formation, is Late Eocene to Lower Oligocene. The sequence is intruded by felsic gabbro, quartz diorite and granodiorite plutons in the eastern and northwestern parts of the range. Lower Miocene to Middle Miocene clastic sediments, with large amounts of andesitic pyroclastic components and limestone, cover unconformably the ophiolite and the dioritic to granodioritic plutons. Middle-Late Miocene folding and thrusting are evident in both the eastern and western flanks of the range. Undeformed Late Miocene to Quaternary sediments cover the western flank, while Quaternary andesitic pyroclastics and lava flows cover the eastern side. Andesitic to dacitic and rhyodacitic volcanic cones and plugs are also common in the eastern side.

Mindoro Range has a core of Carboniferous to Early Jurassic (?) basement, overlain unconformably by Middle to Late Jurassic coastal deposits. An ophiolitic assemblage of chert, spilitic basalts, and basaltic wackes of probable Cretaceous to Paleocene age and large ultramafic masses are thrusted eastward against the basement. Quartz diorite and granodiorite plutons intruding even the ultramafic rocks are distributed along the northwesterly axis of the mountain range. Limited Late Eocene to Late Oligocene limestone units cover unconformably the older rocks, including the granitic plutons. Early Miocene to Late Miocene clastic sediments and limestone skirt the southwestern half of the range. Intense Late Miocene folding of the basinal sediments is evident. Undeformed cover, limited to the range flanks, consists of Pliocene to Recent basaltic to andesitic terrestrial lavas and pyroclastics, tuffaceous shale and sandstone, terrace gravels, reef limestone and alluvium.

The western Panay Ranges include Buruanga Peninsula and Antique Range. Buruanga Peninsula is composed almost wholly of the Carboniferous to Early Jurassic continental-type basement. In contrast, Antique Range is composed of a highly deformed complex of Mesozoic to Oligocene ophiolite, overlain unconformably by Early-Middle Miocene reefal limestone and shallow marine clastics. The complex folding and thrust faulting evidently occurred in Late Miocene, when the blueschist-bearing melange, the Paniciuan formation, was emplaced. This tectonic activity was accompanied by limited andesite volcanism. The undeformed cover is Pliocene to Recent.

Zamboanga Peninsula is similar in many respects to Mindoro. Metamorphosed geosynclinal rocks similar to the known Carboniferous-Early Jurassic basement in Mindoro, constitute the core. An ophiolitic assemblage of spilitic pillow basalts, chert and indurated greywackes, of probable Cretaceous to Paleocene age, and ultramafic rocks are thrusted westward against the basement core. These are overlain unconformably by Early Miocene to Late Miocene sedimentary and volcanic rocks which have been folded in Late Miocene. Intrusion of quartz diorite and granodiorite plutons occurred sometime in Paleogene, and in Late Miocene. The undeformed cover is Pliocene to Recent.

## Central Physiographic Province

The central physiographic province is a complex array of ranges and sedimentary basins with highly variable lithology and structure. The metallogenically important physiographic entities are Luzon Central Cordillera-Caraballo Range, Marinduque, Central Masbate-E. Panay-Guimaras Island-SW Negros Belt, Cebu, Bohol, Leyte, Mindanao Central Cordillera, Misamis-Bukidnon Highlands, Northern Zamboanga-Misamis Occidental Highlands and Daguma Range.

Luzon Central Cordillera is a north-south trending mountain range at the center of northern Luzon. The northwestern portion merges with the Ilocos Range, along a Late Miocene zone of frontal arc-magmatic arc collision. South of this junction, the northern extension of Central Luzon Basin (Ilocos Basin) bounds the western side of the Cordillera. To the east, it is bounded by the Cagayan Basin and the Caraballo Range at the southeast.

There is hardly any physiographic or geological demarcation between Luzon Central Cordillera and Caraballo Range. They are both composed of a core of probable Cretaceous to Eocene-Oligocene calc-alkaline metavolcanics and metasediments intruded in Oligocene to Early Miocene by synkinematic batholiths of quartz diorite and granodiorite represented by Agno, Dupax and Palali batholiths (MMAJ-PBM, 1977; Balce, 1978). These rocks are covered unconformably with early Middle Miocene limestone and clastic sediments rich in volcanic facies. Stocks of calc-alkaline quartz diorite porphyries were intruded in the later part of Middle Miocene in Luzon Central Cordillera. In Caraballo, highly alkaline analcite bearing basalts and pseudo-leucite bearing porphyries were emplaced in Middle Miocene (Baquiran, 1975; Palispis, 1979). Late Miocene to Pliocene strata composed largely of andesitic lavas, pyroclastics and conglomerate are essentially undeformed in the central part of the ranges but steeply tilted basinward on both flanks of the ranges.

Marinduque Island, south of Luzon, consists of a core of Cretaceous to Eocene metavolcanic and metasedimentary rocks overlain unconformably by Late Oligocene to Early Miocene sediments. Folding along the NW-SE direction and synkinematic quartz diorite plutonism occurred in Middle Miocene. Undeformed Late Miocene to Recent cover is limited to the western and eastern flanks of the island range. A Pliocene-Pleistocene volcanic cone is present at the southern tip of the island.

Central Masbate, eastern Panay, Guimaras Island and southwestern Negros constitute a belt of Paleogene diorite-granodiorite batholiths (one K-Ar date: 59 m.y.) intruding presumably Cretaceous to Paleogene metavolcanics and metasediments. Offshore data show that the belt is actually a continuous ridge between the Tertiary Iloilo and Visayan Basins. The Cretaceous to Paleogene rocks are overlain unconformably by Late Oligocene to Middle Miocene clastics and limestone, slightly folded during Late Miocene and intruded by small stocks of quartz diorite porphyry. Undeformed cover ranges from Late Miocene to Recent.

Cebu Island, the site of the largest copper mine in Asia, is a NE trending geanticlinal ridge formed during a folding episode in Late Miocene to Pliocene. It became fully emergent since Late Pleistocene. The core is composed of Lower Cretaceous to Paleocene/Early Eocene basaltic to andesitic metavolcanics, metasediments, deep water to reefal limestone and quartz diorite-granodiorite batholiths intruded in Paleocene to Early Eocene (one K-Ar date: 59 m.y.). These are overlain unconformably by Oligocene to Middle Miocene shallow marine clastics and limestone.

Magmatism at the start of Middle Miocene deposited substantial amounts of andesite lavas and pyroclastics in the eastern part of the island. The plutonic equivalent is the Talamban diorite which intrudes Lower Miocene strata. Contemporaneous with Late Miocene-Pliocene geanticlinal development, shallow marine to terrestrial molasse was deposited on the eastern and western flanks of the island. The undeformed cover is mainly Pliocene to Pleistocene reef limestone.

Bohol Island consists of two NE-NNE trending ridges formed in Late Miocene-Pliocene. The ridge at the islands northwestern edge is a geanticline with basically similar geology as Central Cebu. The ridge at the eastern edge was formed by westward thrusting. The core is composed of strongly foliated metamorphic rocks and serpentinized peridotite. These are thrusted against Lower-Middle Miocene sedimentary rocks. The undeformed cover consists mainly of Pliocene to Pleistocene limestone and lagoonal clastics.

Leyte Island is divisible into two parts: northeastern and western. The northeastern part is underlain by thrusted slices of slightly to strongly foliated metamorphosed volcanic rocks, serpentinized peridotite and Lower to Middle Miocene sedimentary rocks. These are covered along the ridge flanks by undeformed Late Miocene-Pleistocene shallow marine to terrestrial deposits. The western part is a NW-SE folded belt of Early-Late Miocene sediments and volcanics. Late Miocene volcanic facies dominate in the eastern section where the Philippine Fault passes the fold belt longitudinally. Middle Miocene diorite and thrusted sheets of serpentinized peridotite are disposed in the southwestern section. Pliocene to Pleistocene lavas and pyroclastics constitute the undeformed cover. Andesitic volcanic cones are distributed along the belt where the Philippine Fault passes.

Mindanao Central Cordillera, a N-S fold belt at the central part of Mindanao Island, is composed of Cretaceous-Paleogene ophiolitic core of mafic-ultramafic rocks, metabasalts, chert and turbiditic metagreywackes. In the northern part, strongly foliated greenschist with pronounced sedimentary structures are thrusted against the ophiolitic materials. Late Oligocene to Late Miocene sedimentary strata with intercalated andesitic volcanic and pyroclastic facies cover unconformably the ophiolitic rocks. Batholiths and stocks of Middle to Late Miocene quartz diorite are distributed along the axis of the Cordillera. Pliocene to Pleistocene sedimentary rocks along the flanks of the Cordillera are moderately folded. The undeformed cover consists of Late Pleistocene to Recent basaltic to andesitic lavas, pyroclastics, alluvium and terrace gravels. Mount Apo, the highest peak in the Philippines, is at the central part of the Cordillera.

The Misamis Oriental-Bukidnon Highlands is another metallogenically important region. It is composed of strongly folded Early to Late Miocene sedimentary and volcanic sequence, thrusted sheets of ultramafic rocks, Cretaceous-Paleogene metavolcanics/metasediments and Middle-Late Miocene diorite stocks. These rocks are covered unconformably by Pliocene-Pleistocene limestone and volcanic rocks including the extensive olivine basalt lavas and pyroclastics of the Lanao-Bukidnon plateau.

The Northern Zamboanga-Misamis Occidental Highlands consist of folded sedimentary and volcanic deposits of Lower to Middle Miocene age. These are intruded by Middle Miocene quartz diorite batholiths and stocks. Moderately folded Late Miocene to Pliocene undeformed sedimentary cover includes Plio-Pleistocene reef limestone and andesitic lavas and pyroclastics extruded by numerous volcanic cones.

Daguma Range is a NW-SE trending mountain range transverse the N-S and NE-SW trends of other ranges in Mindanao. It is composed mainly of Cretaceous to Eocene metavolcanics and metasediments overlain unconformably by Early Oligocene to Early Miocene sedimentary rocks. These are intruded by pre-Middle Miocene diorite. Along the northeastern and eastern flanks of the range, folded Middle to Late Miocene rocks are intruded by quartz diorite batholiths. Slightly deformed Pliocene-Pleistocene limestone covers the central part of the range. Towards Cotabato Basin, at the northeastern side of the range, Pliocene-Pleistocene sediments are moderately folded. Pleistocene andesite lavas and pyroclastics underlie the volcanic cones in the northwestern part of the range.

## Eastern Physiographic Province

This physiographic province covers the belt of mountain ranges at the eastern edge of the archipelago, facing the Pacific. It includes Northern Sierra Madre, Southern Sierra Madre, Polillo Island Group, Bicol Peninsula-Catanduanes, Samar Island, and the Eastern Mindanao Ranges.

Northern Sierra Madre in the northeastern seaboard of Luzon Island, is divisible into two parallel belts. The eastern belt is composed of upthrusted masses of ultramafic-mafic rocks, plagioclase-hornblende amphibolite and greenschists derived from well-bedded Cretaceous to Early Eocene pelagic clastics, chert, limestone and interbedded basaltic volcanics (Hashimoto *et al.*, 1978). These are intruded by plagiogranites in the southern portion. Unmetamorphosed equivalent of the rocks converted to greenschist are present in the western part of the belt where they are overlain unconformably by andesitic lavas and pyroclastics with fragments of Oligocene-Early Miocene limestone. The western belt is composed of the essentially unmetamorphosed Cretaceous to Eocene sequence, with significant horizons of manganese and stratiform sulfide deposits. This is intruded by synkinematic batholiths of gabbro, tonalite and granodiorite ranging in age from Eocene to Oligocene (K-Ar ages: 27–49 m.y., MMAJ-PBM, 1977). Oligocene to Middle Miocene clastic sediments, limestone and volcanic rocks deposited in the Cagayan Basin compose the wetsern flank of the range. These basinal deposits are steeply tilted and occur even at 1,500-meter elevations. Undeformed Early-Middle Miocene limestone and clastic sediments cover the ultramafic rocks of the eastern belt. An andesitic Quaternary volcanic cone covers the folded Miocene rocks in the northern tip of the range.

Southern Sierra Madre has basically similar geology as Luzon Central Cordillera. Late Cretaceous metavolcanics, turbiditic metasediments and limestone, overlain unconformably by Paleocene to Eocene limestone and marine clastics compose the greater portion. These are intruded by batholiths of Oligocene diorite (K-Ar age: 36 m.y., Wolfe, 1972). Folded Late Oligocene to Middle Miocene limestone, clastics and volcanics are present along the western flank as well as the central highlands. These are intruded by Middle Miocene diorite (Antonio, 1967). The undeformed cover ranges from Late Miocene to Pleistocene consisting mainly of conglomerate and volcanics. The southern part of the range is covered with basaltic to andesitic lava flows and thick sub-terrestrial pyroclastics related to volcanic centers in the Laguna Lake, Mt. Makiling and Mt. Banahaw.

Polillo Island Group, east of Southern Sierra Madre, has a basement of metavolcanics and metasediments and small thrusted bodies of serpentinite and mica schists. This is intruded by diorite, which is assigned an Early Eocene age because it is unconformably overlain by Late Eocene-Early Oligocene clastic sediments and limestone. Folded Late Oligocene-Middle Miocene sediments with few intercalated pyroclastics underlie the eastern portion of the main island. The other islands to the east, except Jomalig Island, are underlain by only slightly folded Late Miocene-Pliocene sediments. Jomalig Island is underlain presumably by Cretaceous volcanics. The undeformed cover is mainly reefal limestone of Pliocene-Pleistocene age.

