

CHEMISTRY AND PETROGRAPHY OF THE SILLAI PATTI CARBONATITE COMPLEX, NORTH PAKISTAN

K.A. BUTT, AMIR ZARIN ARIF, JAMIL AHMED, ABID AHMED & AHMED QADIR

Hardrock Division, Atomic Energy Minerals Centre, P.O. Box 734 (University),
Peshawar, Pakistan.

ABSTRACT

Detailed geology, petrography and chemistry of Sillai Patti sheeted carbonatite complex is presented. The complex is an anastomosing set of dykes intruding metamorphics of possible Proterozoic age. The complex is interpreted to be a product of multiple intrusions. The early phase of the intrusion is represented by peralkaline ultrabasic rocks (pyroxenites). This was followed by the intrusion of carbonatites and its attendant fenitization. There is a considerable petrographic and chemical variability in the complex which is considered to be a function of varying degree of fenitization and hybridization of the earlier ultrabasic rocks by the carbonatite dykes.

INTRODUCTION

Sillai Patti carbonatite is located near village Sillai Patti about 35 km west of Dargai (Fig 1). This dyke-like body was first reported by Ashraf and Chaudhry (1977).

A number of carbonatite occurrences have been reported from NW Pakistan. These include Koga in Swat (Siddique et al., 1967), Loe Shilman in Khyber, (Jan et al., 1981), Jhambil in Swat (Butt et al., 1987), Tarbela (Jan et al., 1981), and Khungi in Mardan (Khattak et al., 1984). All these occurrences were believed to be a part of the alkaline igneous province of NW Pakistan (Kempe, 1983). Le Bas et al. (1987), however, suggested that the alkaline magmatism occurred in two periods, i.e. Carboniferous and Oligocene.

This study presents a detailed geological, petrographic and chemical account of the Sillai Patti carbonatite complex.

REGIONAL GEOLOGICAL SET-UP

The geology of north Pakistan can be conveniently described with respect to three major geological domains: 1) Indo-Pakistan plate, 2) Kohistan Island arc assemblage, and 3) Asian plate.

Two major thrusts separating these domains are the Main Mantle Thrust which marks the boundary between the Indo-Pakistan plate and the Kohistan Island arc, and the Main Karakoram Thrust which separates the Island arc assemblage from the Asian plate in the extreme northern part of Pakistan (Tahirkheli, 1980). Alkaline rocks and carbonatites of the Peshawar Plain are restricted to the Indian plate in Pakistan.

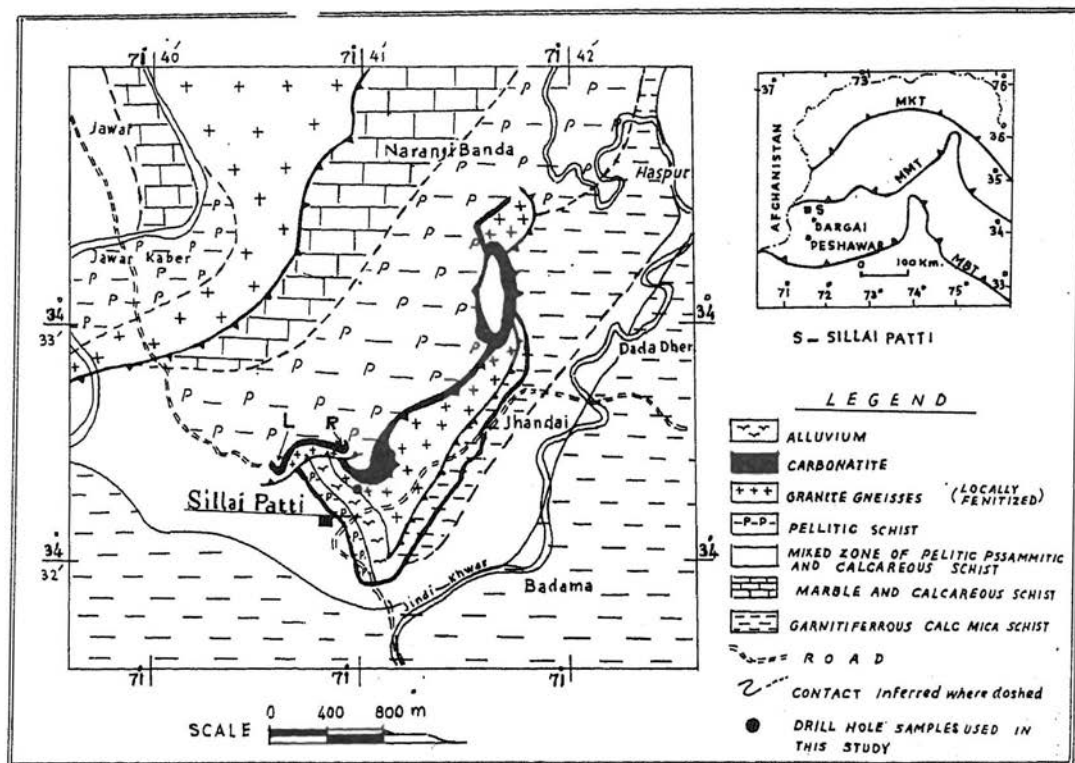


Fig. 1: Geological map of Sillai Patti complex.

FIELD ASPECTS

Geological Mapping

A detailed geological map of Sillai Patti and adjoining areas is presented in Fig. 1. The Sillai Patti carbonatite complex is a series of anastomosing carbonatite dykes which are roughly concordant with the regional strike of the area (Fig. 2). The so-called carbonatite sheet at Sillai Patti is in fact a complex containing several dyke-like carbonatite bodies emplaced either within the metasediments or at the contact of metasediments and granite gneiss, which appears to be a thrust fault (Le Bas et al., 1987). These dykes range in width from 15 cm to 15 m. A road section near village Sillai Patti (Fig. 3) demonstrates the nature of the carbonatite complex. In addition to the mappable zones containing carbonatites, several small zones containing carbonatite veins are also encountered in the same general area.

Weathering Characteristics

In spite of a variety of compositions of carbonatites and hybrid rocks including "Amphibole carbonatite", "Biotite carbonatite" and varieties with little or no mafic minerals, the weathering characteristics are identical. The carbonate minerals, which are white to very light brown on a fresh surface, alter very deep reddish brown, which reflects a high Fe/Mg content of these minerals.

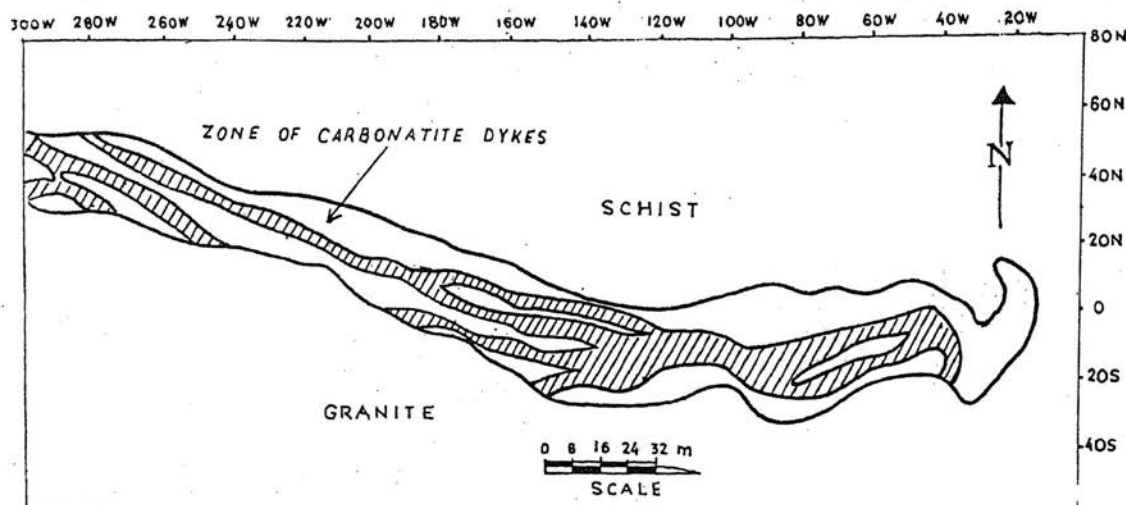


Fig. 2: Radiometric map of part of Sillai Patti complex. High radioactivity is shown by hatched area. Rest is hybrid rocks. Location of the area is shown as R in Fig. 1.

