The

GEOLOGICAL BULLETIN

of the

PUNJAB UNIVERSITY

Number Seven *December* 1968

CONTENTS

GEOLOGY AND PETROLOGY OF THE FELDSPATHOIDAL SYENITES AND THE ASSOCIATED ROCKS OF THE KOGA AREA, CHAMLA VALLEY, SWAT, WEST PAKISTAN

BY

FUZAIL A. SIDDIQUI, M. NAWAZ CHAUDHRY and ABDUL SHAKOOR

Department of Geology, University of the Punjab, Lahore.

Abstract : *The feldspathoidal syenites and associated rocks of the Koga area, first reported by Siddiqui (1965), are described in detail. The area lies in the west central portion of a large intrusion of the socalled Ambela granitic complex, which occupies much of the Buner, Chamla and Khudukhel areas of the southern Swat.*

In the Koga area, three main petrologic types have been distinguished. (1) A calc-alkaline body named Chingalai granodiorite gneiss. (2) Per-alkaline syenites and granites called Babaji Syenites and characterised by granitoid texture and abundance of basic xenoliths. (3) Feldspathoidal syenites called Koga syenites. The contact of type (1) and (2) is occupied by a fault zone. The Koga syenites are intrusive in both (1) and (2) and are similar to Babaji syenites in that both have aegirine augite, abundant ilmenite, sphene and apatite as common constituents. These minerals occur only as accessories in the Chingalai granodiorite gneiss. Babaji syenites appear to be comagmatic with the Koga syenites.

The Koga syenites occupy a roughly oval shaped area with irregular outlines. Field, petrographic and chemical investigations indicate the following sequence of formation : Per-alkaline syenites (with or without quartz)—nepheline syenites—nepheline sodalite syenite—carbonatite. Thus the trend is one of progressive desilication with differentiation.

Flow structure is common indicating that the undersaturated magma was emplaced as a viscous mush with alkali feldspar crystals suspended in a liquid capable of crystallizing nepheline.

INTRODUCTION

Feldspathoidal syenites are among the rarest of all igneous rocks. In spite of their small aerial distribution they excite great interest because of their large mineralogical variability and enrichment in rare elements. So far their origin is not well understood. Any description of a new occurrence has, therefore, a special interest, transcending its significance as a regional or petrographical rock type, for it may provide additional clues to the unraveling of the mystery of alkali rock genesis.

The region, of which the Koga area forms a part, was first investigated by Martin, Siddiqui and King (1962) on a reconnaissance basis. They recorded the occurrence of zircon crystals upto three-quarters of an inch in pegmatites present in a "massive and porphyritic portion of the Ambela granitic complex" near Koga (34°23′, 72°30′). Later on, it was recognized that zircon was accompanied by nepheline and ilmenite and that the surrounding outcrops were of feldspathoidal syenite (Siddiqui, 1965). The occurrence of carbonatite near Naranji Kandao was recognized in August, 1966 (Siddiqui, 1967).

Field mapping was carried out at a scale of 2″=1 mile during summers of 1966 and 1967 by Siddiqui and Shakoor and four M.Sc. students of the Department of Geology, Punjab University. In 1968 detailed field mapping of some portions of the area was carried out by Siddiqui at a scale of 6″=1 mile. For the purpose of field mapping, photographic enlargements of Survey of Pakistan 1″ toposheets were used. A total of 4 months of field work was done.

In all about 250 hand specimens were collected out of which about 80 were studied in detail with the help of thin sections. 11 rocks, representing various petrographic types, were analyzed chemically by Chaudhry. Their modal composition was estimated with the help of a Swift point counter. The purpose of the present paper is, therefore mainly to present field, petrographic, and chemical data on the various rock types and to attempt to elucidate the process of formation of the feldspathoidal rocks of the Koga area. No attempt has been made to give details of physico-chemistry of individual minerals, to which topic it is hoped to return in later contributions.

Fig. 1 is a locality map of the area. The Koga syenites are situated at the border of Swat and Mardan District near the village Koga which is located at a distance of about 35 miles northeast of Mardan. A regular bus service plies between Koga and Mardan *via* Rustam on one hand and Koga and Mingora—the main town of Swat—on the other. A jeepable road connects Koga to Swabi (Mardan District) *via* Chingalai. The relief is moderate. The highest locality in the area is Bagoch Sar (alt. 4763 ft.) while the nearest point of the alluvium filled Chamla Valley (alt. 2300 ft) is at a distance of about 1½ miles from Bagoch Sar.

The outcrop of the Koga syenites is horse-shoe shaped which is open to northeast while the complete body is believed to have an elliptical form as is known to be the case with similar bodies elsewhere in the world (Barth, 1962). The north-eastern portion, together with the central area of the remaining part has been eroded away by the head-ward erosion of the tributaries of the Chamla River, except for a small isolated hill called Bibi Derai (Fig. 2).

Rocks are well exposed in some parts of the area. For instance, the Sahbaga-Chingalai road section provides excellent fresh cuts for collection of samples and study of field relations.

GEOLOGY OF THE AREA

General :

The Koga syenites are closely associated with the Ambela granitic complex and occupy its west central portion.

The rocks immediately northwest and south-west of the Koga syenites, are quartz and/or Na-pyribole bearing alkali syenites and granites with coarse granitoid texture. In the southeast, and separated from the Babaji syenites by a zone of fault breccia, there are outcrops of biotite and hornblende bearing gneisses, hereby collectively named as Chingalai granodiorite gneiss. About 2½ miles west of the southwestern border of the Ambela complex, there is an isolated and roughly triangular outcrop consisting almost entirely of albite porphyries with some metasediments and dolerites.

The Ambela granitic complex, of which the above mentioned syenites and gneisses form a part, appears to occupy the core of an anticline in the Swabi-Chamla Sedimentary Group ; the latter consists of the following formations :—

5. Kala Limestones and Dolomites
4. Swabi Quartzite
3. Swabi Pebbly Shales

——unconformity——

2. Chamla Quartzites
1. Chamla Phyllitic Shales.

Regarding the age of the above formations, Orthoconic nautiloids with crinoidal stems were discovered in a zone at the base of Formation 5 (Martin, Siddiqui & King, 1962) and on the basis of the study of these fossils Davies and Riaz Ahmad (1963) placed the age of the Kala Limestones and Dolomites as Middle Palaeozoic "most probably Silurian to Devonian". Therefore, the formation into which the Ambela granitic complex is intrusive, appears to be at least early Palaeozoic in age.

Radioactive age determination on biotite seperated from zircon bearing feldspathoidal syenite gives a Tertiary Age (Deans 1969, personal communication).

The grade of regional metamorphism of the sedimentary formations is low on the southern, western and northwestern sides of the complex. However in the northeastern part, staurolite and sillimanite bearing schists outcrop with local development of migmatites.

The Koga area :

Fig. 2 is a geological map of the Koga area. Except for the recent alluvium almost the entire area is covered by plutonic rocks that can be sub-divided into three main petrographical types :

(*a*) Chingalai granodiorite gneiss : It is essentially a foliated, porphyritic rock of granitic to granodioritic composition and is exposed all along the southeastern contact of the Koga syenites. Traced eastwards it continues, outside the mapped area, as an axial belt 2½—4 miles wide, through the entire length of the Ambela granitic complex. Moving westwards, this body comes to an abrupt end near Chingalai against a north-south trending brecciated zone which is presumably a fault zone.

The area of the gneiss is intruded by numerous dolerite dykes varying from a few feet to few yards

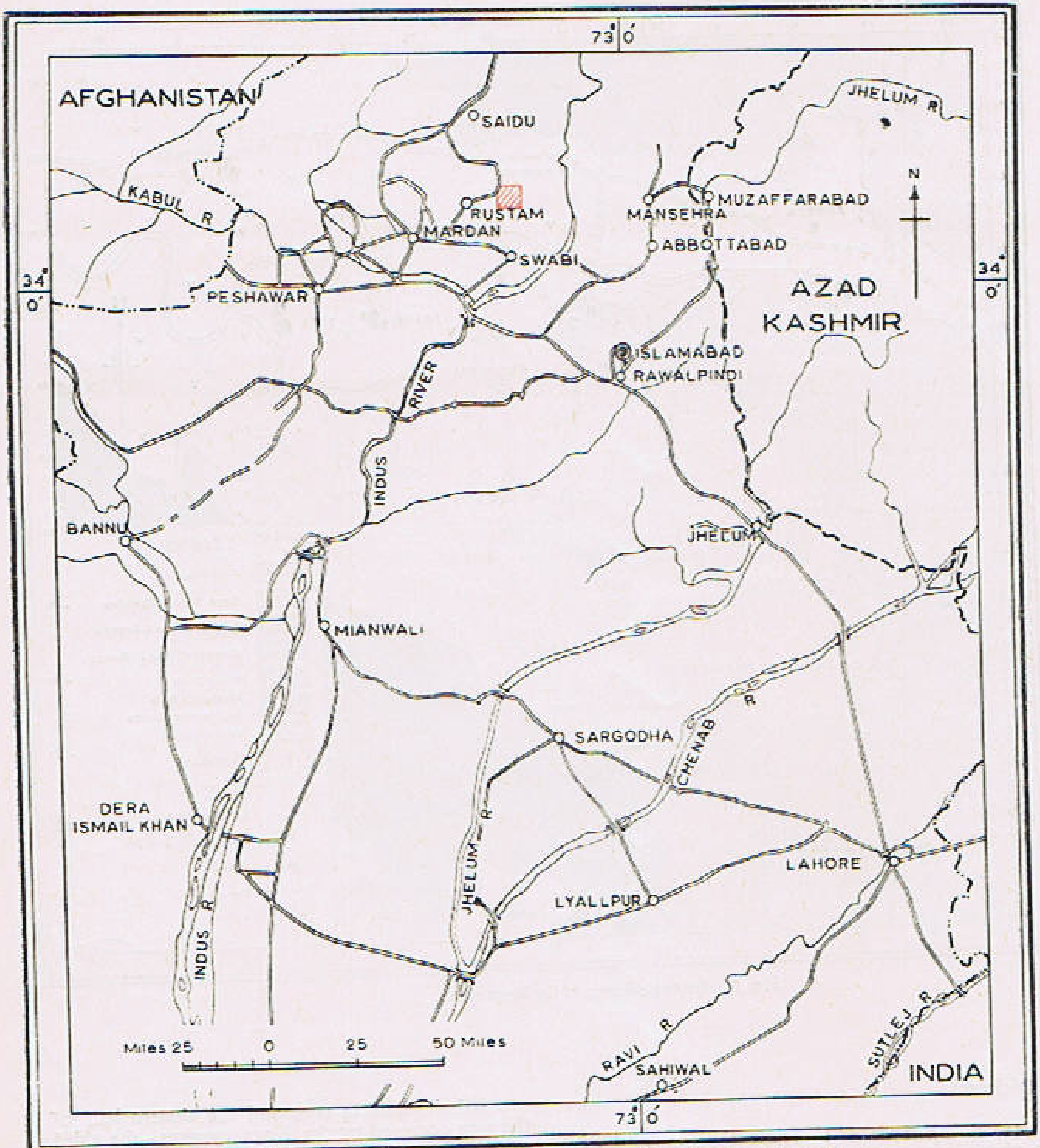

Fig. 1. Locality map of Koga area. Area mapped shown by shaded rectangle.

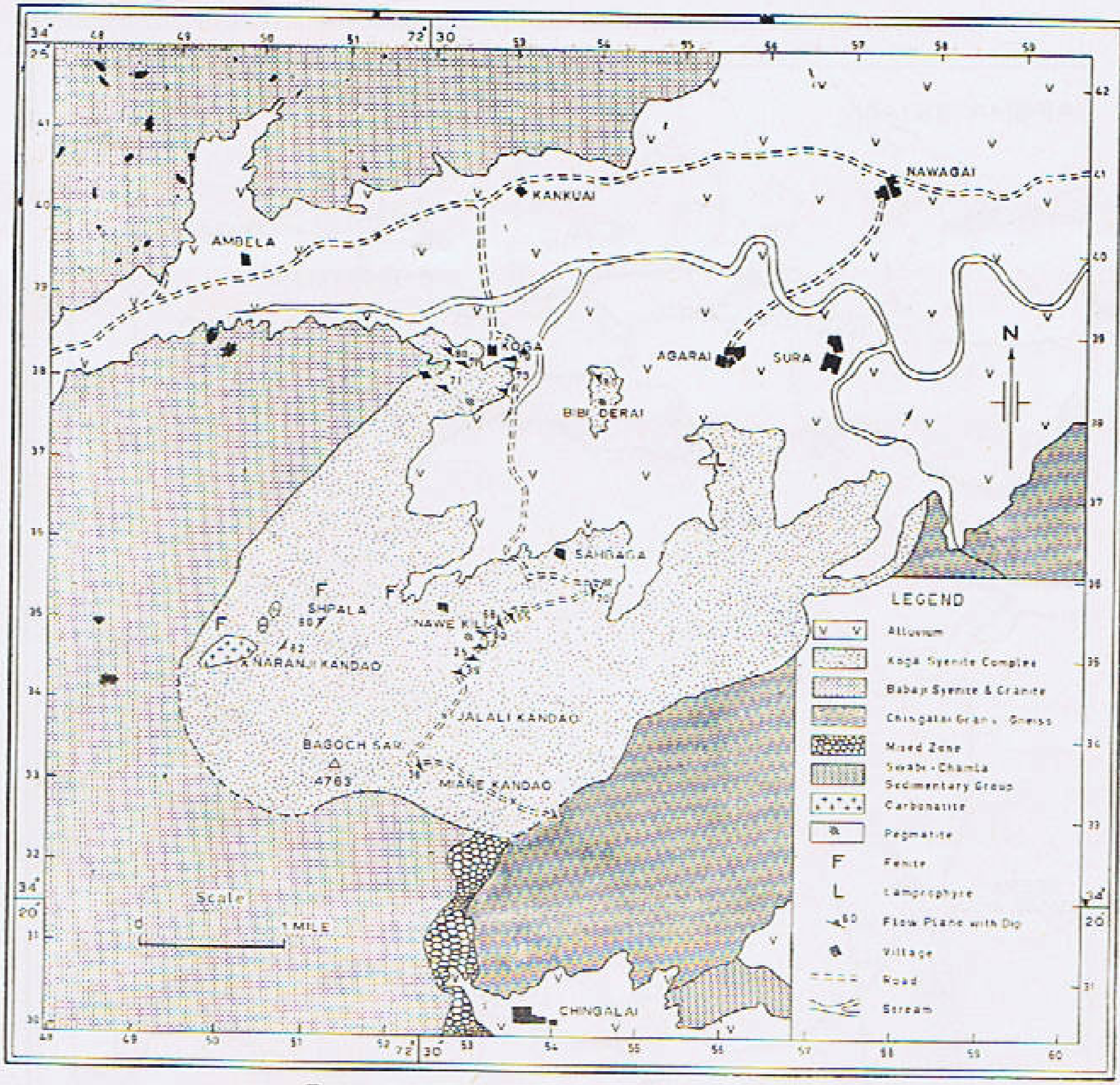

Fig. 2. Geological map of the Koga area.

in thickness.

(*b*) Babaji Syenites : These outcrop west of the above mentioned fault zone and differ from the Chingalai granodiorite gneiss in having a lighter colour and granitoid texture. The northwestern portion of this rock body is characteristically studded with angular xenoliths of a dark doleritic rock which are themselves cut by aplitic veins.

Babaji syenites surround the western half of the area occupied by the Koga syenites—the third main rock type of the area.

(*c*) Koga Syenites : These are confined to an elliptical zone in the middle of the area mapped. The boundary of this zone, as shown on the map, is highly generalized and merely encloses an area within which feldspathoidal syenites are commonly found ; their relative amount generally increasing towards the interior. Koga syenites are clearly intrusive in the first two types and partly replace the Chingalai granodiorite gneiss.

Contact relations of the Koga syenites :

Contacts of the Koga syenites with the above rock types (*a*) and (*b*) are generally irregular and can be best described with reference to some well exposed areas.

On the northern slope of the spur west of the Koga village the contact is best exposed in the bottom of a small stream (Grid Ref. 520383, 1," 43B/7). Here Koga syenites dip southwestwards under the Babaji syenites at 45° to 55°. The former is mylonitized to a finely foliated white rock with black streaks. Shearing is confined however to a 3 feet thick zone while away from the contact the effect gradually diminishes until at about 3½ feet from the contact the primary flow structure of the Koga syenites becomes clearly visible with flow-plane parallel to the plane of contact. It is interesting to note that Babaji syenites on the other hand do not show shearing effects.

Southeastwards, the contact swings abruptly from NW-SE to a NE-SW direction on the southern slope of the spur. It continues in a general southwest direction along this slope to a place just north of Shpala. At this locality, the actual contact is obscured by thick shrub and scree.

In the vicinity of Naranji Kandao, Babaji syenites are fenitized so that there is a gradual decrease in the quartz content as one approaches Naranji Kandao along the Naranji stream. Simultaneously, there is a gradual increase in the amount of divergent aggregates of an acicular soda-pyroxene ; final product being a coarse grained perthite-aegirineaugite rock. The contact of Babaji syenites and Koga syenites is again not well marked. The rock exposed in Naranji Kandao proper is a cancrinite-bearing syenite with flow structure, accompanied with lenses of carbonatite.

From Naranji Kandao. the boundary sweeps around southeastwards and continues around Miane Kandao. From here it turns northeastwards and can be traced to the valley of Allah Dosh Tangi before it disappears under the alluvium of the Chamla valley.

Field relationships within the Koga syenites :

These can be best studied on the basis of observations in the following localities :—

1. Miane Kandao—Sahbaga Road Section.

(*a*) General : The geology of this road section was recorded at a scale of 6" to 1 mile, including positioning of the road (Fig. 3). Moving from southeast to northwest, the first exposure of feldspathoidal rocks is encountered at a place about one third of a mile ESE of Miane Kandao. The rock occurs in the form of a few feet thick almost vertical dyke of nepheline syenite which cuts across the Chingalai granodiorite gneiss ; similar dykes are encountered further northwestwards at irregular intervals. They generally show non-parallel walls and structure based on radiating growth of alkali feldspar crystals (bostonite structure) indicating crystallization under static conditions. Apart from alkali feldspar and nepheline, these dykes generally contain a little blue sodalite and purple fluorite. It is evident that many of these dykes have originated by the replacement of the granodiorite gneiss.

From Miane Kandao the road runs roughly northwestwards for about half a mile when it turns sharply northeastwards. Just before this sharp turn of the road, flow layering is discernable in the middle of a syenite dyke so that it is thought to be an intrusion of the Koga syenitic magma. It is therefore indicative of the ultimate source of those fluids which produced feldspathoidal dykes,by replacement, elsewhere in this road section. Granodiorite gneiss predominates for the next three-quarters of a mile and contains several dykes of syenite, some with white albite and others with nepheline and some sodalite and fluorite. One interesting feature of these rocks is the presence of thin layers and impregnations of an unidentified powdery rosepink mineral. This feature is mostly developed in the vicinity of Jalali Kandao. From Jalali Kandao (Grid Ref. 527344, 1", 43 B/11) to northwards, Koga syenites predominate but contain large xenolithic blocks (measurable into yards) of the granodiorite gneiss. *Thus a zone of transition exists between granodiorite gneiss and Koga syenites with intrusive and replacement dykes of Koga syenites in granodiorite gneiss on one hand and the Koga syenites with xenolithic blocks of granodiorite gneiss on the other.*

Further northwards Koga syenites continue till the bottom of the slope at Sahbaga Bridge where steeply dipping planar flow structure is very well displayed. At places, particularly around the xenoliths of granodiorite gneiss, the flow structure may show a sinusoidal appearance (Fig. 4). Spheroidal weathering is common (Fig. 5). The Koga syenites here include nepheline syenite, nepheline-sodalite syenite, nepheline-cancrinite syenite and nepheline pegmatites.

The Koga syenites commonly show uniform grain size but locally they coarsen to pegmatitic

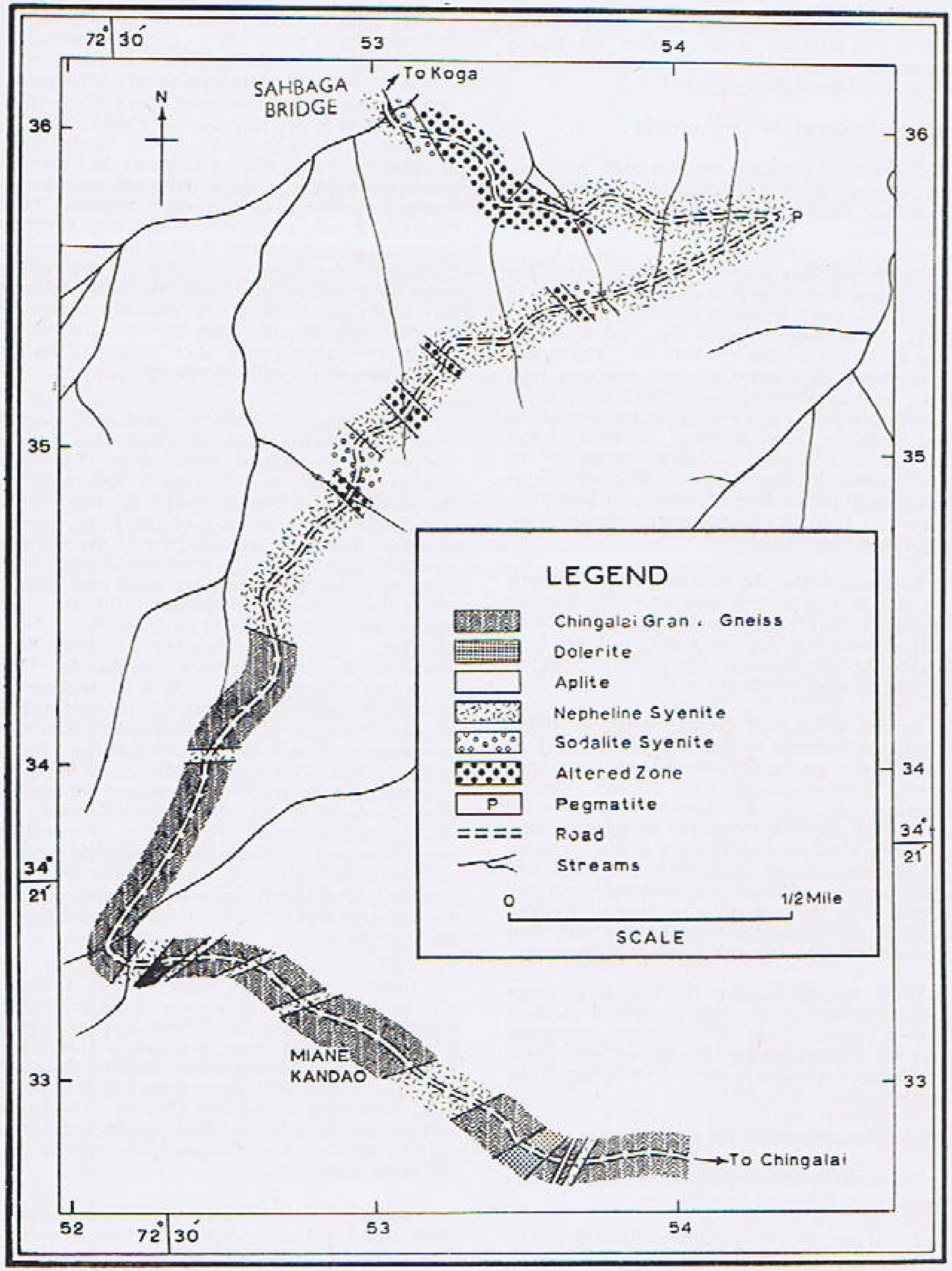

Fig. 3. Geology of Miane Kandao - Sahbaga road section.

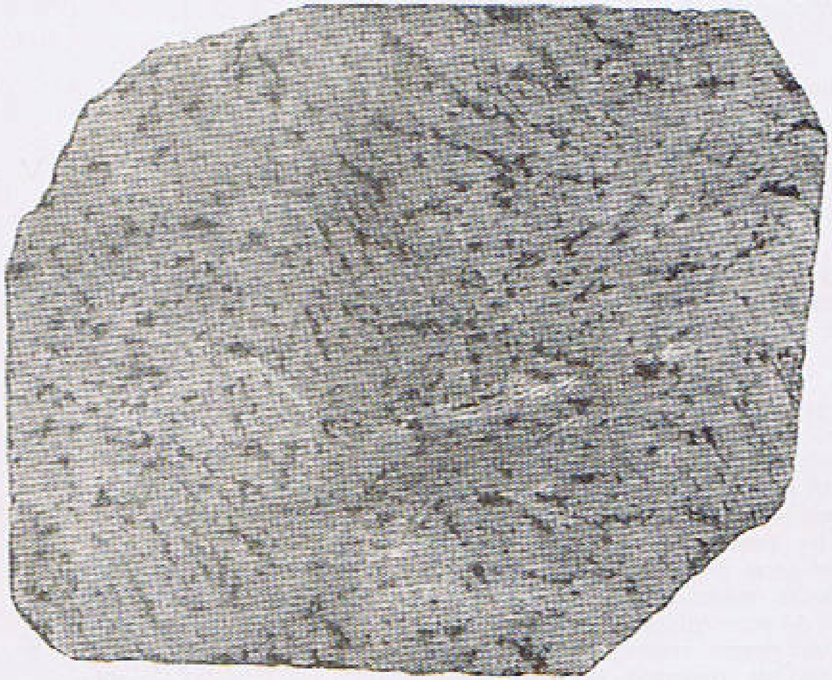

Fig. 4. Sinusoidal flow structure in Koga syenite in the vicinity of xenolithic blocks. (× 2).

Fig. 5. Spheroidal weathering in Koga syenite.

dimension with large alkali feldspar and nepheline (upto 8 cm long), ilmenite (1 cm) and zircon (0.5 cm) crystals. Pegmatites do not have sharp margins. Nepheline syenite with prominent flow structure (Fluidal Nepheline Syenite) may contain cognate inclusions of more or less similar mineralogical composition but with a finer grained aplitic texture and a massive structure. Sodalite syenite occurs in restricted areas and is invariably associated with hydromuscovitized syenite (hereafter called Alte ed Rock Zone). *The association "sodalite syenite—altered rock zone" is so persistent that the highly coloured reddish altered rock zones' may be used as guide to locate sodalite syenite, which is usually rich in zircon.*

(*b*) Xenolithic Blocks : Large oval-shaped blocks of granodiorite gneiss (upto 10×8 sq. feet. outcrop) are abundant in the Koga syenites. The blocks are generally traversed by porphyritic aplites while both are cut by thin veins of the surrounding feldspathoidal syenites. Joint system in the syenite is simple whereas in the blocks it is quite complex. It is probable that the granodiorite gneiss had a joint system of its own on which the joint system of the Koga syenites was imposed later.

(*c*) Hydrothermal Activity : Two features of the rocks exposed in the Miane Kandao-Sahbaga road section appear to be a result of hydrothermal activity. This conclusion is based on the following observations :—

(*i*) Occurrence of cavities and open veins lined with crystals of aegirine augite that show acicular habit (upto 5 mm long) and a tendency to grow normal to the walls of the vein (e.g. locality at Grid Ref. 532352, 1", 43 B/11). A vein further down the road (Grid Ref. 539557, 1", 43 B/11) contains excellent prismatic crystals of greenish black aegirine upto 4 cm long and 1.5 cm in cross-section. These veins are rather rare and occur in nepheline syenite and blocks of the granodiorite gneiss but not in the sodalite syenite.

(*ii*) Occurrence of zones of altered nepheline syenite in the vicinity of sodalite syenite. The zones of alteration are from a few feet to about 100 feet wide with gradational margins over a few feet. In early stages of alteration, nepheline is selectively replaced by bunches of a white, slightly green micaceous mineral, probably hydromuscovite. Alkali feldspar laths remain clearly visible in the hand specimen. At some places the 'altered rock zone' contains some coarse brownish red feldspar crystals with interstices occupied by pyrite (No. 11234) while mafic minerals are generally absent.

In advanced stages of alteration, the feldspar is repl ced by a clayey material and the primary flow structure is destroyed ; the product is an earthy, porous rock, stained with various shades of pink, red and brown. Similar rocks have been described from the Ditro nepheline syenite complex by Streckeisen (1960).

2. Bibi Derai Outcrop :

This is a small isolated hill which rises about 200 feet above the level of the Chamla valley. Its outcrop (Fig. 6) is elongated in the northsouth direction with a length of half a mile and a maximum width of one fifth of a mile.

Koga syenites occupy the northern two thirds of the outcrop while the southern one third and comparatively low lying area is occupied by the Babaji syenites ; the contact between the two runs in the NW-SE direction. The varieties of Koga syenites exposed here include nepheline syenite and nepheline-alkali feldspar pegmatites. Here the nepheline syenite is a tough, greenish grey, white weathering rock which is quite popular as a building stone among the local population. Flow structure marked by the parallel alignment of feldspar laths is well developed and shows a trend parallel to the contact plane. Towards middle of the outcrop and near contact with the Babaji syenite, the grain size coarsens and there is local development of patch

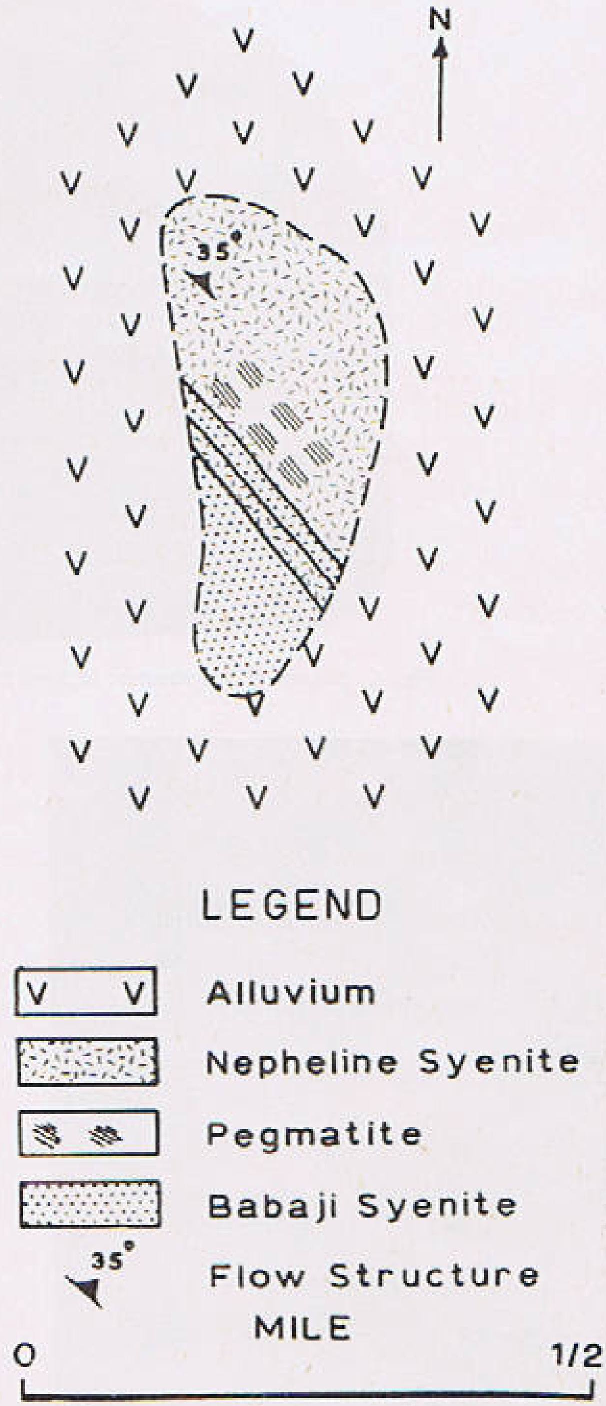

Fig. 6 Geological sketch of the Bibi Derai outcrop.

pegmatites (outcrop area upto 20×20 sq. feet). These pegmatites are bimineralic and contain only nepheline (upto 6") and alkali feldspar (upto 3") crystals. The outlines of these pegmatites are quite irregular and no zoning is visible. In addition some pegmatitic dykes with regular parallel walls (upto 1 foot thick) consisting of nepheline, alkali feldspar and biotite intrude into the fluidal nepheline syenite.

The southern part of the Bibi Derai outcrop is occupied by a coarse grained, massive or sheared syenite with little feldspathoid or quartz. On lithological basis this syenite is correlated with Babaji syenites. The colour is generally white and the main constituent minerals are alkali feldspar, biotite and pyriboles while sphene is a common accessory.

Following observations show that the Koga syenites are younger than and intrusive into the Babaji syenites :—

(*i*) The Koga syenites shows well developed primary flow structure while the Babaji syenites entirely lack it.

(*ii*) A separate dyke of the fluidal feldspathoidal syenite (Koga syenites) cuts across the Babaji syenites at a short distance south of the main contact between the two rock types (Fig. 6).

(*iii*) Babaji syenites are variable in texture and are considerably sheared indicating that they solidified prior to intrusion of the Koga syenites.

3. Koga Outcrop :

The eastern tip of the ridge near Koga offers one of the best and easily accessible exposures for the study of a multiplicity of rock types ranging from aplitic to pegmatitic in texture and oversaturated to undersaturated in composition. Thus, a remarkable variety of rock types and minerals is present in this relatively small area as described below :—

(*i*) Coarse syenite, with or without quartz, at places rich in ilmenite : This syenite contains angular dolerite xenoliths and aplite dykes, typical of the Babaji syenites elsewhere in the area, and is considered part of the same massif.

(*ii*) Aplites with curved cognate inclusions : These aplitic dykes, upto 1 foot thick, are composed of a peculiar mixed rock and cut the coarse grained Babaji syenites. The rock is of white colour and is characterised by curved and embayed cognate inclusions of a light brown shade. The cognate inclusions are found to consist almost entirely of microcline while the main rock is composed of an aggregate of albite and microcline.

(*iii*) Fluidal nepheline syenite, at places rich in melanite : This syenite is essentially similar to the nepheline syenite of the Bibi Derai, except for an abundance of melanite. Its intrusive relation to the Babaji syenites is shown by the presence of narrow dykes that intrude into the Babaji syenite. Furthermore, large xenolithic blocks (measureable in feet) of the latter are found to occur in the former.

(*iv*) Pegmatites : These occupy a zone with irregular outlines, about 10 feet thick and are elongated in a roughly north–south direction. They contain nepheline, ilmenite and alkali feldspar as main constituents, and a host of minor constituents such as zircon, sodalite, and biotite.

4. Other Areas :

Geology of the areas, other than those described above, is not well exposed and relationships are consequently less clear. Only brief notes are given here on such areas as show features of special interest.

About a mile eastnortheast of Sahbaga (Grid Ref. 555367, 1", 43 B/11) a lamprophyre dyke cuts across the Koga syenites. The rock is dense with a slightly porphyritic texture and shows buff sphene wedges that stand out against greenish black amphibole aggregations (No. 10226). Koga syenites along the Landai Pitao Sar ridge are characterized by a protoclastic texture.