Bicol Peninsula-Catanduanes is composed of three distinct physiographic units: 1) Eastern Bicol Ranges, 2) Bicol Basin and 3) Western Bicol Ranges. The Eastern and Western Bicol Ranges merge in a thrusted junction at the northern end of the peninsula. The northeast ranges include the Caramoan Peninsula and the Paracale-Larap Highlands in northeastern Camarines Norte. These are composed of thrusted slices of greenschists, ultramafic rocks and essentially unmetamorphosed volcanics, clastic sediments and limestone of Late Cretaceous to Eocene age. The greenschists are derived from well-stratified sequences of basaltic volcanics, clastic sediments, chert and limestone of unknown age. These rocks are overlain unconformably by folded Oligocene to Early Miocene sediments and volcanics which are intruded by presumably Middle Miocene diorite as represented by the Tamisan diorite in Camarines Norte. The Paracale diorite-granodiorite batholith which yielded a Middle Miocene K-Ar age (16 m.y.), could actually be Paleogene in age as estimated by MIRANDA (1977) on the basis of granodioritic pebble occurrences in the Late Eocene Universal formation near the batholith. Towards Bicol Basin are folded Late Miocene to Pliocene sediments with abundant volcanic facies. The undeformed cover includes Pleistocene volcanics from several volcanic cones between Bicol Basin and the Eastern Ranges, and Quaternary alluvium.

Bicol Basin is underlain by folded Early Miocene to Pliocene sedimentary strata with occasional volcanic interbeds. These are covered by undeformed Pleistocene to Recent alluvium and volcanic rocks. The Western Bicol Ranges have practically the same geology as the Eastern Ranges except for the absence of extensive metamorphic rock exposures.

Samar Island has a core of Late Cretaceous metavolcanics and metasediments with occasional manganiferous beds and chert, and thrusted masses of ultramafic-mafic rocks. These are intruded by Paleogene diorite overlain unconformably by essentially undeformed Early Miocene limestone and clastic sediments. At the central part of the island are extensive deposits of Middle Miocene dacitic and andesitic lavas and pyroclastics containing kuroko-type deposits. Late Miocene to Pliocene clastics and limestone are distributed widely in the northern, eastern and western sides of the Island. These rocks are highly folded in the western part, a downthrown block towards the Visayan Basin.

The Eastern Mindanao Ranges is divisible into a northern and southern parts. The northern part covers Dinagat and neighboring islands wihch is composed mainly of upthrusted ultramafic-mafic rocks and Cretaceous-Paleogene (?) metasediments and basaltic metavolcanics apparently constituting the upper member of an ophiolite sequence. Eocene clastics, containing serpentinized peridotite pebbles (SANTOS-YÑIGO and ESGUERRA, 1961), and limestone occur also as thrusted slices together with the Cretaceous-Paleogene rocks and ultramafic-mafic rocks. Occasional slivers of greenschists, some containing glaucophane (SANTOS-YÑIGO, personal comm., 1980), are thrusted against the ultramafic-mafic rocks. Strongly folded Early-Middle Miocene clastics and limestone complete the thrusted-folded sequence which is intruded by Middle to Late Miocene quartz diorite, andesite and dacite. The undeformed cover consists mainly of Pliocene to Pleistocene andesitic volcanics/pyroclastics, conglomerates and reef limestone.

The southern part of the Eastern Mindanao Ranges has practically the same geology as the northern part (MMEAJ-PBM, 1972). However, unlike the northern part the thrusted ophiolite zone is in the western part, i.e., in the Pujada Peninsula. Hornblende-garnet-amphibolite schist is found as thrusted slices in the ultramafic mass at Pujada Peninsula. Middle Miocene diorite-granodiorite batholiths and stocks are more widely exposed in this part of the ranges.

## TECTONICS

The stratigraphic and structural information for the Philippine Archipelago, although still incomplete, shows basically four periods of crustal evolution or tectnoic stages as indicated by major unconformities and lithologic types. These are: 1) Carboniferous-Early Jurassic (?) or basement stage, 2) Middle Jurassic-Oligocene, 3) Late Oligocene/Early Miocene-Late Miocene/Pliocene and 4) Late Miocene/ Pliocene-Recent.

The Carboniferous-Early Jurassic (?) or basement stage period covers the mainly miogeosynclinal deposits in the Reed Banks, the northern segment of Palawan physiographic province, Mindoro, Romblon Island Group, Buruanga Peninsula and possibly Zamboanga Peninsula. This consists of presumably Carboniferous (Reyes, 1969; Easton and Melendries, 1963), Permian-Late Triassic (Hashimoto and Sato, 1968, 1973) and possible Early Jurassic (Fontaine *et al.*, 1979) sedimentary sequences that have been metamorphosed to low pressure greenschist facies and converted to continental-type basement before Middle Jurassic. Probable pre-Middle Jurassic granitic rocks in Palawan and Mindoro (Andal and Caagusan, 1967) are also included.

The Middle Jurassic-Oligocene period covers a wide variety of lithologies and depositional environments, but ophiolites occupy a major lithologic type. This includes the near-shore to continental deposit over a Middle Jurassic continental platform as represented by Mansalay formation in Mindoro; the non-ophiolitic deep to shallow marine basaltic to andesitic volcanics, limestone and clastic rocks of Early Cretaceous to Paleocene in Central Visayas and Central Mindanao; the Eocene to Oligocene archipelagic basinal deposits with occasional coal measures widespread in the Philippine mobile belt and southern Palawan; and the Paleocene to Oligocene dioritic-granodioritic batholiths in the mobile belt.

The Late Oligocene/Early Miocene-Late Miocene/Pliocene period includes the mainly archipelagic basinal deposits of the period, large amount of volcanic and pyroclastic rocks and dioritic-granodioritic batholiths and stocks formed mainly in Middle to Late Miocene. The broad time boundaries of this period are reflective of the characteristically variable position of unconformities in archipelagic or island arc environments. The close of this period marks the latest stage of folding of the upper crustal material in the Philippines.

The Late Miocene/Pliocene-Recent period is represented by the undeformed cover. It includes the widely distributed lava flows and pyroclastics in the volcanic cones and their immediate vicinities in the mobile belt. These Late Miocene-Recent volcanic rocks are mainly andesitic but basaltic and rhyolitic facies are also present here and there. The olivine basalt mantle of the Bukidnon Plateau, in central Mindanao, is notable. Also included in this tectonic stage are the widespread reefal limestone deposits in Central Visayas and many of the coastal areas in the archipelago.

For spatial consideration, the magmatic belts, ophiolitic belts and areas of Carboniferous to Early Jurassic basement are believed to be the important tectonic elements in the analysis of Philippine metallogenesis (Fig. 3). These are of particular significance in the light of currently held opinion by many geoscientists that the Philippines have evolved by coalition of several trench-arc systems at the boundary of the Pacific and Eurasian plates. The present knowledge on the geometry and evolution of present-day trench-arc systems and marginal sea basins (KARIG, 1971a, b; HILDE and WAGEMAN, 1973) should make the identification of magmatic belts effective. The identification of ophiolite belts, on the other hand, could be effective if the nature and time of emplacement of ophiolites in the archipelago can be determined. It should be kept in mind that ophiolites could be generated in several possible environ-

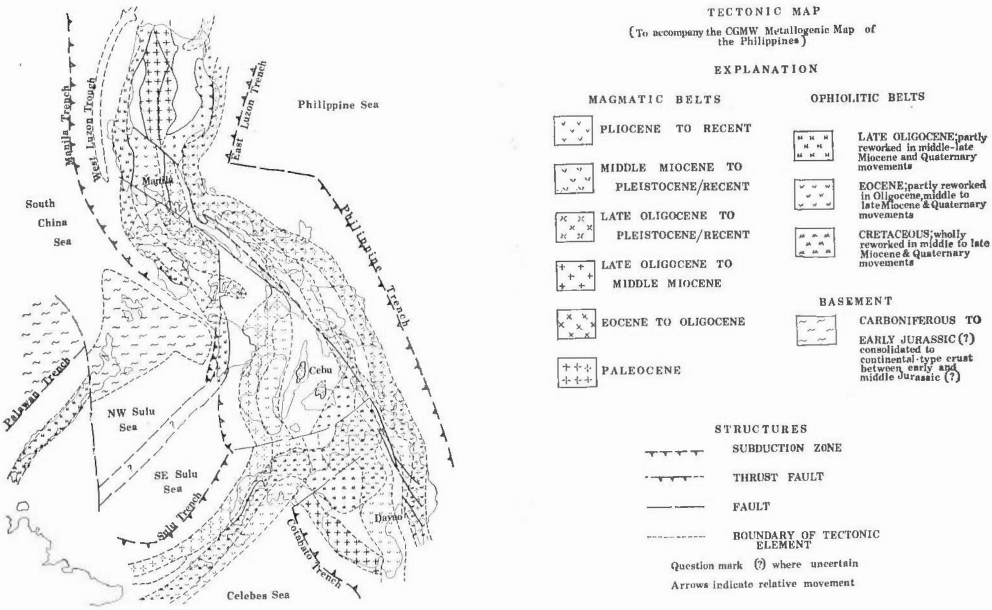


Fig. 3 Tectonic map of the Philippines

ments, i.e., spreading mid-ocean ridges, back-arc basins, ridges of tholeiites, intraplate volcanic centers and "leaky transform faults" (HAWKINS, 1979). Belts of ophiolites obducted at subduction fronts from oceanic crust, formed in normal spreading ocean basins or in back-arc basins, and those developed from island arc tholeiitic magma are particularly of great importance because they should presumably form the frontal zone or arc, paired with calc-alkaline magma zone or arc in an ideal subduction-arc system. The fact that petrological data in the Philippines are scarce, seriously limits the interpretation. But, this should not prevent us from making assumptions if only to make a preliminary identification of discernible patterns of tectonic and, for that matter, metallogenesis.

## Continental Basement Distribution

Continental basement, consolidated in Early Jurassic occurs in a fairly limited area; in the Reed Banks, the northern segment of Palawan physiographic province or the Palawan-Cuyo platform, in Central Mindoro, Romblon Island Group, Buruanga Peninsula and possibly Zamboanga. These areas significantly surround the Sulu Sea. It can be speculated that they were once a part of one continental mass.

## Paired Subduction Zone-Magmatic Belts

The presence of several paired subduction zone-magmatic belts developed in the Quaternary is one of the strongest argument that the archipelago is indeed a product of collision of several trench-arc systems. These paired belts are: 1) Manila Trench/ Central Luzon volcanic belt; 2) Sulu Trench/Negros-Sulu to Zambcanga volcanic belt; and 3) Philippine Trench/Bicol-Mindanao Central Cordillera volcanic belt. Other pairs that are more speculative are the East Luzon Trench-Sta. Ana volcanic belt and the Cotabato Trench/Daguma volcanic belt and the Palawan Trench/Cagayan de Sulu volcanic belt. At least, between the Philippine Trench and Sulu Trench systems, the collision of two converging trench-arc systems is evident. That between Manila Trench and East Luzon Trench systems, and between Cotabato Trench and Philippine Trench systems could also be justified. The Philippine mobile belt, during the Quaternary could therefore be regarded as a region of collision between trench-arc systems of opposite polarity.

In this respect, the Palawan Trench is the only present-day trench without any identifiable magmatic belt pair. However, the absence of present-day seismicity associated with it precludes any subduction activity at present and therefore also present-day magmatism in this region. It might be speculated, nonetheless, that the presumably Late Miocene to Pliocene volcanic piles in Cagayan de Sulu Island and those at the southwestern tip of Mindoro and Cuyo Island group constitutes a Late Miocene-Pliocene magmatic belt related to subduction along Palawan Trench at that time.

## Paired Ophiolitic-Magmatic Belts

As pointed out earlier, coeval belts of ophiolites and calc-alkaline magmatism could lead in the determination of trench-arc polarity especially in older geological periods. The identifiable pairs are: (1) Ilocos to Mindoro ophiolite belt-Luzon Central Cordillera to Marinduque magmatic belt; (2) eastern ophiolite belt-western magmatic belt of northern Sierra Madre; and (3) Antique ophiolite-Negros to Zamboanga magmatic belt.

The pair of Ilocos to Mindoro ophiolite belt-Luzon Central Cordillera to Marinduque magmatic belt almost coincides with the pair of Manila Trench-Central Luzon volcanic belt. The Ilocos to Mindoro ophiolite belt includes Zambales, and its emplacement is evidently Late Oligocene. This age of emplacement coincides with the initial age of calc-alkaline dioritic-granodioritic batholiths and equivalent volcanic piles in Luzon Central Cordillera, southern Sierra Madre and Marinduque which constitute a magmatic belt from Late Oligocene to Pleistocene.

The eastern ophiolite belt-western magmatic belt pair in northern Sierra Madre are of Eocene initiation. The upthrusting of the eastern ophiolite belt can be of the same age as the metamorphism of the co-tectonic greenschists which could be adequately dated as Late Eocene-Oligocene because of the Early Eocene of the upper limestone portion of the metamorphosed sequence (HASHIMOTO *et al.*, 1978). This coincides with the known K-Ar ages of the gabbroic-granodioritic batholiths in the western belt.

The Antique ophiolite belt-Negros to Zamboanga magmatic belt pair coincides with the Quaternary Sulu Trench-Negros to Zamboanga volcanic belt pair. The Antique ophiolite belt although confined to Antique Range could extend to the offshore ridges immediately east of Sulu Trench (Gulfrex Seismic Reflection Profiles, in Bureau of Mines file). Recent geological mapping and tectonic analysis of Antique Range show that the ophiolites there were initially emergent during the Late Oligocene. This corresponds to the age of the thick Late Paleogene welded tuff and andesitic-basaltic lava flows in central Negros Island and elsewhere in Zamboanga. Actually, volcanism and plutonism in the Negros to Zamboanga belt had been intermittent from this time to Pleistocene/Recent. The second upthrusting of the Antique ophiolite during the Late Miocene marked the beginning of renewed magmatic activity in the Negros to Zamboanga magmatic belt.

## Mixed Ophiolitic-Magmatic Belts

Migration of trench-arc elements should naturally result in mixed belts as exemplified by the ophiolitic Zambales Range which is superimposed at the eastern flank by Quaternary volcanism. It is presumable that magmatism and ophiolite generation in island arcs could naturally coincide if the magmatism is of the tholeiitic-type and the ophiolite generation is of the island arc tholeiite-type. In order to differentiate between the two modes of development, petrological data are evidently necessary and coeval relationship between ophiolite generation and plutonism-volcanism should be established. The paucity of petrological data is therefore a great obstacle in the discrimination of the mode of development of mixed ophiolitic-magmatic belts in the Philippines.

