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MAFIC AND ULTRAMAFIC ROCK ASSOCIATIONS IN THE EAST ARC OF SULAWESI+)

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RINGKASAN

Busur Timur Sulawesi, yang terdiri dari Sulawesi Timur dan Tenggara, sebagian besar ditempati oleh suatu komplek luas terdiri dari kelompok batuan ultramafic yang diperkirakan berumur Mesosoik hingga Tersier Bawah. Batuan-batuan tersebut dijumpai bersama dengan intrusi-intrusi batuan beku yang bersusunan gabro. Komplek batuan ultramafik ini merupakan suatu lajur yang terputus-putus, dan dapat diikuti dari bagian paling timur dari Sulawesi Timur ke arah barat dan membelok mengikuti arah struktur Sulawesi Tenggara.

Komplek ini terdiri dari berbagai batuan ultramafic terutama harsburgit dan lersolit, serta dunit & piroksenit. Sebagian besar daerah yang diselidiki terdiri dari batuan-batuan ultramafic yang mengalami berbagai derajat serpentinisasi.

Di beberapa bagian komplek ini, batuan-batuan ultramafic menunjukkan adanya korok-ko-

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rok dan intrusi-intrusi kecil yang bersusunan gabro serta diorit. Asosiasi batuan tersebut dicirikan pula oleh bentuk dan penyebaran yang tidak teratur.

Maksud dari pada tulisan ini adalah untuk mengemukakan data baru mengenai petrologi dan tektonik dari asosiasi batuan-batuan basa dan ultramafic ditinjau dari perkembangan teori dewasa ini. Penyelidikan yang bersifat pendahuluan ini didasarkan pada hasil analisa petrografi batuan, hubungan batuan-batuan satu sama lainnya di lapangan, serta pemetaan yang dilakukan selama berlangsungnya kegiatan explorasi geologi oleh P.T. International Nickel Indonesia.

ABSTRACT

The East Arc (East and South-East Arms) of Sulawesi is largely occupied by a huge complex of ultramafic rocks of presumably late Mesozoic to early Tertiary age. The ultramafic rocks of Sulawesi are closely associated with small masses of gabbroic rocks. The ultramafic complex takes the form of discontinuous belts which can be traced from the eastern-most part of the Eastern Arm west-ward curving to the South-East following the Structural trend of the South-East Arm.

The complex is made up chiefly of harzburgite, lherzolite, with some dunite and pyroxenite. Over most parts of the investigated area, these rocks have been serpentinized to variable degrees.

Dikes and small intrusive bodies of gabbroic and dioritic compositions have been encountered in many places within this belt. This rock assemblage is characterized by irregularity in form and distribution.

The purpose of this paper is to bring up-to-date what is known on the petrology and tectonic setting of the mafic and ultramafic rocks in the light of new available data and current theories. The present preliminary study is mainly based upon petrographic data, and field relations obtained from recent geological exploration activities and mapping by P.T. International Nickel Indonesia.

INTRODUCTION

The ultramafic rocks in Sulawesi are closely associated with small masses of gabbroic rocks. This paper deals with the distribution, petrology and petrochemistry of the rocks.

Samples which are petrographically described in the text were all collected during the helicopter supported field activities of P.T. International Nickel Indonesia, with close cooperation of the Geological Survey of Indonesia and the Geological Department of the Institute of Technology, Bandung.

ACKNOWLEDGEMENT

Grateful acknowledgement is extended to Dr. Warren Hamilton of the United States Geological Survey, Denver, Colorado for valuable discussions on the plate tectonics of Sulawesi, and critical review of this manuscript.

DISTRIBUTION

Sulawesi is characterized by the side by side occurence of two arcs in which each is marked by different igneous rock assemblages. Granite and granodiorite associations are widely distributed in the Western Arc, whereas the Eastern Arc is characterized by the absence or scarcity of granitic rocks and the abundance of mafic and ultramafic rocks.

Large ultramafic complexes are extensively distributed in the East Arm and the northern part of South-East Arm (Fig. 1). The ultramafic intrusions in the East Arm occur as slightly curving elongate bodies with their convex side to the north. The strike of these bodies is parallel to the strike of the enclosing rocks and the dominant structural trend in the area. The tectonic setting of the ultramafic masses conforms to that of the Alpine-type. They extend discontinuously from the eastern-most extremity of the peninsula west-ward and curve southwest-ward before they reach the neck of Sulawesi following the South-East Arm.

The south-western one comprises a south - east trending string of plutons each of relatively small outcrop area. The trend starts at Sua-Sua on the east coast of the gulf of Bone and continues along the shore to Pomalaa. There is a possibility that these bodies are connected via submarine outcroppings.

