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THE GEOLOGY AND PETROGRAPHY OF THE TARBELA "ALKALINE" COMPLEX

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ABSTRACT

The Tarbela complex comprises gabbroic rocks (oldest), dolerites, melteigites, albitites, normal and sodic granites, albite-carbonate rocks/breccia, and carbonatites (youngest), together covering an area of about 1 sq. km. The rocks have been intruded along a fault zone between the Salkhala and Tanawal formations. Some of the gabbroic intrusions display in situ differentiation with one intrusion grading from pyroxenitic outer margin to leucogabbroic/dioritic interior with a core of intrusive albitites.

Amongst typical alkaline minerals, sodic pyroboles are restricted to the sodic granite, and nepheline to the melteigite. However, trace elements in albite-carbonate rocks, the high quantity of albite ± carbonate along with consistent presence of zircon, and rutile/sphene in most albitites are indicative of their alkaline affinity. The gabbroic rocks might also be alkaline, as suggested by the abundance of amphiboles (hornblende, kaersutite, hastingsite), low An–content of plagioclase, clinopyroxene composition, the general absence of primary quartz and the possibly high Ti–content reflected in amphibole, sphene and ilmenite. These observations, coupled with the close field association point towards an overall alkaline nature of the complex.

The rocks show a considerable degree of alteration (autometasomatism) with widespread development of scapolite, carbonate, amphibole, mica, sphene, rutile, etc. The country rocks have been metasomatised in the vicinity of the intrusions and scapolite, albite, carbonate, ? quartz, pyrite have been produced. Some of the albitized sedimentary rocks resemble adinoles.

This paper presents a detailed account of the petrography of the complex together with optical details of the minerals and a geological map. The petrogenesis of the complex is yet not clearly understood and hypothetical schemes based on differentiation under variable P_{CO_2} and liquid immiscibility are presented.

INTRODUCTION

A number of basic to feldspathic intrusions occur in an area of about 1 sq. km. along the west bank of the Indus river at the Tarbela damsite (34° 7'; 72°, 47'). The intrusions (sills, dykes and plugs) are petrographically varied but closely associated, collectively constituting a rather unusual igneous complex. The following sequence of intrusions from oldest to youngest, slightly modified after Kempe and Jan (1980), has been determined in the complex (Fig 1).

1. Gabbroic intrusions, some grading from pyroxenitic outer margins, through mela-gabbros to leuco-gabbros and diorites.

2. Dolerite dykes cutting the gabbroic intrusions.

3. Amphibole albitites, intruding the gabbroic rocks and cut by both sphene albitite dyke and other albitites, that are generally coarser grained than the host amphibole albitites.

4. Other albitites, possibly in the following order:
Carbonate albitites, quartz albitites, and pure albitites (some containing sphene).

5. Albite-carbonate rocks and breccias.

6. Granitic rocks (subalkaline to peralkaline).

7. Coarsely crystalline and porphyritic carbonatite minor intrusions and carbonate veins.

The sequential position of hornblende melteigites, reported in the NE of the mapped area (Siddiqui, 1973), is not known because of the construction work related to Tarbela Dam. For the same reason field relationships between various albitites and granitic rocks (Kempe and Jan, 1970) are not clear.

The country rocks comprise a metasedimentary sequence that consists of graphitic schists, quartz mica schists, phyllites and calcareous rocks of the Pre-cambrian Salkhala Formation (Calkins *et al.,* 1975). This unit is tectonically over-lain by an extension of the Swabi Quartzites, considered by Martin *et al.* (1962) to be the equivalent of the Tanawal Formation (Cambrian). The country rocks partly constitute the western flank of the Indus reentrant of the western Lower Himalayas. The geological setting of the area is characterized by a complex fault system, the "Tarbela fault zone" (Kazmi, 1979). Most of the igneous intrusions in the NE half of the complex are intruded along one of these faults between the Salkhala and Tanawal formations (Fig 2).

The igneous rocks of the Tarbela complex are considered to be related to the Warsak and Shewa-Shahbazgarhi rocks on the basis of close petrographic

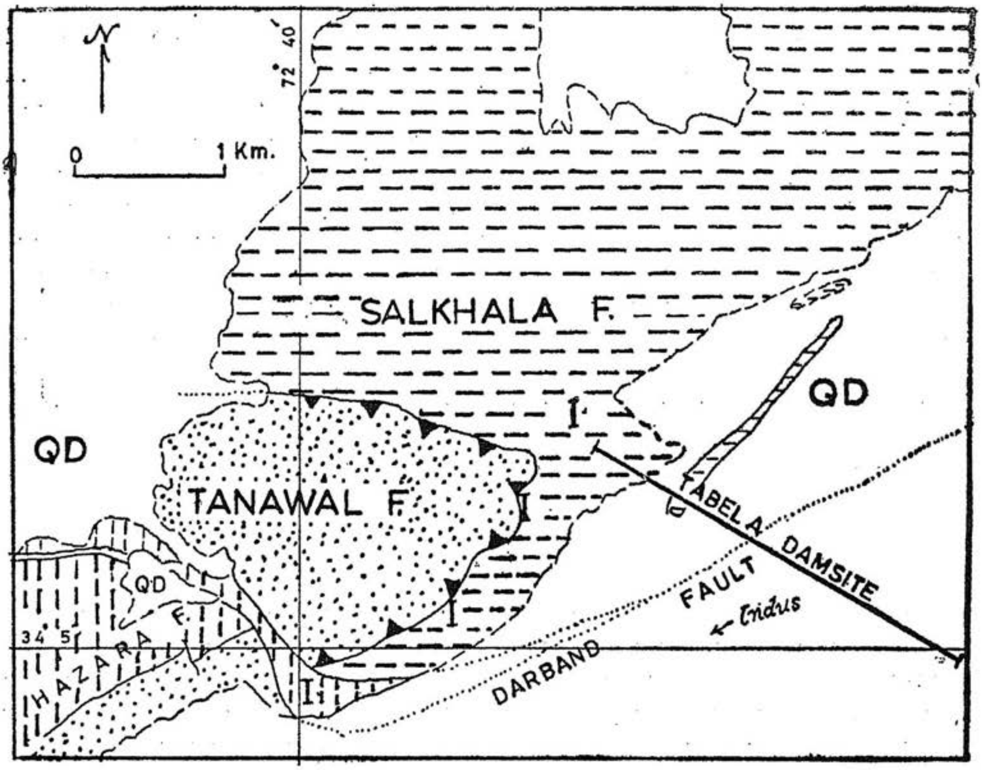

Fig. 2. Geological map of the Tarbela Damsite area. Igneous intrusions shown by I. QD: Quaternary deposits. (After Calkins *et al.,* 1975).

resemblance in the alkaline granites of the three complexes (Kempe and Jan, 1970, 1980). On regional scale, the alkaline rocks of these areas, combined with those of Loe Shilman, Malakand, Koga, Ambela-Utla, and (?) Mansehra constitute a late Cretaceous-Early Tertiary alkaline igneous province around the Peshawar plain.

Together with a geological map at 1 cm=60 m scale, this paper presents a detailed petrography of the complex based on 130 thin sections, 24 of which were point counted for modal compositions. The major mineral phases in the rocks have been studied optically. Geochemical investigation of the complex is scheduled in near future by one of us (M.Q.J.).

GEOLOGY AND PETROGRAPHY

Country Rocks

Salkhala Formation

The formation occupies a narrow band (about 2 km. long and 150 m. wide) along the west bank of the Indus river. Within the mapped area it consists dominantly of pelitic and graphitic schists with subordinate phyllites and calcareous rocks. The schists are fine-grained, thinly laminated and have greenish-grey and dark black colours. The pelitic schists are composed mainly of quartz, with 20 to 40% of chlorite and muscovite, whereas the graphitic schists mainly comprise of graphite with minor quartz, disseminated as minute grains and laminae. Phyllites, grey to black in colour, are composed of varying amounts of micaceous material and quartz. Calcareous rocks are variable in colour and composition, ranging from brown dolomitic and greyish-white recrystallized marly limestones to black and greyish-white marbles. The marbles are composed of carbonate (85 to 90%), with minor amounts of tremolite and plagioclase (4% each). In addition traces of opaque minerals (including pyrite and graphite), quartz, chlorite and muscovite are locally present. At places the calcareous rocks contain abundant scapolite as a metasomatic product connected with the gabbroic intrusion.