The most prominent belt of this type is that from Polillo to eastern Davao. Here the ophiolites were initially emplaced evidently before Eocene. The dioritic-granodioritic plutons were emplaced during Eocene(?)-Oligocene and Middle-Late Miocene. The Middle to Late Miocene plutons could not be therefore considered as coeval to the ophiolites. The Eocene(?)-Oligocene age of emplacement of plutons in Paracale, Camarines Norte and Polillo, is doubtful because of the K-Ar date of 16 m.y. for Paracale. They could not be coeval with the ophiolites because they actually intrude the ultramafic complex without any sign of the gabbro facies found in the Late Oligocene plutons of Zambales Range which are probably of tholeiitic parentage.

## Unpaired Magmatic Belts

The Late Oligocene-Middle Miocene magmatic belt from Negros to Zamboanga and the Early Miocene magmatic belt of Daguma Range are two prominent magmatic belts with no ophiolitic belt pair. Although it is possible that the Antique ophiolite belt was present during the Paleocene, it can be argued that in fact it was not existent because there is not any sign of it now. This does not however negate the possibility that the Masbate-Zamboanga magmatic belt at that time was actually related to an eastward subducting trench at about the present site of Sulu Trench. As in the Marianas, it is not always necessary that an ophiolitic belt be present between the magmatic belt and the trench (Karig, 1971b). The same is true in the case of the Early Miocene plutonism in Daguma Range which could as well be related to subduction along Cotabato Trench.

## Unpaired Ophiolite Belts

The ophiolite belt of southern Palawan, and the presumably Cretaceous ophiolite belt from Tawi-tawi to Leyte cannot be justifiably paired with any magmatic belt. However, the reason for the absence of a magmatic belt pairable to the southern Palawan ophiolite is perhaps because it is submerged offshore in the Philippine

Territory. If this belt is projected to Sabah, then the corresponding magmatic belt is noticeably west of the ophiolite belt. In the case of the Tawi-tawi-Leyte ophiolite belt, which presumably connects to the Cretaceous ophiolite belt from Java through eastern Borneo, the Paleocene diorite-granodiorite batholiths in Cebu and Bohol could be a segment of its magmatic belt pair.

### General Tectonic Framework

Based on the above analysis, the Philippines is believed to have evolved from an Early Jurassic continental massif presumably connected originally with the Indosinian (BURTON, 1972) in Borneo, Malaysia and Indochina. This continental massif was broken up with the formation of South China Sea and Sulu Sea, and perhaps even Celebes Sea. In the early Paleogene, subduction zones formed at ocean-ocean junctions in the western side of Philippine Sea where the oceanic crust migrated west-northwestward. At certain times subduction zones dipping eastward were present at the eastern borders of South China Sea, Sulu Sea and Celebes Sea. Opposite sense of movement of the subduction zones from the Pacific plate, on the one hand, and the Eurasian plate, on the other, resulted in the coalition of at least four trench-arc systems now forming the Philippine mobile belt, i.e., 1) Manila, 2) Sulu, 3) Cotabato and 4) Philippine trench-arc systems. Another trench-arc system is in Palawan-Borneo area which has been inactive since Pleistocene.

## METALLIC ORE RESOURCES

The Philippines is one country fortunate enough to be endowed with relatively vast and varied metallic resources (Table 1). In 1978, it ranked 4th in world production of gold, 9th in copper and contributed 5.9% of the world total chromite production. It produces also nickel, zinc, lead, silver, molybdenum, platinum, manganese, iron and cadmium. A summary of Philippine metallic mineral resources as of December 1978 is shown in Table 1. The bulk of the reserves, in terms of ore in place, including speculative reserves, are: 1. copper; 2. nickel, iron and aluminum in laterite; 3. gold and silver; and 4. chromite, in that order of decreasing volume.

## MINERAL COMMODITY GROUPS

Considering the association of economic mineral commodities, Philippine ore deposits may be classified into the following commodity groups: Group I-copper-gold (Ag, Pb, Zn, Mo, Fe); Group II-chromite-nickel (Cu, Co, Pt, Fe, Al); Group III-manganese. Group I includes copper and gold as major commodities; while silver, lead, zinc, molybdenum and iron which are, in general, merely associated with copper and gold are minor commodities. Group II includes chromite and nickel as major commodities; with copper, cobalt, platinum, iron and aluminum as minor commodities. Group III includes only manganese which occurs as lone commodity in the deposit with the exception only of those in northern Sierra Madre.

Figure 5 shows the distribution of the mineral commodity groups. In general, Group I deposits are concentrated in the central physiographic province of the Philippine mobile belt and Group II deposits are concentrated in the eastern and western physiographic provinces of the PMB and in southern Palawan. There are, however, significant overlappings of the two groups, particularly in Zambales Range, Antique Range, Zamboanga Peninsula, Mindanao Central Cordillera, Samar Island

Table 1 Philippine metallic ore resources as of December, 1978

| Commodity | Identified Reserves | | Hypothetical/ Speculative reserve (in millions of of metric tons) |
|---|---|---|---|
| | Quantity (in millions of metric tons | Grade | |
| Gold | | | |
| Primary | 169.17 | 0.194–19.18Gm Au/MT | 475.00 |
| By-product | 834.70 | 0.150–20.57Gm Au/MT | 4,050.00 |
| Copper | 3,657.29 | 0.50–32.62%Cu | 30,000.00 |
| Chromite | | | |
| Refractory | 7.01 | 27.14–38.00%$Cr_2O_3$ | 54.70 |
| Metallurgical | 10.25 | 10.00–52.30%$Cr_2O_3$ | 66.80 |
| Iron (Lump ore) | 71.10 | 10.00–71.00%Fe | 52.10 |
| Laterite iron ore | 3,513.32 | 20.00–44.98%Fe | 1,408.00 |
| Aluminous Laterite ore | 292.01 | 40.65–41.64%Fe | |
| Magnetite sand | 155.82 | 17.29–65.38%Fe | 37.50 |
| Lead | 6.49 | 0.26–2.5%Pb | — |
| Manganese | 1.50 | 0.65–56.31%Mn | — |
| Cadmium | .05 | 0.01%Cd | — |
| Platinum | .94 | 0.08Oz/MT | — |
| Molybdenum | 71.00 | 0.01–1.52%Mo | — |
| Mercury | 15.90 | 0.05–2.89lbs Hg/MT | — |
| Uranium | .09 | 0.04%$U_3O_8$ | — |
| Nickel | 1,366.12 | 0.23–2.40%Ni | 4,500.00 |
| Zinc | 10.52 | 0.40–7.28%Zn | — |

Source: Bureau of Mines 1978; "Forum of Philippine Mineral Wealth" Natural Resources Management Center, Ministry of Natural Resources, 1978.

and the northern segment of Eastern Mindanao Ranges.

In terms of the tectonic belts discussed previously, Group I deposits are confined to the magmatic belts while Group II deposits are confined to the ophiolite belts. Group III, manganese deposits, are present in the two tectonic belts as well as in the basement.

## GENETIC TYPES

Philippine ore deposits can be further classified into genetic types, considering form, mode of formation, lithologic environment, occurrence, special chemical and mineralogical characteristics and, more particularly, established genetic types considered of significance in relation to geology and tectonics. Depending on whether or not they occur in the place where they were originally formed, these genetic types fall under two general classes: 1) in situ and 2) residual and transported.

Residual and transported deposits in the Philippines include the following types: (1) Ni-Fe-Co laterite, (2) aluminous laterite and bauxite; (3) residual chromite; (4) chromite beach sand; (5) residual iron; (6) magnetite beach sand; (7) placer gold and (8) residual manganese. The first four deposit types are limited to the ophiolite belts. In contrast, types 5, 6 and 7 are limited to the magmatic belts. Type 8, residual manganese, is not restricted in occurrence, but they are generally of negligible quantities. They form by concentration of manganese oxide in weathering zones, particularly over exposed manganiferous sediments and volcanic rocks.

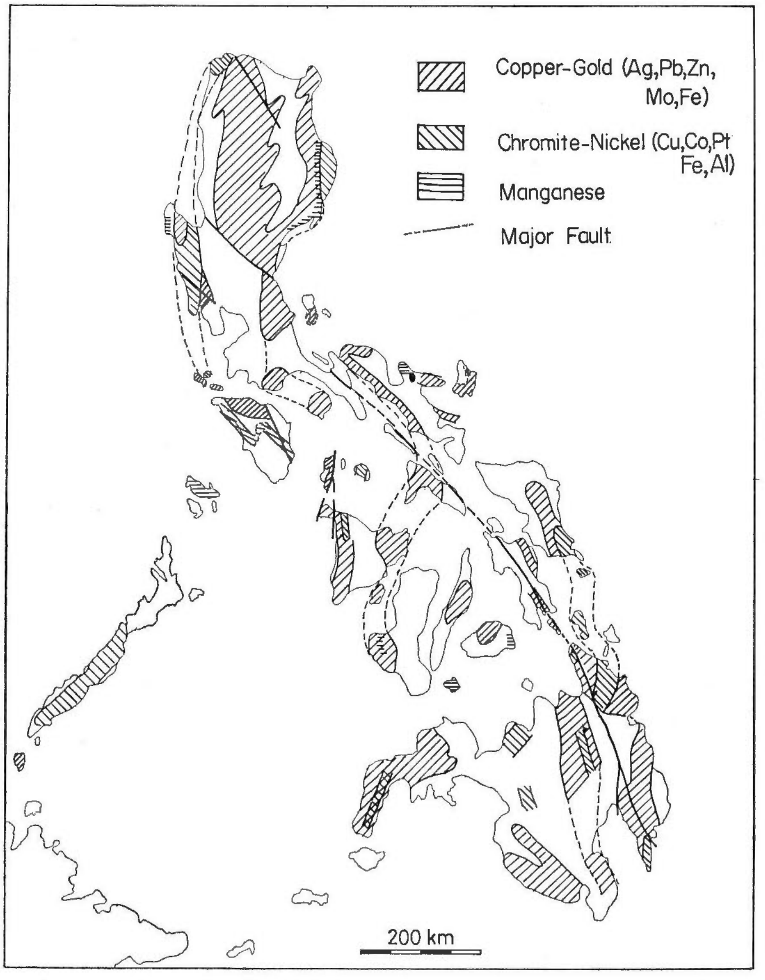


Fig. 5. Distribution of mineral commodity groups (in situ deposits)

The genetic types of in situ deposits in the country are shown in Table 2. Under Group I-copper-gold (Ag, Pb, Zn, Mo, Fe) are: 1) porphyry copper; 2) Cyprus-type; 3) kuroko-type; 4) Besshi-type; 5) luzonite-enargite bearing massive sulfide veins; 6) contact-metasomatic massive Cu-Zn-Pb-Au-Ag sulfide deposits; 7) lead-zinc veins; 8) other unclassified massive sulfide deposits; 9) native copper in basalt; 10) mixed oxide-sulfide type of contact metasomatic Fe-Cu/Fe deposits; 11) oxide type contact metasomatic Fe-Cu/Fe deposits; 12) vein-type gold deposits and 13) disseminated gold deposits. Under Group II-chromite-nickel (Cu, Co, Pt, Fe, Al) are: 1) metallurgical chromite; 2) refractory chromite; and 3) nickel sulfide. Under Group III-manganese are: 1) bedded-type; 2) bog-type and 3) vein-type.

Table 2 Genetic types of in situ deposits in the Philippines.

GENETIC TYPES OF IN SITU DEPOSITS IN THE PHILIPPINES

COPPER-GOLD (Ag,Pb,Zn,Mo,Fe) GROUP
- PORPHYRY COPPER
- MASSIVE SULFIDES
  - CYPRUS-TYPE
  - KUROKO-TYPE
  - LUZONITE-ENARGITE BEARING VEINS
  - CONTACT METASOMATIC Cu-Zn-Pb-Au-Ag
  - LEAD-ZINC VEINS
  - BESSHI-TYPE
  - OTHERS
- NATIVE COPPER IN BASALT
- CONTACT METASOMATIC Fe-Cu / Fe
  - MIXED OXIDE-SULFIDE
  - OXIDE ONLY
- GOLD
  - VEIN-TYPE
  - DISSEMINATED

CHROMITE-NICKEL (Cu,Co,Pt,Fe,Al) GROUP
- CHROMITE
  - METALLURGICAL
  - REFRACTORY
- NICKEL

MANGANESE GROUP
- BEDDED-TYPE
- BOG-TYPE
- VEIN-TYPE

## AGE DISTRIBUTION OF ORE DEPOSITS

The temporal distribution of Philippine ore deposits is best perceived if considered in relation to the previously discussed tectonic stages (Fig. 2).

In the Carboniferous-Early Jurassic (?) stage, only bedded manganese, Besshi-type massive copper sulfide deposits, and possible contact metasomatic iron deposits are known. The bedded manganese deposits occur in the Late Triassic chert-jasperoid fine clastic sequence of Busuanga Island and Buruanga Peninsula. They are generally low-grade and their economic viability depends largely on secondary concentration along fault breccias crossing the manganiferous deposits where grades of 50% Mn and higher are commonly found. The Besshi-type massive copper sulfide deposits are found in Mindoro and Lubang Islands. That in Rapu-rapu and Caramoan Peninsula, in Bicol, could belong to this stage if the host metamorphic rocks would prove to be of pre-Early Jurassic age, inspite of the Oligocene K-Ar date of those metamorphic rocks. They occur as chalcopyrite-pyrite-sphalerite lenses and stringers, usually of negligible amounts, following stratification and foliation in chlorite-actinolite-epidote-quartz-albite greenschist. The contact metasomatic iron deposits in central Mindoro Island may be included in this stage if the related diorite-granodiorite intrusives there should prove to be pre-Middle Jurassic.

In the Middle Jurassic-Oligocene stage, the deposit types represented are metallurgical and refractory chromite, nickel sulfide, bedded manganese, kuroko-type, Cyprus-type, prophyry copper, and possible Besshi-type deposits if the Rapu-rapu and Caramoan metamorphic hosts of massive sulfides would prove to be of Middle Jurassic to Oligocene age. All the metallurgical and refractory chromite, and nickel sulfide deposits in the Philippines are of this stage naturally because the ophiolite hosts are known to have formed at this time. Their distribution is shown in Figure 6.

