PETROLOGICAL AND CHEMICAL STUDIES OF DECCAN TRAP LAVAS FROM WESTERN INDIA

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ABSTRACT

The Deccan basalts constitute one of the world's largest continental flood basalt associations erupted during the Upper Cretaceous-Eocene period and presently cover an area of about 500,000 Km^2. Although the basalts are fairly uniform over most of the Deccan plateau, in parts of western India, they show considerable variety in their field relations, petrography, mineralogy and chemistry. Petrological and chemical studies carried out on basaltic and associated rocks from several localities in western India are described. Major and trace element data for 101 rocks and about 125 partial or complete mineral analyses have been collected during the present study. Atmospheric pressure melting and crystallization relations of 20 samples have also been studied. The data collected presently, and those already available are used to compare and contrast the different regions of the basalt plateau.

Bore hole flows (from Dhandhuka, Wadhwan Jn. and Botad in Gujarat State): These comprise rocks varying from picritic basalts to basalts, which are mildly alkaline in their chemical characters, and thus differ from the common Deccan basalts, which are sub-alkaline and tholeiitic in nature. Mineralogical, chemical and phase-equilibria considerations suggest a parental role to the picritic rocks. Partial melting of an upper mantle composition analogous to a garnet-peridotite at c. 25-30 Kb with the production of c. 20% primary picritic liquid has been proposed. Compositions analogous to such liquids - at least with regard to major elements - may be represented by some of the picritic liquids of the bore hole

sequence. Fairly rapid ascent and supply of such a liquid to plexus of shallow level magma chambers in the crust with or without immediate eruption has been envisaged. The primary picritic liquid may have lost at least some olivines en route. Depending upon the time of pause and rate of heat loss in the low pressure environment, differentiation of the primitive liquid ensued mainly through fractional crystallization of olivine, clinopyroxene and plagioclase. However, the mechanisms of fractionation may not have been simple, for there is a discrepancy between the observed chemical variation of the rock types and their phenocrystal content. The picritic types, particularly the strongly porphyritic oceanitic types may have suffered from low pressure crystal fractionation mechanisms akin to compensated crystal settling, while ankaramitic types may have been influenced by high pressure crystallization. In some basalts, plagioclase may have been selectively enriched. Enrichment of incompatible trace elements in the primitive picritic basalts pose considerable problems. Small amounts of high pressure eclogite fractionation and wall rock reaction may have enhanced the concentrations of trace elements and also probably account for the variability in the parental composition.

<u>Rajpipla area (Broach district, Gujarat State)</u>: The area comprises three periods of igneous activity. In order of decreasing age, they are a) tholeiitic flows, b) alkali basalts and their variants and c) tholeiitic dolerite dykes. The alkali basalts and their lineages constitute a mildly alkaline, moderately potassic differentiated suite ranging from basalts to trachyte, through trachybasalts, feldspar phyric basalts and oligoclase basalts. The

potassic rhyolites of the area may also be related to the alkalic suite. The parental basalt may have been derived from an initial picritic liquid formed at c. 25-30 Kb with c. 20% melting. Extensive high pressure fractionation and wall rock reaction followed by olivine fractionation of the primitive liquid en route has been postulated in order to produce compositions analogous to the parental basalt. Supply of such a liquid to shallow level magma chambers has been envisaged where fairly simple mechanisms of crystal fractionation appear to have produced the diversity from basalts to trachyte.

Other areas studied in Western India include Ambadongar, Panwad, Kawant, Pawagarh and Dedan.

A study of the major element chemistry of basaltic rocks from the different parts of the Deccan basalt plateau have indicated the following points: 1) Basalts of Western India show considerable variety when compared with basalts from Central India. However, within the western part certain regional differences have been found to be present: a) the E-W trending Narmada region appears to contain rocks of extreme diversity along with common basalts. Within the Narmada region, the western part comprising the Rajpipla area seems to be mildly alkaline and moderately potassic while the eastern part around Ambadongar appears to be strongly alkaline and rather sodic in character. b) The Cutch region appears to be mildly alkaline. Strongly alkaline rocks, such as those found in the Narmada region are either absent or have not yet been reported. c) The Bombay-Poona region, although containing very scarce alkaline rocks, seem to provide a wide variation in the tholeiitic rocks themselves.

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Modal data and Petrographic notes of analysed specimens

CHAPTER I

INTRODUCTION

The Deccan basalts constitute one of the world's great continental flood basalt eruptions extruded during the Upper-Cretaceous-Eocene period. It is believed that the northerly migration of India, after the foundering of Gondwanaland, occurred during this period.

Today the lava flows cover an area of 500,000 Km^2, and it is likely that their original extent was something like 2,500,000 Km^2. The main outcrops are confined to central and western India (Fig. 1-1).

The basalt plateaus have been studied by various workers since 1867 and recently (1969) have been the subject of an International symposium (Aswathanarayana, 1969). Two important features are well established by all the previous studies.

1. Predominantly the basalt plateau is composed of horizontally disposed, uniform tholeiitic flows, i.e. flows which are sub-alkaline, silica oversaturated and quartz-normative.

2. Along two linear belts in western India, the basalt plateau provides considerable variety in rock types and structure, and thus departs from the main "basalt plateau" character. Figures 1-2, -3 and -4 summarise broadly the presently available geological and structural details associated with the Deccan basalt plateau.

We shall briefly consider the peculiarities of the basalt plateau in western India, as the present study includes localities

Fig. 1-1. Map showing the outcrops of the Deccan trap and the localities studied.

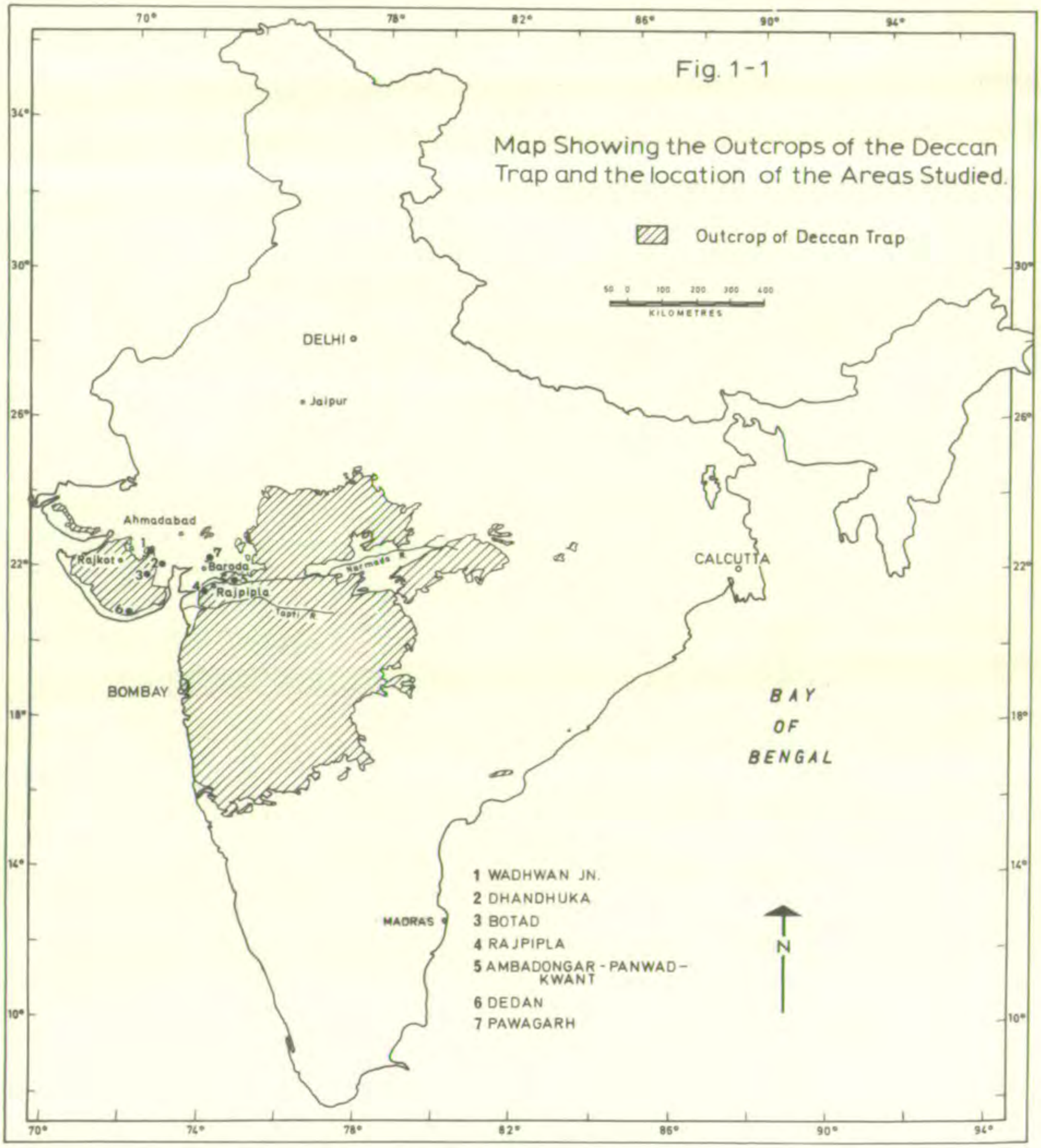


Fig. 1-1

Map Showing the Outcrops of the Deccan Trap and the location of the Areas Studied.

Fig. 1-2. Diagram showing the localities in the Deccan basalt plateau in western India where diverse rock types occur. See Table No. 1-1, for the locality number, its name, the major rock types and references for details.

Fig. 1-3. Distribution of volcanic/subvolcanic/plutonic centres of the Deccan basalt plateau along with the regional trend of dyke clusters and swarms.

Fig. 1-4. Major structural features associated with the Deccan basalt plateau.

Scale = 1:5,000,000

A.

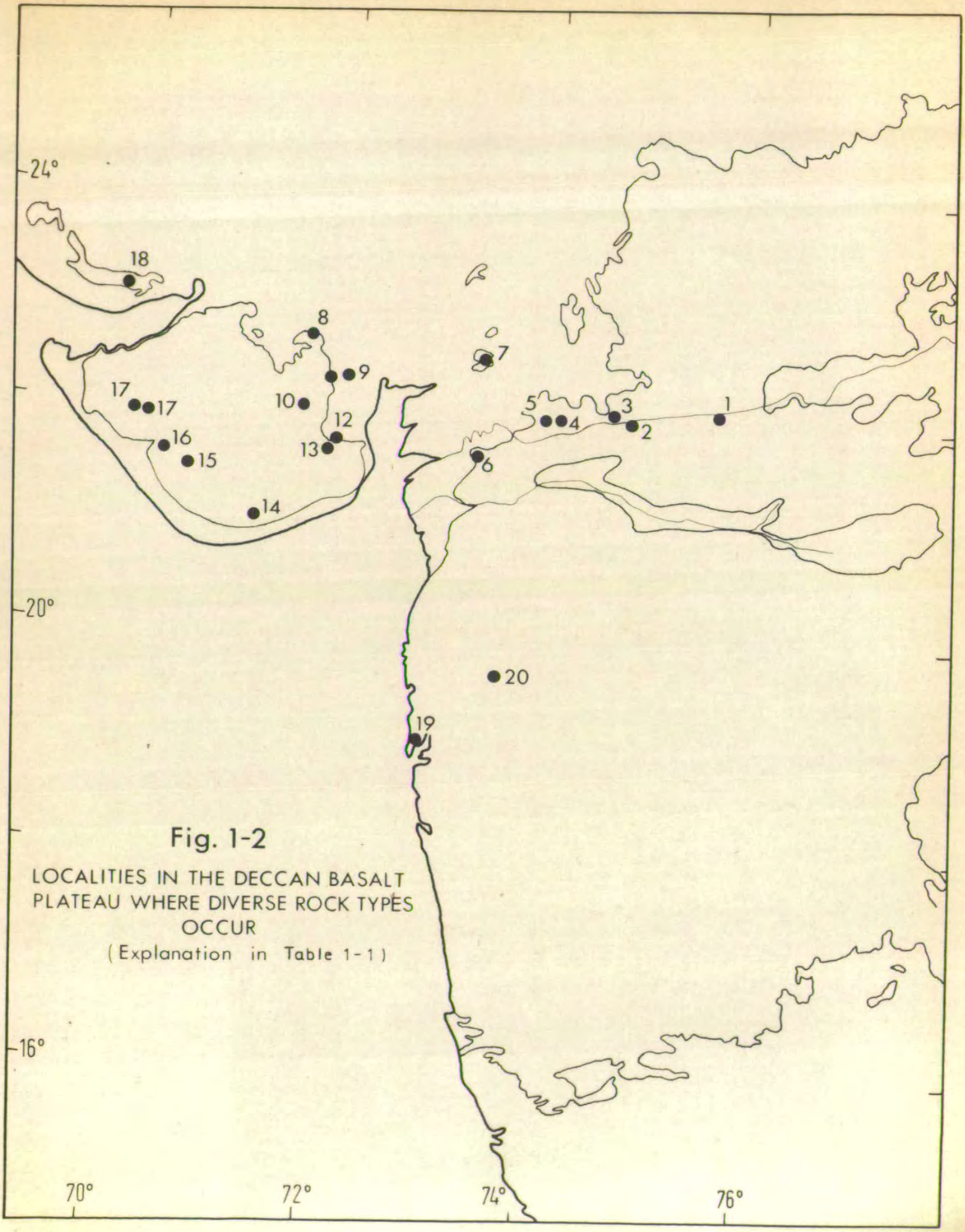


Fig. 1-2

LOCALITIES IN THE DECCAN BASALT PLATEAU WHERE DIVERSE ROCK TYPES OCCUR

(Explanation in Table 1-1)

B.

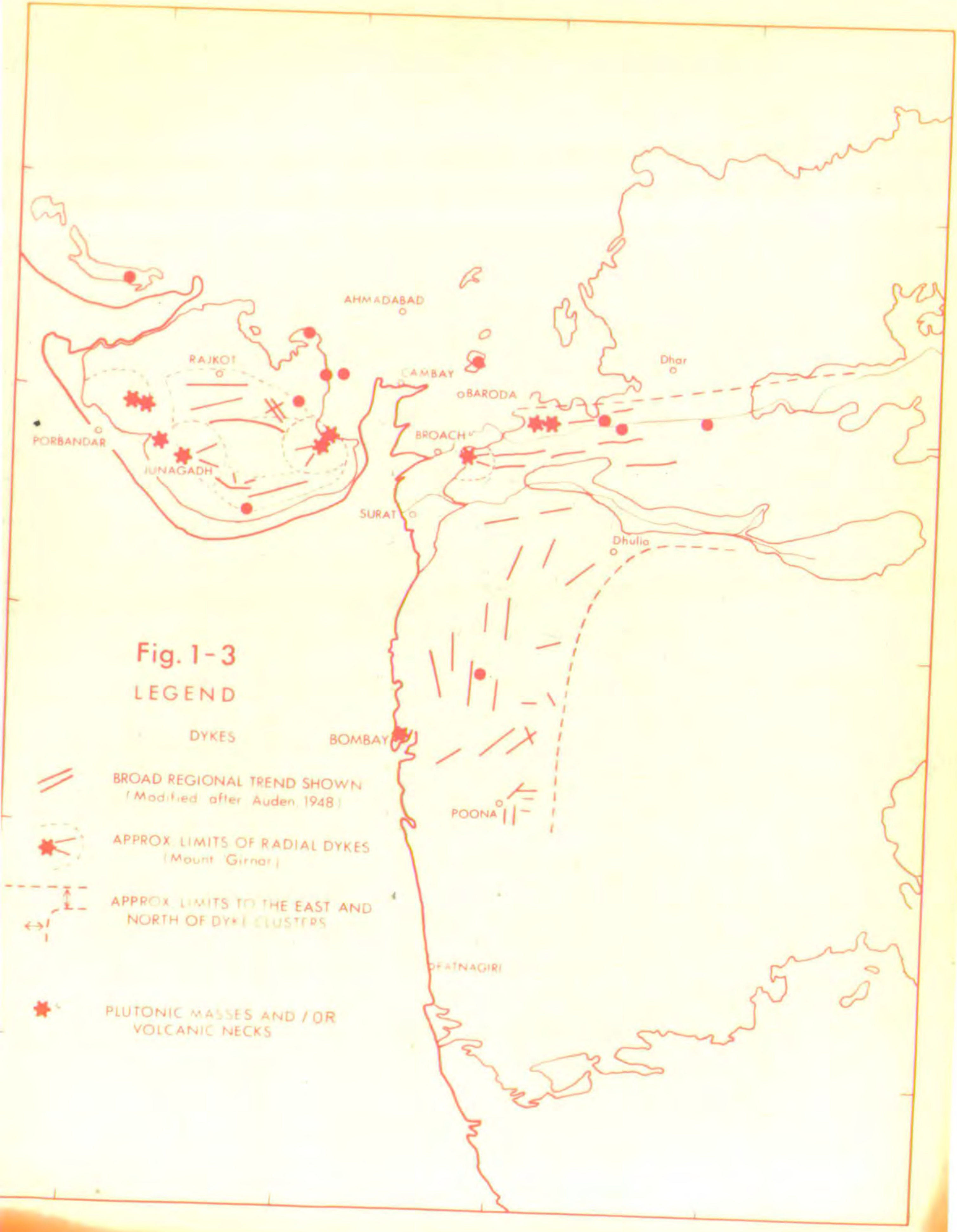

AHMADABAD
RAJKOT
CAMBAY
BARODA
Dhar
PORBANDAR
JUNAGADH
BROACH
SURAT
Dhulia
BOMBAY
POONA
RATNAGIRI
LEGEND
DYKES
BROAD REGIONAL TREND SHOWN
(Modified after Auden 1948)
APPROX. LIMITS OF RADIAL DYKES
(Mount Girnar)
APPROX. LIMITS TO THE EAST AND
NORTH OF DYKE CLUSTERS
PLUTONIC MASSES AND / OR
VOLCANIC NECKS

Fig. 1-3

c.

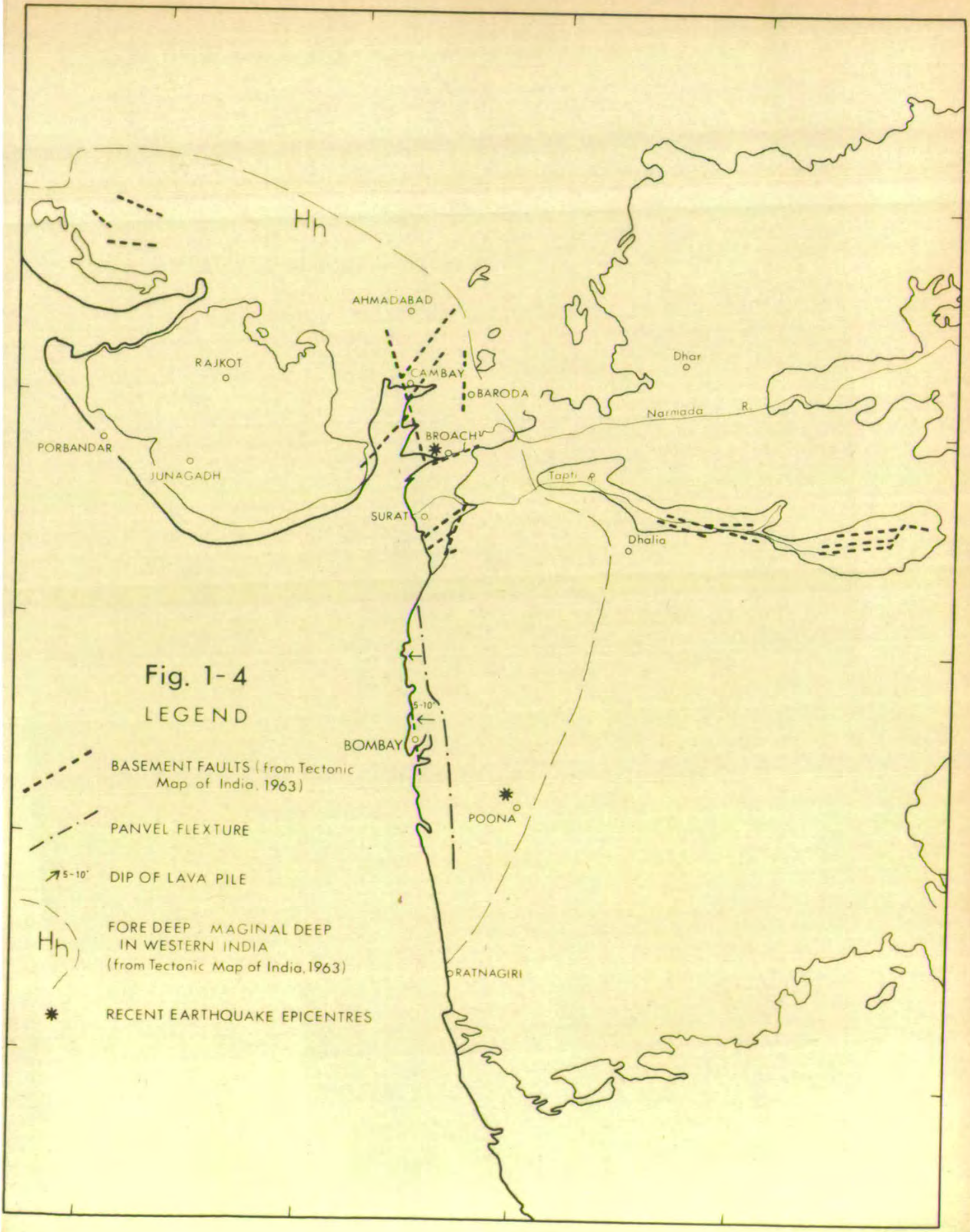


Fig. 1-4

LEGEND
BASEMENT FAULTS (from Tectonic Map of India, 1963)
PANVEL FLEXTURE
5-10° DIP OF LAVA PILE
Hh FORE DEEP . MAGINAL DEEP IN WESTERN INDIA (from Tectonic Map of India, 1963)
RECENT EARTHQUAKE EPICENTRES
Hh
AHMADABAD
RAJKOT
CAMBAY
BARODA
Dhar
Narmada R.
PORBANDAR
BROACH
JUNAGADH
Tapti R
SURAT
Dhalia
5-10°
BOMBAY
POONA
RATNAGIRI

Table 1-1

Locality No.	Name of the Locality	Rock types	References
1	Mandlesar	Minor flows/dykes/ of trachyte, felsite, rhyolite, obsidian, or pitchstone.	Blanford (1869); Bose (1884); Fedden (1884); Krishnan (1925); Dave (1969).
2	Barwani		
3	Dei		
11	Nagnesh		
13	Sihor		
14	Dedan-Rajula		
16	Osham-hills		
4	Ambadongar-Kawant-Panwad	Carbonatite-nephelinite; syenites, trachytes.	Sukeshwala & Udas (1964); Subramaniam & Parimoo (1964).
5	Phenaimata	Layered gabbro, granophyre; nepheline syenite; pseudo-leucite bearing tinguaite dykes.	Sukeshwala & Sethna (1967); Sukeshwala & Sethna (1964).
12	Chogat-Chamadri	Felsite-granophyre-pitchstone.	Fedden (1884); Sinor (1927).
15	Mount Girnar	Olivine-gabbro, diorite, monzonite; Granophyre ring dykes.	Krishnan (1925); Mathur <u>et al</u>.(1926); Subba Rao (1964;1968).
19	Bombay-Bassein	Granophyre-diorite; Rhyolite.	Sukeshwala & Sethna (1962).
6	Rajpipla	Tholeiitic flows; Ankaramitic basalts-alkali basalts-trachybasalts-oligoclase basalts-trachyte potassic rhyolite. Post lava tholeiitic dolerite dykes.	Krishnamurthy (1969); Present work.
7	Pawagarh	Alkalic and tholeiitic basalt flows; Picritic flows; Rhyolite, pitchstone and delenite flows also present.	Fermor (1906); Chatterjee (1961); Sharma (1963); Tiwari (1969).
17	Barda hills	Granophyre felsite, rhyolite & obsidian.	Fedden (1884); Adye (1914); Dave (1969).
18	Keetool hills Cutch.	Analcitised nephelite basalt. Alkali olivine basalts and their differentiates.	Bowen (1927); De (1969).
8	Wadhwan Junction	Picrite basalts (oceanites and ankaramites), three phenocryst basalts and basalts.	West (1958); Present work.
9	Dhandhuka		
10	Botad		
20	Igatpuri	Basalts, oceanites and ankaramites.	Mishra (1969).

from this region.

The two linear belts constitute about one third of the total area and include

a) The ENE-WSW-trending Normada region, stretching from about 22°10'N: 76°00'E in the east to Broach on the west coast, and further west into the Kathiawar peninsula.

b) a N-S-trending belt extending from south of Bombay to Broach in the north, where it intersects the ENE-WSW belt.

The geological features contributing to the diversity of these two regions include the following:

1. The basalt pile attains its maximum thickness in western India. The exposed thickness, above sea-level or local plain level approaches about 4000' at Mahabaleshwar (Fox, 1926), 2200' at Igatpuri (Mishra, 1969), and 2000' at Pawagarh (Fermor, 1906), while bore-hole samples in the Bombay-Kathiawar region have revealed that the flows extend to as much as 1700' below sea level, e.g. 1688' at Dhandhuka (West, 1958; present work).

2. The lava pile along the west coast shows a steady westerly dip of up to 16° (Pascoe, 1964).

3. Flows of simple and compound types occur in the area (Walker, 1969).

4. Flows of tholeiitic, high-alumina and alkali-olivine basalt types occur in fairly close succession (various workers).

5. Known centres of volcanic, sub-volcanic and plutonic complexes from the Deccan basalt plateau are confined to these two belts (Fig. 1-3).

6. Pyroclastic debris are prevalent locally in certain areas.

7. Spilitic pillow lavas in certain localities (Bombay Coast and Normada region) indicate a sub-aqueous eruptive environment in contrast with the predominant sub-aerial types of eruptions of the main Deccan areas.

8. Dyke swarms and clusters groupable into two broad regional directions are present, i.e. north-south and east-west, with local radial patterns around plutonic or volcanic centres (Auden, 1949), as shown in figure 1-3.

9. Rock types of extreme diversity have been found to occur in these two regions. For example: analcitised-nepheline basalt from Ketol (Bowen, 1927); carbonatite and nephelinite from Amba Dongar (Sukeshwala and Udas, 1963); alkali basalts and their variants (Krishnan, 1925; Chaterjee, 1964; Krishnamurthy, 1969); picrite basalts from bore holes (West, 1958; and present work) as well as surface outcrops (Mishra, 1969). Known occurrences of acidic and alkaline rocks have been summarised by Subba Rao (1969). Some of the important occurrences are shown in figure 1-2.

10. Monoclinal flexuring along the west coast and broad gentle anticlinal warping along the Narmada region are present (Tectonic map of India, 1963; Blandford, 1869). (see figure 1-4).

11. Faults in the basement, trending mainly in two directions, namely ENE-WSW and NNW-SSE have been noticed (Tectonic Map of India, 1963) (see figure 1-4).

12. Recent earthquakes have occurred at Broach (1970) and Koyna (1967) (Gupta *et al.*, 1971). (see figure 1-4).

13. Rather high heat flow have been recorded in the western margin of the basalt plateau, i.e. ~ 20.3 ± 3 cal/cm^2 sec (Upper Mantle Project, Indian Report, 1966).

14. Local positive gravity anomaly, changing to negative anomaly with steep "anomaly gradient" (4 milligals/mile) have been found to be present. (Glennie, 1932).

The main object of the research was to study the basalts and associated rock types from several localities, from a petrological and chemical viewpoint, bearing in mind the above mentioned peculiarities of the Deccan basalt sequence in western India.

The following localities have been included in the present study and their locations shown in figure 1-1.

1. Western portions of the Rajpipla hills, Broach district, Gujarat state (73°15' - 73°20'E: 21°40'-21°45'N).
2. Bore hole samples from Botad, Wadhwan Jn. and Dhandhuka, Gujarat state.
3. Sundry localities such as Amba Dongar, Pawagarh and Dedan.

1:1 Collections of samples:-

a) Bore-Hole Samples:-

Portions of the bore-hole samples for the present study were kindly provided from the National Geological Museum at Calcutta, by the Director, Geological Survey of India, as a result of a request by Prof. West, who had collected the samples earlier. Prof. West also gave the field notebooks, and the entire thin section collection for the present study.

b) Rajpipla area and other localities:-

Samples from the Rajpipla area and other localities were mainly collected by the author between 1967-1970. A few samples were provided by the author's colleagues at the University of Saugor, and some came from the Departmental Collections of the Saugor University.

1:2 Previous work:-

a) Rajpipla area:

Blandford (1869, p.132) and Bose (1909, p.123) mention the variable dip of the porphyritic basalts, ENE-WSW trending dykes and possible trachytic plugs, from this region. Auden (1949) briefly mentioned the dykes of the area and their spatial relation to the trachytic plugs. Gani (1966) gave a petrographic account of one of the trachytic plugs and classified the rock as sanidine-trachyte. Petrographic and chemical data of the flows were non-existent. The present author studied and mapped the area during 1967-70 and the results of the study (Ph.D. thesis in preparation to be submitted to the Saugor University) are briefly summarised as follows:

1. An alternation of tholeiitic and alkalic basalt eruptions occurs in the Rajpipla area.
2. The lowest flows (which at places exposes Cretaceous inliers, and thus are possibly basal flows) are tholeiitic and are overlain and cut by alkali basalts and their variants, comprising ankaramitic basalts, alkali basalts, trachybasalts, oligoclase basalts, trachyte and potash rhyolites. Tholeiitic dolerite dykes, with mainly a ENE-WSW-trend, intrude both the earlier suites, and thus represent

Table 1-2. Mineralogical summary of the bore hole flows compared with the common Deccan basalt flows (after West, 1958, p.31, Table 12)

	Bore hole flows			Central India
	Picrite basalts	Three-phenocryst basalts	Basalts	Flows
<u>Phenocrysts</u>:-				
Olivine	FO_{80-94}	FO_{71-82}	Altered	Altered*
Pyroxene	$2V = 53^\circ-59^\circ$	$2V = 54^\circ-58^\circ$	Uncommon $2V = 50^\circ-54^\circ$	Rare
Feldspar	Absent	An_{70-89}	An_{61-69}	An_{55-65}
<u>Groundmass</u>:-				
Felspar	An_{60-76}	An_{62-76}	An_{54-60}	An_{45-55}
Pyroxene	$2V = 49^\circ-58^\circ$	$2V = 50^\circ-56^\circ$	$2V = 44^\circ-53^\circ$	
Olivine	FO_{67-76}	Occasional altered	Altered	FO_{54-68}*

* It is not always easy to decide whether the olivine crystals of these flows were of intra-telluric origin or belong to the groundmass.

the youngest group of rocks in the area.

3. Minerals of economic importance such as fluorite have been brought to light (Udas & Krishnamurthy, 1968).

b) Bore hole samples:-

The bore hole samples comprise picritic flows in association with three-phenocryst basalt and normal basalt types. The samples from the three bore holes were collected during 1924-26 while drilling for water by the Geological Survey of India. A brief account of the samples was given in the Director's General Report of the Geological Survey of India for 1931 (Fermor, 1933). Subsequently, the bore hole samples were the subject of a detailed petrographic and limited chemical study by West (1958) who reported 8 new rock analyses, and 3 partial analyses of minerals. Apart from the excellent petrographic and minerologic account of the bore hole samples, West (op.cit.) also gave a summary of the then existing details of mineralogy and chemistry of the Deccan basalts. Table No. 1-2 indicates clearly the mineralogical difference between the bore-hole samples and the common Deccan basalt. An additional point noted by West (op.cit.) was that the picrite basalts and the three-phenocryst basalts were the earliest to erupt.

West assumed the common Deccan basalt, i.e. a silica-saturated, quartz-normative tholeiite as the parental magma for the bore hole basalts. Since, the difference in mineralogy between the picrite and three-phenocryst basalts and the common Deccan basalt precludes the possibility of the former being derived from the latter through a simple cumulus enrichment/crystal sinking model, West (op.cit.)

postulated an elaborate scheme for the origin of the bore hole basalts, as outlined below.

A long time before the eruption of the traps, a large magma reservoir containing liquid or partly liquid melt of tholeiitic composition was envisaged by West (op.cit.); differentiation by crystal settling of olivines, clinopyroxenes and plagioclases ensued, and during sinking, the crystals might or might not have been redissolved in the superheated portions of the chamber. Since the picrite and three-phenocryst basalts were erupted first, which they could not have been, had the chamber been tapped from the top downwards, West proposed that the entire mass solidified, and subsequently during the late Cretaceous or early Tertiary times, remelted. Thus rocks of varying composition corresponding to the picrite basalts and the three-phenocryst basalts were already available.