Tanawal Formation

The Tanawal Formation occupies much of the NW part of the mapped area and has a thrust contact with the underlying Salkhala Formation. These quartzites are slightly different from those found on the E of Indus at Tarbela. The latter often contain some light pink to greenish and comparatively thin bedded and finer grained quartzitic beds, whilst the former consist mostly of medium-grained, well-bedded quartzite with local siliceous schists. Grey and dark-grey phyllite beds and laminae are occasional, serving as parting planes. The quartzite is composed of abundant quartz with minor muscovite, magnetite, tourmaline and feldspar.

Gabbroic Rocks

Field Relations

The gabbroic rocks constitute about 75% of the complex. They occur generally in dykes and sills but plugs of varying sizes are also common. Amongst the major outcrops, one semi-concentric, loop-like gabbroic body occurs in the central part of the complex near the crushing plant (Fig 1). The northeastern 200 m. thick portion of this body gradually tapers into south-west directed limbs. The intrusion shows *in situ* differentiation from dark marginal mela-gabbros, locally grading into pyroxenitic outermost margins, to interior leuco-gabbros and diorites.

Besides a dolerite dyke, the leuco-gabbroic part is intruded by an amphibole albitite plug that, along with associated gabbros, is cut by a sphene albitite dyke and veins of other albitites. In the central portion of the outcrop, the basic rocks surround an albititic core. Numerous patches and veins of feldspathic (plagioclase) material in the mela-gabbroic portion are characteristically present, furnishing crude layering of alternating mafic and feldspathic material. This outcrop as a whole is a good example of composite intrusion of basic and albititic rocks.

Differentiation from ultramafics to mafics can also be observed in two more outcrops. One gabbroic body (about 200 sq. m. in area) in the NW half of the complex shows a marked concentration of mafic minerals (i.e. olivine, orthopyroxene, amphibole and clinopyroxene) in a cumulative texture in the SW margins, grading into medium to fine-grained gabbros in the NE. Similar concentration of the mafic minerals is observed in the gabbroic outcrops (about 350 sq. m. in area) in the extreme NE of the mapped part of the complex. The rest of the gabbroic bodies though maintaining identity in the petrographic features with the above mentioned basic rocks, do not reveal a systematic differentiation pattern in the field. A characteristic feature of a number of the Tarbela basic outcrops is the presence of albite-carbonate dykes and veins. The latter increase upwards to form networks, ultimately capping the basic rocks in the form of breccia.

Composition and Microscopic Features

Lithologies in the gabbroic intrusions of the complex can be classified into olivine-amphibole pyroxenites, amphibole pyroxenites, mela-, normal-, leuco-gabbros, and diorites. In thin sections the texture is predominantly medium-grained, sub-equigranular and hypidiomorphic. Local variations to fine-grained, sub-porphyritic texture are observed in some amphibole pyroxenites, particularly in the samples from outer margins of the semi-concentric outcrop. Amphibole diorites in some cases become coarser grained with large grains of plagioclase. Amphibole in most of the gabbroic rocks and plagioclase in some is poikilitic or sub-poikilitic. In a few cases the clinopyroxene in the amphibole pyroxenites exhibits an ophitic to subophitic texture. Myrmekitic intergrowth of quartz with plagioclase is observed in a few samples.

The important primary constituents of the gabbroic rocks include clino-pyroxene, amphibole, plagioclase, and opaque minerals. (Amphibole is unequivocal throughout the gabbroic series, warranting for the use as a pre-fix for the individual rock types. However the pre-fix is avoided in this paper because of limited space). Orthopyroxene occurs in minor amounts only in a few pyroxenites and mela-gabbros. Amongst secondary minerals, scapolite, biotite, chlorite, epidote, quartz and sphene are present in varying proportions in most of the rocks and serpentine in the olivine-bearing ones. Apatite is a common accessory in comparatively felsic members of the series.

In fresh specimens of the pyroxenites, clinopyroxene and amphibole make up to 70% and 15% respectively (Table 1). However alteration is common and much of the clinopyroxene has been replaced by amphibole. In fresh rocks the amphibole is unequivocal, whereas clinopyroxene gradually decreases in proportion across the gabbroic series from pyroxenites to gabbros. In leuco-gabbros and diorites, the clinopyroxene is either absent or occurs in minor amounts only. Decrease in the amount of clinopyroxene is accompanied by an appropriate increase in plagioclase + scapolite. The plagioclase ranges from 6% in the pyroxenites to 47% in the gabbros, and even more in the leuco-gabbros and diorites. Orthopyroxene is absent in the majority of the gabbroic rocks, but in a few pyroxenites and mela-gabbros it may reach up to 8%, and in olivine-amphibole pyroxenites up to 30%. Olivine is found only in a few mela-gabbros and olivine-amphibole pyroxenites, in the latter it forms the third constituent in order of abundance. Quartz is subordinate throughout the gabbroic series and, when present, is normally less than 5%. Opaque minerals (magnetite, pyrite and ilmenite) are present in all the gabbroic rocks, being comparatively more abundant in the pyroxenites. Amongst secondary minerals scapolite is the commonest, reaching up to 56% in some highly altered gabbros and diorites. Epidote may reach up to 10%, whilst biotite makes less than 5% of such rocks.

The clinopyroxene in the gabbroic rocks is augitic in composition. It is normally subhedral and equigranular but in sub-porphyritic rocks it occurs both in the phenocryst phase as well as in the groundmass. Alteration of augite to green amphibole, chlorite and opaque dust is common in most of the rocks except where contained poikilitically in the plagioclase. Local replacement of augite by uralite and talc is observed in a few sections.

The amphibole in the gabbroic rocks occurs normally in two and rarely in four varieties. In most of the pyroxenites and mela-gabbros, the primary amphibole is brown hornblende, commonly embayed by green amphibole, chlorite and opaque dust. In some pyroxenites, a reddish brown pleochroic variety of amphibole, probably kaersutite, occurs instead of hornblende. In some gabbros a blue green variety of amphibole (? ferrohastingsite) occurs either independently or associated with brown hornblende, but in rare cases it rims around the latter. All the four varieties of amphibole may contain abundant inclusions of magnetite, ilmenite and pyrite. In some samples biotite, in others chlorite, is intergrown with the amphiboles in a replacement texture.

Plagioclase is in the range of andesine and medium oligoclase in most of the gabbros and diorites, but it is more calcic in the pyroxenite. In diorites, a minor amount of chess-board albite is also present, normally rimming around and replacing the plagioclase. Locally the plagioclase exhibits excellent myrmekitic intergrowth with quartz (Plate 1). Zoning is frequent, with andesine cores grading into oligoclase margins. Alteration of plagioclase to scapolite is a common feature in gabbros and diorites. Saussuritization, kaolinization and other alteration processes cause local clouding as well as secondary development of epidote, biotite, chlorite and white mica.