At Pomalaa the trend branches, one branch going east across the peninsula toward Kendari embracing ultramafics near Andowengga, Makalelu and Benua while the other branch continues south-east through G. Watumohai and Bombakou to the vicinity of Torobulu on the strait of Tioro. The two branches

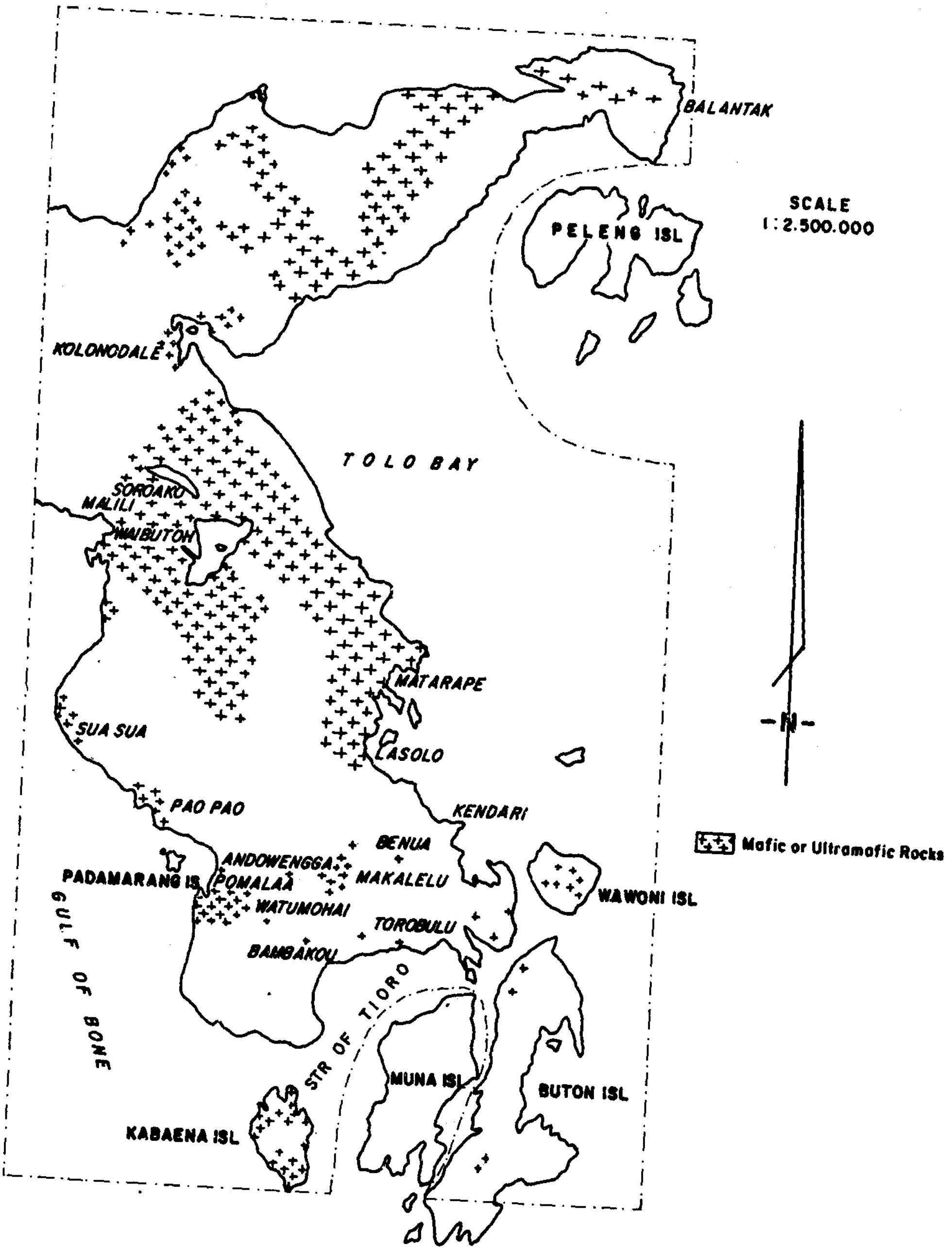

FIG. I MAFIC AND ULTRAMAFIC ROCK DISTRIBUTION S.E. SULAWESI could rejoin at the south-east corner of the peninsula around the Strait Wawoni where there are numerous small ultramafic bodies, both on Wawoni Island and the mainland. Scattered very small occurrences exist well to the south-west of here near the west coast of Buton Island.