The Koga syenites in the area between the Sahbaga-Miane Kandao road and Naranji Kandao are characterized by increasing concentration of cancrinite.

In the area around Naranji Kandao, replacement activity associated with the Naranji Kandao carbonatites has produced three distinct effects :—

(*i*) impregnation of surrounding rocks with calcite and apatite.

(*ii*) development of fenites which form sack-form bodies of a cavitous rock consisting of very coarse, grey to black alkali feldspar, biotite and calcite with minor zircon and apatite.

(*iii*) replacement veins along which Koga syenites and Babaji syenites have been replaced by acicular, divergent to radial aggregates of black aegirine augite. Such veins are most common on the slopes south and southeast of Shpala. A few narrow dykes, upto one foot thick, of fluidal Koga syenites are exposed just south east of Lalu village. These appear to be the westernmost extensions of Koga syenites.

PETROGRAPHY

Associated rocks :

1. Chingalai Granodiorite Gneiss.

This group consists of granitic to granodioritic gneisses with dykes of aplite and dolerite. Various members are described below in turn:—

(*a*) Granodiorite Gneiss : The rocks of this group, are typically peraluminous and are characterized by the abundance of biotite, K-feldspar phenocrysts (upto 2 cm across), and a crude foliation with a hypidiomorphic granular texture. Quartz forms granular mosaics containing strongly strained grains of upto 2 mm size. It is interstitial to other minerals but may also occur as embayed and resorbed inclusions in feldspar.

Plagioclase composition is generally in the oligoclase range (11% to 25% An) while near the dolerite xenoliths it is, locally, andesine in composition and crystals may show reverse zoning. Deuteric alteration to sericite and clinozoisite is common. Hornblende is present in a few cases and contains dust-like opaque inclusions and shows alteration to biotite. At the contact with altered plagioclase, hornblende is replaced by bluish green Na-amphibole ; such a replacement is not seen at the contacts with microcline. It is probable that sodium was released from plagioclase during its alteration.

Biotite is typically brown and characteristically occurs as bent and fractured flakes (Fig. 7). Many crystals are associated with sphene indicating the titanium-rich nature of biotite. Chingalai gneiss is the only rock type of the Koga area in which biotite contains pleochroic haloes that are formed around zircon crystals.

Alkali feldspar is a carlsbad-twinned microperthite with film-like exsolution lamellae of albite. At places it is replaced by plagioclase with the development of myrmekite texture. It is frequently altered to muscovite while cracks within feldspar crystals are filled by granular quartz. Rare accessories include apatite, zircon, ilmenite and tourmaline. Chemical and modal analyses of two specimens of Chingalai granodiorite gneiss are given in Table I.

Fig. 7. Chingalai gneiss (Specimen No. 10277) shows biotite-extreme left, plagioclase in the centre & right, quartz with strain lamellae-middle. × 22 Crossed nicols.

(*b*) Aplites. : Aplite dykes, varying from a few inches to a few feet in thickness, are numerous in Chingalai granodiorite gneiss, with a mineralogy similar to the latter. In the hand specimen the rocks are leucocratic with aplitic (grain size about 1 mm) and occasionally somewhat porphyritic texture with phenocrysts upto 5 mm in size.

Quartz occurs as equidimensional, anhedral grains with uneven extinction. It contains inclusions of amphibole and ore but may itself occur as resorbed inclusions in feldspar. Microcline microperthite occurs as phenocrysts and contains narrow, bead-like bodies of albite and inclusions of amphibole and ore. Carlsbad and tartan twinning of microcline is characteristic. Plagioclase is oligoclase to andesine in composition. In aplites, with doleritic xenoliths, plagioclase shows oscillatory zoning in such a manner that the core and margin are sodic while the intermediate zone is relatively calcic; calcic zones are characterized by deuteric alteration to clinozoisite and muscovite.

Hornblende is the characteristic mafic mineral while brown biotite appears to be almost all secondary after hornblende. Ilmenite, sphene, zircon and apatite are present as accessory minerals.

(*c*) Meta-dolerite : In addition to the dolerite xenoliths there are numerous basic dykes in the granodiorite gneiss. These are massive rocks with a subophitic texture and grain size of about 0.6 mm.

Plagioclase (45%) is labradoritic in composition (64% An) and forms laths upto 0.4 mm long. Hornblende (49%) is pleochroic from colourless through green to brownish green ($2V_x = 60°\text{-}70°$, −ve). Biotite (1%) flakes (upto 0.1 mm), are secondary after hornblende while magnetite (5%), grains (upto 0.2 mm) are disseminated throughout the rock.

TABLE I

Chemical and mineralogical composition of Chingalai granodiorite gneiss

Specimen No.		10263	10277	*Modal analysis* 10263	
SiO_2	..	61.47	58.78	Microcline microperthite	11.3
TiO_2	..	0.67	0.97	Plagioclase (16% An)	42.5
Al_2O_3	..	18.69	17.70	Quartz	22.0
Fe_2O_3	..	1.96	1.21	Biotite	22.1
FeO	..	3.04	5.77	Hornblende	2.0
MnO	..	0.12	0.08	Accessories	0.1
MgO	..	0.79	0.78		..
CaO	..	2.68	3.86		..
Na_2O	..	4.60	5.20		..
K_2O	..	5.00	5.00		..
P_2O_5	..	0.21	0.25		..
H_2O+	..	0.48	0.39		..
H_2O-	..	0.17	0.13		..
Total :	..	99.88	100.12		

The chemical analysis of a sample (No. 11236) from a dyke in Chingalai granodiorite gneiss southeast of Miane Kandao is given in Table 2.

2. Babaji Syenites and Granites.

This group consists of a rather varied assemblage of alkali granites, quartz-bearing aegirine augite and arfvedsonite nordmarkites, quartz-free aegirine-augite syenites and aplites. These rocks are characterized by a general peralkaline nature, enrichment in soda, and a granitoid texture. These are described below :—

(*a*) Nordmarkite: This is best exposed along the Ambela-Babaji Kandao road section outside the area mapped.

Texturally it is coarse grained, hypidiomorphic granular rock (Fig. 8) that is composed of microcline microperthite, albite, quartz, aegirine-augite, arfvedsonite, biotite and ilmenite.

Microperthite crystals (upto 1 cm) occur with an almost equal proportion of soda and potash feldspar phases with acicular inclusions of an opaque unidentified mineral. Albite (6% An) and

TABLE 2 **Chemical analysis of meta-dolerite** (No. 11236).

SiO_2	46.08
TiO_2	3.28
Al_2O_3	12.07
Fe_2O_3	3.33
FeO	11.60
MnO	0.31
MgO	6.81
CaO	11.02
Na_2O	4.20
K_2O	0.50
P_2O_5	0.35
H_2O^+	0.39
H_2O^-	0.09
Total :	100.03

quartz occur as subhedral crystals; the latter shows strain lamellae with uneven extinction.

Subhedral aegirine-augite is pleochroic with large 2V and X $\wedge$ c=40°. Marginal alteration to sodic amphibole and, in turn, to biotite is common. The latter is pleochroic from straw yellow to reddish brown thus indicating a high titanium content. Ilmenite is anhedral and is much altered to leucoxene. Tourmaline, sphene, calcite and euhedral apatite occur as accessories. The chemical composition and mode of a specimen is given in Table 3.

(*b*) Alkali Granite: With increase in the amount of quartz, nordmarkite grades into alkali granite, which is a coarse, hypidiomorphic granular rock composed of quartz, microcline microperthite, albite, biotite, arfvedsonite, sphene, ilmenite and apatite.

Anhedral quartz (upto 4.5 mm) shows uneven extinction and comprises 30 to 40% by volume of the rock as against 5-8% in nordmarkite. Microperthite (upto 1.5 cm) contains almost equal amounts of strongly twinned K-and Na-feldspar phases that are intergrown as coarse regular lamellae. Inclusions of acicular pyribole oriented parallel to (010) and (001) cleavage in addition to those of biotite, ore and apatite are common, Opaque dustlike inclusions are selectively concentrated in K-feldspar phase. Independent albite (1-6% An) laths (upto 0.6 mm) form granular mosaics and occupy the rims and interstices of microperthite crystals. Arfvedsonite (upto 2.3 mm) forms subhedral crystals frequently surrounded by later biotite grains (0.1 mm). Sphene is generally very light brown and non-pleochroic but may in some specimens be slightly pleochroic from pink to yellow. Magnetite and ilmenite are altered to limonite and leucoxene respectively.

(*c*) Alkali Aplites : These usually form dykes upto a foot thick in alkali granites and differ from aplites of the Chingalai granodiorite gneiss in having albite instead of oligoclase or andesine. Their texture is somewhat porphyritic and protoclastic with phenocrysts of microcline in a groundmass of quartz, microcline, albite, aegirine-augite and biotite (Fig. 9).

Microcline (2 mm × 1 mm) forms non-perthitic anhedral grains that have inclusions of a green mineral which is apparently similar to the associated pyroxene. Crystals are generally fractured, with cracks healed by granular quartz. Albite (upto 1.5 mm) forms subhedral grains generally free of inclusions. Quartz (upto 0.3 mm) grains show weak undulose extinction. Pyroxene (upto 0.5 mm) is aegirine augite with a patchy green to light brownish green colour (X$\wedge$ c=11°−15°, Y=X= bottle green, Z=pale brown, −ve.) while biotite (upto 0.2 mm) occurs as thin brown flakes.

Koga feldspathoidal syenites :

Rocks of this group are characterized by silica-undersaturation enough for the presence of feldspathoids such as nepheline, cancrinite and sodalite. They show a remarkable flow structure except in the replacement dykes which commonly show a bostonitic structure. Dolerite bodies inside the Koga syenites are highly sheared and fractured and have been found to be xenolithic.

Various rock types, present in the area covered by the Koga Syenites, are described below :—

1. Nepheline Syenite :

This is by far the most common rock type in the Koga syenites with nepheline as the only feldspathoid present. These rocks are further classified into two main groups (*a*) those in which nepheline is approximately equal to or slightly more than total feldspar, called Foyaites. (*b*) those in which nepheline is less than total feldspar; these include two types :

TABLE 3.

Chemical and modal analyses of nordmarkite (No. 10251).

Chemical Composition			*Modal Analysis*	
SiO_2	..	65.61		
TiO_2	..	0.63	Microcline microperthite	83.2
Al_2O_3	..	17.38	Albite	1.5
Fe_2O_3	..	1.01	Quartz	6.9
FeO	..	1.11	Aegirine-augite	2.8
MgO	..	0.06	Biotite	1.8
CaO	..	1.08	Ilmenite	1.3
MnO	..	0.06	Sphene	1.1
Na_2O	..	7.02	Apatite	0.8
K_2O	..	5.88	Calcite	0.6
P_2O_5	..	0.18		
H_2O+	..	0.41		
H_2O-	..	0.05		
Total :	..	100.48		

(*i*) albite >microperthite—Litchfieldites.
(*ii*) microperthite >albite—Nepheline Syenites (Sensu Stricto).

(*a*) Foyaites: These are confined to a couple of narrow, upto 1 foot thick, dykes of a distinctly green colour even on weathered surfaces, and are seen cutting across the nepheline syenite on the ridge west of Koga.

Texturally these are medium grained, protoclastic and foliated rocks containing nepheline, albite, microcline-microperthite, aegirine augite, biotite and garnet with accessory amounts of sphene, fluorite and zeolite (Fig. 10).

In typical specimens, nepheline (upto 1.5 mm, usually much smaller) forms mosaics with albite grains. Larger grains contain acicular inclusions of pyroxene whereas smaller grains appear to be usually free of them. It is frequently altered to zeolite with radial aggregate. Pure albite (upto 0.7 mm long laths) occurs as clear twinned crystals. Microcline microperthite (upto 5 mm long) is phenocrystic and is slightly turbid.

Pyroxene forms fine prismatic crystals (upto 4.4 mm), often zoned with patchy green pleochroic core (usually rich in brown opaque dust) mantled by light coloured and slightly pleochroic, clear pyroxene. Extinction angle, $X \wedge c = 21°$, indicates its aegirine augitic nature.

Pyroxene appears to be replaced by nepheline and albite as indicated by its embayed margins. Biotite flakes (upto 0.3 mm long) are pleochroic in shades of brown and occur both as primary as well as a secondary phase after pyroxene. Sphene occurs as subhedral twinned wedges. Fluorite occurs as granular aggregates in narrow streaks and is interstitial to other minerals. Zeolite is found as fibrous, radial aggregates with low birefringence,

Fig. 8. Nordmarkite (Specimen No. 11219) shows microcline-microperthite-middle, quartz left top & pyroxene top right (dark) × 22 crossed nicols.

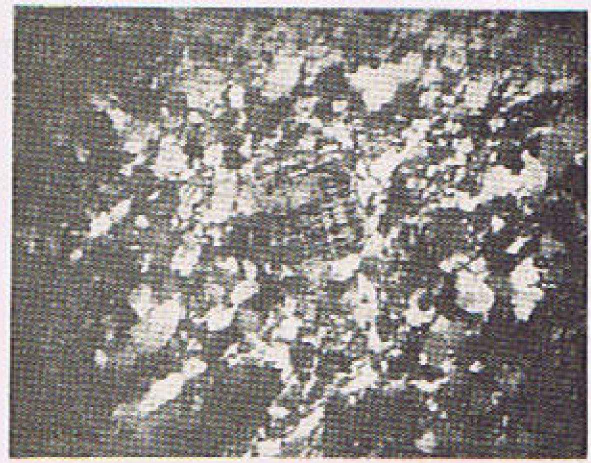

Fig. 9. Alkali Aplite (Specimen No. 11758) shows microcline phenocrysts in a matrix of quartz, albite & microcline, × 22 crossed nicols.

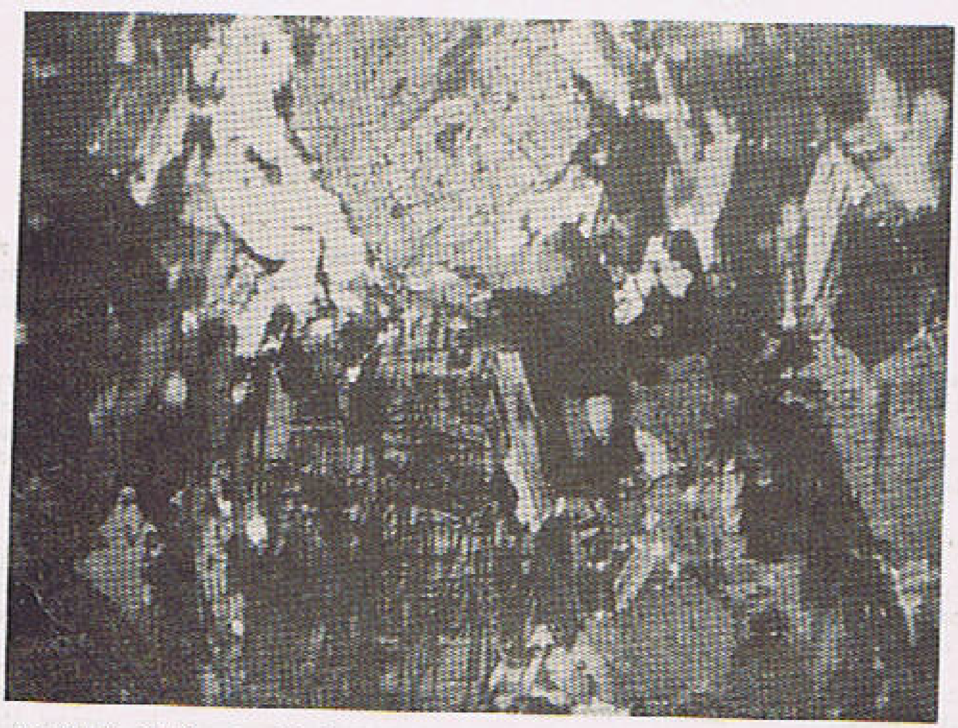

Fig 10 Foyaite (Specimen No. 11761) Microcline-bottom middle, nepheline top middle and bottom right (note acicular inclusions of Na-pyroxene), albite-polysynthetically twinned laths. × 60 crossed nicols.

that form narrow veinlets cutting across several grains and filling joint openings.

A typical specimen (No. 11761) is a protoclastic, foliated, medium grained rock with nepheline 45%, albite 30%, perthite 15%, pyroxene 8%. Minor constituents: fluorite, sphene and zeolites 2 %.

(*b*) Litchfieldites : These are confined to the southeastern part of the area covered by Koga syenites and are characterised by predominance of albite, an abundance of above mentioned minor constituents (Fig. 11) and prominent flow structure marked by parallel alignment of albite laths.

Minerals present include albite, microcline, nepheline, pyroxene, biotite, and a host of minor constituents which include, astrophyllite(?) haematite(?), fluorite, sodalite, and zeolites.

Microcline (upto 1.5 mm long laths) forms subhedral to anhedral grains. Exsolution lamellae of albite are either absent or confined to some doubtful lenticular wisps. Opaque dust, so common in K-feldspar in nepheline syenites and Babaji syenites, is sparse or absent but inclusions of albite and/or pyroxene may be present. Albite (upto 0.5 mm long and upto 3% An) is generally free of inclusions.

Nepheline (upto 0.3 mm) forms mosaics of subhedral to anhedral grains frequently altered to a colourless mica and a brownish dusty material, probably hydroxide of iron and also to fibrous zeolite with low birefringence.

Pyroxene (upto 0.4 mm) occurs as euhedral to subhedral grains, almost colourless with a faint brown tinge. Some grains may be zoned with a light green to yellow pleochroic core and colourless margin. Simple twinning on (100) is common and extinction angle $X \wedge c = 13°$.

Biotite (upto 1 mm) flakes are pleochroic in shades of brown and green, and may contain abundant minute inclusions of an unidentified red mineral and pyroxene. Haematite (upto 0.5 mm) is also present in minor amounts.

Sodalite is a minor constituent and is interstitial to other minerals. Fluorite (upto 0.5 mm, but generally smaller) forms anhedral grains that are scattered throughout the rock in the interstices of other minerals.

One characteristic constituent of these rocks is an intensely pleochroic deep reddish brown to pale yellow, high relief mineral which gives a diffuse biaxial (+ ve or − ve) interference figure. It appears to be astrophyllite but this is yet to be confirmed. Zircon forms small poikilitic crystals containing inclusions of pyroxene and albite and is probably of late stage of crystallization.

Brief petrographic description of two specimens is as follows.

Specimen No. 11201. Texture; flow structure, medium grained. Major constituents; albite 53%, nepheline 25%, microcline 15%, pyroxene 5%, biotite 1%. Minor constituents; zircon, astrophyllite(?) sodalite and fluorite 1%.

Specimen No. 11207: Texture; flow structure, medium grained. Major constituents; albite 60 %, microcline 15%, nepheline 11%, haematite 5%, biotite 3%, fluorite 2%, astrophyllite (?) 3%, zeolite 1%.

(*c*) Nepheline Syenite (Sensu Stricto): This is by far the most common rock type in the area covered by Koga syenites. Texturally it is characterized by a prominent flow structure and medium to coarse grain size. The flow is usually planar but locally it may be curved and sinusoidal. Mineralogically it is characterized by a predominance of microcline-microperthite over nepheline or albite; the three minerals together constituting roughly 90% of the rock. Mafic minerals in order of abundance, are arfvedsonite, aegirine augite and biotite. Minor constituents include melanite, sphene and ilmenite. (Fig. 12).

Carlsbad twinned microperthite (upto 7 mm) occurs as crystals flattened parallel to (010); its grain size is next only to localized deuteric melanite (upto 2 cm). K-feldspar fraction is normally dominant in the perthites but some specimens contain antiperthite. Microcline shows fine tartan twinning while the exsolved albite lamellae are regular and twinned on the albite law.

Subhedral albite (upto 7% An & upto 3 mm long laths) occupies the interstices between larger microperthite grains and frequently align themselves in an imbricate fashion along the boundaries of microperthite crystals. Nepheline (upto 1.5 mm) forms equant, euhedral to subhedral grains, laden with opaque dust and green acicular inclusions, presumably of Na-pyroxene. Similar inclusions have been noted in hypersolvus nepheline syenites of Haliburton-Bancroft area, Canada (Tilley and Gittins, 1964).

Arfvedsonite (upto 1.5 mm) forms subhedral crystals with deep bluish green to yellowish green pleochroism and 'flamy' extinction.

Pyroxene (upto 1 mm) is aegirine augite and

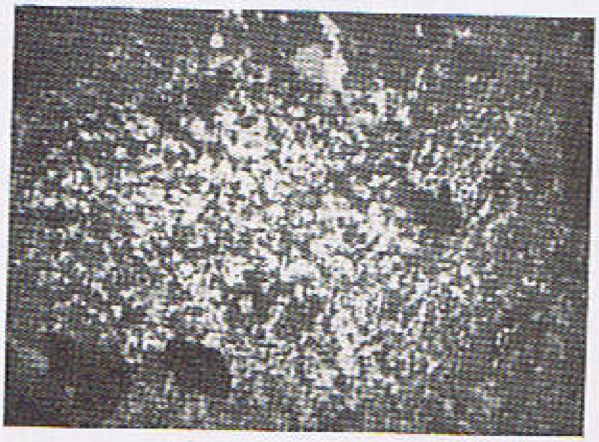

Fig. 11. Litchfieldite (Speciman No. 11774) phenocryst-right middle is nepheline. Pyroxene-left bottom with high relief. Matrix albite with subordinate microcline. ×10 crossed nicols.

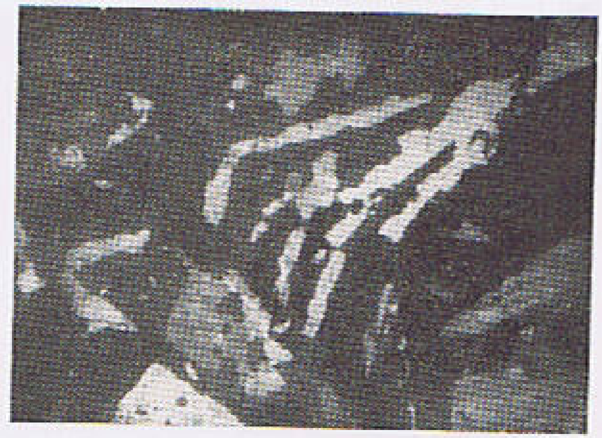

Fig. 13. Poikilitic melanite in nepheline syenite (Specimen No. 11211) shows melanite (dark) containing embayed laths of albite (light) × 22 crossed nicols.

Fig. 12 Nepheline syenite (Sensu Stricto, specimen No. 10260) Phenocrysts of neph line-left. Note acicular inclusions of pyroxene. Matrix consists of microcline microperthite, albite and aegirine augite. Note flow structure. × 22 crossed nicols.

Fig. 14. Nepheline-cancrinite syenite (Specimen No. 11456) shows microcline microperthite-bottom. Vermicular intergrowth of microcline & nepheline right middle, zoned & resorbed Na-pyroxene-left middle. Nepheline & cancrinite grains top. × 22 crossed nicols.

forms subhedral grains that may show marginal alteration to garnet.

Biotite (upto 0.5 mm) occurs as independent flakes as well as secondary growths after pyroxene and amphibole.

Garnet is deuteric or secondary after the mafic minerals. In melanite syenite near Koga, it acquires the role of an essential mineral as poikilitic crystals (Fig. 13) with six sided cross-sections (upto 2 cm, across). In thin section, it is generally brown except for some samples wherein it is only microscopic in size and may lack the brown colour.

Sphene usually occurs as small euhedral crystals and rarely as elongated crystals (upto 0.75 mm long). A few grains of opaque ore are probably ilmenite.

Petrographic notes on two representative samples are as follows.

Specimen No. 10260: Texture; medium grained with strong trachytoid or flow structure, at places curved. Mode : microperthite 40%, nepheline 25%, albite 25%, arfvedsonite 8 %, biotite, sphene and garnet 2 %.

Specimen No. 11211. Texture; medium grained with flow structure, with late stage poikilitic melanite. Mode : microperthite 70%, albite 10%, nepheline (partially replaced by zeolite and cancrinite) 8%, arfvedsonite 7 %, melanite 4%, sphene, biotite, aegirine augite 1%.

Minor varieties of syenitic rocks are described below :

(*i*) Nepheline—Cancrinite Syenite:

In some varieties of nepheline syenites and litchfieldites, cancrinite may attain a concentration of as much as 15%. This is most common in the area between Naranji Kandao and the Miane Kandao—Sahbaga Road section. Some feldspathoidal syenite dykes half a mile northwest of Naranji Kandao have also been found to contain cancrinite. This mineral is most abundant in the vicinity of Naranji Kandao carbonatite and may occur to the exclusion of nepheline. A cancrinite-rich litchfieldite (No. 11765) from a dyke near Lalu (1 mile northwest of Naranji Kandao) is medium grained, light grey in colour and appears white on weathered surface; the fresh surfaces have an oily lustre, due to the presence of nepheline and show strong flow structure. A peculiarity of the rock is the vermicular intergrowth of nepheline and microcline (Fig. 14).

Albite (upto 0.3 mm) lacks twinning and contains inclusions of biotite, while microcline (upto 0.5 mm) shows very fine tartan twinning but, lacks exsolution lamellae of albite. Nepheline (0.3 mm) of these rocks is free from acicular inclusions of pyroxene.

Cancrinite (upto 0.5 mm) shows a platy habit, never shown by nepheline, and is therefore regarded as primary. Maximum interference colour of second order blue (birefringence 0.022) corresponds to almost pure cancrinite (Winchell, 1959.)

Biotite (0.3 mm) is pleochroic in greenish brown to yellow colours while basal sections are green.

Ore (0.3 mm) occurs as hexagonal plates, translucent, reddish on thin edges and is probably haematite. Minor constituents include fluorite, zircon and astrophyllite (?).

A rough mode of a typical specimen is:—albite 50%, microcline 10%, nepheline 20%, cancrinite 15%, ore 2%, biotite 2%, accessories 1%.

(*ii*) Sodalite Syenite :

It is best seen in several zones on the Miane Kandao—Sahbaga road section where it occurs as a medium grained, massive rock with a light bluish grey colour and a flow structure which is less prominent than in the nepheline syenites. Minerals present include antiperthite, albite, sodalite, biotite, cancrinite, pyrite and zircon. Antiperthite (upto 7 mm) is of replacement type with relict patches of microcline inside albite (Fig. 15). Albite also occurs as small inclusions in antiperthite. A mineral (upto 0.4 mm) having birefringence higher than nepheline but lower than cancrinite with low relief and uniaxial negative character is thought to be vishnevite-rich cancrinite. The enrichment of the rock in sulphur is also indicated by the presence of pyrite.

Sodalite (upto 1 mm) is colourless in thin section and contains inclusions of nepheline and cancrinite and appears to be younger than both.

Biotite occurs as clusters (upto 5 mm), made up of individual flakes upto 1 mm long, and cut by veins of granular vishnevite. Wherever biotite and albite occur close to each other, vermicular haematite is present between the two minerals. Zircon crystals are nonpoikilitic and euhedral and attain a size of upto 1 cm.

A rough estimate of modal composition of a typical specimen (No. 11213) is; antiperthite 60%, vishnevitic cancrinite (?) 15 %, sodalite 15 %, biotite 9%, zircon and pyrite 1%.

Fig. 15. Sodalite syenite (Specimen No. 11213) Antiperthite-large twinned grain on left & lower middle, sodalite & vishnevitic cancrinite-granular aggregate middle & right top. Zircon-euhedral crystal-tops middle. × 65, crossed nicols.

Fig. 16. Hand specimen of fenite × ½
F=alkali feldspar ;
C=carbonate ;
Ae=aegirine augite.

Fig. 17. Lamprophyre (Specimen No. 10226) shows sphene-top & bottom left, alkali feldspar-left middle, right bottom. Rest is amphibole with six sided inclusions of apatite (colourless) × 22, crossed nicols.

(*iii*) Hydromuscovitized Syenite :

As mentioned earlier, this rock is mainly confined to the vicinity of sodalite syenite and is believed to be a product of hydrothermal activity. Nepheline syenite in Miane Kandao is also hydromuscovitized.

Texturally the rock is coarse hypidiomorphic granular with microperthite (upto 5 mm) crystals composed of approximately equal amounts of microcline and albite. Microcline grains are seen replaced by albite ; most strongly near hydromica pseudomorphs after nepheline. Twinning on the Carlsbad law is common and occasional twins may have three members; the crystals are cracked along broadly spaced fractures.

Colourless hydromica forms subhedral flakes making divergent aggregates. Mafic minerals are conspicuously absent ; rare pyrite crystals, partly altered to limonite, are present.

(*iv*) Pegmatites :

Patch pegmatites have been noticed at four localities in the Koga syenites; the locations are marked on Fig. 2.

The largest pegmatite body outcrops at about half a mile southwest of Koga. Crystals of nepheline upto 1 foot across occur, along with ilmenite crystals upto 6 inches long. Zircon crystals of a yellow colour and bipyramidal habit upto 4 cm across occur in nepheline. Locally nepheline is replaced by sodalite. Some pieces of purple zircon (upto 1.0 cm.) were found in the scree on top of the ridge southwest of Koga.

In thin section, nepheline shows two types of inclusions (*i*) green, pleochroic acicular inclusions, probably of aegirine augite (*ii*) prismatic inclusions of an unidentified colourless mineral with negative low relief and low birefringence. Both types of inclusions are mainly oriented parallel to the c-axis of nepheline. Cancrinite is interstitial to nepheline and also occurs as fillings of cracks in nepheline; birefringence of 0.022 indicates that it is pure cancrinite. Albite (6 % An), microperthite and muscovite occur as minor constituents.

The second largest pegmatite body occurs in the middle of Bibi Derai outcrop as irregular areas of upto 20 feet across in fluidal nepheline syenite. The mineralogy is simple with green nepheline, upto 6 inches across, intergrown with euhedral alkali feldspar, upto 3 inches long. A third pegmatite body, only about 1 foot across, occurs southwest of Sahbaga and is mineralogically similar to Bibi Derai occurrence.

The fourth pegmatite body was encountered near the hairpin bend in the road south of Sahbaga. Here vein-like pegmatitic bodies upto 6 inches thick occur in fluidal nepheline syenite. Perthite and nepheline crystals upto 3 inches long grow off the walls of the veins. Other minerals present include ilmenite, zircon, biotite and fluorite.

Carbonatite and Fenite :

The occurrence of carbonatite, its mineralogy and structure has been described in an earlier account (Siddiqui, 1967). Trace element content and Sr 87/Sr 86 ratio of two samples is given by Deans and Powell (1968). Since then further outcrops of carbonatite were noticed during summer 1968 on the Shpala—Naranji Kandao path. These are lenticular bodies measurable in yards. Their approximate location has been marked on the map (Fig. 2). In common with the carbonatite outcrops in Naranji Kandao, these are composed of coarse grained calcite (upto 2 cm) and pyroxene with abundant apatite crystals upto 1 cm long and 2 to 3 mm wide. Deep yellow sphene is an important accessory.

One feature of the carbonatite, which did not find mention in the earlier account, is the extensive fenitization associated with it. The location of outcrops of fenite is shown in Fig. 2. They consist essentially of large, smoky or buff coloured potash feldspar crystals upto $10 \times 7 \times 2$ cm in size growing in random orientation (Fig. 16). The angular interstices between the feldspar crystals are occupied by calcite, acicular aegirine augite and biotite. In the outcrops, calcite dissolves out differentially, during weathering, giving rise to angular cavities in fenites.

The best exposures for the study of fenites and their relationship to carbonatite, are found on the slopes immediately north of Naranji Kandao. Here steeply dipping veins can be seen projecting upward into the syenite from the top of the carbonatite. In the lower portion, the veins contain abundant calcite and apatite and minor alkali feldspar. Moving upward, the mineral composition gradually changes to a coarse feldspar-biotite-aegirine augite rock with little or no calcite.

A thin section study of the rock reveals that the Carlsbad twinned, coarse K-feldspar crystals are turbid due to the presence of very fine opaque dust and contain relict inclusions of albite (6% An) which they replace.

Biotite is an abundant mafic mineral and is pleochroic from brown to yellow. Pyroxene is aegiritic in composition; it is mostly bluish green but at places colourless with a light brown tinge. Calcite forms anhedral grains while apatite occurs as colourless prismatic crystals upto 2 mm long, which project into albite and K-feldspar, apparently replacing them.

Lamprophyre

Only one lamprophyre dyke has so far been encountered in the area. It is located at about half a mile south of the village Agarai. The width and length of the dyke are uncertain owing to poor exposure.

In hand specimen, the rock is dense and compact and appears dark greenish black in colour with wedge-shaped specks of white colour. In thin section it is found to be texturally panidiomorphic and composed almost entirely of amphibole and sphene with minor apatite and albite. Amphibole may occasionally form phenocrysts, upto 1 cm long and 4 mm across. A crude parallelism of euhedral sphene crystals is noticable. The bulk of the rock, however, is composed of grains about 3 mm long and 1.5 mm across. Amphibole has the following optics; pleochroism, X = deep green, Y = yellow green, and Z = bluisn green. $Z \wedge c = 36°$, $2V_x$ is moderate, indicating it to be kataphorite (Winchell, (1959, p. 42).

Albite (6% An) is xenomorphic and its grains are about 2 mm across. Apatite (2 mm x 0.5 mm) occurs as colourless prisms. Both sphene and apatite occur as inclusions in amphibole crystals as well as outside them but the included grains are generally smaller. Probably the growth of amphibole isolated them from further supply of ions. Chemical and modal composition of a typical specimen is given in Table 4.

TABLE 4.

Chemistry and mode of lamprophyre (No. 10226)

Chemical Composition			*Mode*	
			Mineral	*Percentage*
SiO_2	..	35.52	Amphibole	70.54
TiO_2	..	7.10		
Al_2O_3	..	11.76	Sphene	17.38
Fe_2O_3	..	6.83		
FeO	..	8.80	Feldspar	9.97
MnO	..	0.31		
MgO	..	5.58	Apatite	2.11
CaO	..	15.76		
Na_2O	..	4.20		
K_2O	..	1.32		
P_2O_5	..	1.28		
H_2O+	..	1.43		
H_2O-	..	0.13		
Total	..	100.02		

CHEMISTRY OF KOGA SYENITES

Six samples were so chosen as to represent the full range of rock types of the feldspathoidal syenites. These were analysed for their bulk chemistry and the analyses are presented in Table 5. In addition five samples representing various associated rock types were also analysed and their chemistry has already been given in Tables No. I to 4.

The contents of CaO, MgO and SiO_2 were determined gravimetrically while Fe_2O_3, MnO, TiO_2 and P_2O_5 were determined by Riley's (1958) colorimetric methods. The alkalies were determined in duplicate by flamephotometric method.

The trends of chemical variation of the feldspathoidal rocks are presented in Figs. 18 to 22. The general variations may be summed up as follows.