0 1 m

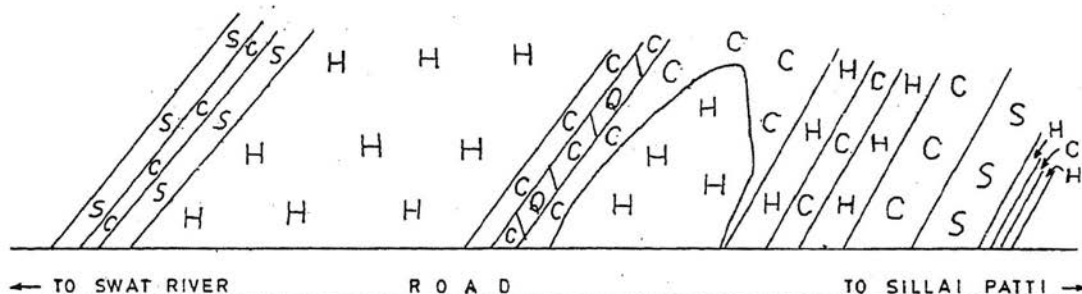


Fig. 3: A geological sketch of a section of Sillai Patti carbonatite complex located near Sillai Patti (Fig. 1). C-Carbonatites, H-Calcareous hornblende, S-Siliceous Schists, Q-Carbonatite with quartz veins.

Radioactivity

Gamma radioactivity of a carbonatite reflects its U-Th and rare earth content. Since these elements are relatively more abundant in the carbonatite as compared to the other rocks, especially the enclosing metasediments, a surface radiometric signature can also be interpreted as the existence of carbonatite material in the area. A detailed radiometric map of a part of Sillai Patti complex is given in Fig. 2. An anastomosing nature of the carbonatite is also reflected on this map. A comparable distribution of Gamma radioactivity was also encountered within the drill holes made in this part of the carbonatite complex (Fig. 4). Immediately outside the complex, the radioactivity decreases substantially to reach normal background levels of the area in general.

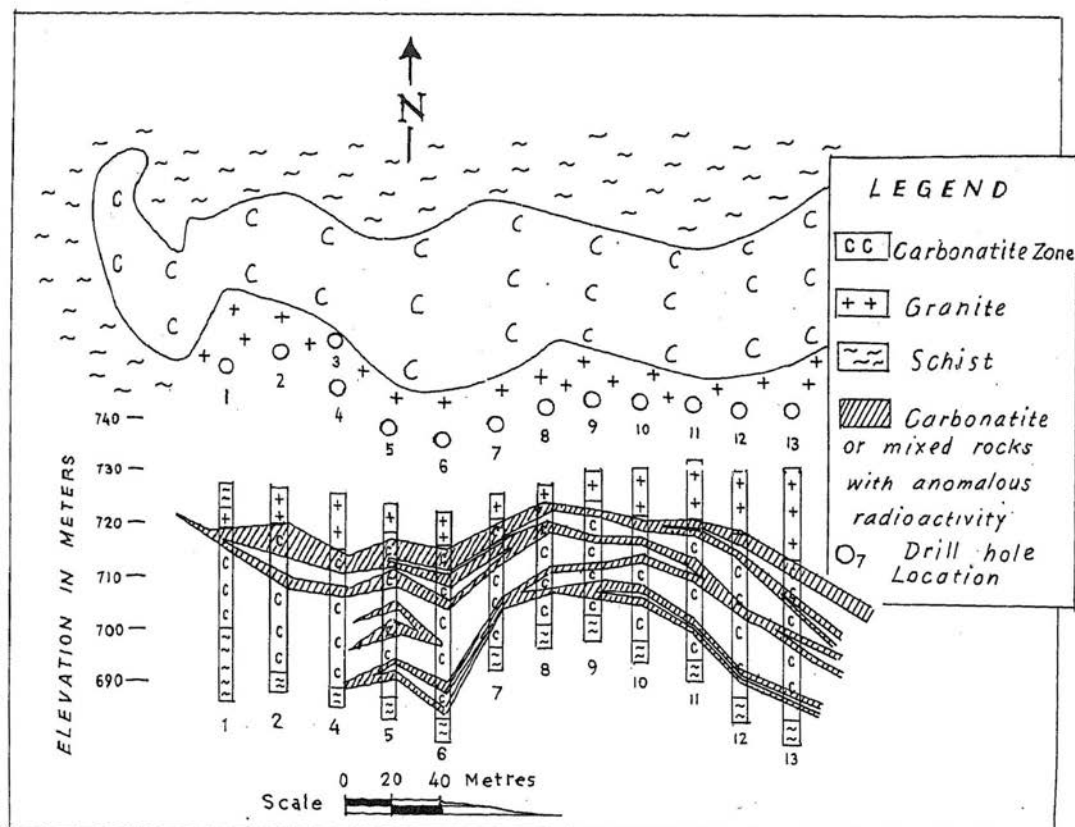


Fig. 4: A drill hole section along the strike of a part of Sillai Patti carbonatite complex showing subsurface distribution of radioactivity. Location is shown as L in Fig. 1.

COUNTRY ROCKS

The country rocks to the Sillai Patti carbonatite are a) Malakand granite gneiss, and b) Metasediments of Swat-Buner schistose group.

The Malakand granite gneiss is in contact with the metasediments of Swat-Buner schistose group of possible Proterozoic age. This contact has been interpreted to be a thrust (Fig. 1). Whereas most of this contact contains hybrid rocks, at places the carbonatite is in contact with the granite. Except at a few places, coarse grained orthoclasites are not present.

The granite gneiss is porphyritic, whitish grey to dark grey and foliated. It contains albite or oligoclase, microcline, muscovite, biotite, epidote and accessory minerals (Chaudhry et al., 1976). The country rock metasediments display much more compositional variations than those given in Le Bas et al. (1987). In general these rocks are made up of quartzites, siliceous to calcareous schists, marbles, amphibolites, garnet-mica schists, and graphitic schists. These have been metamorphosed under epidote-amphibolite facies conditions prior to thrusting (Le Bas, 1987) and intrusion of carbonatite. In the carbonatite complex the following field observations are considered critical.

- 1) Carbonatite dykes are flanked by a distinct alteration/metasomatic halo.

- 2) The intrusion of carbonatite has resulted in the formation of a variety of hybrid rocks due to metasomatism, and contamination of carbonate magma with the country rock material.
- 3) Certain compositions of pelitic rocks have been changed into rocks consisting entirely (100%) of biotite (glimmerite), whereas calcareous rock have been changed into fine grained schists containing 100% hornblende. All possible compositions between these two end members have been observed in the field.
- 4) The Sillai Patti carbonatite complex contains amphibole carbonatite and biotite carbonatite.
- 5) The bulk of the Sillai Patti carbonatite is amphibole carbonatite with only minor biotite carbonatite facies. This may be due to the calcareous nature of the country rocks which have been assimilated by the intrusive carbonatite magma.
- 6) The amphibole carbonatite grades into hornblendite with minor carbonatitic material. Similar compositional variations also exist between biotite carbonatite and pure biotite rock.

PETROGRAPHY

Thirty two thin sections were studied along a single drill hole which penetrated through the entire thickness of the carbonatite body. These rocks can be grouped into three varieties.

- 1) Peralkaline silicate rocks (pyroxenites).
- 2) Carbonatites.
- 3) Syenites (fenitized granite).