The other major belt lies to the north-east across the central mass of crystalline-schists. The ultramafic bodies are relatively large. Approximately 70% of the quadrilateral from Kolonodale to Waibutoh peninsula on the north-west down to Matarape and Lasolo on the East Coast is underlain by ultrabasic rock. The ultrabasics appear to be associated with Cretaceous sediments, dominantly limestones and thinbedded cherts, in contrast to the south-west belt of ultramafics which generally are associated with crystalline-schists.

FIELD RELATIONS

The ultramafic belt is made up chiefly of harzburgite, with some dunite, lherzolite serpentinite and pyroxenite. Closely associated with these rocks are intrusive bodies and dikes of gabbro, diorite, pyroxenite, and basaltic lavas (basalt, diabase, spilite). Lavas of basaltic compositions such as diabase, diabase tuff and melaphyre were found in the northern part of Balantak peninsula at the eastern part of East Arm. According to Kundig (1956) this rock suite represents a volcanic facies of the ophiolite rock series. In many places, basaltic lavas are intruded by diorite dikes which have caused thermal effects within the basalt and diabase along the contact zone. The age relations with the ultramafic is not known, but the authors believe that, possibly, there had been several phases of basaltic extrusions prior to as well as subsequent to the emplacement of the ultramafic mass. The relations of the above rock suite are likely of genetic nature as suggested by the spatial relationship. Such igneous rock assemblages characterize the outer-island arc of Indonesia, and are widely recognized in igneous complexes of the Alpine-type.

The ultramafic belt is characterized by the irregularity in form and distribution, the lack of primary internal structures, and their occurrence along strongly deformed orogenic zones. The common occurrence of huge ultramafic masses with small amount of gabbroic rocks is very characteristic.

In Soroako (South-East Arm) the ultramafics show a very slight change in composition toward the intrusive margins. The rocks are structureless except that foliation (mylonitization) is more confined to peripheral zones of the intrusive body, and this seems to be a general feature of the ultramafic complexes in the East Arc.

Over most parts of the investigated area, the ultramafic rocks exhibit various stages of serpentinization. Outcrops of these rocks in the Soroako area show crosscutting fractures and veinlets of serpentine materials. In many places the rocks give evidence of shearing. The effect of deformation has been observed as narrow zones of intense brecciation in which ultramafic fragments of various sizes are cemented by finely crushed materials. Field observations in Soroako suggest that serpentinization is intensive along zones of brecciation.

The age of the ultramafic rocks is still insufficiently known. Previous reports mentioned that the contacts of the intrusive bodies with the enclosing rocks are obscured by tectonic movement, and therefore precluded relative age dating. A tectonic map of the East Arm compiled by Kundig (1956) displays fault-and overthrust-contact. The nature of the contacts of ultramafic intrusions with the adjacent country rock was later confirmed by recent aerial photographic studies (Francken and Jones, 1971). Kundig (1956) considered the main phase of the magmatic activity to be Upper Cretaceous/Paleocene, although the whole phase may range from Upper Cretaceous to Early Tertiary.

Van Bemmelen (1949) found minor thermal effects within the rocks enclosing the ultramafic bodies in the area of Lake Matano (South-East Arm), and suggested that the temperature of the peridotite magma during the emplacement was not high. In the southern part of the South-East Arm, ultramafic rocks were found in Jurassic sediments without a distinct thermal metamorphism. This might indicate a Cretaceous age (post-Jurassic), and that the rocks represent low-temperature intrusion. However, many examples of high-temperature peridotites from other countries have been reported by several authors (Challis, 1965; Green, 1967), where the mineral associations in the contact zones indicate low-temperature metasomatic reactions which accompanied serpentinization subsequent to the magmatic intrusion.

Brouwer (1947) suggests different age of the ultramafic intrusions from Cretaceous to Early Tertiaty.

PETROLOGY

Ultramafic Rocks

A large number of handspecimens of ultramafic rocks have been collected from the South-East Arm. Samples of their associates originated mostly from the East Arm.

Textural features indicate that the fresh rocks are mostly allotriomorphic-granular with some hypidiomorphic-granular textures. Their grainsize varies from medium to very coarse.

The rocks exhibit features indicative of cataclastic deformation and recrystallization. The development of porphyroclastic textures and suturing and fracturing of mineral grains are very common in these rocks.

In the partially serpentinized rocks there is a marked reduction in grainsize, and they develop pseudo-porphyritic textures. In these rocks, remnants of olivine occur as subsequent granular clusters floating in fine nets of serpentine veinlets. In many strongly serpentinized rocks the original texture is often preserved.