The orthopyroxene, mostly bronzite, is anhedral and interstitial, but locally it clusters in aggregates or contained poikilitically in amphibole. Alteration in bronzite is negligible as compared to co-existing augite. Olivine (Fo $\sim$ 87) occurs very rarely in the pyroxenites and is marginally serpentinized. Amongst opaque minerals magnetite is either interstitial or occurs as inclusions in other minerals. Skeletal grains of ilmenite and anhedral grains of pyrite are present in almost all rocks of the

TABLE 1. MODAL COMPOSITION OF THE BASIC ROCKS

Thin Section	Name of Rock	Pg	Scap	Cpx	Opx	Primary amph.	Secondary amph.	Opaque mins.	Qtz (secondary)	Sph.	Biotite	Neph.	Olivine
TDP 44	Amph. Pyroxenite	6	—	70	1	15	2	5	Tr.	Tr.	—	—	—
TDP 159	Amph. Pyroxenite	11	—	44	8	10	17	10	Tr.	Tr.	—	—	—
TDP 32	Amph. Pyroxenite	9	—	10	—	21	43	13	Tr.	2	1	—	—
TDP 165	Amph. Gabbro	18	6	6	—	10	48	10	2	Tr.	—	—	—
TDP 182	Amph. Gabbro	22	1	6	—	28	30	4	Tr.	4	4	—	—
TDP 155	Amph. Gabbro	3	56	—	—	33	—	3	4	Tr.	—	—	—
TDP 28	Amph. Gabbro	47	10	—	—	6	17	8	3	4	4	—	—
TDP 5	Dolerite	33	—	48	—	4	8	9	Tr.	Tr.	—	—	—
TDP 121	Dolerite	20	—	5	—	21	41	13	Tr.	Tr.	—	—	—
TDP 135(b)	Dolerite	26	—	—	—	31	27	6	Tr.	2	2	—	—
*———	Hb. Melteigite	4	—	—	—	25	37	14	—	—	1	20	—
TDP 213	Olivine amphibole Pyroxenite	—	—	10	30	25	5	5	—	—	—	—	20

Ap. Ep, Rt, CO_3, Tc in trace amounts in most of the rocks, and serpentine upto 3% in olivine-amphibole pyroxenite.
* After Siddiqui (1973).

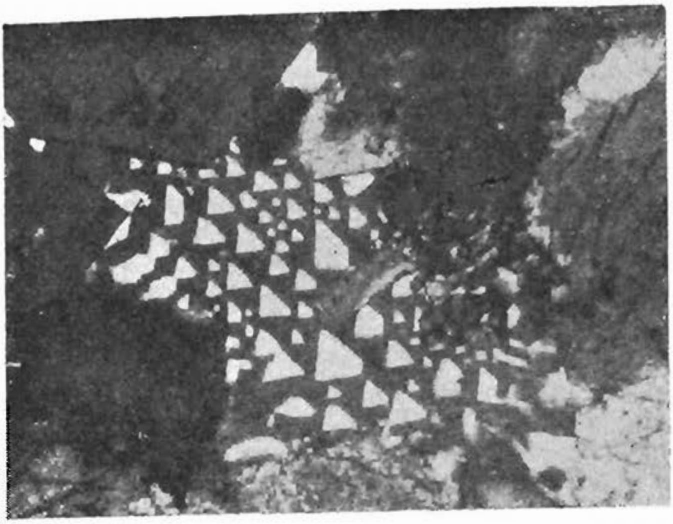

Plate 1. Micropegmatitic intergrowth between quartz and plagioclase in the pyroxenite.

gabbroic series. Ilmenite is altered partially or completely to sphene and sometimes to rutile. Pyrite is oxidized at margins. In some cases biotite, epidote and, rarely, chlorite form reaction rims around opaque minerals, particularly magnetite when contained in plagioclase.

Apatite occurs in fine prismatic grains mostly as inclusions in plagioclase. Amongst secondary minerals epidote is generally minor but common, mostly in the form of aggregates and streaks along fractures. Biotite and chlorite occur mostly in plagioclase, but are also associated with amphibole as well as magnetite. Serpentine is seen in veins and replacing olivine in the olivine-bearing pyroxenites.

Hornblende Melteigite

The rock has been reported by Siddiqui (1973) from the area NE of the presently studied part of the complex. Outcrops are not permissible for study because of constructions related to Tarbela Dam, so the field relations of this rock with the other intrusions of the complex are not known. With the exception of nepheline in the modal composition, the rock resembles the basic rocks of the complex (Table 1).

Dolerites

Minor dykes of dolerite are present in various parts of the complex, generally intruding the basic rocks and metasedimentary sequence. These dolerites are moderately jointed. There are negligible contact effects on the host rocks, but calcareous rocks in contacts may be considerably recrystallized. Some of the larger dolerite bodies are locally gabbroic and have been lumped with the latter on the map. In addition, an earlier phase of dolerites, showing widespread alteration and schistose fabric, is found in the country rocks on both the banks of the Indus river. These may be Permian in age and unrelated to the rest of the igneous rocks.

In thin sections the dolerites are fine-grained, however, local variations to very fine grain size can be observed within a distance of a few millimeters. Texturally the rocks are predominantly sub-equigranular, hypidiomorphic and intergranular but a few rocks are porphyritic to poikilitic. Plagioclase, clinopyroxene, amphibole and magnetite are the principal common minerals. In addition secondary biotite, epidote, sphene, chlorite and carbonate are present in minor proportions in various samples and quartz in one.

The plagioclase is normally andesine in composition and up to 35% in volume (Table 1). It occurs in the groundmass but also as phenocrysts. Zoning is frequent, whereas twinning is not pronounced due to its fine grain size. In rare cases, chess-board albite is also present, seemingly replacing the normal plagioclase.

Clinopyroxene, the principal mafic mineral of the dolerites, is augitic in composition and makes up to half of the total constituents of some rocks. Scarcity or lack of augite in some rocks is caused by its extensive alteration to green amphibole and opaque dust. Weak zoning of clinopyroxene is observed in some cases.

Amphibole is brown hornblende, forming phenocrysts to poikilitic grains. When poikilitic the amphibole contains abundant fine-grained granular inclusions of plagioclase. The brown amphibole is up to 30% in fresh rocks but alteration to green secondary amphibole causes the relative abundance of the latter. Magnetite is the principal opaque mineral but ilmenite is also present, the two constituting up to 13% of the dolerites. The opaque minerals are normally fine-grained and equant, however, in a few cases they occur in the form of fine needles to distinctly elongated grains randomly distributed throughout the rock. Apatite is a common accessory, normally included in the plagioclase. Secondary epidote is locally present in some sections in the form of aggregates and streaks.

Albitites

Field Relations

The albitites, though less voluminous than the gabbroic rocks, constitute important petrographic units of the complex. They occur principally in the core of the composite semi-concentric outcrop near the crushing plant, with a few minor intrusions in the basic rocks as well as in the metasedimentary sequence elsewhere in the mapped area. In the western part of the complex, the albitites are marginally associated with the gabbroic bodies. These albitites, unlike the rest of albitites, are probably metasomatic in nature, formed by the albitization of metasediments. The albitites can be broadly classified into (a) amphibole albitites, (b) carbonate albitites, (c) quartz albitites, and (d) pure albitites (some of which contain sphene).

The principal outcrop of (a) is a plug-like intrusion (about 10 m. in diameter) cutting the leuco-gabbroic portion of the semi-concentric outcrop. The intrusion itself is cut by dykes of similar composition, but darker in colour and finer-grained in texture. In addition, veins of carbonate-albitites and a dykelet of sphene albitites (15 cm. thick) cut both the amphibole albitites and gabbros. Apart from occurrences as distinct intrusions, the existence of some amphibole albitites differentiated from the gabbroic rocks cannot be ruled out (e.g. TDP–181). The type (b) albitites are restricted to an isolated outcrop (about 100x100 m. in area) in the core of the semi-concentric composite intrusion. The albite crystals of these albitites, in the lower parts of the outcrops, are dark in colour due to higher proportions of secondary mafic inclusions. These albitites locally attain a pegmatitic aspect with plagioclase crystals up to 6 cm. long. The field relationships of the types (c) and (d) albitites are obscured by the excavation of the rocks for nearby crushing plant. However, minor intrusions and veinlets of these varieties can be observed in the vicinity of type (b) albitites as well as in the broken blocks.

Composition and Microscopic Features

The albitites are medium-grained, subequigranular and hypidiomorphic, but those in thin veins are fine-grained and porphyritic. Albite is the principal component of these rocks and ranges from 70 to 83% (Table 2). One of the minerals amphibole, carbonate, and quartz constitutes the second important component after albite in various types. Ilmenite, rutile, apatite and zircon are common accessories in these rocks, and tourmaline in a few. Minor amounts of secondary biotite, chlorite, white mica, and epidote are present in different varieties.