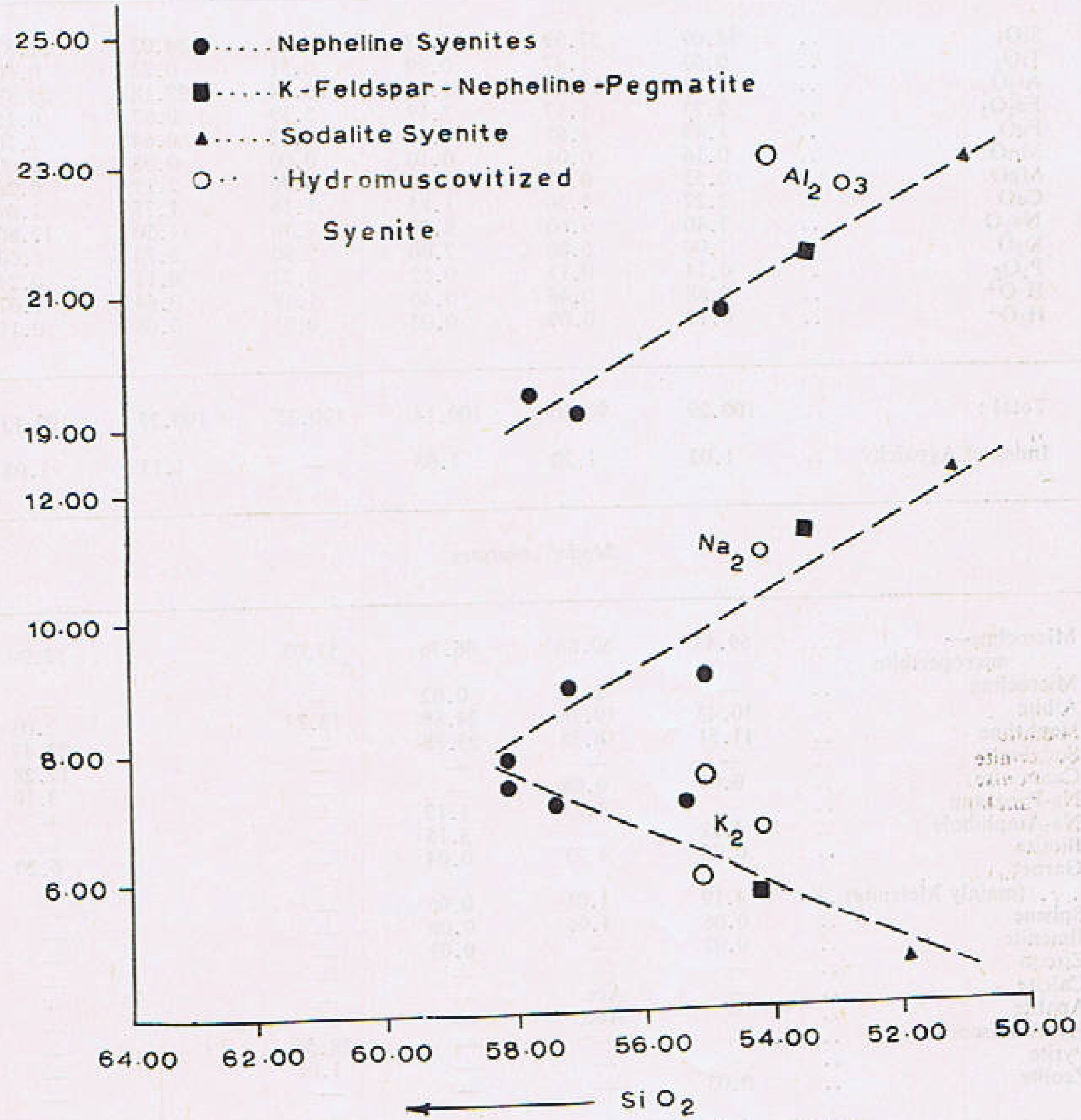

Fig. 18. Variation of Na_2O, Al_2O_3 and K_2O with respect to SiO_2 in Koga syenites.

TABLE 5

Chemical and mineralogical composition of Koga syenites.

Chemical Analyses

Sample No.		11211	10279	10260	11233	10259	11213
SiO_2	..	58.09	57.39	55.37	55.24	54.03	51.87
TiO_2	..	0.63	1.47	0.99	0.31	0.72	0.60
Al_2O_3	..	19.32	19.24	21.03	23.44	22.18	23.98
Fe_2O_3	..	2.23	1.17	2.19	3.39	0.67	0.15
FeO	..	1.49	1.61	1.54	0.72	0.64	2.76
MnO	..	0.16	0.04	0.10	0.00	0.08	0.00
MgO	..	0.53	0.51	0.30	0.96	2.17	0.26
CaO	..	2.27	1.30	1.85	1.16	1.77	1.69
Na_2O	..	7.40	9.60	9.20	7.70	11.50	12.80
K_2O	..	7.00	6.80	7.00	5.80	5.70	4.60
P_2O_5	..	0.14	0.12	0.12	0.22	0.11	0.24
H_2O^+	..	0.88	0.46	0.40	1.18	0.64	1.07
H_2O^-	..	0.15	0.09	0.05	0.21	0.08	0.11
Total :	..	100.29	99.80	100.14	100.33	100.29	100.13
Index of Agpaicity	..	1.02	1.20	1.08	—	1.13	1.08

Modal Analyses

		11211	10279	10260	11233	10259	11213
Microcline—microperthite	..	69.46	50.88	46.76	57.09		52.90
Microcline	..	—	2.12	0.02	—		—
Albite	..	10.43	19.76	24.88	13.27		2.05
Nepheline	..	11.51	16.58	23.88	—		23.47
Sodalite	..	—	—	—	—		12.28
Cancrinite	..	0.03	0.08	—	—		3.10
Na-Pyroxene	..	—	4.23	1.12	—		—
Na-Amphibole	..	4.22	—	3.15	—		—
Biotite	..	0.05	4.23	0.04	—		6.20
Garnet (mainly Melanite)	..	4.19	1.06	0.06	—		—
Sphene	..	0.06	1.06	0.06	—		—
Ilmenite	..	0.02	—	0.03	—		—
Zircon	..	—	—	—	—		—
Calcite	..	—	Acc.	—	—		—
Apatite	..	—	Acc.	—	—		—
Hydromuscovite	..	—	—	—	28.56		—
Pyrite	..	—	—	—	1.08		—
Zeolite	..	0.03	—	—	—		—

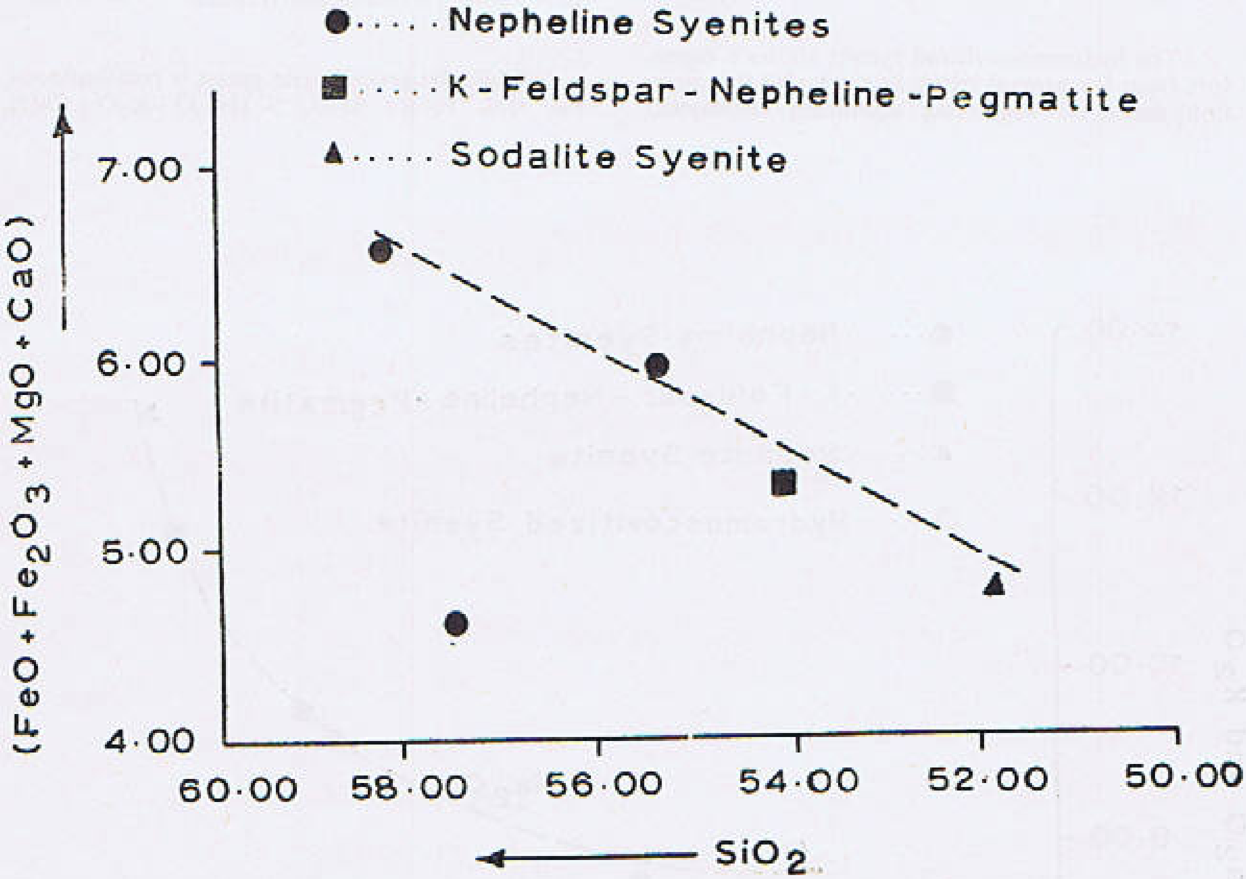

Fig. 19. Variation of ($FeO + Fe_2O_3 + MgO + CaO$) with respect to SiO_2 in Koga syenites.

As shown in Figs. 18 & 19, SiO_2 decreases with youngness of the rocks and the sequence is one of progressive desilication with differentiation. With decrease in SiO_2, the contents of K_2O and ($CaO + MgO + FeO + Fe_2O_3$) decrease while the amounts of Na_2O and Al_2O_3 increase. The amount of CaO increases (Fig. 20) with increase in ($CaO + MgO + FeO + Fe_2O_3$). In Fig. 19 one specimen of nepheline syenite (No. 10279) shows departure from the general trend by being very low in ($CaO + MgO + FeO + Fe_2O_3$). This rock differs from the others in having a protoclastic foliated structure. It appears that the mafic rich rest liquid was selectively squeezed out during shearing but the mechanism is not clearly understood.

In Fig. 21 the values of Na_2O and K_2O are plotted against ($Na_2O + K_2O$). Both Na_2O and K_2O first increase but later on diverge strongly in such a

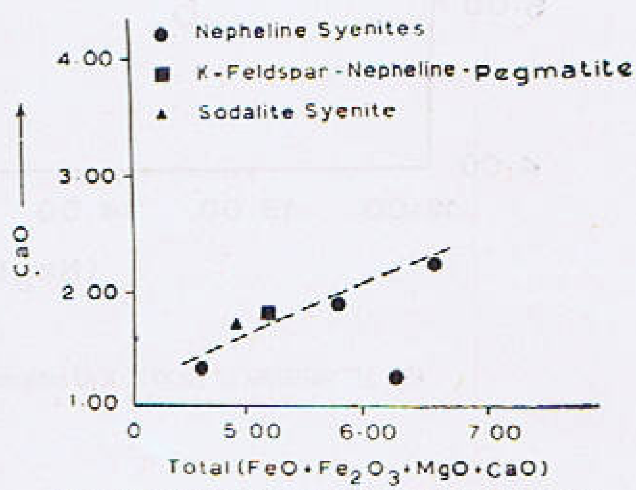

Fig. 20. Variation of CaO with respect to ($FeO + Fe_2O_3 + MgO + CaO$) in Koga syenites.

manner that K_2O decreases while Na_2O increases equally with increase in the total alkalies.

The hydromuscovitized syenite shows a departure from the general trend, as shown by the variation diagrams, suggesting significant enrichment in Al_2O_3 and depletion in Na_2O. Moreover it contains the least amount of total alkalies as compared with the unaffected syenites.

While the granodiorite gneiss is peraluminous, *i.e.* Mol. Prop. $Al_2O_3 > (Na_2O+K_2O+CaO)$,

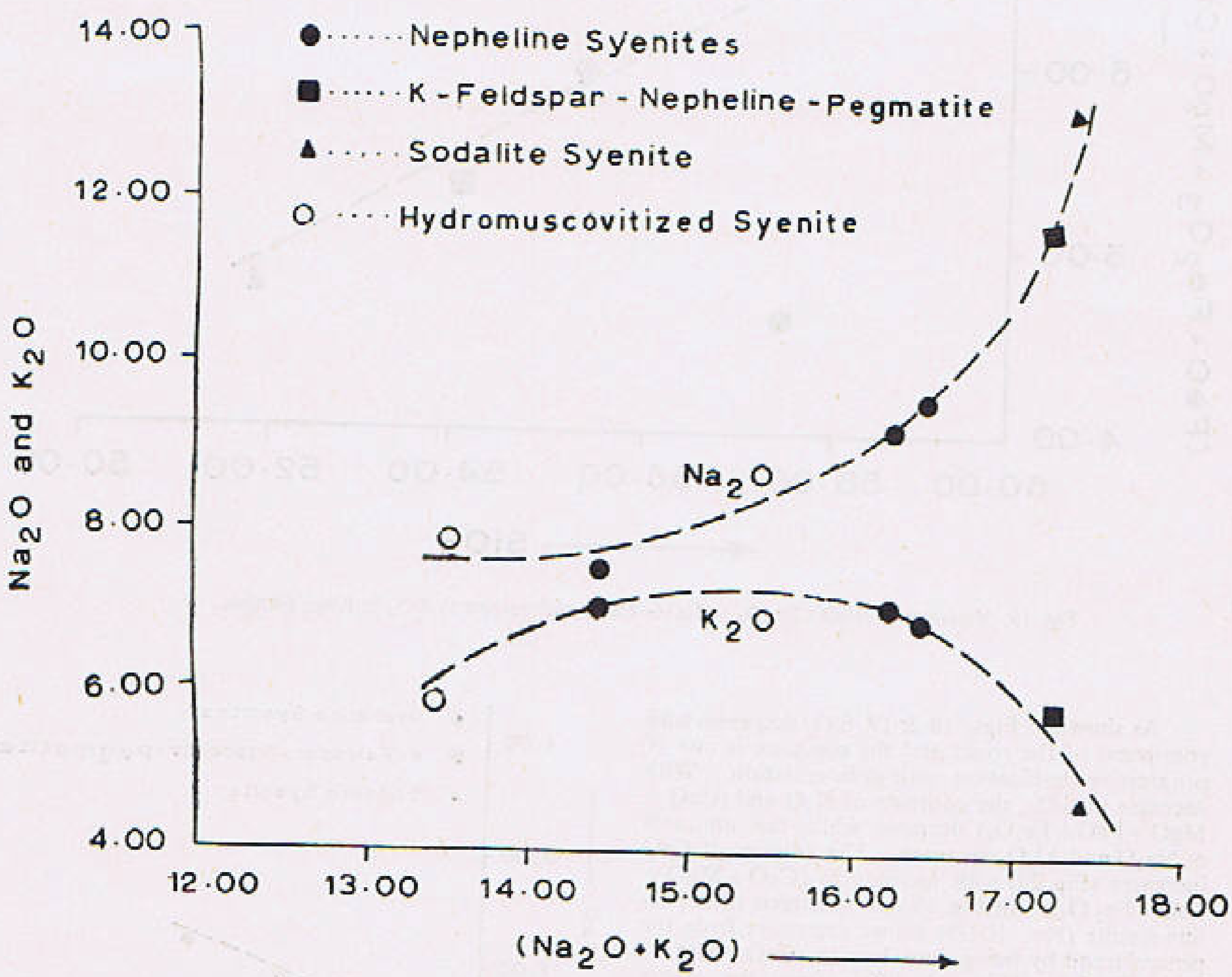

Fig. 21. Variation of Na_2O & K_2O with respect to (Na_2O+K_2O) in Koga syenites.

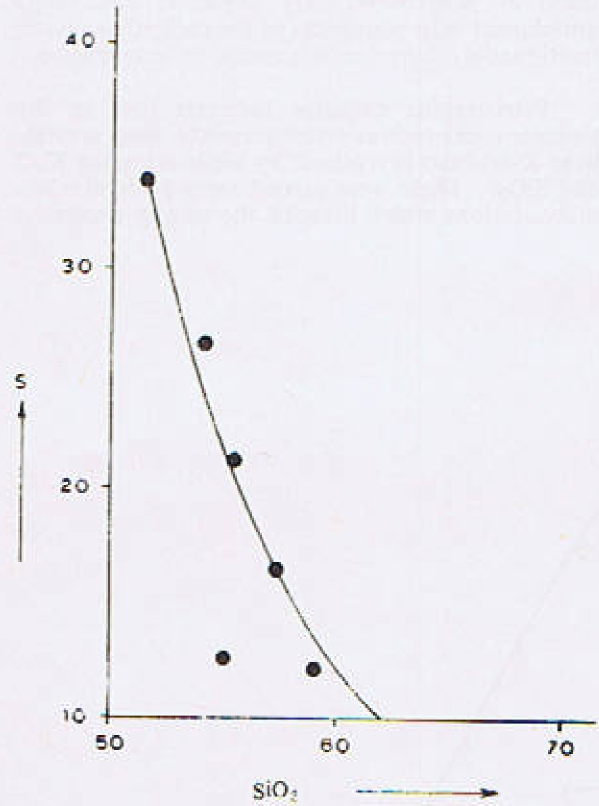

Fig. 22. Variation of Rittman's serial number with respect to SiO_2 in Koga syenites.

Babaji syenites and Koga syenites are peralkaline *i.e.* Mol. Prop. $Al_2O_3 < (Na_2O + K_2O)$, as defined by Shand (1947).

In Fig. 22, Rittman's serial number, $s = \frac{(Na_2O + K_2O)^2}{SiO_2 - 43}$ is plotted against weight percentage SiO_2 for the Koga syenites. With youngness s increases while SiO_2 decreases. According to Rittman (as quoted by Barth, 1962) this indicates assimilation of limestone to be responsible for the process of desilication.

However, this interpretation cannot be supported by evidence in case of Koga syenites. It is concluded that the above relationship between s and SiO_2 does not, in all cases, indicate limestone assimilation.

SUMMARY AND CONCLUSIONS :

The rock association of the Koga area is that of the granite-syenite-nepheline syenite type involving the process of derivation of undersaturated magmas from an oversaturated parent. Thus the Koga syenites are another example of complexes which include granite but close with nepheline syenite (Group B complexes of Tilley, 1958). The Ditro (Roumania), Berdiaush (Urals) and Vredefort (S. Africa) complexes are examples of this type of association. Regarding the origin of these, Tilley (1958), concluded that "the problem of interpretation of the sequences of this group of complexes remains."

Attention has been mostly focussed in this study on the Koga syenites as they form a separate unit in the area. More work is required on the Babaji syenites and Chingalai granodiorite gneiss to justify detailed discussion at this stage.

The mineralogical and chemical characters of the main rock types of the area are summerized as follows.

(*i*) Chingalai granodiorite gneiss and aplites—peraluminous, characterized by abundant quartz and biotite, plagioclase composition is in the andesine range.

(*ii*) Babaji syenites—peralkaline, mainly syenite, characterized by the presence of Na-pyroxene and amphiboles; sphene and apatite are important accessories.

The aplitic and granitic varieties are rich in quartz, have microcline microperthite and albitic plagioclase; mafic constituents are the same as in the syenites.

(*iii*) Koga syenites—peralkaline, have almost the same mafics and minor constituents as Babaji syenites but distinguished by the presence of feldspathoids instead of quartz.

It can be seen that while the Babaji syenites and the Koga syenites appear to be comagmatic, the Chingalai granodiorite gneiss belongs to a different and perhaps an older plutonic episode. On textural basis, the foliated Chingalai granite gneiss is thought to have suffered orogenic movements, while the Babaji syenites and Koga syenites appear to be late or post—orogenic as indicated by their granitoid and trachytoid textures respectively.

The magmatic origin of the Koga syenites is indicated by a prominent flow structure. At places, particularly near the xenolithic blocks, the flow is disturbed and sinusoidal and is believed to have been induced in the viscous Koga syenite magma by its relative movement against the xenolith blocks.

Fig. 23 is a plot of normative contents of SiO_2, $NaAlSiO_4$ and $KAlSiO_4$ in the Koga syenites. The plots do not fall entirely in the low temperature trough of Petrogeny's Residua System but show a trend of progressive SiO_2 depletion and Na_2O enrichment with youngness of the rock; thus crystal fractionation alone does not appear to be operative.

Petrographic evidence indicates that in the younger rocks such as sodalite syenite, early crystallized K-feldspar is replaced by albite releasing K_2O and SiO_2. These were carried away by hydrothermal solutions which invaded the nearby nepheline

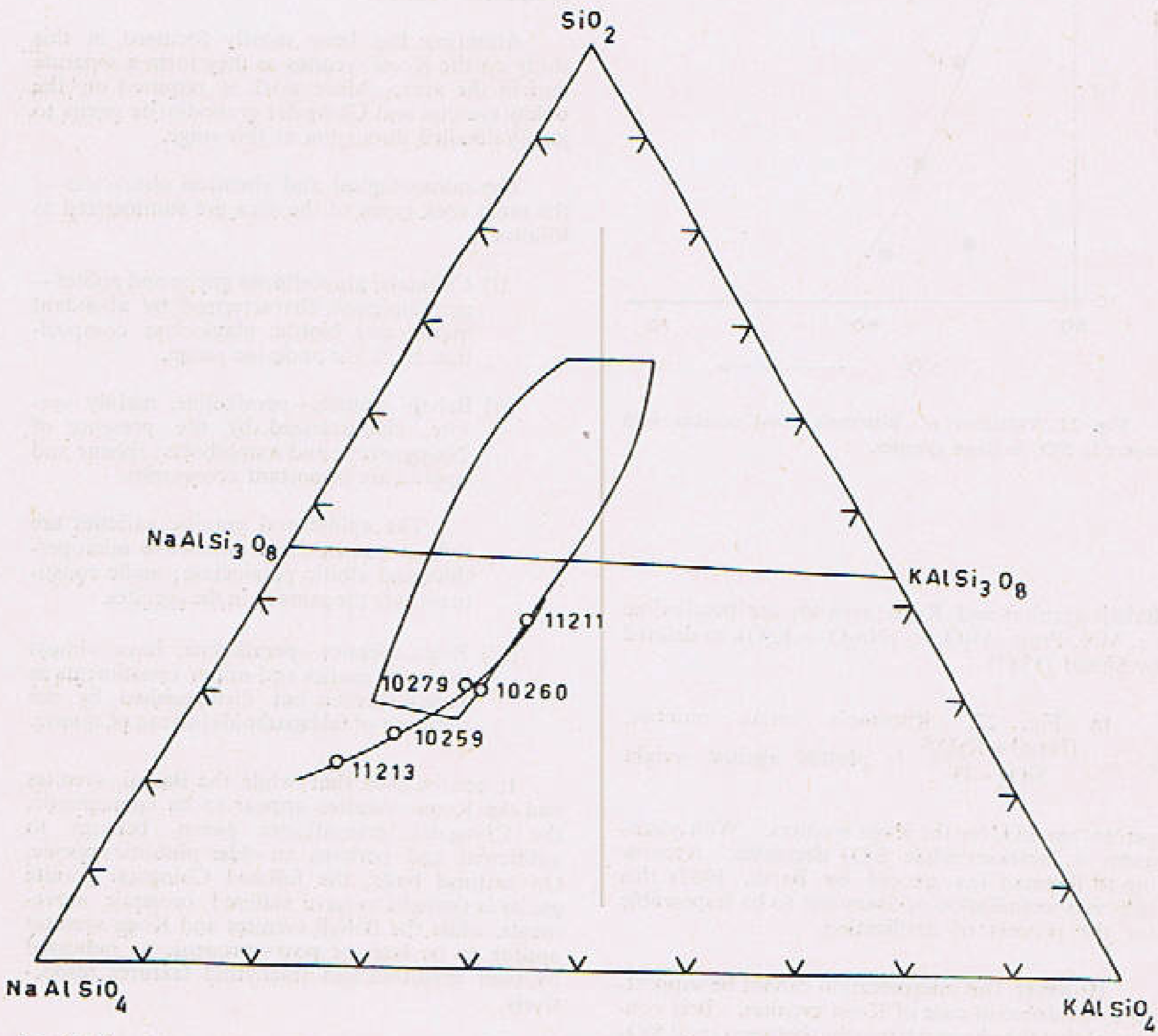

Fig. 23. Plot of normative contents of SiO_2, Na Al SiO_4 and KAl SiO_4 of Koga syenites in Petrogeny's Residua System.

syenite and brought about hydromuscovitization and argillization of the rocks.

Feldspathoidal syenite complexes are classified by petrologists into two main types (*i*) agpaitic and (*ii*) miaskitic. Agpaitic rocks are defined by Sörensen (1960) as (i) being peralkaline, nepheline syenites, characterized by the presence of aegirine, Na- amphibole, and/or aenigmatite, instead of biotite, diopsidic pyroxene and hornblende (*ii*) containing complex zirconium and titanium silicates instead of zircon and sphene and (*iii*) being rich in fluorine, chlorine and water.

While Koga syenites are peralkaline (agpaitic coefficient *i.e.* Mol. Prop. $Na_2O + K_2O/Al_2O_3$ greater than 1 in the analysed samples, see Table 5), they do contain zircon and sphene. Chlorine and fluorine are abundant only in sodalite syenite which occupies restricted portions of the outcrop. Even this contains abundant zircon and biotite. At the same time complex zirconium and titanium silicates are missing.

In this connection it may be mentioned that according to Heinrich (1967) carbonatites are essentially restricted to miaskitic rocks. It is therefore concluded that Koga syenites are miaskitic. Now, the Index of Agpaicity of all the analysed samples of Koga syenites is greater than 1, (Table 5) whereas Barth (1962) restricts the term 'Miaskitic' for rocks with Index of Agpaicity equal to or less than 1. The authors accept Sörensen's above definition of agpaitic rocks and would observe that Index of Agpaicity alone is not a reliable criterion for distinguishing between agpaitic and miaskitic nepheline syenites.

Regarding the origin of carbonatite in Koga syenite its coarse grain size and structures indicative of crystallization under static conditions (Siddiqui, 1967) show that the carbonatite magma crystallized at depth and that no connection with the surface was established.

Evidence shows that carbonatite was derived as a late differentiate from the Koga syenite magma as supported by the following facts.

(*i*) occurrence of calcite in late veins associated with the sodalite syenite.

(*ii*) increase of cancrinite with proximity of carbonatite in conformity with the magmatic sequence of crystallization to be nepheline—cancrinite—calcite.

The difficulty of high tem perature of melting of calcite in postulating a late magmatic derivation of carbonatite has been successfully overcome by the laboratory synthesis of simplified carbonatite fluids (Wyllie and Tuttle, 1960, 1962) Their results show that fairly mobile carbonatite magma can exist at 683°—450°C at pressures of 1000-10 bars.

Naranji Kandao carbonatite bears certain remarkable similarities with the Lueshe carbonatite of Kivu, Congo. The sövites of that area have been described (Meyer and De Bethune, 1960) as follows "Lueshe sövite shows, as far as carbonatites go, an unusual coarse grain. It is a holocrystalline coarse grained rock, mainly composed of calcite crystals upto 1 cm with varying amounts of aegyrine, apatite, alkali feldspars, pyrrhotite and pyrochlor. The micas, biotites and vermiculite are frequent. Aegyrine is by far the most important silicate mineral; it occurs in needles, bundles or suns." The description could almost word for word apply to Naranji Kandao carbonatite except for the absence of pyrochlor and pyrrhotite, and its coarser grain size (a maximum of 10 cm).

One interesting feature of the Naranji Kandao carbonatite is the presence of embayed grains of milky quartz, upto 1 cm. These appear to be the remnants of quartzose material which might have been incorporated from Babaji syenites by stoping action of the carbonatite magma. Similar corroded grains of quartz have been reported from the Firesand River carbonatite by Heinrich and Vian (1967).

The authors are aware of the limestone syntexis hypothesis (Daly, 1918) concerning the origin of alkaline rocks. As pointed out by Tilley (1958), in reactions between limestone and igneous magma, the production of nepheline is to be attributed to a desilication of the albite component of plagioclase and the feldspathoid is often accompanied by wollastonite. However, no wollastonite has been noticed in the Koga syenites nor any relict xenoliths of limestone have been noticed. Thus, if limestone syntexis had operated in the area, there is no evidence to substantiate its efficacy.

Of the theories that attempt to explain the genesis of granite-syenite association, the one based on the experimental studies in the system Na_2O—Al_2O_3— Fe_2O_3—SiO_2 (Bailey and Schairer, 1966) appears to fit the available evidence best. They suggest that if the existence of a peralkaline parent magma be assumed then it follows that it will be "peculiarly sensitive to any changes that will initiate a trend in the residual liquid towards either undersaturation or oversaturation", in the following two manners :—

(*i*) Transition from a peralkaline syenite magma to an oversaturated composition :

It is thought to be affected by the incongruent melting of acmite as suggested originally by Tilley (1958). It is known from experimental studies in the relevant systems that haematite is the early phase to crystallize which might be resorbed by the rest liquid to form acmite. If haematite is not resorbed the rest liquid would be enriched in silica initiating a trend towards silica enrichment in later differentiates.

(*ii*) Transition from a peralkaline syenite magma to an undersaturated composition :

For this transition Bailey and Schairer (op. cit.) suggest a mechanism based on incorporation of Fe^{3+} instead of Al^{3+} in the alkali feldspar molecule. Thus some $NaFe^{+3}\ Si_3O_8$ may crystallize in the early stages in place of $NaFe^{+3}\ Si_2O_6$ (acmite). The excess silica required for the crystallization of ferric-bearing feldspar would tend to deplete the rest liquid in SiO_2, thus producing a slightly undersaturated magma and initiating a trend towards undersaturated late derivatives.

The alternative liquid trends-oversaturated or undersaturated-are thought to develop by slight differences in PO_2, PH_2O or total pressure; the high oxidation state of iron tending to favour formation of iron-bearing feldspars. The presence of K in the magma would only accentuate the entry of iron in feldspars to form Fe^{3+}bearing K-feldspars, as these are known from several localities (Deer et. al., 1963). That iron has played a significant role in the crystallization of feldspars is indicated by the presence of minute oriented inclusions of opaque ore in the microperthites of Babaji syenites.

In the Koga area, a peralkaline magma is thought to be the parent magma which had differentiated along two contrasting trends; a trend towards SiO_2 oversaturation as indicated by the presence of quartz-rich aplite dykes, and the other towards SiO_2 undersaturation as shown by the formation of feldspathoid bearing Koga syenites.

ACKNOWLEDGEMENTS

The authors wish to thank Professor F.A. Shams Geology Department, Punjab University for critically reading the manuscript. M. Mujtaba helped in the point counting of some thin sections.

REFERENCES

Bailey D.K. and J.F. Schairer 1966. The System $Na_2O—Al_2O_3—Fe_2O_3—SiO_2$ at 1 Atm, and the Petrogenesis of Alkaline Rocks. *Journ. Petrol.* 7. pp. 114-170.

Barth, T.F.W. 1962. Theoretical Petrology, 2nd ed. John Wiley and Sons, New York, London.

Daly, R.A. 1918. Genesis of the Alkaline Rocks. *Journ. Geol.* **26**. pp. 93-134.

Davies R.G. and Riaz Ahmad 1963. The Orthoconic nautiloids of the Kala limestone and the probable age of the Swabi Formations. *Geol. Bull. Punjab Univ.* No. **3**. pp. 1-6.

Deans, T. & J.L. Powell 1968. Trace elements and strontium isotopes in carbonatites, fluorites and limestones from India and Pakistan. *Nature*, **218**, pp. 750-752.

Deer W.A., R.A. Howie and J. Zussman 1963. Rock Forming Minerals., vol. 4. New York. John Wiley and Sons. pp. 32-46.

——— 1966, An Introduction to the Rock Forming Minerals , Longman, London, p. 188.

Heinrich, E.Wm. and R.W. Vian 1967. A barite-quartz phase in the Firesand River Carbonatite, Wawa, Ontario. *Canad. Mineral.* **9**, pp. 252-257.

Heinrich E. Wm. 1967. Carbonatites—Nil-Silicate Igneous Rocks. *Earth Science Reviews.*, pp. 203-210.

Martin N.R., S.F.A. Siddiqui and B.H. King 1962. A Geological Reconnaissance of the Region between the Lower Swat and Indus Rivers of Pakistan. *Geol. Bull. Punjab Univ.* No. **2**, pp. 1-14.

Meyer, A., P. De Bethune 1960. The Lueshe carbonatite (Kivu, Belgian Congo), *Int. Geol. Congress*,, Part XIII. pp. 304-309.

Riley, J. P. 1958. The rapid analysis of silicate rocks and minerals. *Analy. chem. Acta.*,p. 413.

Shand, S.J. 1947. Eruptive Rocks, 3rd ed., London and New York.

Siddiqui, S.F.A. 1965. Alkaline Rocks of Swat, Chamla, *Geol. Bull. Punjab Univ.* No. **5**. p. 52.

———1967. Note on the Discovery of Carbonatite rocks in the Chamla Area, Swat State, West Pakistan. *Geol. Bull. Punjab Univ.* No. **6**, pp. 85-88.

Sörensen, H. 1960. On the Agpaitic rocks. *Rep. Intern. Geol. Congress.* Part XIII. p. 319.

Streckeisen, A. 1960. On the Structure and origin of the nepheline-syenite complex of Ditro (Transylvania, Roumania), *Rep. Inter. Geol. Congress* Part XIII, pp. 228-238.

Tilley, C.E. 1958. Problems of Alkali Rock Genesis. *Quart. Journ. Geol. Soc.* London, pp. 323-360.

Tilley, C.E. and J. Gittins 1964. Igneous Nepheline bearing rocks of Haliburton—Bancroft Province of Ontario., *Journ. Petrol.* **2**, pp. 38-48.

Winchell, A.N. 1959. Elements of Optical Mineralogy, Part II, John Wiley & Sons, New York.

NODULAR CHROMITE WITH PARTICULAR REFERENCE TO HINDUBAGH DEPOSITS, WEST PAKISTAN—A REVIEW

BY

A.K. SNELGROVE AND A. P. RUOTSALA

Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan, U.S.A.

Abstract : *Nodular chromite in serpentine, together with rare nodular serpentine in chromite, the latter with or without a subrounded chromite nucleus, are odd and intriguing constituents of the Alpine-type Zhob Valley igneous complex near Hindubagh, West Pakistan.*

An electron microprobe analysis across a chromite nodule reveals little change in concentration of Cr or Fe ; a_0 spacing ranges from 8.34 A to 8.30 Å from edge to center.