Olivine occurs as fractured rounded grains varying in size from 2-6 mm. Strong undulatory extinction and kink banding parallel to (100) in olivine crystals are evidence of high temperature strain. The presence of sub-parallel oriented elongate grains of olivine and schlieren of finely granulated materials at a high angle to the kink banding, make the rock appear foliated.

Ortho-pyroxene occurs as short prisms with ragged crystal edges. It shows exsolution lamellae of clino-pyroxene along cleavage traces of the ortho-pyroxene host. Clino-pyroxene is also present as individual grains interstitial to olivine. Intergrowth textures of olivine and pyroxene suggest simultaneous crystallization. Small unaltered exsolution lamellae of clino-pyroxene are often found in completely serpentinized ortho-pyroxene grains (bastite).

In the partially serpentinized rocks the primary minerals (olivine and pyroxene) are fractured and dissected by numerous veinlets of pale-green serpentine. Olivine is typically replaced by serpentine with mesh structure, whereas pyroxene is commonly replaced by bastite. The alteration pattern within the olivine grains are controlled by the original irregular rectangular fractures. Serpentine can be found as pale-green to brownish green flakes, massive seams, cross-fiber veinlets, and nearly isotropic matrix. Several grains of pyroxene display rims and veinlets of talc aggregates. Talc and tremolite are the alterations of pyroxene. Muscovite flakes are occasionally present in some sections.

Fine particles of magnetite, native ferro-nickel alloy and chrome-spinel are usually associated with serpentine masses. Trains of magnetite particles occur as discontinuous string following the original crystal outline of olivine grains. Magnetite is partly representing the iron that was set free during serpentinization. These opaque particles are also present as irregular blebs in serpentine masses, as veinlets and thin rims enclosing olivine crystals.

Within the Soroako ultrabasic complex (Fig. 2) there are three areas underlying the dominant hills east of the main road north of Wowondula to Soroako in which the bedrock is a partially to strongly serpentinized lherzolite. The primary