The albite is normally subhedral, with well-developed albite twin lamellae and some Carlsbad twins. Weak concentric zoning is observed in some grains. In all types of the albitites chess-board albite is associated with normal albite, often rimming around the latter (Plate 2). In a few sections a fibrous material is observed radiating from the margins of normal albite (Plate 3). It may be plagioclase formed by steaming hot solutions during the late stages of crystallization, or an intimate intergrowth of quartz and albite on a very fine scale resulting due to replacement of the albite margin.

The amphibole is restricted only to amphibole albitites, where it occurs in subhedral, interstitial grains. Locally secondary biotite and, rarely, chlorite may be intergrowth with it. Inclusions of magnetite, ilmenite and sphene are common in the amphibole.

TABLE 2. MODAL COMPOSITION OF THE ALBITITES

Thin Section	Rock	Normal Ab	Chess-board Ab	Fibrous	Amph	Qtz	CO_3	Opaque mins	Sph	Bio
TDP 22	Amph. Albitite	76.3	—	—	13.3	—	—	2.7	6.9	—
TDP 181	Amph. Albitite	74.2	Tr.	—	12.5	Tr.	—	7.0	3.0	3.2
TDP 173	Amph. Albitite	64.0	Tr.	—	22.6	—	Tr.	5.8	7.2	Tr.
TDP 15	CO_3– Albitite	69.2	8.4	4.0	—	6.0	9.4	0.3	Tr.	2.4
TDP 17	CO_3– Albitite	72.3	8.6	---	—	5.2	11.0	0.6	1.0	1.0
TDP 170	CO_3– Albitite	74.8	8.1	—	—	6.5	8.1	2.1	Tr.	Tr.
TDP 137	CO_3– Albitite	68.2	Tr.	—	—	1.0	24.1	6.5	Tr.	Tr.
TDP 177	CO_3– Albitite	78.4	2.5	2.0	—	7.0	9.1	0.8	Tr.	Tr.
TDP Top	CO_3– Albitite	78.8	Tr.	3.2	—	1.0	14.0	2.5	Tr.	0.4
TDP 47	Qtz. Albitite	37.2	45.0	—	—	16.3	Tr.	Tr.	Tr.	Tr.
TDP dyke*	Sph. Albitite	53.3	20.2	—	—	Tr.	Tr.	Tr.	6.1	—

* 20.4% "isotropic" fine-grained material.

Ap, zir, rut, scap, white mica, ch, tc, ep in trace amounts in most of them and traces of tourmaline, allanite and cpx in TDP–42, –137, –173 respectively.

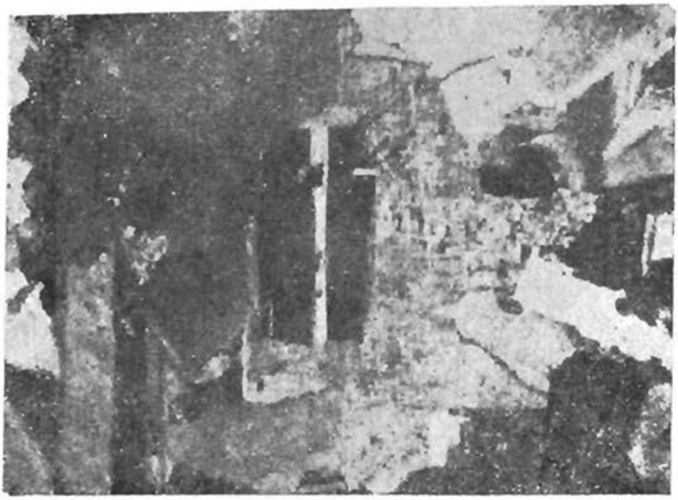

Plate 2. Chess-board albite rimming around normal albite in the albitite.

In the carbonate albitites, carbonate is the major primary mineral after albite and is interstitial between albite grains. It looks primary and is stained brown to varying extents, except locally, when filling fractures it is clear and

Plate 3. Fibrous material (either a myrmekitic intergrowth or a secondary plagioclase) radiating from the margin of albite in the quartz albitite.

colourless. Quartz, subordinate to carbonate in the carbonate albitites, becomes second most abundant mineral (up to 26%) in the quartz albitites. Besides being interstitial, it also forms intergrowths with normal as well as chess-board albite (Plate 4).

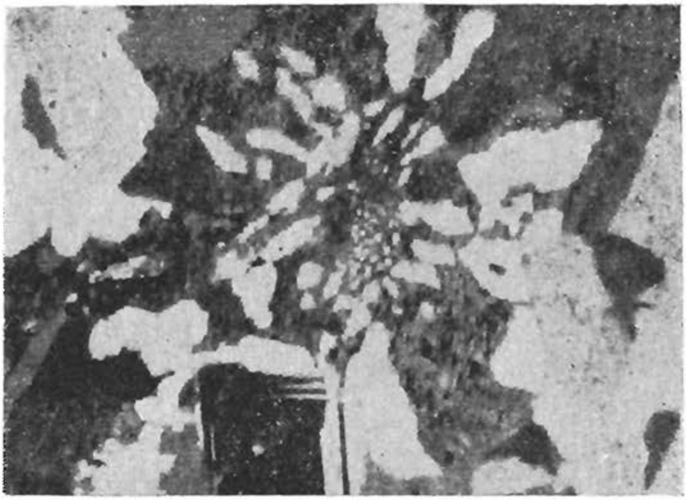

Plate 4. Chess-board albite and quartz intergrowth in the quartz albitite.

Among the accessories, ilmenite generally occurs as anhedral interstitial grains as well as inclusions. It is commonly in the process of alteration to sphene and rutile. Other opaque minerals, i.e. magnetite and pyrite, are restricted to amphibole albitites. Sphene occurs in minor proportions in most of the albitites, however, it reaches up to 6% in some (e.g. sphene albitite dyke). Apatite and zircon are common accessories, normally disseminated in albite as inclusions.

Granitic Rocks

These rocks occur in the form of minor intrusions both in the W and NE parts of the complex. The NE outcrop is an isolated patch of weathered granite enclosed in the graphitic schists. The western granite is associated with the gabbros. Some of these rocks are medium grained, equigranular and hypidiomorphic whilst others are fine-grained and porphyritic. Albite is the principal component (40 to 55%), and is generally loaded with white mica and biotite inclusions. K–feldspar, in discrete grains as well as in the perthitic form ranges from minor to appreciable proportions in some of the rocks. Quartz is in the range of 20 to 30% and occupies interstices between the albite grains. Biotite makes 5 to 13% and white mica up to 10% of the rocks. Biotite has secondary rutile needles, mostly along the margins but sometimes extending up to the central parts. In one section, biotite has pleochroic haloes after pyrochlore or zircon. The other constituents include oxidized pyrite, rutilized ilmenite (3%), rutile (3%), sphene (2%), chlorite (1%), with traces of zircon, apatite, allanite and secondary calcite.

In addition, alkaline porphyritic microgranites have been reported from the complex by Kempe and Jan (1970). The outcrops are no more available for study because of the constructions related to Tarbela Dam. These rocks, unlike the above mentioned granitic rocks, contain alkaline pyroboles such as aegirine and riebeckite, and thus are petrographically similar to the Shewa-Shahbazgarhi, Warsak alkaline granites and to some of the syenites from Koga (Siddiqui *et al.,* 1968) and Loe Shilman (Jan *et al.,* this volume).

Albite-Carbonate Rocks/Breccias

In the central and western parts of the complex, the dominant alkaline type is albite-carbonate rocks and breccias. These rocks occur in the form of veins and dykelets intruding the metasedimentary as well as the gabbroic rocks. In the gabbroic bodies of NW half of the complex, the proportions of these veins and dykelets gradually increase upwards, ultimately forming a cap. Inclusions of the country rocks, gabbros and albitites are abundant in these rocks (Plate 5).