The peralkaline silicate rocks and carbonatites are included in what has been referred to as carbonatite complex. Syenitic rocks form both at the immediate contact of the overlying granite as well as xenoliths of metasomatized granite within the carbonatite complex.

Peralkaline Silicate Rocks (Pyroxenites)

Textures: These are medium to coarse grained, hypidiomorphic, granular rocks with large crystals of poikilitic hornblende. Inclusions in poikilitic amphiboles are calcite globules, apatite and relict pyroxene. Calcite is coarsely crystalline or highly granulated. Euhedral apatite is generally coarse grained and is traversed by calcite along fractures. Biotite invariably shows bent lamellae and uneven strained extinction. These rocks are traversed by calcite and/or siderite/baryte veins. Amphiboles invariably show platelets of oriented iron ore along cleavages or twin plains. Zoning is fairly conspicuous in the amphiboles throughout the complex.

Mineralogy: The peralkaline silicate rocks contain varying proportions of hornblende, pyroxene, calcite, biotite, apatite, sphene, magnetite and albitic plagioclase. Other minerals are in minor amounts and include siderite, epidote, hematite, zircon, limonite, pyrochlore, and aeschyanite. The growth of epidote at the expense of hornblende suggests metamorphic effects. Development of soda rich amphibole has been observed. On the basis of chemical analyses (Table I) in one sample, it has been designated as magnesio-arfvedsonite. These rocks have a mineralogical composition reminiscent of vibetites (Barth and Ramberg, 1966). On the basis of petrographic data these are interpreted to be partly fenitized and hybridized pyroxenites.

The composition of the epidote appears to range from clinozoisite to epidote. Baryte

TABLE-1: MAGNESIO-ARFVEDSONITE ANALYSIS FROM SILLAI PATTI CARBONATITE COMPLEX.*

Oxide Wt %		Cations/23 Oxygen	
SiO ₂	55.51	Si	7.76
TiO ₂	0.20	Al	0.10
Al ₂ O ₃	0.61	Fe ³⁺	0.92
FeO _t	10.57	Ti	0.02
MnO	0.02	Fe ²⁺	0.31
MgO	18.65	Mn	0.00
CaO	5.13	Mg	5.38
Na ₂ O	5.51	Ca	0.77
K ₂ O	2.19	Na	1.49
		K	0.30
Total	98.39		

*Microprobe analysis, average of 4 spots (Analyst: M. Barkatullah)

occurs in veins as well as disseminated grains. Skeletal magnetite intergrowths with calcite have been observed, suggesting a possible exsolution of iron from iron-rich calcite crystallized at high temperature. Siderite occurs both as veins as well as euhedral grains poikilitically enclosed in calcite. At places extreme granulation of calcite is observed along with recrystallized grains. Deformed and bent lamellae of biotite are also common. Rare aegirine grains and, at places, albitic plagioclase are also present.

It may be added that a complete spectrum of rock types ranging from pyroxenites (now represented by hornblendites with minor calcite) to carbonatites (with subordinate silicate minerals) is encountered. Although varying in proportions, the constituent minerals in these rocks essentially display similar characteristics.

Carbonatites

Textures: The carbonatites are medium to coarse grained crystalline rocks. Calcite is anhedral whereas anhedral to subhedral amphibole, biotite and epidote are characteristic. Large crystals of epidote are common and invariably associated with biotite. These may be poikiloblastic with inclusions of calcite, biotite, apatite and ore. Apatite tends to be euhedral and is occasionally completely enclosed in calcite.

Mineralogy: The rocks consist essentially of a high iron calcite, siderite, biotite, hornblende and magnesio-arfvedsonite. Biotite-epidote association has been frequently observed in these rocks suggesting a metamorphic effect.

Syenites

Textures: These are medium to coarse grained, hypidiomorphic, granular in texture. The varieties containing higher proportion of feldspathic minerals tend to exhibit a granoblastic texture with anhedral albitic plagioclase and K-feldspar. In such rocks calcite and ferromagnesian minerals are restricted to the feldspar grain boundaries.

Mineralogy: Potash feldspar is a major felsic mineral, and hornblende, biotite, and some clinopyroxene represent ferromagnesian minerals. Other minerals include epidote, chlorite, magnetite, and traces of blue amphibole (magnesio-arfvedsonite). No feldspathoids were ob-

served. Compositional ranges are mainly due to the variation in the feldspar content at the expense of ferromagnesian minerals. On the basis of petrographic investigations, these rocks are considered to be fenitized granite gneiss.

DEFORMATION TEXTURES

Deformation textures are abundant in all the rock types described above. These include deformation lamellae in calcite, bent and aligned biotite flakes and, at places, extreme granulation of calcite. These rocks are therefore considered to be highly deformed.

METAMORPHISM

There appears to be a lot of epidote/clinozoisite both in the silicate as well as carbonatite rocks. Epidote is invariably associated with biotite in the carbonatites. Epidote/clinozoisite minerals occur in regionally metamorphosed rocks or hydrothermally altered feldspar. Hydrothermal alteration associated with carbonatites are not known elsewhere to produce epidote (Gtins, written communication).

The existence of epidote in Sillai Patti carbonatite therefore reflects a metamorphic event. Epidote is also produced in retrograde re-adjustments associated with cataclastic metamorphism, particularly of basic igneous rocks (Deer et al., 1962). It is, therefore, possible that the intrusion of carbonatite and related rocks in the area were either syntectonic or pre-tectonic. This is in contrast to the interpretation put forth by Le Bas et al. (1987) that the carbonatites are post-tectonic.

Alternatively, the epidote was produced during greenschist to epidote-amphibolite facies metamorphism of the Proterozoic country rocks as well as the carbonatite complex. Regional metamorphism of siliceous limestone (which would be chemically equivalent to carbonatite) and metabasites (chemically equivalent to peralkaline silicate rocks of Sillai Patti complex) produced epidote. In intermediate and high pressure metabasites, epidote appears in the greenschist facies and in epidote amphibolite facies. In intermediate and high-pressure metamorphism of a siliceous carbonatite rock, epidote is produced in epidote amphibolite facies (Miyashiro, 1973). Pending a comparative study of metamorphic assemblage of the country rocks, it can be stated that the possibility of a regional metamorphic effect on the carbonatite complex cannot be completely ruled out.

Since the possibility of a pre-tectonic nature of the carbonatitic complex cannot be disregarded, it is possible that these rocks were metamorphosed upto epidote-amphibolite facies alongwith the country rocks. If this is the case, then the K-Ar dates reported by Le Bas et al. (1987) may only represent metamorphism post-dating the intrusion of the carbonatite, so the carbonatite may in fact be much older, and chronologically equivalent to the Carboniferous carbonatites of the region.

Rifting of the Indian continent and related extensional tectonics have been postulated during Carboniferous (Crawford, 1974). The alkaline magmatism during Carboniferous, therefore, finds a more plausible explanation.

CHEMISTRY

Thirty two whole-rock analyses of carbonatites and peralkaline silicate rocks of the Sillai Patti carbonatite complex are presented in Table 2. The analyses were performed chemically, using atomic absorption spectrophotometer and fluorimeter.

TABLE-2: CHEMICAL ANALYSES OF ROCKS OF SILLAI PATTI CARBONATITE COMPLEX.