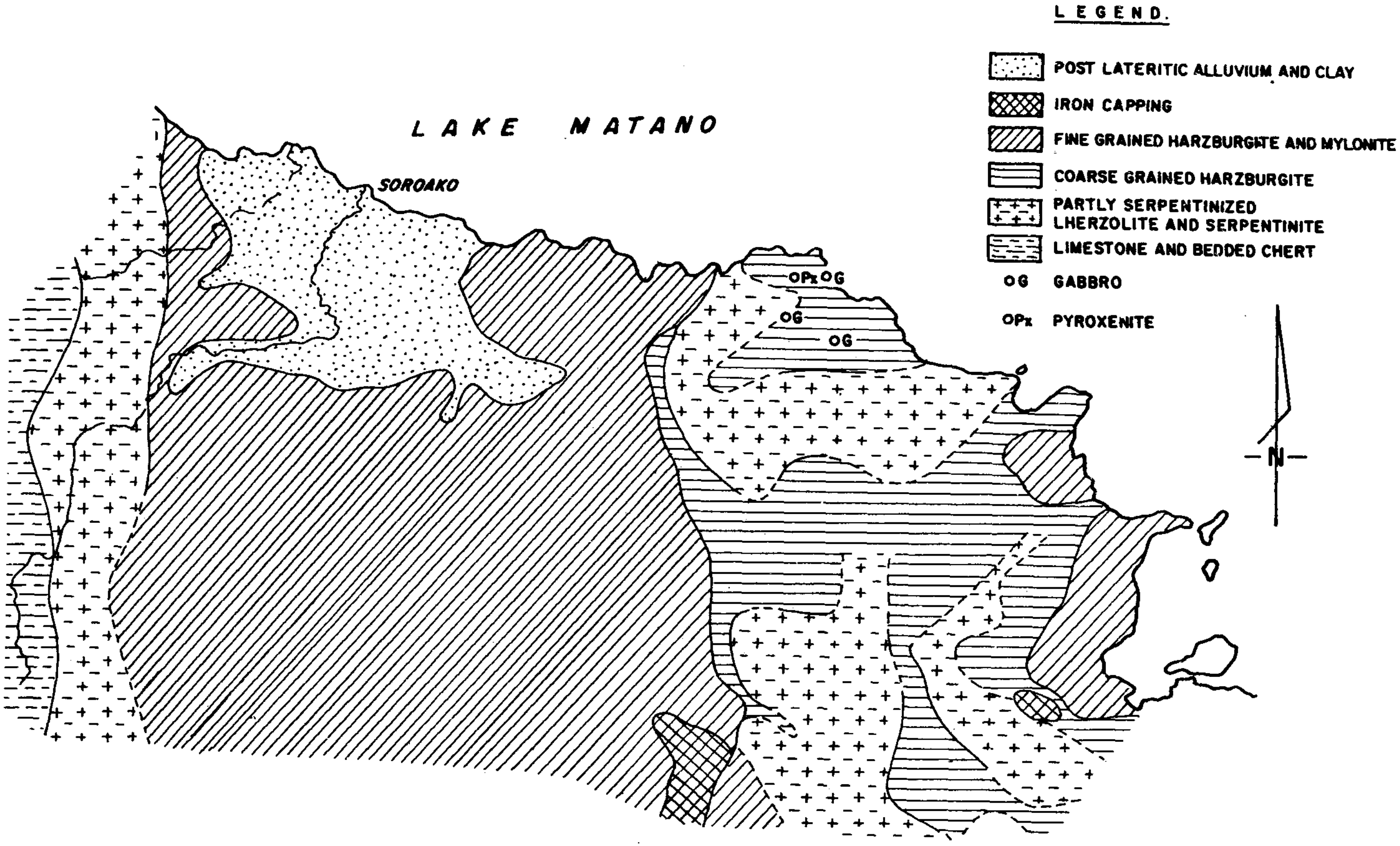

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FIG. 2 SOROAKO AREA (GENERALIZED GEOLOGY) igneous minerals are subhedral olivine with cups-shaped interstitial ortho-pyroxene and diallage. The olivine has some strain lamellae, and the pyroxene shows some bent cleavege traces.

Perioditite samples from Soroako and Pomalaa are immediately distinguishable by the absence of strain effects in the Pomalaa ones.

Elsewhere in the Soroako area, the bedrock is essentially unserpentinized, serpentine being restricted to the immediate vicinity of joints as a thin rim, or to the fine-grained matrix of tectonic breccias.

Anorthosite, Gabbro and Diorite

Anorthosite seems to be the least common rock type among the three intrusive rocks. These rocks are mostly medium-, coarse-grained to pegmatitic with hypidiomorphic-granular textures. Ophitic and porphyritic textures were observed in several sections of gabbros. Fine-grained varieties of gabbroic rocks which have been found in some places are likely chilled margins of the intrusive bodies against the enclosing country rock.

Clino-pyroxene and labradorite are the principal minerals in the gabbroic rocks; the former is also present in some diorites. Clino - pyroxene exhibits partial serpentinization, chloritization, and uralitization along fractures and cleavage traces. In several sections, prismatic crystals of pyroxene are partly intergrown with labradorite in an ophitic fashion.

Olivine is present in a few sections of gabbroic rocks. It is usually fractured and is partially serpentinized along the fractures.

Green to olive green hornblende is the principal mineral in the diorites. It is present as ragged crystal grains and as fibrous actinolitic aggregates (secondary). The latter is commonly accompanied by chlorite and epidote granules. Embayments of several plagioclase grains bu hornblende suggest replacement relationship. Hornblende is partly derived from the alteration of pyroxene.

Plagioclase shows compositional zoning and polysynthetic albite twinning. The crystals are often fractured and show ragged crystal faces. In many sections plagioclase grains are clouded by clay particles, sericite, chlorite, epidote and calcite. The compositions of plagioclase in the diorites and gabbros vary from intermediate andesine to intermediate labradorite.

The accessory minerals in the rock include quartz, analcite, zeolite- and carbonate-minerals which are often present as veinlets and openspace filling.

THE ORIGIN OF ULTRAMAFIC ROCKS

General

The association of mafic-ultramafic rocks of the Alpine-type is known from many orogenic zones in various parts of the globe. Coleman (1971) plotted the ultramafic belts on a world map along with the plate boundaries, and found out that they display very cloce correlation in space and time. Another significant feature which he noted was the intimate association of Phanerozoic ultramafic rocks with blue-schists. This rock assemblage is also known from the East Arc of Sulawesi. Hamilton (1970) interpreted the geology of the East Arc in terms of subduction geology, and accepted two subduction complexes. The western subduction zone (Mesozoic) dipped eastward, the eastern one (Tertiary) dipped west-ward. Zwart (1967) considered Sulawesi as paired Circumpacific belts consisting of a high-pressure belt on the ocean side and a low-pressure belt on the continental side. According to Mitchell and Reading (1971) many of the ultramafic rock associations in such high-pressure belt were emplaced as cold intrusions during metamorphism.