The kuroko-type deposits of this stage is represented by the massive chalcopyrite-sphalerite-pyrite-tennantite-galena deposit in Dupax, Nueva Vizcaya (Fig. 7). The host formation is the Cretaceous-Eocene Caraballo formation II (MMAJ-PBM, 1977) which is composed of amygdaloidal basalt lavas, dark green basaltic tuff breccia and alternations of tuffaceous shale and sandstone. The ore occurs in discontinuous irregular masses, with internal colloform texture and breccia-structure, in soft white

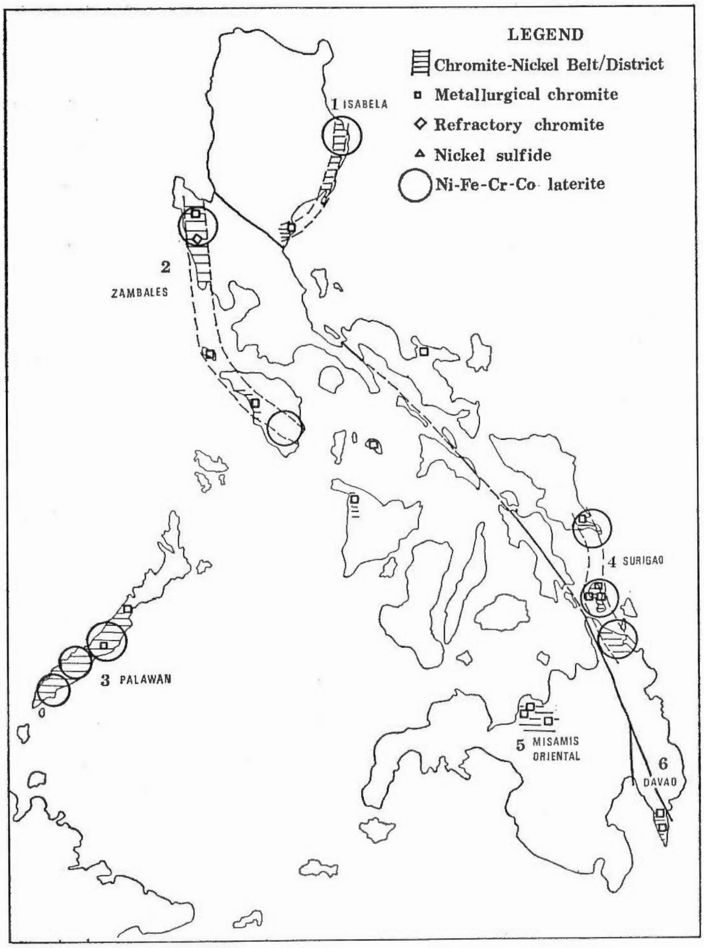


Fig. 6. Distribution of chromite-nickel deposits

to green gray hydrothermal mud together with white silica masses, possibly, after siliceous sinter. Zoning of massive pyrite, massive chalcopyrite-pyrite with small amounts of black sphalerite, and massive sphalerite-chalcopyrite masses is discernible. Red mudstone almost always covers the sulfide-bearing zone and, in turn, the mudstone is overlain by non-hydrothermally altered gray to green claystone, siltstone, sandstone and light colored tuff breccia. The deposit is evidently volcano-exhalative. Although most of the volcanics and pyroclastics in the host formation is basaltic, it can be classified as kuroko-type and not Cyprus-type because the deposit does not come close to pillow basalts and the host formation is not ophiolitic. Similar deposits in the same rock formation are found in San Mariano, Isabela. The scarce information about these deposits serves to classify them as kuroko-type deposits.

All the Cyprus-type deposits known in the country are of this stage. Their locations are shown in Figure 7. The major localities are Zambales Range, Antique Range, Balabac Island and eastern Leyte. The Barlo deposit in northern Zambales Range is the most representative of this type of deposit. It is a massive pyrite-chalcopyrite-sphalerite-bornite-tetrahedrite-tennantite ore occurring as lenticular bodies in the so-called "boulder gouge" zone, composed of hydrothermal clay, with boulders of silicified

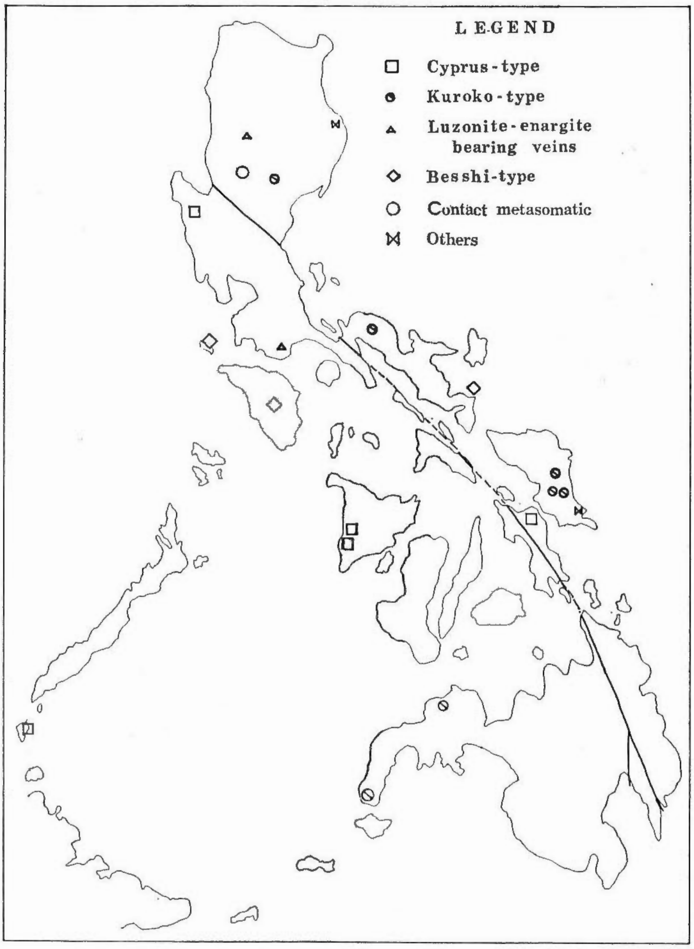


Fig. 7. Distribution of massive sulfide deposits

volcanic rocks and sulfides filling spaces in pillow basalt lavas. Eocene chert and pelagic sediments are present in the hanging wall of the deposit. The Cyprus-type deposits in Antique are thrusted bodies of massive pyrite-sphalerite-chalcopyrite-chalcocite conformable to bedded Cretaceous red chert at the tops and amygdaloidal pillow basalt at the bottoms. Calcite, gypsum and silica are the gangue minerals. In Balabac, the massive sulfide deposits in Cretaceous-Paleogene strata are composed of chalcopyrite, pyrite, bornite, and sphalerite (JOHN, 1963). It was classified by TAYLOR and HUTCHISON (1978) as Cyprus-type. In eastern Leyte, the Cyprus-type deposit is composed of pyrite, chalcopyrite, galena, sphalerite and chalcocite occurring together with foliated metamorphosed red cherty shale, pillow basalts and metasediments.

The poryphyry copper deposits of this stage are limited to central Visayas, but they constitute the giant porphyry copper deposits in the country (Fig. 8). Included are the Atlas Mine deposits in Toledo, Cebu; Sipalay, Hinobaan, Basay and several other deposits under exploration in southwestern Negros; and many indications in Guimaras Island, eastern Panay, and Bohol. The age of these deposits is presumably Paleocene, following the 59 m.y. K-Ar age found on the Guimaras and Toledo diorites.

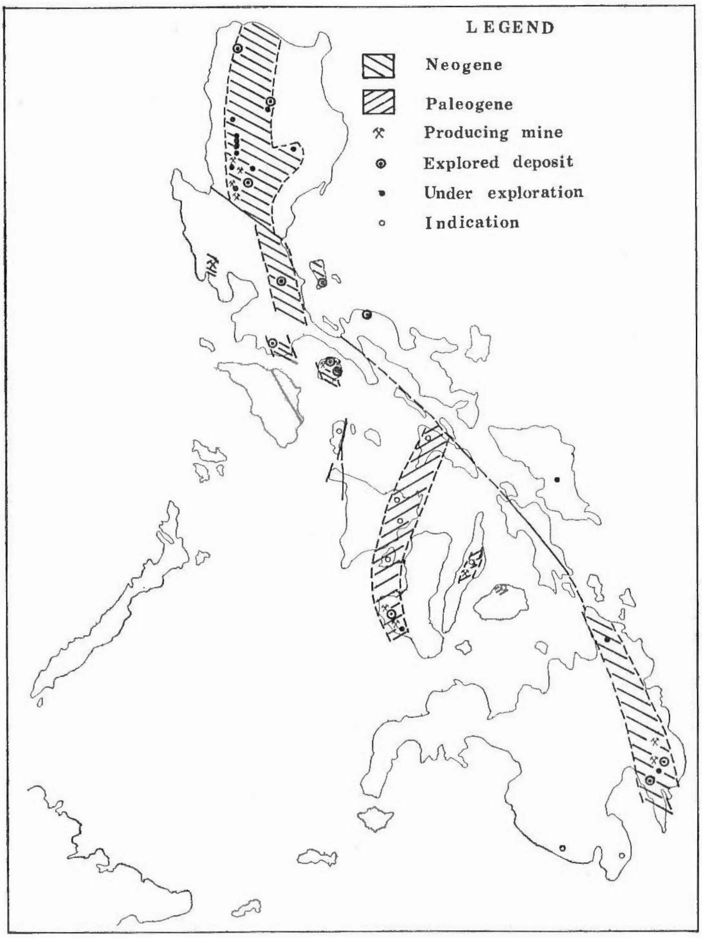


Fig. 8. Distribution of porphyry copper deposits

In the Late Oligocene/Early Miocene-Late Miocene/Pliocene stage, the ore types represented are porphyry copper, kuroko-type, luzonite-enargite bearing massive sulfide veins, contact metasomatic Cu-Zn-Pb-Au-Ag and Fe-Cu/Fe, and both vein-type and disseminated gold.

The porphyry copper deposits of this stage are distributed in Luzon, Marinduque and eastern Mindanao. There are indications in Samar, Cotabato, Bukidnon, Misamis Oriental and northern Zamboanga (Fig. 8). The belts from Luzon Central Cordillera to Marinduque and that in eastern Mindanao are distinctive. The only major deposit that is not included in these belts is the Dizon deposit in southern Zambales Range.

The deposits in Larap, Camarines Norte and Polillo Island probably belong to the eastern Mindanao belt. These two porphyry copper deposits are, however, exceptional because of their high molybdenite content.

The kuroko-type deposits of this stage include those in Samar Island, Camarines Norte, southern Sierra Madre, Zamboanga Peninsula and northeastern Mindanao (Fig. 7). All of them are associated with dacitic volcanics and pyroclastic rocks formed in Middle-Late Miocene. The only deposit being mined at present is the Bagacay deposit in central Samar. The ore is massive pyrite, chalcopyrite, sphalerite,

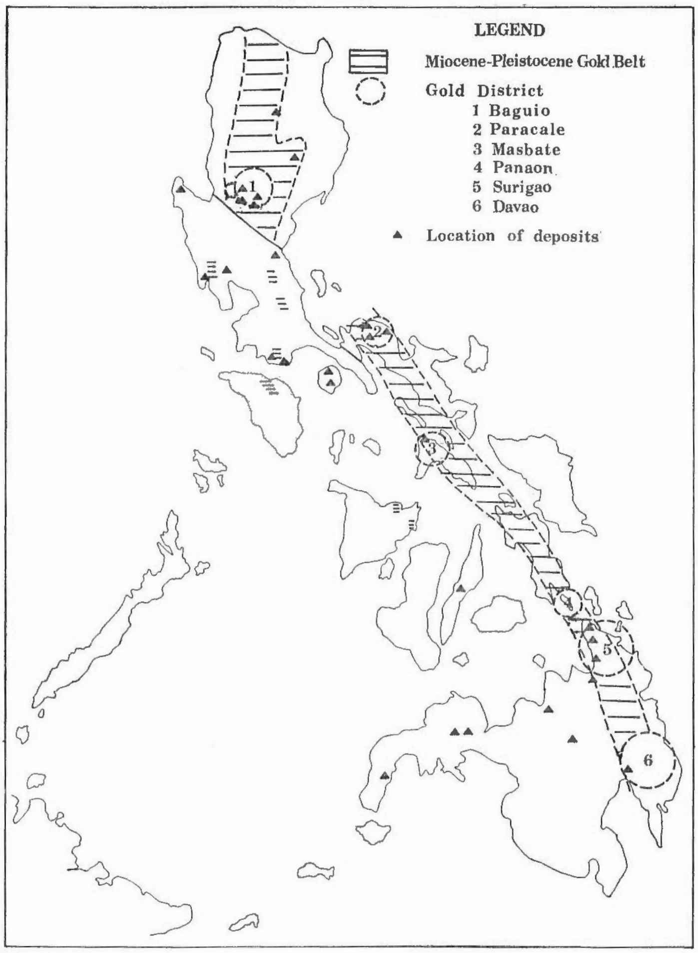


Fig. 9. Distribution of gold deposits

galena, tetrahedrite, tennantite and bornite with gangue minerals of barite, gypsum and calcite. Colloidal texture is common. Red mudstone is present on top of the sulfide deposit. Basaltic dikes and sills are common near the deposit.

The luzonite-enargite bearing massive sulfide veins in Mankayan, Benguet and Lobo, Batangas are the only deposits of this type known in the Philippines. Both are Pliocene in age. The Mankayan deposit of Lepanto Consolidated Mining Co. Inc., is principally enargite and luzonite with tennantite, pyrite, chalcopyrite, native gold, silver tellurides, hessite, calaverite (?) and krennerite (?) (GERVASIO and FERNANDEZ, 1967; GONZALES, 1956). The gangue minerals are barite and quartz. The ore is massive irregular vein with recognized replacement features. The host rock is a series of basaltic to latitic lavas and pyroclastics. The deposit in Lobo, Batangas is composed of chalcopyrite, bornite, chalcocite, tetrahedrite, pyrite, enargite and luzonite. Barite is the principal gangue. The host rock is andesitic to trachytic volcanics (TUPAS, 1960).