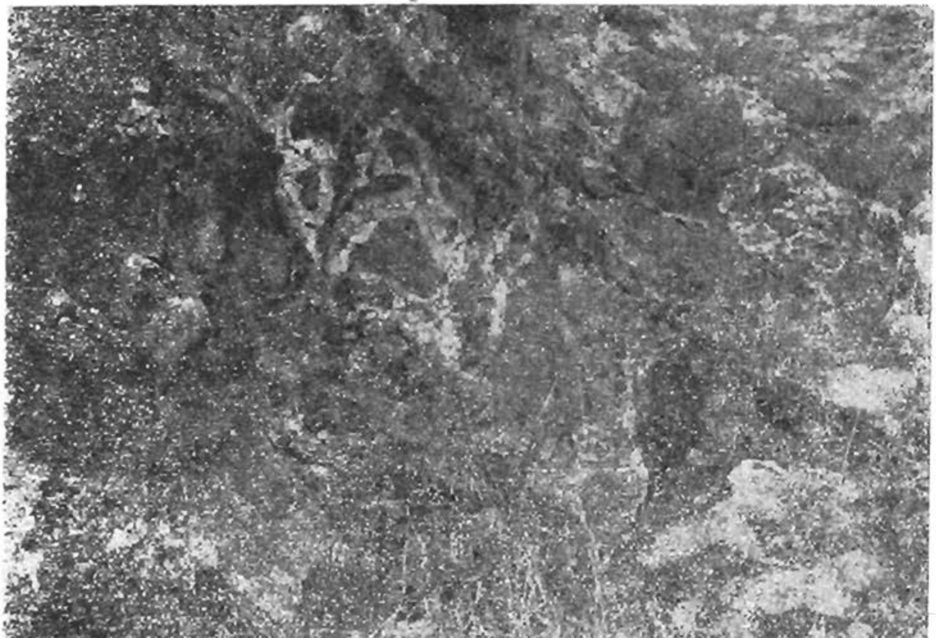

Plate 5. An outcrop of the albite-carbonate breccia having inclusions of siderite, calcite, albitites, quartzite and gabbros.

Compositionally the rocks can be divided into three types:

(a) Quartz-albite-carbonate breccia.
(b) Albite-carbonate breccia.
(c) Albite-carbonate rocks.

The first type is composed of medium to coarse grains and fragments of carbonate, sub-rounded and fractured grains of quartz and medium-grained anhedral albite. The carbonate, making up to 80%, is mostly stained brown and lined with opaque brown material along cleavages and grain boundaries. Quartz and albite reach up to 8% each. Rarely a clear variety of calcite with albite inclusions surrounds quartz and brown-stained carbonate. Breccias of type (b) are similar to (a), except for the low quantity of quartz. Type (c) rocks are made up of generally fine-grained, brown-stained carbonate matrix with albite as disseminated grains as well as irregular patches and veins. Mutual proportions of carbonate and albite are variable and either of the two minerals may be predominant. Xenoliths and veins of fine-grained albitites and carbonate albitites are common in these rocks (Plate 6). The albitite inclusions, in general, resemble adinoles (albitized sediments) rather than the common intrusive albitites.

Plate 6. Xenoliths of fine-grained albitite (or adinole) in the albite-carbonate breccia.

Carbonatites and Carbonate Veins

A white coloured coarsely crystalline, irregularly brecciated mass of carbonatite (2x4 m. in dimensions) is found in the central part of the complex. The body cuts both the albite-carbonate breccia as well as the quartzites. Under the microscope, the carbonatite is equigranular and comprises entirely of euhedral crystals of calcite. Another whitish-grey porphyritic carbonatite body (3x6 m in area) occurs in the south of the above mentioned carbonatite outcrop. It consists of euhedral phenocrysts of calcite (up to 2 cm. in size) enclosed in a fine-grained groundmass of the same composition. Numerous oxidized veins, pockets and disseminations of pyrite are found in this body which on weathering furnish a rusty brown colour to the rock. Beside these intrusive bodies, some carbonate veins are observed to be intersecting the basic bodies. These veins have a coarse grained pegmatitic texture and are composed of brown and white carbonates, apparently in equilibrium relations. The trace elements in an albite-carbonate rock and in a vein (Table 3), are suitable for considering them to be of alkaline nature (Kempe and Jan, 1970, 1980).

MINERALOGY

Techniques

The compositions of the important mineral phases have been optically determined from the refractive indices and extinction angles, and in the case of clinopyroxenes, the optic axial angles. The R.Is (expected to be accurate to $\pm$ 0.002) have been determined by oil immersion method, the matching oils checked with a refractometer after each determination. The 2Vs of the clinopyroxenes were determined by Universal Stage and Malard-Tobi methods and calculated from the refractive indices. The determined values by the two methods closely match, but are some 10° lower than those derived from the R.Is. The discrepancies may have been caused by zoning in the grains coupled with slight errors in the determination of either one or more of the indices.

Plagioclase

The R.Is (α = 1.539–1.545; γ = 1.553–1.557) obtained from four samples, one each from the pyroxenites, mela-, normal-gabbros, and diorites, suggest the compositional range from An_{40} to An_{21}. It is noticeable that the An-content gradually decreases from the pyroxenites to diorites. In all the four samples the An-contents of individual grains obtained from α and γ R.Is. are different, suggesting a persistent zoning in the plagioclase. The interior of the zoned grains is occupied by andesine that grades marginally to oligoclase.

Fifteen plagioclase compositions were determined in the albitites. The An-content is based mostly on α, along with γ in a few cases. The R.Is of the normal albite are α = 1.527 – 1.533; γ = 1.537–1.540, corresponding to An 0-8%. The An-content of the chess-board albite in 4 samples is found to be analogous to the associated normal albite, but in one sample it is comparatively more sodic. The plagioclase in the albitites is only slightly zoned with thin more sodic margins than the core.

Morphology and Genesis of Chess-Board Albite

Morphologically the chess-board albite is twinned according to roc tourns law (Barth, 1969) and is characterized by two sets of narrow discontinuous lamellae, oriented normal to each other. The twin boundaries are stepped and terminate abruptly. At places only one set of narrow discontinuous lamellae is observed looking like normal albite. Such a pattern may have developed by coalescence from chess-board albite under shearing effect caused by excessive internal energy stored in the chess-like pattern of twinning (Cartsen, 1966; Ashraf and Chaudhry, 1976).

The development of the chess-board albite in the albitites appears texturally to have been controlled by late magmatic crystallization in the presence of abundant volatiles. However, replacement of normal plagioclase by chess-board type at lower temperatures and in the presence of volatiles may be a more common phenomenon in the gabbros and dolerites. Presence of a moderate stress field may have contributed in the replacement origin (Ashraf and Chaudhry, 1976).

The possibility of exsolution of excessive Na in the form of chess-board albite from plagioclase, as suggested by Exner (1949), does not seem to be compatible with the texture, as well as with the close analogy in the An-contents of the associated normal and chess-board albite. In some albite-carbonate breccias, shearing has produced a chess-board-like pattern due to slight displacements in the grains along parallel fractures normal to the albite twin planes.

Clinopyroxene

Optical properties of the clinopyroxene have been determined in three samples from differentiated gabbroic outcrop near crushing plant (Table 4). These samples represent pyroxenites, mela-gabbros and normal gabbros. Composition of the clinopyroxene based on these properties is augitic. One of the three clinopyroxenes plots along the compositional trend of clinopyroxenes from the Garbh Eilean alkali basaltic sill, Shiant Isle (Murray, 1954). The other two, however, plot along or slightly above the compositional trend of the Skaergaard intrusion Fig. 3A). The Ca-content of the latter two pyroxenes is comparatively lower than what is common of typical alkaline basic rocks. However it is within the range ($Wo_{38} - Wo_{48}$) of pyroxenes (Fig 3B) from the alkalic suite of Hakeakala and West Maui Volcanoes (Foder *et al.*, 1975).

Orthopyroxene

The R.Is (α = 1.676–1.686) obtained from two orthopyroxenes, one in a pyroxenite and the other in a mela-gabbro, suggest a composition corresponding to bronzite (En 78–81). The anhedral grains of bronzite in these rocks display good cleavages and commonly have a pleochroism of α = light pink, γ = smoky green.