The origin of Alpine ultramafic within orogenic zones have been argued among petrologists over many years. The main disagreement has been the mechanism of emplacement, whether the rock represents cold intrusion or high temperature emplacement of intrusion derived from igneous melt. Several authors have ascribed the origin of ultramafic intrusive bodies to either crystal accumulation from a mafic magma, crystallization of an ultramafic magma, or residuum from partial melting of a primitive mantle (Challis, 1965; Davies, 1968; Thayer & Himmelberg, 1968; Loney et al, 1971).

The main differences of opinion in the concept lie in the depth at which magmatic differentiation takes place, the mechanism of emplacement, and differentiation in situ. In reviewing the current hypotheses for the origin of Alpine ultramafic rocks it is significant to note that the theories have two features in common; these are:

1. the upper mantle is the source of ultramafics and
2. the tectonic setting and re-intrusion of the ultramafic rocks (tectonic emplacement).

Intrusion of the Ultramafic Rocks

The ultramafic belt of the East Arc displays many features of the Alpine-type peridotite, these are: the irregularity in form and distribution; close relationship of mafic-ultramafic rocks with preferential occurrence of the latter with gabbro rather than diorite; predominance of olivine over pyroxene in many ultramafic bodies; borders of the ultramafic intrusions are commonly serpentinized and faulted/thrusted against the enclosing rocks; the occurrence of chromite with nodular and orbicular textures in the dunitic parts of the ultramafics.

Previous investigations and results of recent geologic reconnaissance in many parts of the East Arc mentioned that most ultramafic intrusions are bounded by fault contacts. Aerial photographic interpretations provide evidence of either tectonic or unconformable contact with the surrounding country rock. Similar to other known Alpine-type peridotites, the ultramafic rocks in the area under consideration exhibit evidence of tectonic deformation which has complicated the contact effects.

Primary thermal contacts of these intrusive bodies with the adjacent rocks have never been observed in the field. Since detail observations along the contact zones were never carried out, nothing can be said on the nature of the reaction zones.

Beside tectonic deformation, the failure to recognize the nature of thermal metamorphism at the contact of ultramafic bodies may be the result of Ca-metasomatism at the contact rocks by the release of Ca during the process of serpentinization. Coleman (1967) suggested that the reaction zones developed at the same time of the tectonic emplacement of peridotite. Serpentinization and tectonic movement occured at the same time, and therefore the alteration is not related to the igneous intrusion.

Van Bemmelen (1949) recognized the presence of crystalline-schists, amphibolites, epidote - rocks, garnet-epidote-muscovite-schist near the border of a peridotite intrusion in the central part of the South-East Arm (Lasolo area). He thouhgt that their position suggests genetic relationship with the emplacement of the intrusion. To the present authors it seems that the rocks are the result of regional metamorphism prior to the ultramafic intrusion. However, forcefully emplaced intrusions could generate thermal aureoles containing minerals and structures commonly associated with regional metamorphic rocks (Pitcher & Read in Joplin, 1968). If the above mentioned rocks are thermal metamorphic rocks as the consequence of peridotite intrusion, the facies would place them in the hornblende-hornfels facies or higher, indicating a temperatur range of 550° - 700°C (Turner & Verhoogen, 1960).

Examintaion of ultramafic rocks under the microscope reveals that the rocks are mostly allotriomorphic-granular and are made up of interlocking anhedra of pyroxene and olivine in variable proportions; hypidiomorphic textures are also common. Intergrowths of olivine and pyroxene suggest typical igneous textures indicating simultaneous crystallization in a fluid magma. Evidence of cataclastic deformation is reflected by the presence of strained crystals, fracturing and granulation of the primary constituents (mainly olivine) and the formation of ultramafic mylonites. Olivine grains in these rocks display kink banding and strong undulatory extinction, indicating that the rocks have been subjected to considerable stress. The presence of these textures seems to suggest deformation (plastic?) after the rocks have developed primary crystallization textures. Such deformation was very likely accompanied by recrystallization, both processes have obliterated much of the primary textures, and the rock obtained metamorphic textures.

A sample of unserpentinized lherzolite collected near Soroako was analysed and found to contain about 1.60% CaO and 1.44% Alumina.

Table 1

Fe	CaO	SiO_2	Cr_2O_3	MnO	Ni	MgO	Al_2O_3	TiO_2	Co	Total
6.24	1.60	44.1	.42	.13	.23	44.2	1.44	.031	.009	100.00

As such the lherzolite is less calcic than most and might best be described as a harzburgitic lherzolite.

X-Ray Fluorescence analyses of ortho-pyroxene, clinopyroxene and olivine separated from this sample are given in the table.