A literature survey suggests that chromite nodules exhibit a primary texture, although magmatic resorption, rolling during gravitational segregation, and hydrothermal alteration are possible rounding mechanisms. Overgrowth and cataclasis appear to be inadequate explanations of this texture. Compositional zoning of chromite, either additive or subtractive, and on individual nodular or granular ore body, and on regional scales is noted in various deposits elsewhere.

It is concluded that nodular chromite is of early magmatic origin and is a product of one generation of fractional crystallization of dunite magma, the component minerals of which became separated by crystal setting, not necessarily at the present site. Although analogy may be used to support the formation of nodular chromite by either liquid immiscibility or fractional crystallization, the latter is preferred because it is consistent with phase equilibrium studies of the system $MgO\text{-}SiO_2\text{-}Cr_2O_3$.

INTRODUCTION

While on a field trip in 1961 to the Zhob Valley igneous complex, near Hindubagh, Quetta Division, with staff and students from the University of Sind, Hyderabad, West Pakistan, the senior author became interested in the origin of the nodular chromite of that area.

The purposes of this paper are to review the literature and to attempt a general explanation of the formation of the peculiar round texture found in some chromite deposits. This texture is variously termed nodular, leopard or leopard skin, orbicular, eye, spherical, globular, egg or ovoid, grapeshot, elliptical, xenomorphic (allotriomorphic) granular; kugel, niere (*Germ.*); and noduleux, bulbeau (*Fr.*). The texture has been observed or described in chromite ores from many parts of the world, such as from Hindubagh, West Pakistan (Asrarullah, 1961*a*, *b*; Bilgrami and Ingamells, 1961 ; Bilgrami, 1963, 1964*a*, *b*; Shams, 1964); Bridgs Creek, Josephine Country, Oregon (Bastin, 1950); Shade Mine, Illionois River District, Josephine Country, Southwestern Oregon (Ramp, 1957); John Day Region, Oregon (Stanford University Museum); Octopus Mine, Siskiyou Country, California (Bastin, 1950); Castle Crag Mine, Shasta Country, California (Bastin, 1950); Cyprus Chrome Co. Ltd., Mine, Kokkinoroysos, Cyprus (Camborne School of Metalliferous Minning Museum, England); Iran (Haeri, 1961); Rodiani, Greece (Panagus and Ottemann, 1966); Tontouta area, New Caldonia (Maxwell, 1959), Twambe, Tanganyika (E. Wm. Heinrich, personal communication).

In general, nodular form is an exceptional mode of occurrence of form. The common habit in the typical dunite association is fine to medium size anhedral disseminations, more rarely concentrated in massive granular bodies of various shapes (stratiform bands, podiform, sackform, and fusiform bodies, schlieren, and veins) which are larger than the nodules described herein.

The Zhob Valley igneous complex "consists of serpentinites, dunites, harzburgites and other varieties of peridotite, pyroxenite, anorthosite, troctolite, and gabbro, all cut by later dykes of dolerite and rodingite." (Bilgrami 1964, *a*). It is of the Alpine type.* The complex invades sedimentary beds of Triassic to early Eocene age and the intrusives are believed to be of Eocene age (Asrarullah, 1961*a*). In the complex, "grapeshot" (nodular) ore is generally confined to bands in the rocks of Jungtorghar and the western slopes of Saplaitorghar :

> "The........bands consist of globules of chromite which are enclosed in pale-green serpentine. The globules vary from a fraction of a centimeter to two or three centimeters, though it is unusual to find globules of various diameters within the same band. Most globules are undeformed spheres and this strongly suggests that the grapeshot ore exhibits a primary texture. The proportion of the globules to the serpentine....may vary from 5% to 95% in the various bands, though the variation within the same band is less marked. Where the concentration of globules is exceptionally high, massive ore bands are formed. All stages from a few disseminated globules to massive bands of almost pure chromite, apparently produced by the squashing together of chromite nodules, have been observed. In another kind of banding, globules of serpentine are enclosed in chains of chromites. Some specimens of this kind of ore exhibit a slightly modified, settled texture, while others show an imperfectly developed gneissic banding." (Bilgrami, 1964, *a*).

The chromite occurs only in dunite and serpentinite (Bilgrami, personal communication). According to Asrarullah (1961*a*), "In the Hindubagh area the grade of ore decreases from west to east,."** This fact led the senior author to suggest that the dip of the complex might be eastward; the basis of this postulation is the principle (Goldschmidt, 1937) that, in an isomorphous series, the metallic constituents with the smaller ionic radii tend to form a tighter bond than the larger ions (newest values are $Cr^{3+} = 0.63$ Å, $Fe^{3+} = 0.64$Å – Ahrens, 1964). Assuming that chromite with a high Cr/Fe ratio formed first and toward the base of the intrusion, that base should lie to the west. Actually, the structure of the igneous complex is imperfectly known. "There is no apparent directional relation between the veins, bands, and lenses of chromite ore bodies and the boundaries of the intrusives, but in place there is a parallelism between adjacent ore bodies." (Asrarullah, *op. cit.*).

ADDITIONAL DATA

The specimens studies in this investigation were taken from Sra Salawat mine 136, and were kindly supplied by Mr. R. G. Bogue, then with the U.S. Geological Survey-AID Program in Quetta. A chemical analysis by Bilgrami (1963, Table 1, Analysis 2) shows: Cr_2O_3 54.41%; Al_2O_3 13.86%; Fe_2O_3 3.98%; $TiO_2$0.45%; V_2O_5 0.07%, FeO 12.26% NiO 0.16%; MgO 14.24%; MnO 0.20; CaO 0.08%; H_2O 0.21%; SiO_2 0.24%; Total 100.16.

An ARL electron microprobe traverse across a 7.5 mm. chromite nodule was kindly furnished by Dr. P. B. Moore of the University of Chicago. According to his analysis, there are little, if any, changes in concentration of chromium or iron from edge to center of the nodule.

The unit cell edges (a_0) for chromite specimens from edge and center of a chromite nodule were determined by X-ray diffraction, using a 114.57 mm. Debye-Scherrer powder camera and Cr Kα (vanadium-filtered) radiation. The a_0 was calculated from the (422) spacing of chromite. The unit cell edges for chromite from margin and center of the chromite nodule are 8.34 A° and 8.30A°, respectively.

Two serpentine mineral associations found within the chromite nodules and in their interstices are quite different. Mixtures of antigorite and clino-chrysotile occur within chromite nodules, but X-ray differaction (General Electric recording diffractometer, Cr Kα radiation) of the serpentine in the matrix revealed a complex association consisting of antigorite and a serpentine with spacings which do not match published data. The three most intense spacings are 7.9 Å, 4.75Å and 2.49 Å.

*Peridotite-gabbro complex in which "strong deformation of semisolid rocks is implied by irregular form and internal structure, lack of cryptic layering, prominent lineation and foliation crossing the boundares between najor rock units, and cataclastic textures" in contrast is *stratiform* complexes, such as the Bushveld and Stillwater, in which "crystallization of a molten magma in place with little or no disturbance is indicated by features attributable to crystals settling and reaction of settled crystals with entrapped magma, great lateral persistence of compositional layers, cryptic layering, and systematec upward progressinon from peridotitic to gabbroic or granitic rocks." (Thayer 1960, p. 247.)

**Grade of ore depends upon Cr_2O_3 as well as Cr/Fe ratio. For high grade ore Cr_2O_3 should be over 48— and Cr/Fe ratio 3 : 1. In Hindubagh igneous complex Cr/Fe ratio decreases from west to east............very few Zhob Valley chromites have been analyzed for Fe_2O_3 as well as FeO and no definite conclusions can be drawn from these anaalyses. I do not think RO and R_2O_3 groups always behave entirely independently." (S.A. Bilgrami, personal communication, April 13th, 1968.)

ORIGIN OF NODULAR TEXTURE

A number of hypotheses have been proposed by various workers to explain the phenomena of chromite deposits and the origin of the nodular texture that some of them display. These are discussed below, in the order that the writers consider to reflect their pertinence, and evaluated as to their applicability to the Zhob Valley occurrences :

a. Orthomagmatic origin of nodular texture.

In the Alpine type of deposits, chromite is believed by Thayer and others to have formed originally by fractional crystallization of fluid magma and settling out of chromite in the lower crust of upper mantle, from where it gets remobilized and moved up into the upper crust. At the upper levels in the crust, the deposits exhibit features resulting from flowage and recrystallization of semisolid crystal mushes formed by partial re-fusion and mechanical distruption of stratiform-type layered rocks. This remobilization took place along eugeosynclinal belts under strong deformation.

The silicate minerals were crushed and recrystallized and secondary layering was extensively developed in many masses, but fracturing, fragmentation, and granulation of chromite indicate that it acted as a brittle soid at least during the later movements. The chromite ore bodies have been torn from layers and carried up as fragments which were deformed to varying degrees. . . . The orientation of fusiform and tabular bodies and their internal structures parallel to the structures in the surrounding peridotite seem better explained by flowage alone, similar to xenoliths in gneiss, than by some combination of flowage and injection (Thayer, 1961, p. 213).

Zengin (1961) disagrees with the view that nodular chromite represents a rather deep level of magma because he finds that in Turkey this type of occurrence is limited to some sections along the contacts of the country rocks and mineralized zones, rather than being representative of the whole mass.

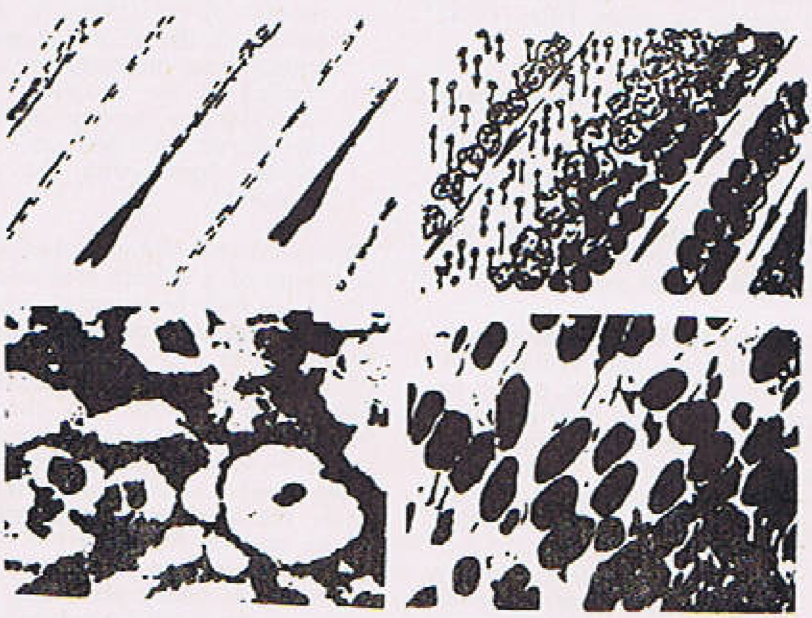

Fig. 1 Top : Mechanism of chromite nodule formation (Borchert, 1951). Lower left : Nodular serpentine (white) with inclusions and matrix of chromite (black), Hindubagh, (Shams, 1964). Lower right : Formation of a chromite band by accumulation, Hindubagh, (Bilgrami, 1964,a).

Vogt's concept of "synneusis" (together-swimming), for minerals which segregated early from a magma, is used by Bastin (1950) as a criterion of magmatic origin. Bastin states that :

> "On textural evidence alone, this relationship might be explained as an automorphic replacement of olivine by chromite. However, fractures in the olivine and contacts between olivine grains exerted no control on chromite distribution. It is more likely that olivine was still liquid when the chromite crystallized as Vogt concluded.".

This statement is concerned, of course, with mineral paragenesis rather than nodular texture *per se*. Sampson's chain texture in chromite (1932, p. 130) may be a variety of synneusis texture, but Jackson (1961, p. 235) believes "the chain effect is caused by fortuitous sectioning of tightly packed chromite octahedra."

Gravitation segregation and accretion of chromite grains and their rounding by rolling to form stratiform layers where the dips are sufficiently steep (over 25°) are depicted by Borchert (1961; see Fig. 1, top). This mechanism is examplifield at Hindubagh as shown in Fig. 1, bottom right.

From the theoretical point of view and without specific reference to nodular chromite, Tiller (1964) states that :

> "It may be quantitatively shown that a spherical particle undergoing transport-controlled growth into a supercooled bath will be unstable, when subject to perturbation, when the radius of the sphere is greater than just seven times the critical radius, Re, predicted by homogeneous nucleation theory." This relationship has not been explored in the present study.

By experimenting with the flow of plastic particles in oil in a tube, Bhattacharji and Smith (1964) have shown that flowage differentiation, due to inherent flow properties of solid and fluid mixtures, is capable of causing crystal segregation in nature, such as in the Muskox Intrusion, a Precambrian layered ultramafic-mafic pluton situated in the Northwest Territories of Canada. They find that early-crystallized, high-temperature minerals, such as olivine, can be concentrated in the center of a vertical conduit. In their experiment, spherical and rod-shaped particles rotated* as they moved from the walls of a recatangular lucite conduit toward the center. The implication is that olivine, and possibly chromite, can be concentrated by flowage and no preceding gravitative differentiation is necessary.

Instead of representing early crystallized chromite, perhaps nodular chromite should be interpreted as representing immiscible droplets of chromite liquid on the ultramafic magma. Keith (1954) shows that melts rich in silica and Cr_2O_3 may form such immiscible liquids and Drever (1960) cites evidence for immiscibility in picritic intrusions.

Globular masses of pyrrhotite, pyrrhotite-pentlandite, and pyrrhotite-chalcopyrite are common in anorthosites and allied rocks, and are regarded by Newhouse (1936) as having separated from the magma due to liquid immiscibility. Newhouse did not include chromite in this study but he noted that petrographers since the time of Rosen busch had considered the opaque oxides as having crystallized early.

McDonald (1965) attempted to account for formatin of silicate inclusions in chromite in terms of electrostatic charges:

> "Crystallization of chromite-rich liquid droplets proceeded from the margin of the droplet, inward. Nucleation would probably be initiated by the contamination of the surface of the droplet by crystallites or small crystals suspended in the silicate magma rather than by spontaneous nucleation resulting from supercooling of the droplet......Mineral grains or crystallites, having unsatisfied electrostatic charges on their surfaces, would be attracted to the liquid with the greatest dielectric constant".

This approachis of doubtful value since the dielectric constants of a silicate melt and a chromite-rich liquid can only be surmised. McDonald refers to experimental work on liquid lead (Chalmers, 1964) to the effect that the supercooling required for growth is maintained by conduction of heat from the solid-liquid interface into the crystal. Furthermore, the interface advances uniformaly and tends to be smooth, following the configuration of the solid-liquid interface into the crystal. Furthermore, the interface advances uniformally and tends to be smooth, following the configuration of the isothermal surface that would exist if no solidification was taking place and if the crystal was isotropic to thermal conduction.

Any explanation of the origin of chromite

*Dr. Bilgrami, in a personal communication, observes that evidence of rotation is also found in Hindubagh peridotites.

nodules must take into account the coexistence of serpentine nodules (originally olivine) in chromite, and of a chromite nucleus in some serpentine nodules.

McDonald (1965, 1967) discussed certain chromite grains with centrally-located, rounded silicate inclusions* from chromite seams in the Lower Critical Zone, Western Bushveld Complex. On the basis of these inclusions he postulated the existence of a chromite-rich immiscible liquid. Most chromite, he finds, crystallized directly from the magma and settled to the floor of crystal accumulation, accompanied by chromite-rich immiscible droplets that had crystalline margins. These droplets crystallized from the margin inwards to leave silicate inclusions within chromite grains, and enriched the granular accumulation of chromite by gravity settling and crystallization *in situ*. Jackson (1966) questions the growth of inclusion-bearing chromites from outside in, and also the hypothesis that a Cr_2O_3-rich liquid might separate from a basalt. In any event, a probably high surface tension of chromite droplets can be assumed, and a greater specific gravity than that of silicate melts is apparent.

Bilgrami (1964*a*) suggests that the nodular chromite of Hindubagh probably was formed by liquid immiscibility in the magma. He is of the opinion that similar textures shown by ferrochrome globules in slag lend support to his theory, and he questions the low temperature of emplacement of peridotite as postulated by others.

Shams (1964), distinguishes three structures in West Pakistan chromite-bearing serpentinites: (*a*) lenses and bands of coarsely crystalline chromite in serpentine which suggest segregation by gravity-settling of chromite crystals, with banding developed by magmatic flow; (*b*) nodular chromite in a groundmass of serpentine, ascribed to crystallization from globules of liquid of chromite composition in a liquid of ultrabasic composition; and (*c*) nodular serpentine in a groundmass of chromite, with the serpentine sometimes containing subrounded inclusions of chromite, suggesting the presence of two immiscible liquids before consolidation took place. Shams calls attention to the difficulty, in view of the experimental data on phase equilibria of the systems MgO-Cr_2O_3-SiO_2 and iron oxides $-$ Cr_2O_3-SiO_2, of explaining the high temperatures required for liquid immiscibility. However, he points out that in the light of the recent discovery of a high-temperature Alpine-type peridotite (temperature 800°—1000°C) in Venezuela, and of the experimental evidence that ultrabasic liquid can exist at as low a temperature as 1000°C, there is a possibility that locally ultrabasic liquid may be available. He ascribes a subordinate role to liquid immiscibility in the origin of chromite deposits because of the less common occurrence of his structural types (*b*) and (*c*).

In the layered intrusion at Skaergaard, East Greenland, where Wager and Mitchell (1951) noted a rapid depletion of chromium during early stages of formation, Wager (1959) proposed that variations due to differences in the proportions of primary crystal phases, "should probably be divided into two types; one, which is usually on a small scale due to winnowing effect (acting on crystals of different densities during movement by convection currents); the other, which may be on a small or large scale, due to differing powers of crystal nucleation." His hypothesis is that the order of crystallization of the primary precipitate minerals in the rhythmic units is considered to be due to their respective powers of nucleation from a somewhat supercooled magma. The three settled ("cumulus") minerals were chromite, bronzite, and basic plagioclase :

> "Although all three should be separating from the liquid if equilibrium conditions existed, one of these crystal phases may well nucleate more easily than the others from the super-saturated liquid. It is likely that the crystals of simple structure such as spinels would nucleate before those of complex structure. . . ."(Wager, 1959).

Wager recommends that the "power of nucleation of the different mineral species involved in layered intrusions should be investigated experimentally to decide whether or not the order is the one suggested by the known types of rhythmic units."

Some light is shed upon silicate-chromite relationships by phase-equilibrium studies in the system MgO-$SiO_2 - Cr_2O_3$ (Keith, 1954). Keith's ternary diagram is reproduced as Fig. No. 2. It can be seen that only a small percentage of Cr_2O_3 is necessary to form stable crystalline phases of Cr_2O_3 or picrochromite, $MgCr_2O_4$**. Furthermore, if one assumes, a composition of about 60% SiO_2, 40% MgO, and 1—4% Cr_2O_3, it can be seen that either forsterite or picrochromite will crystallize first from the liquid, depending upon the exact composition. Geochemical data show that trivalent chromium and ferric iron are very similar. Ahrens (1964) states that ionic radii are 0.63 Å for trivalent

*Thayer (personal communication, December, 9th 1966) observes that no true nodular chromite has ever been described in stratiform complexes.

**Natural chromites contain up to 15% MgO, and thus approach picrochromite in composition.

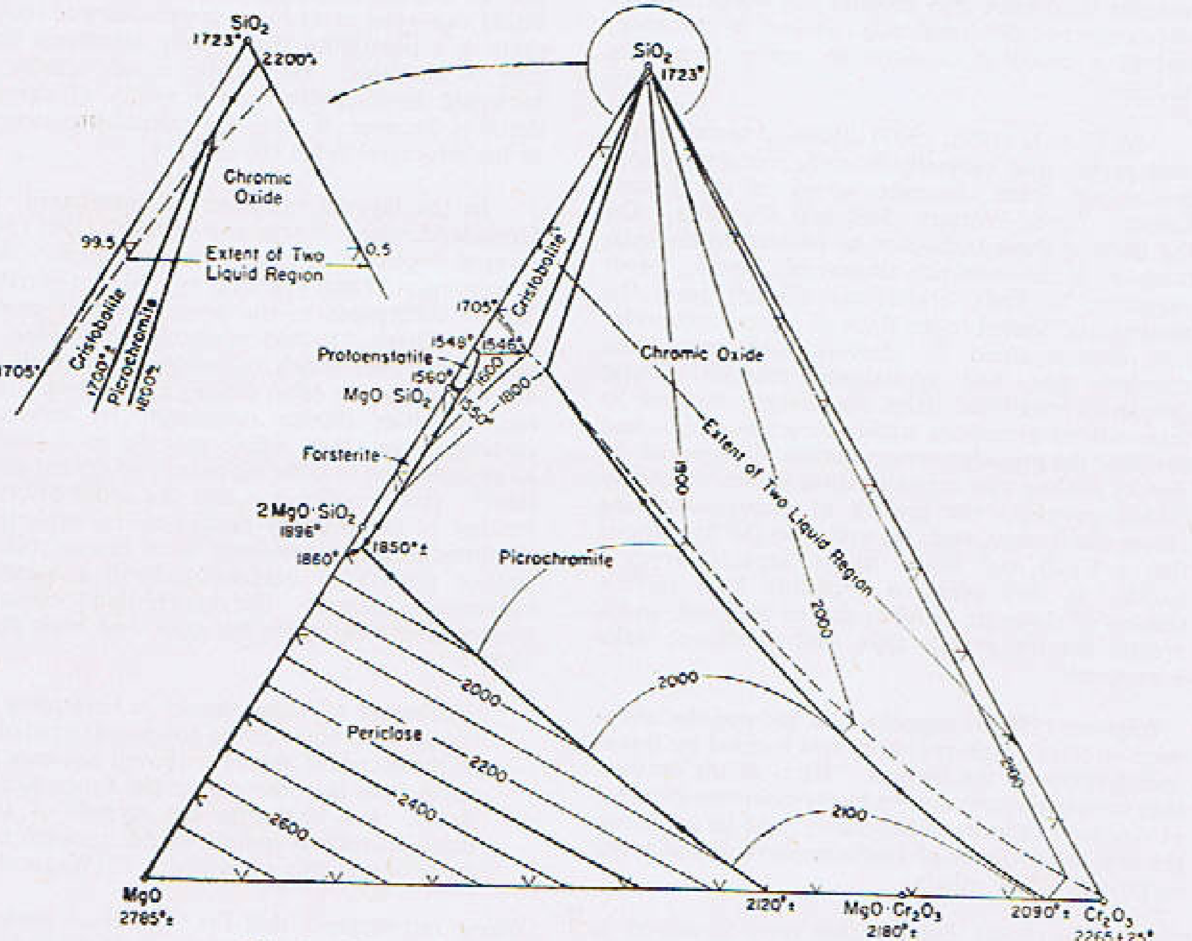

Fig. 2. The system MgO-Cr_2O_3-SiO_2, Keith (1954).

chromium, and 0.64 Å for ferric iron. According to Green (1959), electronegativities (Cr^{3+}, e=1.6; Fe^{3+}, e=1.8), cation field strengths (Cr^{3+}, i = 4.76; $Fe_3{}^+$, i =4.69), third ionization potentials (Cr^{3+}, I=31.00 V; Fe^{3+}, I=30.60 V), and indices of ionic replacement (Cr^{3+}=0.22; Fe^{3+}=0.22) are identical or very nearly so. The only property which is significantly different is that of the melting point of the oxides (Cr_2O_3=1990 C°; Fe_2O_3=1565° C). This indicates that chromium forms a more ionic bond with oxygen and would tend to deplete early in the crystallization sequence. This is corroborated by observations of Wager and Mitchell (1951) and Taylor (1965). Ulmer (1966) finds that complete solid solution exists among spinels up to 1300°C; however, such solid solutions may involve defect spinels which contain trivalent ions in excess of a 1:2 divalent to trivalent ion ratio.

Unusually high concentrations of chromium in magma are not necessary for the formation of chromite. Vogt (1921, p. 323) suggested that if the concentration of chromium in a magma is 1000 p.p.m. chromite will form as a separate phase. However, large chromite bodies would require large amounts of magma, and as Bilgrami (1961, p. 1736) remarks, "The numerous chromite veins in the Hindubagh area suggest that the concentration of chromium in the original Hindubagh magma was fairly high. The abrupt fall in the chromium content of the successive rocks shows that the chromite crystallized during a relatively short time".

If initial magma composition is such that it falls to the left of the forsterite-picrochromite cotectic boundary (Fig. 2), forsterite would crystallize first. It would continue to crystallize until the composition reached the forsterite-picrochromite cotectic, and then picrochromite and forsterite would crystallize together. Similarly, an initial composition to the right of the foresterite-picrochromite cotectic would result in picrochromite as the first phase to crystallize. If, fortuitously, the composition were somewhere on the forsterite-picrochromite cotectic, picrochromite and forsterite would crystallize simultaneously. Inclusions of olivine in chromite, therefore, would imply a magmatic composition to the left of the forsterite-picrochromite cotectic, whereas inclusions of chromite in olivine would imply composition to the right of the forsterite-picrochromite cotectic with respect to these two phases. Since the cotectic represents a composition of between one and two percent Cr_2O_3, small variation in chromium concentration would affect the crystallization sequence rather drastically.

Because of its presumed irrelevance, it is not proposed to review here the controversy over the late-magmatic (Bateman, 1951) or hydrothermal (Thayer, 1956) origin. Nor will pneumatolytic-phase chromite (Borchert, 1961) be discussed, for the same reason.

It seems from the foregoing that the Hindubagh chromite is of early magmatic origin and has formed pre-olivine, simultaneously with olivine, and, in smaller part, post-olivine (as in the matrix of serpentine nodules)—all of one generation, and probably as a result of fractional crystallization. Bilgrami (1963) infers that chromites which show a high Cr/Fe ratio are earlier than those showing a lower ratio, but he does not specify a time gap.

Possible post-depositional effects will be considered next.

(*b*) Resorption and hydrothermal aleration in nodule formation.

Rotund and concave shapes of chromite have been ascribed to magmatic resorption or corrosion of early-formed grains, aggregates, and crystals. These effects are not readily distinguishable from those produced by hydrothermal action. Typical illustrations of chromite grains with concavities, commonly attributed to partial resorption of early-formed chromite, appear in text-books such as that of Park and MacDiarmid (1964, Figs. 4-31).

Two types of resorption are recognized by de Wijkerslooth (*see* Rechenberg, 1961) : (1) magmatic corrosion, and (2) hydrothermal, accompanied by the recrystallization of new minerals. Rechenberg cites the Camasirlik, Turkey, orebodies as having grains originally 1-1.8 mm. in size, but now reduced to 0.07—0.5 mm., with interstices filled by serpentine, chlorite, tremolite, etc. This is interpreted by the present authors as an example of cataclasis plus hydrothermal alteration.

An illustration of supposedly resorbed chromite is found in the Shade Mine, Illinois River District,

Fig. 3. (*a*) Chromite cores (white) surrounded by a substance of higher reflectivity. Silicate matrix stippled. Rodiani, Geece. (Panagos and Ottemann, 1966). 100x.

(*b*) Nodular chromite (black) in serpentine from Shade Mine, Oregon, with halos of chromite and sheaths (diagramatic) of chlorite.

(*c*) Chromite grain, translucent (diagrammatic hatching) and opaque, with chlorite rim. Mount Albert, Quebec, (MacGregor, et al. 1963).

Josephine County, Oregon (Ramp, 1957). Ramp notes that:

> "Nodular chromite consisting of aggregates of spherical or ellipsoidal chromite as much as 3/4 inch in diameter disseminated in the dunite or serpentine occurs at several places in the area. Those examined appear to have been large, probably euhedral crystals of chromite that have been rounded by abrasion and/or re-solution."

He observes that corroded chromite grains in dunite and inclusions of olivine in chromite grains show that chromite may crystallize earlier than the surrounding olivine, and also that olivine may start crystallizing earlier than the chromite. Most striking is his illustration (Fig. 3, a, herein) of chromite halos, together with sheaths of chlorite surrounding nodules. This relationship was first interpreted by the present authors as evidence of magmatic resorption, with residual chromite halos, but it is now recognized that the chlorite rims are clearly post-magmatic and related to the serpentine mineralogy (Thayer, 1966, p. 693), while the chromite grains in halos are probably residuals of hydrothermal attack similar to those described by Miller (1953) in the Webster-Addie Ultramafic Ring, Jackson County, North Carolina.

Both resorption and hydrothermal attack have undoubtedly affected a rounding of some chromite grains, but these mechanisms do not appear adequate to explain most nodular chromite occurrences.

c. Diastrophic origin of nodules.

The question of the efficacy of diastrophism in producing nodular or elliptical structures in chromite naturally arises for the Alpine type complexes which have undergone strong deformation.

Is the coarse sugary texture of fresh dunite with equant anhedral grains of olivine and chromite, so often seen in laboratory collections in North America, of protoclastic origin—produced by differential flow of magma before complete solidification? Are the sugary grains once euhedral crystals altered in shape after precipitation, either by continued growth or by reaction with interstitial magma (Jaskson, 1961, p. 13); or are they produced by cataclasis—fracturing, granulation, and perhaps rotation? (The sugary texture of the familiar chromite-olivine specimens from Balsam, North Carolina, is commonly interpreted as cataclastic.)

Abundant examples of bodies of chromite which are evidently of disturpted character are to be found in the literature.

Thayer (1966) has applied the term "pull-apart" to a texture best shown, perhaps, in nodular ore by fractures transverse to the longest axes of elliptical nodules. These fractures he explains as tensional, and formed by stretching of the ore in a direction parallel to the orientation of the layers.

The mechanism of nodule formation depicted by Borchert (1961, Fig. 1 herein) may account for accumulation and compaction, but the common and striking disintegration of these brittle nodules as viewed microscopically must be largely a post-consolidation effect.

Nodular chromite boundaries in general are sharp; they are often sheathed by chlorite or serpentine. The lack of slikcensided boundaries, such as those which commonly characterize the larger podiform, fusiform, and sackform masses of chromite, is interpreted by the authors as militating against a purely mechanical, post-consolidation formation of nodules. Nor are these nodules regarded as prophyroblasts. In other words, nodular chromite is not typically of dynamic metamorphic origin.

ZONATION OF CHROMITE

The literature survey on which this article is largely based revealed a number of zonal chemical variations in chromite which merit discussion. Generally, compositional zoning in chromite deposits occurs on individual nodular or granular ore-body, and on regional scale, and may be a primary or a secondary feature; the latter being either additive or subtractive in nature. A regional decrease in ore grade from west to east at Hindubagh has already been noted in the Introduction (Asrarullah, 1961*a*); this is ascribed by Bilgrami (1963) to earlier formation of chromite with a high Cr/Fe ratio.

In the case of the Stillwater Complex, Hess (1960) advanced a diffusion theory to account for overgrowth of chromite *crystals*. Jackson (1961, pp. 60-61, 80) finds that "the amount of overgrowth in any particular chromite was proportional to the rate of accumulation of settled crystals" and concluded that "Most of the postdepositional enlargement occurred either at the surface of the crystal mush or within a few inches of it, in contact with magma saturated with respect to, and crystallizing chromite". He believes that "the rounded corners of some olivine and chromite crystals were probably caused by partial resorption prior to deposition" and uses the term "secondary enlargement" to describe the continued growth of settled crystals in certain layers after deposition, as noted by Hess. No zoning at the outer margins of enlarged chromite individuals was observed. Jackson (in press) now uses the more definitive term "overgrowth" instead of "secondary enlargement" which might result from non-magmatic processes.

Maxwell (1949, p. 540) cites A. C. Tester to the effect that peripheral chromite zones at the Tiebaghi mine, New Caledonia, contain less Cr_2O_3 than that at the center of the deposit. In many New Caledonia deposits a sheath of chlorite or kaemmererite surrounds black-bordered chromite grains. Maxwell states that "Development of chlorite is attributed to outward migration of alumina from the chromite by Lewis, as quoted by Fisher" (Fisher, 1929). Amin (1948) postulates that magnesia also migrates outward to form magnesite, and the black border develops as a result of residual enrichment of chromite in iron oxide. Fisher, however, believes that the iron oxide was deposited on the chromite grains, rather than being a product of residual concentration. Maxwell's conclusions on New Caledonian chromite are :—

(*i*) magnetite in the serpentine derived from olivine, develops at the time of serpentinization;

(*ii*) movement of iron oxide, resulting in "bleaching" of serpentine adjacent to chromite, takes place in the presence of the serpentinizing solutions;

(*iii*) addition of iron oxide to chromite grains; it at least postdates the corrosion of these grains because black margins and "whiskers" of magnetite dust are developed equally on crystal faces and corroded wisps of chromite grains. It appears that iron has been concentrated in and on the chromite grains, either by adhering to the grain margins as magnetite crystals or by actually entering the chromite crystal structure and forming opaque margins of the grains.

Miller (1953), in describing secondary alteration of chromite in the Webster-Addie Ulteramafic Ring, North Carolina, illustrates chromite grains partially altered to opaque black material with a calculated composition of Cr_{77} Al_5 (Mg_{34}). Abstraction of $MgO.Al_2O_3$, increase of FeO, Fe_2O_3, and loss of some Cr_2O_3 to kaemmererite theoretically yield an end product of ideal chromite-magnetite solid solution.

The margins of Egyptian chromites (Amin, 1948) contained in talc-carbonate and in serpentine are fractured and altered to an opaque black mineral. This change is ascribed by Amin to hydrothermal fluids acting on the chromite, leading to the concentration of iron oxide, which gives chromite the black color, and release of alumina which forms chlorite interstitially.

"Leopard" chrome ore of Motsali is another exception to the usual compact form of lenses and pods in the Rodiani area, Greece (Panagos and Ottemann, 1966). Marginal phases are developed as zones around chromite grains*, along cracks in individual grains, and around voids and small channels in the grains (Fig 3, b, herein). These marginal zones have higher reflectivity than the interior of the chromite grains and in transmitted light appear darker. X-ray diffraction indicates that both border and interior have spinel structures. The unit cell edge (*a*) of chromite at the core is around 8.24 A°, and that of the marginal zones 8.34A°. Higher reflectivity and higher unit cell edge, in addition to chemical results of an electron microprobe anaylsis, are interpreted by Panagos and Ottemann as clear evidence of enrichment of iron in the marginal phase of the chromite grains. They have not yet decided whether the genesis is a late-stage magmatic feature or an effect penecontemporaneous with serpentinization.

On a *regional* scale, MacGregor and Smith (1962-3) have studied the approximate correlation of chrome spinels of the Mount Albert, Alpine-type ultramafic pluton, Gaspe, Quebec, with respect to unit cell edge, index of refraction, and color. They find that nodular chromite grains show zoning or rims composed of another spinel phase, as revealed by increasing illumination. They also noted that the intrusion can be zoned on the basis of chrome spinel composition—spinels with the cell edge 8.30 A° (rich in chromium and iron), occur near the margins of the intrusion, whereas those with cell edge 8.20A° are found at the center. The unit cell edge ranged from 8.14 to 8.32 A°. This compares with 8.30 to 8.34 A° in the one Hindubagh nodule measured in the present investigtion as discussed above. It has not yet been determined if this range is sufficient to cancel out the effect of R^{2+} cation substitution in tertrahedral positions *viz-a-viz* those of R^{3+} cation substitution in the octahedral sites.