	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*	12*	13*	14*	15*	16*
SiO ₂	25.60	31.57	35.79	36.28	20.98	34.76	36.40	34.96	17.74	19.12	7.20	36.00	14.94	6.60	6.30	9.27
TiO ₂	2.69	2.57	2.45	2.21	3.69	4.30	3.69	2.77	0.55	0.74	0.74	1.84	1.47	0.55	0.25	0.21
Al ₂ O ₃	4.95	5.90	4.42	7.21	5.24	6.01	6.87	7.06	5.76	7.32	3.87	8.06	11.80	3.68	1.32	2.22
P ₂ O ₅	1.60	0.80	0.40	0.41	2.51	0.97	1.04	0.96	3.54	2.66	3.30	2.03	1.80	2.09	3.60	3.30
Fe ₂ O ₃	14.67	16.64	15.85	13.29	10.32	15.98	16.04	13.98	6.84	5.91	8.41	12.67	6.68	11.84	6.50	5.24
FeO	1.93	2.55	3.11	3.99	1.85	3.43	2.72	1.3	4.18	4.0	3.08	1.10	3.26	1.32	2.30	2.74
MnO	0.20	0.28	0.36	0.28	0.22	0.34	0.34	0.28	0.26	0.34	0.42	0.20	0.38	0.42	0.38	0.42
MgO	3.58	3.88	3.91	3.94	3.61	4.01	3.94	3.97	3.88	3.44	3.15	3.35	3.15	2.95	3.45	3.35
CaO	22.82	18.47	15.22	13.67	25.68	14.00	14.50	13.36	25.50	26.86	33.82	12.12	30.18	28.59	36.99	38.13
Na ₂ O	0.94	1.48	1.83	2.69	1.32	2.37	2.32	2.37	1.05	0.94	0.7	2.37	0.97	0.43	0.62	0.48
K ₂ O	0.31	0.53	0.89	1.93	1.25	1.95	2.05	2.29	2.29	3.85	1.35	7.71	2.05	0.77	0.43	0.92
CO ₂	16.74	12.94	11.95	10.74	21.29	8.5	6.92	10.49	24.44	21.99	30.86	9.67	21.39	36.88	32.84	29.03
SrO	0.18	0.16	0.16	0.16	0.22	0.34	0.16	0.21	0.56	0.96	1.22	0.42	0.90	0.92	1.11	0.97
H ₂ O ⁺	0.25	0.40	0.06	0.15	0.08	0.07	0.30	0.35	0.31	0.1	0.24	0.28	0.25	—	0.12	0.18
H ₂ O ⁻	0.76	0.50	0.60	0.68	0.38	0.56	0.26	0.43	0.29	0.64	0.15	0.75	0.10	0.48	0.40	0.14
SO ₂	1.44	0.80	1.47	1.33	2.52	1.78	0.99	1.78	1.92	1.68	2.28	1.15	2.00	2.80	1.42	1.97
Cl	0.9	0.02	0.11	0.11	0.13	0.12	0.02	0.05	0.14	0.09	0.15	0.17	0.08	0.10	0.10	0.12
V	—	—	0.05	0.05	—	0.05	0.05	0.05	—	—	—	0.5	—	—	—	—
ZrO ₂	—	—	0.05	0.05	—	0.05	0.05	0.05	—	—	—	0.5	—	—	—	—
Total	99.56	99.09	99.5	99.9	101.29	100.51	99.18	97.64	99.25	100.64	100.94	100.59	100.43	100.42	98.13	98.69
Th	—	—	210	190	—	130	120	150	—	—	—	110	—	—	—	—
U	—	—	4	6	—	6	22	6	—	—	—	12	—	—	—	—
CU	—	—	45	5	—	51	17	56	—	—	—	60	—	—	—	—
Li	—	—	12	12	—	12	15	13	—	—	—	26	—	—	—	—

	17*	18*	19*	20*	21*	22*	23*	24*	25*	26*	27*	28*	29*	30*	31*	32*	33	34	35
SiO ₂	9.63	30.55	35.98	35.50	16.48	18.43	19.18	16.63	14.45	14.78	10.45	12.71	15.95	12.53	30.81	10.37	55.54	68.69	69.70
TiO ₂	0.21	0.74	0.74	2.58	0.36	0.36	0.36	0.36	0.67	0.22	0.28	0.74	0.72	0.36	0.28	0.26	0.56	0.56	0.16
Al ₂ O ₃	2.64	6.53	9.63	5.79	1.88	2.19	3.78	5.0	3.92	1.79	3.35	2.52	4.50	4.91	6.89	6.33	18.99	13.41	15.37
P ₂ O ₅	2.37	2.06	1.46	1.2	2.54	2.97	2.97	3.46	1.64	3.26	3.30	3.23	3.50	1.46	2.45	3.52	0.24	0.12	0.20
Fe ₂ O ₃	7.72	7.31	3.64	11.95	7.77	7.48	8.67	5.72	6.21	4.82	4.87	7.39	5.79	5.57	6.09	4.28	2.90	3.23	2.04
FeO	2.22	1.94	2.88	2.98	0.13	0.02	2.80	1.94	1.80	1.06	1.97	0.31	0.15	2.32	0.17	1.62	1.38	0.58	0.52
MnO	0.40	0.22	0.20	0.20	0.36	0.14	0.16	0.14	0.16	0.14	0.14	0.14	0.14	0.12	0.10	0.12	0.04	0.08	0.05
MgO	3.35	3.71	3.28	3.08	3.28	3.35	3.48	3.39	3.38	2.98	3.15	3.38	3.68	3.71	3.88	3.6	0.52	0.62	0.86
CaO	35.68	22.08	18.89	11.50	34.19	33.57	32.18	30.43	34.81	32.64	36.69	35.44	32.97	35.68	23.00	35.68	3.57	1.37	1.30
Na ₂ O	0.16	0.69	4.04	4.04	1.32	1.32	1.37	1.48	0.16	0.99	0.70	0.99	1.37	0.43	5.39	0.78	3.77	4.00	3.93
K ₂ O	0.51	2.65	1.97	3.37	0.79	0.67	0.99	0.79	0.58	0.55	0.64	1.25	1.56	0.63	2.05	1.42	5.89	3.52	4.94
CO ₂	31.35	17.34	15.14	14.07	26.47	26.37	21.41	27.74	29.31	29.11	32.10	24.41	25.07	28.49	16.42	29.19	2.57	0.77	—
SrO	0.92	0.61	0.61	0.21	1.04	0.70	0.70	0.76	0.80	0.90	1.09	0.99	0.71	0.66	0.40	—	0.15	0.06	—
H ₂ O ⁺	0.14	0.19	0.22	0.44	0.46	0.65	0.97	0.52	0.34	0.08	0.19	0.17	0.10	0.10	0.09	0.29	1.73	1.55	0.63
H ₂ O ⁻	0.31	0.12	0.18	0.69	0.41	0.24	0.34	0.34	0.45	0.36	0.18	0.22	0.5	0.30	0.53	0.18	0.12	0.06	0.13
SO ₂	2.02	1.95	0.84	0.97	1.39	1.08	1.74	1.62	1.98	1.96	2.64	2.78	1.89	1.04	0.12	1.34	0.20	0.08	—
Cl	0.09	0.08	0.11	0.09	0.12	0.05	0.90	0.08	0.07	0.86	0.08	0.08	0.08	0.09	0.08	0.08	0.01	0.01	—
V	—	0.05	—	0.05	0.05	0.05	—	—	—	0.05	—	0.05	0.05	—	0.05	—	—	—	—
ZrO ₂	—	0.05	—	0.05	0.05	0.05	—	—	—	0.05	—	0.05	0.05	—	0.05	—	—	—	—
Total	99.72	99.88	99.81	99.27	99.81	100.25	102.00	100.40	100.66	97.61	101.82	98.29	99.76	99.40	100.43	99.58	98.18	98.09	100.27
Th	—	50	—	180	60	80	—	—	—	50	—	100	80	—	50	—	—	—	—
U	—	2	—	5	13	N.D.	—	—	—	2	—	N.D.	5	—	N.D.	—	—	—	—
CU	—	60	—	60	60	60	—	—	—	60	—	60	60	—	60	—	—	—	—
Li	—	30	—	40	16	12	—	—	—	12	—	12	10	—	10	—	—	—	—

*Calcareous hornblende, + Carbonatites, O Fenitized granite, 33 Fenitized granite (Hanging Wall), 34 Schists (Foot Wall), 35 Average Malakand granite gneiss (Shams, 1983)
SiO₂ to ZrO₂ in percentage, Th to Li in ppm.