Amphiboles

Whilst the amphibole albitites normally contain pale green amphibole only occasionally accompanied by a blue-green type, up to four varieties of amphibole

TABLE 3. TRACE ELEMENTS IN ALBITE-CARBONATE ROCK AND VEIN

No.	Rock		Sr	Ba	Ce	Y	Nb	Zr	Sn	Zn
			Trace Elements (in ppm.)							
1.	Albite carbonate rock		100	nd	nd	nd	120	1300	nd	700
2.	Ab–CO_3–vein	Albite rich fraction	70	100	520	60	100	830	100	nd
		CO_3–rich fraction	60	190	nd	40	nd	nd	nd	nd

TABLE 4. OPTICAL PROPERTIES AND COMPOSITION OF CLINOPYROXENE IN THE GABBROIC ROCKS

Sample No.	Rock	$\gamma : Z$	α	β	γ	δ	2 Vs. (I	II	III)	Composition Augite
TDP 161	Pyroxenite	44°	1.679	1.688	1.712	.033	60°	47°	46.5°	(En_{44}, Wo_{40}, Fs_{16})
TDP 165	Mela-Gabbro	31°	1.688	1.696	1.716	.028	63°	—	46°	Augite (En_{38}, Wo_{38}, Fs_{24})
TDP 31	Normal Gabbro	—	1.692	1.699	1.716	.024	62°	51°	—	Augite (En_{35}, Wo_{42}, Fs_{23})

2Vs.
I. Calculated with the help of R.Is. II. Obtained from universal stage. III. Obtained from Malard–Tobi Method.

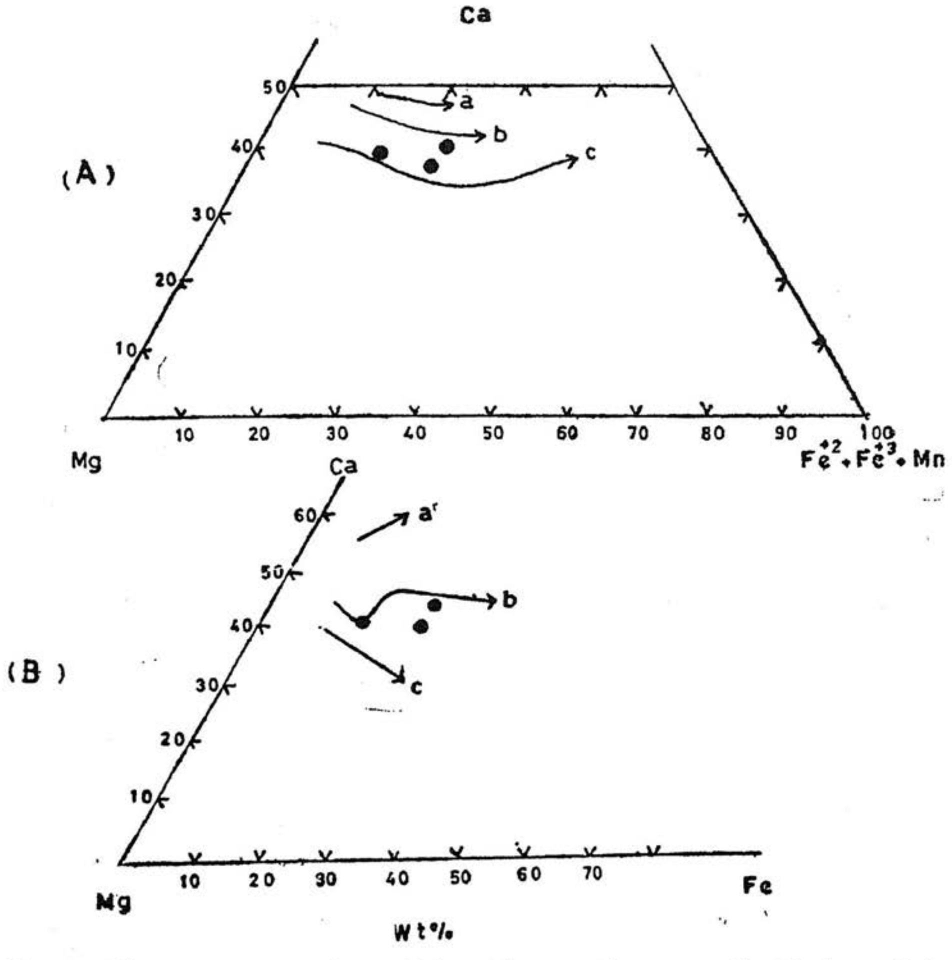

Fig. 3. Clinopyroxenes in the Tarbela gabbroic rocks compared with the variation trends of pyroxenes from:
A– (a) Black Jack teschenite sill, Gunnedah, New South Wales (Wilkinson, 1956).
(b) Garbh Eilean alkali basaltic sill, Shiant Isles (Murray, 1954).
(c) Skaergaard intrusion (Brown, 1957).
B– (a) Nephelinitic suite) Hakeakala and West Maui
(b) Alkalic suite) volcanoes, Hawaii
(c) Tholeiitic suite) (Foder *et al.*, 1975).

are observed in various samples of the gabbroic series and dolerites. The optical properties, though deficient in computing the exact constitution (Jan and Howie, in prep.) are used to acquire an idea about their approximate composition. The commonest primary amphibole is hornblende characterized by pleochroic scheme α = yellow, β = brown and γ = greenish brown, with α = 1.671 and γ 1.686 in one sample.

The other variety is kaersutite having an extinction angle of 10° and a pleochroic scheme of α = straw yellow, β = reddish brown and γ = deep reddish brown. A less common amphibole with α = colourless, β = light green and γ = bluish green and extinction angle of 22° is found in some rocks, either surrounding the brown hornblende or in independent grains. Other optical properties suggest that it may be (?)ferrohastingsite. A fourth variety of a green secondary amphibole locally fibrous is common in the altered rocks, where it embays both the primary amphibole as well as the clinopyroxene.

Scapolite

Scapolite is a common secondary mineral in the gabbroic rocks as well as in the calcareous country rocks. The R.Is (ε = 1.539, 1.543 and ω = 1.546, 1.549) of scapolite in two gabbroic rock samples suggest compositions corresponding to Me_{13} and Me_{23}. The R.Is of scapolite in a marble were determined, and also X-ray powder photograph (Kempe, 1973, personal communication to M.Q. Jan). The values (ε = 1.543–1.545; ω = 1.558–1.566) reveal that the crystal is zoned, indicating a composition between Me_{30} – Me_{40}. Microprobe analyses of scapolite from a hornblende gabbro and a granite reveal Me (100(Ca+Mg+Fe+Mn+Ti)/(Ca+Mg+Fe+Mn+Ti+Na+K)) contents of 28.3 and 33.9, respectively (M.Q.J. unpublished data).

Carbonate

The R.Is (ω = 1.695, ε = 1.54) in the stained brown primary carbonate in a carbonate albitite rock suggest that compositionally it is intermediate between calcite, dolomite and siderite. Carbonate in two carbonatite intrusions, however, is pure calcite with ω = 1.569.

Apatite

Apatite is a common accessory mineral of almost all the plagioclase bearing rocks, where it is often included in the latter in the form of prismatic euhedral grains. The R.I (ω = 1.634) of apatite in a carbonate albitite rock suggest that it is fluorapatite in composition.

Quartz-Albite Intergrowths

Myrmekite-type intergrowths between quartz and albite (both chess-board and normal) is present in various rocks of the complex. The intergrown quartz may be in vermicules, rectangular beeds or blobs, but in a few thin sections of gabbros regularly spaced triangles of quartz are set in a plagioclase "matrix" (Plate 1). In addition to the fibrous (?) intergrowth referred to in petrography, the following general features have been noted in the intergrowths.

1. The volume of the intergrowth varies from one to another rock-type as well as in different parts of the same rock.

2. The quartz: albite ratios range from 1:2 to 1:14 in the intergrowths, many being 1:2 to 1:4. Variations in the ratios are found even within a single thin section.

3. The vermicules and blobs may be restricted to the selective parts of the enclosing albite grains. Within the limits of a plagioclase grain the intergrown quartz is in optical continuity but is often more abundant and finer grained in the core than in the periphery. In a number of cases, a part of an albite grain may contain abundant quartz whilst the rest of the grain is totally devoid of it.

4. The intergrown quartz grains are optically continuous in most cases and contained in a single albite grain, but in a few cases more than one albite grain share the optically continuous quartz vermicules and blobs.