Wilson (1953, p. 58) believes that an important

*Thayer, in a personal communication (December, 5th 1966) observes that these are indeed relatively coarse aanhedral grains rather than nodules. He also points out that Fisher (1929) in relation to marginal enrichment in iron was referring to a addition of magnetite in Pennsylvania, while Amin (1948) in Egypt, Miller (1953) in North Carolina, and Panagos and Ottemann (1966) in Greece, are dealing with hydrothermal and not magmatic alteration.

characteristic of oxide ores associated with ultrabasic intrusives is the constancy of composition laterally. This constancy has been noted in the Bushveld intrusive, the Bird River chromite deposits of Manitoba, the Stillwater complex of Montana, and the Selukwe deposits of Southern Rhodesia. Decreases of concentrations of alumina, chrome, and magnesia, and increases of both ferric and ferrous iron upward are found in chromite of the Bushveld intrusive.

DISCUSSION

The unit cell edge measurements of chromite from center to edge of Hindubagh nodule are similar. An electron microprobe traverse across one nodule has shown that composition is essentially constant from edge to center.

Although crystallinity is difficult to determine in nodules, fracture patterns suggest that the nodules consist of either single crystals or aggregates of coarse crystals. There seems to be little or no zoning within these chromite nodules.

It appears that chromite and olivine (which later altered to serpentine) crystallized more or less simultaneously and chromite settled by gravity. The lack of magmatic zoning probably means that relatively large amounts of chromium and iron were available, and that equilibrium between melt and chromite was approached. More magnesium than iron must have been available and the overall composition of the magma changed very little while the nodules formed.

It is possible, of course, that the zoned crystals once formed were partially resorbed, but for the Hindubagh occurrences the authors favour the simpler mechanism described above.

Phase relationships in the MgO-$Cr_2O_3-SiO_2$ system show that less than 2% Cr_2O_3 is necessary to form $MgCr_2O_4$, picrochromite, from a silicate melt. The Hindubagh chromite nodules contain about 14% MgO, thus approaching picrochromite in composition.

Probably the most important determinant in the formation of chromite deposits is the original Cr_2O_3 content of the magma. Massive "bedded" deposits probably reflect comparatively large Cr_2O_3 contents, while the nodular types represent simultaneous chromite and olivine crystallization along the picrochromite-forsterite cotectic boundary of Fig. 2. This type may grade into layered deposits. As Bilgrami points out in a personal communication (November 2, 1966), "Conditions under which crystallization was taking place may also play an important role in determining which kind of deposits will form."

By the analogy of ferrochrome nodules in slags, an argument can be made for liquid immiscibility in the formation of nodular chromite (Bilgrami, 1964, *a*). However, study of the system MgO-$SiO_2-Cr_2O_3$ indicates that the liquid immiscibility field is limited to that portion in which Cr_2O_3 (and not picrochromite) melt separates from a siliceous one. Since these are not the phases found in chromite deposits, and because by referring to the system MgO-SiO_2-Cr_2O_3 one can readily explain the presence of an olivine nucleus in chromite nodules and *vice versa*, the present authors favour fractional crystallization as the primary mechanism of nodule formation.

Resorption would tend to form spherical shapes, which have the lowest surface energy. Some modification as a result of gravitational rolling or of hydrothermal attack may also have taken place. Overgrowth of grains, or granulation of larger chromite masses after the solid stage was reached, seems incompetent to account for typical nodular texture.

SUGGESTIONS FOR FURTHER WORK

Additional electron microprobe data are needed to determine the generality of the results described herein.

A regional study of unit cell edge variations in chromite in Hindubagh should throw light upon the structure of the associated ultramafic complex.

Remnent magnetism of chromite nodules and masses might reveal clues to the mechanism of their accumulation.

ACKNOWLEDGEMENTS

The senior author gratefully acknowledges his indebtedness to Dr. S. A. Bilgrami of Pakistan Chrome Mines, Ltd., for hospitality and guidance, and to Mr. R. G. Bogue of the U. S. Geological Survey for specimens. Dr. P. M.B. Moore, Department of Geophysical Sciences, University of Chicago, generously provided electron microprobe data. Dr. Bilgrami, Dr. T. P. Thayer of the U. S. Geological Survey, an authority on chromite, and Drs. J. P. Dobell, B. M. Hamil, J. Kalliokoski, and D. W. Pollock of Michigan Technological University, kindly made valuable and much appreciated suggestions on correcting or improving the manuscript.

Figs. 1 and 3 were drafted by Mr. Abraham Diaraj. Fig. 2 is reproduced by permission of the editor of the American Ceramic Society.

REFERENCES

Ahrens, L.H.(1964) The significance of the chemical bond for controlling the geochemical distributions of elements. *Physics and Chemistry of the Earth*, Part V, 1—54.

Amin, Mahmoud Sayed (1948) Origin and alteration of chromites from Egypt. *Econ. Geol.*, **43**, 133—153.

Asrarullah (1961 *a*) Chromite and its mining in West Pakistan. *Pakistan Geog. Review*, **16**, 14—26.

..........(1961 *b*) Geology of chromite in West Pakistan. *CENTO Symposium on Chromite Ore*, Ankara, Turkey, 1960, 38—53.

Bastin, Edson S. (1950) Interpretation of ore textures. *Geol. Soc. Amer. Mem.* 45.

Bateman, Alan M. (1951) The formation of late magmatic oxide ores. *Econ. Geol.* **46**, 404—426.

Bhattacharji, Somdev, and Charles H. Smith (1964) Flowage differentiation. *Science*, 145—153.

Bilgrami, S. A., and C. O. Ingamells (1960) Chemical composition of Zhob Valley chromites, West Pakistan. *Amer. Mineral*, **45**, 576—590.

..........(1961) Distribution, of Cu, Ni, Co, V, and Cr in rocks of the Hindubagh igneous complex, Zhob Valley, West Pakistan. *Geol. Soc. Amer. Bull.* **72**, 1729—1738.

..........(1962) Mineralogy and Petrology of the Hindubagh igneous complex, West Pakistan. *Rec. Geol. Surv., Pakistan*.

..........(1963) Further data on the chemical composition of Zhob Valley chromites. *Amer. Mineral.*, **48**, 573—587.

..........(1964 *a*) The regional distribution of chemically different chromites from Zhob Valley, West Pakistan *Geol. Bull. Punjab Univ.*, **4**, 1—16.

.... (1964 *b*) Mineralogy and petrology of the central part of the Hindubagh Mining District, Zhob Valley, West Pakistan. *Rec. Geol. Surv. Pakistan*, **X**, 2-c, 1—28.

Borchert, Hermann (1961) Erfahrungen in Turkischen Chromerzlagerstatten. *CENTO Symposium on Chrome Ore*, Ankara, Turkey, 1960, 92—107.

Bowen, N. L. (1928) *The evolution of the igneous rocks*. Princeton Univ. Press.

Cameron, Eugene N., and Mark E. Emerson (1959) The origin of certain chromite deposits of the eastern part of the Bushveld complex. *Econ. Geol.* **54**, 1151—1213.

Chalmers, Bruce (1964) *Principles of Solidification*. John Wiley & Sons, Inc.

Drever, H. L. (1960) Immiscibility in the picritic intrusion at Igdlorssait, West Greenland. *XXI Internat. Geol. Cong.*, Copenhagen, 1960, Rept., **13**, 47—58.

Fisher, L. W. (1929) Origin of chromite deposits. *Econ. Geol.*, **24**, 691—721.

Goldschmidt, V. M. (1937) The principles of distribution of chemical elements in minerals and rocks. *Jour. Chem. Soc.*, 655—673.

Green, Jack (1959) Geochemical table of the elements for 1959. *Geol. Soc. Amer. Bull.* **70**, 1127—1183.

Greig, J. W. (1928) On the evidence which has been presented for liquid silicate immiscibility in the laboratory and in the rocks of Agate Point, Ontario. *Amer. Jour. Sci.*, **15**, 375—402.

Haeri, Yeganeh (1961) Geology of Iran's chromite deposits. *CENTO Symposium on Chrome Ore*, Ankara, Turkey, 1960, 21—26.

Helke, Adolph (1962) The metallogeny of chromite deposits of the Guleman District, Turkey. *Econ. Geol.*, **57**, 954—962.

Hess, H. H. (1960) Stillwater igneous complex, Montana. *Geol. Soc. Amer. Mem.* 80.

Jackson, Everett, D. (1961) Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana, *U. S. Geol. Surv. Prof. Paper* 358.

..........(1966) Liquid immiscibility in chromite seam formation. *Econ. Geol.*, **61**, 777—780.

..........(in press) Ultramafic cumulates in the Stillwater, Great Dyke, and Bushveld intrusions. In *Ultramafic and related rocks*, Wiley, P. J., ed., John Wiley, chap. 2, sec. II.

Keith, M. L. (1954) Phase equilibria in the system $MgO-Cr_2O_3-SiO_2$. *Amer. Ceramic Soc. Jour.*, **37**, 490—496; phase diagram reproduced in: Levin, E. M., C. R. Robbins, and H. F. McMurdie (1964) *Phase Diagrams for Ceramists, Amer. Ceramic Soc.*, 247, Fig. 715.

McDonald, J. A. (1965) Liquid immiscibility as one factor in chromitite seam formation in the Bushveld igneous complex. *Econ. Geol.*, **60**, 1674—1685.

..........(1967) Liquid immiscibility in chromitite seam formation— a reply. *Econ. Geol.* **63**, 288—291.

MacGregor, I.D., and Charles H. Smith (1963) The use of chrome spinels in petrographic studies of ultramafic intrusions. *Canadian Mineral.* **7**, 403—412.

Maxwell, John C. (1949) Some occurrences of chromite in New Caledonia. *Econ. Geol.* **44**, 525—544.

Miller, Roswell III (1952) The Webster—Addie ultramafic ring, Jackson Country, North Carolina, and secondary alteration of its chromite. *Amer. Mineral.* **38**, II—12, 1134—1147.

Newhouse, W. H. (1936) Opaque oxides and sulphides in common igneous rocks. *Geol. Soc. Amer. Bull.* **47**, 1—52.

Panagos, A., and J. Ottemann (1966) Chemical differentiation of chromite grains in nodular chromite from Rodiani (Greece). *Mineralium Deposita*, **1**, 72—75.

Park, C. F., and R. A. MacDiarmid (1964) *Ore Deposits*. Freeman.

Ramp, Len (1957) Nature and origin of southwestern Oregon chromite deposits. *Min. Engrg.*, Aug., 894—897.

Rechenberg. H. P. (1961) The chrome ore deposits of Kavak, Eskisehir (Turkey). *CENTO Symposium on Chrome Ore*, Ankara, Turkey, 1960, 146—156.

Sampson, Edward (1929) May chromite crystallize late? *Econ. Geol*, **24**, 632—641.

..........(1932) Magmatic chromite deposits in Southern Africa. *Econ. Geol.* **27**, 113—144.

..........(1942) Chromite deposits In *Ore Deposits as Related to Structural Features*, W. H. Newhouse, ed., Princeton Univ. Press.

Shams, F. A. (1964) Structures in chromite-bearing serpentinites, Hindubagh, Zhob Valley, West Pakistan. *Econ. Geol.*, **59**, 1343—1347.

Taylor, S. R. (1965) The application of trace element data to problems in petrology. *Physics and Chemistry of the Earth*, Part VI Thayer, T. P. 133—214.

..........(1960) Some critical differences between Alpine-type and stratiform periodtite-gabbro complexes. *XXI Internat. Geol. Cong.*, XIII, 247—259.

..........(1961) Application of geology in chromite exploration and mining. *CENTO Symposium on Chrome Ore*, Ankara, Turkey, 1960, 197—223.

..........(1966) Serpentinization considered as a constant-volume metasomatic process. *Amer. Mineral.* **51**, 685—710.

Tiller, W. A. (1964) Dendrites. *Science*, **146**, 871—897.

Ulmer, Gene C. (1966) Experimental investigations in chromite spinels. Symposium on Magmatic Ores, Stanford University, November 1966., *Econ. Geol.* 61, 793—794.

U. S. Geological Survey (1962) *Geological Survey Research in* 1962, A69.

U. S. Geological Survey (1964) *Geological Survey Research in* 1964, A3.

Vogt, J. H. L. (1921) The physical chemistry of crystallization and magamatic differentiation of igneous rocks. *Jour. Geol.*, **29**, 318—350.

Wager, L. R. (1959) Differing powers of crystal nucleation as a factor producing diversity in layered igneous intrusions. *Geol. Mag.* **96**, 75—80.

..........and R. L. Mitchell (1951) Distribution of trace elements during strong fractionation of a basic magma—a further study of the Skaergaard intrusive, East Greenland. *Geochim. et Cosmochim. Acta*, **1**, 129—208.

Wilson, H. D. B. (1953) Geochemical control of chromium, vanadium, and titanium ore deposits. *Canadian Inst. Min. and Met. Trans.*, **56**, 9—12.

Zengin, Yusuf (1961) The distribution of chromite reserves in successive layers and scattered layers. *CENTO Symposium on Chrome Ore*, Ankara, Turkey, 1960, 122.

PETROLOGY OF THE BASIC MINOR INTRUSIVES OF THE MANSEHRA-AMB STATE AREA, NORTHERN WEST PAKISTAN. PART I—THE DOLERITES.

BY

F.A. SHAMS and ZULFIQAR AHMED

Department of Geology, Punjab University, Lahore.

Abstract : *The dolerite members of the basic minor intrusives, of the Mansehra-Amb State Area, have been subjected to detailed petrographic and mineralogical investigations. In addition to modal variation of various constituent minerals, pyroxene minerals have been studied to understand their relationship in co-existence. The chemical nature of the dolerites and their trend in mineralogical phase variations are comparable to those of the well known tholeiitic provinces of the world. An outstanding feature of pyroxenes of these dolerites is that their maximum magnesian content is higher than most of the known cases of similar origin.*

This is the first detailed study of dolerites of the Mansehra-Amb State Area.

INTRODUCTION

The geology of the Mansehra-Amb State Area, is being described by the senior author elsewhere (Shams, 1969). The area constitutes the hard crystalline core of a major syntaxial loop of the northwest Himalayas (Wadia, 1931). It is composed of pelitic and psammitic schists and quartzites with rare gritty and conglomerate members. Younger than these are the granitic bodies that occupy more than half of the area. Disregarding ages of various formations, basic magma seems to have injected into them throughout the long period of plutonic evolution of the area. In accordance with their relative age of emplacement, these intrusives are met with as all sort of varieties between ophitic dolerites to granoblastic garnet amphibolites. Thus the basic magma had been a close witness of almost all the plutonic episodes that affected the area.

Assuming that the basic magma was tapped from a common source, it is thought instructive to study its differentiation trend as well as effects of regional metamorphism on rocks formed out of it. In this article, the former aspect is being presented ; the second part of the paper will be presented later.

DESCRIPTION OF THE DOLERITES.

Field Relations.

Dolerite bodies are met with almost everywhere in the area. Generally, they are present as inclined sills of variable thickness (from few inches to over 100 feet) and length (from few feet to over thousand feet). These are emplaced generally along the foliation planes of the enclosing rocks (Fig. 1). Rarely cross-cutting bodies are present that occupy diagonal joint openings of the enclosing rocks (Fig. 2). Surface weathering is fairly common and large scale spheriodal weathering is exhibited by closely jointed bodies.

Due to relatively small size of the bodies, differentiation effects are not conspicuous in the field except for the presence of rare patches of coarse-grained and somewhat leucocratic material that may be called pegmatitic dolerite. Progressive variation of grain size, from margin inwards, is sometimes desplayed by relatively thick sills that otherwise are rare in the area.

Petrographic Description.

General : Petrographically, the dolerites of the Mansehra-Amb-State Area are pyroxene-

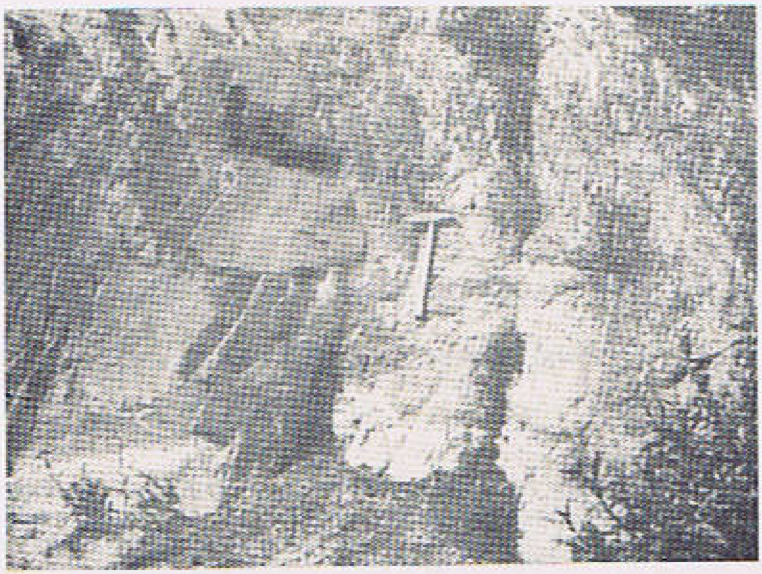

Fig. 1. Showing a dolerite sill emplaced along the foliation plane of the Susalgali gneiss, Khaki-Oghi road section.

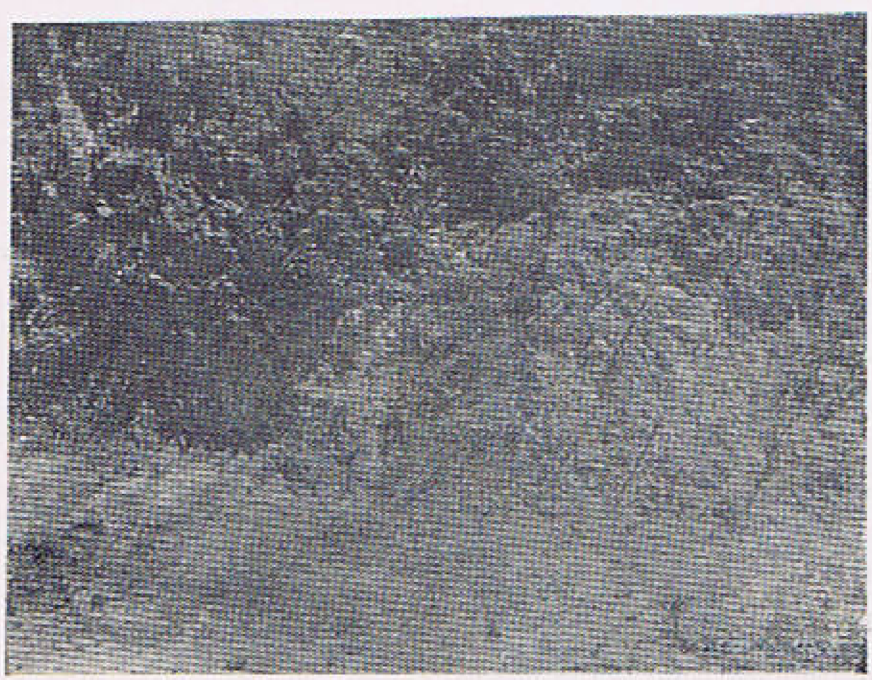

Fig. 2. Showing a dolerite body emplaced discordantly in a metamorphic sequence near Potha.

plagioclase rocks ; only in rare cases, they contain feebly to predominantly altered olivine crystals. In coarse-grained varieties, micropegmatitic intergrowths of quartz and orthoclase are invariably present. From chilled marginal portions to coarse-grained phases in the central portions of dolerite bodies, all sort of textural varieties are present. In the medium-grained dolerites, that are predominant in the area, ophitic texture is strongly developed.

Mineralogy :

On the basis of study of rock sections the more important features of individual minerals are described below, while sequence of their paragenetic crystallization is given in Table 1.

(i) Plagioclase Feldspar

The modal proportion of the plagioclase feldspar varies from 38 % to 50.5% while its composition lies between An_{64} and An_{45}.

The plagioclase feldspar occurs as twinned laths of variable size (0.68-3.90 mm), sometime even within a single section of rock. The plagioclase crystals generally occur as divergent laths and some time make local pools. Many a varieties of twinning pattern are present which make combinations within a single crystal. An interesting wedge-like twinning is frequently seen that terminates sharply over variable length. Zoning is occasionally present and is more common in coarse varieties.

The plagioclase crystals are mostly fresh with feeble alteration along fractures while cloudiness is common in the plagioclase of altered dolerites. In slightly metamorphosed dolerites, bent and fractured crystals are present.

(ii) Pyroxene Minerals

The pyroxene minerals constitute 27% to 44% of the rocks and have average grain diameter varying from 0.98 to 4.14 mm. The pyroxenes occur as coexisting paires of Ca-rich and Ca-poor species except for pegmatitic differentiates, where a single pyroxene, variety ferroaugite, is present. The individual members of various coexisting pairs show systematic variation as is described in detail in a later part of this article.

The pyroxene minerals occur both as single as well as composite crystals that commonly make local aggregates. Mostly, the crystals are homogeneous but in the coarse-grained varieties of the rock, very faint blebs and lamellae of probably inversion origin are present ; whenever present, these are restricted to local zones within the crystal. Twinning is fairly common which is mostly of a simple type but rarely a peculiar radiating type is seen.

(iii) Olivine

Olivine-bearing dolerites are rather rare in the area and the content of olivine in them varies

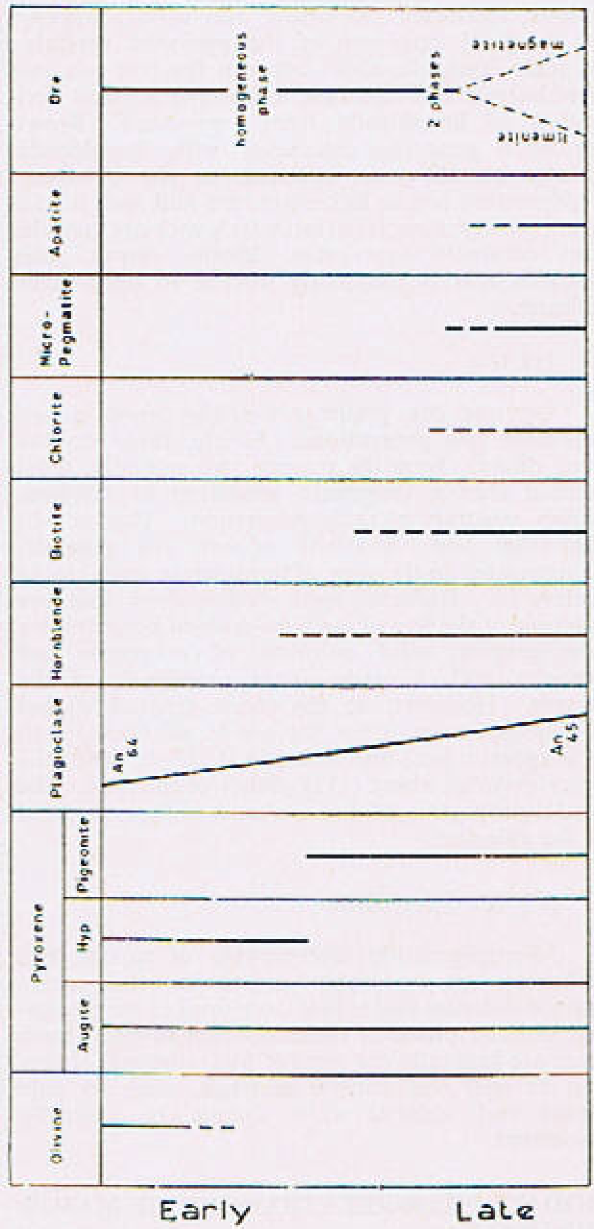

Table 1 Showing paragenetic range of minerals of the dolerites.

between 5% to 12% only. The olivine occurs as colourless, anhedral to subhedral grains that are always altered to different magnitude and sometime completely to serpentine and ore.

(iv) Hornblende and Biotite

These minerals are present mostly in the coarse-grained dolerites. The hornblende is green in colour, distinctly pleochroic and mostly appears as marginal extension of the pyroxene crystals; in such cases, the areas between the two minerals are charged with ore dust, suggesting a direct derivation of hornblende from pyroxene. Brown biotite is generally associated with hornblende, mostly on the side opposite to the pyroxene. Independent biotite flakes are rare and such a fraction is always associated intimately with ore granules and dendritic aggregates. Biotite shows paler margins and is frequently altered to deep green chlorite.

(v) Ore

Opaque ore grains are fairly common and represent two generations. Firstly, those crystallized directly from the magma and secondly, those formed during magmatic alteration of ferromanesian minerals of early generation. That is why that the later fractions of ore are generally concentrated in the area of hornblende and biotite formation. Reflected light studies show that ore fraction of the fine to medium-grained dolerites is a homogeneous solid solution of magnetite and ilmenite, with a predominant proportion of the former. However, in the coarse grained patches of differentiation origin, the ore is an intergrowth of magnetite host and ilmenite lamellae, with the latter oriented along (111) planes of the host. The modal proportion of ore increases with coarseness of the dolerites.

(vi) Micropegmatite

Micropegmatitic intergrowths of quartz and orthoclase are invariably present in the coarse grained dolerites and is best developed in the pegmatitic dolerite phase of differentiation origin. Such areas are generally the areas of hydrothermal alteration as well and enclose minerals, such as pale biotite and chlorite while apatite is generally associated.

MODAL NTER-RELATIONSHIP OF MAJOR MINERALS:

24 selected specimens of dolerites were subjected to detailed modal analysis with the help of a wift point counter; the data is given in Table 2.

With the help of this data, two graphs were prepared. One of these shows modal variation of plagioclase in relation to pyroxene minerals (Fig. 3). Their inverse relationship is fairly well exhibited.

The second diagram (Fig. 4) relates the anorthite content of the plagioclase feldspar to the modal ratio of plagioclase to pyroxene. The diagram shows that with the increase in the magnitude of this ratio, the anorthite content of the associated plagioclase decreases systematically.

THE PYROXENE CRYSTALLIZATION

It is now well established that the nature of pyroxene crystallization and their phase transformation are either controlled by or are dependent upon the nature of the parent basic magma and its rate of cooling (Poldervaart and Hess, 1951; Wilkinson, 1956, Yagi 1953, etc.). This aspect of the dolerites of the Manschra-Amb State Area has been investigated in detail.

Co-existing pyroxene minerals were separated from each dolerite rock under investigation and their composition was estimated by determining appropriate refractive indices with the immersion method and 2 V with a Leitz 4-axes universal stage. For the sake of former determinations, liquids with interval of 0.002 were used and a source of filtered white light was employed. The data are given in Table 3 and plotted on Hess' diagramme (Hess, 1949) as Fig. 5. Following are the main conclusions :—

(*i*) Pyroxene minerals crystallized mostly in pairs in such a manner that a Ca-rich clinopyroxene was associated with either a Ca-poor ortho-pyroxene or a clinopyroxene phase. The late pegmatitic differentiates, however contain single pyroxene in the range of ferroaugite.

(*ii*) The Ca-rich clinopyroxene phase started with a composition of diopside (Wo_{43} $En_{48\cdot2}$ $Fs_{8\cdot8}$) and extended to ferroaugite ($Wo_{38\cdot3}$ $En_{23\cdot9}$ $Fs_{32\cdot8}$) The Ca-poor pyroxene phase started with a composition of enstatite (Wo_2 En_{89} Fs_9) and extended to hypersthene (Wo_2 En_{70} Fs_{28}). The latter was succeeded by pigeonite (range from $Wo_{9\cdot3}$ $En_{59\cdot8}$ $Fs_{30\cdot9}$ to $Wo_{8\cdot2}$ $En_{43\cdot1}$ $Fs_{48\cdot7}$).

(*iii*) While the initial composition of pyroxenes of both the series was unusually rich in the enstatite molecule, the maximum enrichment in the

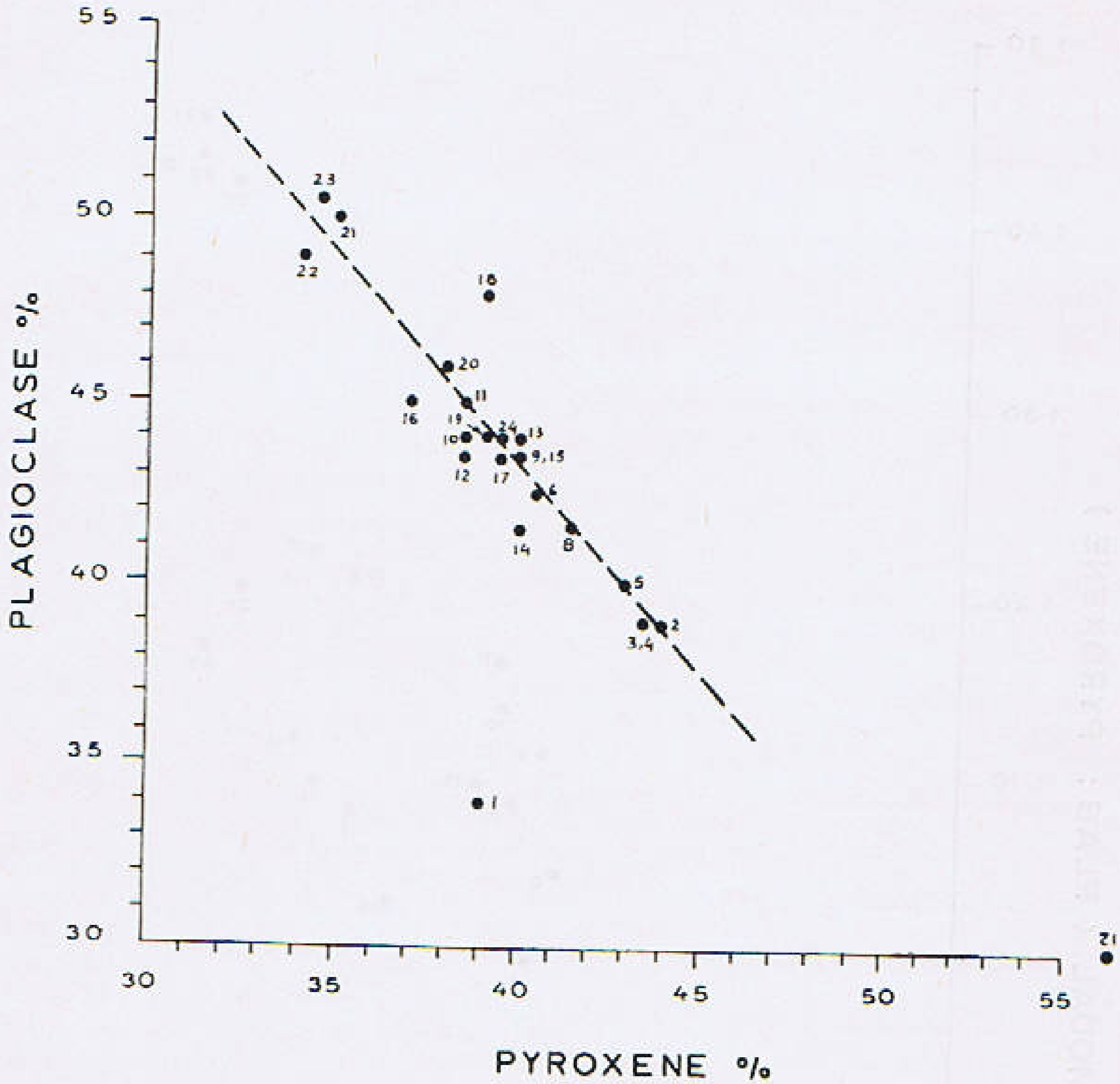

Fig. 3. Showing modal variation of plagioclase in relation to pyroxene in the dolerites.

ferrosilite molecule was not extensive.

(*iv*) The maximum concentration of the plotted positions are found in the areas of augite and magnesian pigeonite.

The generalized trend of pyroxene crystallization is comparable to those from well known basic complexes of tholeiitic affinity such as Skaergaard Intrusion (Wager and Deer, 1939), Tasmanian Dolerites (McDougall, 1961) and Palisade Sill (Walker, 1940) etc. The main reason for the concentration of plotted positions of pyroxenes in the case of dolerites under study, lies in somewhat random sampling so that material, carrying augite and pigeonite association, became available in abundance accidently. At the crystallization stage of pegmatitic facies of dolerites, only single pyroxene crystallized in the range of ferroaugite. The pyroxene crystallization, at this stage, seems to have crossed the limit of so-called 2 pyroxene field. The poor iron enrichment of the pyroxenes, however, seems to be due to somewhat poor differentiation of the parent magma in addition to the remote

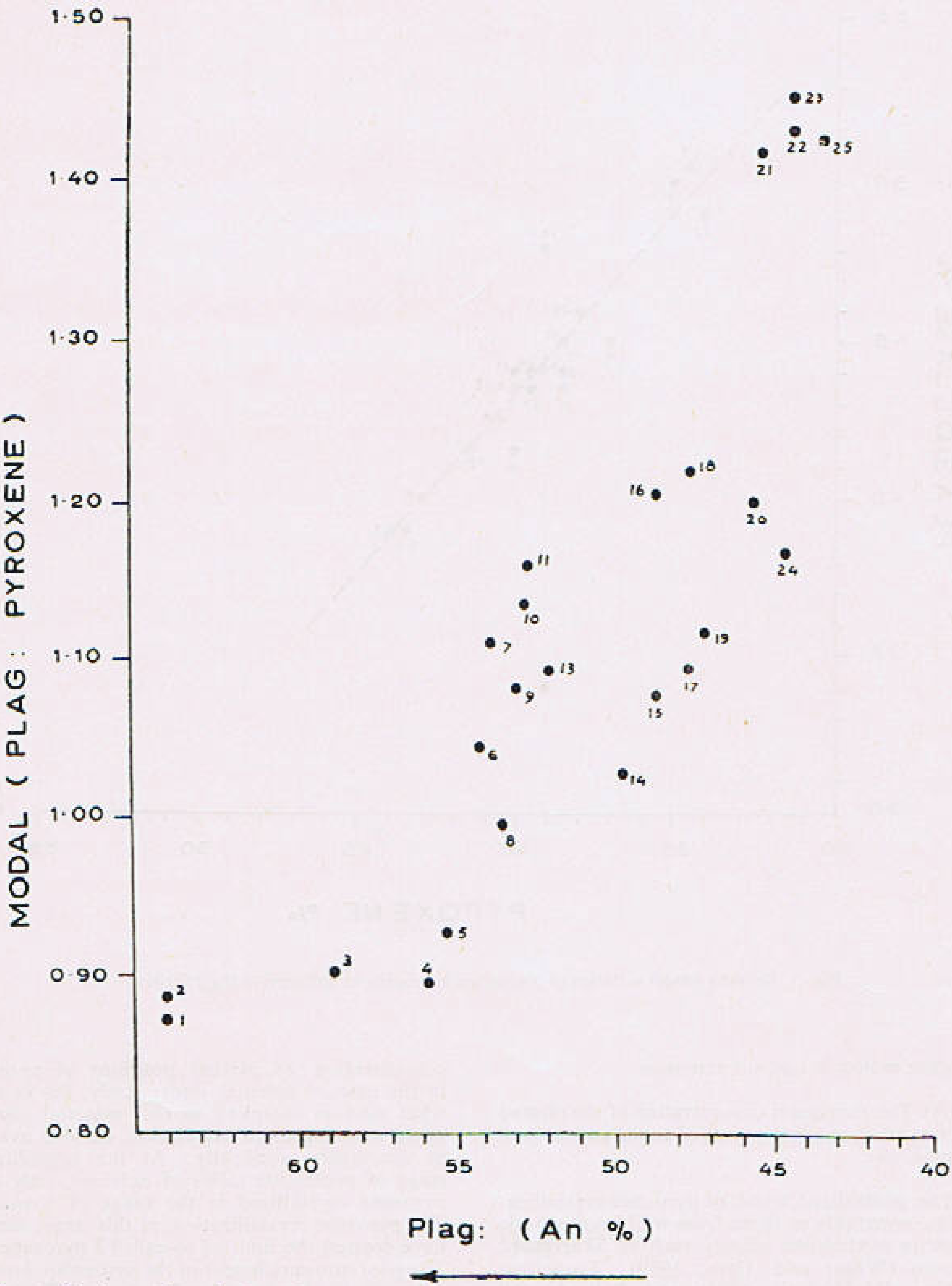

Fig. 4 Showing relationship of anorthite content of plagioclase and the modal ratio of plagioclase to pyroxene of the dolerites.