1:3 Need for a re-study:-

West postulated such a scheme of evolution based largely on "space" and "time", which had a considerable influence on the then existing concepts of parental or primary magmas. However, in the light of studies carried out subsequently on basalt genesis and evolution, both in the laboratory and in other flood basalt provinces, a reconsideration of the question of the parental magma and the origin of the bore hole basalts has become necessary.

Recent experimental work [O'Hara (1965); O'Hara & Yoder (1967); Ito & Kennedy (1967); Green & Ringwood (1967)] have shown that the initial partial melt from probable upper-mantle compositions, under simulated upper mantle conditions is "picritic" in character, and the picrite basalts at hand could be of such an origin. However, the picritic character of a rock could also result from near-surface enrichment of olivine and pyroxene by gravitative accumulation from normal basaltic (<u>but with similar mineralogy</u>) magmas as in the case of Hawaiian picrites (Macdonald, 1949; Muir & Tilley, 1957; Powers, 1955; Murata & Richter, 1966).

Furthermore, picritic magmas have been postulated as possible parents in other flood basalt areas such as Baffin Bay, West Greenland (Clarke, 1970) and Karroo (Cox <u>et al</u>., 1965; Jamieson, 1969). Therefore, a re-study of the bore hole flows has been undertaken.

Additional reasons for pursuing such a study are as follows:

1. One of the bore holes (Dhandhuka) provides the opportunity of studying a thick sequence of the basalt pile (≃ 1300') including the <u>base</u> of the succession. It is rare elsewhere in Western India to find a basalt sequence with <u>the basal</u> flows. The nature of the volcanic products/flows at the commencement of a volcanic cycle and the significance of such products in understanding the regional evolutionary scheme of a particular volcanic cycle has recently been emphasized with regard to the Karroo volcanic cycle (Cox, 1972). Such a study of the bore hole sequence, along with other areas where the basal flows are exposed (as at Pawagargh) could throw some light on the early evolution of the Deccan Volcanic cycle.

2. Bore hole samples provide a convenient opportunity of studying either a single flow or a series of flows in one place across their thickness. Such a study is usually substantially more difficult

in the field.

1:4 Present Work:-

a) Bore hole samples:

A total of 38 new bore hole samples have been analysed for major oxides and the trace elements Ba, Zr, Y, La, Ce, Rb, Sr, Nb, Zr, Cu, Ni, Cr and V.

About 100 partial or nearly complete analyses of minerals such as olivines, clinopyroxenes, plagioclases and ore minerals have been determined by electron probe micro-analyser.

Atmospheric pressure melting studies under Ni/NiO buffer have been carried out on 12 of the bore hole samples.

Modal data has been obtained for 220 thin-sections, in order to study the variation in the amounts of minerals within and between flows.

b) Rajpipla area:-

The main aim with regard to the Rajpipla area was to understand the mechanism of differentiation scheme postulated from earlier studies (Krishnamurthy, 1969, and Ph.D. thesis in preparation). No trace element data, and only a few major oxides analyses were available previously. In the present study all the available lava flows were analysed for major oxides and trace elements as with the bore hole samples. Apart from the analyses of whole rocks, major and trace element studies were conducted on

a) separated groundmasses, and

b) separated phenocrysts of clinopyroxene and plagioclase phenocrysts in order to study the partioning of elements betwemn the different phases during the evolution of the alkaline series.

Two alkali basalts and 4 tholeiitic basalts of the area have also been studied under atmospheric pressure melting conditions using the Ni/NiO buffer.

It is hoped that such studies cast some light on the evolution of the alkaline series, as well as the relations between the alkaline and tholeiitic basalts.

On the more general scale, however, the present studies from these localities in western India, may also have some bearing on the origin and evolution of basic magmas in general, with particular reference to the evolution of the Deccan basalts themselves.

1:5 Plan of the thesis:-

The text comprises the presentation of the data, the interpretation and discussion of the data and conclusions.

Since the localities studies include different areas, they have been dealt with in separate parts. The first part deals with the bore hole samples while the second details the Rajpipla area. Studies carried out on samples from other localities are incorporated in part three.

Brief methods of sample preparation and analytical techniques used are given in Appendix A. Descriptions of the analysed specimens, are given in Appendix B.

PART I

CHAPTER II

PETROGRAPHY

INTRODUCTION

Petrographic details of the bore hole flows, their modal data and their classification are considered in this chapter.

Sections of the three bore holes are given in Fig. 2-1. Individual thickness of the flows, their nature, and intervening beds, if any, are also indicated.

A total of 48 flows have been identified from the three bore holes, using several criteria (either individually or collectively) such as the type of rock, vesicularity, and brick red coloration or red bole indicating a break in the succession (West, 1958, p. 6).

The flows of the bore holes are all porphyritic to varying degrees, the common phenocrysts being olivine, clinopyroxene and plagioclase.

Modal data on the phenocrysts for some 220 samples, covering practically the entire length of the volcanic column have been collected during the present study and is considered in a later part of the present chapter.

2:1 Classification of the Bore Hole Flows:-

The main aim of classification in the present case is to group the bore hole flows into alkalic, tholeiitic or transitional types so that rock names used in the descriptions become more meaningful. Such an attempt has not been made previously. However, it must be stressed that classification attempts to group rocks,

SECTION OF THE BORE HOLES

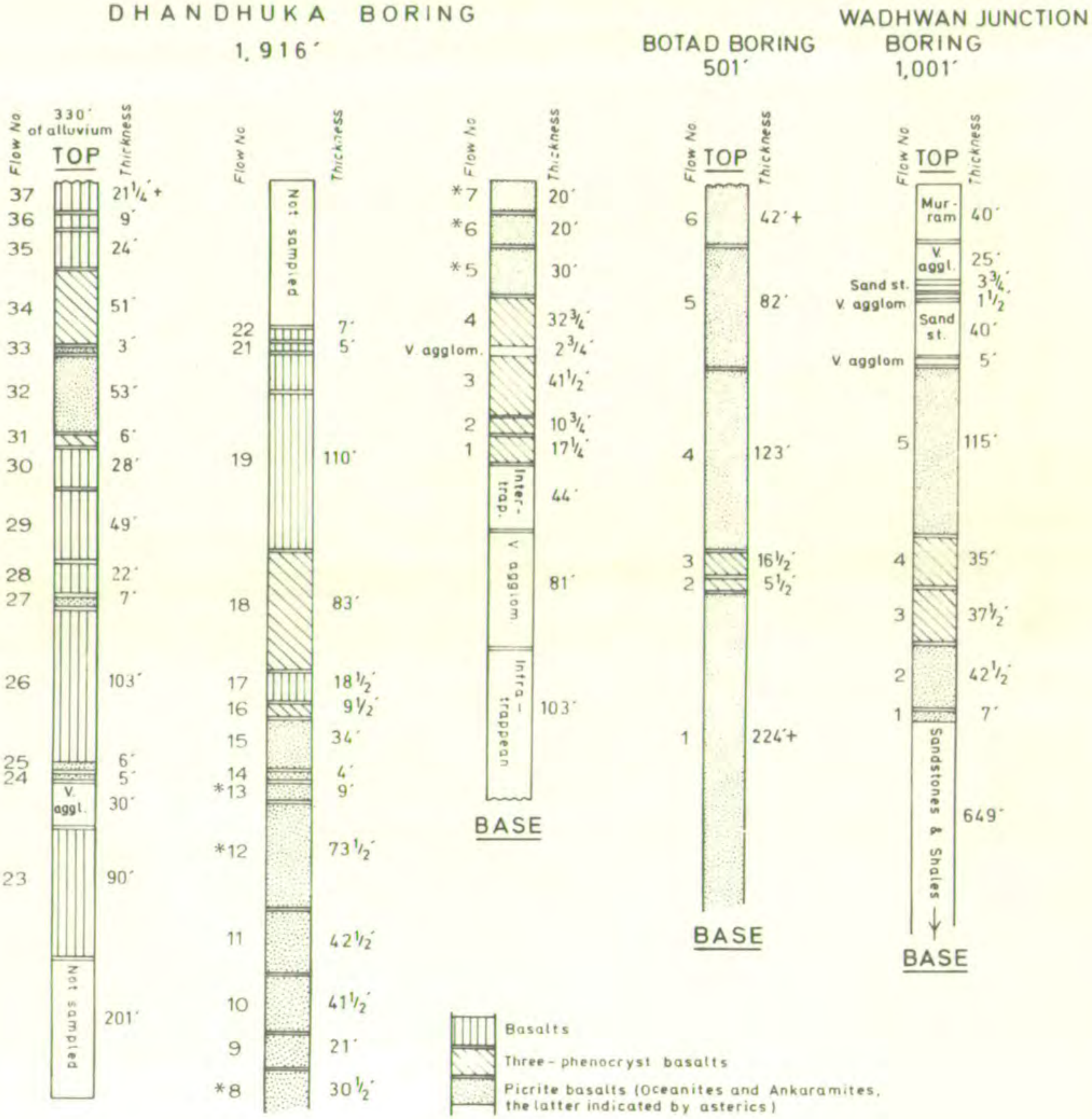


Fig. 2-1

which in reality represent a natural spectrum of compositions, and therefore, has its inherent flaws.

Several criteria have been proposed in the classification of basaltic rocks (Wilkinson, 1967) though only some of them are effective. In the present case, three important criteria, such as the nature and amount of modal minerals (Table 2-2), the amount of total alkalies in relation to the amount of silica (Fig. 2-2), and normative minerals, have been used.

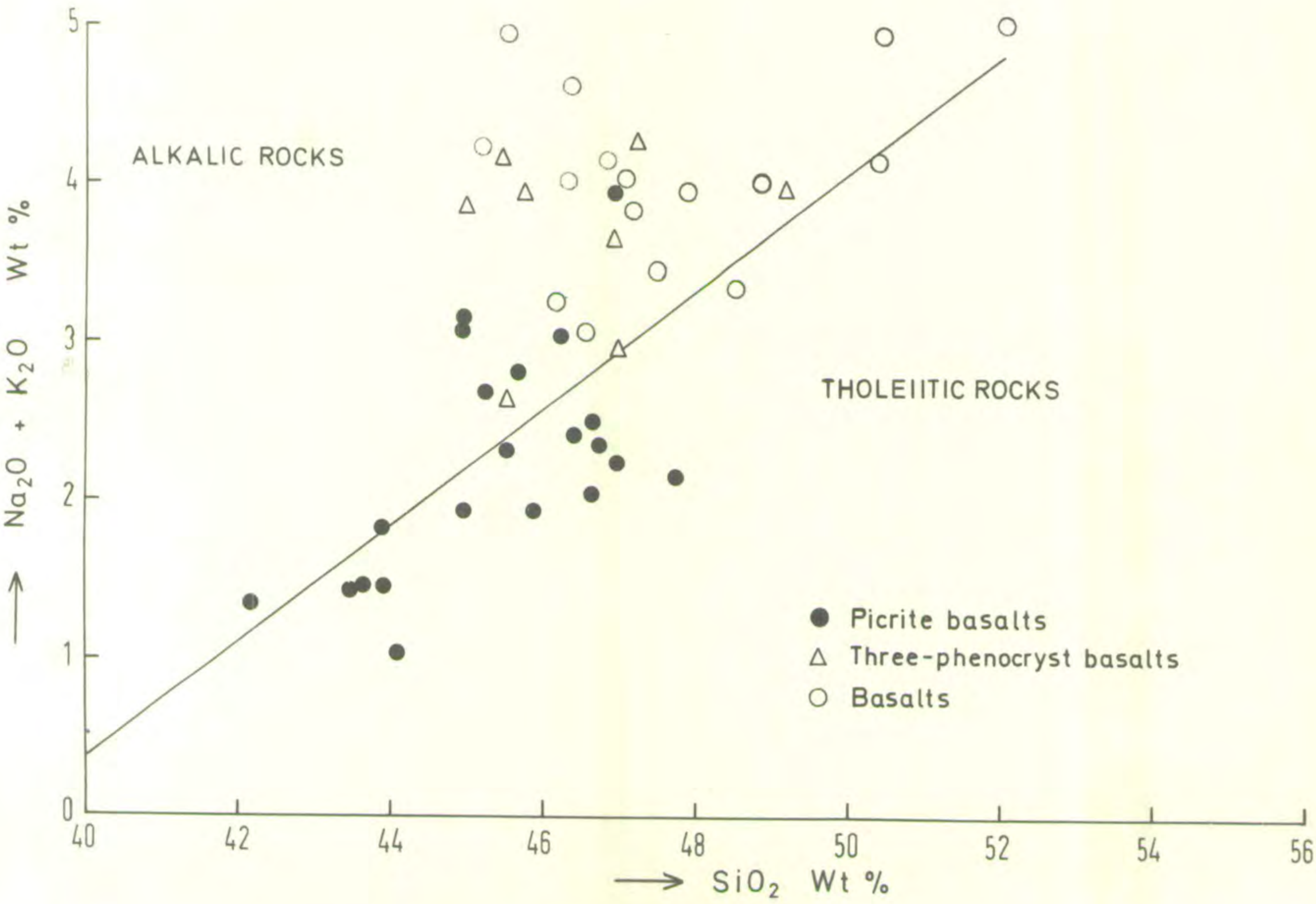
a) Modal mineralogy:

Positive mineralogical criteria, such as the presence of fairly uniform clinopyroxene (i.e. diopside-diopsidic augite) and olivines of two generations (both as phenocrysts and in the groundmass)(Wilkinson, 1967) appear to suggest that the bore hole suite is alkalic in nature. Negative mineralogic criteria include the absence of hypersthene or pigeonite in the mode.

b) Total alkalis Vs silica:

In the simple total alkalies Vs silica plot (Fig. 2-2), using the Hawaiian boundary line for separating the tholeiitic and alkali basalts, the flows sampled in the bore-hole show intergradation. As one progresses from the more basic picrite basalts to the less basic basalts, the plotted compositions grade from the tholeiitic field to the alkaline field, suggesting a transitional chemical character. Between $\simeq$ 45-48% of SiO_2, the total alkalies range from $\simeq$2-4%.

Fig. 2-2: Plot of total alkalies (wt.% $Na_2O + K_2O$) vs. wt.% SiO_2 for the bore hole flows. The boundary line separating the alkalic rocks from tholeiitic types is taken from Macdonald and Katsura (1964, Fig. 1).



ALKALIC ROCKS
THOLEIITIC ROCKS
→ $Na_2O + K_2O$ Wt %
→ SiO_2 Wt %
0
1
2
3
4
5
40
42
44
46
48
50
52
54
56
● Picrite basalts
△ Three-phenocryst basalts
○ Basalts

Fig. 2-2

c) Normative minerals:

The transitional chemical character of the flows is further supported by a consideration of the normative minerals Ol, Cpx, Opx, Ne and Qz, in the simple Fe- and K-free basalt system, represented by Di-Fo-Ne-Qz (Yoder & Tilley, 1962). Two points have to be kept in mind while using such a diagram.

1. Since it is norm based, factors such as oxidation state of rocks and post magmatic alteration affect the presence, absence or abundance of minerals (especially Ol, Hy, Qz and Ne) and, therefore, the position of the plotted points.

2. The treatment is restricted to rocks of basaltic compositions (i.e. those with > 80% normative basalt components in the simple basalt system).

Fig. 2-3a and 3b are projections from plagioclase onto the Qz-Di-Ol and Ne-Di-Ol planes, looking down across the critical plane of silica undersaturation (Ol-Di-Pl) and the critical plane of silica oversaturation (Pl-Di-Hy).

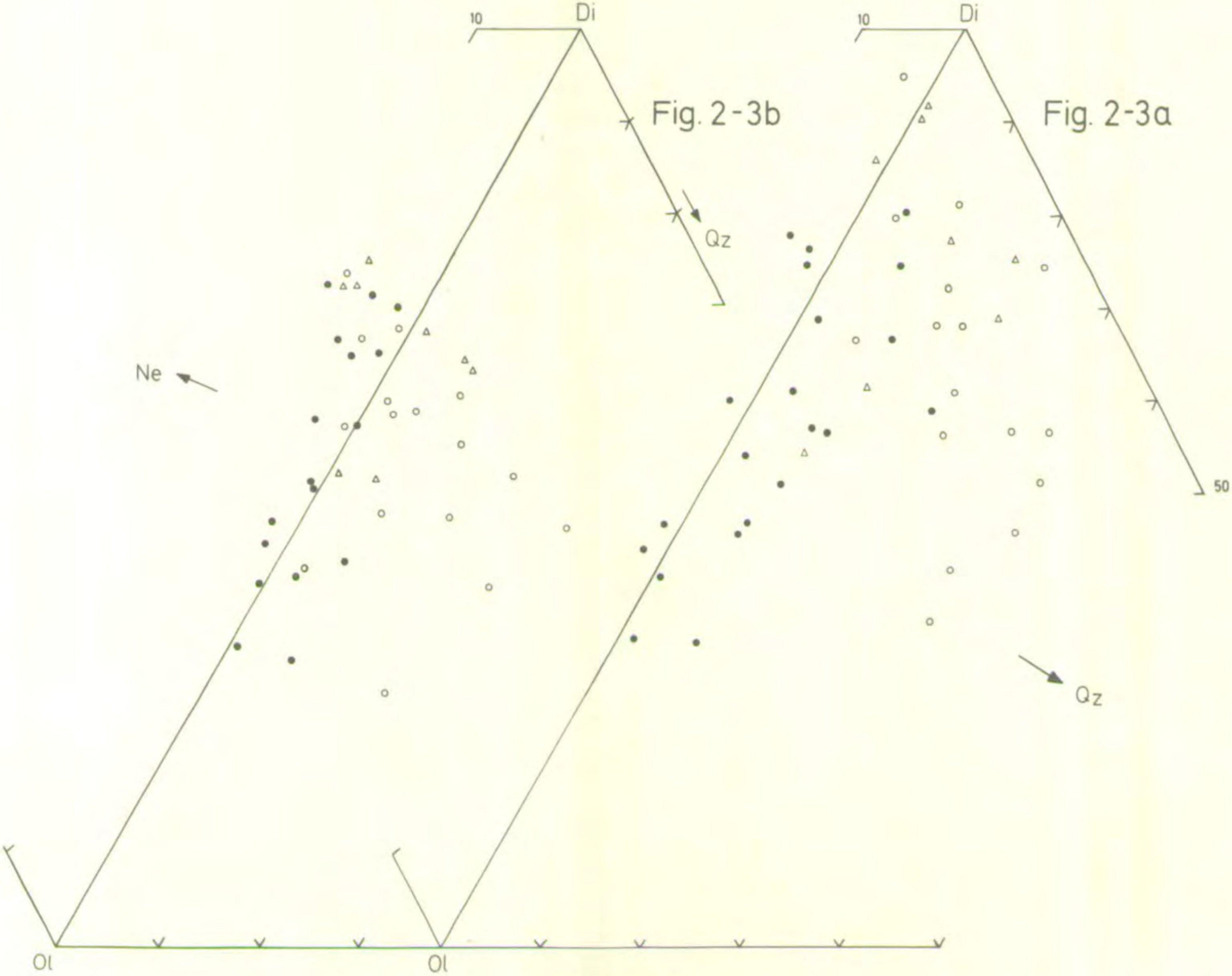
Normalisation of FeO:Fe_2O_3 of the analyses:

The high and widely varying $Fe_2O_3 \times 100/FeO + Fe_2O_3$ ratios (10-69%) appear to be the result of the altered olivines in all the basalts and in some picrite basalts and the alteration of groundmass glass or minerals. Therefore, it was found necessary to normalise the $Fe_2O_3 \times 100/Fe_2O_3 + FeO$ values to 15% in most of the flows, this being the ratio given by some of the freshest samples (No. 129 and 274, see Table 4-2). In these samples the olivines are fairly fresh and groundmass not much altered. Such a normalisation of

Fig. 2-3a: Normative plot (in wt.%). Plagioclase projection onto Ol-Cpx-Qz and Ol-Cpx-Ne, *before* standardising the Fe_2O_3:FeO ratio.

Fig. 2-3b: Same as above *but* after standardising the Fe_2O_3:FeO ratio to give 15% of Fe_2O_3/FeO + Fe_2O_3.

Symbols as in Fig. 2-2.



Wt % PLOT

the Fe_2O_3:FeO, serves the useful function of achieving internal consistency, when considering closely related flows (Coombs, 1963).

As can be seen from Fig. 2-3a and 3b, the recalculation does not greatly affect the normative character of the suite as a whole, and the following three types can be recognised both prior to (Fig. 2-3a) and after (Fig. 2-3b) recalculation, even though the number of flows belonging to each type might vary as shown on Table 2-1.

1. Alkali basalts: Ol + Ne normative
2. Olivine tholeiites (undersaturated): Ol + Hy normative
3. Tholeiites (oversaturated): Hy + Qz normative.

The plotted compositions thus straddle the critical plane of silica-undersaturation, i.e. the Ol-Di-Pl plane (or the olivine-gabbro divide) which is a thermal barrier at low pressures (up to 8 Kb) (Yoder and Tilley, 1962, Fig. 2). Several possibilities exist, as to the crossing of the divide in natural compositions, and these will be taken up in the chapter on petrogenesis. However, it is possible to say from the normative mineral characters, of the bore hole flows, (Table 2-1) that they belong to what has been termed the transitional or mildly alkaline group of basalts, such as found in The Red Sea (Gass et al., 1973) Reunion (Upton and Wadsworth, 1972), Skye (Thompson, et al., 1972), Mauritius (Baxter, 1973) etc.

2:2 Nomenclature:

The nomenclature of the flows adopted here is essentially similar to the one followed by West (1958). However, additional

Table 2-1

Normative classification of the analysed bore hole flows:

	Number of flows	
Rock type	Prior to normalisation of FeO: Fe_2O_3 % Ne. in brackets.	After the normalisation of FeO: Fe_2O_3 to give 15% of $\frac{Fe_2O_3 \times 100}{FeO + Fe_2O_3}$ % Ne in brackets
1. Alkali basalts: Ol + Ne normative	9 (up to 3.8%)	17 (up to 5.9%) averages 1.9%
2. Olivine tholeiites: Ol + Hy normative	14	17
3. Tholeiites: Hy + Qz normative	16	5

mineralogical and chemical data, obtained during the present work, have been used to effect some modifications in the scheme adopted earlier.

Two main rock groups have been distinguished. They are:

1. Picritic or Picrite basalts (with >10% MgO) with varying amounts of olivine (up to 38% by volume) and clinopyroxene (up to 22%) phenocrysts, together with groundmass olivine, clinopyroxene, plagioclase and ore.
2. Basalts with phenocrysts of olivine, clinopyroxene and plagioclase in a groundmass containing these three minerals along with ore.

2:3 Picrite Basalts:

The picrite basalts have further been subdivided on the basis of the domination of olivine or clinopyroxene phenocrysts. Two main types have been identified on the basis of the amounts of modal olivine and clinopyroxene.

1. Oceanites: those in which Ol > Cpx either with groundmass plagioclase or lacking groundmass plagioclase
2. Ankaramites: those in which Cpx > Ol.

Though such a grouping is convenient from a nomenclature viewpoint, gradational types occur between the two.

The term limburgite, used earlier by West (1958) to describe some of the very strongly porphyritic oceanites lacking groundmass plagioclase, has been discontinued for the following reasons:

1. The rocks so termed lack the strongly undersaturated character of the limburgites proper (Troeger, 1935; Wilkinson,

1967, p. 207) and

2. The rocks are very rich in MgO content (20-24%), when compared to the 8-16% range of MgO values quoted for such rocks from the literature, and

3. The commonly used textural criteria that limburgites are composed of phenocrysts of olivine and/or clinopyroxene enclosed in a predominantly dark brown glassy matrix is lacking for the flows at hand.

2:4 Basalts:

With regard to the basalts, two main types have been recognised:

1. Three-phenocyrst basalts: Flows with phenocrysts of olivine (up to 5.4%), clinopyroxene (up to 8.4%) and plagioclase (up to 21.3%) and where the plagioclase phenocrysts are [illegible] more calcic than An_{70}.

2. Normal basalts: Flows with phenocrysts of dominant plagioclase (up to 32%), olivine (up to 8%) and scarcer clinopyroxene (up to 4%), and where the plagioclase phenocrysts are labradorite An_{60-65}. However, occasionally flows with clumps containing plagioclases of An_{80-88} have been found as shown in the petrographic remarks (Table 2-3).

The entire classification scheme, along with the number of flows in each type are shown in Table 2-2.

2:5 Petrography:

Generalised petrographic summary of the three group of flows and detailed petrographic account of each of the 48 flows have

Table 2-2

Summary of the classification scheme for the bore hole flows

Main types	Sub-types based on modal mineralogy and chemistry	Main features Modal minerals	Total No. of flows	No. of flows analysed	No. of alkali basalt flows*	No. of olivine-tholeiite flows*	No. of tholeiite flows*
Basalts <8% MgO	Normal basalts >3% MgO <5.5% MgO	Dominant phenocrysts of plagioclase with labradorite composition An_{60-65}; minor amounts of olivine and scarce clinopyroxene	16	14^a	4	5	5
	Three-phenocryst basalts <8% MgO >5% MgO	phenocrysts of plagioclase of bytownitic composition along with olivine and clinopyroxene	12	7^b	3	4	-
Picrite basalts ≥ 10% MgO	Ankaramites	Cpx > olivine with groundmass plagioclase. Modal amounts of Cpx:Ol range from 14:12 to 3:1 in volume %	7	6^c	3	3	-
	Oceanites	Ol > Cpx, either with or lacking groundmass plagioclase. Modal amounts of Ol:Cpx range from 38:10 to 2:1 in volume %	13	12^d	7	5	-

a = 2 duplicates b = 1 duplicate * based on post-normalisation norms.

c = 1 duplicate d = 2 duplicates

already been given by West (1958) and therefore, is not duplicated here. Instead a petrographic summary is given in Table 2-3. The composition of the minerals indicated in the table, however, have been determined by electron microprobe analyses during the present work. Brief petrographic descriptions of the analysed flows are given in Appendix B, Table B-1.

2:6 Modal variations of the phenocrystal minerals in the flows:

Modal data for all the flows was not available from the previous work, and has been collected during the present study, and is briefly considered in this section. The collected data are illustrated in Figs. 2-4a, -4b and -4c. The following features can be observed from the modal data:

1. In general the majority of the flows are fairly uniform with regard to the distribution of the phenocryst minerals.
2. In certain thicker picrite basalt flows (such as No. 7, 11 and 12 from Dhandhuka and No.5 from Botad) there is a tendency for the central portions of the flows to be richer in phenocrysts relative to the top and bottom parts of the flow. Such a feature may be related to the slow cooling of the former compared with the latter after eruption.
3. There is a tendency in some thicker three-phenocryst basalt and basalt flows (such as No. 20, 28 and 37 at Dhandhuka and No. 3 at Wadhwan Junction) for the upper parts to be richer in phenocrysts of plagioclase feldspars when compared with lower portions.
4. Ore phases may be conspicuous as microphenocrysts in certain three-phenocryst basalts and picrite basalts (as in flows No. 3 and

Table 2-3

Petrographic Summary of the Bore Hole Flows.

Main types	Sub-types	Petrographic features	Remarks	Range in flow thickness in feet	Total No. of flows
Basalts	Normal Basalts	Gray to grayish black, porphyritic, with total phenocrysts up to 35%; average specific gravity of non-vesicular flow ≃ 2.85; Phenocrysts: Dominantly of plagioclase (An_{65-55} up to 32%) occurring up to 1cm. in length but averaging 2 mm; minor amounts of altered olivine (up to 7%) up to 2 mm, averaging 0.5 mm, and clinopyroxene ($Ca_{44-40}Mg_{45-43}Fe_{17-11}$; up to 4%)(Plate 2-1). Groundmass: Fine grained (≃0.1 mm.) comprising dominant plagioclase (An_{50-55}), minor altered olivine, clinopyroxene and titanomagnetite and ilmenite. Fresh or altered glass may be present as well as/or along with secondary minerals sparse needles of apatite in some flows, while phlogopite and kaersutitic amphibole may be present in the microvesicles and/or in the main groundmass of others.	Flows are confined only to the Dhandhuka bore, and occur upto a depth of 1248½ feet. Presence of clusters with bytownitic plagioclase (An_{88-80}) either alone/or with clinopyroxene has been seen in some flows (Plate 2-2).	3-100	16
	Three-phenocryst basalts	Grayish black in colour, and range from nearly aphyric to moderately porphyritic types with up to 30% total phenocrysts. They differ from the basalts (1) in containing plagioclases of bytownitic composition and (2) in the mode of occurrence of the phenocrystal minerals, which are invariably in clumps or clusters (Plate 2-3) Phenocrysts: Plagioclase (An_{88-70}; 1.5-21%) up to 6 mm. long, averaging 2 mm.; olivine (Fo_{86-84} ; 1-5%) up to 2 mm. long; clinopyroxene ($\sim Ca_{40}Mg_{43}Fe_{17}$; 0.5-8%) up to 7 mm., averaging 2 mm. Groundmass: Fine to medium grained (≃.15 mm) composed of plagioclase (An_{70-65}), altered olivine, clinopyroxene, ilmenite and titanomagnetite with intersertal to intergranular texture. Needles of apatite and plates of phlogopite are present in some flows; secondary minerals in vesicles.	Phenocrysts are mainly in clusters composed of either 1) plagioclase alone "anorthositic" or 2) with olivine and clinopyroxene "gabbroic" (Plate 2-4). Marginal corrosion and fairly complex zoning are common in these clusters (Plate 2-5). Grade into basalts and picrite basalts, with change of modal minerals.	5½-83	12

Table 2-3 (Contd.)

Main types	Sub-types	Petrographic features	Remarks	Range in flow thickness in feet	Total No. of flows
Picrite Basalts		Black, dense rocks (average specific gravity 3.1) which range from nearly aphyric (up to 3% total phenocrysts) to strongly porphyritic types with phenocrysts of yellowish-green to glassy olivine and pale clove brown clinopyroxene in varying sizes up to a maximum of 1 cm., averaging 2 to 5 mm. in length. Phenocrysts: Magnesian rich olivines Fo_{90-86}; 0.5 - 38%) and clinopyroxenes ($Ca_{46-43}Mg_{52-44}Fe_{11-5}$; 0.5 - 22%); scarce microphenocrysts (up to 2%) of chromite. Groundmass: Very fine to medium grained ($\simeq$ 0.15 mm) comprising plagioclase (An_{80-75}) olivine (Fo_{84-80}), clinopyroxene ($\sim Ca_{45}Mg_{40}Fe_{15}$) and titanomagnetite and ilmanite.	olivines are nearly fresh to moderately altered: **at times olivine** and clinopyroxene show what appears to be resorption features (Plate 2-**10)**. Olivines and clinopyroxenes occur in clumps in some flows (Plate 2-11	4-224	20
	Oceanites (Plate-6)	Petrographic features similar to above but in the mode Ol > Cpx. In some strongly porphyritic oceanites there is some scarcity of groundmass plagioclase (Plate 2-**9)**.	At times, clinopyroxene may show strong marginal zoning (Plate 2-8).		
	Ankaramites (Plate-7)	Petrographic features similar to the oceanites except for the fact that Cpx > Ol in the mode.	Gradational types are common when there is a paucity of phenocrysts.		

Plate:2-1

Specimen No. 41. Basalt

Phenocrysts of labradorite, in a groundmass of labradorite, clinopyroxene, iron ore and glass.