These analyses were conducted on core samples from a drill hole that penetrated the entire thickness of the carbonatite complex. Chemical variation along the entire thickness of the carbonatite complex is plotted in Figs. 5 and 6. The significance of this spatial chemical variation is discussed as follows:

Potash

The K_2O content shows a slight increase in the granitic rocks in contact with the carbonatite complex as compared to the average K_2O content of the Malakand granite gneiss. This reflects fenitization effects restricted to the margin of the carbonatite complex.

Since all the pyroxenites are within the carbonatite complex and there are no such rocks available which might have escaped the effects of carbonatite intrusion and attendant fenitization, only the differences in K_2O content with respect to distance from carbonatite contact are discussed. Sample Nos. 1, 2, 3 and 4 (Fig. 5) represent pyroxenites and sample No. 5 carbonatite. Maximum K_2O content is observed in samples close to carbonatite. This would suggest an addition of K_2O into the pyroxenites.

Similarly sample Nos. 6, 7, 8, 9 and 10 registered a continuous increase followed by a sharp drop in sample No. 11. Sample Nos. 7, 8, 9 and 10 are petrographically classified as hybrid rocks. The chemical variation suggests that hybridization or assimilation of fenitized pyroxenite can explain such a K_2O increase towards sample No. 11 which is pure carbonatite.

The K_2O content registers an increase over the pyroxenites as well as syenitic fenite, whereas the carbonatite rocks show a drop in K_2O on the diagram (Fig. 5). This reflects alkali loss of carbonatites to pre-existing rocks both within and outside the carbonatite complex.

Silica

Variation of SiO_2 content across Sillai Patti carbonatite complex is shown in Fig. 5. SiO_2 content of the granitic rocks close to the contact of the carbonatite complex shows a significant drop whereas carbonatitic rocks seem to have acquired silica from the adjoining pyroxenites as well as country rock granite and metamorphics. The average SiO_2 content of the carbonatites of this complex is fairly high. Field evidence for remobilization of SiO_2 in the form of quartz veins has been observed. Petrographic study, however, suggests that the high SiO_2 content of carbonatite may be partly due to the xenocrystic nature of feldspar, amphibole and biotite in the carbonatites.

Loss of SiO_2 from pyroxenite to carbonatite (Sample No. 11) is represented by sample Nos. 6 to 10. Sample No. 7 being the farthest from carbonatite shows relatively higher SiO_2 content and sample Nos. 8 and 6 register a loss of SiO_2 as the carbonatite is approached. Thus, movement of SiO_2 from pyroxenite and the country rock into the carbonatites is indicated. However a high SiO_2 content of carbonatite suggests assimilation of fenites by the carbonatites. A varying degree of such an assimilation is apparent from the variation in SiO_2 content of carbonatites represented by sample Nos. 23 to 30, 14 to 17.

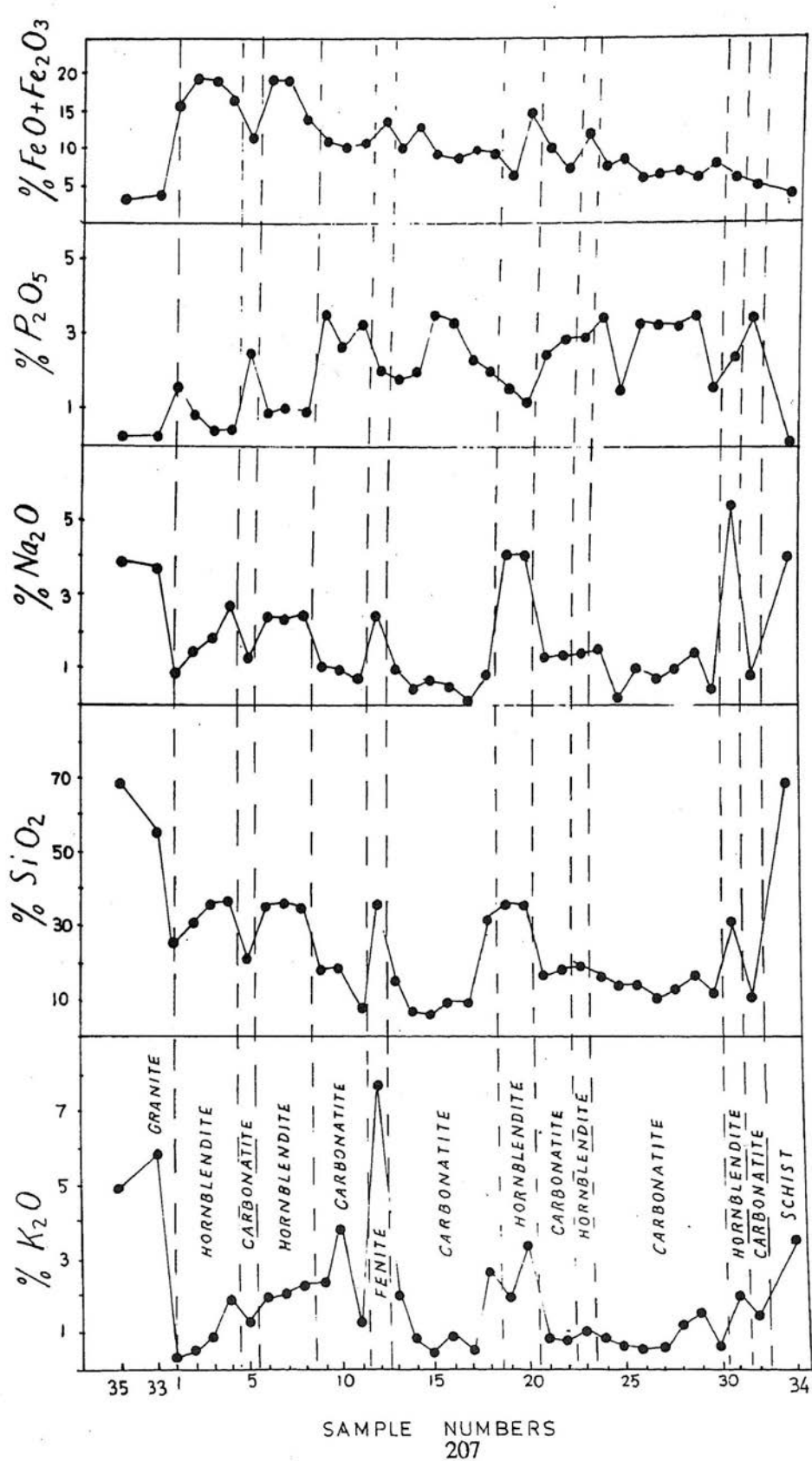


Fig. 5: Chemical variation across Sillai Patti carbonate complex. X-axis of the diagram shows samples from a drill hole located at D (Fig. 1). Sample No. 33 represents granite at the top contact of the carbonate complex, taken from 16 meter depth. Sample No. 1-32 are samples of various rock types of the carbonate complex between 16 m & 57 m depth. Sample No. 34 is from schist at the bottom contact of carbonate complex below 57 m. No. 35-Average Malakand granite gneiss (Shams 1983).