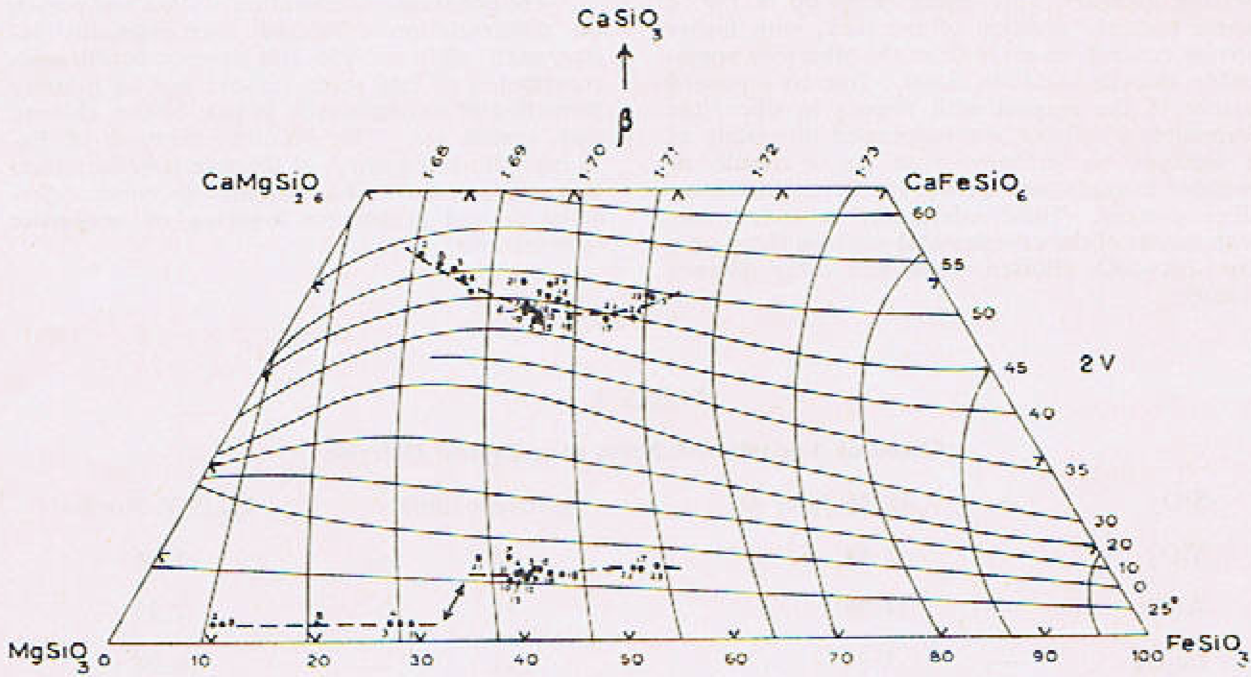

Fig. 5 Showing variation trends of associated pyroxenes in the dolerites.

possibility that dolerites containing pyroxene with higher ferrosilite content, might have escaped sampling.

CONCLUSION AND DISCUSSION

The petrographic investigations of the dolerites, particularly the instability of olivine, the trend of pyroxene crystallization and the presence of micro-pegmatitic residue etc. all point towards tholeiitic affinity of the parent basic magma. In order to check up this conclusion, specimen of a typical dolerite (MAS 6851) taken from near the Mansehra Rest House, (Grid ref. 110412 toposheet 1" 43 F/3) was chemically analyzed ; the data are given in Table 4 alongwith corresponding C.I.P.W. normative composition.

The chemical composition and the presence of appreciable Q value in the Norm of the analyzed dolerite up-holds the conclusion that the basic magma had a tholeiitic affinity. The poor water content (0.60%) and the predominance of various anhydrous silicate minerals in the dolerites show that the magma was dry as well.

There is no field or petrographic evidence to prove extensive differentiation of the dolerite bodies ; the most important reason for this may be their thin dimensions. As a rsesult of somewhat rapid cooling, crystallization of the magma proceeded rapidly so that differentiation effects could develop either within interatelluric spaces as micropegmatite or as thin coatings on primary joint surfaces and joint fillings in the form of pegmatitic phase. The crystallization behaviour of the dolerite bodies, therefore approached more near those of thick volcanic flows rather than plutonic masses. This might be the main reason for the widespread preservation and lack of prominent inversion textures in pigeonitic pyroxene and the poor differentiation of the parent magma. However, the paragenetic crystallization behaviour and abundance ratio between major mineral constituents, such as pyroxene and plagioclase, are in conformity with the accepted principles.

The inverse relationship between modal proportion of plagioclase and pyroxene may mean that, with differentiation, the magma was being depleted progressively in mafic relative to salic constituents. It has been mentioned already that the olivine phase, which was highly magnesian ($Fo_{80\cdot5-91}$), started to crystallize earlier than the pyroxene minerals. This sequence of crystallization, whenever developed, resulted in the depletion of magma in mafic constituents in such a manner that the modal portion of pyroxene was suppressed in the olivine-bearing dolerites. This effect shows up in Fig. 4 where plotted position of the rock, with higher olivine content lies away from the otherwise appreciably smooth variation trend. Due to saturated nature of the magma with respect to silica, the formation of olivine got suppressed ultimately as it changed to orthopyroxene as a result of reaction towards melt with progressively increasing silica content. These inferences are in harmony with results of the experimental work on the system Dp—Fo—SiO_2 (Bowen, 1914) and other relevant studies.

The late stage concentration of silica and potash on differentiation developed micropegmatite intergrowth while volatile and aqueous constituents contributed to late stage reactive and/or primary formation of minerals such as pale biotite, chlorite and apatite etc. The dehomogenization of Fe-Ti ore, into intergrowth of ilmenite lamellae inside magnetite, is also to be attributed to minor differentiation and progressive lowering of magmatic temperatures.

TABLE 4

Chemical Analysis and Norm of a Typical Dolerite.

				Corresponding		C.I.P.W. Norm :
SiO_2	—	48.96 % by wt.				
TiO_2	—	1.84	,,	Q	—	2.64
Al_2O_3	—	14.36	,,	or	—	2.22
Fe_2O_3	—	3.74	,,	ab	—	16.24
FeO	—	8.98	,,	an	—	29.47
MnO	—	0.20	,,	ap	—	0.34
MgO	—	7.35	,,	il	—	3.50
CaO	—	11.38	,,	mt	—	5.57
Na_2O	—	1.91	,,	hy	—	18.76
K_2O	—	0.38	,,	dp	—	21.35
P_2O_5	—	0.13	,,			
H_2O^+	—	0.08	,,			
H_2O^-	—	0.60	,,			
Total	—	99.60	,,			

Analyst : Dr. E.L.P. Mercy,
Edinburgh, U.K.

REFERENCES

Bowen, N.L. 1914 The ternary system diopside—forsterite—silica *Amer. Journ. Sci.*, **38**, 207-64.

Hess, H.H. 1949 Chemical composition and optical properties of common clinopyroxenes. *Amer. Mineral.*, **34**, 621-666.

McDougall, 1. 1961 Optical and chemical studies of pyroxenes in a differentiated Tasmanian dolerite. *Amer. Mineral.*, **46**, 661-687.

Poldervaart, A. and Hess, H.H. 1951 Pyroxenes in the crystallization of basaltic magmas. *Journ. Geol.*, **59**, 472-489.

Wadia, D.N. 1931 The syntaxis of the northwest Himalayas : Its Rocks, Tectonics and Orogeny. *Rec. Geol. Surv., India*, **65**, 89-200.

Wager, L.R. and Deer, W.A. 1939 Geological investigation in east Greenland, Part III. The Petrology of the Skaergaard intrusion, Kangerdlugssuag, east Greenland. *Meddel. om. Gronland*, **105**, 1-352.

Walker, F. 1940 Differentiation of the Palisade diabase, New Jersery. *Bull. Geol. Soc. Amer.*, **51**, 1059-1106.

Wilkinson, J.F.G. 1956 Clinopyroxenes of alkali basalt magmas *Amer. Mineral.*, **41**, 724-743.

Yagi, K. 1953 Petrochemical studies of the alkalic rocks of the Morotu District, Sakhalin. *Bull. Geol. Soc. Amer.*, **64**, 769-810.

TABLE 2

Modal Composition of Dolerites.

Sr. No.	Specimen Number	% Plag.	% Pyrox.	Plag/Pyrox.	% Iron Oxide	% Biotite	% Hornbl.	% Mesostasis	% Chlorite	% Oilvine	Average Plag. Comp.	Max. length of Plag. laths in m.m.	Max. Diameter of Pyroxene grains in m.m.
1.	6747	34	39	0.87	3	2	3	—	2	12+ Serpentine 5%	An_{64}	2.85	2.25
2.	6269	39	44	0.89	3	3	3	—	2	5+ Serpentine 1%	An_{64}	1.65	2.25
3.	6325	39	43.5	0.90	6	4	5	—	2.5	—	An_{59}	0.68	0.60
4.	6255	39	43.5	0.90	5	3	5	0.5	3.5	—	An_{55}	1.88	1.35
5.	6036	40	43	0.93	5.5	5	4	0.5	2	—	$An_{55.5}$	0.99 with rare phenocrysts =1.80	0.90
6.	6680	42.5	40.5	1.05	5	3	4	1.5	3.5	—	An_{55}	2.25	1.20
7.	7066	44	39.5	1.11	4	3	4	1	4.5	—	An_{55}	1.35	1.20
8.	7220-A	41.5	41.5	1.00	2.5	3.5	5	—	6	—	An_{54}	2.70	2.18
9.	6365	43.5	40	1.09	4	3	5	1.5	3	—	An_{54}	1.80	1.95
10.	7067	44	38.5	1.14	5	3	3	2.5	4	—	An_{54}	1.50	1.05
11.	7220-B	45	38.5	1.17	5	4	3	2	2.5	—	An_{54}	2.18	2.03
12.	6189	43.5	38.5	1.13	5	3	5	1.5	2	—	An_{54}	1.73	1.13
13.	6505	44	40	1.10	5	2.5	4	1.5	3	—	An_{53}	1.80	1.05
14.	6265	41.5	40	1.04	5	3	4.5	1	5	—	An_{51}	2.33	2.55
15.	6680	43.5	40	1.09	5	3	4	2	2.5	—	An_{53}	1.95	1.88
16.	6981	45	37	1.22	6	2	3	2.5	4.5	—	An_{50}	2.48	1.95
17.	7155	43.5	39.5	1.10	5	2	4	3	3	—	An_{49}	2.55	2.10
18.	6046	48	39	1.23	4.5	2	3	2.5	1	—	An_{49}	3.00	3.60
19.	6904	44	39	1.13	5	3.5	3	2.5	3	—	$An_{48.5}$	3.60	3.45
20.	6999	46	38	1.21	6	3	4	2	1	—	An_{47}	2.10	2.40
21.	6970	50	35	1.43	6	2	3	3	1	—	An_{47}	2.48	1.50
22.	6038	49	34	1.44	7	3	3	3	—	—	An_{46}	2.48	1.95
23.	6219	50.5	34.5	1.46	6	3	4	3	—	—	An_{46}	2.55	1.58
24.	6202	44	39.5	1.12	5.5	3	4	3	2	—	An_{46}	3.30	1.88
25.	SZ 1	38	26.5	1.43	17.7+ Limonite 5%	1.8	3	8	—	—	An_{45}	3.90	4.15

54155

TABLE 3

Optical data and estimated compositions of pyroxene and olivine minerals

Sr. No.	Specimen Number	Ca-RICH PYROXENES					CA-POOR PYROXENES: ORTHO PYROXENES (Hypersthene Series)							CA-POOR PYROXENES: CLINO-PYROXENES (Pigeonite series)					OLIVINES				
		β	$2V_\gamma$	Estimated composition			α	β	γ	2V	(Estimated composition) (Assuming 2% Wo in each case)				$2V_\gamma$	Estimated composition			α	β	γ	$2V_\gamma$	Estimated composition
1.	6747	1.688	46°	Wo_{39}	$En_{45\cdot5}$	$Fs_{15\cdot5}$	1.688	1.698	1.705	63°	Wo_2	En_{70}	Fs_{48}						1.650	1.666	1.690	87°	Fo_{91}
2.	6269	1.681	53°	Wo_{43}	$En_{48\cdot2}$	$Fs_{8\cdot8}$	1.665	1.670	1.678	80°	Wo_2	En_{89}	Fs_9						1.671	1.686	1.710	92° or $2V_\alpha$—88°	$Fo_{80\cdot5}$
3.	6325	1.685	50°	$Wo_{41\cdot3}$	En_{46}	$Fs_{12\cdot7}$	1.685	1.695	1.700	70°	Wo_2	En_{72}	Fs_{26}										
4.	6255	1.686	48°	$Wo_{49\cdot3}$	$En_{45\cdot6}$	$Fs_{14\cdot1}$	1.684	1.693	—	65°	Wo_2	En_{71}	Fs_{27}										
5.	6036	1.696	42°	$Wo_{35\cdot9}$	$En_{41\cdot0}$	$Fs_{23\cdot1}$								1.694	18°	Wo_8	En_{55}	Fs_{37}					
6.	6680	1.695	44°	Wo_{37}	En_{41}	Fs_{23}								1.693-4	23°	$Wo_{7\cdot9}$	$En_{56\cdot4}$	$Fs_{35\cdot7}$					
7.	7066	1.694	44.5°	$Wo_{37\cdot5}$	$En_{41\cdot1}$	$Fs_{21\cdot5}$								1.692-3	11°-12°	$Wo_{9\cdot2}$	$En_{56\cdot8}$	Fs_{34}					
8.	7220-A	1.693	52°	Wo_{42}	En_{47}	Fs_{11}	1.665	1.670	1.680	85°	Wo_2	En_{88}	Fs_{10}										
							1.677	1.682	1.689	77°	Wo_2	En_{79}	Fs_{19}										
9.	6365	1.697	46°	$Wo_{38\cdot5}$	$En_{38\cdot4}$	$Fs_{23\cdot1}$																	
10.	7067	1.694	43°	$Wo_{36\cdot8}$	$En_{41\cdot3}$	$Fa_{21\cdot9}$																	
11.	7220-B	1.695	44°	Wo_{37}	$En_{40\cdot7}$	$Fs_{22\cdot3}$								1.694	20°	$Wo_{7\cdot6}$	$En_{55\cdot6}$	$Fs_{36\cdot8}$					
12.	6189	1.696	43°	$Wo_{36\cdot5}$	$En_{40\cdot3}$	$Fs_{23\cdot2}$								1.692	25°	$Wo_{6\cdot8}$	$En_{58\cdot9}$	$Fs_{35\cdot2}$					
13.	6505	1.696	43°	$Wo_{36\cdot1}$	$En_{40\cdot1}$	$Fs_{23\cdot8}$								1.693	20°	$Wo_{7\cdot6}$	$En_{57\cdot0}$	$Fs_{35\cdot4}$					
14.	6265	1.698	46°	Wo_{38}	$En_{37\cdot6}$	$Fs_{24\cdot4}$								1.693-4	22°	Wo_7	$En_{56\cdot2}$	$Fs_{36\cdot8}$					
15.	6680	1.696	42°	$Wo_{35\cdot7}$	$En_{40\cdot3}$	Fs_{24}								1.693	20°	$Wo_{7\cdot5}$	$En_{5\cdot4}$	$Fs_{3\cdot1}$					
16.	6981	1.699	45°	$Wo_{37\cdot5}$	En_{37}	$Fs_{25\cdot5}$								1.695	18°	$Wo_{8\cdot0}$	$En_{54\cdot6}$	$Fs_{37\cdot4}$					
17.	7155	1.704	44.5°	Wo_{36}	En_{34}	Fs_{30}								1.696	20°	$Wo_{7\cdot5}$	$En_{53\cdot9}$	$Fs_{38\cdot6}$					
18.	6046	1.699	43°	Wo_{36}	$En_{37\cdot6}$	$Fs_{26\cdot4}$								1.706	16°	$Wo_{8\cdot1}$	$En_{45\cdot5}$	$Fs_{46\cdot4}$					
19.	6970	1.693	52°	Wo_{40}	En_{40}	Fs_{20}								1.697	22°	$Wo_{7\cdot5}$	$En_{52\cdot6}$	$Fs_{39\cdot9}$					
20.	6038	1.705-6	45°	$Wo_{36\cdot2}$	$En_{63\cdot1}$	$Fs_{30\cdot7}$								1.688	12°	$Wo_{9\cdot3}$	$En_{59\cdot8}$	$Fs_{30\cdot9}$					
21.	6219	1.711-12	49°	$Wo_{38\cdot3}$	$En_{28\cdot9}$	$Fs_{32\cdot8}$								1.706-7	10°	$Wo_{8\cdot0}$	$En_{44\cdot9}$	$Fs_{47\cdot1}$					
22.	Sz1	1.711	44°	$Wo_{38\cdot1}$	$En_{28\cdot4}$	$Fs_{33\cdot5}$ (Ferroaugite)								1.709	10°	$Wo_{8\cdot2}$	$En_{43\cdot1}$	$Fs_{48\cdot7}$					

THE DATING AND CORRELATION OF THE NARI AND THE GAJ FORMATIONS

BY

M. H. KHAN

Oil and Gas Development Corporation, Karachi

Abstract : *The development of the Upper Nari and the Gaj Formations in the neighbourhood of Karachi is somewhat different from that found in the type sections along the Nari and the Gaj rivers in Sind, for which reason the Upper Nari/Gaj boundary has previously been placed at different levels. On the basis of the diminution in the degree of abundance of Spiroclypeus followed by the appearance and thereafter occurrence in increased abundance of Miogypsina, two distinct biozones can be recognized in these formations. The foraminiferal assemblages indicate that the Upper Nari Formation ranges in age from Rupelian to Early Aquitanian, whereas the Gaj Formation belongs to the Late Aquitanian to Burdigalian age.*

INTRODUCTION

Some years ago the writer reviewed the lithological and paleontological characteristics of the Upper Nari and the Gaj Formations exposed in the foot hills north of Karachi with the object of establishing criteria for their distinction. This work was undertaken in connection with the first deep test well drilled by the Pakistan Petroleum Limited at Drig Road, Karachi.

The development of the Upper Nari and the Gaj Formations in the neighbourhood of Karachi is somewhat different from that found in the type sections along the Nari and the Gaj rivers. The Upper Nari Formation along these rivers consists almost entirely of thick to thin beds of sandstones with subordinate development of olive-green to brown shales and is completely devoid of calcareous beds. The succession is virtually unfossiliferous. The Upper Nari Formation in Karachi area consists of sandstones and shales intercalated with several fossiliferous calcareous beds in the upper part. The limestone bands have resemblance and contain more or less the same faunal assemblages as those of the Gaj Formation. The Gaj Formation along the Nari and the Gaj rivers is essentially a succession of shale and sandstone and calcareous beds constitute only a small proportion of the total thickness of this formation, but in the foot hills north of Karachi the Gaj Formation is dominated by limestone. There are numerous intercalations of soft, grey sandstones resembling those of the lower part of the Upper Nari Formation.

In the type areas there is not much difficulty in placing the Upper Nari/Gaj boundary which is taken above the last thick massive sandstone and below the thick succession of multicoloured shales and dark ferruginous sandy limestone. But because of the great lithological resemblance of the upper part of the Upper Nari with the lower part of the Gaj Formation, the interformational contact in the Karachi area has not been drawn always at the same place. It has been variously taken at the top of a thick bed of very hard, ferruginous and gritty sandstone and at the base of the upper or lower bands of hard and white limestones, largely composed of corals. The latter positions cannot form the basis for a lithostratigraphic boundary, while the former seems to be in approximate correspondence with the boundary taken in the type areas as it is based, more or less, on the same lithologic criteria.

The foraminiferal faunal assemblages of the upper part of the Upper Nari and the Gaj Formations have many species in common. From a detailed examination of samples and micropaleontological data collected by the Burmah Oil Company from the Upper Nari and the Gaj Formations exposed in the Orangi Nala, Band Murad Khan and Mutrani sections, the writer observed that in the Upper Nari Formation faunal species of *Spiroclypeus* are predominant, while the Gaj Formation is characterized by the predominance of the species of *Miogypsina*. In other words the diminution in the degree of abundance of *Spiroclypeus* is followed by the appearance and thereafter occurrence in increased abundance of *Miogypsina* and disappearance of *Spiroclypeus*. This change can be made use of to distinguish two distinct biozones in the Upper Nari/Gaj succession exposed in the foot hills north of Karachi. Subsequent examination of the rock cuttings from Karachi Test Well showed that these biozones can also be recognised in the subsurface succession.

The assessment of the Upper Nari/Gaj faunas for dating indicates that the Upper Nari Formation ranges in age from Rupelian to Early Aquitanian and the Gaj Formation from Late Aquitanian to Burdigalian.

It may be mentioned here that, the paucity of material preculuded naming of all the species recorded from the Upper Nari and Gaj formations. Wherever, identification on species level could not be made with precision, the species have been distinguished on the basis of open nomenclature, pending further detailed study. This, however, does not affect the conclusions drawn on the dating of the Nari and the Gaj formations. The writer intends to publish a fuller account of the Gaj/Nari faunas at a later date.

BIOZONES

1. Orangi Section

In the Orangi section 2400 feet of the Gaj Formation and 2010 feet of the Upper Nari Formation are exposed. The fauna recorded is shown in Fig. No. 1, A. Paleontological evidence admits distinction of two biozones in asscending order as under.

(*i*) *Spiroclypeus blanckenhorni ornata* Zone : This biozone covers the entire succession from the base of the lowest exposed bed (sample No. F.B.B. 1563) upto 320 feet above the top of the Upper Nari (sample No. F.B.B. 1532) from top of 460 hill (south of Pir Mangho) and is characterized by the presence in abundance of *Spiroclypeus blanckenhorni ornata, S. ranjae, S. margaritatus, S.* sp., which are restricted to this zone. Other forms which occur in this zone are *Eulepidina dilatata, E. formosa, Nephrolepidina* cf. *angulosa, N.* spp., *Miogypsinoides* sp. In the uppermost part of this zone *Miogypsina globulina* and *M. intermedia* first appear sporadically, but their maximum development takes place in the succeeding biozone. In other words the passage from the predominantly *Spiroclypeus*—bearing beds to those containing *Miogypsina* in abundance is gradual and for some thickness the ranges of these two forms overlap each other. Since this overlap in the ranges of *Spiroclypeus* and *Miogypsina* has been observed in other surface as well as subsurface sections in Karachi well, it has considerable correlative value. In the Orangi section the overlap extends to about 500 feet.

(*ii*) *Miogypsina globulina* Zone : The *Spiroclypeus blanckenhorni ornata* Zone is succeeded by *Miogypsina globulina* Zone and as the name suggests is characterized by the presence in abundance of *Miogypsina globulina, M. intermedia, M.* sp., *Miogypsinoides dehaarti, M.* sp. The Lepidocyclinids are practically absent from the upper half of this biozone. The *Miogypsina globulina* Zone extends from the top of the *Spiroclypeus blanckenhorni ornata* Zone to the top of the Gaj Formation.

2. Band Murad Khan Section

This section exposes 2340 feet of the Gaj Formation and 2055 feet of the Upper Nari Formation. The fauna recorded is shown in Fig. 1, B.

The *Spiroclypeus blanckenhorni ornata* and *Miogypsina globulina* Zones can also be recognised in this section. The *Spiroclypeus blanckenhorni ornata* Zone covers the succession from the base of the lowest exposed bed upto 85 feet above the top of the Upper Nari and is characterized by the presence in abundanceof *Spiroclypeus blanckenhorni ornata* and rare occurrence, in the topmost part, of *Miogypsina globulina*. Like the Orangi section the passage from the predominantly *Spiroclypeus* to *Miogypsina*-bearing beds is transitional and in this section the overlap between the ranges of these two forms extends to about 180 feet. The succession from the top of the *Spiroclypeus blanckenhorni ornata* Zone to the top of the Gaj Formation falls within the *Miogypsina globulina* Zone and can be distinguished by the abundance of *Spiroclypeus blanckenhorni ornata*. The Lepidocylinids do not extend into the upper half of this biozone.

3. Mutrani Section

This section exposes 360 feet of the Gaj Formation which can be correlated with the *Miogypsina globulina* Zone of Orangi and Band Murad Khan sections. The fauna recorded is shown in Fig. 1, C from which it will be seen that *Miogypsina globulina, M. intermedia, M. tani* and *M. gunteri* are present in abundance and *Spiroclypeus* is absent.

4. Karachi Test Well No. 1

The fauna recorded from the Gaj and part of the Upper Nari Formations penetrated by Karachi Test Well No. 1 is shown in Fig. 1, D.

It will be seen that the seccession from surface down to 1780 feet corresponds to the *Miogypsina globulina* Zone and is characterized by a fairly rich assemblage consisting of *Miogypsina globulina, M. gunteri, M. tani, M. cushmani, Miogypsinoides dehaarti, Nephrolepidina* cf. *angulosa, N.* spp., *Eulepidina dilatata, Austrotrillina howchini.* The *Spiroclypeus blanckenhorni ornata* Zone can be recognised from below a well depth of 1780 feet and is characterised by the persistant occurrence in abundance of *Spiroclypeus blanckenhorni ornata* and *S. margaritatus,* followed by a marked decrease in the frequencies of the species of *Miogypsina.* As due to contamination the lower limits of the species cannot be fixed from flush cuttings so that the base of the *Spiroclypeus blanckenhorni ornata* Zone cannot be precisely defined. However, from below 3920 feet there is a marked decrease in fauna and the formation from below 4960 feet is virtually barren. The succession in the range 4960-7875 feet in Karachi Test Well No. 1 both in its lithology and in the absence of fauna bears great resemblance to the Upper Nari Formation developed in the type areas.

The top of the Upper Nari Formation in Karachi Well No. 1, applying the same lithologic criteria as in the case of the surface sections, can be taken at the top of a white, coarse-grained quartzitic sandstone at 2390 feet and the base at the top of dark to light-greyish brown, argillaceous limestone at 7875 feet. The total thickness of the Upper Nari Formation penetrated by Karachi Well No. 1 is 5485 feet as against 3500 feet exposed along the Gaj River.

CORRELATION OF THE NARI AND THE GAJ FORMATIONS WITH THE EUROPEAN TYPE STAGES

The distinct foraminiferal assemblages characterizing the European Stages of Oligocene (Lattorfian, Rupelian, Chattian) and Lower Miocene (Aquitanian, Burdigalian) are all represented in the type Tertiary succession of Sind (see Figs. 1-2). These foraminiferal assemblages are of world-wide geographical distribution and can be followed through Europe and Mediterranean region to the Middle East, East Africa, Pakistan, India, and the Far East (Eames *et al*., 1962).

Lattorfian faunas are represented by the upper most part of the Khirthar Limestone (Gorag Member of Colombo Plan Survey, 1961 ; Khan, 1967) which contains *Nummulites intermedius/fichteli, Palaeonummulites incrassatus, Borelis pygmaea, Austrotrillina pausialveolata* but no *Eulepidina*.

Rupelian faunas of part of the Gorag Member and the Lower Nari Formation (calcareous Nari of some authors) are characterized by the continuance of the above forms from the Lattorfian and first appearance of *Eulepidina dilatata, Peneroplis glynnjonesi, Archaias operculiniformis, A. evolatus, Nephrolepidina tournoueri, N.* cf. *marginata, Praehapydionina, Meandropsina* sp.

The Chattian is represented by greater part of the Upper Nari Formation (sandy Nari of some authors). In the Mediterranean region the Chattian faunas, which are associated with the regression preceding the Neogene transgression, are poorly developed or missing and contain mostly brackish water forms (Eames *et al., op. cit*). The marine Chattian faunas of Europe and the Middle East are characterized by the persistance of forms from the underlying Rupelian, but in which true *Nummulites* became extinct.

In Sind, as far as is known, marine Chattian forminiferal faunas are not developed, Like the Mediterranean region, the later part of the Oligocene epoch witnessed a recession of sea from north to south and the formation of a predominantly arenaceous succession of the Upper Nari Formation of deltaic and fluviatile origin. In the southern region, however, marine conditions prevailed during the deposition of the upper part of the Upper Nari Formation.

The entire Upper Nari Formation, with the exception of the basal part, in the type northern area is sporadically fossiliferous, whereas, in the south in the neighbourhood of Karachi the upper part of this formation contains intercalations of limestone beds containing marine fauna younger than the Chattian.

Aquitanian faunas are represented by the *Spiroclypeus blanckenhorni ornata* Zone which in the Karachi region extends from the upper part of the Upper Nari Formation to the basal beds of the Gaj Formation. These beds contain *Eulepidina dilatata, Nephrolepidina* cf. *angulosa,* which persist form the Rupelian, *Spiroclypeus blanckenhorni ornata, S. ranjae, S. margaritatus, Miogypsina globulina, M. intermedia, Miogypsinoides* sp. which appear for the first time and range up into the Gaj Formation of the Burdigalian age.

Burdigalian faunas are represented by the *Miogypsina globulina* Zone which in the Karachi area extends from some distance above the base to the top of the Gaj Formation. These beds contain *Miogypsina globulina, M. intermedia, M. cushmani, M. tani, M. gunteri, Miogypsinoides dehaarti, M.* sp., *Nephrolepidina* spp., *Austrotrillina howchini, Taberina malabarica* and in the lower part *Eulepidina*. More or less same fauna characteizes the Gaj Formation in the Gaj River area. In Pakistan *Eulepidina* ranges upto Early Burgalian but in many parts of the world (Sicily, South-western

France, East Africa) it did not survive the Aquitanian.

AMENDMENTS TO THE DATING OF THE TERTIARY SUCCESSION IN SIND.

The dating of the geological formations representing the Tertiary succession in Sind, on the basis of evidence of larger foraminifera presented here and in an another paper by the writer (Khan, 1967) leads to conclusions which in some cases differ from the other published accounts.

The Khirthar Formation was correlated by Vredenburg (1909) and Nuttall (1927) with the Lutetian stage of Europe. Davies (1940) considered the upper part of this formation to extend up into the Auversian. The investigations of the writer have shown that the Khirthar Formation is not wholy Lutetian in age but extends upto the Rupelian. There is a paleontological break between the Lutetian and the Lattorfian and a large part, if not the whole of Auversian and the entire Bartonian, is not represented. In some areas the time-hiatus is still more pronounced where the beds containing Lutetian faunas are directly succeeded by beds containing Rupelian faunas.

Eames *et al.* (*op. cit.*) regarded the presence of Lattorfian in Pakistan as doubtful, but the writer has described the Lattorfian faunas from the upper part of the Khirthar Formation in which *Eulepidina* is absent (Khan, *op. cit.*).

The Nari Formation was previously regarded as Oligocene, Lattorfian to Chattian in age (Cotter, 1956). Vredenburg (1906) considered the Upper Nari Formation as Middle Aquitanian. Eames *et al.* (*op. cit.*) were of the view that no satisfactory published evidence exists for the presence of Chattian in Pakistan and that the Upper Nari Formation of the Aquitanian age rests with a paleontological break upon the Lower Nari Formation of Rupelian age. From the evidence given above it will be seen that in the Gaj River section the Lower Nari and the basal part of the Upper Nari are of Rupelian age and are succeeded by thick to thin sandstones and subordinate shales representing the regressive facies of the Chattian similar to that developed in the Mediterranean region. These beds contain poor benthonic foraminifera which are not well known. The Chattian Upper Nari Formation is directly overlain by the Late Aquitanian to Burdigalian Gaj Formation indicating a paleontological break in the Gaj River area. In the Karachi area the lower part of the Upper Nari Formation is of similar lithofacies as in the Gaj river area and is sparsely fossiliferous. The upper part contains Aquitanian faunas. The Nari Formation as a whole is, therefore, of Middle Oligocene (Rupelian) to Lower Miocene (Aquitanian) in age.

A chart showing comparative dating of the Tertiary Seccession in the former Sind in comparison to the European stages is shown in Fig. 3.

ACKNOWLEDGEMENT

The writer is indebted to the Manager, Pakistan Petroleum Limited for permission to publish this work. His thanks are also due to Mr. S.H. Khursheed who assisted the writer in the prepration of this paper.

REFERENCES

Colombo Plan Cooperative Project 1961 The reconnaissance geology of part of West Pakistan. Maracle Press Limited, Ontario.

Cotter, G. de P. 1956 Lexique Stratigraphique International. **3** (8), pp. 181-182.

Davies, L.M. 1940 The upper Khirthar beds of north-west India. *Quart. Journ. Geol. Soc. London*, **96** (2), pp. 199—234.

Eames, F.E. Banner, F.T., Blow, W.H. and Clarke, W.J. 1962 Fundamentals of Mid-Tertiary stratigraphical correlation. Cambridge University Press.

Khan, M.H. 1967 Time-hiatus at the Oligocene/Eocene boundary in Sind. *Pak. Journ. Sci. Ind. Res.*, **10** (4), pp. 287-95.

Nuttall, W.L.F. 1926 The zonal distribution of the larger foraminifera of the Eocene of western India. *Geol. Mag.*, **63**, pp. 495—504.

Vredenburg, E. 1906 *Nummulites douvillei*, an undescribed species from Kachh with remarks on zonal distribution of Indian *Nummulites, Rec. Geol. Surv. India*, **34**, pp. 79—95.

.. .. 1909 The geology of Sarawan, Jhalawan, Mekran, and the state of Las Bela, considered principally from the point of view of economic development. *Ibid.* **38**, pp. 189—215.