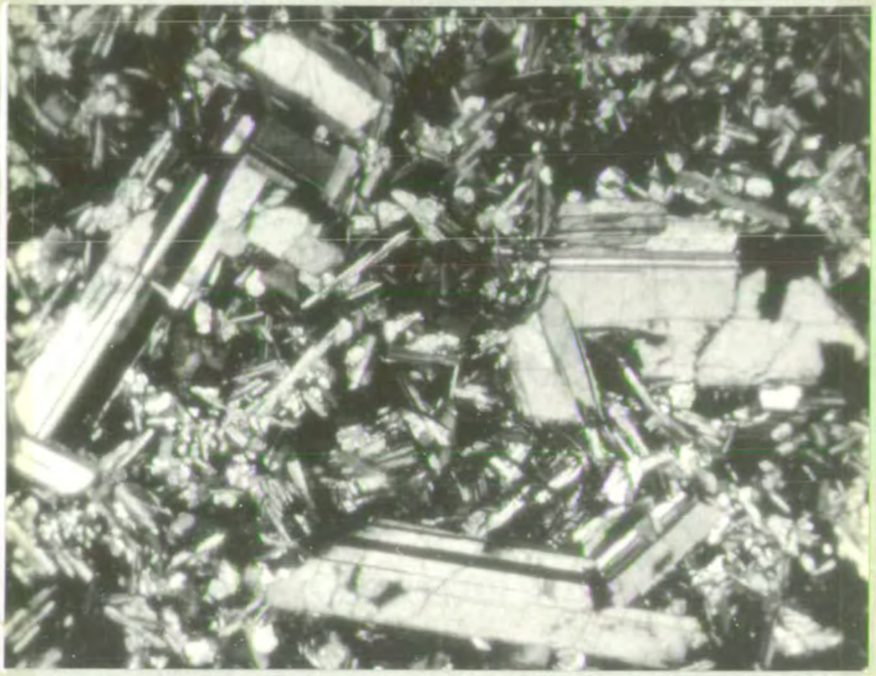
X 25 Crossed Nicols

Plate:2-2

Specimen No. 70. Basalt

A cluster of plagioclase of bytownitic composition

X 25 Crossed Nicols



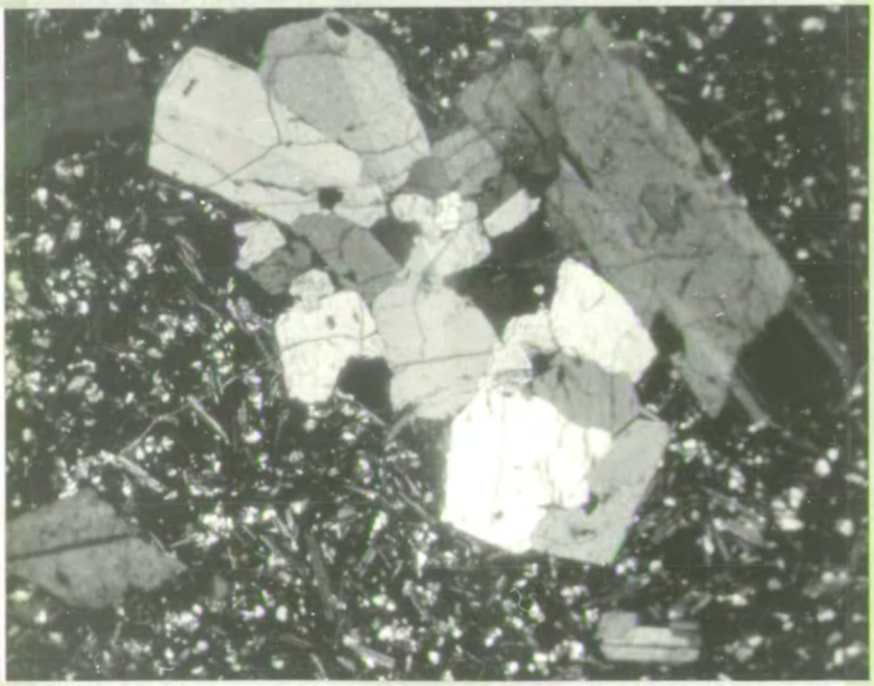


PLATE: 2-3

Specimen No. 384. Three-phenocryst basalt

A cluster composed mainly of plagioclase of bytownitic composition.

X 25 Crossed Nicols

PLATE: 2-4

Specimen No. 385 Three-phenocryst basalt

A cluster composed of clinopyroxene and plagioclase phenocrysts. Note the iddingsitised olivine phenocrysts at the top left hand side. Groundmass is mainly composed of microlites of labradorite, augite and ore.

X 25 Crossed Nicols

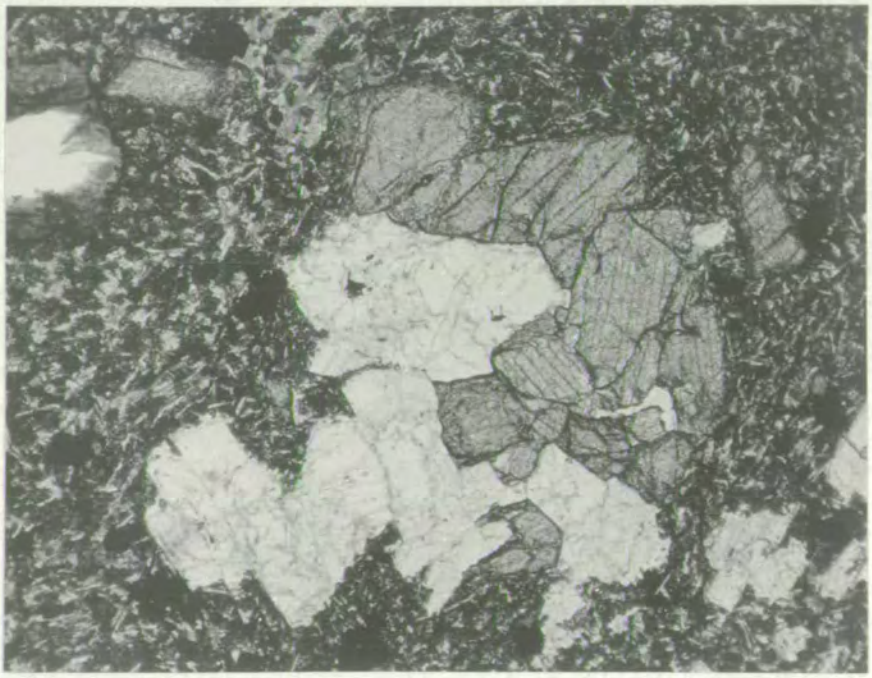


PLATE: 2-5

Specimen No. 384 Three-phenocryst basalt

Zoning in one of the plagioclase phenocrysts belonging to a cluster.

X 25 Crossed Nicols

PLATE: 2-6

Specimen No. 119 Oceanite

Euhedral to subhedral phenocrysts of olivine and clinopyroxene, in a groundmass of olivine, clinopyroxene, bytownite, titano-magnetite and scarce glass.

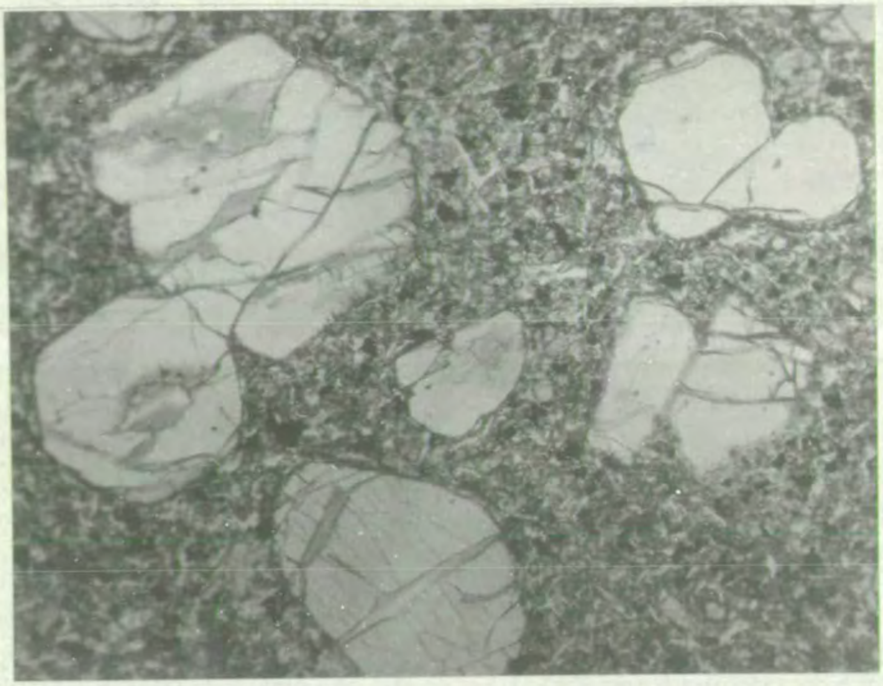
X 25 Plane polarised light.

PLATE: 2-7

Specimen No. 284 Ankaramite

Clinopyroxene phenocrysts predominating over the olivines. Part of a single phenocrystal olivine with an iddingsitised rim can be seen at the left hand side of the plate. Note also the feeble marginal zoning in the case of the clinopyroxene phenocrysts indicated by the slightly darker shades of the rims relative to the cores. Groundmass is mainly as in Plate 2-6.

X 25 Plane polarised light.



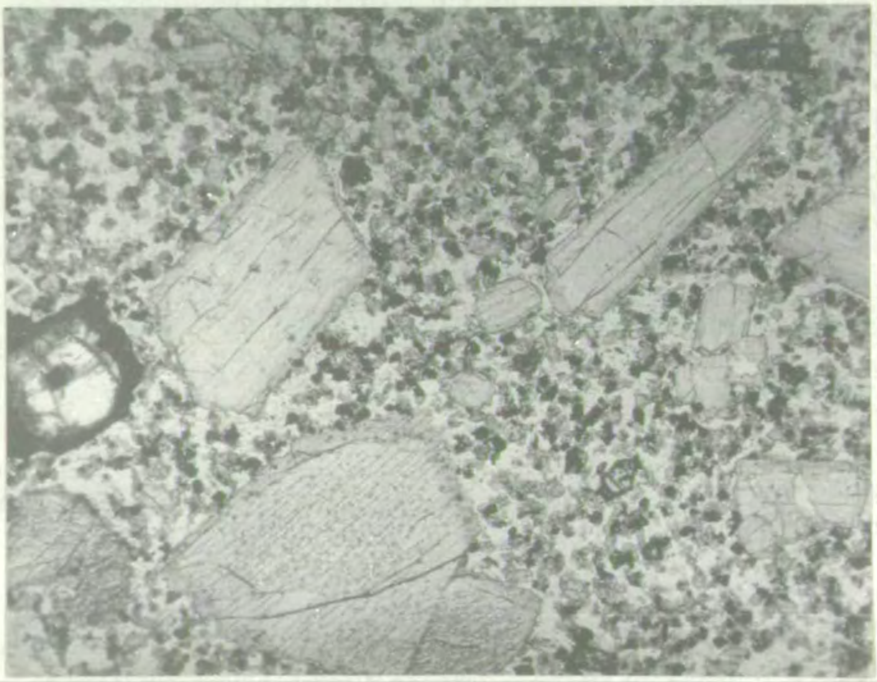


PLATE: 2-8

Specimen No. 246

Clinopyroxene phenocryst showing strong marginal zoning.

X 25 Crossed Nicols

PLATE: 2-9

Specimen No. 391 Oceanite lacking graoundmass plagioclase

The groundmass here is mainly composed of clinopyroxenes, ore and glass.

X 250 Plane polarised light.

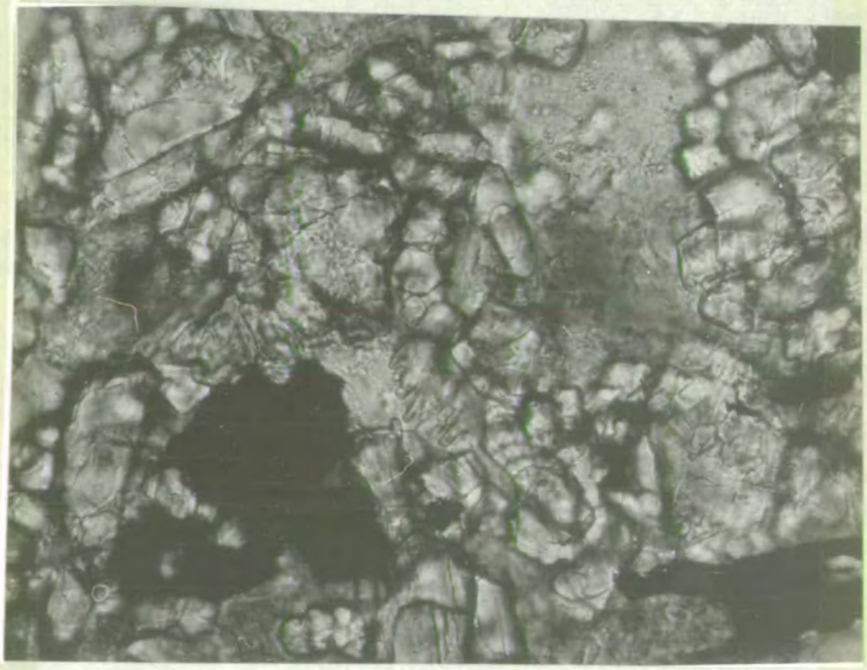


PLATE: 2-10

Specimen No. 381 Corroded olivine phenocryst in oceanite

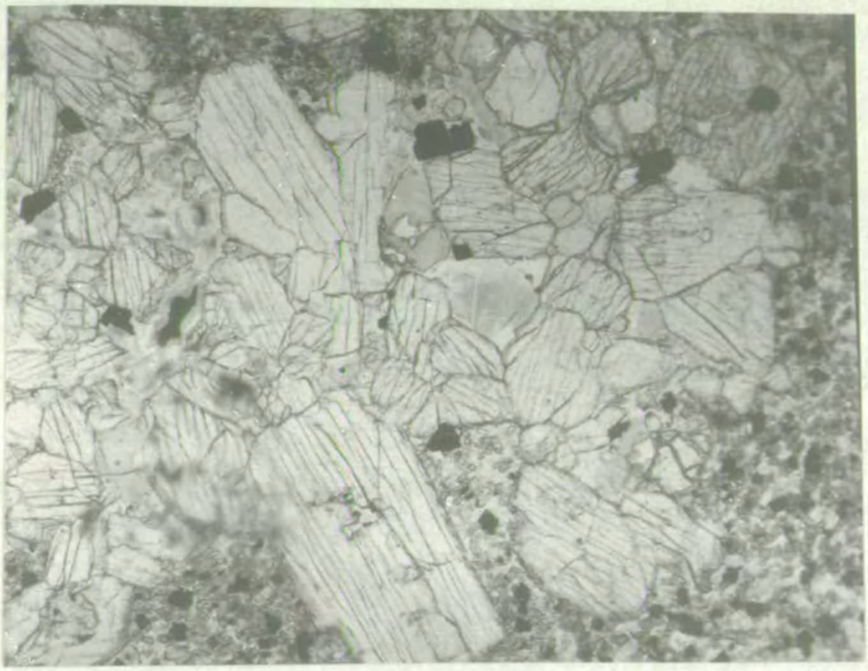
X 25 Plane polarised light.

PLATE: 2-11

Specimen No. 244

Glomeroporphyritic aggregate of clinopyroxenes in an ankaramite. Note the scarce microphenocrysts of ore in the cluster.

X 25 Plane polarised light.



Modal data (in volume percent) of phenocrysts (both for individual specimens and the average) in the flows of the bore holes.

Fig. 2-4a: Dhandhuka bore

Fig. 2-4b: Botad bore

Fig. 2-4c: Wadhwan Junction bore

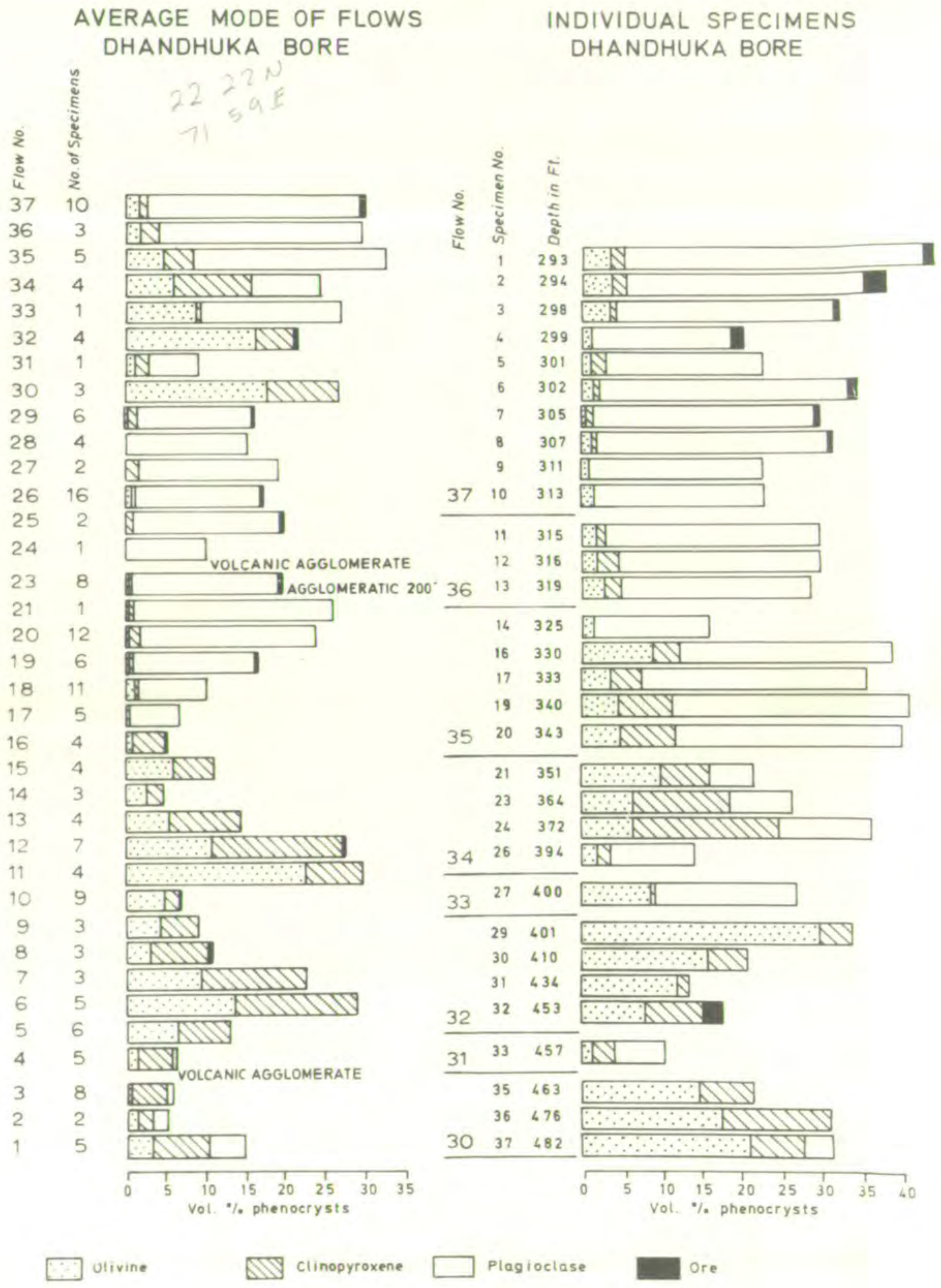

AVERAGE MODE OF FLOWS
DHANDHUKA BORE
22 22N
71 59E
Flow No.
No. of Specimens
37 10
36 3
35 5
34 4
33 1
32 4
31 1
30 3
29 6
28 4
27 2
26 16
25 2
24 1
VOLCANIC AGGLOMERATE
23 8
AGGLOMERATIC 200'
21 1
20 12
19 6
18 11
17 5
16 4
15 4
14 3
13 4
12 7
11 4
10 9
9 3
8 3
7 3
6 5
5 6
4 5
VOLCANIC AGGLOMERATE
3 8
2 2
1 5
0 5 10 15 20 25 30 35
Vol. % phenocrysts
INDIVIDUAL SPECIMENS
DHANDHUKA BORE
Flow No.
Specimen No.
Depth in Ft.
1 293
2 294
3 298
4 299
5 301
6 302
7 305
8 307
9 311
37 10 313
11 315
12 316
36 13 319
14 325
16 330
17 333
19 340
35 20 343
21 351
23 364
24 372
34 26 394
33 27 400
29 401
30 410
31 434
32 32 453
31 33 457
35 463
36 476
30 37 482
0 5 10 15 20 25 30 35 40
Vol. % phenocrysts
Olivine
Clinopyroxene
Plagioclase
Ore

Fig. 2 - 4a

INDIVIDUAL SPECIMENS DHANDHUKA BORE

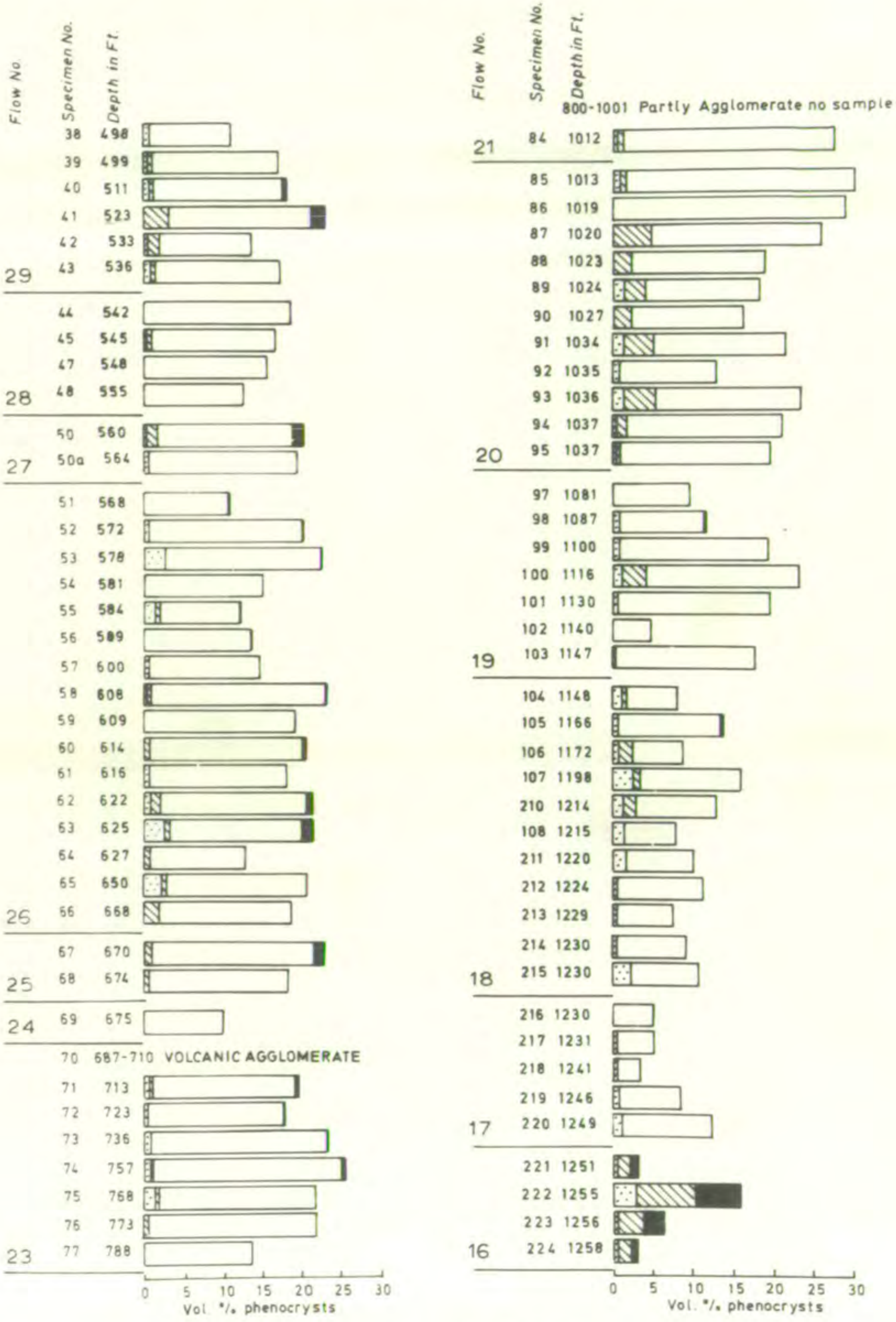


Fig. 2-4a (Cont.)

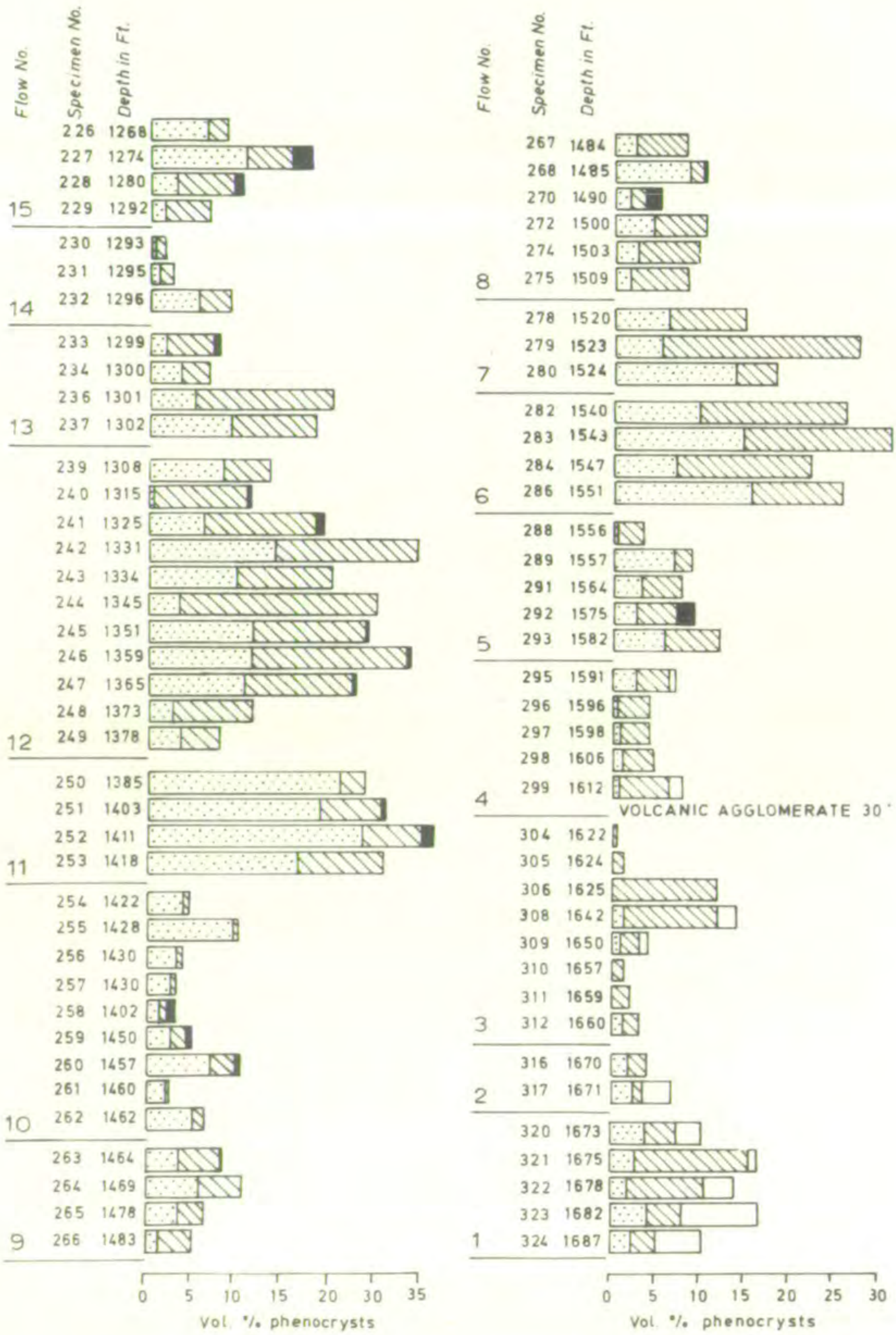

Flow No.
Specimen No.
Depth in Ft.
226 1268
227 1274
228 1280
15 229 1292
230 1293
231 1295
14 232 1296
233 1299
234 1300
236 1301
13 237 1302
239 1308
240 1315
241 1325
242 1331
243 1334
244 1345
245 1351
246 1359
247 1365
248 1373
12 249 1378
250 1385
251 1403
252 1411
11 253 1418
254 1422
255 1428
256 1430
257 1430
258 1402
259 1450
260 1457
261 1460
10 262 1462
263 1464
264 1469
265 1478
9 266 1483
0 5 10 15 20 30 35
Vol. % phenocrysts
Flow No.
Specimen No.
Depth in Ft.
267 1484
268 1485
270 1490
272 1500
274 1503
8 275 1509
278 1520
279 1523
7 280 1524
282 1540
283 1543
284 1547
6 286 1551
288 1556
289 1557
291 1564
292 1575
5 293 1582
295 1591
296 1596
297 1598
298 1606
4 299 1612
VOLCANIC AGGLOMERATE 30'
304 1622
305 1624
306 1625
308 1642
309 1650
310 1657
311 1659
3 312 1660
316 1670
2 317 1671
320 1673
321 1675
322 1678
323 1682
1 324 1687
0 5 10 15 20 25 30
Vol. % phenocrysts

Fig. 2-4a (Cont.)

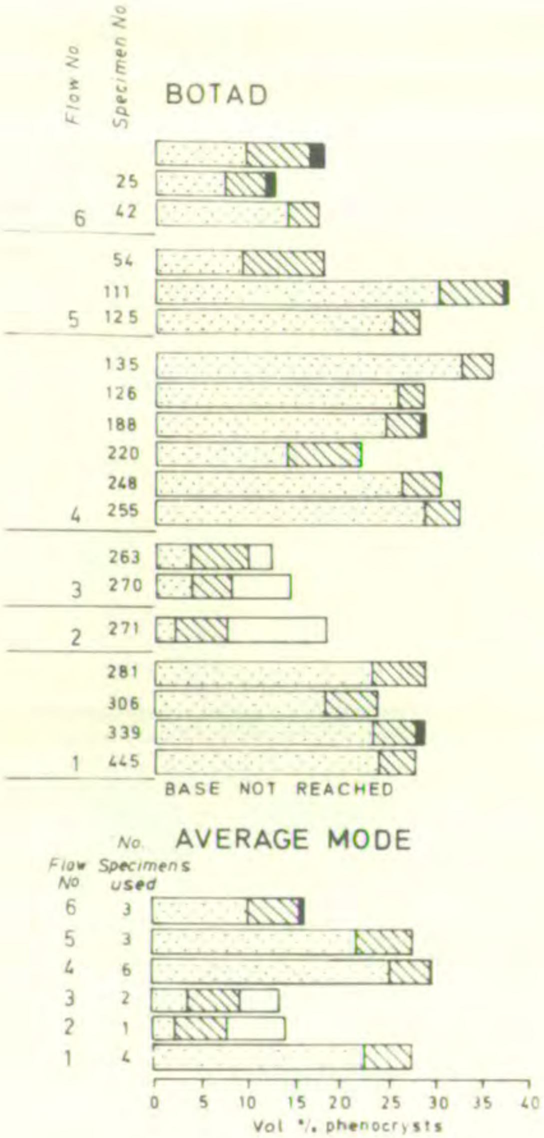


Fig. 2-4b

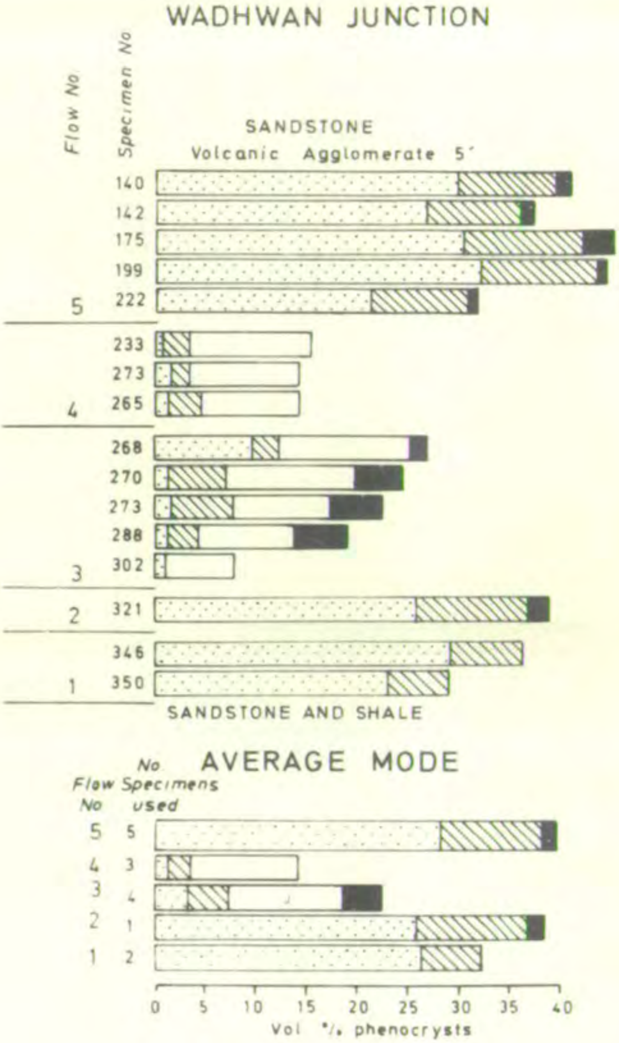


Fig. 2-4c

5 at Wadhwan Junction).