Another type of deposit in this stage is contact metasomatic copper-zinc-lead-gold-silver. It occurs only in the Thanksgiving Mine in Benguet. The orebody is at the contact zone between Late Miocene diorite porphyry and Middle Miocene limestone. The ore minerals are sphalerite, chalcopyrite-pyrite, cubanite, magnetite, pyrrhotite, gold and Au-Ag tellurides (BALCE, 1978; CALLOW, 1967; CALLOW and WORLEY, 1965).

Contact metasomatic Fe-Cu/Fe deposits are of two sub-types: a) those containing oxide only and b) those containing mixed oxide and sulfides. The first sub-type includes the deposits in Lamin, Ilocos Norte; Talamban, Cebu; Masara, Davao; and Sibuguey district, Mindanao. They are massive magnetite-hematite deposits in contact with metamorphic garnet-pyroxene-epidote skarn along Middle Miocene diorite contacts. The second sub-type includes the deposits in Sta. Ines, Rizal; Larap, Camarines Norte; and Marinduque Island. The Larap deposit is representative. It consists principally of massive magnetite-hematite with minor chalcopyrite, pyrite, and molybdenite. It grades downward to disseminated magnetite-chalcopyrite-pyrite-molybdenite ore which is classified as porphyry copper-type. The deposits in Marinduque Island also led to the porphyry copper deposits of Ino-Capayang. The Sta. Ines deposit has indications of leading also to porphyry copper.

Most of the vein-type and disseminated gold deposits are in this tectonic stage (Fig. 9). The principal ones are in Baguio, Paracale, Masbate, Panaon (Leyte) Surigao and Davao districts. It is evident that these principal areas are within the zone of the Philippine Fault and, therefore, a genetic relation is suggested. In the Baguio, Masbate, Panaon (Leyte), Surigao and Davao districts, the gold veins cross diorite and quartz diorite intrusive bodies as well as the surrounding rocks. Typically, the mineral suite of the gold-bearing veins consists of native gold, chalcopyrite, bornite, enargite, pyrite, sphalerite, galena and gold-silver tellurides; with quartz, calcite and gypsum as gangue. In the Paracale districts, Camarines Norte, the gold veins are localized in the granodiorite stock. Where the veins cross the intrusive border with serpentinized ultramafic rocks the values abruptly diminish. The ore minerals are native gold, galena, sphalerite and chalcopyrite; with quartz as dominant gangue.

The only known disseminated gold deposit in the country is in Ron-rono, Nueva Vizcaya. It occurs in dacitic-andesitic (?) lavas and pyroclastics which are intruded by Miocene monzonite (MIRANDA *et al.*, 1973). The gold dissemination is in the dacitic rocks.

Ore deposits in the most recent tectonic stage, Late Miocene/Pliocene-Recent, are limited to gold, mercury and all the residual and transported deposits. The vein-type gold mineralization in this stage is evidently a carry-over of that in the preceeding stage. This includes Baguio, Panaon, Surigao and Davao districts. The important placer gold deposits are in the river valleys of Benguet, eastern Nueva Vizcaya (Caraballo Range), Paracale, northern Mindoro, Masbate, Surigao and Davao. The only mercury deposit is in central Palawan along the transcurrent fault zone separating continental northern Palawan and the ophiolitic south. Mercury, as cinnabar, is present in vein network in hydrothermally altered ultramafic rocks and opalite.

## ORE DEPOSITS IN TECTONIC BELTS

In situ deposits in Philippine ophiolite belts are chromite, nickel sulfide, Cyprus-type massive copper-zinc-lead, mercury, bedded manganese and Besshi-type deposits. Copper and platinum group metals are minor components of nickel sulfide deposits. Where the ophiolite belts are overlapped or superimposed by magmatic belts, porphyry copper, kuroko-type massive sulfide, contact metasomatic Fe-Cu/Fe, and even gold deposits occur together with the diagnostically ophiolitic ore deposits. This is the case with the eastern part of Zambales Range, Mindoro, Zamboanga Peninsula, Misamis Oriental, Mindanao Central Cordillera and the belt from Camarines Norte to Davao in the eastern physiographic province.

In magmatic belts, the ore deposits are extensive porphyry copper, kuroko-type, contact metasomatic Cu-Zn-Pb-Au-Ag, contact metasomatic Fe-Cu/Fe, luzonite-enargite bearing massive sulfide veins, and gold. These deposits are largely found in the central physiographic province because this region is largely covered by magmatic belts from Paleocene to Recent.

## SUMMARY

The Philippine archipelago is divided into four physiographic provinces. Eastern, central and western physiographic provinces occupy the "Philippine mobile belt," while Palawan physiographic province is in the "stable or aseismic belt." Four tectonic stages bounded by major unconformities are identified. These are: 1) Carboniferous-Early Jurassic (?) or basement stage, 2) Middle Jurassic-Oligocene, 3) Late Oligocene/Early Miocene-Late Miocene/Pliocene and 4) Late Miocene/Pliocene-Recent. The tectonic elements considered are magmatic belts, ophiolite belts and areas of the Carboniferous-Early Jurassic (?) continental basement. Paired subduction zone-magmatic belts, paired ophiolitic-magmatic belts, mixed ophiolitic-magmatic belts, and unpaired ophiolitic and magmatic belts are present.

Metallic mineral resources in the Philippines are relatively vast and varied. In 1978, it ranked 4th in world production of gold, 9th in copper and contributed 5.9% of the world total chromite production. The ore deposits are classified into mineral commodity groups: Group I-copper-gold (Ag, Pb, Zn, Mo, Fe); Group II-chromite-nickel (Cu, Co, Pt, Fe, Al); Group III-manganese. Group I deposits are concentrated in the central physiographic province of the Philippine mobile belt which is largely composed of magmatic belts. Group II deposits are concentrated in the eastern and western physiographic provinces of the PMB and in southern Palawan, which are mainly ophiolitic belts.

Genetic types of Philippine ore deposits fall under two classes: a) in situ and b) residual and transported. Residual and transported deposits in the country are of the following types: 1) Ni-Fe-Co laterite; 2) aluminous laterite and bauxite; 3) residual chromite; 4) chromite beach sand; 5) residual iron; 6) magnetite beach sand; 7) placer gold and 8) residual manganese. The first four deposit types are limited to the ophiolite belts; types 5, 6 and 7 are limited to the magmatic belts; and type 8, residual manganese, is not restricted to any belt but it occurs in only negligible quantities.

Genetic types of in situ deposits known so far are: 1) porphyry copper; 2) Cyprus-type; 3) kuroko-type; 4) Besshi-type; 5) luzonite-enargite bearing massive sulfide veins; 6) contact metasomatic massive Cu-Zn-Pb-Au-Ag sulfide deposits; 7)

lead-zinc veins; 8) other unclassified massive sulfide deposits; 9) native copper in basalt; 10) mixed oxide-sulfide type of contact metasomatic Fe-Cu/Fe deposits; 11) oxide type contact metasomatic Fe-Cu/Fe deposits; 12) vein-type gold deposits; 13) disseminated gold deposits; 14) metallurgical chromite; 15) refractory chromite; 16) nickel sulfide; 17) bedded-type manganese; 18) bog-type manganese and 19) vein-type manganese.

In the Carboniferous-Early Jurassic (?) tectonic stage, bedded manganese, Besshi-type, and contact metasomatic iron deposits are represented. In the Middle Jurassic-Oligocene stage, the deposit types represented are metallurgical and refractory chromite; nickel sulfide; bedded manganese; kuroko-type; Cyprus-type; porphyry copper; and possibly Besshi-type deposits. In the Late Oligocene/Early Miocene-Late Miocene/Pliocene stage, the deposits are porphyry copper, kuroko-type, luzonite-enargite-bearing massive sulfide veins, contact metasomatic Cu-Zn-Pb-Au-Ag, contact metasomatic Fe-Cu/Fe and both vein-type and disseminated gold. In the latest tectonic stage, Late Miocene/Pliocene-Recent, vein-type gold, mercury and all the residual and transported deposits are represented.

In situ deposits in the Philippine ophiolite belts are chromite, nickel sulfide, Cyprus-type massive Cu-Zn-Pb, mercury, bedded manganese and Besshi-type deposits. In magmatic belts the ore deposits are porphyry copper, kuroko-type, contact metasomatic Cu-Zn-Pb-Au-Ag, contact metasomatic Fe-Cu/Fe, luzonite-enargite bearing massive sulfide veins, and gold. Mixing of characteristic deposit types is due to the overlapping or superimposition of the two tectonic belts. Most of the Philippine gold deposits are along the zone of the Philippine Fault.

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# Fluid Inclusion Studies of Several Philippine Porphyry Copper Deposits*

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## ABSTRACT

Fluid inclusions in porphyry copper deposits of the Philex, Marcopper, Sipalay, Basay and Atlas mines were studied. Polyphase, gaseous and liquid inclusions were found in these deposits, but the mode of occurrence of these fluid inclusions varied from deposit to deposit, and suggested a relationship between hte hydrothermal activity and the pattern of mineralization and wall-rock alteration. A vertically extended pipe-shaped orebody was rich in high-salinity polyphase inclusions but poor in low-salinity liquid inclusions, suggesting a significant contribution of magmatic water to the formation of the ore deposit. Liquid inclusions were predominant in a laterally extended flat-lying orebody, indicating an intense activity of circulating meteoric water. Biotitization was pervasive in the former case and sericitization was overprinted on biotitization in the latter case.

## INTRODUCTION

Many porphyry copper deposits have been found along the Pan-Pacific belt, especially on the west coasts of North and South America, the Philippines, Papua-New Guinea and Solomon Islands. Besides these areas, additional occurrences are reported from Fiji, North Borneo, Celebes, Sumatra, Burma, and Kamchatsuka.

More than 25 occurrences of the porphyry copper type mineralization have been reported from Papua-New Guinea and Solomon Islands since the discovery of Panguna, Bougainville, in 1964. In the Philippines, more than ten mines are being operated at present and active explorations are progressing in many places.

The age of mineralization of these deposits in the southwestern Pacific region including the Philippines varies from Early Tertiary to Quaternary. Some of the deposits in Papua-New Guinea and Solomon Islands are very young, 1 to 3 m.y. B.P. Most of these young deposits are distributed along island arcs and the porphyry copper mineralization has been discussed from the viewpoints of the plate tectonics by MITCHELL and GARSON (1972), GUILD (1972), SILLITOE (1972), and TITLEY (1975). It is inferred that the temporal and spacial distributions of porphyry copper deposits are related to the activity of old and active subduction zones.

In Japan, however, porphyry copper-type mineralization has not been reported yet, although the islands belong to a part of island arcs. There will be a possibility to find the porphyry copper-type mineralization in Japan, but it is still uncertain whether

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or not this type of mineralization does occur in these islands.

Fluid inclusion studies of the Philippine porphyry copper deposits had not been reported. The author aimed to reveal the features of the ore-forming fluids of porphyry copper dposits in the Philippines by means of the fluid inclusion study (IMAI *et al.*, 1978; TAKENOUCHI, 1980), and to know the similarity and dissimilarity between porphyry copper deposits and hydrothermal vein-type deposits. The work, however, is in the first stage and only the mode of occurrence and temperature data of fluid inclusions are reported in the present paper.

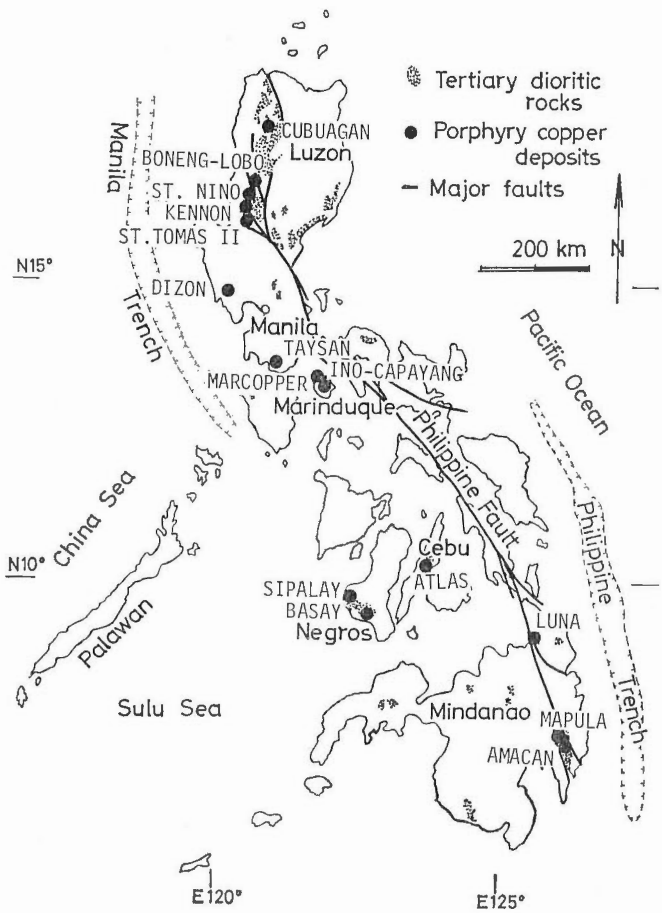


Fig. 1. Locality map of main porphyry copper deposits in the Philippines.

## PORPHYRY COPPER DEPOSITS IN THE PHILIPPINES

In the Philippines, the porphyry copper-type mineralization occurs in an intimate genetic relation with dioritic to quartz dioritic intrusives of Late Miocene or Paleocene age (WOLFE, 1972; PELTON and SMITH, 1976; MOTEGI, 1977; SAEGART and LEWIS, 1977). Ore deposits of the Paleocene group occur in the middle part of Cebu Island and in the southwestern part of Negros Island (Fig. 1). They are distributed along the eastern margin of the Stable Zone which occupies Parawan

Island and Sulu Sea. Ore deposits of the Atlas, Sipalay and Basay mines belong to this group.