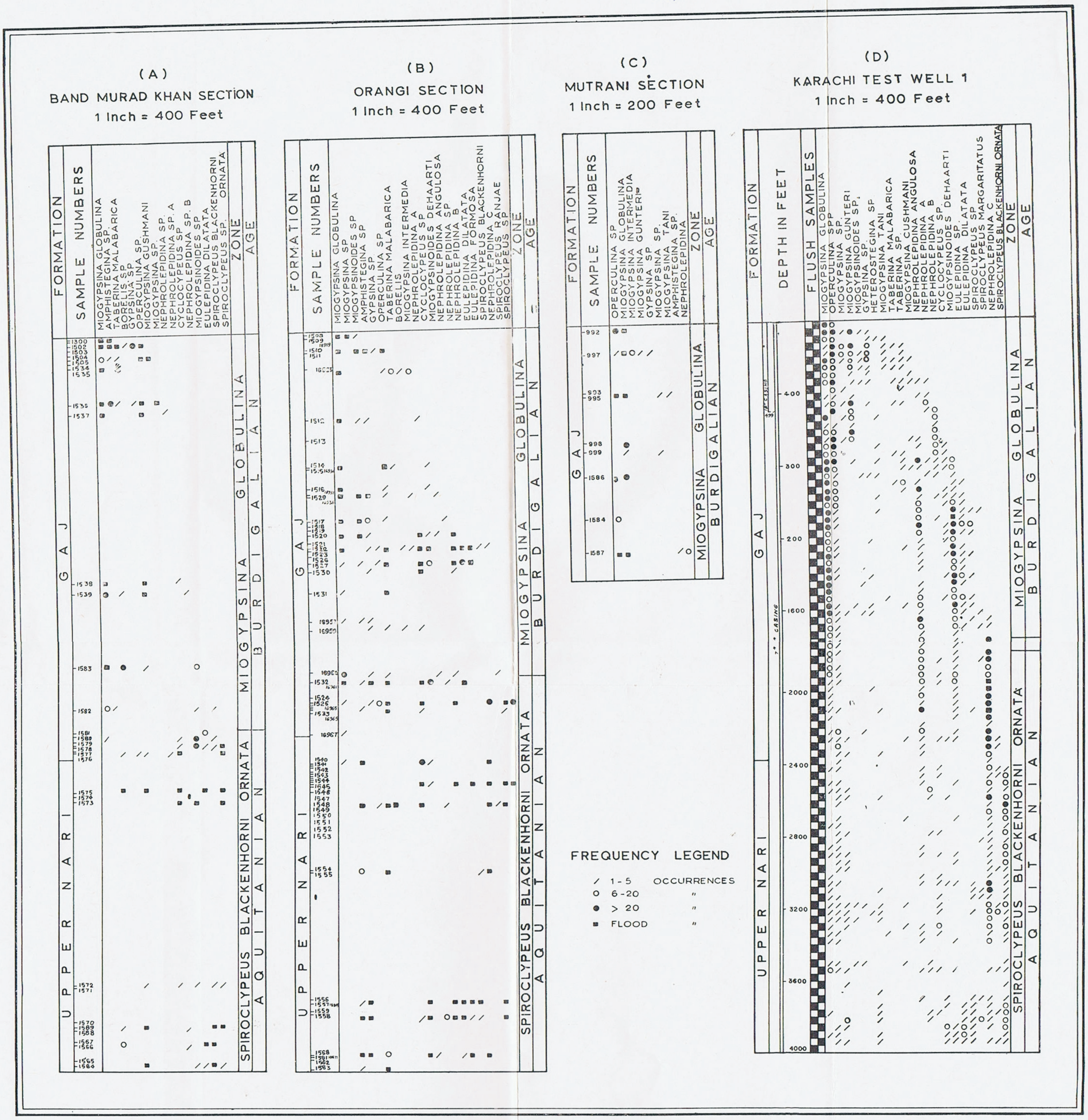

Fig. 1. Chart Showing ranges of larger Foraminifera in the Gaj/Upper Nari Formations.

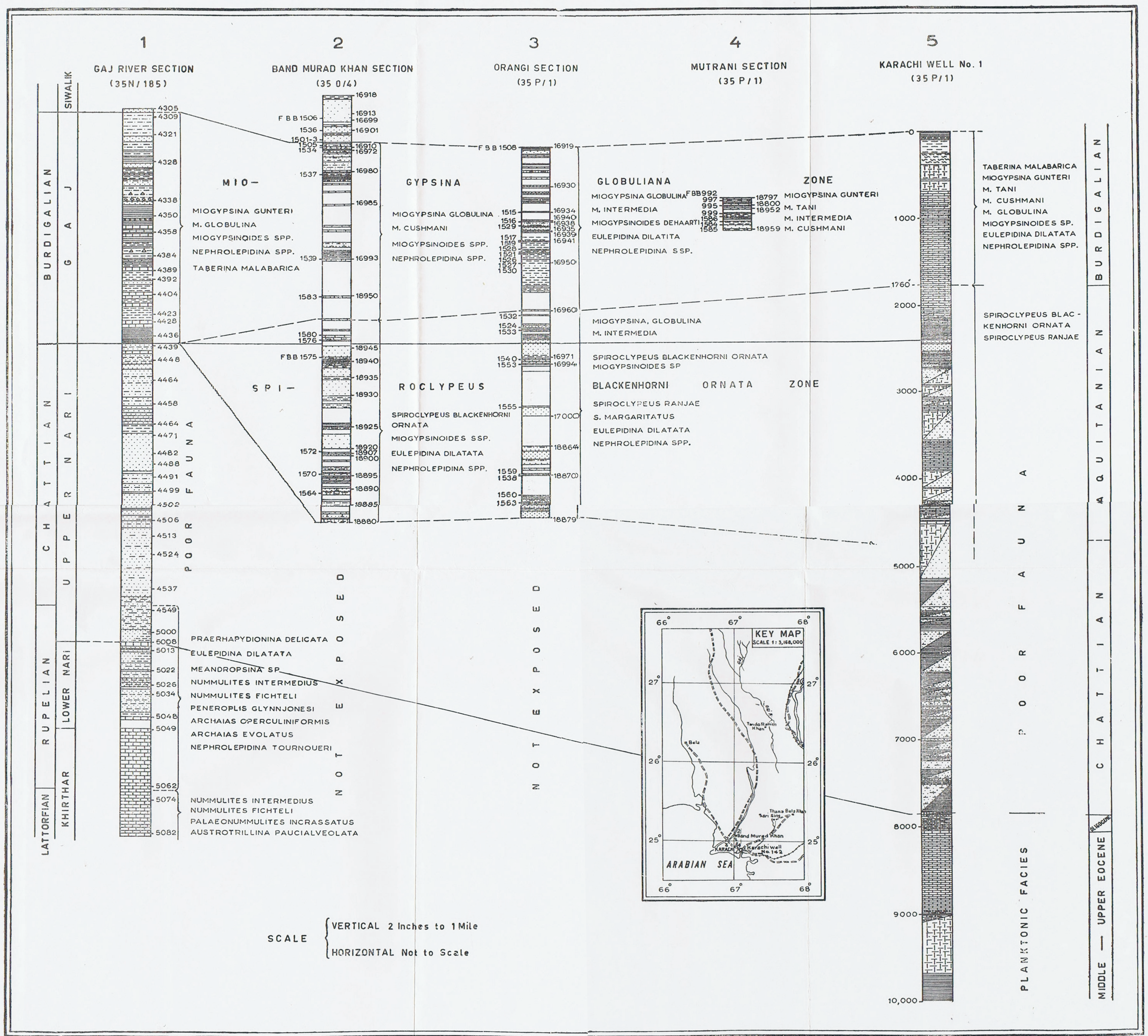

Fig. 2. Chart Showing Correlation between Gaj river and Karachi area.

<table>
<tr><th colspan="2"></th><th>GAJ RIVER</th><th>FOOT HILLS N. OF KARACHI</th><th>KARACHI WELL - 1</th></tr>
<tr><td rowspan="2">LOWER MIOCENE</td><td>BURDIGALIAN</td><td>GAJ</td><td>GAJ</td><td>GAJ</td></tr>
<tr><td>AQUITANIAN</td><td></td><td>UPPER PART UPPER NARI</td><td>UPPER PART UPPER NARI</td></tr>
<tr><td rowspan="3">OLIGOCENE</td><td>CHATTIAN</td><td>UPPER NARI</td><td rowspan="6">NOT EXPOSED</td><td>LOWER PART UPPER NARI</td></tr>
<tr><td>RUPELIAN</td><td>LOWER NARI</td><td rowspan="5">PLANKTONIC FACIES</td></tr>
<tr><td>LATTORFIAN</td><td>KHIRTHAR (GORAG MEMBER)</td></tr>
<tr><td rowspan="2">UPPER EOCENE</td><td>BARTONIAN</td><td rowspan="2"></td></tr>
<tr><td>AUVERSIAN</td></tr>
<tr><td>MIDDLE EOCENE</td><td>LUTETIAN</td><td>KHIRTHAR (BRHAUI LST.)</td></tr>
</table>

Fig. 3. Showing dating of Khirthar, Nari and Gaj Formations in comparison to European stages.

EXPLANATION OF PLATE I

Figure 1	..	*Miogypsina globulina* (Michelotti) median section ×16, Karachi Well No. 1.
Figure 2	..	*Miogypsina cushmani* Vaughan median section ×25, Karachi Well No. 1.
Figure 3	..	*Miogypsina? intermedia* Drooger median section ×16, Karachi Well No. 1.
Figure 4	..	*Miogypsina tani* Drooger median section ×24, Goth Ibrahim Hydiri.
Figure 5	..	*Miogypsina gunteri* Cole median section ×24, Karachi Well No. 1.
Figures 6, 7	..	*Miogypsinoides dehaarti* van der Vlerk 6 vertical section ×51, 7 median section ×35 Karachi Well No. 1.
Figures 8, 9	..	*Spiroclypeus margaritatus* (Schlumberger) 8 vertical section ×24, 9 median section ×25
Figure 10	..	*Nephrolepidina* sp. C. median section ×23, Karachi Well No. 1.

LARGER FORAMINIFERA OF GAJ/UPPER NARI

PLATE 1

EXPLANATION OF PLATE II

Figure 1	..	*Spiroclypeus ranjae*, Tewari median section ×13, Pir Mangho.
Figure 2	..	*Spiroclypeus blackenhorni ornata*, Henson median section ×12, Pir Mangho.
Figure 3	..	*Spiroclypeus* sp. median section ×22, Karachi Well No. 1.
Figure 4	..	*Nephrolepidina* sp.B. median section ×21, Karachi Well No. 1.
Figure 5	..	*Nephrolepidina* cf. *angulosa* (Provale) median section ×36, Karachi Well No. 1.
Figure 6	..	*Nephrolepidina* sp.A. median section ×25, Karachi Well No. 1.

LARGER FORAMINIFERA OF GAJ/UPPER NARI

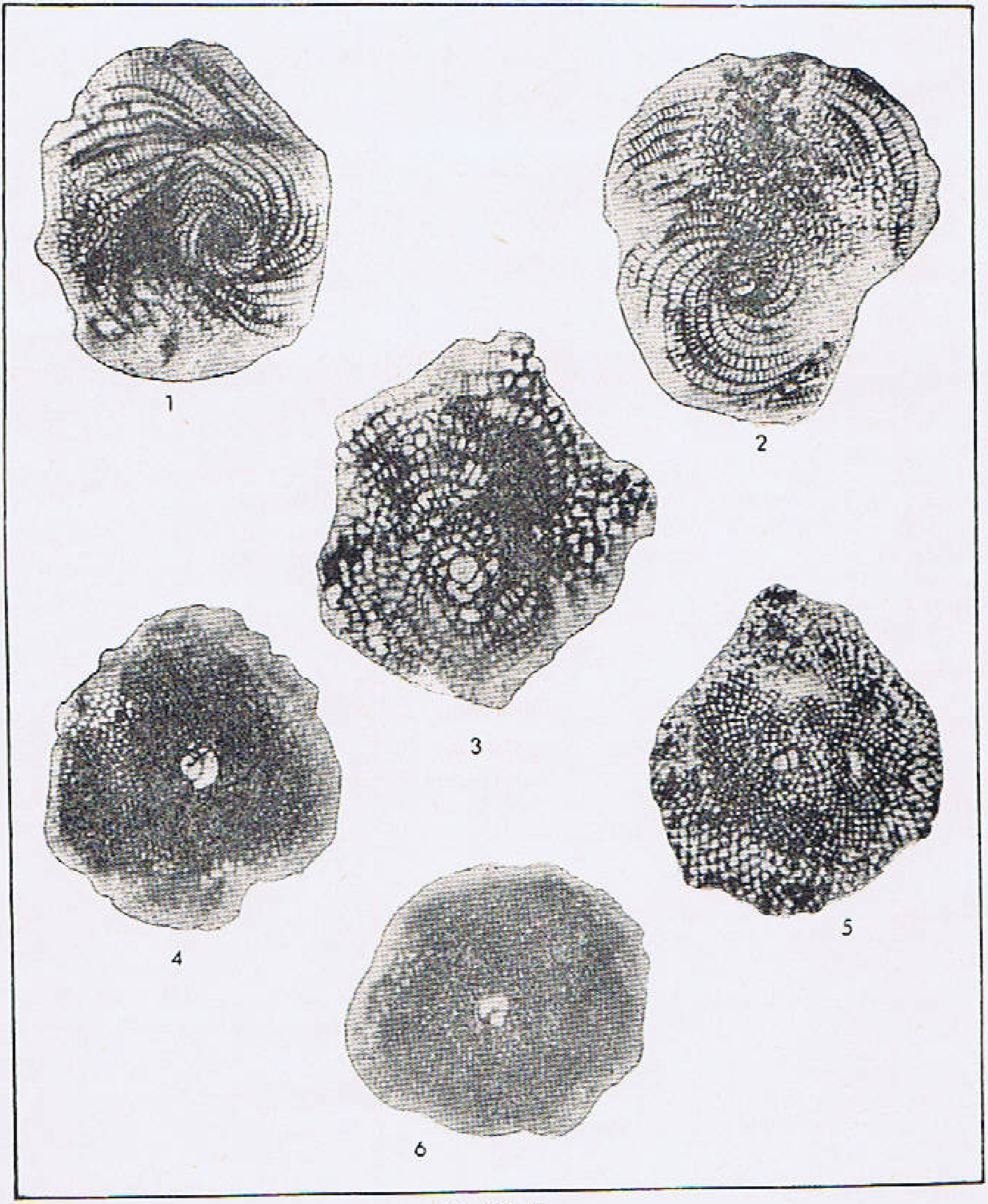

PLATE II

CLASSIFICATION OF THE AMPHIBOLE GROUP BASED ON (Na+K) ATOMS VERSUS [Al]^4 ATOMS WITH PARTICULAR REFERENCE TO HORNBLENDES FROM ALKALI POOR ENVIRONMENTS

BY

M. NAWAZ CHAUDHRY

Department of Geology, University of the Punjab, Lahore.

Abstract : *Chemical analyses, optical data and specific gravities are presented for five hornblendes from alkali poor skarns. When the chemical analyses are plotted on the diagram ($Al^6+Fe^{3+}+Ti$) versus $[Al]^4$, all positions fall within the area enclosed by the common hornblendes. However when the same data are plotted on (Na+K) versus $[Al]^4$ diagram, three of them fall outside the hornblende field. This fact shows the unsuitability of the latter method of classification for these amphiboles which have crystallized in an alkali poor environment.*

INTRODUCTION

Lime-silicate skarns are developed within a basic dyke at its contact with a Na-Li aplite dyke. At the Meldon granulite quarry, near Okehampton, Devonshire, in the southwest England, the aplite dyke is 60 to 80 feet in thickness and occurs three quarters of a mile north-west of the main Dartmoor Granite (Worth, 1920). The aplite consists of albite, quartz and lepidolite as the main and topaz, elbaite, apatite and petalite as the accessory minerals. In the Meldon granulite quarry this dyke comes in contact discordantly with a dyke of doleritic composition belonging to the "dark igneous series" (Worth, op. cit.) At the contact, garnet-hedenbergite, amphibole-axinite, amphibole-pyrrhotite-axinite and axinite-chlorite-mica-calcite skarns are developed. Considerable chemical reconstitution has taken place during the skarn formation. For instance, some of the amphibole-bearing areas show appreciable depletion in alkalies.

METHODS OF STUDY AND RESULTS

Five hornblendes were separated from skarn rocks. The chemical analyses, the number of ions calculated on the basis of 24 (O, OH, F), the optical and the physical properties are given in Table 1 Their refractive indices were determined by the single variation method using sodium light. The accuracy of these determinations was $\pm$ 0.001. The samples were chemically analysed by combined gravimetric and colorimetric methods. The contents of CaO and MgO were checked by the atomic absorption method of Walsh and Howie (1967). The contents of Fe_2O_3, MnO and TiO_2 were doubly checked by Riley's (1958) method. Fluorine was determined by the method of Grimaldi, Ingram and Cuttitta (1955).

The optical, physical and the chemical data show that these amphiboles belong to the common hornblende series. The replacement ratios of Mg to Fe, expressed as $100\times Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn^{2+})$, in these hornblendes, show a variation from 57.74 to 76.70. The Ca content shows a restricted range from 1.924 to 1.991 atoms per formula unit. These values are a little higher than the most common upper range of 1.8 ± 0.1 Ca atoms per formula unit (Deer, Howei and Zussman, 1962). Except in the sample MN 313, the (Na+K) atoms per formula unit are lower than most of the common hronblendes. The deficiency is believed to be due to the alkali poor environments in which these hornblendes crystallized. The deficiency has important implication on the validity of (Na+K) versus $[Al]^4$ classification for these hornblendes as will be shown later in this paper.

The refractive indices and the specific gravities show an inverse relationship with the extent of replacement of Mg by Fe expressed as $100 \times Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn^{2+})$.

CLASSIFICATION OF THE AMPHIBOLE GROUP AND THE POSITION OF THE PRESENT HORNBLENDES-A DISCUSSION.

Different classifications have been advanced by various workers such as, by Kunitz (1930), Sundius (1944) and Miyashiro (1957). But the most widely accepted and the simplest classification is based on the predominant cations in the 'X' position (Deer, *et al.* 1962). This classification uses the end members tremolite $Ca_2\ Mg_5\ (Si_8\ O_{22})\ (OH,\ F)_2$, edenite $Na\ Ca_2\ Mg_5\ (Si_7\ Al\ O_{22})\ (OH,\ F)_2$, pargasite $Na\ Ca_2\ Mg_4\ (Al,\ Fe^{3+})\ (Si_6\ Al_2\ O_{22})\ (OH,\ F)_2$ and Tschermakite $Ca_2\ Mg_3\ (Al,\ Fe^{3+})\ (Si_6\ Al\ O_{22})\ (OH,\ F)_2$. The variations within the field, embraced by these four end members, are based on the relationships (i) $(Al^6+Fe^{3+}+Ti)$ versus $[Al]^4$ and (*ii*) (Na+K) versus [Al]4 atoms per formula unit. Detailed diagrams based on this mode of classification are given by Deer. *et al.* (1962). Here outline of these diagram with area of common hornblende superposed are given in the Figs. 1 and 2. The chemical data of the present amphiboles have been plotted on these diagrams. In the Fig. 1 with classification based on $(Al^6+Fe^{+3}+Ti)$ versus $[Al]^4$ atoms per formula unit, all the five amphiboles fall within the field embraced by the common hornblendes. But when the same amphiboles are plotted on the diagram based on the relation (Na+K) atoms versus $[Al]^4$ atoms (Fig. 2), plots of three of the samples fall outside the hornblende field, although from the optical, physical and the chemical data they are common hornblendes, except for their lower content of alkalies. The lower content of alkalies in these hornblendes is not unexpected since they have crystallised in an alkali poor environment. For instance the skarn rock from which the sample MN 314 was separated contained $Na_2O = 0.16\%$, $K_2O = 0.07\%$, and the sample from which MN 125 was purified contained $Na_2O = 0.25\%$ and $K_2O = 0.15\%$, when the dolerite dyke (MN 25) itself contained $Na_2O = 2.91$ and $K_2O = 0.51$.

The above facts show that the classification based on (Na+K) versus $[Al]^4$ atoms per formula unit is not applicable to these hornblendes, while the classification based on $(Al^6+Fe^{3+}+Ti)$ versus $[Al]^4$ is more suitable. It is well known that sodium and potassium substitute for calcium in the 'X' formula sites. However, sodium and potassium are generally the minor constituents of the hornblende series. Therefore it is stressed that a classification, based on the sum of the two minor constituents as one of its essential parameters, can not hold if the relative amounts of the minor constituents fall below a certain minimum tacity assumed from a given chemical data for the purpose of a classification. Three of the present hornblendes lend support to this belief.

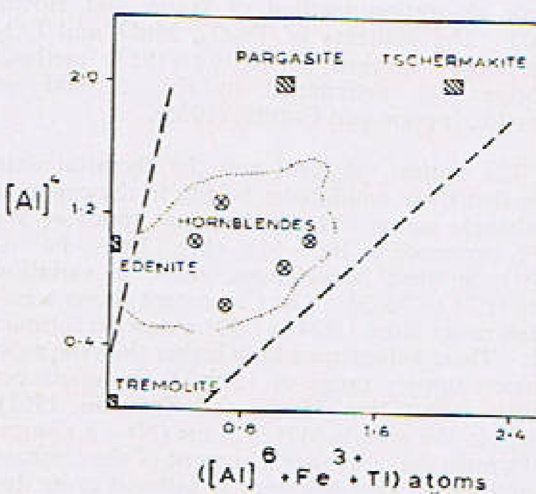

Fig. 1. The Amphible diagrame with area of common hornblendes superimposed.

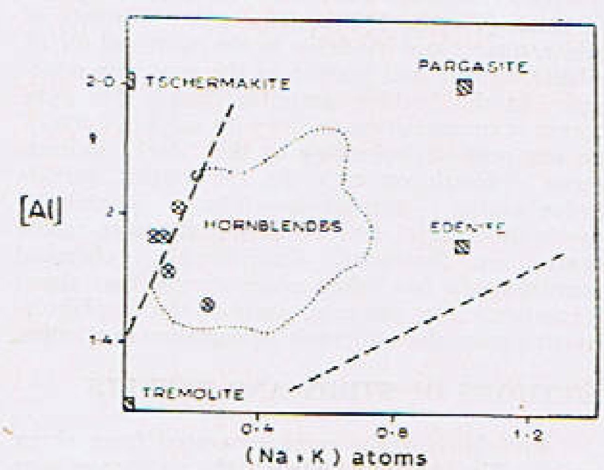

Fig. 2. The Amphibole diagrame with area of common hornblendes superimposed.

ACKNOWLEDGEMENT

The author is grateful to Prof. F.A. Shams for critically reviewing the manuscript.

TABLE 1

Hornblende analyses

	M125	MN314	MN316	MN56	MN313
SiO_2	48.48	49.23	50.68	46.68	50.06
TiO_2	0.38	0.06	0.00	0.18	0.24
Al_2O_3	6.46	12.47	10.54	8.89	5.42
Fe_2O_3	3.70	1.29	1.42	2.65	2.89
FeO	7.89	7.31	6.48	9.54	12.86
MgO	17.43	13.81	14.79	16.07	12.27
CaO	12.68	13.12	13.02	12.41	12.52
Na_2O	0.28	0.25	0.38	0.43	0.70
K_2O	0.10	0.10	0.14	0.17	0.30
MnO	0.24	0.31	0.24	0.44	0.54
H_2O^+	1.25	1.41	1.41	1.49	1.26
H_2O^-	0.13	0.16	0.13	0.19	0.11
F	1.67	0.92	1.09	1.52	1.29
	100.69	100.44	100.32	100.66	100.46
$-F \equiv O$	0.70	0.39	0.46	0.64	0.54
Total :	99.99	100.05	99.86	100.02	99.92
α	1.625	1.624	1.623	1.627	1.629
γ	1.647	1.645	1.642	1.655	1.657
D	3.14	3.12	3.12	3.20	3.21
Numbers of Ions on the Basis of 24 (O, OH,F)					
Si	6.981	6.969	7.150	7.555	7.355
Al	1.019	1.031	0.850	1.245	0.645
Z	8.000	8.000	8.000	8.000	8.000
Al	0.078	1.050	0.903	0.272	0.294
Ti	0.042	0.007	0.000	0.020	0.027
Fe^{3+}	0.401	0.138	0.151	0.289	0.320
Mg	3.741	2.913	3.110	3.466	2.687
Fe^{2+}	0.950	0.865	0.765	0.155	1.580
Mn	0.029	0.037	0.029	0.054	0.067
Y	5.241	5.010	4.958	5.256	4.975
Ca	1.957	1.991	1.969	1.924	1.971
Na	0.078	0.068	0.103	0.120	0.197
K	0.019	0.019	0.023	0.031	0.056
X	2.054	2.078	2.095	2.075	2.224
OH	1.212	1.332	1.328	1.438	1.234
F	0.761	0.412	0.487	0.696	0.600
	1.973	1.744	1.815	2.134	1.834
$100Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn)$	71.31	73.69	76.70	69.82	57.74

Analyst. M. Nawaz Chaudhry.

REFERENCES

Deer, W.A., Howie, R.A., and Zussman, J., 1962 Rock Forming Minerals, Longman, London. **2,** 203.

Grimaldi, F.S., Ingram, B., and Cuttitta, F., 1955 Determination of small and large amounts of fluorine in rocks. *Analyt. chem.* **27,** 918.

Kunitz, W., 1930 Die Isomorphieverhaltnisse in der Hornblendegruppe. *Neues Jahrb. Min.*, **60,** 171.

Miyashiro, A. 1957. The chemistry, optics and genesis of the alkali-amphiboles. *Journ. Fac. Sci. Univ.* Tokyo., *Sec.* 2, **11,** 57.

Riley, J.P., 1958 The rapid analysis of silicate rocks and minerals. *Acta. Analytica Chim.* **19.** (5) 413.

Sundius, N., 1944 On the substitution relations in the amphibole group. *Arabok Sverge Geol. Undersok* **38,** (2)

Walsh, J.N. and Howie, R.A., 1967 Determination of calcium and magnesium in rocks and minerals by atomic absorption spectrophotomertry. *Trans. Inst. Mining* and *Metall.,* (Applied earth sciences). **76,** 119.

Worth, R.H., 1920 The geology of the Meldon valleys near Okehampton on the northern verge of Dartmoor. *Quart Jurn. Geol. Soc.,* London **75,** 77.

NOTICES, ABSTRACTS AND REVIEWS

NOTE ON THE GEOLOGY OF AREA AROUND NATHIAGALI, DISTRICT HAZARA, WEST PAKISTAN.

INTRODUCTION

The geological investigation around Nathiagali, District Hazara, West Pakistan, was initiated during the summer of 1963 in order to understand (*a*) the lithostructural features of the Hazara Slate Formation, (*b*) the nature and inter-relationships of calcareous bands that occur within the Hazara Slate Formation, (*c*) the nature of the base of post-Hazara slate rock sequence and (*d*) the tectonic style. During the subsequent years, as the emphasis shifted to other geological problems and to other areas as well, detailed and more extensive investigations were postponed. However, in the following paragraphs are summarised the few conclusions that were arrived at during the preliminary survey.

THE HAZARA SLATE FORMATION

The Hazara Slate Formation mainly consists of intercalations of argillaceous and arenaceous rocks, including silty shales, mudstones, siltstones and greywackes, with a predominantly argillaceous composition. The subordinate arenaceous layers vary in thickness from less than a millimeter, repeating many times within an inch, to several feet and locally may repeat to constitute a predominantly psammitic zone. In addition, layers of algal biostromes are present occasionally. The presence of these different rock units helps in dividing the formation into a number of recognisable zones. In the Tanol area the Hazara Slate Formation has been estimated to be more than 10,000 feet thick (Muhammad Ali, 1962).

Around Nathiagali a psammitic zone, more than 500 feet thick, forms the highest peak in the region (Miranjani peak, alt. 9780 ft.) and is composed, essentially, of thickly bedded arenaceous rocks, showing cross-bedding, ripple-marks and slump structures. This zone separates two predominantly argillaceous zones with prevalent graded-bedding. Flute casts are also seen in the younger pelitic zone below the apparent paraconformity between the slates and the much younger Maira Formation of Toarcian (Liassic) age, at about 2 miles from Baragali bazaar towards Bagnotar, on the Nathiagali-Abbottabad road. The lower pelitic zone is graphitic at places.

The Hazara Slate Formation represents flysch type geosynclinal sediments that were re-deposited through the process of turbidity currents. The recipient sedimentary depression is believed to have experienced a number of oscillatory earth movements of essentially epeirogenic nature that caused variations in the depth of the basin. In some cases shallowing gave rise to growth of algal reefs and the deposition of sporadic thick arenaceous layers. Presence of gypsum lenses underneath one of the algal biostromes indicates desiccating environments in a restricted water body. As the base of the Hazara Slate Formation is not exposed in the area mapped it is difficult to establish the exact number of major oscillatory movements. In general, the rock sequence had suffered a fairly low grade of metamorphism ; for instance, in the area mapped (Fig. 1) rocks reached the slate grade only. Simple modification of the shape and size of the grains shows that the recrystallisation was mainly due to the load of overlying sediments and regional tectonic stresses. Cleavage is poorly developed and is restricted to argillaceous rocks mainly, while bedding plane fissility is somewhat better developed.

CALCAREOUS BANDS WITHIN THE HAZARA SLATE FORMATION

Apart from early observers, the outcrops of limestone inside the Hazara Slate Formation were noted by Waagen and Wynne (1872), Middlemiss (1896) and other later workers. There have been some differences of opinion regarding their stratigraphic positions and relative ages. Middlemiss (op. cit., p. 11) considered some of them as calcareous intercalations within the slates, such as his so-called "Lungurial band." Certain other limestone bands, such as the one intersected by the Nathiagali-Abbottabad road between Kalabagh and Baragali, were considered as of 'Trias Limestone'. Some workers on the other hand considered all of them to be much younger in age (Triassic/Infra Trias) as compared with the surrounding slate formation (Cambrian and/or Precambrian). Their present positions were generally regarded as the result of tectonic disturbances such as folding or faulting (Marks and Muhammad Ali, 1961 ; Davies, 1963). Present studies however indicate an indiginous position of some of the calcareous bands inside the slates, atleast those characterized by the algal growths.

These bands, hereby called algal limestones, show two different structural characters and lithological sequence in the area mapped, as is described below :—

(*i*) **The Langrial Algal Limestone.**

This band is exposed in the Bakot da Katha, however, it is better developed near Langrial (Grid ref. 175852, 1", 43 G/1) on the Lora-Maqsood road (Lungurial band of Middlemiss) which is outside the mapped area. It occurs at about 500 ft. below the paraconformity so that it is believed to belong to the Upper Pelitic Zone of the Hazara Slate Formation. It is fairly uniform in character and its large nodular structure remains more or less unchanged throughout its thickness as well as along the lateral extent of the outcrop in the area studied (Fig. 2) and even elsewhere

Fig. 2. Nodular Structure in the Langrial Algal Limestone.

in the Hazara region. The interbedding of thin layers of limestone and slate at their mutual contact zone and the algal growths along bedding planes within the adjoining slate layers (Fig. 3) indicate its indiginous nature. In the vicinity of the outcrop, isolated algal calcareous masses, varying in size from fraction of an inch to several feet accross along their long dimension, can be seen inside slate formation. Penecontemporaneous fragmentation is commonly associated with the larger concentration of such bodies. As a result of differential weathering, the isolated patches of algal material on the mudcracks separate as sub-discoidal bodies about 2 inches thick and upto one foot long along the greater dimension (Figs. 4 & 5).

Fig. 3. Calcareous algal growths along bedding planes in the Hazara Slate Formation.

Fig. 4. An isolated algal growth in the Hazara Slate Formation.

(*ii*) The Miranjani Algal Limestone.

This band is well exposed near Nathiagali, particularly along the Nathiagali-Baragali forest road and along the southern slopes of the Miranjani peak. Quite often its base is composed of a thinly bedded, very fine-grained limonitic dolomite of pale yellow colour. Thickness of this bed is about

Fig. 5. Lower view of an isolated algal growth showing mud cracks.

25 ft. near Lassan (Grid Ref. 425062, 1", 43 F/8), where a gypsum lense, having a maximum thickness of about 35 ft., intervenes between the dolomite and the slates.

The sequence overlying the dolomitic bed is better exposed on the Nathiagali-Baragali forest road. The first 14 ft. of rock, overlying the dolomite, is an apparently massive, palish grey (exposed surface) limestone with green siliceous patches. Next 13 ft. show the effect of penecontemporaneous brecciation with oncolites (algal pisolites) and occasional algal stromatolites ; the former are more abundant near the upper portion. This layer is overlain by bluish grey limestone, 8 ft. 6 inches in thickness, characterised by better development of algal stromatolites. Next 10 inches again is a brecciated layer and succeeded by somewhat impure clayey limestone with pyrite cubes. The upper half, about 16 ft. thick is a layer of darker shade and contains greenish chert. The uppermost bed, about 16 ft. thick, once again represents a zone of better developed algal stromatolites. The entire calcareous

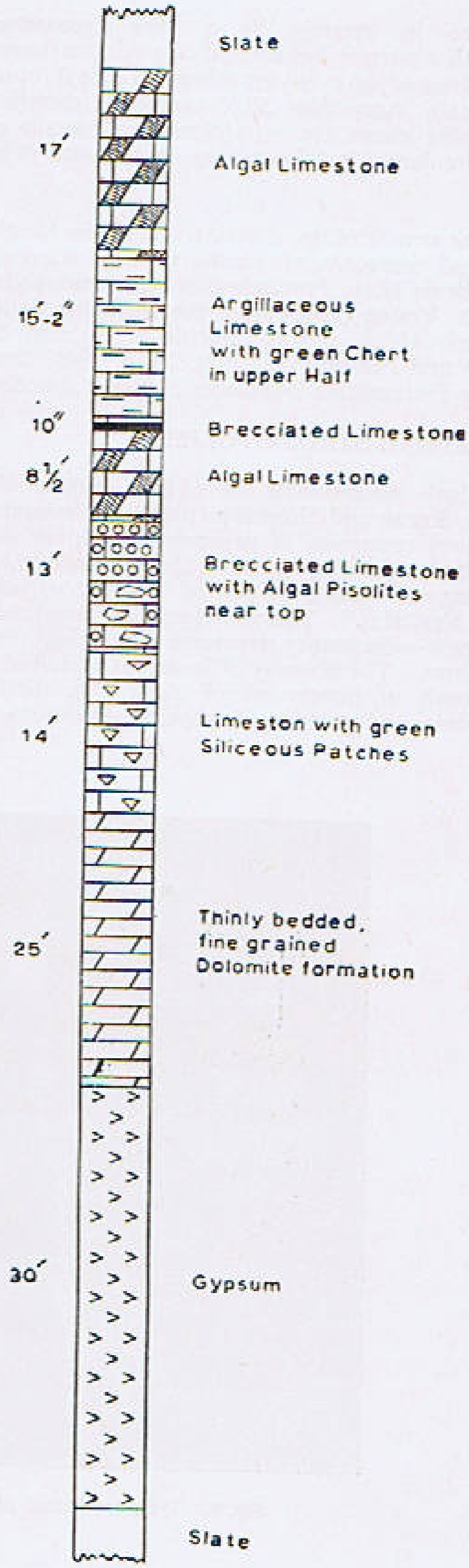

Fig. 6. Litholog showing the intraformational details of the Miranjani Algal Limestone near Lassan.

sequence is overlain by a thick arenaceous bed with a normal but somewhat gradational contact as base of the overlying sub-greywacke is found to contain more than 50% carbonate material. A litholog shows the intraformational details of the Miranjani Algal Limestone near Lassan (Fig. 6).