A variety of factors such as the mode of emplacement of the flows, the viscosity of the flow, the density contrasts between the different phenocrystal minerals and the melt in which they are suspended, the initial temperature of eruption, the cooling rate, the thickness of the flow etc. could contribute to the modal variations of the phenocrystal minerals in a lava flow.

CHAPTER III

MINERALOGY: BORE HOLE SAMPLES

A knowledge of the mineral chemistry of the bore hole flows - especially of the phenocryst phases - is necessary in order to understand their evolution. The chemical composition of the phenocryst and groundmass minerals wherever possible, has been determined by electron microprobe, and is presented in this chapter. Optical determinations of minerals have not been duplicated, and are essentially taken from West's (1958) work. These are tabulated, along with compositions obtained through probe analyses (see Table No. 3-7) at the end of the chapter.

3:1 Olivines:

Olivine is one of the important constituents, both as phenocrysts and as groundmass crystals, in the picrite basalts. Apart from slight alterations around the edges and along cracks of some of the crystals, the olivines of the picrite basalts of Botad and Wadhwan Junction are perfectly fresh. On the contrary, in the picrite basalts of Dhandhuka, the olivine phenocrysts are partly or completely altered to serpentine and iddingsite. Olivine occurs as a minor mineral in both the three-phenocryst basalts and basalts, where they are found to be invariably altered - with the exception of two three-phenocryst basalt flows from Botad - to a variety of substances such as iddingsite, dellesite, serpentine or calcite (cf. West, 1958).

Electron probe analyses of 10 olivines (8 phenocrysts and two groundmass crystals) are given in Table 3-1. Two partial analyses of phenocrystal olivine, from hand-picked material (West, 1958;

Table 3-1

Olivine Analyses

Flow No.	D-6	W-5	B-6	B-6	D-5	D-5	D-5	W-1	W-1	D-12	B-2	B-2	B-2
	Picrite Basalts										Three-phenocryst basalts		
Specimen No.	283 P	392 P	110 P	110 GM	292 P_C	292 P-R	292 GM	380 P_1	380 P_2	244 P	126 P_1	126 P_2	126 P_3
SiO_2	39.70	39.36	40.24	40.32	41.60	40.86	40.92	39.74	40.35	40.76	39.77	40.63	39.49
Al_2O_3	0.91	0.44	0.02	0.02	-	-	-	0.06	0.02	0.02	0.03	0.06	0.04
TiO_2	-	-	0.02	0.06	-	-	-	0.05	0.05	-	-	-	-
FeO	10.39	12.79	11.21	14.50	10.97	12.21	13.15	13.36	9.41	12.02	15.15	11.39	13.98
MgO	47.20	46.64	47.75	44.20	47.10	46.33	45.53	45.78	48.92	46.68	44.48	47.45	45.74
CaO	1.07	0.42	0.44	0.45	0.30	0.38	0.41	0.36	0.40	0.46	0.31	0.30	0.30
NiO	-	-	0.31	-	-	-	-	0.28	0.39	0.33	0.23	0.39	0.31
Na_2O	-	-	-	-	-	-	-	-	0.003	-	0.04	0.02	0.04
Cr_2O_3	-	-	-	-	-	-	-	-	-	0.07	-	-	-
Total	99.27	99.65	99.89	99.55	99.97	99.98	100.01	99.62	99.55	100.33	100.01	100.24	99.90
					FORMULA ON THE BASIS OF 4 OXYGEN ATOMS								
Si	0.991	0.986	0.995	1.012	1.023	1.010	1.017	0.977	0.994	1.009	0.999	0.999	0.991
Al	0.027	0.013	-	-	-	-	-	0.009	-	-	0.003	0.009	0.006
Fe	0.218	0.268	0.232	0.305	0.226	0.253	0.275	0.279	0.194	0.248	0.319	0.234	0.293
Mg	1.765	1.741	1.760	1.654	1.727	1.715	1.680	1.712	1.797	1.723	1.667	1.740	1.710
Ca	0.030	0.001	0.011	0.012	0.009	0.001	0.001	0.011	0.010	0.010	0.009	0.007	0.006
Ni	-	-	0.006	-	-	-	-	0.006	0.007	-	0.005	0.007	0.005
						ATOMIC RATIOS							
Mg	88.98	86.66	88.35	84.4	88.4	87.1	85.9	86.0	90.3	87.4	83.9	88.0	85.3
Fe	11.02	13.34	11.65	15.6	11.6	12.9	14.1	14.0	9.7	12.6	16.1	12.0	14.7

Note: D = Dhandhuka P = Phenocryst B = Botad GM = Groundmass W = Wadhwan Junction
C = Core R = Rim
- Denotes not determined in all the tables to follow, unless stated otherwise.

p.21) have also been included in the table.

The analysed olivines range in composition from Fo_{90} to Fo_{84}, and thus belong to the chrysolite type (Deer et al., 1962; p. 22).

The olivine phenocrysts of the picrite basalts range in composition from Fo_{90} to Fo_{87}. Very feeble normal zoning has been occasionally observed as in the case of No. 292 (see Table 3-1). The groundmass olivines are slightly more iron rich, ranging from Fo_{86} to Fo_{84}.

The three analysed olivine phenocrysts of the three-phenocryst basalts vary in composition from Fo_{88} to Fo_{84}, the one showing higher forsterite content may be a possible xenocryst. The optical estimates (West, 1958) give a range from Fo_{82} to Fo_{71}. Thus on the whole, the olivines of the three-phenocryst basalts are more iron rich than those of the picrite basalts.

The completely altered nature of the olivines in the basalts precludes their compositions being known. However, it is not unreasonable to assume that they are slightly more fayalitic than or of similar composition to those in the three-phenocryst basalts, since they show some mineralogical and chemical affinities to them.

An important feature of the olivine phenocrysts of the picrite basalts is their high forsteritic content, averaging Fo_{88}. They also contain high amounts of NiO, which varies from 0.28-0.39%. Some of the big crystals carry inclusions of chromite (see chromite analyses, Table 3-5). In these respects the olivines of the picrite basalts resemble those obtained from peridotite or dunite nodules (Ross et al., 1954), as well as those present in the peridotites or picrites of some layered intrusions such as

Rhum, Stillwater and Bushveld (Wager and Brown, 1968).

Such a high Fo content in the olivines of the picrite basalts precludes the possibility of their having been formed by cumulus enrichment from normal basalts or three-phenocryst basalts containing olivines with lesser Fo content. This is in fact one of the main mineralogical reasons for ascribing to the picrite basalts a probable parental role in the petrogenetic considerations of the bore hole flows.

3:2 Clinopyroxenes:

Apart from the olivines, clinopyroxenes are the dominant phenocrysts in the picrite basalts, particularly in the ankaramitic types. Their amounts decrease in the three-phenocryst basalts, while in the basalts they are scarce.

Partial or complete electron probe analyses of 23 clinopyroxenes are presented in Table 3-2. One wet chemical analysis of a hand-picked pyroxene from an ankaramite, quoted by West (1958; p.24) is also included in the table. The compositions of the clinopyroxenes are expressed as atomic % of Mg, Ca, and Fe^{+2} in the pyroxene quadrilateral (Fig. 3-1), the nomenclature system shown being after Poldervaart and Hess (1951).

The pyroxene phenocrysts of the picrite basalts plot mainly in the endiopside-diopside field, while the pyroxenes of the whole suite cluster around the junction diopside-endiopside-salite-augite. The phenocrysts range in composition from $Mg_{52-44}Ca_{46-43}Fe_{11-5}$ in the picrite basalts to $Mg_{45-43}Ca_{44-40}Fe_{17-11}$ in the basalts and three-phenocrysts basalts. The composition of a single groundmass

Table 3-2

Clinopyroxene Analyses: Picrite basalts

Flow No.	W-1	D-12	D-12	D-12	D-12	D-12	D-12	D-12	D-6	D-5	D-5	B-6	B-6
Specimen No.	380 P-1	244 P-1-C	244 P-1-R	244 P-3	244 P-4	244 P-5	244 P-6	242 P	283 P*	292 P-C	292 P-R	110 P	110 GM
SiO_2	51.23	51.41	49.96	52.98	52.70	52.49	52.29	52.58	50.89	54.60	50.42	53.74	51.77
TiO_2	0.67	0.49	1.66	0.42	0.50	0.47	0.37	0.62	-	0.46	1.48	0.57	1.18
Al_2O_3	2.23	1.84	3.85	1.56	1.77	1.76	2.13	2.16	3.52	1.44	3.95	1.38	1.42
FeO	5.28	3.84	6.88	3.50	3.97	3.72	4.14	4.47	4.99	3.29	7.03	3.89	8.99
MgO	16.23	16.78	13.77	17.05	16.80	16.98	17.18	17.14	18.34	18.20	15.09	17.06	13.64
CaO	22.55	23.06	22.15	23.36	22.96	22.77	23.15	22.73	22.09	21.58	21.87	22.91	21.56
Na_2O	0.20	0.21	0.39	0.23	0.18	0.17	0.18	-	-	-	-	0.14	-
K_2O	0.01	0.02	0.02	0.01	0.01	-	-	-	-	-	-	tr	-
Cr_2O_3	0.38	1.12	-	0.81	0.55	-	0.97	-	-	-	-	-	-
NiO	0.09	0.08	0.05	0.09	0.07	0.05	0.05	-	-	-	-	0.95	-
Total	98.87	98.84	98.72	99.99	99.52	98.40	100.48	99.70	99.83	99.67	99.84	100.61	98.56

Number of ions on the basis of 6 oxygen atoms

Si	1.914	1.915	1.884	1.940	1.947	1.946	1.920	1.929	1.869	1.978	1.869	2.000	1.957
Al^4	0.086	0.081	0.116	0.060	0.053	0.004	0.080	0.071	0.131	0.022	0.131	-	0.043
Al^6	0.012	-	0.056	0.006	0.022	0.072	0.013	0.023	0.021	0.038	0.041	0.063	0.020
Fe	0.163	0.119	0.218	0.107	0.122	0.116	0.128	0.137	0.097	0.100	0.218	0.121	0.284
Mg	0.904	0.931	0.752	0.931	0.904	0.938	0.940	0.937	1.004	0.988	0.834	0.837	0.767
Ca	0.902	0.919	0.895	0.917	0.907	0.905	0.911	0.893	0.869	0.838	0.869	0.871	0.871
Ti	0.017	0.013	0.047	0.023	0.013	0.014	0.013	0.017	-	0.013	0.041	0.016	0.034
Na^+	0.012	0.014	0.028	0.016	0.012	0.014	0.012	-	-	-	-	0.008	-
K	-	-	-	-	-	-	-	-	-	-	-	-	-
Cr	0.009	0.031	-	0.022	0.015	-	0.009	-	-	-	-	0.026	-

Atomic %

Ca	45.8	46.7	48.3	46.9	47.0	46.2	46.0	45.4	44.1	43.5	45.2	47.6	45.3
Mg	45.9	47.3	40.3	47.6	46.7	47.9	47.5	47.6	51.0	51.3	43.4	45.8	39.9
Fe	9.3	6.0	11.7	5.5	6.3	5.9	6.5	7.0	4.9	5.2	11.4	6.6	14.8

Note: Symbols as in Table 3-1

P^* Handpicked material analysis taken from West (1958)

Table 3-2 (Contd.)

	Three-phenocryst basalts								Basalts					
Flow No.	D-1	D-1		B-2	B-2	W-3	W-3	D-3	D-35	D-35	D-34	D-34	D-34	D-29
Specimen No.	321	321 P-C	321 P-R	126 P-1	126 P-2	384 P-1	384 P-2	304 P	19 P-1	19 P-2	21 P-1	21 P-2	21 P-3	40 P
SiO_2	50.81	50.53	51.81	50.63	51.01	50.61	50.08	50.51	49.78	51.11	50.56	50.05	50.89	50.43
TiO_2	0.87	0.72	1.33	0.97	0.81	0.91	1.25	1.08	1.70	1.31	0.93	1.28	0.77	1.21
Al_2O_3	3.07	3.58	2.39	3.65	3.03	3.48	3.36	3.16	3.46	3.04	3.68	2.94	3.79	2.57
FeO	7.13	7.53	9.71	6.20	5.37	6.02	7.50	6.78	8.10	7.34	5.36	10.01	5.13	10.34
MgO	15.76	15.02	14.76	15.41	16.10	15.58	14.67	14.99	14.41	14.94	15.77	14.64	15.77	14.80
CaO	21.24	21.09	19.73	21.97	21.60	22.02	21.69	22.02	20.55	21.10	22.27	19.95	21.90	19.07
Na_2O	-	-	-	0.29	0.25	0.26	0.29	0.25	0.34	0.27	0.27	0.39	0.23	0.30
K_2O	-	-	-	-	-	-	-	0.02	0.02	0.07	0.01	0.01	-	0.01
Cr_2O_3	-	-	-	0.01	0.06	0.05	0.03	-	-	-	-	-	-	-
Total	98.88	98.47	99.73	99.14	98.22	98.91	98.87	98.81	98.36	99.19	98.85	99.26	98.48	98.72

Number of ions on the basis of 6 oxygen atoms

Si	1.899	1.898	1.929	1.866	1.914	1.901	1.906	1.900	1.881	1.906	1.882	1.921	1.899	1.910
Al^4	0.101	0.102	0.071	0.114	0.086	0.099	0.094	0.100	0.119	0.094	0.118	0.079	0.101	0.090
Al^6	0.034	0.056	0.034	0.047	0.049	0.042	0.045	0.040	0.096	0.041	0.063	0.044	0.064	0.104
Fe	0.220	0.237	0.302	0.192	0.169	0.190	0.218	0.212	0.257	0.228	0.168	0.294	0.159	0.328
Mg	0.878	0.841	0.820	0.855	0.877	0.849	0.764	0.818	0.811	0.831	0.875	0.746	0.875	0.836
Ca	0.851	0.849	0.788	0.875	0.868	0.885	0.813	0.889	0.832	0.842	0.888	0.752	0.875	0.774
Ti	0.024	0.020	0.037	0.027	0.023	0.025	0.034	0.031	0.047	0.036	0.027	0.034	0.023	0.034
Na	-	-	-	0.022	0.018	0.020	0.022	0.018	0.022	0.016	0.018	0.026	0.018	0.020
Cr	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Atomic %

Ca	43.7	44.1	41.3	45.5	45.4	46.0	45.3	46.3	43.8	44.3	46.0	42.0	45.8	40.0
Mg	45.0	43.6	42.9	44.5	45.8	44.1	42.6	42.6	42.7	43.7	45.3	41.6	45.8	43.1
Fe	11.3	12.3	15.8	10.0	8.8	10.1	12.1	11.1	13.5	12.0	8.7	16.4	8.4	16.9

Fig. 3-1: (top figure) Clinopyroxene compositions plotted in terms of variation in Ca, Mg and Fe expressed in atomic %. The classification scheme of Poldervaart and Hess (1951), and the boundary fields for the pyroxenes are shown. Tie lines between phenocrystal and groundmass clinopyroxenes, and core-rim relations in zoned crystals are also indicated.

(bottom figure) Crystallization trends of clinopyroxenes and/or compositions of clinopyroxenes from other volcanic series and layered intrusions;

B = Black Jack, teschenite sill (Wilkinson, 1957)
G = Garbh Eilean (Murray, 1954)
GI = Gough Island (Le Maitre, 1962)
SK & BK = Skaergaard and Bushveld) (Wager and
R = Rhum) Brown, 1968)
KE = Kap Edward)
XX = clinopyroxenes from dunite/peridodite nodules (Ross <u>et al</u>., 1954)

The field of clinopyroxenes from the bore hole suite (dotted line) and the Rajpipla area (full line) (Chapter 8) are also shown.

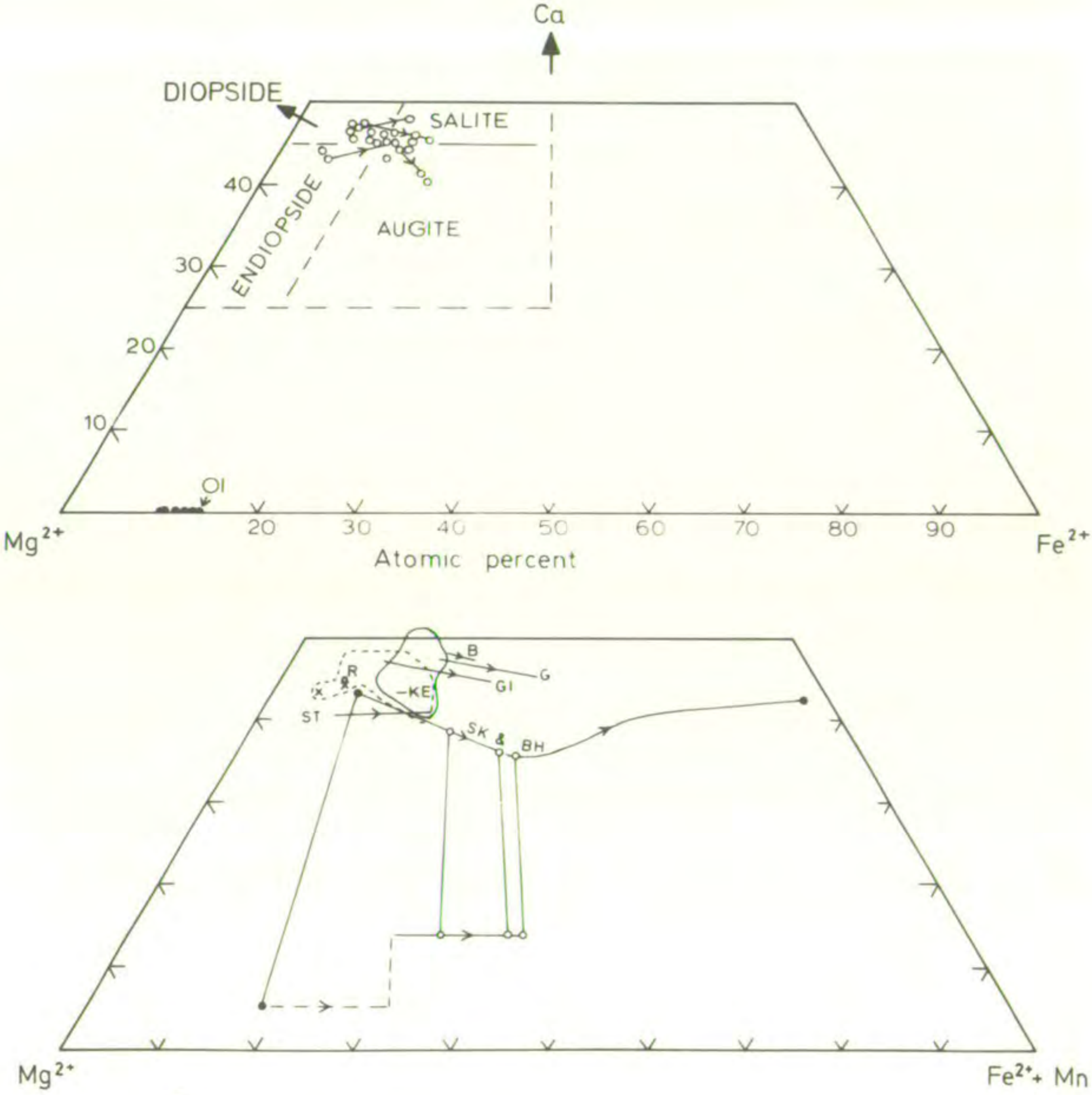

Ca
DIOPSIDE
SALITE
ENDIOPSIDE
AUGITE
40
30
20
10
Ol
Mg^{2+}
20
30
40
50
60
70
80
90
Fe^{2+}
Atomic percent
B
G
Gl
R
X
KE
ST
SK
&
BH
Mg^{2+}
Fe^{2+}+ Mn

Fig. 3-1

pyroxene ($Ca_{45}Mg_{40}Fe_{15}$) from a picrite basalt (No. 110, Table 3-2) falls approximately within the range of the phenocryst compositions found in the basalts. The overall compositional change of the pyroxenes being gradational and rather limited.

Zoning in the pyroxenes is not common, and wherever observed, is sharp, often as thin bands up to a width of 0.5 mm. In some cases, as in No. 244 (see plate 2-8) the zoning is confined to the outermost part of the phenocryst and appears to be of normal type (see Table 3-2). Twinning on (100) is occasionally seen in some of the phenocrysts. Inclusions of ore minerals in the pyroxenes are very scarce.

3:3 Si-Al-Ti Variations in the clinopyroxenes

The Si-Al-Ti variations of ~~the~~ clinopyroxenes have been dealt with in considerable detail in recent years, as they appear to vary according to the physico-chemical conditions during crystallization. A study of the variation of these elements, therefore, might throw some light on the evolutionary history of the flows.

The variations in the SiO_2, Al_2O_3 and TiO_2 of the analysed clinopyroxenes (Table 3-2) have been shown in Fig. 3-2, where they are plotted against the FeO/FeO+MgO ratio of the pyroxenes. Such a ratio, commonly referred to as the iron-magnesium ratio serves as a good index of pyroxene variation and evolution in the present case. With evolution, the TiO_2 contents of the pyroxenes gradually increase; a sharp initial increase of Al_2O_3 is followed by a slight decrease; SiO_2 decreases sharply, becoming

Fig. 3-2: Variation of Al_2O_3, TiO_2 and SiO_2 in the clinopyroxenes plotted against their FeO/FeO + MgO ratio.
Tie-lines shown are between core and rim phenocrystal and groundmass clinopyroxene.

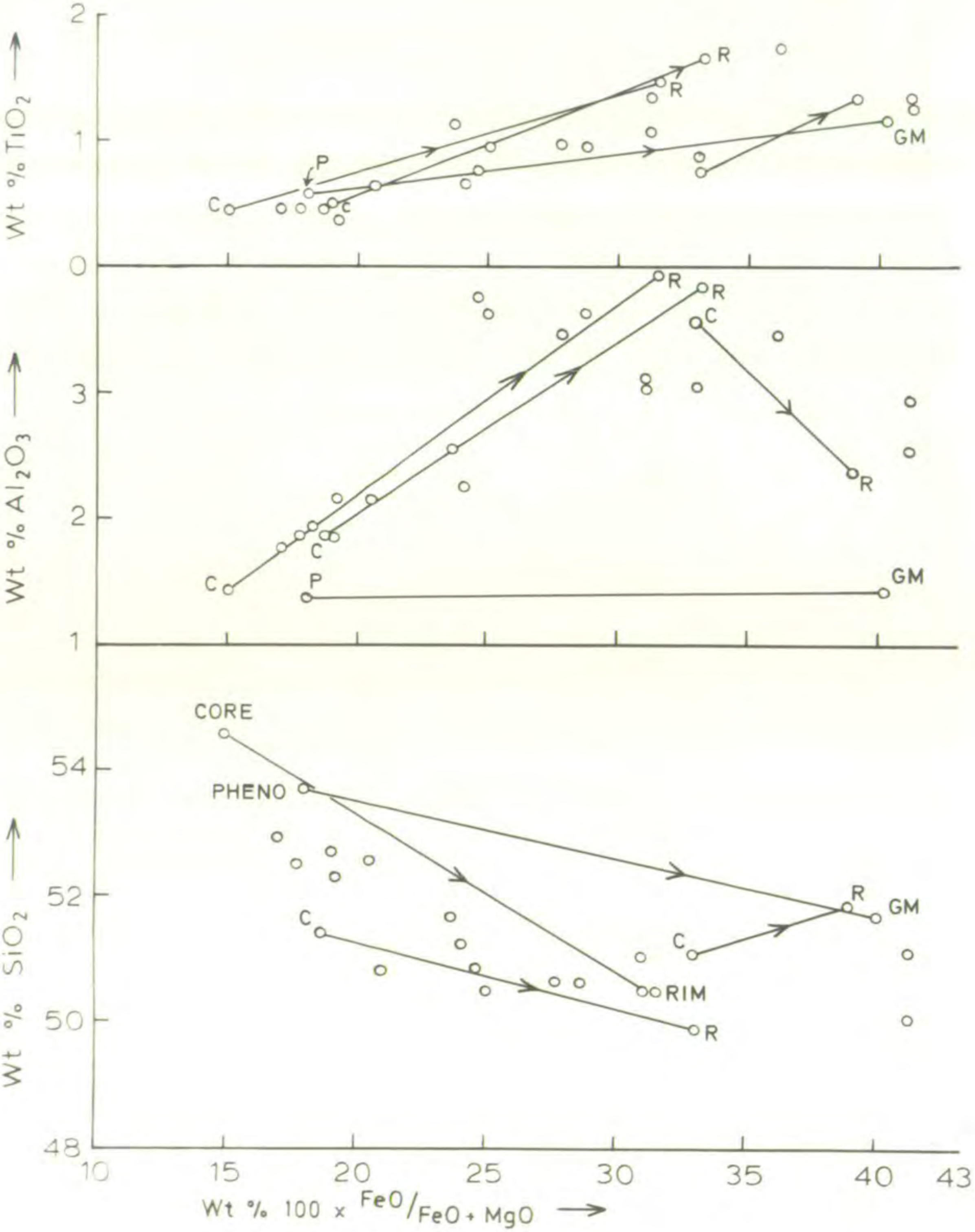

Wt % TiO2 →
2
1
0
C
P
c
R
R
GM
Wt % Al2O3 →
3
2
1
R
R
C
R
C
C
P
GM
Wt % SiO2 →
54
52
50
48
CORE
PHENO
C
C
R
GM
RIM
R
10
15
20
25
30
35
40
43
Wt % 100 x FeO/FeO + MgO →

Fig. 3-2

Fig. 3-3a: Relation between atomic proportions of Si and total Al in the analysed clinopyroxenes.

Fig. 3-3b: Relation between Al-Ti.

Fig. 3-3c: A plot of the relative proportions of Al in the tetrahedral site and Al in the octahedral site of clinopyroxenes of bore hole flows. The boundary lines for the different occurrences are after Aoki and Katsura (1968, Fig. 2, p. 335). Tie lines join phenocryst-groundmass/core-rim pairs.

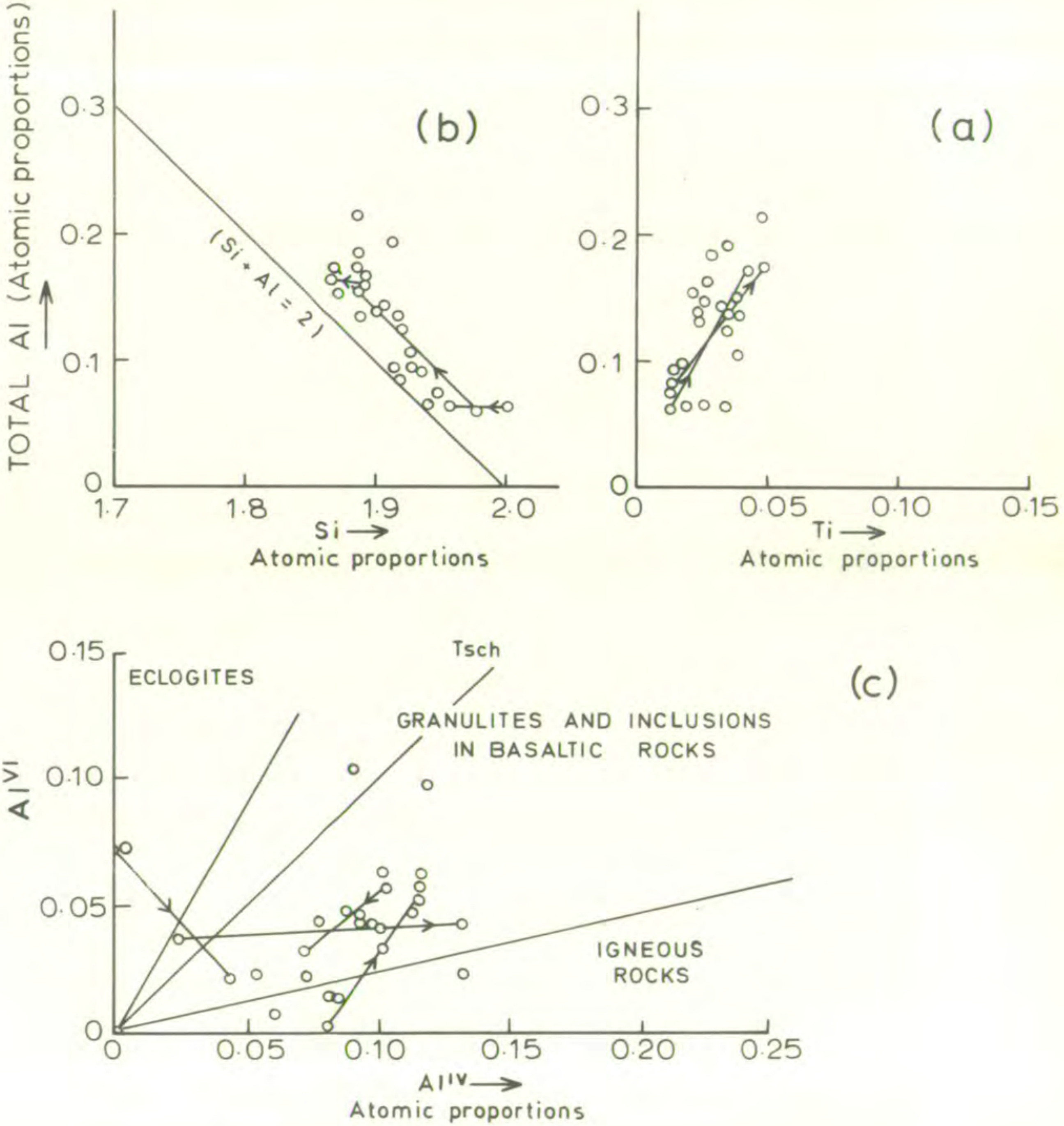

(b)
TOTAL Al (Atomic proportions)
0.3
0.2
0.1
0
(Si + Al = 2)
1.7
1.8
1.9
2.0
Si
Atomic proportions
(a)
0.3
0.2
0.1
0
0
0.05
0.10
0.15
Ti
Atomic proportions
(c)
Al^{VI}
0.15
0.10
0.05
0
ECLOGITES
Tsch
GRANULITES AND INCLUSIONS IN BASALTIC ROCKS
IGNEOUS ROCKS
0
0.05
0.10
0.15
0.20
0.25
Al^{IV}
Atomic proportions

Fig. 3-3

rather constant or increases slightly? These changes can be seen clearly in the case of the zoned crystals (Fig. 3-2). Within the clinopyroxene series Al and Ti show a sympathetic variation (Fig. 3-3a), while Al and Si show the opposite (Fig. 3-3b). The Si-Al variation taken together, is broadly consistent with the transitional chemical character of the whole series, which ranges from olivine-tholeiites → mildly-alkaline, alkali olivine basalts → olivine-tholeiites and quartz-tholeiites. Such an inference seems to support the contention of Kushiro (1960) that the molecular concentration of SiO_2 in the magma, which in turn reflects the silica saturated or undersaturated character of the liquid, is important in the Si-Al distributions in the clinopyroxenes. According to Kushiro (1960), other factors such as the composition of the magma, the degree of fractionation and temperature, which might affect the Si-Al distribution in clinopyroxenes, are also dependent on the molecular concentration of SiO_2, in the magma.

Polybaric phase equilibria considerations, dealt with in Chapter 6, have suggested that crystallization of phenocrysts - particularly in the picrite basalts - may have taken place at elevated pressures. The effect of pressure on the amount of Al_2O_3 in the clinopyroxenes has been stressed by a number of workers, and the Al_2O_3 content of the analysed clinopyroxenes may throw some light on this point. According to Aoki and Kushiro (1968), clinopyroxenes formed at higher pressures, contain larger amounts of Al_2O_3 as a result of substitution of Al^{+3} in the octahedral site, whereas intermediate and low pressures give rise to clinopyroxenes having moderate to lower amounts of Al^{+3} in the octahedral site. A large majority of the analysed clinopyroxenes contain low to moderate amounts of Al^{+3} in the octahedral site (see Table 3-2). A plot of Al in the tetrahedral site (Al^{IV}) against Al in the octrahedral site (Al^{VI}) of the clinopyroxenes is shown in Figure 3-2c, and a large number of them plot in the field of pyroxenes belonging to the granulites and nodular assemblages, thereby suggesting crystallization under elevated pressures.