5. The rocks containing the intergrowths generally also have independent albite and quartz grains, the latter being much smaller in size than the dimensions of the optically continuous quartz in the intergrowth.

6. The rocks containing the quartz-albite intergrowths may not have K–feldspar in their modal composition.

Myrmekitic intergrowths are considered to be polygenetic. The proposed genetic models include simultaneous or direct crystallization, recrystallization of quartz and associated plagioclase, replacement of plagioclase by K–feldspar and vice versa, and solid state exsolution (Phillips, 1974, 1980). The origin of the intergrowths at Tarbela is not yet fully understood. None of the above given models can explain all the petrographic features of the Tarbela intergrowths which might owe their origin to a complex process, possibly involving silica metasomatism.

METASOMATISM

The Tarbela igneous rocks are usually full of secondary green amphibole, scapolite, epidote, biotite, white mica, chlorite, sphene, leucoxene, rutile, carbonate and possibly, chess-board albite. Lack of a parallel fabric and presence of replacement textures in the rocks suggest that the process of alteration was of internal origin (autometasomatism) and brought about by late magmatic hydrothermal or pneumatolytic solutions rather than caused by metamorphism. Explosive CO_2 activity is evidenced in the albite-carbonate breccia. The country rocks display varying degrees of chlorite–, soda–, CO_2–, and SiO_2 metasomatism, the most striking product being euhedral scapolite crystals (upto 4 cm long) in limestones in contact with the gabbros (Plate 7).

Plate 7. Euhedral scapolite crystals in limestone.

A number of calcareous outcrops in the vicinity of the intrusions also contain up to 4 cm long whitish grey prismatic "crystals" with square pinacoidal ends, or elongated lensoid (boat-shaped) bodies. These are aggregates of albite (with traces of quartz and carbonate in a few) in a carbonate matrix. The matrix may also contain patches, veins and isolated grains of albite with minor quartz in some cases. The aggregates are randomly distributed throughout the finer-grained matrix but in a few banded rocks may have a parallel fabric and selective concentration along certain bands. The albite grains in the cores of the aggregates are generally finer grained than in the marginal parts. The morphology of some of these aggregates is tetragonal and identical to that of the scapolite in the limestones. It is possible that they are albite pseudomorphs after scapolite. Thus, a two stage metasomatism, scapolitization followed by albitization may have taken place in some calcareous rocks.

Disseminated albite is also found in fine-grained banded metasediments near albite-carbonate breccia in the isolated outcrop SE of the road and SW of the power house. The grain size and albite: carbonate ratios vary from band to band and some are made up of veins and patchy to elongated albite aggregates in carbonate matrix. An extremely fine-grained rock with albite veins and networks and euhedral phenocrystic calcite; a sheared fine–to medium-grained rock with distinct parallel fabric and composed of deformed albite with minor oxidized pyrite, are two other interesting rocks in this outcrop. Whether these are albitized metasediments (adinoles) is not clear (cf. Kempe and Jan, 1980); the possibility of a quickly cooled minor intrusion for the former case cannot be ruled out. Both the metasediments and igneous rocks frequently contain pyrite which may also occur in veins and nodules (as in a carbonatite). A metasomatic origin seems likely for some of it.

PETROGENESIS AND CONCLUSIONS

The Tarbela alkaline complex is characterized by an unusual association of diverse lithologies comprising gabbroic rocks (including pyroxenites, gabbros, and diorites), dolerites, albitites, alkaline and sub-alkaline granites, albite-carbonate rocks/breccia, and carbonatites. Apart from the sodic granites, which contain aegirine and riebeckite, none of the other rocks contains sodic pyrobole. However, the alkaline affinity of the albitites, albite-carbonate rocks/breccia and granitic rocks cannot be ruled out on the basis of predominance of the albite, presence of Ti-bearing minerals (ilmenite, sphene and rutile) and consistent presence of zircon. Preliminary trace element data of albite-carbonate rocks (Table 3) further support the alkaline affinity of these rocks. Bowden (1966) found significantly higher Zr contents in the peralkaline rocks than in the associated rocks of Nigeria. The Zr versus Nb and Y plots (Fig. 4) for the Tarbela albite-carbonate rocks

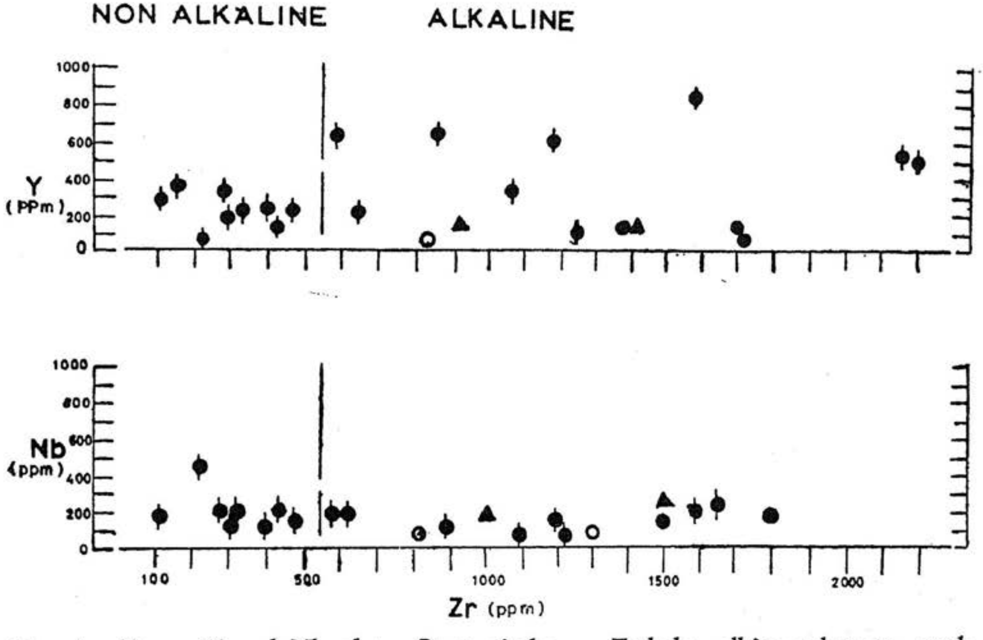

Fig. 4. Zr vs. Y and Nb plots. Open circles — Tarbela albite-carbonate rock (Kempe and Jan, 1980); solid circles — Warsak granites (Kempe, 1973); Solid triangles–Shahbazgarhi granites (Kempe, 1973); ticked circles–Nigerian granites (Bowden and Turner, 1974).

are similar to those of the Nigerian peralkaline granites (Bowden and Turner, 1974), and the alkaline granites of Warsak and Shewa-Shahbazgarhi (Kempe, 1973).

It is not certain whether or not the basic rocks are of alkaline affinities since typical alkaline minerals are absent in them, with the exception of the melteigites. However, lack of primary quartz and high proportion of the amphibole point towards the possibility of normative olivine and (?) nepheline. High content of Ti (reflected in the brown hornblende, kaersutite, ilmenite and sphene), presence of ferrohastingsitic amphibole (a common mineral of basic alkaline rocks) and low An-content of the plagioclase suggest that they might be alkaline. The presence of hornblende melteigites in the area (Siddiqui, 1973) and the close field association point towards a possible connection between the basic and alkaline rocks of the Tarbela complex.

In the absence of geochemical data, the petrogenesis of the petrographically varied rock association at Tarbela cannot be satisfactorily explained. Following the genetic classification of the alkaline rocks (Rock, 1976), two distinct categories are recognizable in the complex: (a) carbonatic—albitites, albite-carbonate rocks/breccia, melteigites and carbonatites, characterized either by low or suppressed An-content and crystallization of primary CO_3, and (b) gabbroic—pyroxenites, gabbros, diorites and their possible fractionated derivatives i.e. sub-alkaline and alkaline granites. Presence of plagioclase with comparatively higher An-content is characteristic of this category. The fundamental difference between the two categories lies in the conditions of PCO_2, being higher in the former. The unusual association of essentially antipathetic categories (Rock, 1976) in the case of the Tarbela complex can be explained only if PCO_2 is assumed to have varied during the course of fractionation.