Ore deposits of the Miocene group occur in the northern part of Luzon Island, Zambales Range to Marinduque Island, and eastern part of Mindanao Island. Deposits in Luzon and Marinduque Island are distributed parallel to the Manila trench which is situated to the west of Luzon Island and subducts to the east, and those in Mindanao Island are parallel to the Philippine trench which is situated to the east and subducts to the west. Ore deposits of the Philex, Marcopper and Dizon mines belong to this group.

These deposits show some common features as follows.

1) Intrusive rocks genetically related to the mineralization are quartz dioritic or granodioritic.
2) Biotitization is the major wall-rock alteration in the ore zone and chloritization is pervasive in the outer zone of a pipe-shaped orebody.
3) Sericitization is pervasive in the ore zone of a mushroom-shaped orebody.
4) Mineralization is mainly controlled by network of sulfide-bearing quartz veinlets, and dissemination of sulfides is not intense.
5) Gold content of ores is generally high in younger deposits and, in some deposits, reaches as high as 1 g/t, but molybdenum content is low. Older deposits are generally richer in molybdenum than the younger ones.

## FLUID INCLUSIONS IN PORPHYRY COPPER DEPOSITS

The general patterns of mineralization and wall-rock alteration of porphyry copper deposits in the southwestern United States are given by LOWELL and GUILBERT (1970). The wall-rock alteration is classified to potassic, phyllic, argillic and propylitic zones from the center of mineralization to the periphery, and the high grade ore shell is located around the boundary between the potassic and phyllic zones.

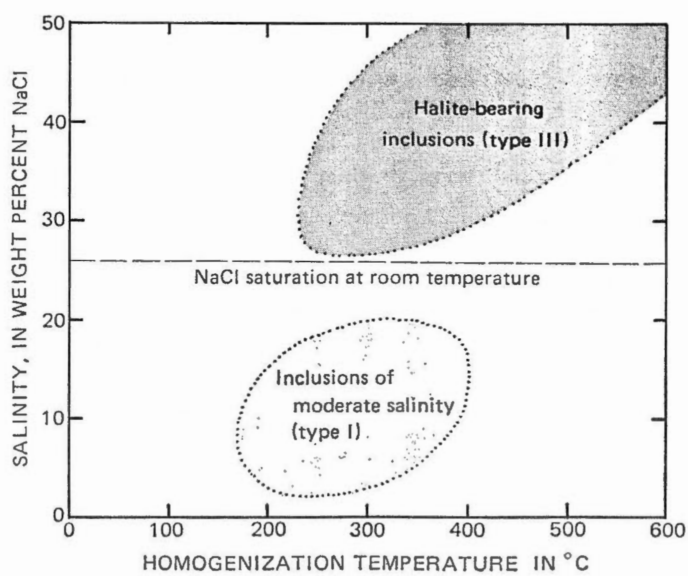


Fig. 2. General scope of temperature and salinity of fluid inclusions found in porphyry copper deposits (NASH, 1976).

Fluid inclusions from many porphyry copper deposits in the United States have been studied in connection with the mineralization and wall-rock alteration. According to NASH (1976), fluid inclusions of porphyry copper deposits are classified into three groups, that is, (I) liquid inclusions of high densities and various homogenization temperatures (II) gaseous inclusions having low and various degrees of filling, and (III) polyphase fluid inclusions of high salinities and high homogenization temperatures (Fig. 2).

Polyphase inclusions commonly contain a cubic crystal of halite and, in many cases, of sylvite. Besides these crystals, anhydrite, hematite and opaque minerals are reported in inclusions of this type. They are primary, pseudo-secondary and secondary in origin, and show shapes of negative crystal or simpler forms.

Gaseous inclusions often occur associated with polyphase inclusions, indicating "boiling phenomena" of solutions. They occur also as clouds or groups distributed along planes, suggesting gas-prevailing environment. Shapes of negative crystal predominate in this type of inclusion.

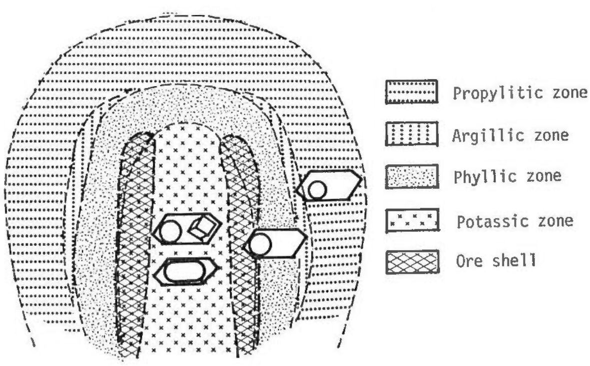


Fig. 3. Schematic figure showing the distribution of fluid inclusions and zoning of wall-rock alteration of porphyry copper deposits (Redrawn from LOWELL and GUILBERT, 1970).

Liquid inclusions of many stages occur along various planes reflecting introduction of solutions during repeated fracturing. They are generally associated with propylitic or sericitic alteration, or with relatively late-stage ore veins.

Distribution of these three types of fluid inclusion in porphyry copper deposits is systematic. Polyphase inclusions predominantly occur in the potassic core zone, often with gaseous inclusions. On the other hand, liquid inclusions predominate outside the ore shell (Fig. 3).

Stable isotope studies of water in minerals and fluid inclusions of porphyry copper deposits revealed that the core contained fluids rich in the heavy water which was in contact with magmas or rocks at high temperatures, while the outside of the ore shell contained much of the light water of the meteoric origin (SHEPPARD and TAYLOR, 1974; HALL *et al.*, 1974; SHEPPARD and GUSTAFSON, 1976; BATCHELDER, 1977).

Therefore, it is inferred that the fluids responsible for mineralization and wall-rock alteration of porphyry copper deposits would have been formed by mixing of high-temperature and high-salinity fluids of magmatic origin and low-salinity fluids of meteoric origin.

Zoning of wall-rock alteration of some porphyry copper deposits in the Southeast

Asia is not as clear as those of the United States, possibly because of overlapping of different alterations. Fluid inclusion study is very limited in this type of deposits of the Southwest Pacific region. CHIVAS and WILKINS (1977) studied the Koloula deposit, Guadalcanal Island, and EASTOE (1978) reported the result on the Panguna deposit, Bougainville Island.

## SANTO TOMAS II DEPOSIT (PHILEX MINE)

In north Luzon, several porphyry copper deposits occur especially along the western margin of the Agno batholith which is a dioritic complex of Middle Miocene age (Fig. 4). They are the Boneng-Lobo, St. Niño, Kennon and St. Tomas II deposits on the western side of the batholith and Tawi Tawi on the eatsern side.

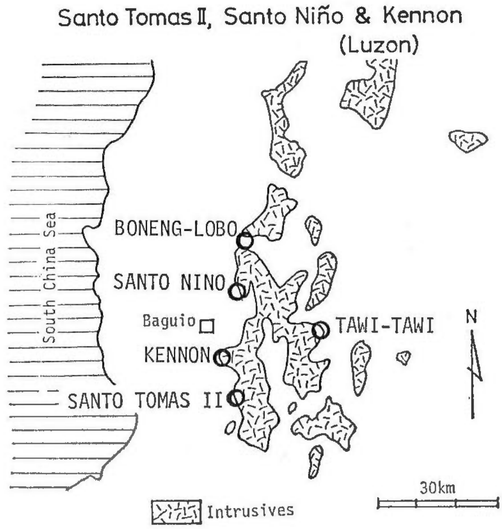


Fig. 4. Porphyry copper deposits around the Agno batholith in North Luzon.

The St. Tomas II deposit is a pipe-shaped stockwork body with quartz veinlets in a stock of Miocene diorite complex intruded into pre-Tertiary meta-volcanics (Fig. 5). The orebody has a horizontal section of 700 m (E-W) by 560 m (N-S), and extends downwards almost vertically to more than 1,000 m from the surface. The ore reserve is reported to be 120 million tons averaging 0.48% Cu and 0.93 g/t Au (RETARDO, 1972; SERAFICA and BALUDA, 1977). The stock which has a horizontal section of about 370 m (E-W) by 230 m (N-S), comprises fine-grained diorite, diorite porphyry and porphyritic andesite.

The orebody consists mostly of a network of quartz veinlets accompanied by chalcopyrite, pyrite, magnetite and some biotite. Dissemination is important in high grade ores, especially in quartz diorite. Biotitization and silicification are the main wall-rock alterations.

Quartz samples collected from the 1,190 m level contain a great number of inclusions, among which polyphase fluid inclusions of high-salinity are the most abundant succeeded by gaseous inclusions and lesser liquid inclusions. Polyphase and gaseous inclusions occur closely associated and are distributed at random, in clusters, or along curved or branched planes. The inclusions which are distributed at random, would be primary in origin, but those along curved or branched planes are evidently secondary.

Polyphase inclusions contain a large cubic crystal of halite, an intermediate-sized crystal of sylvite and occasionally a flake of hematite. In addition to the above mentioned solid phases, anisotropic and prismatic crystal, anisotropic granular crystal and opaque minerals are often recognized, but all of these smaller phases are not necessarily observed in every polyphase inclusions. Gaseous inclusions which occur intimately associated with polyphase inclusions suggest the boiling of high saline fluids. Liquid inclusions occur in irregular or tabular shapes.

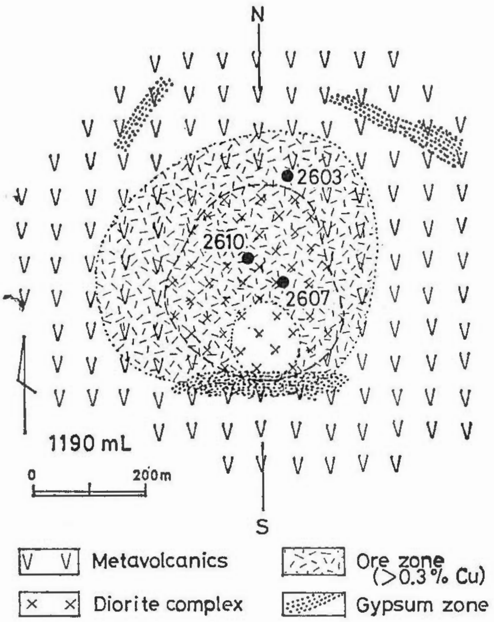


Fig. 5. Schematic geologic map at 1190 mL of the Santo Tomas II orebody of the Philex mine, and locality of samples.

Upon heating, sylvite in polyphase inclusion dissolved at a temperature between 100° and 200°C, and halite dissolved between 450° and 550°C. The temperature data are shown in Figure 6. The bubble generally disappeared immediately after the dissolution of halite, but, in some cases, it was still observed even at 600°C indicating a very high homogenization temperature. This fact shows that the boiling fluids were almost saturated with NaCl at about 500°C, and that some inclusions trapped two heterogeneous phases, that is, the gaseous and liquid phase, at their formation.

No remarkable difference was observed in the temperature data between the samples collected at the surface and the 1,190 m level.

The homogenization temperatures of liquid inclusions concentrated around 200°C, and the salinity was between 1 and 3 wt.% NaCl equivalent.

In order to know the chloride concentration of inclusion, the temperature data were plotted on the KCl-NaCl-$H_2O$ ternary phase diagram (Fig. 7; REODDER, 1971). Figure 8 shows the NaCl and KCl concentration of polyphase inclusions from the

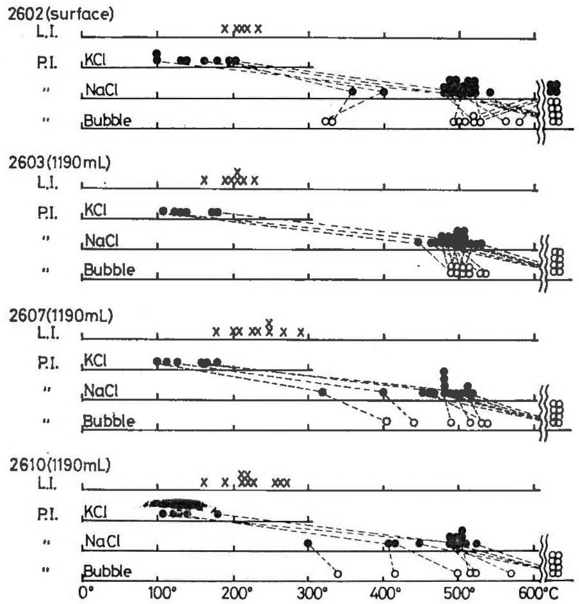


Fig. 6. Temperature data of fluid inclusions from the Santo Tomas II deposit. L.I.: Filling temperature of liquid inclusion, P.I.: Disappearance temperature of the phases in polyphase inclusion. Broken line ties the temperatures measured on the same inclusion.

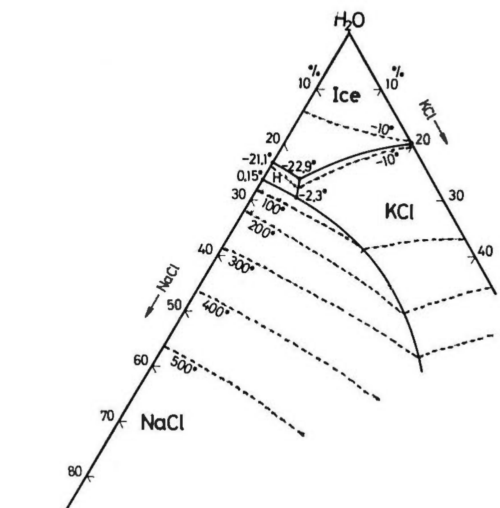


Fig. 7. KCl-NaCl-$H_2O$ ternary phase diagram (ROEDDER, 1971).

St. Tomas II deposit. The NaCl concentration distributes in a range between 30 wt.% and 51 wt.%, clustering between 43 wt.% and 51 wt.%, and the KCl concentration is in a ragne between 13 wt.% and 27 wt.%, mostly between 13 wt.% and 21 wt.%.