3:4 Chromium content of the clinopyroxenes:

An additional feature of the clinopyroxenes, especially those from the picrite basalts, is their high chromium content, which were found to range from 0.38% to 1.12% (see Table 3-2). In having such high chromium contents, the clinopyroxenes resemble those obtained from dunite or peridodite nodules (Ross et al., 1954).

3:5 Normative character of the pyroxenes:

Coombs (1963) demonstrated the relationship betwenn the normative character of the clinopyroxenes and the chemical character of the host rock. Accordingly, clinopyroxenes from alkaline rocks (nepheline-normative) are in general nepheline-normative, while those from oversaturated, tholeiitic rocks are quartz normative. Mildly alkaline and transitional rocks, contain clinopyroxenes which are either nepheline normative or olivine and hypersthene normative. Normative minerals of some of the analysed clinopyroxenes are given in Table 3-2b. All of them contain either olivine + hypersthene or very small amounts

Table 3-2a

Normative compositions of some of the analysed clinopyroxenes

Specimen No.	380	244-Core	244-Rim	244-3	244-4	244-5	110-5	126-1	19-1	19-2	21 P-2	40
Or	0.03	-	0.12	0.06	0.06	-	-	-	0.18	0.42	0.06	0.06
Ab	-	-	0.17	1.65	1.53	-	1.18	0.25	2.92	2.30	3.32	2.57
Ne	0.93	0.97	1.72	0.16	-	0.82	-	1.21	-	-	-	-
An	5.22	4.07	8.81	3.20	4.01	4.98	3.12	8.73	7.96	6.93	6.29	5.71
Di	85.69	87.02	81.91	88.85	87.27	86.35	86.57	80.66	76.69	78.86	75.40	72.80
Hy	-	-	-	-	1.39	0.82	6.24	-	1.19	3.24	1.42	9.12
Ol	6.26	4.83	4.07	4.09	3.97	5.72	0.42	7.29	7.78	5.74	11.06	7.41
Cr	0.57	1.67	-	1.19	0.81	1.42	1.39	-	-	-	-	-
Il	1.29	0.94	3.19	0.80	0.95	0.70	1.08	1.86	3.28	2.51	2.45	2.33

of nepheline in their norm, and thus conform to the mildly alkaline to transitional nature of the flows.

3:6 PLAGIOCLASE FELSPARS

Plagioclase felspars are confined to the groundmass in the picrite basalts, whereas they are the dominant phenocrysts in the three-phenocryst basalts and basalts. The composition of the plagioclase felspars have been obtained by the following methods:

Optical:

1. From refractive index, determined in sections cut perpendicular to the optic axis (West, 1958, p. 26).

2. From universal stage techniques (West *op.cit.*) (Method not specified)

Chemical:

3. Partial or nearly complete, electron probe analyses (present work).

The compositions of the plagioclases, obtained through optical methods are summarised in Table 3-3.

Table 3-3.

	Picrite basalts	Three-phenocryst basalts	Basalts	Reference
Phenocrysts	Absent	An_{89-70}	An_{69-61}	West (1958)
Groundmass	An_{76-60}	An_{76-62}	An_{60-54}	West (1958)

About 50 nearly complete microprobe analyses have been carried out on plagioclase felspars and are presented in Table 3-4a, b and c. Because of lack of compositional variation, some of the "spots" have been averaged, especially if they are from a single specimen.

It can be seen that some of the plagioclase analyses have low totals, and are probably due to loss of soda during probe analyses. Such a loss probably accounts for the high calcic nature of these plagioclase compositions. For these analyses, compositions based on CaO alone have been estimated, and are shown in the Tables 3-4a, b and c. The compositions so obtained are slightly less calcic than those based on low totals.

Picrite Basalts

Plagioclase felspars are generally confined to the groundmass in this group. Very rarely they are seen as microphenocrysts (as in Specimen No. 110) and occur up to 0.5 mm. in width. The compositional range of the microphenocrysts and groundmass microlites from one specimen (No. 110, Table 3-4a) was found to be An_{88} to An_{74}. Groundmass plagioclase is lacking in some of the strongly porphyritic, magnesium rich oceanites, as in specimen No. 393.

Three-phenocryst basalts

The three phenocryst basalts contain plagioclases of bytownitic composition (An_{88-72}; see Table 3-4b). Normal zoning has been occasionally observed and probe data on one zoned crystal (No.126, Table 3-4b) shows variations from An_{80} to An_{72}. Two important features with regard to the plagioclase phenocrysts of the three-phenocryst basalts need to be emphasized.

Table 3-4a

Plagioclase analyses. Picrite basalts (Groundmass microlites/ microphenocrysts)

Flow No.	B-6	B-6	B-6
Specimen No.	110-1	110-2	110-3
SiO_2	45.55	48.92	48.3
Al_2O_3	32.96	30.59	31.44
FeO	0.75	0.78	0.78
CaO	17.45	14.85	15.56
Na_2O	1.25	2.75	2.41
K_2O	0.09	0.21	0.16
MgO	0.09	0.18	0.10
TiO_2	0.05	0.09	0.08
Total	98.19	98.37	98.83
Mol. %			
An	88.1	74.2	77.4
Ab	11.3	24.7	21.8
Or	0.6	1.1	0.8
Compositions based on CaO alone (in wt. %)			
An	86.6	73.7	77.2

Table 3-4b

Plagioclase analyses: Three phenocryst basalts

Specimen No.	126 P	126 P-CORE	126 P-RIM	384 P(10)	304 P	304 P(6)	389 P	389 P
SiO_2	48.18	47.82	50.56	46.89	48.72	47.38	47.15	47.25
Al_2O_3	31.61	32.26	29.85	32.47	30.60	31.05	32.24	32.04
FeO	0.55	0.49	0.59	0.64	0.63	0.66	0.69	0.68
CaO	16.00	16.91	14.24	17.08	16.22	16.94	17.00	16.55
Na_2O	1.72	2.27	2.78	1.41	2.35	1.91	1.34	1.42
K_2O	0.14	0.13	0.25	0.11	0.14	0.11	0.14	0.13
MgO	0.04	-	-	-	0.60	0.19	-	-
TiO_2	-	-	-	-	0.05	0.05	-	-
Total	98.24	99.88	98.27	98.60	99.31	98.29	98.56	98.07
Mol. %								
An	83.1	79.9	72.2	86.4	88.1	82.5	86.5	85.6
Ab	16.3	19.6	26.0	13.0	11.6	16.9	12.6	13.4
Or	0.6	0.5	1.8	0.6	0.3	0.6	0.9	1.0
Compositions based on CaO only (in wt.%)								
An	79.3	83.9	70.6	84.7	80.5	84.0	84.0	82.1

P = Phenocrysts

P(10) = Phenocrysts - Average of 10 spots.

Table 3-4c

Plagioclase analyses: Basalts

Specimen No.	19 P(11)	19 GM	77 P(6)	31 MP	40 P	40 P	40 P-CL	40 P-CL
SiO_2	51.32	51.40	53.09	52.76	54.31	53.52	48.17	47.94
Al_2O_3	29.38	29.22	28.68	28.12	27.41	28.32	32.44	32.64
FeO	0.55	0.60	0.78	0.86	1.36	0.61	0.89	0.69
CaO	13.39	13.25	12.44	13.00	11.57	11.79	16.05	16.24
Na_2O	3.65	4.38	4.08	4.09	4.59	4.05	1.85	1.93
K_2O	0.33	0.49	0.36	0.38	0.46	0.35	0.11	0.13
MgO	0.19	0.12	0.14	0.16	0.13	0.14	0.09	0.01
TiO_2	0.13	0.17	0.13	0.13	0.08	0.09	0.09	0.06
Total	98.90	99.03	99.70	99.50	99.91	98.87	99.69	99.57
Mol. %								
An	65.5	60.9	61.3	62.9	56.7	60.5	82.2	81.7
Ab	32.3	36.5	36.5	36.0	40.7	37.4	17.1	17.5
Or	2.2	2.6	2.2	1.1	2.6	2.1	0.7	0.8
Compositions based on CaO alone (in wt.%)								
An	66.4	65.7	61.7	64.5	57.4	58.5	79.6	80.6

Abbreviations used:

P = Phenocryst

MP = Microphenocryst

GM = Groundmass plagioclase

P(11)=Average of 11 spots

P-CL =Plagioclase belonging to the anorthositic or gabbroic cluster

1. The phenocrysts of plagioclases are fairly large individual crystals measuring up to 6 mm. in length, averaging 2 mm. The phenocrysts tend to clump together either alone, or with olivine or with both olivine and clinopyroxene. In some flows, these "patches" cover fairly large areas (up to 7-8 mm^2) and resemble gabbroic or anorthositic patches, suggesting that such compositional types were probably crystallizing during the intratelluric stage of evolution (see plate 2-3).

2. The bytownitic nature of the plagioclases occurring in such "clumps".

Basalts

Plagioclase phenocrysts of the basalts generally range in composition from An_{66} to An_{57} (Table No. 3-4c) while the groundmass composition varies from An_{54} to An_{61}. An important feature, not recognised previously by West (1958) is the occurrence of scarce clusters of bytownitic (An_{82}) plagioclase, as noticed in the specimen No. 40 (Table 3-4c). Such rare occurrences of clusters, suggest their possibility of being xenocrysts, apparently picked up from the three phenocryst basalts.

Twinning and Zoning

Twinning on albite-law is very common while albite-carlsbad law can also be seen. Zoning, though not strong, can be seen occasionally, and appears to be normal, as indicated by the probe analyses (No. 126 and 384, Table 3-4b).

Marginal zonation, often in very fine strips, can be seen in the plagioclase phenocrysts belonging to the clusters (Plate 2-5), and some of them show what appears to be resorption features.

Calcic nature of the plagioclase phenocrysts

The bytownitic nature of the plagioclase phenocrysts, particularly in the three phenocryst basalts may be related to the picritic nature of the parent magma (dealt with in subsequent chapters) and/or due to the physical conditions during crystallization, particularly P_{H_2O} (Yoder, 1969). The earliest plagioclase to crystallize in equilibrium with mafic magmas, especially in layered intrusions, have been generally found to range in composition from An_{90-85}, but marked variations from this range in the initial plagioclase compositions are not uncommon, as at Skaergaard, where the earliest plagioclase is of An_{77} composition (Wager and Brown, 1968). As pointed out by Brown (1967), it is not certain whether such changes in the initial plagioclase composition are due to subtle changes in parental magma compositions between the different layered intrusions, or due to the influence of P_{H_2O}. According to Yoder (1969), in the water-saturated systems Diopside-Anorthite-H_2O and Albite-Anorthite-H_2O, with increasing P_{H_2O}, the eutectics are depressed to lower temperatures and shifted towards more anorthite rich compositions. Textural evidence, presented earlier (see Plate 2-3) suggests that some plutonic or intra-telluric crystallization (presumably at elevated pressures) probably occurred during the crystallization of the plagioclase phenocrysts. The presence of small amounts of phlogopite in the groundmass of some three phenocryst basalts, and the occurrence of 4 beds of volcanic agglomerate in the bore hole succession may be taken as evidences for the role of volatiles, particularly H_2O vapour and hence the influence of P_{H_2O}, in the composition of the plagioclase phenocrysts.

3:7 ORE MINERALS

The ore minerals are generally confined to the groundmass, apart from the occasional inclusions seen in the olivine phenocrysts (in the picrite basalts) and scarce microphenocrysts ($\simeq 0.25 \times 0.25\ mm^2$) in some of the picrite basalts (Plate 2-11). 18 Partial analyses of the ore minerals belonging to the different groups of flows have been analysed by electron microprobe, and the data are presented in Table No. 3-5a and b. The following points could be inferred from the analyses.

1. The ore mineral enclosed in the olivine appears to be chromite (Table 3-5a).

2. The scarce microphenocrysts of ore, in the picrite basalts also appear to be chromites (Table 3-5a).

3, The groundmass ores in the picrite basalts have been found to be both titano-magnetite* and ilmenite, the latter being from a strongly porphyritic oceanite (specimen No. 392, Table 3-5b).

4. The groundmass grains in the basalts appear to be titano-magnetites.

The chromites included in the olivine phenocrysts, and present

---

* The term titano-magnetite has been tentatively used simply from comparisons with published analyses (Deer et al., 1962, Vol.5, Table 12, p.72), since the term is normally preferred for samples "where the presence of an ulvöspinel phase can be demonstrated by X-ray or similar techniques"...(Deer et al., op.cit.)

Table 3-5a

Chromite analyses. Picrite basalts

Specimen No.	Microphenocrysts			Inclusions in olivines	
	392	110-1	110-2	380	110
SiO_2	0.10	0.07	0.05	0.09	0.09
TiO_2	1.91	-	1.45	1.64	1.76
Al_2O_3	10.77	16.51	13.77	11.36	16.61
FeO	24.55	22.85	24.04	27.35	31.19
Cr_2O_3	48.20	45.04	46.28	46.06	40.50
MgO	10.19	12.35	10.71	11.15	8.21
Total	95.72	96.82	96.30	97.65	98.36

Table 3-5b

Analyses of Ore Minerals

Specimen No.	Picrite basalts				Basalts			
	392	110-1	110-2	110-3	19-1	19-2	19-3	389
SiO_2	0.12	0.40	0.20	0.07	0.08	0.22	0.26	0.14
TiO_2	48.53	29.86	24.30	29.12	28.46	29.55	28.95	20.81
Al_2O_3	-	2.18	2.22	1.95				
FeO	44.55	62.88	67.62	63.22	65.15	67.10	65.06	71.89
MgO	3.96	0.08	0.43	0.53	0.63	0.53	0.49	0.36
CaO	-	0.19	0.12	0.09	0.03	0.09	0.03	0.11
Total	97.16	95.59	94.89	94.98	94.35	93.49	94.79	93.31
Recalculated analyses:*								
Ulvospinel basis								
FeO		56.40	52.16	56.40	56.83	58.92	57.98	48.92
Fe_2O_3		8.37	17.22	7.66	9.25	9.09	7.66	25.52
Sum		97.48	96.65	95.82	95.31	100.04	95.37	95.86
Ilmenite basis								
FeO		38.08	36.79	38.80	38.94	40.38	39.66	36.00
Fe_2O_3		27.44	34.21	27.75	29.03	29.67	28.23	39.88
Sum		98.23	98.27	98.31	97.20	102.48	97.62	97.30

* After Carmichael (1967, p. 39)

in the picrite basalts resemble those chromites analysed from dunite or peridotite nodules from basalts (Ross et al., 1954), as shown in Table 3-5a.

Preliminary reflected light studies on these titano-magnetites have shown them to be homogeneous indicating that the rate of cooling below 600°C was sufficiently rapid to prevent any unmixing (Vincent, et al., 1957).

Even though data is scarce, for any detailed evaluation of the variation in the chemistry of the ore minerals, the following general comments may be made.

1. In the more basic picrite basalt as in the case of No. 392 (with 21.6% MgO), the chromites are richer in Cr_2O_3, total iron, TiO_2 and poorer in Al_2O_3, when compared with the chromites in the less basic (≃ 13.6% MgO) picrite basalt i.e. No. 110.

2. In addition, the groundmass ore in the former appears to be ilmenite, with 3.96% MgO, which is rather high, when compared with the compiled ilmenite analyses (Deer et al., 1962, Vol. 5, Table 5, p. 29).

3. The titano-magnetites appear to contain generally, higher TiO_2 contents (averaging 28.6%) than analogous titano-magnetites reported (Deer et al., 1962, Vol. 5, Table 12, p. 72; Wilkinson, 1965, p. 532).

3:8 Other Minerals

Phlogopite

Occasional flakes of mica have been noticed in some of the picrite basalts (Flow Nos. 10, 11 and 12 at Dhandhuka) and basalts (Flow No. 18 and 34 at Dhandhuka) being present either in the

Table 3-6

Phlogopite Analyses

Flow No. 34				
Specimen No. 21	P-1	P-2	P-3	P-4
SiO_2	40.08	39.44	40.40	39.65
TiO_2	4.80	4.94	4.50	4.74
Al_2O_3	10.93	10.90	10.89	10.60
FeO	9.08	8.91	9.06	8.92
MgO	19.76	19.45	20.10	19.72
CaO	0.06	0.07	0.11	0.10
Na_2O	0.90	0.92	0.70	0.91
K_2O	8.16	8.43	6.78	8.04
Total*	93.77	93.07	92.53	92.67
MgO/FeO	2.17	2.18	2.21	2.21

Note:- H_2O^{+*}, H_2O^{-*}, and F^* contents of the phlogopites constitute about 3-6% of the total. (From phlogopite analyses Deer et al., 1962; No.3, p.198, Table 18).

groundmass or in the micro-vesicles. The analysed mica (both from the groundmass and from the microvesicle) from specimen No. 21 (Table 3-6) was found to be phlogopite, with MgO/FeO ratios just exceeding 2, the limiting ratio for distinguishing phlogopites from biotites. The phlogopites are fairly rich in TiO_2, when compared with similar reported types (Deer *et al.*, Vol. 3, 1962).

Hornblende

Very scarce crystals of hornblende are found in some of the microvesicles and plagonite patches of Flow No. 18 Specimen No. 108 at Dhandhuka. The optical properties of the hornblende were found to be as follows:

Pleochroic scheme: X = straw yellow.
Y = pale brown
Z = brown

Absorption scheme: $Z \geq Y > X$

Extinction angle: $Z \wedge C = 21^\circ$ (maximum angle observed in a single section)

Apatite

Needles of apatite have been found in some flows, especially in the glassy portions (Flow No. 5 at Wadhwan Junction, 1, 3, 23, 29 and 37 at Dhandhuka).

Secondary minerals

A variety of secondary minerals, such as green palagonite, celadonite, delessite, chlorophaeite, chalcedony, opal, calcite, laumontite, heulandite, chabazite, stilbite etc. have been identified, and found to be present in the macro- and microvesicles (West, 1958).

Summary

The mineralogical summary of the bore hole flows are presented in Table 3-7.

Table 3-7

Mineralogical summary of the bore-hole flows

Minerals	Picrite Basalts	Three phenocryst basalts	Basalts	Method
Phenocrysts: Olivine	Fo_{94-80}	Fo_{82-71}	Altered	Optical
	Fo_{90-87}	Fo_{88} (Rare) to Fo_{84} (Common)		Probe
Clinopyroxene	$2V = 53^\circ - 59^\circ$ $\beta = 1.680-1.684$	$2V = 54 - 58$ $\beta = 1.681$	$2V = 50 - 54$	Optical
	$Mg_{51-46}Ca_{48-44}Fe_{5-9}$*	$Mg_{46-43}Ca_{46-41}Fe_{9-16}$	$Mg_{46-42}Ca_{46-40}Fe_{8-17}$	Probe
Plagioclase	Absent	An_{89-70}	An_{55-70}	Optical
		An_{72-88}	An_{57-66}	Probe
Ores	Chromites^{x}	Absent	Absent	Probe
Groundmass: Olivine	Fo_{76-67}	Altered	Altered	Optical
	Fo_{86-84}			Probe
Clinopyroxene	$2V = 49-58$ $\beta = 1.675$	$2V = 50-56$ $\beta = 1.678$	$2V = 44-53$ $\beta = 1.690-1.710$	Optical
	$Mg_{40}Ca_{45}Fe_{15}$			Probe
Plagioclase	An_{65-76}	An_{62-76}	An_{54-60}	Optical
	An_{88-74}		$An_{61}-An_{54}$	Probe
Ores	Chromite, Titano-magnetite and ilmenite	Titano-magnetite and scarce ilmenite		Probe

* In case of two zoned phenocyrsts the rims gave $Mg_{43-40}Ca_{48-45}Fe_{11-12}$.

x microphenocryst. <u></u>Note: Optical estimates of compositions of plagioclases, are taken from West (1958).

CHAPTER IV

GEOCHEMISTRY

4.1. Introduction

Major and trace element data of the bore hole samples are presented in this chapter. The variations in chemistry are briefly considered with regard to the petrographic and mineralogical changes, the more detailed aspects of which are dealt with in Chapters 6 and 7. Compositional variation with reference to the sequence of eruption is also considered.

The distribution of the different groups of flows in the bore holes, and the number of samples analysed in each group (including those presented by West, 1958) are given in Table 4-1.

Table 4-1

Rock type	Total number of flows present	Number of representative samples analysed
Basalts	16	14[a]
Three-phenocryst basalts	12	7[b]
Picrite basalts	20	18[c]

a = Excludes 2 duplicate analyses
b = " 1 " analysis
c = " 3 " analyses.

Petrographic descriptions of the analysed samples are given in Appendix B (Table B-1).

The analyses of the samples carried out during the present study, together with their CIPW norms are given in Table 4-2.

Table 4-2: Chemical analyses of bore hole flows (Present work)

A. Picrite basalts

Flow No.	D-32	D-30	D-15	D-12^a	D-11	D-10	D-9	D-8^a	D-7^a	D-6^a	D-5^a	W-5	W-2	W-1	B-6	B-5	B-4	B-1	B-s
Specimen No.	30	37	227	244	252	259	266	274	279	285	293	391	381	380	111	116	119	129	148
Wt.%																			
SiO_2	47.75	45.85	45.20	46.60	46.44	44.95	46.90	46.60	46.70	46.90	45.90	43.85	44.51	44.15	45.65	43.60	43.85	44.85	46.27
TiO_2	1.85	1.51	2.40	1.97	1.99	2.46	2.21	2.23	2.10	2.02	2.30	1.41	2.31	1.44	2.03	1.36	1.41	1.59	2.22
Al_2O_3	11.21	8.59	11.09	9.90	9.28	11.82	11.25	11.21	9.92	9.59	10.88	6.49	9.41	6.35	11.07	8.42	8.76	10.21	11.80
$Fe_2O_3^*$	1.54	1.57	1.76	1.61	1.61	1.72	1.63	1.55	1.62	1.63	1.60	1.64	1.71	1.55	1.62	1.59	1.63	1.63	1.56
FeO	8.74	8.92	9.95	9.31	9.11	9.72	9.25	8.79	9.17	9.22	9.06	9.05	9.67	8.79	9.19	9.01	9.14	9.14	8.72
MnO	0.14	0.15	0.18	0.14	0.17	0.16	0.16	0.16	0.18	0.17	0.16	0.19	0.18	0.19	0.17	0.20	0.18	0.20	0.17
MgO	10.19	16.01	9.96	12.98	15.23	10.42	10.43	10.50	11.09	12.78	10.56	20.60	14.95	22.37	13.70	20.94	19.16	16.09	11.27
CaO	11.43	10.62	13.12	12.97	11.11	12.11	12.03	12.03	13.27	12.22	12.77	9.34	9.70	8.33	11.81	9.97	10.64	11.59	12.21
Na_2O	1.54	1.32	1.47	1.62	1.75	2.08	2.91	1.12	1.57	1.42	1.98	1.15	1.15	0.64	1.79	1.06	1.35	1.38	2.21
K_2O	0.65	0.63	1.23	0.90	0.67	1.11	1.08	0.93	0.82	0.80	1.20	0.32	1.19	0.40	1.01	0.43	0.46	0.54	0.88
P_2O_5	0.27	0.24	0.31	0.30	0.29	0.35	0.30	0.29	0.30	0.27	0.32	0.20	0.31	0.17	0.35	0.19	0.21	0.25	0.39
H_2O+	4.07	3.01	3.78	2.49	2.34	3.31	2.29	3.53	3.99	2.84	2.76	5.51	3.25	5.50	1.21	2.97	1.47	1.92	0.98
Cr_2O_3	0.14	0.11	0.10	0.15	0.22	0.07	0.09	0.13	0.19	0.25	0.13	0.30	0.26	0.29	0.12	0.26	0.28	0.21	0.10
TOTAL	99.42	99.72	100.60	100.98	99.87	100.28	100.53	99.07	100.82	100.11	99.62	100.05	99.59	100.17	99.11	99.40	98.54	99.60	98.78
F/M$^{\Delta}$	50	40	54	46	45	52	51	50	49	46	50	34	43	32	44	34	36	40	48
ppm																			
Ba	400	200	495	365	275	545	435	355	305	305	620	130	245	110	500	190	225	240	545
Zr	140	110	145	129	132	185	172	142	132	135	159	105	115	95	170	105	110	120	200
Sr	300	200	315	340	265	400	350	280	290	273	285	145	170	96	435	215	245	265	495
Rb		14	36	27	26	33	26	16	15	23	32	10	27	9	22	9	10	9	19
Y	25	22	24	22	20	27	26	25	25	23	26	20	18	19	23	20	20	22	25
La	25	20	20	25	20	25	20	20	15	20	25		30	25	25	10	15	20	35
Ce	45	20	35	30	20	70	23	45	20	25	40		22	20	35	20	15	20	50
Ni	335	593	233	313	651	231	204	317	390	419	357	954	813	962	423	802	721	545	293
Cr	975	783	718	1051	1525	509	600	897	1 325	1692	860	2039	1770	2005	794	1799	1916	1439	709
V	266	237	321	274	234	327	171	290	215	276	280	177	224	199	271	194	218	222	293
Nb	30	25	39	37	32	50	38	34	31	30	30	27	31	26	39	26	27	25	36
Zn	73	76	101	75	87	76	81	81	94	78	86	74	97	85	85	74	77	71	79
Cu	92	101	116	102	86	109	110	110	121	89	124	82	124	80	103	86	97	103	122
CIPW NORMS (Calculated Water Free)																			
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Or	4.02	3.89	7.51	5.38	5.14	6.74	6.44	5.74	4.96	4.85	7.27	1.95	7.27	2.48	6.05	2.59	2.78	3.25	5.26
Ab	13.62	11.66	10.51	12.05	14.84	11.77	14.11	9.91	13.70	12.28	11.86	10.24	9.65	5.67	11.02	8.75	8.46	10.94	15.10
Ne	-	-	21.23	0.99	0.22	3.44	5.93	-	-	-	2.93	-	-	-	2.32	0.23	1.79	0.54	2.14
An	22.81	16.41	20.73	17.39	20.00	20.27	14.74	23.87	18.18	17.96	17.86	12.32	17.90	14.04	19.51	17.53	16.99	20.57	20.19
Di	28.09	29.76	36.05	36.99	25.81	31.81	35.60	29.54	38.57	34.28	36.64	28.12	24.02	22.64	30.27	25.65	28.76	29.36	31.56
Hy	22.37	9.96	-	-	-	-	-	18.70	2.99	8.64	-	6.89	13.98	18.23	-	-	-	-	-
Ol	2.21	22.20	15.73	20.10	25.91	17.65	15.68	4.56	14.10	14.62	15.58	34.18	18.91	30.83	23.53	39.40	35.13	28.95	18.08
Mt	2.33	2.38	2.63	2.36	2.50	2.57	2.39	2.35	2.42	2.42	2.39	2.51	2.57	2.36	2.38	2.36	2.42	2.41	2.31
Cr	0.21	0.16	0.15	0.22	0.34	0.10	0.13	0.19	0.28	0.38	0.19	0.46	0.40	0.44	0.18	0.40	0.43	0.31	0.15
Il	3.68	3.00	4.70	3.80	4.56	4.81	4.26	4.43	4.10	3.93	4.50	2.83	4.54	2.89	3.91	2.66	2.75	3.08	4.29
Ap	0.66	0.58	0.76	0.71	0.69	0.85	0.71	0.71	0.71	0.64	0.78	0.50	0.76	0.40	0.82	0.45	0.50	0.59	0.92

Abbreviations

$$F/M^{\Delta} = \frac{FeO + Fe_2O_3 \times 100}{FeO + Fe_2O_3 + MgO}$$

$Fe_2O_3^*$ = standardised to give 15 per cent of $Fe_2O_3/FeO + Fe_2O_3$.

D = Dhardhuka

B = Botad

W = Wadhwan Jn.

a = Ankaramitic type

Table 4-2 (contd.) B. Three-Phenocryst Basalts. C. Basalts.