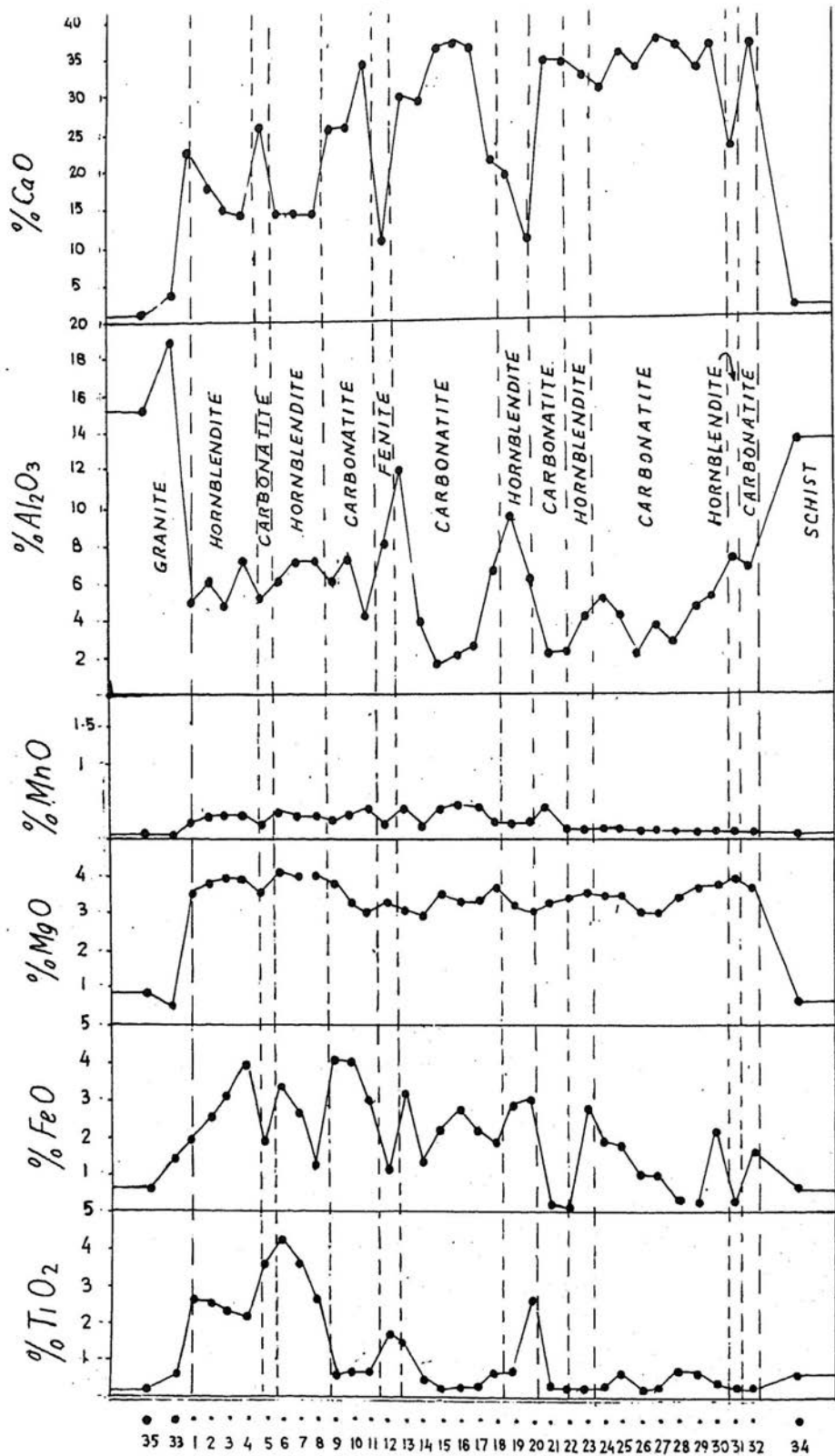


Fig. 6: Chemical variation across Sillai Patti carbonatite complex. For explanation refer to Fig. 5.

Soda

In contrast to the trends established for carbonatite complexes elsewhere, the behaviour of Na_2O is not in conformity with that of K_2O (Fig. 5). An addition of Na_2O is recorded in pyroxenites represented by sample Nos. 2, 3 and 4, whereas the granitic rocks show a loss in Na_2O content (sample 33). Similarly, fenite represented by sample No. 12 shows a Na_2O content much less than the country rock granite gneiss which is considered to be its parent rock. A marked acquisition of Na_2O content in the pyroxenite is demonstrated in a thin sheet of pyroxenite represented by sample No. 31.

Phosphorus

The P_2O_5 content of the carbonatite complex is in general higher than its country rocks (Fig. 5). However, the P_2O_5 maxima are recorded on carbonatitic rocks, while pyroxenites and fenites show minima on the curve.

Iron (Total)

Iron is either subtracted from the basic igneous rocks during fenitization or remains unchanged (Verwoerd, 1966). In case of Sillai Patti complex the highest iron content of the carbonatite is recorded in sample No. 5 representing a thin carbonatite flanked by fenitized pyroxenites. This may suggest a loss of iron from pyroxenites to carbonatites. The central parts of the pyroxenites record the maximum iron whereas carbonatites the minimum. This may also reflect progressive assimilation of pyroxenite by carbonatite rather than movement of iron during metasomatism. Variation in total iron is shown in Fig. 5.

Titania

The TiO_2 content of the peralkaline silicate rocks including ijolites, peridotites and pyroxenites is generally higher than carbonatites (Barth and Ramberg, 1966). Fig. 6 shows the variation of TiO_2 across the carbonatite complex. Carbonatitic portions of the complex invariably contain less than 1% TiO_2 whereas the pyroxenites record high TiO_2 . Within the carbonatites some high values were obtained which may suggest assimilation of pyroxenitic material by the carbonatites. Sample No. 25, 28 and 29 are such examples.

Manganesia

No significant interpretation can be proposed from the available data presented in Fig. 6.

Alumina

The granitic gneiss at the contact records an increase in Al_2O_3 (Fig. 6). A generally high Al_2O_3 content of the carbonatitic rocks of the complex as compared to a typical carbonatite is characteristic.

Magnesia

Magnesia content of the carbonatite complex remains practically constant (Fig. 6). Both carbonatites and pyroxenites have comparable MgO content. Whether this is due to metasomatic equilibration or inherent MgO content of the two rock types is not clear.

Calcium

The variability of CaO within carbonatitic or pyroxenitic parts of the complex can be explained by the amount of introduction of calcitic material into pyroxenites and assimilation of ferromagnesian minerals by carbonatites (Fig. 6). This is also supported by the petrographic observations.

In addition to the spatial variation in chemistry of the carbonatite complex, the chemical data was also plotted on $(\text{Na}_2\text{O} + \text{K}_2\text{O}) - (\text{MgO} + \text{Fe}_2\text{O}_3) (\text{t}) - \text{CaO}$ (Fig. 7) (Le Bas, 1981). Most carbonatites plot close to ferrocarbonatite. There is a tendency for increasing alkalis as well as $\text{MgO} + \text{Fe}_2\text{O}_3 (\text{t})$, which can be attributed to assimilation of fenitized pyroxenite by the carbonatitic magma. Fractional crystallization in these small carbonatite sheets has probably played a minor role in the compositional variations presented herein. Similarly, the pyroxenites also show an alkali as well as calcium enrichment attributable to fenitization and carbonatization.