The stromatolites, characteristic of the Miranjani algal biostrome, are similar to those described as Collenia (Late Precambraian calcareous algae) by R.B. Young (1940) from the Dolomite Series of South Africa, and as Collenia willisii n.sp. by Fenton and Fenton (1937, Fig. 18, p. 1945) from the late-Precambrian Belt Series of North America.

THE ALGAL STROMATOLITES

Algal stromatolites have been defined by Logan, Rezak and Ginsburg (1964) as "laminated structures composed of particulate sand, silt and clay-sized sediments, which have been formed by the trapping and binding of detrital sediment particles by an algal film." These workers considered them as organo-sedimentary structures rather than fossil organisms. The diversity of form was explained as the result of interaction of algal film, detrital sediments and factors of physical environment.

It is suggested that from the basic geometric form of hemispheroid all such structures could be derived like *collenia* (laterally linked hemispheroid, close-linked—LLH-C type or space-linked—LLH-S type), *cryptozoon* (discrete vertically stacked hemispheroids, hemispheroidal laminae reaching or overlapping the base of preceeding ones—SH-C type. When upper hemispheroidal laminae do not reach the base of the preceeding ones—SH-V type) and *oncolites* (spheroidal structures—SS type).

In the Nathiagali area, the main algal bodies represent the repeated compounding of LLH-C and SH-V type structures with very narrow interstructural spaces (Fig. 7 & 8). As the collenia-type structure is the dominant form in the area studied, it appears that these organo-sedimentary structures developed on protected inter-tidal mud flats.

Oncolites or the spheroidal structures (SS type) also exhibit a variety of forms and sizes (Fig. 9) The algal pisolitic structures are mainly of two types. (*a*) A flat somewhat discoidal form that is most common. It seems to have developed as a result of concentric growth of algal laminae around lithic chips, most of which are angular slate fragments.

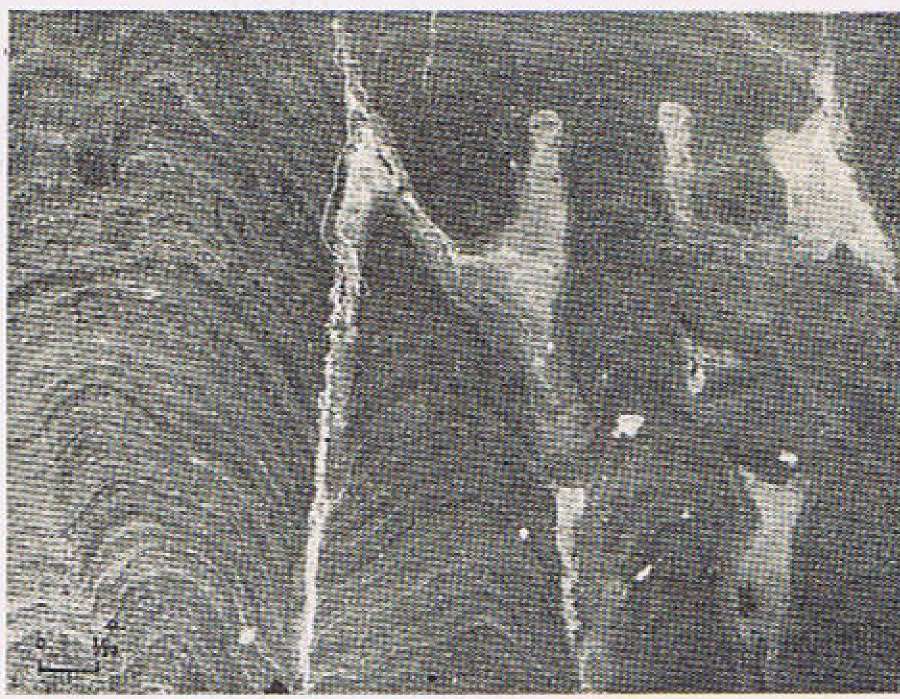

Fig. 7. Typical structures in the main algal bodies of the Nathiagali area.

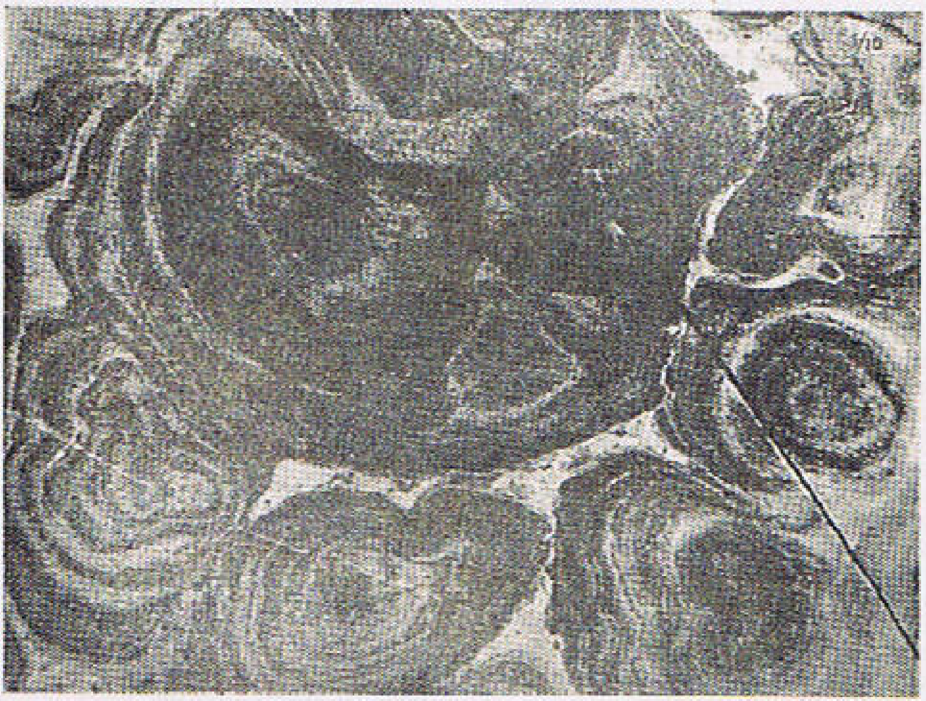

Fig. 8. Section perpendicular to the axes of algal growths in the Miranjani Algal Limestone.

Fig. 9. Oncolites in Miranjani Algal Limestone.

The maximum size of such pisolites is about 6 mm, but structures upto 1 cm across have been seen. (*b*) A nearly spherical form with an average diameter of about 4 mm and composite in nature. Stacking of algal spheroids is found to have taken place around bits of granular carbonate, slate fragments, broken pisolites or clusters of tiny oolites. The algal growth however is not strictly concentric due to inclusion of larger fragments as well as oncolites. The pisolites are encased in a sandy calcareous cement with abundant tiny oolites having an average diameter of 0.3 mm.

The algal stromatolites can be quite useful in the determination of structural attitude of the carbonate rocks as the apices of their hemispheroidal form point towards the top of the bed. On the basis of such a study of the Miranjani biostrome no sign of isoclinal folding in the Nathiagali region has been found ; this also suggests that the biostrome underlies the psammitic zone. It has been mentioned already that the contact of calcareous sequence is gradational with the overlying greywacke bed, which is always present in the mapped area. Therefore there is no doubt that the contact between the biostrome and the overlying slate sequence is a normal sedimentary contact, and the biostrome is a part of the Hazara Slate Formation.

Some of the calcareous bands within the slates north of Khanpur, belong to younger ages, such as bands of limestone of Jurassic age and dolomite of Abbottabad Formation (?) etc. The inter-relationships between various indiginous algal biostromes and their detailed petrographical features are being investigated.

NATURE OF THE BASE OF POST-HAZARA SLATE FORMATIONS

It has been established already that the oldest rocks that overly the Hazara Slate Formation in the studied area, belongs to the Toarcian (Upper Liassic) age (Davies and Gardezi, 1965), following the discovery of the ammonite Bouleiceras cf. nitiscan Thevenin in the Maira Formation (110 ft. in thickness) that underlies the limestone formation of Jurassic age.

One of the interesting features of the contact between the Hazara Slate Formation and the younger Maira Formation is the apparent concordance in structural disposition between the two. This apparent paraconformity is highly interesting as the Abbottabad Group a few miles towards north-west and the Tanols further west intervene between the slates and the Maira Formation. Gardezi and Ghazanfar (1965) observed no marked structural discordance between the Maira Formation and the Hazira Formation/Haematitic band of the Abbottabad Group. Also there is no structural discordance between the Hazara Slate Formation and the Tanols between Thapla and Tarbela (Muhammad Ali, op. cit., p. 32).

Detailed investigation on the nature of contact between the Hazara Slate Formation and the younger rock is in progress. This shall also check the hypothesis that the Infra Trias (Abbottabad Group) was deposited in a graben (Marks and Muhammad Ali, op. cit.).

TECTONIC STYLE

Apparently the rocks in the mapped area form a number of fold limbs as a result of repeated thrusting towards south-east in a more or less imbricate fashion ; the fold limbs are more often overturned. A generalized sketch section (Fig. 10) suggests the probable structure across the strike.

An interesting feature of the structural complexity of the area is the swing in the prevalent strike direction that varies from N 52° E in western zone to S 30°E in central zone and to N 70°E in eastern zone. It seems that the stress system that could have caused the phase of cross-folding included a shear couple with a horizontal component having a dextral movement. If such a stress couple had existed it was not in conformity with the stress field generated by the piercing of pointed wedge of the platform (Indian Shield) into the newely rising fold belt as suggested by Wadia (1931). This anomalous situation is not the lone example. Similar trend is seen in the so-called "Boundary Fault" separating sedimentary formations from the metamorphic sequence near Banda Pir Khan (Grid Ref. 305246, 1" 43 F/8). The true nature of such features and their relationship with the strutural trends in the syntaxial bend are under investigation.

The small scale folding in the mapped area is mainly in the form of kinking (Knickung) or knicking. Mainly the argillites have been affected by such knicking, which often show sub-horizontal attitude. Another set of knick planes, with steeper attitude is also probable. Superimposed folding in the limestone of Jurassic age is more obvious. Here the minor superimposed folds have developed across the earlier prevalent strike. The strikes of the newly developed folds remain parallel to the Bakot da Katha-Kala Bagh-Sher Muhammad Gali thrust, which shows the same swing in the trend as shown by the regional strike direction. Before the development of this thrust, a longitudinal reverse slip fault or thrust had already brought the lower pelites of the Hazara Slate Formation against the Mesozoic formations. The two thrusts have a

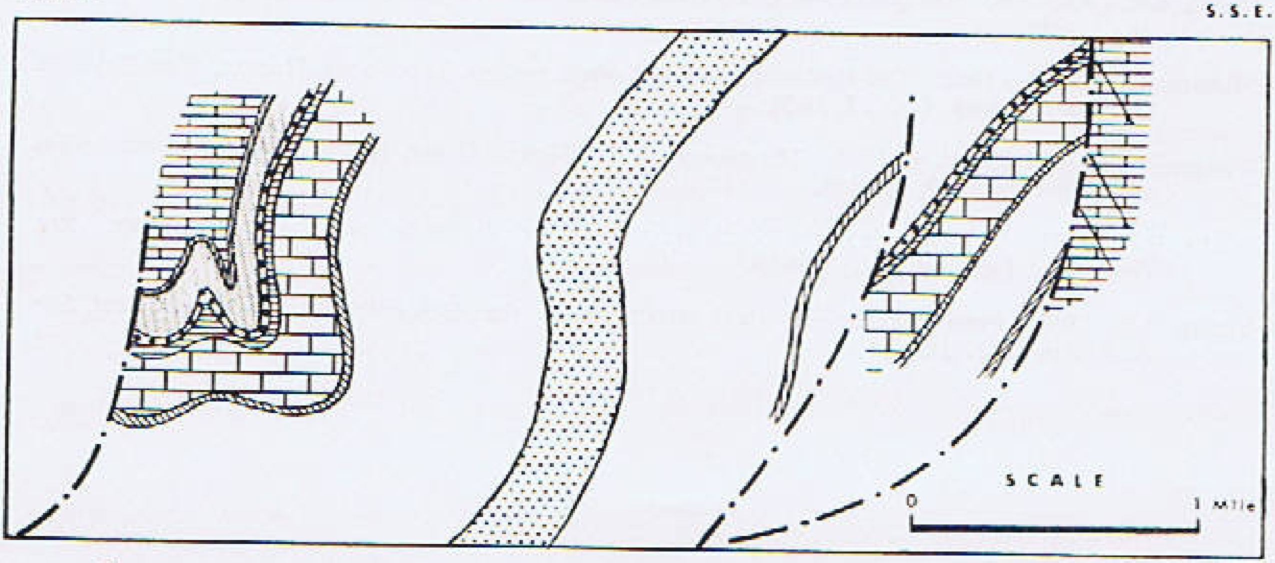

Fig. 10. A generalized sketch section suggesting the probable structure across the strike in the Nathiagali area Legend same as for the Fig. I.

somewhat angular relationship indicating a slight clock-wise shift in the direction of movements. Thus at least three phases of movements can be recognised. Extention of this work in the adjacent areas, now in progress, will yield greater information on the orogenic phases in this region.

ACKNOWLEDGEMENT

The author is grateful to Prof. F.A. Shams, Department of Geology, Punjab University, for his help in the final preparation of this manuscript. Thanks are also due to Mr. Arshad Hussain for his assistance in the preparation of map and illustrations.

A.H. GARDEZI
Department of Geology,
Punjab University.
Lahore.

REFERENCES

Davies, R.G., 1963. Some preliminary observations on the geological structure of the Hazara Slate Formation in the area of the Lora-Maqsud road. *Geol. Bull. Punjab. Univ.*, **3**, 32-38.

Davies, R.G., and Gardezi, A.H., 1965. The presence of Bouleiceras in Hazara and its geological implications. *Geol. Bull. Punjab. Univ.*, **5**, 23-30.

Fenton, C.L., and Fenton, M.A. 1937. Belt Seies of the north : stratigraphy, sedimentation, paleontology. *Geol. Soc. America Bull.* **48**, 1873-1970.

Gardezi, A.H., and Ghazanfar, M., 1965. A change of facies at the base of the Jurassic in District Hazara, West Pakistan. *Geol. Bull. Punjab. Univ.*, **5**, 53-55.

Logan, B.W., Rezak, R., and Ginsburg, R.N., 1964. Classification and environmental significance of algal stromatolites. *Journ. Geol.*, **72**, 68-83.

Marks, P., and Muhammad Ali, Ch., 1961. The geology of Abbottabad area, with special reference to the Infra Trias. *Geol. Bull. Punjab. Univ.*, **1**, 47-55.

Middlemiss, C.C., 1896. The geology of Hazara and the Black Mountain. *Mem. Geol. Surv. India.*, **26**, pp., 1 -290.

Muhammad Ali, Ch., 1962. The stratigraphy of the south western Tanol area, Hazara, West Pakistan. *Geol. Bull. Punjab. Univ.*, **2**, 31-38.

Waagen, W., and Wynne, A.B., 1872. The geology of the Mount Sirban in the Upper Punjab. *Mem. Geol. Surv. India.*, **9**, 331-350.

Wadia, D.N., 1931. The syntaxis of the North-West Himalaya : Its rocks, tectonics, and orogeny. *Rec. Geol. Surv. India.* **65**, Pt. 2, 189-220.

Young, R.B., 1940. Further notes on algal structures in the Dolomite Series. *Trans. Geol. Soc. S. Africa*, **43**, 17-22.

78/79

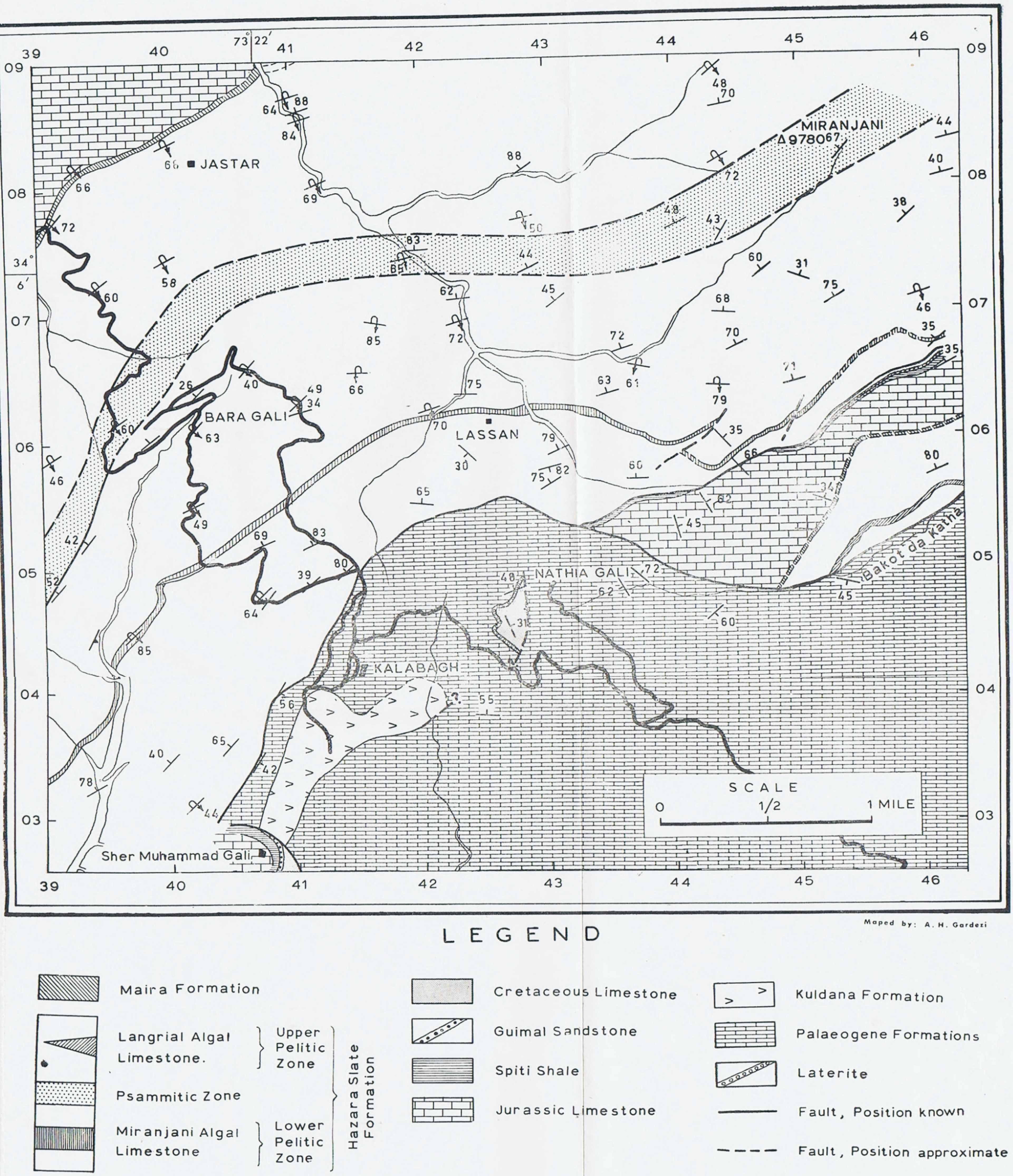

Fig. 1 Geological map around Nathia Gali, District Hazara.

REMARKS ON THE PROPOSED "ABBOTT-ABAD GROUP" OF GARDEZI & GHAZANFAR

In course of a note on the change of facies at the base of the Jurassic in the Hazara District of West Pakistan, Gardezi and Ghazanfar (1965) proposed "Abbottabad Group", a new stratigraphic name, to include the Abbottabad Formation, the Hazira Formation and the Haematite Formation. As the geographical name, Abbottabad, is preoccupied for the Abbottabad Formation (Marks and Muhammad Ali, 1962), the designation of the proposed group should be rejected.

In the same note, they stated that the Hazira Formation and the Haematite Formation, new names proposed by them, are both lateral equivalents. However, while the name of the former rock unit conforms to the normal practice of stratigraphic nomenclature, the latter is contrary to it. In view of the fact, that the two entirely different facies belong to the same lithostratigraphic unit, it appears more appropriate to combine them under a single formation. The writer, therefore, proposes that a new stratigraphic name, KIHAL FORMATION (Section exposed near Kihal, 1" 43 F/4 gride 268120, in the environs of Abbottabad) should be designated to include the HAZIRA MEMBER (the Hazira Formation of authors) and the SHEKHAN BANDI MEMBER (the Haematite Formation of authors). The latter member derives its name from the locality, Shekhan Bandi (1" 43 F/4, grid 272130) in the vicinity of Abbottabad.

In the summer of 1961, the author, after a general reconnaissance of the area, measured and examined, in detail, the following three good stratigraphic sections of Middlemiss' 'Triassic'. of the Mount Sirban, near Abbottabad, primarily to find if any evidence exists for the exact dating of these deposits (Aftab Ahmad, 1962, p. 52) ;

(i) Along the Hazara Trunk Road, 2¼ miles south of Abbottabad,

(ii) Eastern slopes of Shekhan Bandi, 1 mile east of Abbottabad,

(iii) On the slopes east of Dotar village.

The sampling of the sections was done at intervals varying from 1 to 70 feet depending on the lithological variation and the occurrence of fossils.

The succession exposed along the Hazara Trunk Road and that of Shekhan Bandi conformably overlies the cherty limestone of the Abbottabad Formation. At these localities the lower pyroclastic and clastic part of the 'Triassic' constitutes the Hazira Formation or the Haematite Formation of Gardezi and Ghazanfar (1965).

According to our observations, the Hazira Member is exposed along the Hazara Trunk Road, where it is 192 feet thick and consists of buff and brown siltstones, usually well-stratified in beds of thickness varying from 5 inches to 5 feet. The sequence is uniform in composition except for the presence of two dark grey calcareous bands, 3 to 5 feet thick. Local concentrations of glauconite occur, one forming a very thin layer of 6 inches above the underlying cherty limestone of the Abbottabad Formation.

The Shekhan Bandi Member, at its type locality, is 268 feet thick and is developed as red quartzitic limestone, followed by quartzite breccias. red and white sandstone with a massive haematite sandstone about 40 feet thick towards the top. The quartzite breccias repeatedly occur in the section, while they increase in thickness from the base upward. The thickness of the beds varies from 10 inches to 75 feet.

At both localities, a band of pure white sandstone, 3 feet thick, marks the top of each member, which, in turn, is overlain by the upper calcareous part of the 'Triassic', which is now proved to be of Jurassion in age. Both the members have sufficient geographical distribution in the Sirban Hill.

AFTAB A. BUTT

Department of Geology.
University of the Punjab,
Lahore.

REFERENCES

Ahmad, A., 1962 Waagen and Wynne's 'Triassic' of the Hazara Mountains. *Geol. Bull. Panjab. Univ.*, **2**, 52-53.

Gardezi, A.H., and Ghazanfar, M., 1965. A change of facies at the base of the Jurassic in district Hazara, West Pakistan. *Ibid.*, **5**, 53-55.

Marks, P., and Muhammad Ali, Ch., 1962. The Abbottabad Formation : A new name for Middlemiss' Infra-Trias. *Ibid.*, **2**, p. 56.

GEOHYDROLOGY OF THE INDUS RIVER WEST PAKISTAN

by

A.K. Snelgrove D.Sc., Fulbright Professor in Geology, 1961-62, University of Sind, at present Prof. and Head, Department of Geology and Geological Engineering, Michigan Technological University, U.S.A., published by Sind University Press, 1967.

It is neither a text book nor a research thesis, but is an attempt by the writer to systematise the current knowledge about the River Indus and its plains in the form of a book. Need of such a book must be in the mind of the author when he wrote that "a scientist visting Pakistan cannot fail to be nonplussed by the multiplicity of governmental agencies dealing with various aspects of the Indus." (p.1).

The plains of Indus and its tributaries have been described as granary of combined India. Of late, however, a rapidly expanding population and a rapidly worsening state of these plains affected with waterlogging and salinity have led to redoubled efforts at improvements in methods of planning, landuse, irrigation and reclamation. All this has let loose a tornado of scientific investigation carried out with an objective end of improving the agricultural potential of the land. Investigations on the river itself have mainly been connected with water and power development or irrigation. The Indus plains have the world's largest canal network. The traditional water budget, however, has been upset by the more recent Indus Basin Treaty (1960).

In the course of these investigations and development works, a wealth of hydrologic information has been collected which lies spread and scattered over innumerable pages of scores of scientific reports. The writer has gone through a substantial amount of this literature and out of his notes the present book has emerged. For all students and workers in hydrology, irrigation, soils and such other activity connected with the land resources of the Indus Basin the book would provide a useful background and an introductory guide to the extensive literature in this field. Although it is a systematic account starting from the geographical setting and physiography to tectogenesis and economic geology the book need not be read as a whole for comprehension. Reference may only be made to individual chapters of interest.

In the preliminary chapters concerned with the history and physiography of the Indus Basin the author mainly relies upon the pioneer geographical studies made in this regard by Prof. M.B. Pithawalla (1936, 1959). From the source of the Indus in Kailas Parbat in the heart of the Himalayas at 17000 ft. and from the fact that it first flows northwestwards before it takes a turn to the east and then to the west, Pithawalla concludes that Indus is antecedent to the Himalayas. He then recognized several stages in the history of its development. The first stage is the late geological period when the Indus flowed from east to west to the north of Ganges and shifted southwards with each upwards movement of the Himalayas leading to the deposition of Siwaliks. The westwards Indus drainage was disrupted and reversed by the uplift of the Potwar. Later on the trend was a westerly migration of the river worked out mainly by the geographical situation of the archaeological remains of the ancient Indus Valley Civilization. Recent studies on the physiography of Indus plains were made by Fraser (1958) in their report on the landforms, soils and present landuse of the Indus plains. Brief mention of this and other works is also made in the preliminary chapters.

After the preliminaries, Snelgrove touches briefly upon data and opinions about meandering and floods in the Indus Basin. This is followed by a chapter on the irrigation practices and a description of the barrages and dams on the River Indus.

Describing the aquifer and basement, the writer mentions that geophysical surveys have indicated 3 main buried ridges, the Shahpur, of which the eroded preCambrian outcrops in Rachna Doab are supposed to be a part, the buried prolongation of the Aravalli axis between Delhi and Hardwar (India) and, the third below Sukkur. All three occurring in the Indus Basin and possibily acting as obstacles to the free flow of groundwater in the alluvial aquifer. The aquifer itself in the northern plain consists of a heterogeneous mixture of medium to fine grained sand with lenses of one material grading into another (White House Interior Panel Report p. 260) while in Sind the alluvium is more sandy than silty or clayey but clay belts are found on the surface. (Pithawalla).

The book carries a long chapter on Salinity and Waterlogging. This problem which to a great extent is the bye-product of our extensive canal network was the subject of investigation by the U.S. Scientific Mission on Waterlogging and Salinity in West Pakistan (1961) whose work was then continued by the White House Interior Panel headed by Dr. Roger Revelle. Research contribution in this regard have also been made by other workers but the Panel's report along with the work done by WAPDA* have served as the principal sources for Dr. Snelgrove's chapter on Salinity and Waterlogging. The writer is all praise for the investigations and recommendations made by the Panel. Not all the praise for the recommendations is justified. Typical of most American plans the report excludes just the basic factor connected with development works of all sorts—the people. Naturally it recommends that the limited governmental resources should be concentrated in the most promising areas to the neglect of less productive parts. Summaries of the WAPDA master plan and the White House Interior Panel report are both included in this chapter.

Not much work has been done on soil erosion in West Pakistan. The book makes brief mention of the amount of erosion connected with various Indus tributaries and of the problem of erosion and silting connected with the canals.

In the Indus Basin two of the topographical features established by recent geophysical work are a gap in the burried Shahpur ridge and the other about 70 miles long submarine extension of the Indus valley (the Swatch). Snelgrove postulates that these two features are more or less in line with a 200 mile long fault in the Carlsberg escarpment out in the Arabian sea near the island of Socotra. He terms the buried topographic feature, Shahpur Gap—Indus Synclinorium—Swatch—Carlsberg Ridge fault, as the *Indus lineament* and suggests that the lineament marks the structurally controlled course of the ancient Indus River.

The book also contains a number of maps and diagrams illustrating hydrologic, geomorphic and geophysical data mentioned in the text. Most of these are either reproduced or compiled with modifications by the writer. The cartographic quality of most of these is, however, poor. A useful bibliography is given at the end.

Snelgrove has done a fairly commendable work on the whole in bringing together a large amount of scattered facts and figures to build up a systematic introduction to the geohydrology of the Indus River.

That a foreigner should have had to come to do this compilation and editing is atleast partly due to the lack of adequate library facilities in Pakistan and the fact that the government shows strange hesitation in making scientific reports public to Pakistanis.

MUNIR GHAZANFAR
Department of Geology,
University of the Punjab,
Lahore.

REFERENCES

Fraser, I.S., 1958, Report on a Reconnaissance Survey of the Landforms, Soils and Present Land Use of the Indus Plains, West Pakistan, 1953-54. Resource Survey Division, Photographic Survey Corporation, Ltd., Toronto, Canada.

Pithawalla, Maneck B ; 1936, A Geographical Analysis of the Lower Indus Basin (Sind) Part I, Karachi.

Pithawalla, Maneck B ; 1959, A Physical and Economic Geography of Sind (The Lower Indus Basin) Sindhi Adabi Board, Karachi.

*W.A.P.D.A : Water and Power Development Authority

STAFF LIST OF THE DEPARTMENT OF GEOLOGY, UNIVERSITY OF THE PUNJAB (AT THE 31st DECEMBER, 1968).

1. Teaching Staff :

Name and Qualifications	*Subject*	*Appointed*
Professor of Geology	Vacant	..
Readers :		
Mr. F.A. Shams, M.Sc. (Pb.), M.A. (Cantab), Head of the Department.	Mineralogy, Petrology, X-Ray Crystallography.	November, 1956.
Mr. M.A. Latif, M.Sc. (Pb.),* M.Sc. D.I.C. (London), F.P.T.C. (Vienna)	Micropaleontology, Stratigraphy.	July, 1957.
Dr. Aziz-ur-Rehman, M.Sc. (Pb.), D. Rehr. Nat. (Munich).	Applied Geophysics.	February, 1960.
Mr. A.H. Gardezi, M.Sc. (Pb.), M.Sc. D.I.C. (London).	Petroleum Geology, Structure.	March, 1962.
Lecturers :		
Dr. M.A. Chaudhry, M.Sc. (Pb.), Ph. D. (Reading).	Sedimentology, Geomorphology.	June, 1959.
Dr. Aftab. A. Butt, M.Sc. (Pb.), Ph. D. (Utrecht).	Micropaleontology, Stratigraphy.	June, 1959.
Dr. S.F.A. Siddiqui, M.Sc. (Pb.), Ph. D. (London).	Mineralogy, Petrology, Mapwork.	July, 1960.
Mr. Z.A. Saleem, M.Sc. (Pb).**	Geohydrology, Geophysics.	June, 1961.
Mr. M. Ghazanfar, M.Sc. (Pb.), M.Sc. (Sheffield)	Structural Geology.	January, 1965.
Mr. H.M. Malik, M.Sc. (Pb.), M.Sc. D.I.C. (London).	Engineering Geology.	March, 1965.
Mr. A. Shakoor, M.Sc. (Pb.)***	Petrology	May, 1985.
Mr. Zulfiqar Ahmad, M.Sc. (Pb.).	Mineralogy, General Geology	August, 1967.
Mr. Farooq A. Khan, M.Sc. (Pb.), M. Phil. D.I.C. (London).	Subsurface Geology, Stratigrahy	October, 1967.
Mr. A. Baset, M.Sc. (pb.).	Palaeontology,	October, 1967.
Dr. Ali Rahmat, M.Sc. (Pb.), D.E.A., Ph.D. (Montpellier).	Hydrology.	November, 1967.
Dr. Mohammad Nawaz, M.Sc. (Pb.), Ph. D. (London).	Mineralogy, Petrology.	January, 1968.
Mr. Ahmad Mahmood, M.Sc. (Pb).	Mineralogy, Petrology.	April, 1968.
Mr. Mirza A. Samad Beg, M.Sc. (Pb.).	Petroleum & Structural Geology.	April, 1968.
Mr. Haroon Q.A. Khan, M.Sc. (Alig).	Palaeontology, Stratigraphy.	September, 1968.

*On duty leave at Vienna, Austria.
**On duty leave at the Department of Hydrology, University of New Mexico, Socorro, U.S.A.
***On duty leave at the Department of Geology, University of Leeds, Leeds, U.K.

Name and Qualifications	*Subject*	*Appointed*
Research Assistants :		
Mr. S. Taseer Hussain, M.Sc. (Pb.).*	.. Palaeontology	.. April, 1966.
Mr. Fazal-ur-Rehman, M.Sc. (Pb.).	.. Geochemistry	.. December, 1966.
Mr. Shafeeq Ahmad, M.Sc. (Pb.).	.. Geochemistry	.. January, 1967.
Mr. Tansneem Noorani, M.Sc. (Pb.).	.. Structural Geology.	.. May, 1967.
Mr. S. Mahmood Raza, M.Sc. (Pb.).	.. Palaeontology	.. October, 1968.
Demonstrators :		
Mr. Mohammad. Naeem.	.. Palaeontology	.. November, 1968.
Mr. Khurshid Alam Butt.	.. Mineralogy	.. November, 1968.
Mr. S. Mohammad Mehdi Zaidi.	.. Mineralogy	.. November, 1968.
Mr. Nusrat Kamal Siddiqui.	.. Petroleum	.. November, 1968.
Mr. Russell Nazir Ullah.	.. Geophysics	.. November, 1968.

2. Technical and Service Staff :

Mr. S.A. Kazmi, M.I.S.T. (London).	.. Chief Technician	.. March, 1963.
Mr. M. Aslam	.. Junior Technician	.. June, 1964.
Mr. H. Siddiqui	.. Junior Technician	.. June, 1965
Mr. Arshad Hussain	.. Geological Illustrator	.. March, 1966
Mr. Mahmood Ahmad	.. Draftsman	.. January, 1967
Mr. G.R. Bhatti, B.A. (Pb.).	.. Office Assistant	.. September, 1963
Mr. K. Ahmad, B.A. (Pb.).	.. Library Assistant	.. August, 1965
Mr. M. Riaz.	.. Stenographer.	.. November, 1967
Office and Library Staff	.. 6	
Laboratory Assistants	.. 9	
Drivers	.. 1+1 (summer only)	
Service Staff	.. 3	

*On duty leave at the Geological Institute, Utrecht, Holland.