Flow No.	D-34	D-18	D-16	D-4	D-3	D-1	W-3	D-37	D-36	D-35	D-33	D-29	D-26	D-25	D-23	D-21	D-20	D-19	D-17
Specimen No.	26	108	222	299	312	321	387	2≠	13	19	27	41	60	67	77	84	90	99	219
Wt.%																			
SiO$_2$	46.96	45.40	44.92	49.15	45.70	47.15	46.80	47.10	47.00	47.40	46.19	50.45	45.80	52.00	50.40	46.75	46.50	46.35	45.56
TiO$_2$	2.16	3.30	2.68	2.52	2.62	2.55	2.31	2.56	3.03	2.49	2.23	3.03	3.06	2.32	3.13	3.06	3.56	3.70	3.59
Al$_2$O$_3$	14.35	14.20	12.79	13.76	14.26	13.74	15.78	16.08	14.53	15.99	16.50	15.24	15.09	16.16	14.92	15.07	14.01	14.32	13.31
Fe$_2$O$_3$*	1.83	2.02	1.84	1.69	1.65	1.53	1.55	1.62	1.79	1.61	1.60	1.77	1.93	1.37	1.79	1.77	2.06	2.06	2.02
FeO	10.34	11.42	10.41	9.62	9.33	8.64	8.78	9.20	10.17	9.15	9.05	10.06	10.96	7.82	10.17	10.08	11.69	11.66	11.43
MnO	0.15	0.15	0.18	0.15	0.21	0.16	0.14	0.15	0.17	0.14	0.14	0.16	0.18	0.16	0.18	0.15	0.20	0.18	0.19
MgO	5.38	5.43	6.86	6.02	7.93	6.12	6.61	5.44	5.61	5.80	5.72	3.75	4.28	2.82	3.93	5.12	4.89	4.90	4.99
CaO	11.84	11.32	12.22	10.61	9.86	10.38	12.49	10.48	10.86	11.17	8.99	9.59	9.21	8.69	8.81	9.81	11.45	10.11	10.08
Na$_2$O	2.08	2.74	1.98	2.38	2.12	2.55	2.70	2.77	2.75	2.44	2.00	3.09	2.83	2.59	3.31	3.12	2.17	2.94	2.66
K$_2$O	0.88	1.41	1.85	1.61	1.80	1.70	0.94	1.07	1.32	1.03	1.29	0.93	1.17	2.41	1.63	1.03	0.91	1.57	2.33
P$_2$O$_5$	0.29	0.46	0.37	0.43	0.43	0.37	0.30	0.32	0.36	0.31	0.34	0.40	0.38	0.39	0.42	0.38	0.42	0.46	0.37
H$_2$O+	2.54	1.62	3.73	2.60	4.31	4.52	2.06	1.97	1.68	2.16	5.60	2.22	2.63	2.43	1.48	4.20	2.47	2.06	3.62
TOTAL	100.18	99.54	100.34	100.54	100.22	100.98	100.46	98.96	99.27	99.69	99.65	100.34	100.52	99.15	100.17	100.44	100.33	100.31	99.76
F/M$^{\Delta}$	69	71	64	65	58	62	61	67	68	65	65	76	75	77	75	70	74	74	73
ppm																			
Ba	310	595	880	1145	665	1115	355	415	575	450	340	510	470		470	400	315	465	1545
Zr	150	235	185	318	205	205	152	185	200	172	300	250	252	238	260	220	250	260	255
Sr	380	493	610	425	365	475	460	510	480	510	295	510	452	618	410	660	455	459	540
Rb	16	35	52	43	39	34	23	28	25	24	26	32		65		27	20	24	60
Y	23	29	29	31	25	29	25	28	27	27	38	37	29	31	38	31	36	35	38
La	15	45	35	55	50	30	20	25	30	20	45		55	35	35	30	50	40	50
Ce	40	110	80	85	75	70	45	50	50	40	90		105	95	75	55	105	80	115
Ni	81	76	129	92	96	117	82	76	54	75	74	43	46	40	38	69	68	60	79
Cr	175	54	165	124	116	209	213	136	90	199	110		46	24	32	74	40	33	47
V	293	433	392	312	346	317	259	320	384	287	301	324	364	339	334	397	511	478	447
Nb	34	43	65	40	41	41	33	40		35		41	42	44	44	39	41	45	55
Zn	60	101	102	90	102	87	75	74	88	60	83	95	97	90	103	115	111	110	130
Cu	84	130	90	92	90	71	77	69	113	85	60	124	125	125	128	124	130	163	132
CIPW Norms																			
Qz	-	-	-	-	-	-	-	-	-	-	-	2.72	0.49	5.08	0.06	-	-	-	-
Or	5.40	8.51	11.35	9.69	11.05	10.57	5.62	6.50	7.98	6.21	8.10	5.54	7.03	14.72	9.75	6.32	5.44	9.40	14.25
Ab	18.29	17.35	10.85	20.57	18.71	22.71	17.78	24.2	23.24	21.16	17.94	26.48	24.46	22.60	28.35	27.40	18.71	22.80	16.61
Ne	-	3.40	3.53	-	-	-	2.93	-	0.30	-	-	-	-	-	-	-	-	1.36	3.61
An	28.27	22.91	21.42	22.56	25.11	22.17	28.64	29.24	24.01	30.40	34.30	25.42	25.57	26.24	21.32	24.98	26.42	21.65	18.16
Di	25.54	26.07	32.14	23.33	18.74	24.19	26.46	18.35	23.76	20.03	8.83	16.94	15.52	13.15	16.84	19.00	24.05	21.96	25.87
Hy	11.49	-	-	12.68	1.35	2.67	-	3.94	-	7.00	21.91	13.52	17.24	10.69	14.03	1.92	12.79	-	-
Ol	3.31	11.28	11.75	2.78	16.31	9.34	11.14	9.54	11.31	7.22	1.10	-	-	-	-	10.80	1.666	11.58	10.51
Mt	2.75	2.99	2.77	2.49	2.49	2.33	2.28	2.42	2.65	2.39	2.47	2.60	2.86	2.04	2.62	2.65	3.05	3.04	3.03
Il	4.26	6.40	5.29	4.88	5.19	5.10	4.45	5.01	5.89	4.84	4.50	5.83	5.93	4.54	6.02	6.02	6.90	7.14	7.06
Ap	0.70	1.09	0.91	1.02	1.04	0.92	0.71	0.78	0.85	0.73	0.85	0.94	0.90	0.95	1.00	0.92	1.00	1.09	0.90

Note:
2≠ Includes 0.20% CO$_2$

Table 4-2a. Analyses of Bore Hole Samples from West (1958)

	Basalts				T.P.B.	Picrite Basalts		
Flow No.	D-27	D-26	D-19	D-28	W-3	D-6	B-1	W-5
Specimen No.	50a	58	99	45	384	283	129	393
Wt.%								
SiO_2	48.53	46.39	45.20	47.90	45.54	45.43	43.45	42.18
TiO_2	3.02	3.15	3.84	3.25	2.17	2.01	1.74	1.26
Al_2O_3	15.58	16.43	15.18	16.88	16.05	9.46	10.35	6.76
$Fe_2O_3{}^*$	1.82	1.89	2.03	1.53	1.58	1.65	1.78	1.57
FeO	10.33	10.70	11.55	9.24	8.92	9.38	10.41	8.88
MnO	0.33	0.16	0.20	0.29	0.34	0.21	tr	0.31
MgO	3.95	4.08	4.90	4.65	7.32	14.50	18.18	23.17
CaO	9.26	9.52	9.71	8.66	11.46	11.69	11.10	8.35
Na_2O	2.62	2.72	2.64	2.75	2.01	1.39	1.07	0.84
K_2O	0.70	1.28	1.59	1.24	0.59	0.88	0.39	0.52
P_2O_5	0.31	0.44	0.47	0.25	0.23	0.19	0.17	0.16
H_2O+	1.42	1.34	1.88	1.40	2.15	2.36	0.50	4.61
H_2O-	2.18	2.01	1.59	2.05	1.46	0.44	0.50	1.44
TOTAL	100.05	100.11	100.78	100.09	99.81	99.59	99.64	100.05
F/M^{Δ}	75	76	73	70	59	43	40	31
			CIPW Norms (calculated water free)					
Qz	3.25	-	-	-	-	-	-	-
Or	4.26	7.80	9.64	7.88	3.61	5.32	2.31	3.25
Ab	22.94	23.78	22.38	25.04	17.61	12.11	6.86	7.53
Ne	-	-	0.31	-	-	-	1.24	-
An	29.78	29.83	25.56	32.42	34.39	17.59	22.63	14.00
Di	13.17	13.37	17.24	10.07	18.96	32.97	25.70	23.03
Hy	17.18	8.66	-	3.00	7.38	0.24	-	1.88
Ol	-	6.50	13.21	11.94	10.87	24.93	34.91	44.93
Mt	2.73	2.83	3.02	2.39	2.38	2.47	2.61	2.42
Il	5.95	6.17	7.49	6.65	4.27	3.93	3.34	2.55
Ap	0.76	1.07	1.14	0.62	0.54	0.45	0.40	0.40

$Fe_2O_3{}^*$ and F/M^{Δ} as in Table 4-2.

Chemical analyses reported in West (1958) are given in Table 4-2a.

4:2 Normative character of the flows:-

The normative character of the flows have already been described (see Chapter 2, Section 2:1,c, page 13).

In summary, the flows constitute a group in which both nepheline and quartz occur in the norm, but neither of them exceed ~6% in amount, and thus indicate the transitional or mildly alkaline character of the bore hole suite.

4:3 Frequency distribution of major and trace elements:-

Minimum, maximum and mean values for each chemical variable in all the analysed samples are presented in Table 4-3. Histograms, presented in Figs. 4-1a and 4-1b show the frequency distribution of the major and trace element data respectively. The lack of normal distribution of the data can be clearly seen from the figures. Such a feature indicates that one cannot attach much significance to the mean values, given in Table 4-3. In this context, the minimum, maximum and mean values for each chemical variable, in each group of flows, namely, basalts (Table 4-4), three-phenocryst basalts (Table 4-5) and picrite basalts (Table 4-6) may be more meaningful than the average given in Table 4-3.

Fig. 4-1a: Histograms of major oxide distributions in the bore hole flows.

Fig. 4-1b: Histograms of trace element distributions in the bore hole flows.

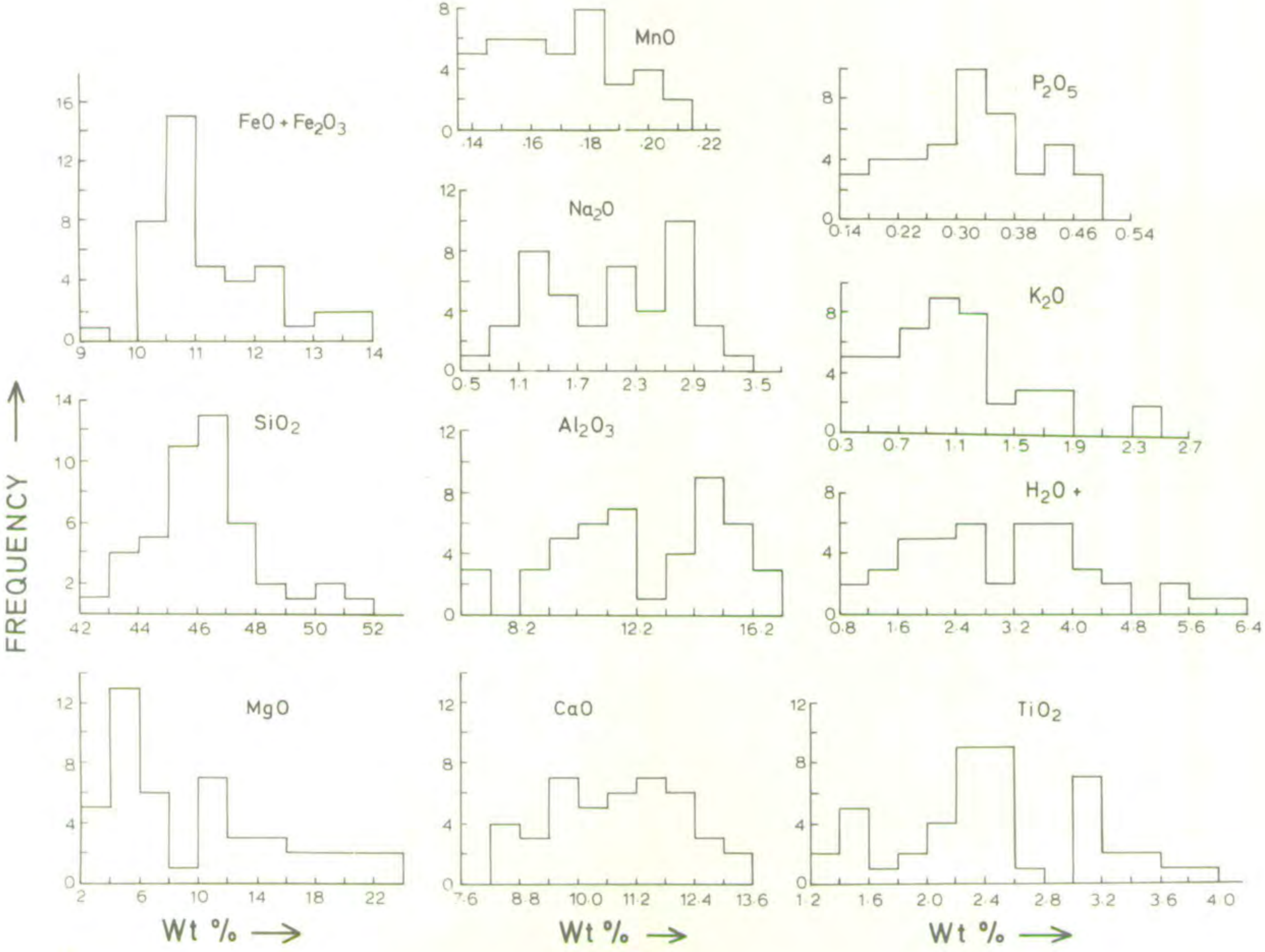

FREQUENCY
FeO + Fe2O3
16
12
8
4
0
9
10
11
12
13
14
MnO
8
4
0
.14
.16
.18
.20
.22
P2O5
8
4
0
0.14
0.22
0.30
0.38
0.46
0.54
Na2O
12
8
4
0
0.5
1.1
1.7
2.3
2.9
3.5
K2O
8
4
0
0.3
0.7
1.1
1.5
1.9
2.3
2.7
SiO2
14
10
6
2
42
44
46
48
50
52
Al2O3
12
8
4
0
8.2
12.2
16.2
H2O +
8
4
0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
6.4
MgO
12
8
4
0
2
6
10
14
18
22
CaO
12
8
4
0
7.6
8.8
10.0
11.2
12.4
13.6
TiO2
12
8
4
0
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
Wt %
Wt %
Wt %

Fig. 4 -1a

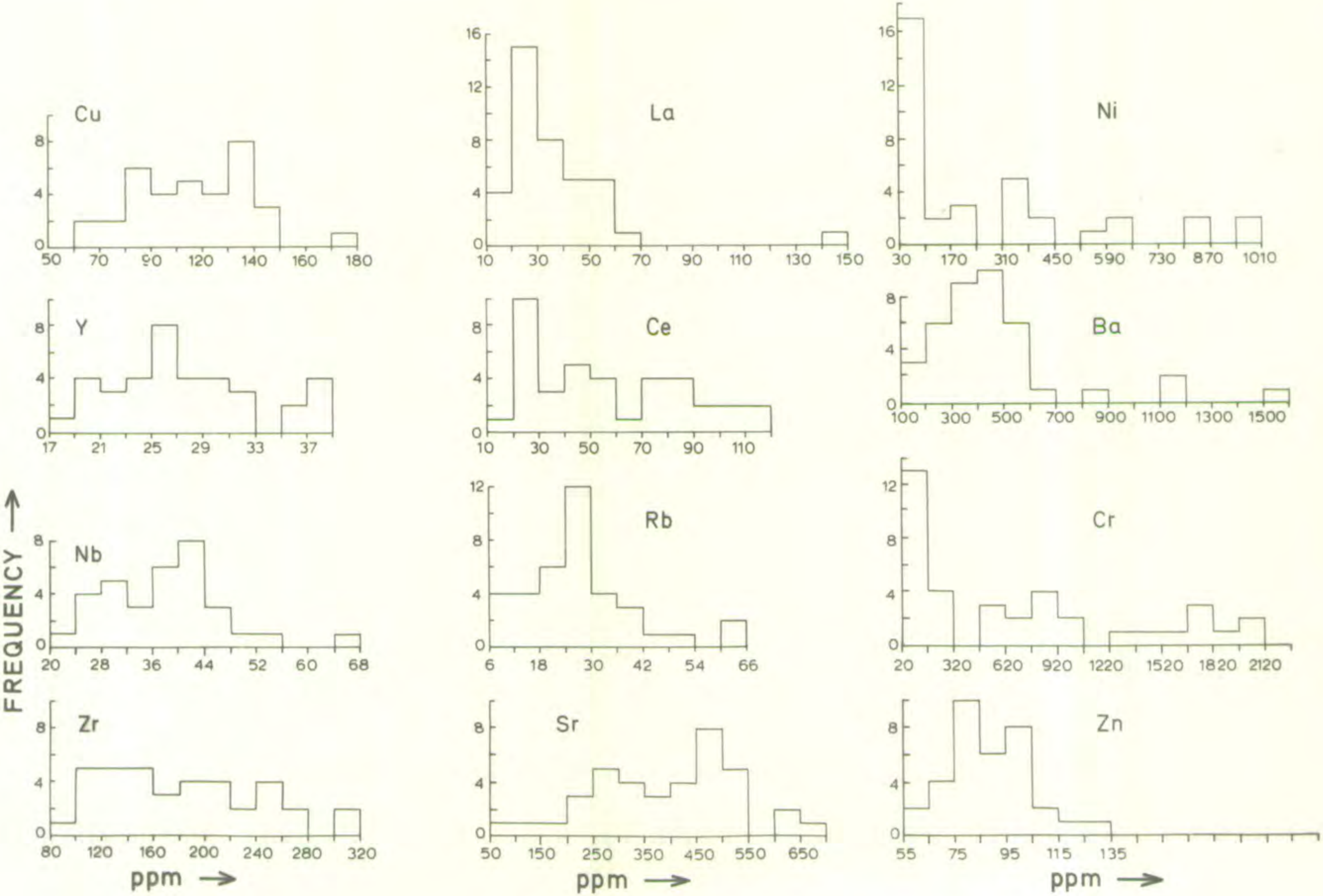

FREQUENCY
Cu
0 4 8
50 70 90 120 140 160 180
La
0 4 8 12 16
10 30 50 70 90 110 130 150
Ni
0 4 8 12 16
30 170 310 450 590 730 870 1010
Y
0 4 8
17 21 25 29 33 37
Ce
0 4 8
10 30 50 70 90 110
Ba
0 4 8
100 300 500 700 900 1100 1300 1500
Nb
0 4 8
20 28 36 44 52 60 68
Rb
0 4 8 12
6 18 30 42 54 66
Cr
0 4 8 12
20 320 620 920 1220 1520 1820 2120
Zr
0 4 8
80 120 160 200 240 280 320
Sr
0 4 8
50 150 250 350 450 550 650
Zn
0 4 8
55 75 95 115 135
ppm
ppm
ppm

Fig. 4 - 1b

Table 4-3

Summary of chemical analyses (38 samples present work; 8 samples from West (1958)).

Wt.%	Max.	Min.	Mean	σ	Anhydrous mean
SiO_2	52.00	42.18	46.33	1.881	47.83
TiO_2	3.84	1.26	2.42	0.663	2.50
Al_2O_3	16.88	6.35	12.52	2.971	12.93
Fe_2O_3) FeO)	13.75	9.49	11.32	1.040	11.70
MnO	0.34	0.14	0.18	0.047	0.19
MgO	23.17	2.82	9.78	5.664	10.11
CaO	13.12	8.33	10.75	1.363	11.10
Na_2O	3.31	0.64	2.06	0.700	2.13
K_2O	2.41	0.32	1.07	0.480	1.12
P_2O_5	0.47	0.16	0.32	0.084	0.33
H_2O+	6.05	0.98	2.99	1.228	-
In ppm (Present work - 38 analyses only)					
Ba	1545	110	466		
Zr	318	95	181		
Sr	660	96	380		
Rb	65	9	26		
Ni	962	38	268		
Cr	2039	24	667		
V	511	171	303		
Nb	65	25	37		
Zn	130	71	83		
Cu	163	60	104		
Y	38	18	27		
La	55	10	29		
Ce	115	15	53		

Table 4-4

Basalts (12 analyses, present work)

Wt. %	Max.	Min.	Mean	σ
SiO_2	52.00	45.56	47.62	2.107
TiO_2	3.59	2.23	2.98	0.494
Al_2O_3	16.50	13.31	15.10	0.964
Fe_2O_3	2.06	1.60	1.78	0.211
FeO	11.69	7.82	10.12	1.187
MnO	0.19	0.14	0.17	0.016
MgO	5.72	2.82	4.77	0.909
CaO	11.45	8.69	9.94	0.924
Na_2O	3.31	2.00	2.72	0.385
K_2O	2.41	0.91	1.39	0.512
P_2O_5	0.46	0.32	0.38	0.043
H_2O+	5.60	1.48	2.71	1.192
In ppm				
Ba	1545	315	541	
Zr	300	172	237	
Sr	660	295	492	
Rb	65	20	33	
Y	38	27	33	
La	55	20	38	
Ce	115	40	78	
Ni	78	38	60	
Cr	136	24	76	
V	511	301	374	
Nb	55	35	43	
Zn	130	60	96	
Cu	163	60	115	

σ = standard deviation

Table 4-5

Three phenocryst basalts (7 analyses, present work).

Wt. %	Max.	Min.	Mean	σ
SiO_2	49.15	44.92	46.58	1.417
TiO_2	3.30	2.16	2.59	0.361
Al_2O_3	15.99	12.79	14.13	0.902
Fe_2O_3	2.02	1.53	1.73	0.174
FeO	11.42	8.64	9.79	0.994
MnO	0.21	0.14	0.16	0.024
MgO	7.93	5.38	6.34	0.892
CaO	12.49	9.86	11.25	0.994
Na_2O	2.74	1.98	2.36	0.310
K_2O	1.85	0.88	1.46	0.399
P_2O_5	0.46	0.31	0.38	0.065
H_2O+	4.52	1.62	3.05	1.133
In ppm				
Ba	1145	310	724	
Zr	318	150	207	
Sr	610	365	458	
Rb	52	16	35	
Y	31	23	27	
La	55	20	36	
Ce	110	40	54	
Ni	129	n76	96	
Cr	213	54	151	
V	433	259	336	
Nb	65	33	42	
Zn	102	60	88	
Cu	130	71	91	

Table 4-6

Picrite basalts (19[a] analyses, present work).

Wt. %	Max.	Min.	Mean	σ
SiO_2	47.75	43.60	45.58	1.196
TiO_2	2.46	1.36	1.96	0.383
Al_2O_3	11.82	6.49	9.94	1.618
FeO Fe_2O_3	11.71	10.28	10.80	0.399
MnO	0.20	0.14	0.17	0.017
MgO	22.37	9.96	14.10	4.058
CaO	13.27	8.33	11.41	1.376
Na_2O	2.91	0.64	1.55	0.503
K_2O	1.23	0.32	0.81	0.289
P_2O_5	0.39	0.17	0.28	0.058
Cr_2O_3	0.07	0.30	0.18	0.076
H_2O+	5.50	0.98	3.01	1.230
<u>In ppm</u>				
Ba	620	110	341	
Zr	200	95	136	
Kb	36	9	21	
Y	27	18	23	
La	35	15	22	
Ce	70	15	31	
Ni	962	204	464	
Cr	2039	509	1232	
V	327	171	247	
Nb	50	25	32	
Zn	101	71	82	
Cu	124	80	103	
Sr	495	96	282	

a = Includes one surface flow at Botad
(B-s of Table 4-2).

4:4 Variation Diagrams:-

In spite of criticism of the use of conventional Harker type (i.e. oxide vs. oxide plot) variation diagrams (Chayes, 1967; Pearce, 1968), such diagrams are simple, but when several different types are used in conjunction they can effectively portray the chemical variations encountered in complex natural systems. MgO, has been chosen here, as a simple index of variation for the following reasons.

1. A study of the range and variance of the different major constituents (Table 4-7) clearly show that five major oxides such as SiO_2, CaO, MgO, Al_2O_3 and Total iron ($FeO+Fe_2O_3$) account for 98% of the total variance, and in that MgO alone amounts to 66%.

2. Olivine, clinopyroxene and plagioclase are the three dominant phenocryst phases, and with the exclusion of minor oxides, their compositions can be expressed in terms of the above mentioned five major oxides. Mineral control lines and simple graphical extract calculations of these phenocryst phases can also be shown in such simple oxide vs. oxide plots.

3. Simple assessment of the overall variation can be made in such MgO vs. oxide plots, which is not feasible in the case of diagrams based on the differentiation index, determined by the amount of salic minerals in the norm excluding anorthite (Thornton and Tuttle, 1960) or the solidification index, which is a measure of the percentage of MgO in the sum of $MgO + FeO + Fe_2O_3 + Na_2O + K_2O$ (Kuno, 1968).

Table 4-7

An analysis of the variance of the major oxides (all the 46 analyses as in Table 4-3).

Wt.%	σ	σ^2	% of total variance	
SiO_2	1.881	3.54	7.29	7.29
TiO_2	0.663	0.44	0.91	
Al_2O_3	2.971	8.83	18.18	18.18
Fe_2O_3 FeO	1.040	1.08	2.22	2.22
MnO	0.047	0.002	0.004	
MgO	5.664	32.08	66.06	66.06
CaO	1.363	1.86	3.83	3.83
Na_2O	0.700	0.49	1.01	
K_2O	0.480	0.23	0.47	
P_2O_5	0.084	0.007	0.0014	
				97.58

4:5 Major oxide variation:-

Figure 4-2 (wt.% MgO plotted against other oxides) portrays the major oxide variations of the bore hole flows, and with decreasing MgO, the following features can be observed:

a) the fairly continuous variation in the major oxides (except for the absence of compositions between 8-10% MgO) with gentle slope changes at ~10-12% MgO (seen in the CaO and Al_2O_3 plot) and at ~5-6% MgO (seen in the plots of TiO_2, SiO_2, total iron and Na_2O(?)) the latter being very subtle and not very conspicuous.

b) gradual increase of Al_2O_3 with falling MgO.

c) initial increase of CaO, followed by a decrease from ~10-12% MgO.

d) the fairly constant amount of total iron from 24 to 6% of MgO, and then a slight tendency to increase at lower MgO values.

e) the gradual but very slight increase of SiO_2 and TiO_2 from 24-6% of MgO, followed by a tendency to increase slightly in rocks with low MgO.

d) K_2O and Na_2O show a slight increase with falling MgO. The increase in the latter being marked at ~ 5% MgO.

e) P_2O_5 shows a slight increase with falling MgO while MnO shows very little change.

4:6 Trace element variation:-

The trace elements studied comprise both "incompatible" (Ba, Zr, Nb, La, Ce, Rb and Sr) and "compatible" (Cr, V, Ni and Y) elements (Ringwood, 1966). These trace elements are plotted

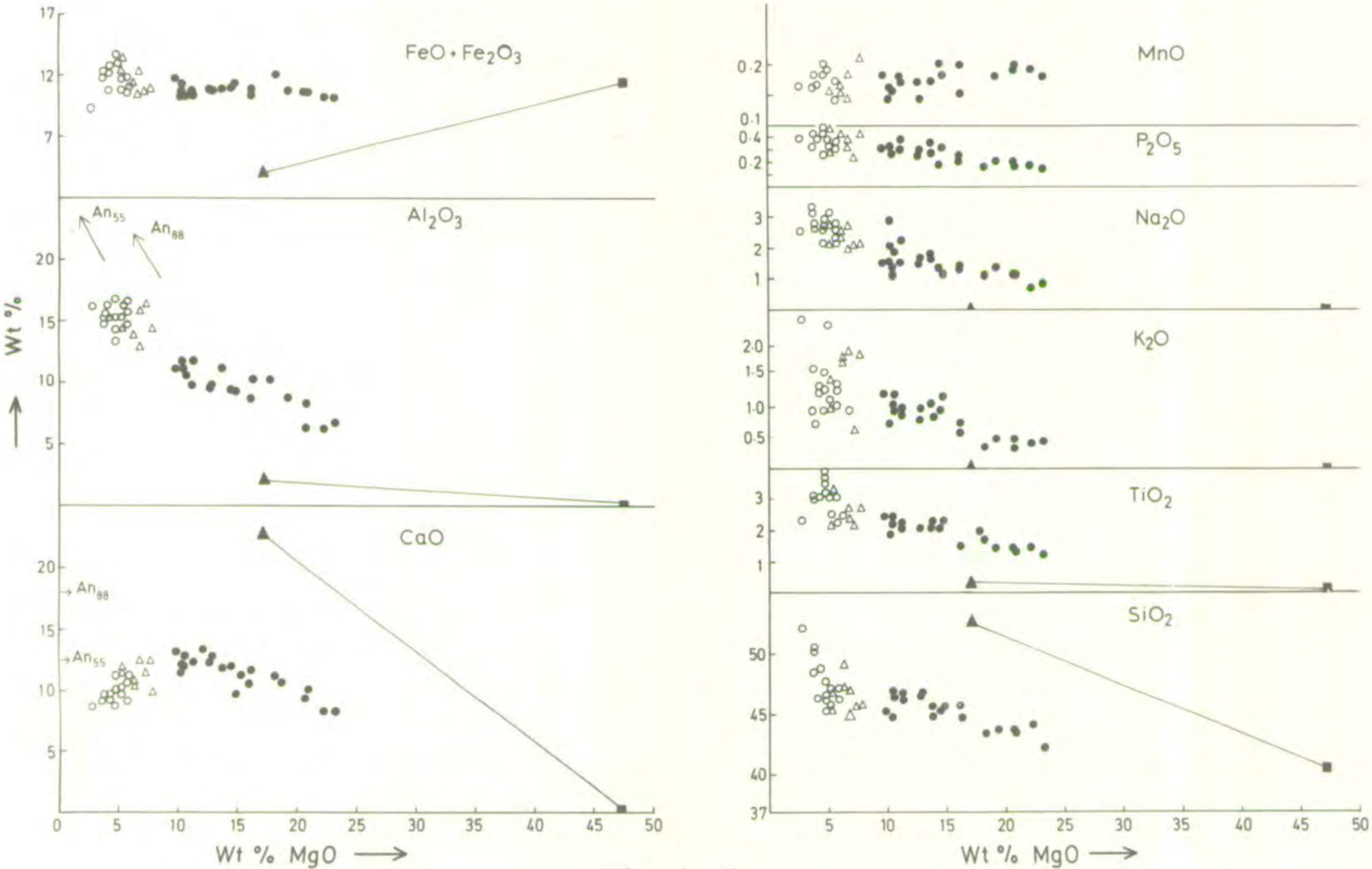
Fig. 4-2: Variation diagrams for major oxides with MgO in the bore hole flows. Solid lines are olivine-augite tie lines.

Filled square = average of 8 olivine phenocrysts excluding "rim" compositions in the case of zones crystals from picrite basalts (see Table 3-1)

Filled triangle = average of 10 clinopyroxene phenocrysts excluding rim compositions in the case of zoned crystals from picrite basalts (see Table 3-2)

Arrows indicate the compositional range of the analysed plagioclase feldspars from the three-phenocryst basalts and basalts.

Other symbols as in Fig. 2-2.



FeO + Fe$_2$O$_3$
Al$_2$O$_3$
CaO
An$_{55}$
An$_{88}$
Wt %
Wt % MgO
17
12
7
20
15
10
5
0
25
30
35
40
45
50
MnO
P$_2$O$_5$
Na$_2$O
K$_2$O
TiO$_2$
SiO$_2$
0·2
0·1
0·4
3
2
1
2·0
1·5
1·0
0·5
37

Fig. 4-2

Fig. 4-3: Variation of trace elements with MgO in the bore hole flows.

Symbols as in Fig. 2-2.

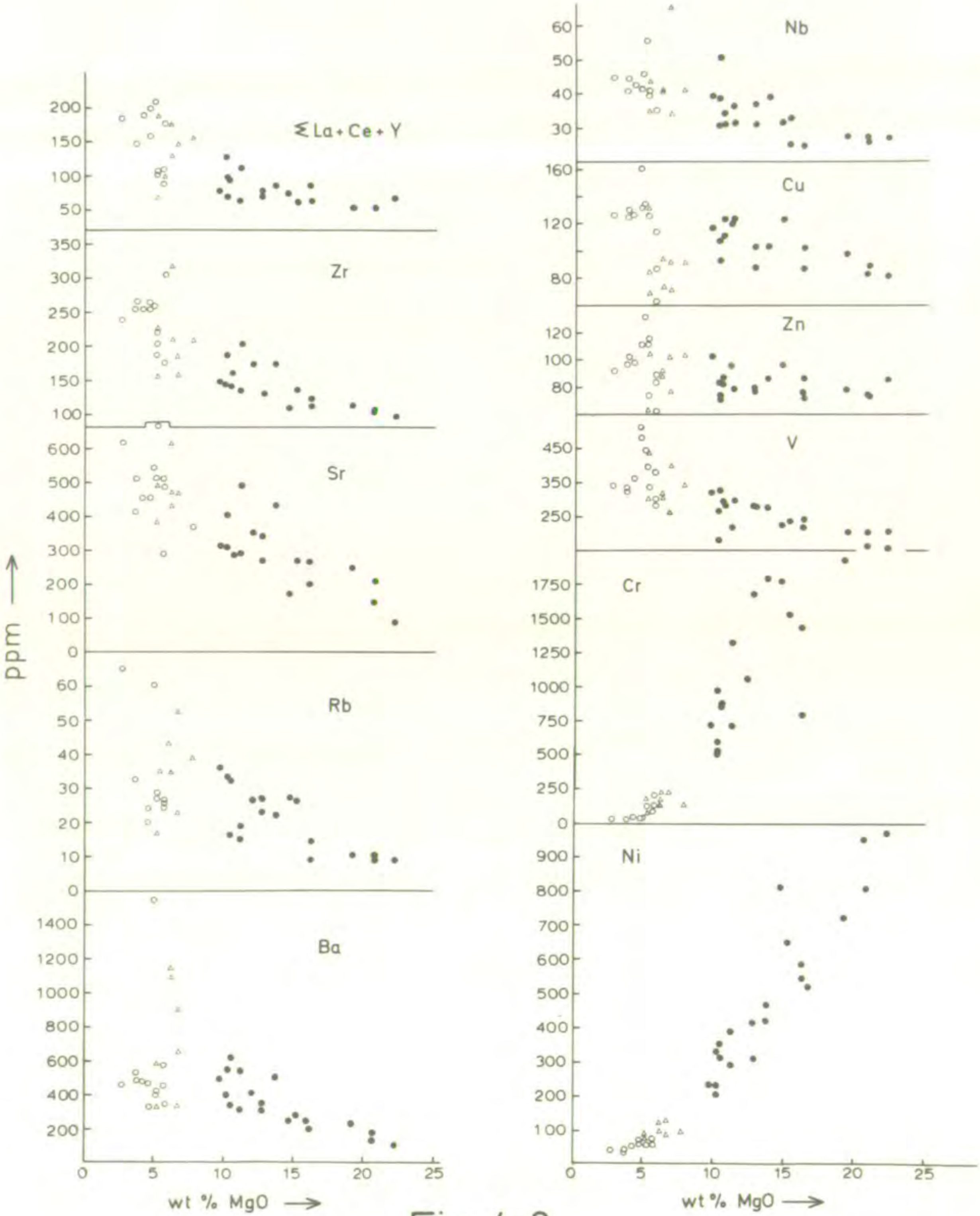


Fig. 4-3

against wt.% MgO (Fig. 4-3) as in the case of major oxides. The trace element variations are broadly consistent with those observed for the major oxides. Variations observed in individual trace elements or closely related pairs are briefly considered in the following section.

Nickel and chromium:-

Both Ni and Cr show a strong decrease initially (from ~23-10% MgO) and thereafter decrease rather slowly. They appear to be preferentially enriched in the olivines and clinopyroxenes respectively (see olivine and clinopyroxene analyses, Tables 3-1 and 3-2). There is a fair amount of scatter in both Ni and Cr and such a feature could be attributed to

a) the varying amounts of olivine and clinopyroxene phenocrysts in the analysed flows, especially in the picrite basalts and

b) presence of minor amounts of chromite both as microphenocrysts and as inclusions in some olivine phenocrysts of the picrite basalts (see Table 3-5a).