Table 2

	Olivine	Enstatite	Clino-pyroxene
Fe	6.93	4.49	1.96
SiO_2	40.3	44.1	53.2
MgO	50.8	33.5	18.5
Al_2O_3	.41	3.23	3.47
CaO	.07	1.86	21.7
Cr_2O_3	.02	.58	.86
MnO	.13	.14	.08
Ni	.29	.06	.04
Co	.010	.005	.005
TiO_2	.02	.05	.09
LOI	.23	.40	.64

The projections of the mineral compositions onto the CaO-MgO-FeO phase triangle is shown in Fig. 3. The chemical compositions are, in a general sense, quite comparable to normal ultramafic plutonic minerals. In particular, the olivine is about 91 mole % forsterite with the normal minor substitution of about .29 weight % of nickel. The pyroxenes in contrast are virtually devoid of nickel and contain abundant chromium and aluminum. The physical separation of the clino-pyroxene from ortho-pyroxene was not complete. This has a noticeable effect on the calcium analyses of each phase but otherwise they are so similar in composition that the error due to contamination is well within the accuracy of the analyses.

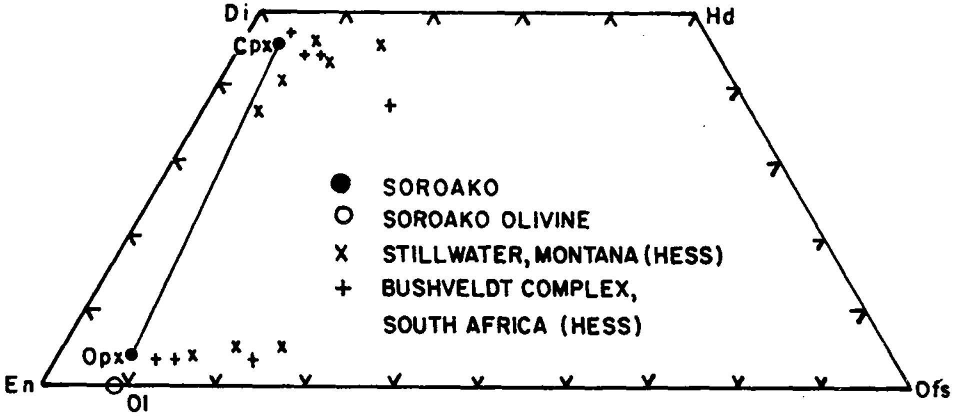
The mineral analyses can be used to yield rough estimates of the temperature and pressure of crystallization of the lherzolitic sample. These estimates (Table 3) are based on the Al-content to clino-pyroxene and the Fe/Mg ratios of the two pyroxene and olivine. Incomplete separation of the two pyroxene makes it impossible to use the Ca analyses, but the Fe, Mg and Al are relatively unaffected.

The Fe/Mg determinations are mutually compatible and are plotted at B of Fig. 4 which gives the temperature/depth dependence of the mineralogy of lherzolitic rock compositions.

Table 3

		Method	Estimated Temperature-Pressure
B	1. Fe/Mg :	Olivine-Orthopyroxene	1025°C@1kb-900°C@7kb
	2. Fe/Mg :	Clinopyroxene-Orthopyroxene	925°C
A	$Al_2O_3 + Cr_2O_3$	of Clinopyroxene	1100°C@8kb-1250°C@5kb

The Al determination gives a much higher temperature or pressure, and is plotted at A. The points are both well on the high temperature/low depth side of "normal" depth temperature curves for the mantle.



PYROXENES FROM SOROAKO

FIG. 3 COMPOSITION OF PYROXENES AND OLIVINE FROM SOROAKO PROJECTED ON TO THE ENSTATITE – FERROSILITE – WOLLASTONITE TERNARY DIAGRAM.

It is suggested that the two pressure-temperature pairs are compatible with the following abridged history of the Soroako ultrabasic complex:

Stage 1 consists of crystallization or partial melting at a depth of about 30 kilometres (upper mantle?) represented by the T,P pair A. The Al and Cr content of the clino-pyroxene are quenched in at this point. Feldspar - bearing pegmatites may have segregated at this time; note that A is just at the upper pressure limit for stability of feldspar. Within the framework of plate tectonics this would likely occur at a mid-oceanic ridge after a slow adiabatic rise up through the mantle.

Stage 2 consists of cooling with attendant cataclasis and deformation from A through T,P pair B. Relatively mobile, Fe and Mg are able to react quickly enough to follow the thermal cooling equilibrium down to this point.