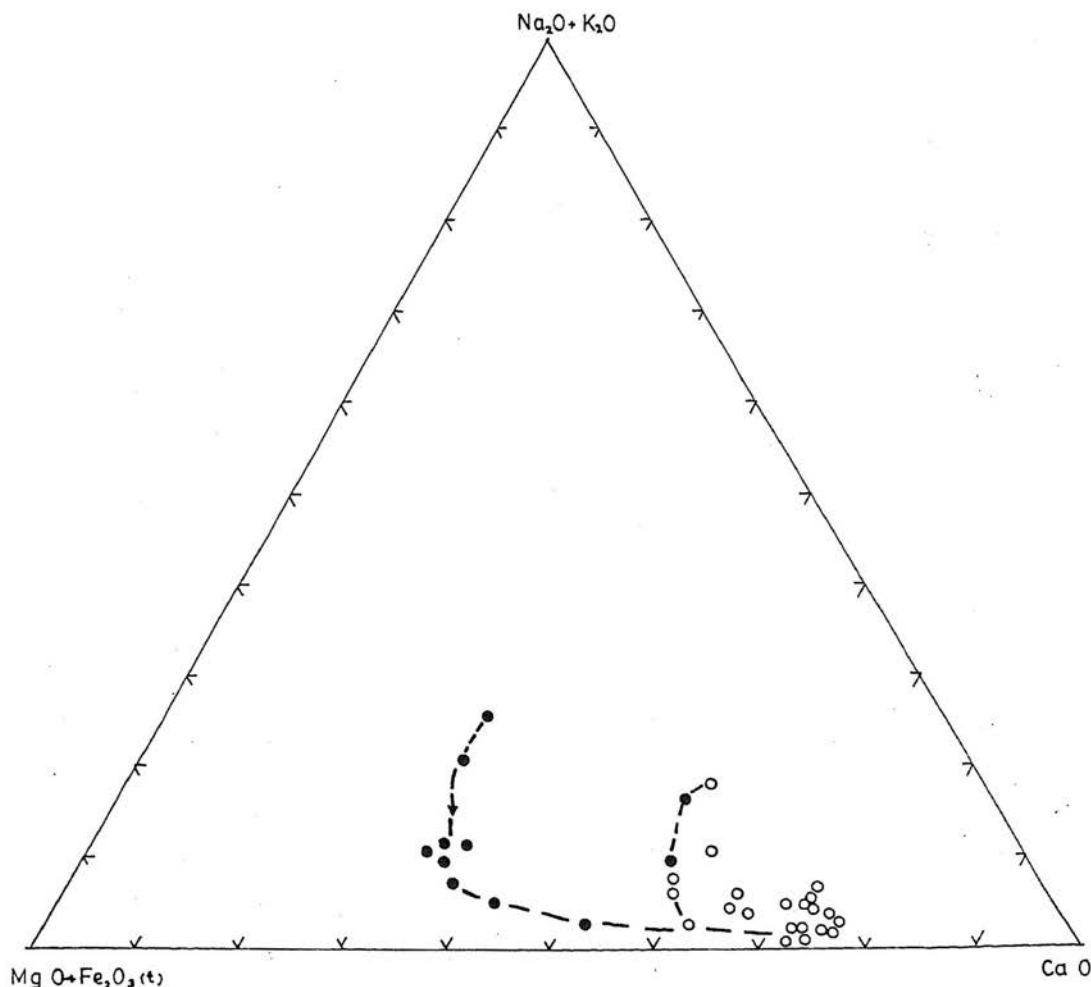


Fig. 7: $\text{Na}_2\text{O} - \text{K}_2\text{O} - \text{MgO} + \text{Fe}_2\text{O}_3(\text{T})$ plot of Sillai Patti carbonatite complex. Open circles are carbonatites, solid circles hornblende.

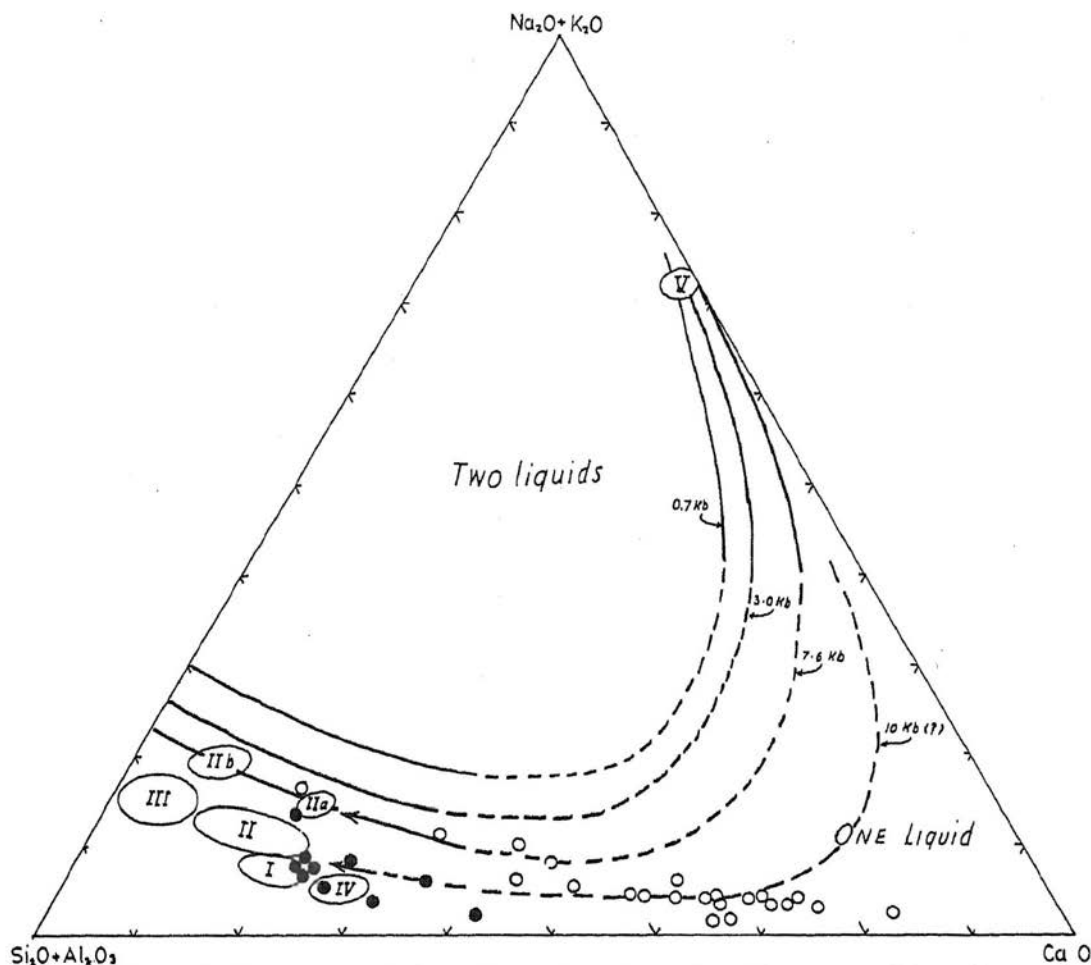


Fig. 8: $(\text{Na}_2\text{O} + \text{K}_2\text{O}) - (\text{SiO}_2 + \text{Al}_2\text{O}_3) - \text{CaO}$ showing silicate fields (I-Mafic magma, II-nephelinites and ijilites, IIa-Alnoite, IIb-Urtites, III-nepheline syenite, IV-Syenites, V-natrocarbonatite) around two liquid boundaries for 0.7, 3, 7.6 and 10 Kb (extrapolated at 1100°C . (After Le Bas, 1987).

In Fig. 8, data on Sillai Patti carbonatite complex has been plotted on liquid immiscibility plot showing silicate fields. Two trends are obvious on this diagram. There is a systematic increase in alkalis as well as (Si + Al). Referring back to spatial chemical variation diagrams (Figs. 5 and 6), some of the chemical variations are attributed to fenitization around carbonatite dykes. The evolution of carbonatite magma is considered by Le Bas (1987) in two distinct stages, i.e. loss of alkalis followed by fractional crystallization. Since the spatial chemical variations reflect a trend towards fenitization in the complex, the variation of alkalis in the carbonatites could have been explained by a differential loss of alkalis from them. But, there is a corresponding gain in (Si + Al) by the carbonatites. The carbonatites with a high alkali content are also higher in (Si + Al). Thus we cannot attribute a loss of alkali on one hand and a gain on the other to the same carbonatitic intrusive event. We are therefore left with two possibilities:

- 1) Either an earlier carbonatitic intrusive/extrusive event was responsible for the fenitization of the silicate rocks and the later carbonatites assimilated these rocks to show such trends.