Vanadium:-

V shows a progressive increase with decreasing MgO, and is probably present in the titano-magnetites, found as scarce microphenocrysts in some of the three phenocryst basalts and basalts.

Zirconium and Niobium:-

With decreasing MgO, both Zr and Nb show a gradual increase, suggesting that they were enriched in the residual liquids.

Barium and Rubidium:-

Both Ba and Rb show a close positive correlation with potassium (Fig. 4-4a and 4-4b) and show maximum enrichment in the basalts. With regard to their enrichment and abundance, the following features need to be pointed out.

1. There is a fairly wide difference in the absolute concentrations of these two elements, and the closely related major element i.e. potassium, within any single group of flows, particularly in the basalts (see Table 4-8).

2. The K/Rb ratios (Fig. 4-4b) of the flows show a fair amount of scatter, the ratios ranging from 240 to 542 with an average of 359, compared with the average of 430 for basic rocks (Erlank, 1968, p. 880).

Strontium:-

Sr shows a steady increase with decreasing MgO. The slight spread in the amounts of Sr, particularly in the basalts, is probably related to the varying amounts of plagioclase phenocrysts in the flows.

Lanthanum, Cerium and Yttrium:-

There is an increase in the total amounts of La, Ce and Y with decreasing MgO, and thus they appear to have been enriched in the residual liquids. However, these elements show a fair amount of variation even at a particular stage of evolution, say MgO content (see Fig. 4-3) and in this respect show similarities to the variations of K, Ba and Rb.

Copper and Zinc:-

There are no clearly discernible trends in the variations of Cu and Zn. The basalts on the average tend to contain higher amounts of Cu and Zn, when compared with the amounts present in three phenocryst basalts and picrite basalts. Preliminary optical

Fig. 4-4a: Plot of potassium vs. barium.

Fig. 4-4b: Plot of potassium vs. rubidium.

Symbols as in Fig. 2-2.

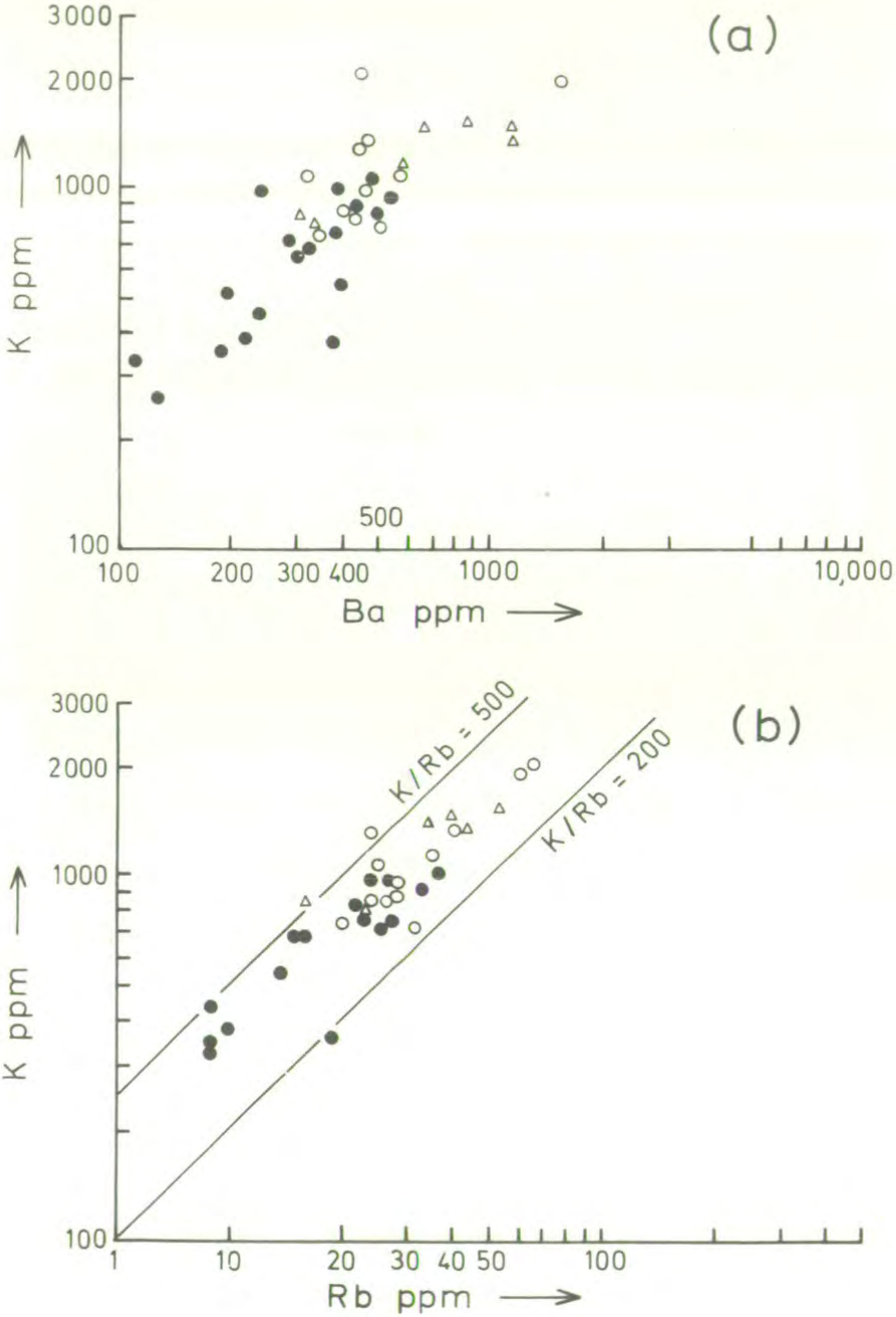

(a)
3000
2000
1000
100
K ppm
500
100
200
300
400
1000
10,000
Ba ppm
(b)
K/Rb = 500
K/Rb = 200
3000
2000
1000
100
K ppm
1
10
20
30
40
50
100
Rb ppm

Fig. 4-4

Table 4-8

Observed limits of variation in the concentrations of K, Rb and Ba in the different types of analysed samples.

Type of flow	Concentrations in ppm					
	K		Rb		Ba	
	Min.	Max.	Min.	Max.	Min.	Max.
Basalts	7552	20000	20	65	400	1545
Three-phenocryst basalts	7801	15353	14	36	310	1145
Picrite basalts including Oceanites and Ankaramites	2656	10208	9	36	110	620

studies have not indicated the presence of any sulphide minerals.

4:7 Sequence of eruption and the nature of chemical change:- Introduction

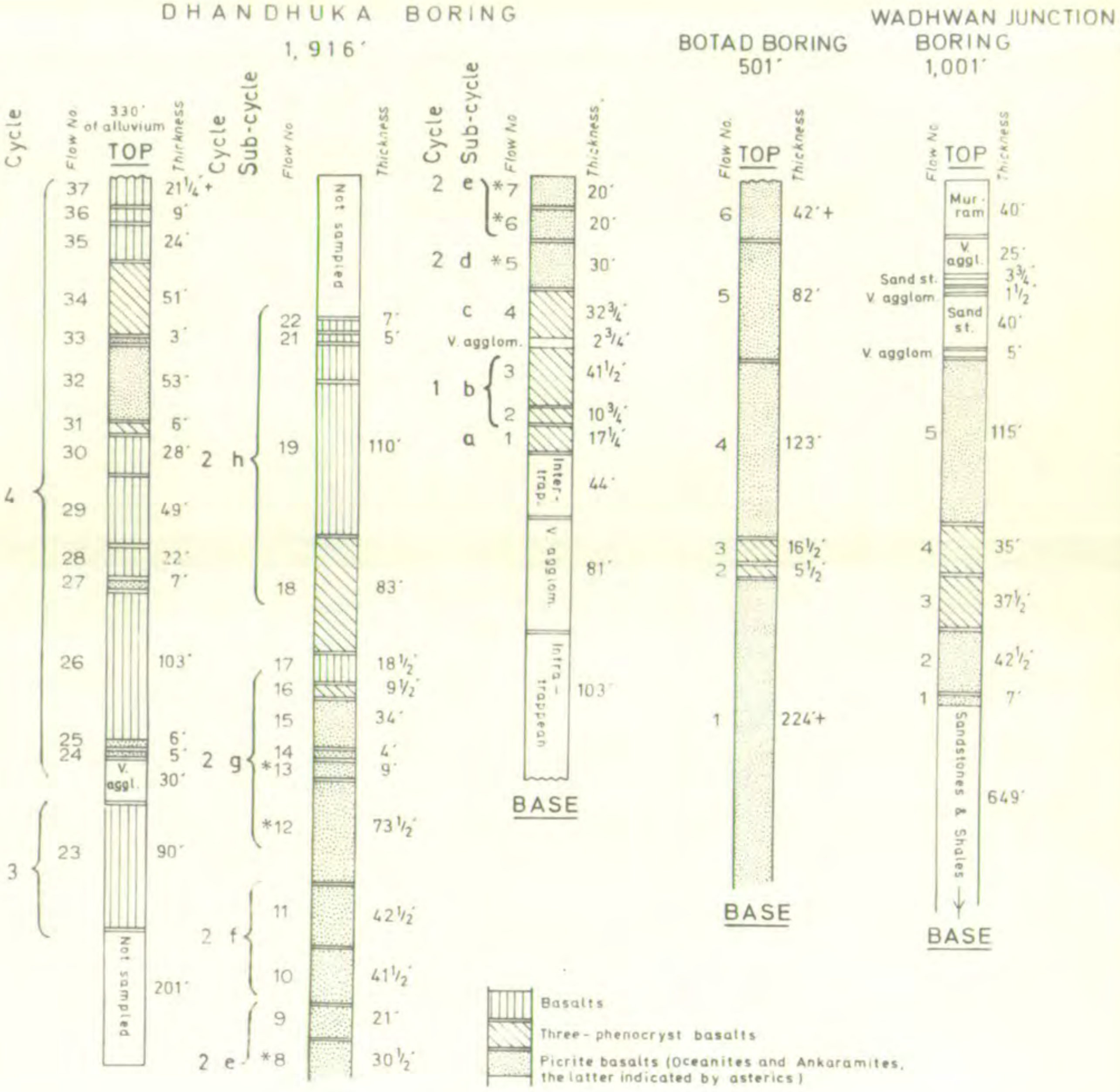
Of the three bore holes, the Dhandhuka bore penetrates a maximum thickness of 1916 feet comprising 1599 feet lavas and about 315 feet agglomerates, the remaining being beds of inter-trappeans and "infra-trappean". Since it covers a larger section, and comprises all the three groups of flows, it is taken to show the nature of the variation in a more representative way. The sections of the three bore holes are reproduced in Fig. 4-5. At Dhandhuka, the lowest bed of volcanic agglomerate overlies a bed of "infra-trappean" (sandstones and grits), a formation presumed to be of Turonian age (late Cretaceous) (Pascoe, 1964). The lowest flow of this bore, however, overlies a bed of inter-trappean rock, which indicates that there has been a break in the volcanic sequence at the start of the cycle, at Dhandhuka.

4:8 Delineation of Volcanic cycles and sub-cycles and the nature of chemical variation:-

The cyclical nature of the volcanic phenomena appears to be fairly well established from studies conducted on presently active volcanic fields, such as in Hawaii (Richter et al., 1970). However, identification of the different cycles may not be easy, particularly in ancient volcanic terrains. In the present case, horizons of volcanic agglomerates are taken to represent the beginning of a cycle, large or small. Beds of red bole on top of a lava flow and/or

Fig. 4-5: Section of the bore hole flows. The various cycles and sub-cycles in the case of the Dhandhuka bore has been indicated.

SECTION OF THE BORE HOLES



the reddened top of a flow are assumed as indicators of minor breaks in the cycle, i.e., the beginning of a sub-cycle. On this basis, a total of 4 cycles and 8 sub-cycles have been recognised at Dhandhuka.

Chemical variation of the major oxides and trace elements for the Dhandhuka succession are shown in Figs. 4-6a and 4-6b respectively and the following points emerge from a study of the variations.

1) a cycle invariably appears to start with either the slightly evolved three-phenocryst basalts as in cycles No. 1 and 2 or with evolved basalts, as in No. 3 and 4. However, in the case of the Wadhwan Junction flows, the cycle appears to have started with picrite basalts.

2) A cycle may be composed of entirely evolved liquids, i.e. basalts as in No. 3, or, on the other hand may comprise both basalts and picritic types, as in No. 2 and 4.

3) Within a sub-cycle, however, the erupted products may comprise entirely picritic compositions with varying MgO contents as in sub-cycle No. 2-d, -e, -f, and -g or may be composed of slightly evolved compositions as in No. 2-c.

Although these variations point out the randomness of the eruptive mechanisms which are probably to a large extent dependent upon the magma pressure and local tectonic conditions, they have an important bearing on the low pressure evolution experienced by the parental or primitive liquid. The chemical variations, when considered in conjunction with the nature of the erupted rocks may indicate the time of pause, the rate of heat loss, and the probable

Fig. 4-6a: Major oxide variation with sequence of eruption at the Dhandhuka bore. Different volcanic cycles and sub-cycles are indicated at the left hand side of the diagram. Asterisks indicate more than one analyses from the same flow but from different levels.

Symbols as in Fig. 2-2.

DHANDHUKA BORING : VARIATIONS IN MAJOR OXIDES WITH SEQUENCE OF ERUPTION

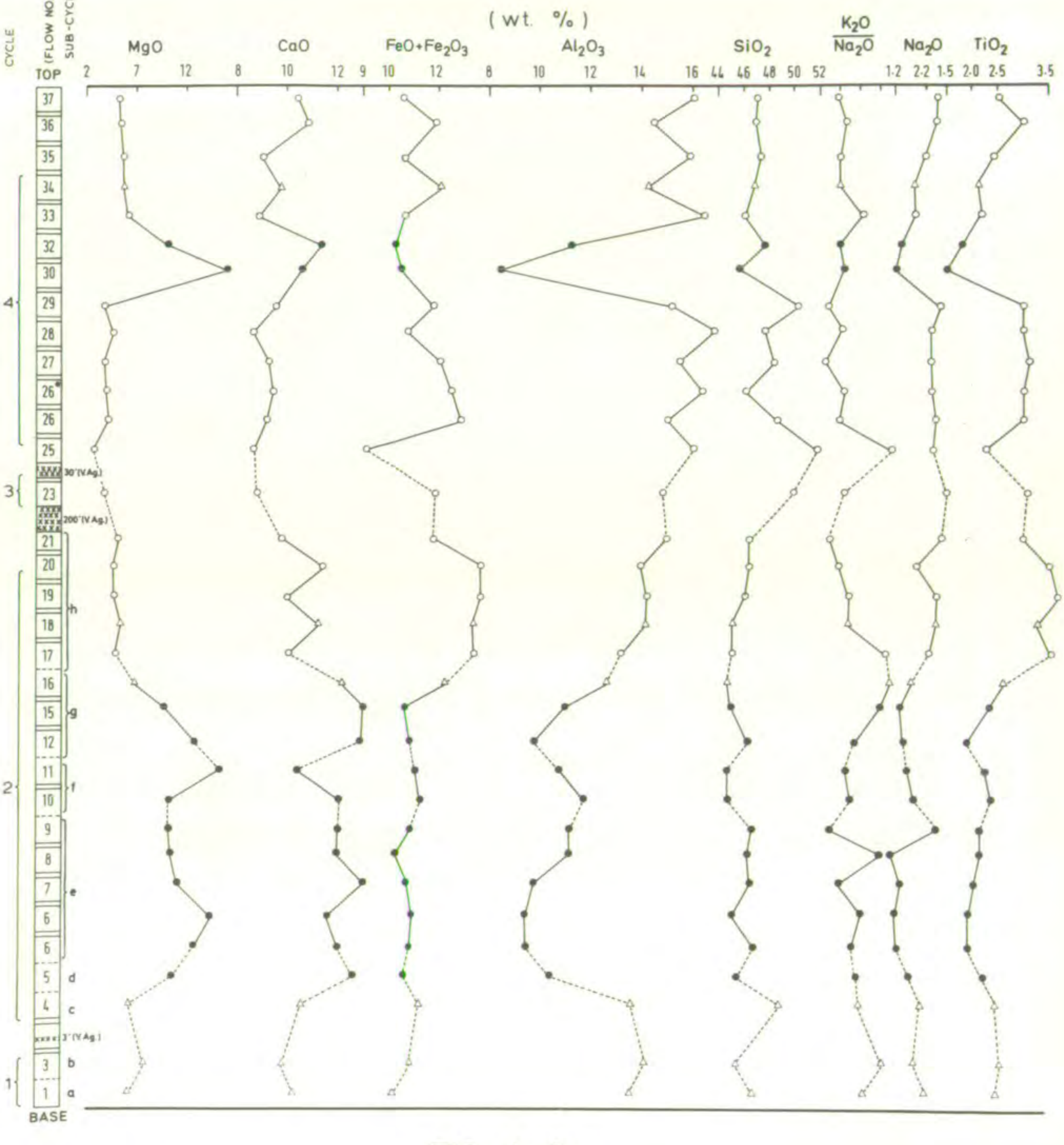


FIG. 4-6a

Fig. 4-6b: Variation of potassium and other trace elements with sequence of eruption at the Dhandhuka bore (P_2O_5 is in wt.%; and the rest of the elements in ppm).

Symbols as in Fig. 2-2.

DHANDHUKA BORING : VARIATIONS OF TRACE ELEMENTS WITH SEQUENCE OF ERUPTION

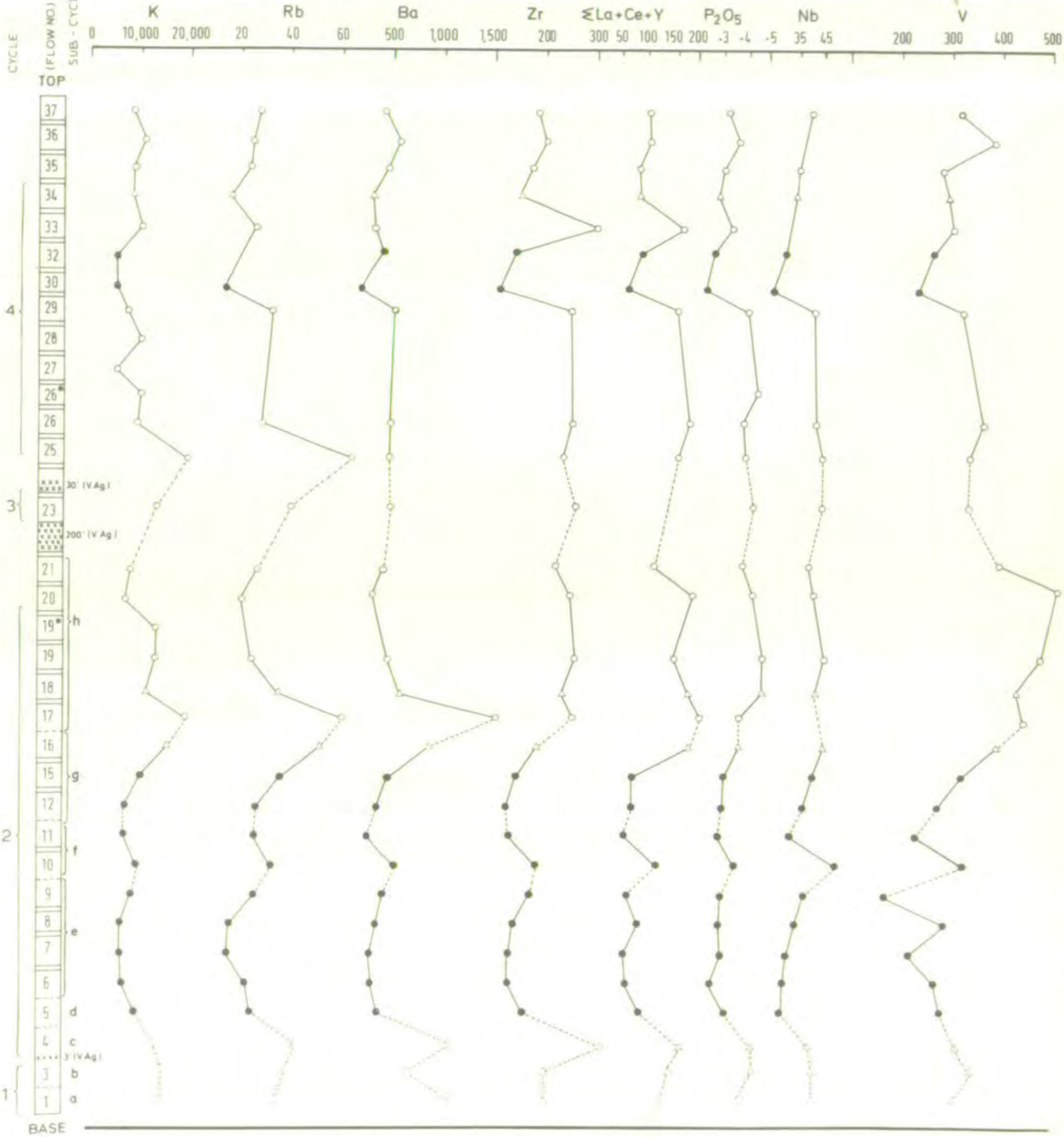


FIG. 4-6b

mechanism of fractionation prior to eruption. Some of these aspects are considered in Chapter 6 (see Section 6:7).

4) Some of the analysed specimens from flows, such as Nos. 1, 3, 4, 17, 23 and 25, and which are the first to erupt at the beginning of a cycle or sub-cycle contain higher amounts of elements such as K, Rb, Ba, Zr, Nb, Y, La, Ce, Zn and Cu, than those present in samples at a comparable stage of evolution, say MgO content (see Figs. 4-6a-6b). Such a feature could be either due to volatile transfer or thermal-diffusion resulting from a single parental magma or related to changes in the parental magma compositions supplied to the volcanic sub-stratum between cycles and sub-cycles. Slight variations in the parental compositions have been found to be present from a consideration of the K_2O/Na_2O and K/Rb ratios and other petrogenetic considerations dealt with in Chapter 7, and these may account for the variations of these elements. Such variations in parental magma compositions are not uncommon, for example, in the case of the summit eruptions at Kilauea, Hawaii, parental compositions have been found to change with date of eruption (cf. Wright and Fiske, 1971).

4:9 Silica-saturation and the order of eruption:

The principle of silica saturation or undersaturation is based here on the appearance of normative quartz or normative olivine + hypersthene and/or nepheline respectively. However, it is not certain how far the influence of oxidation and post-deuteric alterations has affected the original $FeO:Fe_2O_3$ ratios, which influence the normative character (see Chapter 2).

Fig. 4-7: Silica saturation or undersaturation (i.e. presence of normative quartz or olivine + hyperthene and/or olivine + nepheline) with sequence of eruption at Dhandhuka bore.

Symbols as in Fig. 2-2.

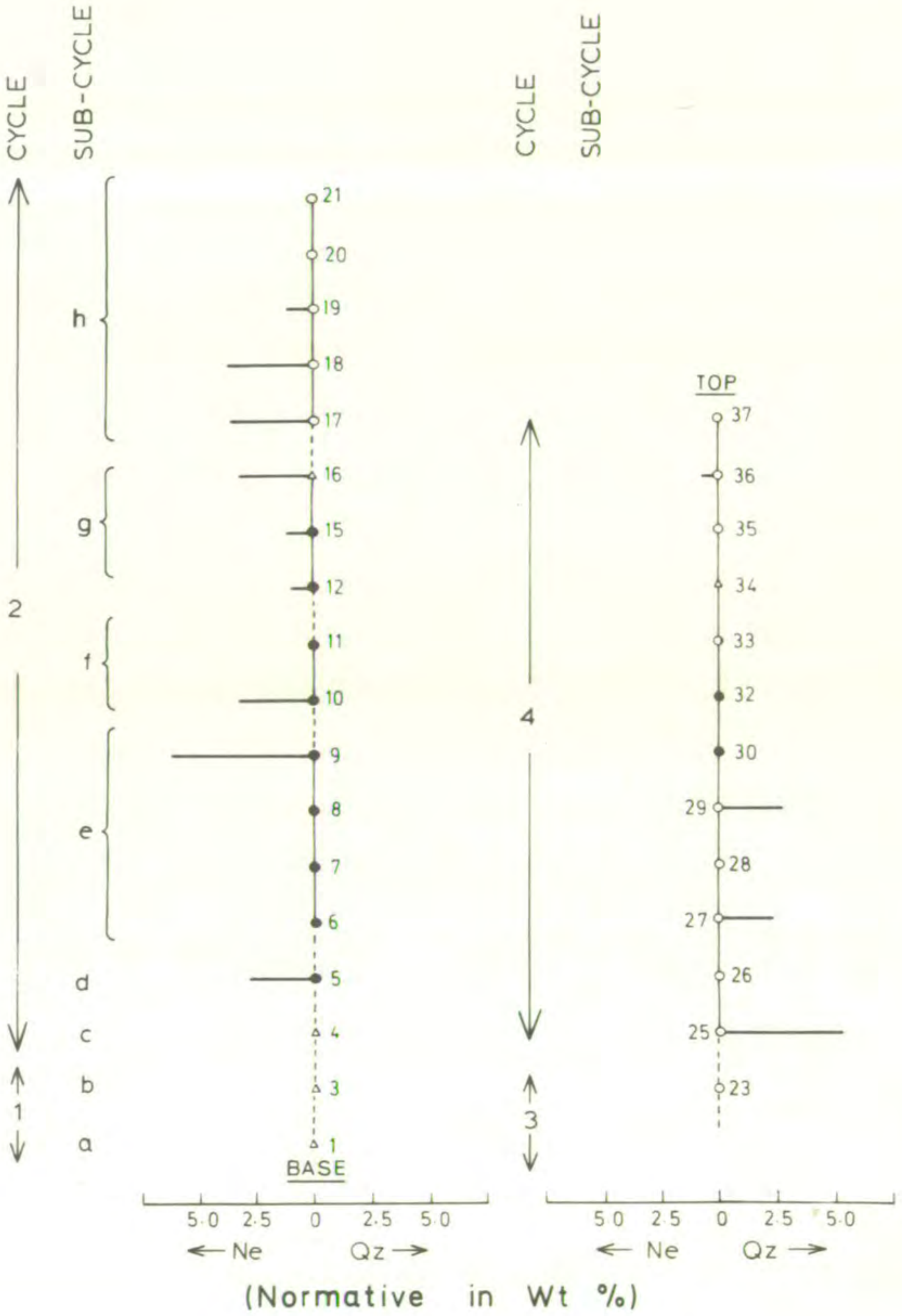

CYCLE
SUB-CYCLE
2
1
h
g
f
e
d
c
b
a
21
20
19
18
17
16
15
12
11
10
9
8
7
6
5
4
3
1
BASE
CYCLE
SUB-CYCLE
4
3
TOP
37
36
35
34
33
32
30
29
28
27
26
25
23
5·0
2·5
0
2·5
5·0
← Ne
Qz →
(Normative in Wt %)

Fig. 4-7

A consideration of the silica saturation of the bore hole flows, as shown in Fig. 4-7, clearly indicates the slightly undersaturated and alkaline character of the flows of cycle 1 and 2. On the contrary, flows belonging to cycles 3 and 4 appear to be both quartz-normative (silica oversaturated) and olivine + hypersthene normative (slightly undersaturated). Such variations in the silica saturation of the different cycles when used in conjunction with data of experimental petrology, might place some limits on the depth (i.e. pressure) at which the various magma types developed during a cycle (Kushiro, 1968), or alternatively suggest possible variations in the degree of melting.

CHAPTER V

ATMOSPHERIC PRESSURE MELTING EXPERIMENTS

Atmospheric pressure melting and crystallization relations of samples from some selected bore hole flows are described in this chapter. The data obtained are analysed in the light of the observed petrographic, mineralogical and chemical variations in the following chapter so as to assess the causes of diversity in the bore hole flows.

5:1 Introduction:-

The main purpose of subjecting the samples to atmospheric pressure melting experiments is

a) to ascertain the order of crystallization of the various minerals

b) to seek whether the very low pressure conditions of crystallization recreated in the laboratory is valid for the observed phase assemblages in the rocks or not.

and c) to use the observed equilibrium crystal-liquid, relationship of the various phases of the individual samples, to track the course of fractional crystallization or crystal settling in natural systems, so as to see whether the observed diversity could be achieved by such a process.

5:2 Method:-

12 samples covering the entire compositional range of the observed flows have been included in the melting experiments (Table 5-1). The melting studies were carried out under Ni/NiO buffer (log fo_2 $10^{-10} - 10^{-7}$), which approximately reproduces the

Table 5-1

Specimen No.	Pirrite basalts					Three-phenocryst basalts					Basalts	
	380	252	259	244	285	312	387	321	299	19	90	219
SiO_2	44.15	46.44	44.95	46.60	46.90	45.70	46.80	47.15	49.15	47.40	46.50	45.56
Al_2O_3	6.35	9.28	11.82	9.90	9.59	14.26	15.78	13.74	13.76	15.19	14.01	13.31
TiO_2	1.44	1.99	2.46	1.97	2.02	2.62	2.31	2.55	2.52	2.49	3.56	3.59
Fe_2O_3	1.55	1.61	1.72	1.61	1.63	1.65	1.55	1.53	11.69	1.61	2.06	2.02
FeO	8.79	9.11	9.72	9.31	9.22	9.33	8.78	8.64	9.62	9.15	11.69	11.43
MnO	0.19	0.17	0.16	0.14	0.17	0.21	0.14	0.16	0.15	0.14	0.20	0.19
MgO	22.37	15.23	10.42	12.98	12.78	7.93	6.61	6.12	6.02	5.80	4.89	4.99
CaO	8.33	11.11	12.11	12.97	12.22	9.86	12.49	10.38	10.61	11.17	11.45	10.08
Na_2O	0.64	1.75	2.08	1.62	1.42	2.12	2.70	2.55	2.38	2.44	2.17	2.66
K_2O	0.40	0.67	1.11	0.90	0.80	1.80	0.94	1.70	1.61	1.03	0.91	2.33
P_2O_5	0.17	0.29	0.35	0.30	0.27	0.43	0.30	0.37	0.43	0.31	0.42	0.37
H_2O+	5.50	2.34	3.31	2.49	2.84	4.31	2.06	4.52	2.60	2.16	2.47	3.62
Cr_2O_3	0.29	0.22	0.07	0.15	0.25	-	-	-	-	-	-	-
Total	100.17	99.87	100.28	100.98	100.11	100.22	100.46	100.98	100.54	99.69	100.33	99.76
Original Fe_2O_3	2.96	4.80	5.63	3.98	6.28	6.68	5.27	5.47	6.87	5.91	9.96	9.21
FeO	7.38	6.37	5.81	6.94	4.57	4.30	5.10	4.70	4.44	4.85	4.79	4.24
Norms			Calculated water free									
Q	-	-	-	-	-	-	-	-	-	-	-	-
Or	2.48	4.05	6.74	5.38	4.85	11.05	5.62	10.57	9.69	6.21	5.44	14.25
Ab	5.67	15.05	11.77	12.05	12.28	18.71	17.78	22.71	20.57	21.16	18.71	16.61
An	14.04	15.70	20.27	17.39	17.96	25.11	28.64	22.17	22.56	30.40	26.42	18.16
Ne	-	-	3.44	0.99	-	-	2.93	-	-	-	-	3.61
Di	22.64	30.62	31.81	36.99	34.28	18.74	26.46	24.19	23.33	20.03	24.05	25.87
Hy	18.23	3.05	-	-	8.64	1.35	-	2.67	12.68	7.00	12.79	-
Ol	30.83	23.14	17.65	20.10	14.62	16.31	11.14	9.34	2.78	7.22	1.66	10.51
Mt	2.36	2.38	2.57	2.36	2.42	2.49	2.28	2.33	2.49	2.39	3.05	3.03
Il	2.89	4.96	4.81	3.80	3.93	5.19	4.45	5.10	4.88	4.84	6.90	7.06
Cr	0.44	0.34	0.10	0.22	0.38	-	-	-	-	-	-	-
Ap	0.40	0.71	0.85	0.71	0.64	1.04	0.71	0.92	1.02	0.73	1.00	0.90
Mode in Vol. %			Phenocrysts									
Olivine	29.1	23.0	2.8	3.3	15.5	1.2	9.8	2.0	0.6	4.0	-	0.6
clinopyroxene	7.4	6.3	1.5	21.8	10.0	1.5	2.8	12.4	5.0	4.9	2.0	-
Plagioclase	-	-	-	-	-	-	12.8	1.0	1.6	25.7	11.6	6.3

equilibrium oxygen fugacities of basaltic liquid determined experimentally by Fudali (1965), as well as those values measured in holes drilled through the crust of Makopuhi lava lake, Kilauea volcano, in Hawaii (Sato and Wright, 1966). Several runs were also carried out under iron/wüstite buffer (log $fo_2 10^{-11} - 10^{-14}$) to find out whether there is any major change in the observed phase assemblages between the two buffer systems. It was found that the phase assemblages were broadly similar, except in the following respects:

1. The liquidus temperatures were higher in the iron/wüstite buffer, compared with the Ni/NiO buffer, by about 20 to 30°C.
2. The ore phase which was prevalent at the Ni/NiO buffer was scarcer under the iron/wüstite buffer.