From the result of fluid inclusion study at the St. Tomas II deposit, it is inferred that the ore-forming fluids were high in temperature, rich in chlorides and other substances and were in the boiling condition. Predominance of polyphase and gaseous inclusions and scarcity of liquid inclusions indicate an intense activity of high-temperature boiling fluids of presumably magmatic origin at the main stages of mineralization, and feeble attacks of low-salinity hydrothermal solutions of meteoric origin at the waning stages of hydrothermal activities.

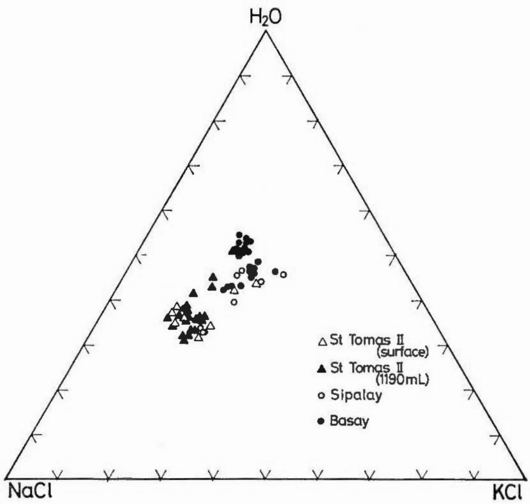


Fig. 8. NaCl and KCl concentration of polyphase inclusions from deposits of the Philex, Sipalay and Basay mines.

The vertically extended shattered zone which is centered in the diorite complex, would have been a more permeable pathway for the ore-forming fluids from the depths than the surrounding meta-volcanics. The fact that biotitization predominates over sericitization, indicates survival of potassium metasomatism caused by high-temperature hydrothermal fluids from feeble hydrogen metasomatism brought by solutions of meteoric origin. The occurrence of fluid inclusions agrees well with this observation.

## TAPIAN DEPOSIT (MARCOPPER MINE)

The Tapian deposit of the Marcopper mine occurs at the southeastern end of the Mahinhin diorite complex which occupies the center part of Marinduque Island in the NW-SE direction (Fig. 9). On the northwestern end of this complex, the Ino-Capayang deposit is located (VERGARA and TANTOE, 1977). Recently, the new San Antonio orebody was found underneath an old tailing pond, 4 km to the north of the Tapian orebody (PANGAN and MANGAOANG, 1977). The minable ore reserve is reported as 102 million tons at an average grade of 0.58% Cu and 0.34 g/t Au (LOUDON, 1976).

The geology of the Tapian deposit is reported by LOUDON (1972 and 1976). The

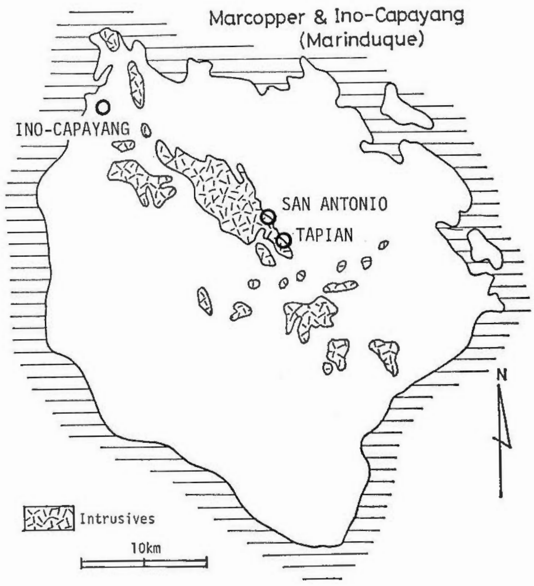


Fig. 9. Porphyry copper deposits around the Mahinhin stock in Marinduque Island.

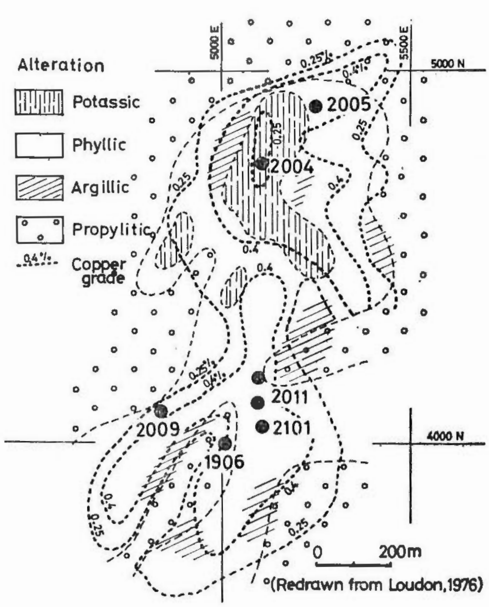


Fig. 10. Pattern of wall-rock alteration of the Tapian orebody of the Marcopper mine, and locality of samples.

Mahinhin diorite complex consisting of Middle Miocene granodiorite, quartz diorite and porphyries, is intruded into Paleocene sedimentary rocks. Ores occur mainly within the diorite complex, largely as veining and partly as dissemination. The zoning patterns of mineralization and wall-rock alteration are irregular in the horizontal plane (Fig. 10) but mushroom-like in the vertical section. The wall-rock alteration trends from an inner small potassic zone to an outer propylitic zone through a broad phyllic zone. Potassic zone is restricted to the low-grade core. Mineralization is mainly associated with silicification and sericitization. Post-ore gypsum-calcite veins occur at lower parts of the orebody.

In contrast to the St. Tomas II deposit, liquid inclusions are the most common in this deposit, followed by gaseous and small high-salinity polyphase inclusions. Liquid inclusions are generally irregular or flat in shape and distributed along curved planes or in clusters. The degree of filling varies largely suggesting a wide range of filling temperature. In some samples, inclusions are almost liquid type and polyphase inclusions are scarcely observed.

Polyphase inclusions contain the similar solid phases to those of the St. Tomas II deposit, but the volume of bubble at a room temperature is relatively small compared to the total volume of inclusion, indicating a high density of fluid at the trapping. As the size of polyphase inclusion is characteristically small, observation of polyphase inclusion in the heating-stage is very limited.

Temperature data of polyphase and liquid inclusions are shown in Figure 11. The

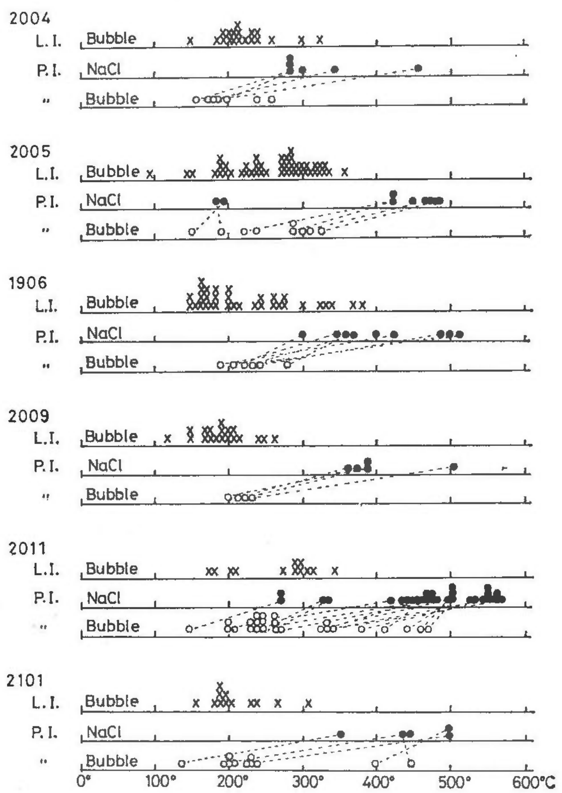


Fig. 11. Temperature data of fluid inclusions from the Tapian orebody.

disappearance temperature of halite varied from 280° to 550°C, and bubble generally disappeared at a temperature lower than halite did, in a range between 160° and 460°C. From the temperature data, salinities of polyphase inclusions are estimated to be 35–50 wt.% NaCl equivalent.

Homogenization temperatures of liquid inclusions show a bimodal distribution, that is, temperature ranges from 150° to 240°C and from 270° to 340°C. The temperature ranges are much wider and higher than that of the St. Tomas II deposit. The salinities of liquid inclusions were not determined because of their small sizes.

Many liquid inclusions are evidently secondary in origin and polyphase inclusions occur sparsely among the liquid inclusions. Scarcity of polyphase inclusions and abundance of liquid inclusions are characteristic of this deposit.

From the result of fluid inclusion study, it is inferred that hydrothermal fluids of various conditions would have been involved in the formation of the Tapian deposit, and that the activity of low-salinity solutions was so intense that most of high-salinity inclusions formed in earlier stages were flushed out and overlapped by the formation of abundant liquid inclusions. Formation of small meager potassic zones and phyllic-ore zone of irregular shapes, and development of the flat-lying top part of orebody, suggest an intense participation of circulating meteoric water to the formation of orebody, and are in good accordance with the mode of occurrence of fluid inclusions.

## CANSIBIT DEPOSIT (SIPALAY MINE)

The deposit of the Sipalay mine comprises the Cansibit, Binulig and Baclao orebodies. They are distributed along an isolated stock which is situated to the northwest of a dioritic batholith which extends in the NW-SE direction at the southwestern part of Negros Island (Fig. 12). The orebodies are found along the contact

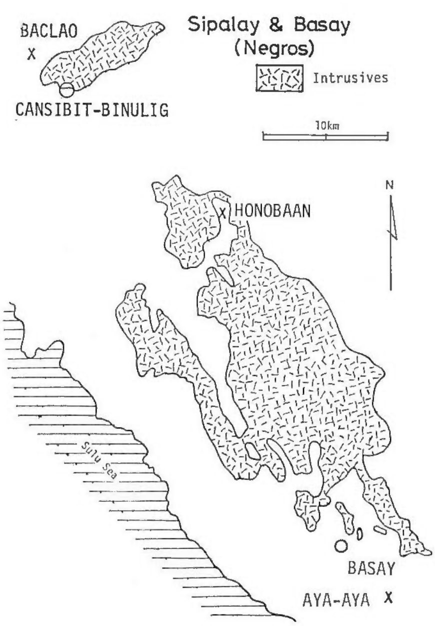


Fig. 12. Porphyry copper deposits in the southwestern part of Negros Island.

mainly in quartz diorite of Paleocene age but partly in meta-volcanics of Late Cretaceous age (Muyco, 1972). The Cansibit orebody is the largest one among the three. It takes a thick funnel-like shape and extends nearly vertically as deep as 800 m below the surface. High copper values occur in highly silicified and shattered zones with intense veining and dissemination in some parts. Low-grade core is absent. Silicification is the most intense in the central part of the orebody, and sericitization and kaolinization are observed successively outwards. In the meta-volcanics, chloritization is predominant. Quartz-gypsum veins are commonly observed in the lower part of the orebody.

Fluid inclusions in quartz from the Cansibit orebody were small in size and most of them were not suitable for the temperature measurement. Among the three types of inclusion, gaseous inclusions predominate, being succeeded by polyphase inclusions and a less number of liquid inclusions. Figure 13 shows the temperature data of polyphase inclusions.

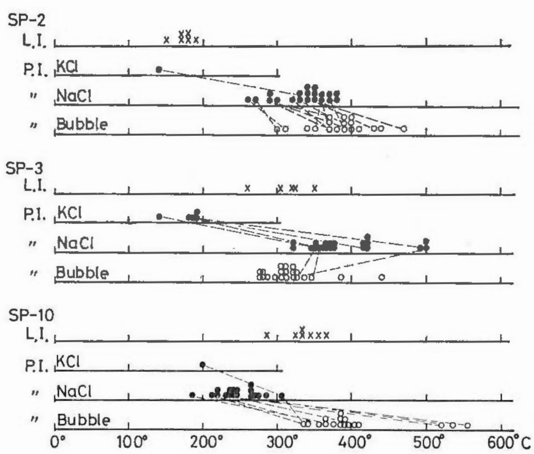


Fig. 13. Temperature data of fluid inclusions from the Cansibit orebody of the Sipalay mine.

Determination of dissolution temperature of sylvite was limited because of the small size of inclusion. Halite generally disappeared in a temperature range between 255° and 500°C, but the crystal of polyphase inclusion in a sample (SP-10) collected from the northeastern part of the orebody disappeared at a temperature between 180° and 350°C. In the two samples (SP-2, SP-10), bubble of inclusion homogenized to liquid after the dissolution of halite in a temperature range between 300° and 550°C but mostly between 350° and 400°C. In case of a sample (SP-3) collected from the northern place deeper than the other two samples, bubble disappeared before the dissolution of halite at a temperature between 275° and 350°C. Most of the dissoltuion temperature of sylvite shown in Figure 13 were determined on the polyphase inclusions in this sample. Homogenization temperature of liquid inclusion varied from 150° to 365°C, but it seems that the data tend to concentrate in two ranges, that is, from 150° to 190°C and from 300° to 365°C.

The variety in the mode of occurrence of fluid inclusions at the Cansibit orebody indicates a complex history of hydrothermal activity in the formation of the deposit.

## DEPOSIT OF THE BASAY MINE

The Basay mine is located near the southwetsern coast of Negros Island, at 45 km to the southeast of the Sipalay mine. Several orebodies have been found in dioritic rocks of Paleocene age and in meta-volcanics of Late Cretaceous age, at the south-eastern end of the batholith mentioned in the former paragraph (Fig. 12). The Central, Southeast and Nabore orebodies have been developed but no geologic report is available at present.

The Southeast orebody occurs along a NE-SW fault, whereas the Central orebody is found close to the Southeast orebody and is cut into three parts by two NE-SW faults.