- 2) Or the silicate rocks themselves are inherently rich in alkalis. The second possibility is discussed in the following:

Based on experimental data, Wyllie (1966) suggested that the minerals olivine, pyroxene, melilite, dolomite and calcite may precipitate simultaneously from carbonatitic magmas at low to moderate temperatures, and that the proportion of silicate to carbonate minerals would be small and the crystalline product would have little resemblance to silicate rocks (peridotites). He further suggested that some altered ultramafic rocks may, in fact, represent crystallization from a magma rich in CO_2 and H_2O . The rocks of Sillai Patti complex seem to fit such a description. The reader is referred to Fig. 8 where some of the silicate rocks of the complex plot close to "alnoite field" (IIa). Most of the silicate rocks of Sillai Patti complex would approach an alnoitic composition if we consider the petrographic evidence of CaCO_3 introduction as well as chemical evidence of increase in alkalis. Alnoite is considered to be the product of a magma at higher levels from which late stage carbonate magma has not separated. Fractional crystallization of such a magma could cause some alkali enrichment in late stage carbonate rich fractions. It may be emphasised that in the genesis of carbonatite complexes, the evidence of liquid immiscibility has been exploited to its fullest whereas the other possibilities indicated by the same set of experimental data have generally been neglected.

It is, therefore, possible that the compositional variation in the rocks of the Sillai Patti complex is a product of a complex process involving fenitization, hybridization and assimilation of the earlier silicate rocks by the intruding carbonatite magma.

Since alkali loss from carbonatite has been demonstrated by the spatial chemical variations (Fig. 5), the differences of various elements within the carbonatites, i.e. alkalis, silica and Al_2O_3 can only be explained by progressive carbonatization of the pyroxenites. Varying degrees of such a process would lead to the type of chemical variation observed within the carbonatite complex. Petrographic evidence reveals complete gradation from more than 90% calcite to less than 10% calcite within the complex and, at places, the boundary between carbonatite and fenitized and carbonatized pyroxenite is difficult to establish.

CHEMISTRY AND PETROGRAPHY OF THE CARBONATE MINERALS

Calcite in the carbonatites invariably contains exsolved magnetite both as minute inclusions as well as skeletal intergrowths with calcite. Goldsmith et al. (1962) claimed that 45 wt % FeCO_3 could exist as solid solution in calcite. Experimental data of Wyllie (1966) suggests that excess iron in the system $\text{CaO} - \text{MgO} - \text{CO}_2 - \text{H}_2\text{O}$ would lead to precipitation of iron oxide in addition to ankerite. Textural data on Sillai Patti carbonatites suggest that a high iron calcite/ankerite and siderite were the carbonate phases. With subsolidus drop in temperature, excess iron exsolved as magnetite. The Sillai Patti carbonatites seem to have crystallized under very high pressure because of the presence of both magnetite and siderite (cf. Wyllie, 1966). Attention of the reader is invited to analysis No. 14 (Table 2) which contains more than 90% modal calcite. Total iron in this rock is 13.16% and MgO content is 2.95%. Similarly analysis No. 7 represents a rock which contains less than 10% carbonates. This rock has an Fe_2O_3 (t) content of 18.76%. As mentioned earlier, since the silicate mineralogy of both the carbonatites and silicate rocks is identical and primary magnetite is not sufficiently high, most of the iron contained in the carbonatite (analysis No. 14) is in carbonate minerals. Textural evidence suggests that this excess iron was exsolved as skeletal iron oxide intergrown with calcite.

MINERALIZATION

The Sillai Patti carbonatite is invariably radioactive. A radiometric map of a part of the complex is given in Fig. 2. Since the complex has been described as consisting of ultramafic rocks on one hand and anastomosing carbonatite dykes on the other and since a complete spectrum of hybrid rocks also occur in the complex, the radioactivity provides a handy tool to map such dykes. Fig. 2 shows the zones of high radioactivity which coincide with pure carbonatite end members. Hybrid rocks, as well as slightly carbonatized ultramafic rocks, are also weakly radioactive which is considered to be the dissemination of radioactive material from carbonatites. U-Th radioactivity and associated fluorite or baryte are usually indicative of presence of rare-earth minerals in carbonatites (Le Bas, 1987). Minerals identified from radioactive zones in Sillai Patti complex include pyrochlore, monazite, huttonite, thorite, aeschyanite and baryte.

DISCUSSION AND CONCLUSIONS

Field and laboratory data suggest that the Sillai Patti carbonatite is not a single dyke. It consists of anastomosing system of carbonatite dykes intruding metasediments and alkali silicate rocks. A complete spectrum of rock types intermediate between the carbonatites and alkaline silicate rocks is also present. These are a product of varying degree of fenitization and hybridization due to carbonatite intrusion.

Alkaline silicate rocks show the effect of fenitization in close proximity to the carbonatite dykes but considering their bulk chemical composition these could not have been derived from either the metasediments or the granitic rocks enclosing the carbonatite complex. These rocks are interpreted to be alkaline ultramafic rocks (pyroxenites) reconstituted due to later carbonatite intrusion and their attendant fenitization. Alternatively, their bulk rock compositions are also reminiscent of alnoites which are considered to be the product of a magma at higher levels from which the late stage carbonate magma has not been separated. Considering the unstable tectonics of the region, it is likely that in lower crustal magma reservoir, where liquid immiscibility is generally envisaged to take place (Le Bas, 1987), the parent magma did not get sufficient residence time to effect complete immiscibility and an alnoitic magma was intruded to upper crustal levels to give rise to such rocks.

The carbonatites of Sillai Patti occur as anastomosing dyke system. Such a feature is characteristic of late stage ferro-carbonatites. The carbonate of carbonatite is exceptionally high in Fe and it shows exsolved iron oxide textures. These rocks are therefore interpreted to be ferro-carbonatites. This is further supported by the facts that they are invariably associated with U-Th rare earth mineralization. The process of fenitization also appears to have operated in the complex. A compositional gradation of rock types between carbonatites and alkali pyroxenites is also encountered in the complex. Petrographic data suggest that hybridization of partly fenitized pyroxenites is the major process in the production of such intermediate rock types. Identical ferromagnesian mineralogy of the carbonatites, pyroxenites and the hybrid rocks also supports such a conclusion. It, therefore, follows that much of the ferromagnesian mineral content of the carbonatites as well as the hybrid rocks may be xenocrystic in origin. Chemical data on these rocks is also in conformity with such an interpretation.

Radioactivity is restricted to the carbonatites and its immediate environs. As the content of ferromagnesian minerals increases in the carbonatites, their U-Th and rare earth contents decrease as indicated by a decrease in radioactivity.

The Sillai Patti carbonatite shows abundant evidence of granulation in calcite and the development of metamorphic minerals such as epidote. This would suggest that these rocks have suffered some post-consolidation metamorphism. The nature of metamorphic effects has not been the main purpose of this study. However, metamorphosed nature of this carbonatite is amply indicated (John Gittins, written communication). If such is the case, the K-Ar data, reported by Le Bas et al. (1987) may require some reinterpretation.

Le Bas et al. (1987) reported a Carboniferous age for ijolite from Koga area. Panjal volcanics of Permo-Carboniferous age from Kashmir in North Pakistan have been interpreted by Butt et al. (1985) to represent basaltic rocks associated with an incipient ocean possibly related to rifting of the Indian continent. Carwford (1974) considered the Panjal traps in Kashmir, Rajmahal traps of West Bengal and Bihar, and Sylhet traps of Bangladesh to be associated with rifting of Gondwanaland. These tensional events favourably coincide with a Carboniferous-Permian carbonatitic and alkaline magmatism near Koga. In view of the above, and the metamorphosed nature of Sillai Patti complex, it is possible that the alkaline and carbonatitic magmatism belongs to a tensional event during the breakup of Gondwanaland. Further geochronological data is required to substantiate this interpretation.

Acknowledgements: Critical reading of the manuscript by Dr. Ihsanullah Mian and Dr. M. Qasim Jan helped improve the manuscript. M. Barkatullah of NCE in Geology, University of Peshawar, is thanked for the microprobe analysis of the amphibole.

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