Stage 3 consists of deformation with access of water and attendant serpentinization to parts of the complex when cooling dropped T to below 500°C. Retention of original water in the relatively undeformed lherzolitic rocks may have aided preferential serpentinization there. This could be complementary to the harzburgites and dunites being refractory residues that remained after partial melting of lherzolite and removal (carrying any H_2O with it) of a basaltic liquid. However, this is speculative and access of water during cold intrusion into the present location cannot be excluded. Such water from the country rock is an acceptable explanation of the serpentinized mylonite on the west edge of the Soroako area. The last two stages in any case could occur at any time after the first. But the serpentinization and cataclasis, since they seem to have been oriented relative to local structural elements in Sulawesi, likely occurred during the final emplacement of the present complex.

The mineral assemblage of the ultramafic rocks under consideration conforms with the spinel-peridotite facies (field # II in Fig. 4) (forsterite-enstatite-diopside-chrome spinel), which according to MacGregor (in Loney et al, 1971) has relatively small stability field at high temperatures and moderately high pressures. On this basis it may be inferred that the deformation and recrystallization of the rocks occurred in the upper mantle; crystal environment should have produced plagioclase-peridotite, or garnet-peridotite, depending on the pressure (Loney et al, 1971).

For the Papuan ultramafic belt Davies (1968) suggested that the ultramafics represent primary mantle material and the mafic rocks represent primitive oceanic crust. He believed that the ultramafic belt was formed tectonically by obduction

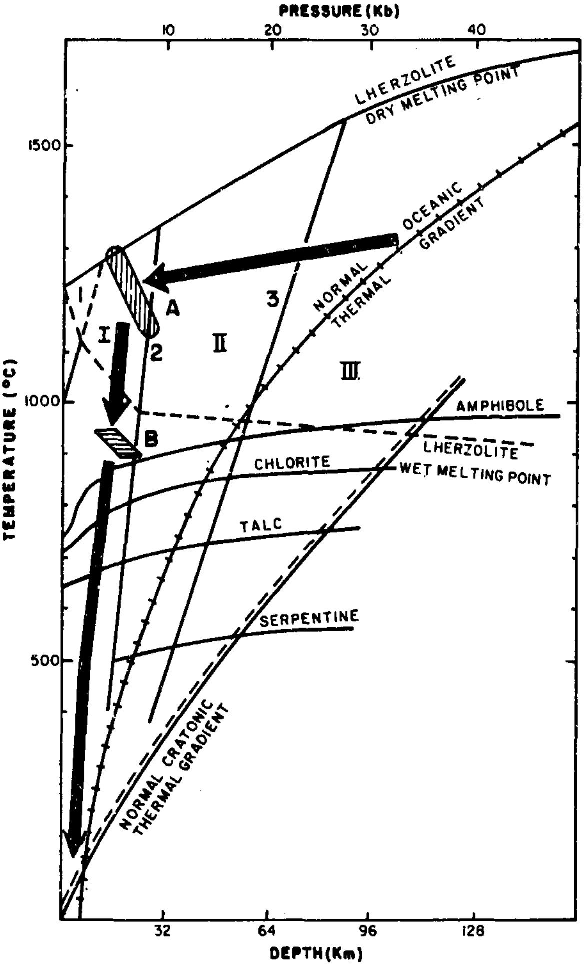


FIG.4 THE INFERRED EQUILIBRATION TEMPERATURES OF THE LHERZOLITIC SAMPLE DISCUSSED IN THE TEXT SUPERIMPOSED ON THE FACIES OF A CHROME-FREE LHERZOLITE COMPOSITION. FIELD LABELLED IN ROMAN NUMERALS ARE :

I FELSPAR — LHERZOLITE
II SPINEL — LHERZOLITE
III PYROPE — LHERZOLITE

THE PRESENCE OF CHROMIUM IN REAL LHERZOLITES RELAXES THE PHASE-RULE AND ALLOWS SPINEL AND FELSPAR FIELDS TO OVERLAP.

of the oceanic plate onto continental crust from east to west.

Challis (1965) stated that the New Zealand ultramafics have formed from fractional crystallization of a tholeiitic magma.

The present authors are very much influenced bu the fact that small intrusive masses of gabbro are closely associated with the ultramafic rocks.

On the basis of the present availeble informations it has been tentatively concluded that the ultramafics of the East Arc have gone through a complicated history which involved:

1. fractionation of a basaltic or lherzolitic magma (?);
2. deformation and recrystallization at great depth (upper mantle?);
3. tectonic transport of the semi-solid material into higher levels in the crust.

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