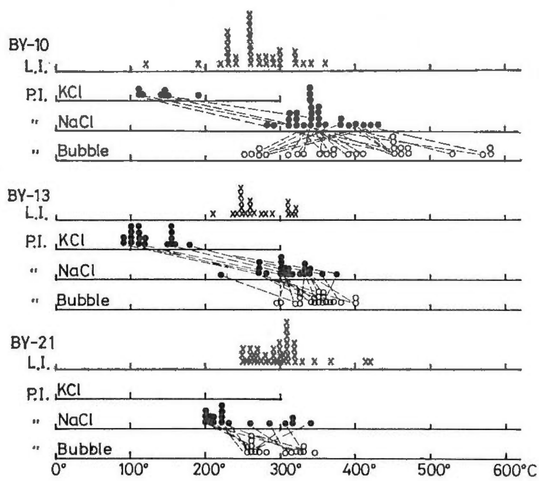


Fig. 14. Temperature data of fluid inclusions from the Southeast and Central orebodies of the Basay mine.

Fluid inclusion study was made for samples from two drilling cores of the Central orebody and a drilling core of the Southeast orebody. The samples from the Central orebody were richer in polyphase inclusions than the one from the Southeast orebody and higher disappearance temperatures of halite and bubble were obtained from the former. Determination of disappearance temperature of sylvite was carried out only on the inclusions in the former two samples.

In the two samples obtained from propylitic or sericitic zone at shallow places of the Central orebody, liquid inclusions predominate over polyphase inclusions. Homogenization temperature of liquid inclusion had a maximum frequency of distribution around 250°C but it ranged up to 320°C (BY-10 and 13, Fig. 14).

The sample obtained from biotite zone at a deeper level of the Southeast orebody, contained a small number of polyphase inclusions which had relatively low disappearance temperatures of halite and bubble, and a large number of gaseous and liquid inclusions. Homogenization temperature of liquid inclusion distributed between 250°C and 330°C with a maximum frequency at 310°C (BY-21, Fig. 14).

The mode of occurrence of fluid inclusions in this sample agrees with the fact that the Southeast orebody has been formed along a large fault which would have served as a pathway of circulating hydrothermal solutions of meteoric origin as well as of ore-forming fluids.

## BIGA DEPOSIT (ATLAS MINE)

The Atlas mine is situated in the center of Cebu Island. The ore deposit comprises the Lutopan (Frank), Biga and Carmen orebodies (Fig. 15). The mine is the largest copper mine in the Philippines, producing 61,000 t/day of ores. The ore reserve is about 900 million tons at an average of 0.47% Cu.

The mineralized area forms a horst extending in the NE-SW direction and the geology consists of Late Cretaceous meta-volcanics and Paleocene dioritic stocks. The mineralization is localized by several diorite stocks which lie along three NNE-SSW trends (MADAMBA, 1972).

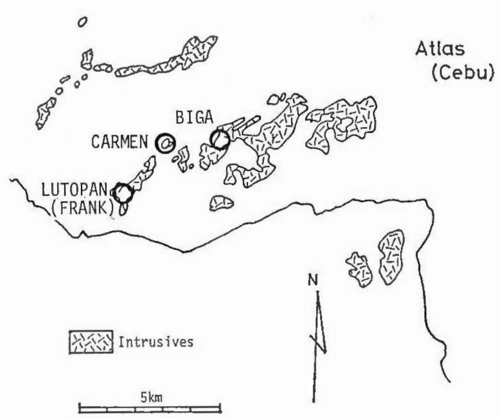


Fig. 15. Porphyry copper deposits in the central part of Cebu Island.

The Biga orebody which has a horizontal section of 1,700 × 500 m occurs in diorite and meta-volcanics and extends downward steeply as deep as 450 m from the surface. Mineralization is mostly controlled by stockwork of veinlets accompanied with dissemination. An inner high grade ore zone comprises chalcopyrite and bornite, and accompanies an intense silicification. Sericitization and silicification predominate in the ore zone, although biotite alteration is recognizable in the core part. The orebody is characterized with an extensive development of coarse-grained anhydrite and films of gypsum.

Several quartz samples collected from the Biga open pit were investigated. The size of fluid inclusions was so small (generally smaller than 10 $\mu$m) that it was difficult to measure the disappearance temperature of phases in inclusions. The number of inclusions observed in this deposit was few as compared with the other Philippine porphyry copper deposits.

Polyphase inclusions were generally found in quartz from veins which accompanied sulfides or magnetite, but they were generally smaller than 10 $\mu$m and the number was much fewer than that of liquid inclusions. In some parts, they were observed in a close association with gaseous inclusions, suggesting the boiling of fluids.

Liquid inclusions of either primary or secondary origin were also very small in size and classified into two groups according to their degree of filling.

Quartz crystals associated with anhydrite are generally deficient in liquid inclusions as well as polyphase and gaseous inclusions, but where they occur the size is smaller than a few $\mu$m. In general, it seems that liquid inclusions predominate over polyphase and gaseous inclusions in the Biga orebody, and that the polyphase inclusions were probably formed at the time of mineralization although they were mostly flashed out by later hydrothermal activity.

Figure 16 shows the temperature data of fluid inclusions from the Biga orebody. The number of measured polyphase inclusions was very limited. The quartz samples which contained polyphase inclusions (AT-9 and AT-13), accompanied chalcopyrite and pyrite. Disappearance temperature of halite of polyphase inclusion in the sample AT-13 was much higher than that of bubble. Gaseous inclusions occasionally exist

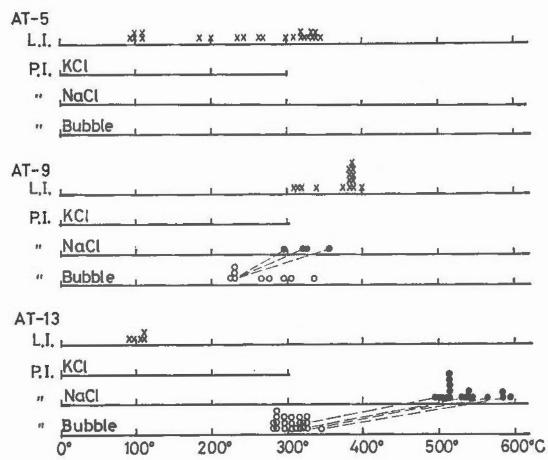


Fig. 16. Temperature data of fluid inclusions from the Biga orebody of the Atlas mine.

with polyphase inclusions, but their presence would not necessarily indicate the boiling of the fluids, because a relatively narrow range of disappearance temperature of bubble indicates the trapping of homogeneous fluids but not of boiling fluids. The disappearance temperature of halite also concentrated in a certain range indicating that the fluids were homogeneous concerning salinity, that is to say, they were not oversaturated with halite. Therefore, the homogenization upon dissolution of halite is attributable to the trapping of high-salinity homogeneous fluids at high pressure conditions.

Homogenization temperatures of liquid inclusions distributed in a wide range from 100° to 400°C, but most of them are either around 100°C or in a range between 300° and 400°C.

## CONCLUDING REMARKS

Since the first copper production from the Atlas porphyry copper deposit in 1955, many deposits of this type have been found in the Philippines. At present, more than ten mines are in operation. Saegart and Lewis (1977) reported that the developed ore reserve of the porphyry copper deposits in the Philippines amounts to

3.2 billion tons at an average of 0.46% Cu and 0.30 g/t Au.

Porphyry copper deposits in the Philippines tend to occur along the peripheries of Tertiary dioritic intrusives, especially along the Agno batholith in North Luzon, Mahinhin stock in Marinduque Island, batholith in the southwestern part of Negros Island, stocks in the central part of Cebu Island, and stocks in East Mindanao.

The characteristics of some of these deposits can be summarized as follows.

(1) Geologic age of the intrusives genetically related to the mineralization, is either of Paleocene or Late Miocene.
(2) The intrusives genetically related to the mineralization are dioritic in composition.
(3) Either biotitization or sericitization predominates in the wall-rock alteration of the ore zone. Sulfide mineralization accompanies silicification.
(4) Zoning of wall-rock alteration is irregular or indistinct.
(5) Mineralization is controlled mostly by veining of sulfide-bearing quartz veinlets, but partly by dissemination.
(6) The total sulfide content and pyrite to chalcopyrite ratio are generally lower compared to those in ore deposits of the United States. According to SAEGART and LEWIS (1977), the former is 6 wt.% and the latter varies from 1 to 4.
(7) Gold and magnetite content is 0.3 g/t and 3 wt.% in average, respectively (SAEGART and LEWIS, 1977).
(8) Anhydrite and gypsum are common in these deposits.

SILLITOE (1979) suggested that porphyry copper deposits generated in island arcs tend to be richer in gold and poorer in molybdenum than those in continental margins, and that this has been caused not by geotectonic setting but by local factors related to the internal evolution of systems. He also pointed out that gold-rich porphyry copper deposits are abundant of magnetite and quartz of replacement origin.

Fluid inclusion data for porphyry copper deposits of the southwestern Pacific region are very few, except for the detailed studies carried out at the Koloula, Guadalcanal, by CHIVAS and WILKINS (1977) and at the Panguna, Bougainville, by EASTOE (1978).

Studies of fluid inclusions of the Philippine porphyry copper deposits revealed that the variety of the occurrence of fluid inclusions depends not on the geologic age of the ore deposit, but on the geologic features of deposit. GUSTAFSON (1978) discussed the space-time relationship of intrusion and mineralization of porphyry copper deposits. Depth and size of intrusions, volatile evolution of magma, geologic structure, ground water incursion and others could be the factors controlling the pattern and range of temperature and pressure conditions.

Polyphase and gaseous inclusions were abundant in a vertically extended pipe-shaped deposit such as the Santo Tomas II orebody of the Philex mine, but liquid inclusions were scarce. The mode of occurrence of fluid inclusions indicates that high-temperature and high-salinity fluids in the boiling condition would have dominantly contributed to the formation of the deposit, and that the participation of low-salinity meteoric water in the late stages was less (Fig. 17). This hydrothermal activity has resulted in the formation of pervasive biotite alteration of the ore zone.

On the other hand, liquid inclusions were abundant in a laterally extended flat-lying deposit such as the Tapian orebody of the Marcopper mine, but polyphase inclusions were scarcely observed. These liquid inclusions would have been formed by an intense activity of circulating meteoric water which has caused pervasive sericitization

Table 1 Location of samples reported in this paper

| Mine | Orebody | No. | Location | | Wall-rock | Alteration |
|---|---|---|---|---|---|---|
| Philex | St. Tomas II | 2602 | Caved surface | | Diorite | Biotit. |
| | | 2603 | 1190mL, cc 3, | Fringe Sl-13 | Meta-volcanics | *do.* |
| | | 2607 | *do.* | Sl-27 | Diorite | *do.* |
| | | 2610 | *do.* cc 4, | Fringe Sl-22 | *do.* | *do.* |
| Marcopper | Tapian | 2004 | 312mL, | N part | Qz. diorite | K-feld., biotit. |
| | | 2005 | 348mL, | *do.* | *do.* | Sericit. |
| | | 1906 | 372mL, | S part | *do.* | Argill. |
| | | 2009 | 390mL, | *do.* | Meta-rocks | Sericit. |
| | | 2011 | 348mL, | *do.* | Qz. diorite | Argill. |
| | | 2101 | *do.* | *do.* | *do.* | Sericit. |
| Sipalay | Cansibit | SP-2 | −78mL, | S side | Oz. diorite | Silicif. |
| | | SP-3 | −115mL, | N side | *do.* | Sericit. |
| | | SP-10 | −40mL, | NE part | *do.* | *do.* |
| Basay | Central | BY-10 | +102mL, | Center | *do.* | Biotit., silicif. |
| | | BY-13 | −52mL, | *do.* | *do.* | Chlorit. |
| | Southeast | BY-21 | −175mL, | *do.* | *do.* | Biotit. |
| Atlas | Biga | AT-5 | 240mL, | N end | *do.* | K-feld. |
| | | AT-9 | *do.* | Center | *do.* | Sericit. |
| | | AT-13 | *do.* | S end | Meta-volcanics | Biotit. |

Fringe cc: Fringe cross cut, Sl: Slusher line, K-feld.: Potassic feldspar,
Biotit.: Biotitization, Sericit.: Sericitization, Argill.: Argillization,
Silicf.: Silicification, Chlorit.: Chloritization, Qz. diorite: Quartz diorite.

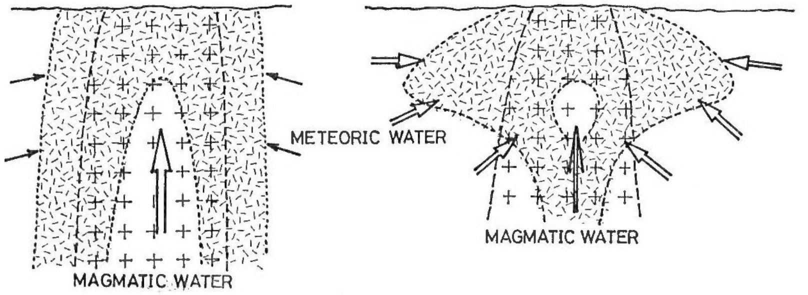


Fig. 17. Schematic figures showing the relationship between the shape of orebody and participation of magmatic and meteoric water in the formation of porphyry copper deposits.

of the ore zone (Fig. 17). In the Biga orebody of the Atlas mine, liquid inclusions were much more to be found than polyphase inclusions which were mainly found in quartz associated with sulfides and magnetite. The size of fluid inclusions in this orebody was so small that the number of temperature determination was very limited.

The mode of occurrence of fluid inclusions in the deposits of the Sipalay and Basay mine is intermediate between the above-mentioned two types. In these deposits, both of biotitization and sericitization were observed but sericitization was more intense than biotitization.

The present result indicates that the features of ore-forming fluids of porphyry copper deposits are in a close relationship with the shape of orebody, wall-rock alteration, and evolution of hydrothermal systems, although more data on fluid inclusions will be necessary to arrive at any conclusion.

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- a. 地　質
- b. 岩石・鉱物
- c. 古生物
- d. 火山・温泉
- e. 地球物理
- f. 地球化学

B. 応用地質に関するもの
- a. 鉱　床
- b. 石　炭
- c. 石油・天然ガス
- d. 地下水
- e. 農林地質・土木地質
- f. 物理探鉱・化学探鉱および試錐

C. そ の 他

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- e. Geophysics
- f. Geochemistry

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- a. Ore deposits
- b. Coal
- c. Petroleum and Natural gas
- d. Underground water
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