Fig. 5 presents a hypothetical scheme for the genesis of various rock types based on magmatic differentiation (under varying PCO_2) and liquid immiscibility. The parent magma is assumed to be an alkali basalt, plotting close to the critical plane of undersaturation on Ne–Si join in the basaltic tetrahedron (Yoder and Tilley, 1962). Such a magma may directly crystallize (with *in-situ* differentation) into the gabbroic rocks of the complex. Conversely the parent magma might have differentiated to a mafic trachyte magma (Kuno, 1968; Coombs and Wilkinson, 1969; Macdonald, 1974). Due to immiscibility the trachytic magma might have split into a mafic fraction, corresponding to the gabbroic rocks, and an albititic fraction (enriched in soda, silica, and volatiles i.e. halogens) corresponding to the albitites (Shimron, 1975). The latter rocks could have also developed by direct differentiation of the trachytic magma under (?) increased PCO_2 that causes the suppression of An-content and development of carbonate minerals. However, some of the marginal bodies closely associated with the gabbroic rocks may owe their origin to metasomatism.

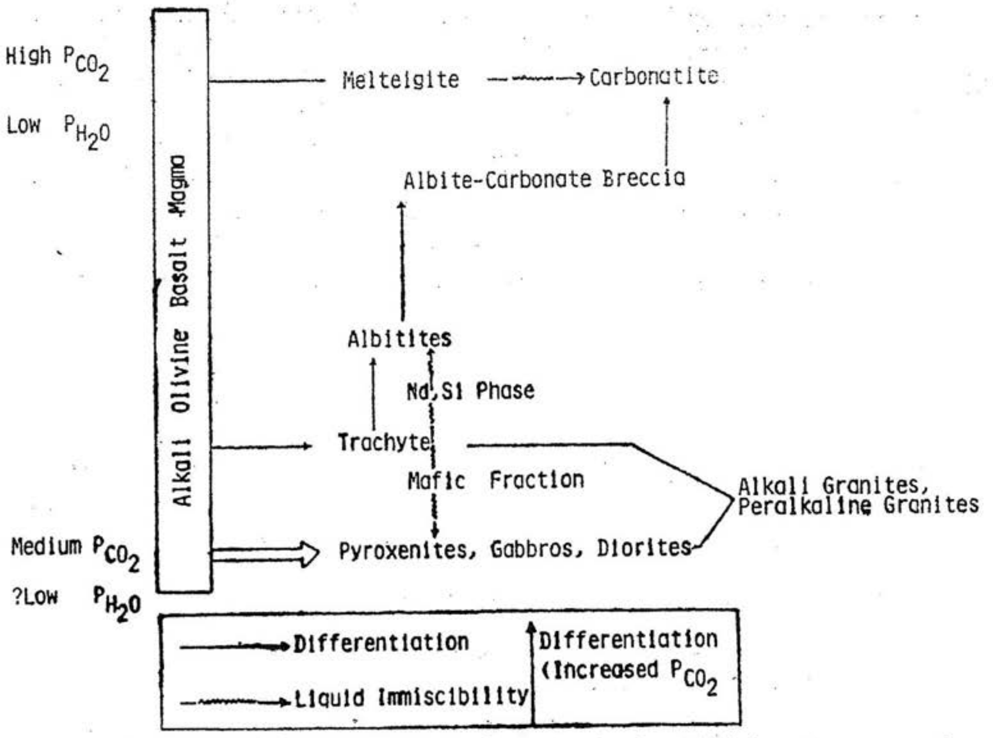

Fig. 5. Flow sheet diagram for the evolution of the Tarbela igneous rocks involving various mechanisms under varying P_{CO_2} conditions.

The sub-alkaline and alkaline granites of the complex possibly owe their origin to the differentiation of the trachytic magma under the conditions of strong fractionation and alkali enrichment (Macdonald, 1974; Bowden and Turner, 1974; Weaver *et al.*, 1972; Von Breeman and Upton, 1972). However these rocks could have also been produced by differentiation of the mafic immiscible fraction or from the parent alkali basalt magma.

Under still higher PCO_2 the parent magma by fractionation of nepheline, olivine and carbonate minerals may give rise to carbonated olivine poor nephelinite similar to the melteigites of the complex (Rock, 1976). The carbonatites may have developed as an immiscible product from such a magma or from the albitites by the complete suppression of plagioclase, causing the calcite crystallization as the only major mineral phase.

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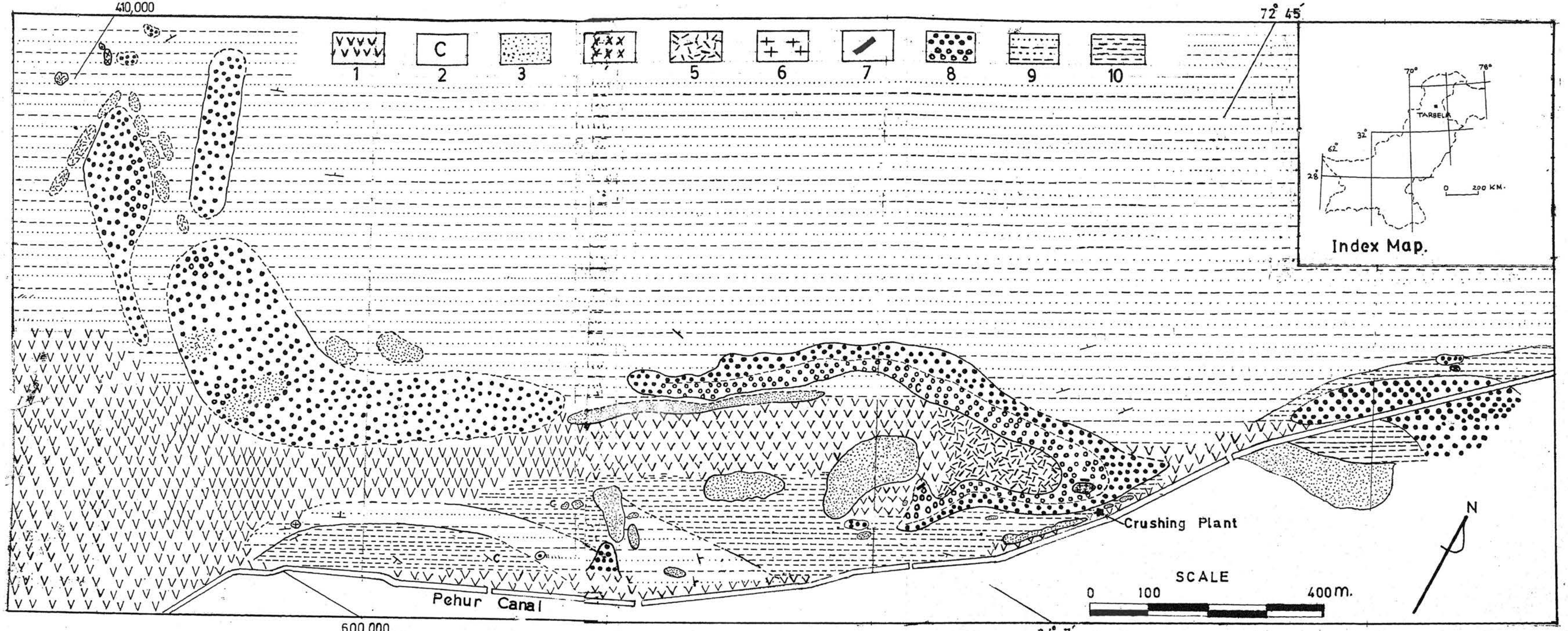

Fig. 1. Geological map of the Tarbela alkaline complex (1) Overbarden/alluvium, (2) Carbonatite intrusions, (3) Albitecarbonate breccia, (4) Granites, (5) Albitites (including carbonate, quartz and pure albitites), (6) Amphibole Albitites, (7) Dolerite dykes, (8) Gabbroic intrusions: a–Melanocratic, b–Leucocratic, (9) Tanawal Formation, (10) Salkhala Formation.