Capsules of silver-palladium ($Ag_{40}Pd_{60}$) were used for containing all the runs <u>below 1230°C</u> and platinum for <u>one</u> run at ~ 1248°C. All the runs were of 18 hours duration. This 18 hour duration for the runs is a compromise between short runs which do not quite reach equilibrium and longer runs subject to errors of iron or volatile loss (G.M. Biggar, personal communication). Iron and alkali loss were determined in two samples at ~ 1210°C (see Table 5-2) and were found to be negligible for the $Ag_{40}Pd_{60}$ containers, in which the majority of the runs were carried out. It is likely that the losses may be still less significant at lower temperatures. However, the loss may be significant in the single run using a platinum container. The techniques adopted for the atmospheric pressure melting studies were after Biggar and O'Hara (1968).

Table 5-2.

Iron and soda loss during 18 hours run under Ni/NiO buffer in $Ag_{40}Pd_{60}$ containers at ~1210°C.

Specimen No.	Total Fe	In wt. %		
	Before the run	as FeO After the run	Na_2O Before the run	After the run
KAD-R	14.33	14.14	2.33	2.37
321	10.32	10.22	2.76	2.84

Note: Determinations of Fe and Na were by Atomic absorption spectrometry.

Fe and Na loss calculated according to Mg recovery.

The charges at this temperature were wholly of glass.

The phases in the experimental charges were determined mainly through optical studies. Individual "run" data are presented in Table 5-3, while a summary of the data is given in Table 5-4. In Figure 5-1, the liquidus temperature of the various samples has been plotted against $FeO + Fe_2O_3 \times 100/$ $FeO + Fe_2O_3 + MgO$ or the so-called iron-magnesium (F/F + M) ratio.

5:3 Melting and crystallization results:-

The following features are observed in the melting data portrayed in Figure 5-1.

1. The liquidi of the flows (excepting No. 387 and 19) lie on a smooth curve when plotted against F/F + M.

2. Olivine is the liquidus phase for flows with < 60 F/F + M, and it shows a long range of crystallization varying from $\simeq 210^\circ$ for the most basic picrite to $\simeq 35^\circ$ for the least.

3. For the flows with > 60 F/F + M, the liquidus phases were found to be:

a) olivine + clinopyroxene (No. 321, 299 and 312)

b) olivine and clinopyroxene + plagioclase (No. 219)

and c) plagioclase (No. 387, 19 and 90).

4. The temperature of appearance of clinopyroxene either following olivine or cotectic with olivine is generally higher ($\simeq 1240^\circ C$) in the picrite basalts than in the case of Hawaiian picrite basalts ($\simeq 1160^\circ C$), for example (see Fig. 5-1) (Thompson & Tilley, 1969). However, with iron enrichment, the temperature of appearance of clinopyroxene shows a slight decrease, as against plagioclase which appears to show a slight increase.

Table 5-3

Atmospheric pressure melting run data. Phases identified and the approximate amounts of crystals (in volume %; visual estimate) are also given.

Run No.	Specimen No.	380	252	244	285	259	312	387	321	19	299	219	90
	F/F+M	31.6	41.3	45.6	45.9	52.3	58.0	60.9	62.4	64.9	65.2	72.9	73.7
	Run temp. in °C												
10	1248	Ol+Ore+Gl ~50	Ol+Ore+Gl ~20	Ol+Ore+Gl ~5	Ol+Ore+Gl ~5-10	Ol+Ore+Gl ~2-3	Gl+Ore ~4	Gl+Ore ~2					
7	1227	Ol+Cpx+Ore+Gl ~70	Ol+Cpx+Ore+Gl ~25-30	Ol+Cpx+Ore+Gl ~20-25	Ol+Cpx+Ore+Gl ~20	Ol+Cpx(?)+Ore+Gl ~10	Gl+Ore(?)	Pl+Ore+Gl ~10		Gl+Ore			
11	1214						Ol+Cpx(?)+Gl ~15	Pl+Gl ~15		Pl+Gl ~2			
1	1197	Ol+Cpx+Gl ~80 Q*Ore	Ol+Cpx+Gl ~35-40 Ore scarce	Ol+Cpx+Gl ~50	Ol+Cpx+Gl ~30-40	Ol+Cpx+Gl ~20	Ol+Cpx+Gl	Ol+Cpx+Pl+Gl ~35-40	Gl	Pl+Ol+Cpx+Gl ~5-10	Gl	Gl	Gl
9	1185	Ol+Cpx+Gl ~85	- do - ~50		Ol+Cpx+Gl+Ore ~50	Ol+Cpx+Gl+Ore ~25	Ol+Cpx+Ore+Gl		Gl+ +Ore ~2	Ol+Cpx+Pl+Ore Q. Ore ~15	Gl+Ore ~2	Gl	Pl+Ore+Gl ~5-10
2	1174	- do -	- do - No Ore ~75	Ol+Cpx+Gl ~60 Q.Ore	- do - +Pl Q.Ore	Ol+Cpx+Pl+Gl Q.Ore	Ol+Cpx+Pl+Gl	- do -	Ol+Cpx+Gl ~10	- do - No Ore ~25-30	Ol+Cpx+Gl ~2	Gl	Pl+Gl ~15
3	1160	- do - ~90	Ol+Cpx+Pl+Gl ~85	Ol+Cpx+Pl+Gl ~70	Ol+Cpx+Pl+Gl ~80	- do - No Ore	- do - Q.Ore	- do -	- do - ~40	- do -	Ol+Cpx+Pl+Gl ~5	Gl	Pl+Ol+Cpx+Gl Q.Ore
4	1137	- do - +Pl(?) <5% Gl	- do - ~90	- do -	- do - ~90	- do - ~40	- do -	- do -	- do - Q.Ore	- do -	- do - ~25	Ol+Cpx+Pl ~20	- do -
8	1119		- do - +Ore	- do - +Ore ~85-90	- do - +Ore ~90	- do - +Ore	- do - +Ore	- do - +Ore	- do - +Ore	- do - +Ore ~80	- do - +Ore	- do - +Ore ~30-40	- do - +Ore ~50
5	1109	Just baked	- do - ~98	- do - ~95	- do -	- do - ~60	- do -	- do -	- do -		- do -	- do - ~60-70	- do - ~70-80
6	1087		Just baked			- do - ~70-80						- do - ~80	- do - ~90

Q* = Quench F/F+M = $FeO+Fe_2O_3 x100/FeO+Fe_2O_3+MgO$ Ol = olivine Cpx = clinopyroxene Pl = plagioclase

Table 5-4

Results of one atmosphere melting experiments on some selected bore hole samples.

Rock types	Specimen No.	Highest temperature of crystallization of major phases*	$\frac{FeO + Fe_2O_3}{FeO+Fe_2O_3+ Mg}$ x 100
Picrite basalts	380	Ol^x($\simeq$1450); Cpx (1240); Pl(1150)	31.6
	252	Ol^x(1350); Cpx (1236); Pl(1165); Ore (1128)	41.3
	259	Ol (1265); Cpx (1230); Pl (1175); Ore (1128)	52.3
	244	Ol^x(1310); Cpx (1236); Pl (1166); Ore (1128)	45.6
	285	Ol^x(1310); Cpx (1240); Pl (1179); Ore (1130)	45.9
Three-phenocryst basalts	312	Ol (1220); Cpx (1215); Pl (1180); Ore (1130)	58.0
	387	Pl (1230); Ol + Cpx (1200); Ore (1130)	60.9
	321	Ol + Cpx (1179); Pl (1167); Ore (1130)	62.4
	299	Ol + Cpx (1180); Pl (1165); Ore (1130)	65.2
	19	Pl (1215); Ol + Cpx (1190); Ore (1128)	64.9
Basalts	90	Pl (1180); Ol + Cpx (1167); Ore (1130)	73.7
	219	Ol + Cpx + Pl (1155); Ore (1130)	72.9

Note: * Estimated by study of run data and the amount of phases present (as in Table 5-3).

Ol = olivine

Cpx = clinopyroxene

Pl = plagioclase

x = olivine liquidus estimated after Roeder & Emslie (1970).

All temperatures are determined up to ± 5°C or better.

Fig. 5-1: Liquidus temperature vs. $FeO+Fe_2O_3$ x 100/ $FeO+Fe_2O_3+MgO$. The liquidus curve for the Kilauean lavas (Thompson and Tilley, 1969) is indicated.

Arrows indicate the temperature of appearance of Cpx. and Plag. in the Kilauean lavas (Thompson and Tilley, op.cit.)

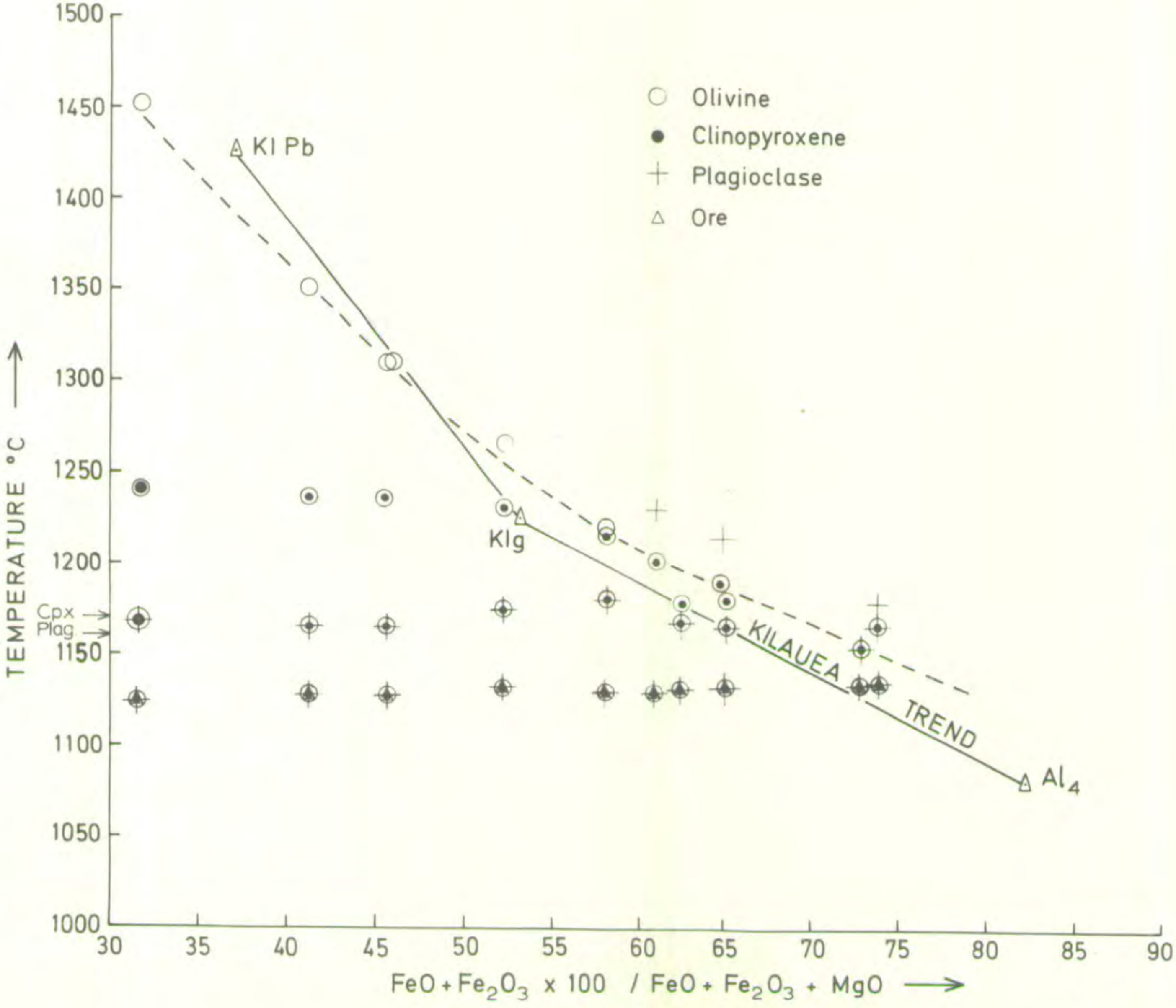

1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
TEMPERATURE °C
Cpx
Plag
30
35
40
45
50
55
60
65
70
75
80
85
90
FeO + Fe$_2$O$_3$ x 100 / FeO + Fe$_2$O$_3$ + MgO
○ Olivine
● Clinopyroxene
+ Plagioclase
△ Ore
Kl Pb
Klg
Al$_4$
KILAUEA TREND

Fig. 5-1

5. Plagioclase appears on the liquidus in three samples (No.387, 19 and 90; Fig. 5-1) and in sample No. 219 is cotectectic with olivine and clinopyroxene.

6. With the exception of some early chromites (?) the ore phase appears invariably at lower temperatures, i.e. at ≃ 1135°C, than olivine, clinopyroxene and plagioclase.

7. The four-phase boundary or curve representing the equilibrium olivine + clinopyroxene + plagioclase + liquid is reached at ≃ 1155 - 1160°C at ≃ 62 F/F + M, excluding two samples in which plagioclase appears on the liquidus.

8. Eruption temperatures deduced from a comparison of modal phenocryst contents in the rocks with the amounts of solid phases estimated visually in the experimental charges appear to range from ≃ 1200-1240°C for the picrite basalts and from about 1150 to 1200°C for the basalts.

CHAPTER VI

DIFFERENTIATION

6:1 Introduction:-

A synthesis of the petrographic, mineralogical and chemical data presented so far, is attempted in this section, so that possible causes of the observed diversity may be assessed. Although it is being increasingly recognized by petrologists that the diversification of a body of magma can commence from its place of origin and is in all probability a continuous or semi-continuous process, for the sake of clarity and ease of handling, the problem may be approached in two steps.

1. By attempting to explain the observed variation in terms of low pressure processes of differentiation through crystal fractionation.

2. If such a low pressure differentiation process cannot satisfactorily account for all the observed diversity, the diversity may be either related to the chemical characters imposed on the primitive initial liquid during its formation in the source region or to the effects of subsequent polybaric and polythermal fractionation suffered by the initial liquid during its ascent.

Both these aspects are considered in this chapter. The origin of the parental liquids is dealt with in the next chapter.

6:2 Differentiation:-

The chemical variations of the major oxides of the bore hole flows are summarised in Figure 6-1, along with the petrographic types encountered and their phenocrystal minerals. The following

Fig. 6-1: Summarised variation diagram (visual estimate) for the major oxides with MgO. Average olivine composition as in Fig. 4-2 is indicated.

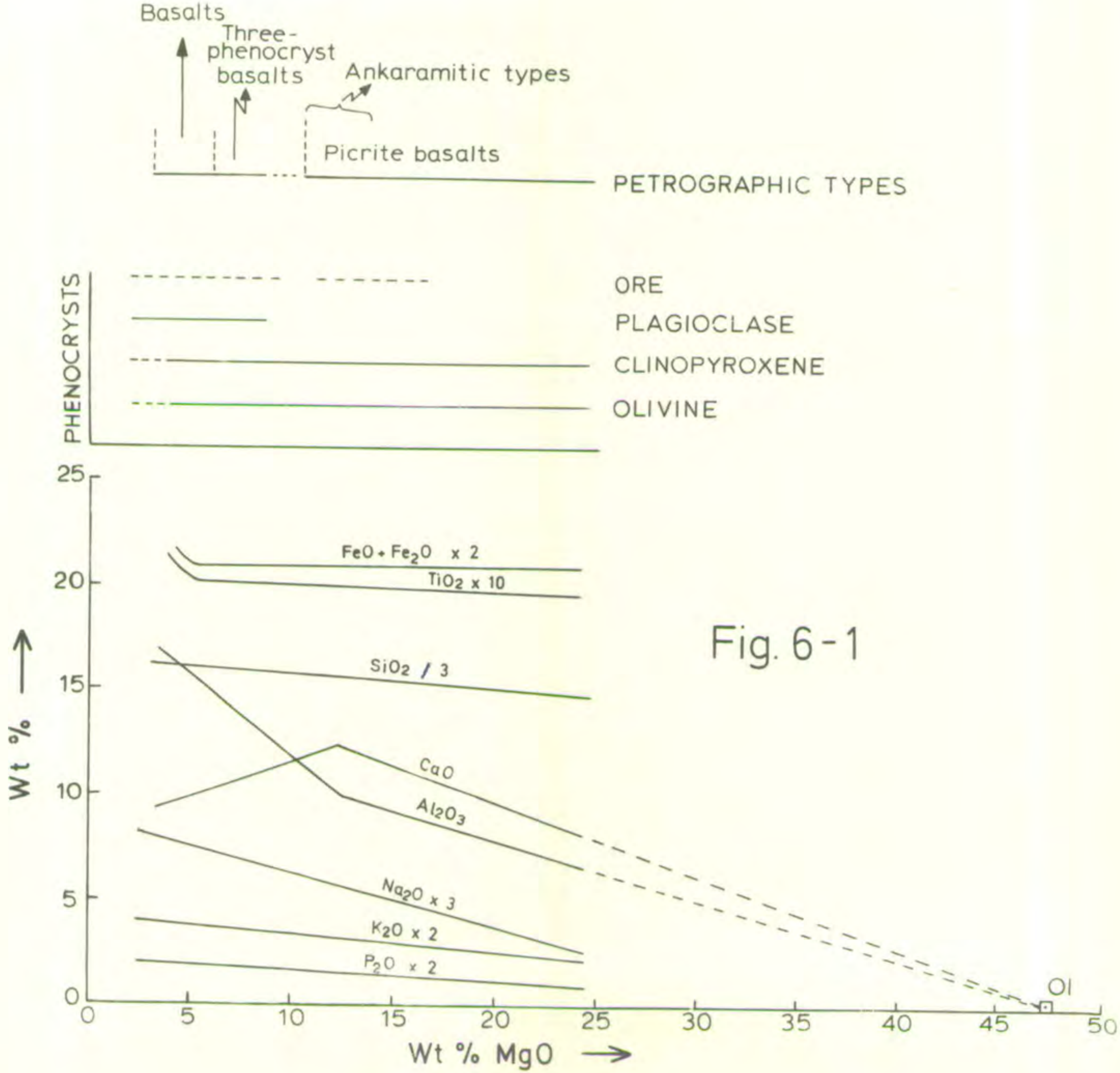

Basalts
Three-phenocryst basalts
Ankaramitic types
Picrite basalts
PETROGRAPHIC TYPES
PHENOCRYSTS
ORE
PLAGIOCLASE
CLINOPYROXENE
OLIVINE
FeO + Fe2O x 2
TiO2 x 10
SiO2 / 3
CaO
Al2O3
Na2O x 3
K2O x 2
P2O x 2
Ol
Wt %
Wt % MgO
0
5
10
15
20
25
30
35
40
45
50

Fig. 6-1

lines of evidence appear to suggest that the observed diversity from the picrite basalts to basalts has been strongly influenced by a process of crystal fractionation - presumably due to crystal settling or differential movements of crystal and liquid. However, as will be shown later, the actual process of crystal fractionation may not have been simple.

1. The petrographic, mineralogical and chemical variations between the different rock types are fairly gradational and could be explained by crystal fractionation. However, it must be mentioned that because of the mineralogical differences between the basalts and picrite basalts, particularly with respect to the olivines and clinopyroxenes (see Table 3-7, Chapter 3), it is highly unlikely that the picrite basalts could be derived from the basalts through accumulation of early formed olivines and clinopyroxenes.

2. The variation diagram (Fig. 6-1) shows conspicuous slope changes at ~ 10-12% MgO (seen in the CaO and Al_2O_3 plots), while the slope changes at ~5-6% MgO (seen in the FeO + Fe_2O_3, TiO_2 and SiO_2(?) plots) are rather less marked. Such features are common in basaltic suites evolving through fractional crystallization. Assuming a simple model of crystal settling, the summarised chemical variation, in conjunction with the "compatible" element variation detailed in the previous chapter (see Section 4:6), is broadly consistent with the following scheme of mineral controlled evolution acting on a single parental magma:

a) olivine fractionation and/or accumulation for flows with > 12 to 13% MgO (see Fig. 4-2 for comparison of raw analytical data with mineral compositions).

b) olivine and clinopyroxene fractionation and/or accumulation for flows with $\gtrsim$ 6 to 13% MgO (see Fig. 4-2).

and c) olivine and clinopyroxene + plagioclase (?) fractionation for flows with $\lesssim$ 6 % MgO. (see Fig. 4-2).

A single sample of basalt (specimen No.D67, Table 4-2) is depleted in total iron and TiO_2 and contains more of SiO_2 than the rest of the flows, and therefore, appears to have evolved by fractionation involving an ore mineral.

3. There is a progressive increase in certain major oxides and trace elements such as K_2O, Na_2O, P_2O_5, Al_2O_3, Rb, Ba, Sr, Zr, rare earths and Nb in the evolved basalts because some of these are largely rejected by the major fractionating phenocryst phases. However, it is doubtful whether the variations of certain elements such as K, Ba, Rb, Nb, Zr, La, Ce and Y can be entirely explained by fractionation of olivine, clinopyroxene and plagioclase acting on a single parent magma, for they show wide variations at comparable stages of evolution (e.g. measured by MgO content; see Fig. 4-3, Chapter 4).

However, consideration of the phenocryst phases of the different petrographic types (see Fig. 6-1) indicates further discrepancies in the implied scheme of evolution. Flows with > 12-13% MgO, and which seem to lie on an olivine control line in fact contain phenocrysts of both olivine and clinopyroxene, while some of the flows (with the exception of picrite basalts of ankaramite types) in the ~6-8% MgO range, comprising three-phenocryst basalts and basalts, and apparently lying on an olivine + clinopyroxene control, contain up to 12% by volume of plagioclase phenocrysts, apart from minor amounts of olivine and clinopyroxene. Flows with $\gtrsim$ 5 to 6% of MgO, contain abundant plagioclase phenocrysts (up to 25% by volume) and small amounts of olivine and clinopyroxene.

Such a discrepancy between the observed phenocrysts and the chemical variation casts doubts on the validity of any simple model of crystal fractionation. Therefore, considerations of alternative mechanisms becomes necessary. Discordance between chemical variation of the rock types and their phenocryst phases has been interpreted in a number of ways. For example, variations in the olivine rich basalts of the Nuanetsi Province, noted by Cox et al., (1965) has been interpreted by Jamieson (1966;1969) as being caused by crystal fractionation at high pressures followed by the growth of low pressure phenocrysts without further fractionation. Cox and Bell (1972) proposed a new model of low pressure crystal fractionation termed "compensated crystal settling" to account for an analogous discrepancy in a suite of strongly porphyritic picrite basalts from New Georgia. They also invoked a process of "selective fractionation" of phases (crystals sinking at different rates) in which slow sinking of plagioclases relative to ferromagnesian minerals has resulted in the production of strongly felspar phyric basalts.

In order to understand the possible model or models of fractionation for the bore hole flows, we must now attempt to answer the following questions.

1. Whether the observed phenocrysts have originated at near atmospheric pressures or whether all or some of them have originated

at high pressures? This leads us to considerations of atmospheric pressure melting and phase relations, as well as crystallizations and phase relations at elevated pressures.

2. Do low pressure models, such as compensated crystal settling and selective fractionation explain the variation? and

3. What are the implications of the observed sequence of eruption (with reference to the petrographic types and the nature and amounts of phenocryst present in them) for the various models?

6:3 Atmospheric pressure melting and phase relations:-

Atmospheric pressure melting and phase relations presented earlier (see Chapter 5) can be effectively portrayed by a consideration of the lava compositions in the simple anhydrous-pseudo-quarternary basalt system comprising olivine-clinopyroxene-plagioclase-quartz and olivine-clinopyroxene-plagi0clase-nepheline, and projecting them from any one of the compositions on to the other three, following the methods of O'Hara (1965). In the present case two projections, namely quartz onto Ol-Pl-Cpx (Figure 6-2a) and nepheline onto Ol-Pl-Cpx (Figure 6-2b) have been used since in these projections one can show:

a) the primary phase fields of the three dominant minerals (Ol, Cpx and Pl), found as liquidus or sub-liquidus phases during the atmospheric pressure melting studies.

b) the probable order of crystallization, and

c) the composition of the rock with reference to these three minerals.

The field boundaries based on the present work are shown, as also the boundaries for <u>tholeiitic rocks</u>, based on melting studies

Fig. 6-2a: Projection of experimentally studied samples (those with numbers, are as given in Table 5-1) along with others, in the pseudo-quatternary basalt system after Yoder and Tilley (1962) and O'Hara (1965). Projection from quartz on to the plane Di-Ol-Plag. Atmospheric pressure phase boundaries, determined during the present work are indicated, as also the boundary determined by other workers (see text)

Fig. 6-2b: Projection from nepheline onto Ol-Cpx-Plag.

Symbols as in Fig. 2-2.

Fig. 6 - 2 a

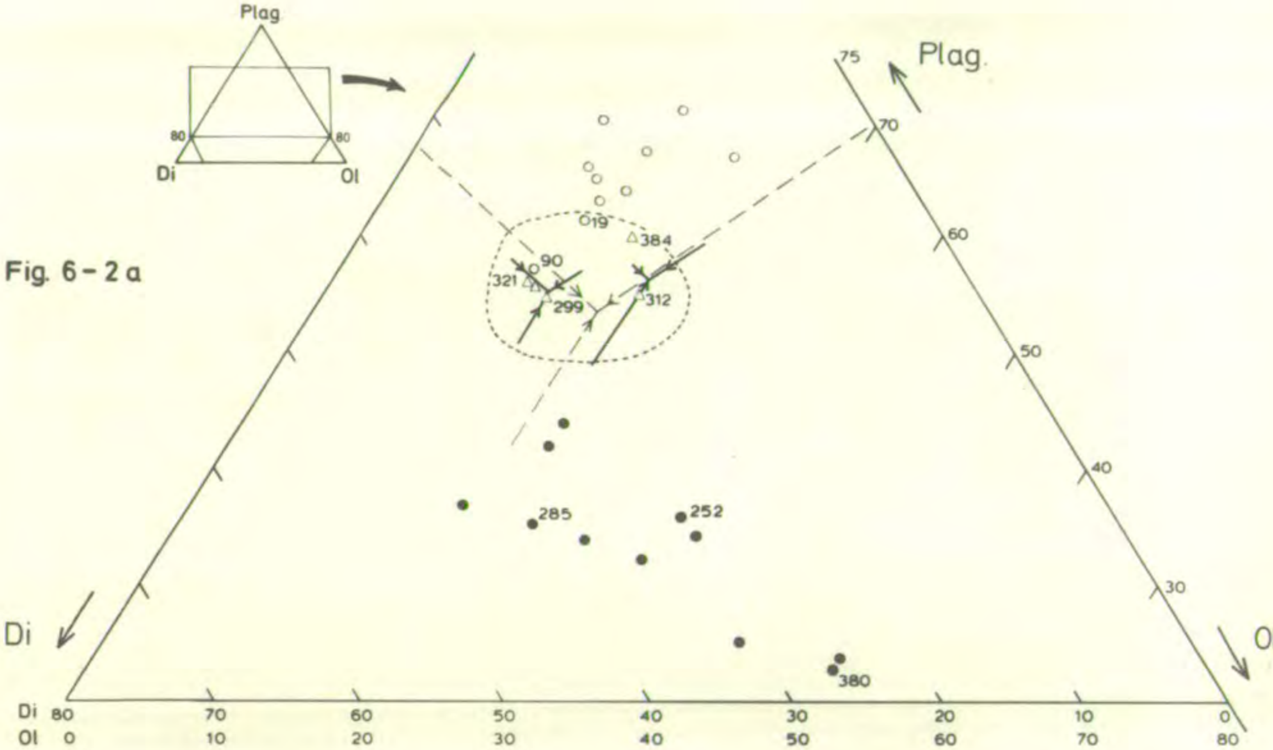
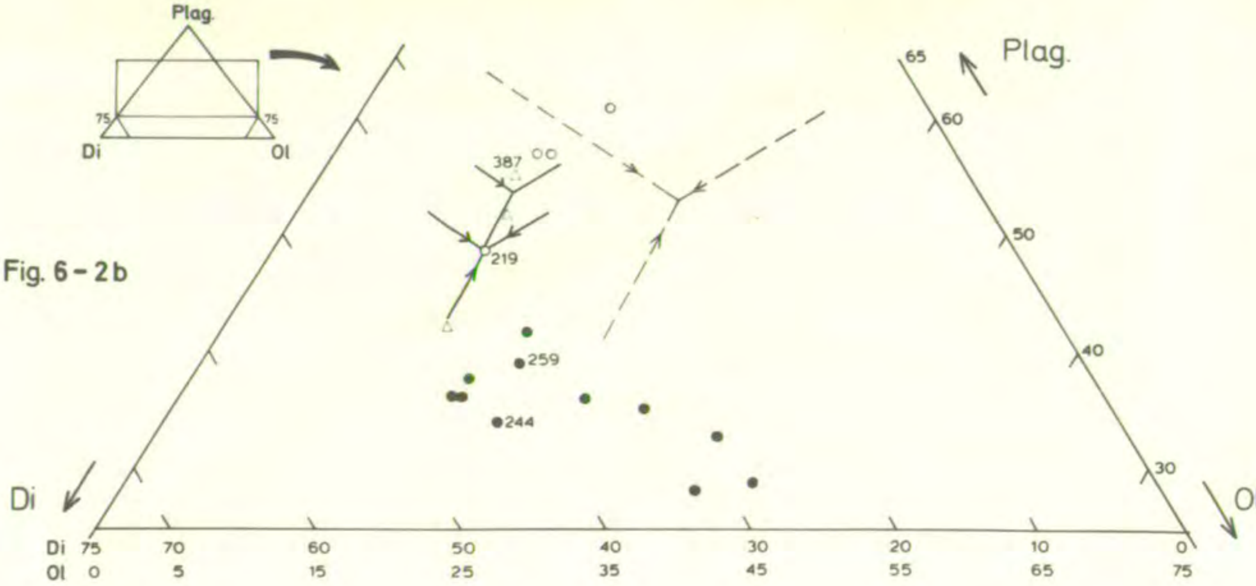


Fig. 6 - 2 b



conducted by Tilley et al., (1963;1964;1965;1967) taken from Cox and Bell (1972). The dotted line indicates the field in which fall those melted rocks, which show "near cotectic" behaviour i.e., those rocks which show the entry of either all three phases (Ol, Pl and Cpx) within a temperature interval of ~30°C, or the second and third phases within that interval. As was noted by Cox and Bell (1972, p.5) the relatively scattered grouping of near cotectic samples within the dotted area in the diagram (Figure 6-2a) indicates the degree of uncertainty in the location of the phase boundaries. In fact this point was found to be true in the case of the bore hole flows, for which there is no single boundary curve or surface in the quarternary, which can satisfy the observed phase relations. Nevertheless, one can see from the diagram, that the majority of the three-phenocryst basalts and a few basalts plot around the four-phase invariant point. Most of the picrite basalts plot well within the olivine field while the majority of the ankaramitic types plot near the olivine-clinopyroxene boundary surface of Cox and Bell (1972). Basalts, which are strongly plagioclase-phyric plot in the plagioclase field.

The plotted positions of the picrite basalts, particularly the oceanitic types, correspond closely with the observed order of crystallization i.e. fairly long range of olivine crystallization followed by clinopyroxene (see the plotted positions of No. 380, 252 and 285 and the sequence of crystallization; figure 6-2a, -b; Table 5-4). Such a feature suggests the possibility that these flows could have been formed due to crystallization of 20-40% of crystals analogous to the low pressure conditions portrayed in the diagram. On the contrary, in the case of at least one of the ankaramitic types (No. 244, see Table 5-4, Fig. 6-2b) which plots in the olivine field close to the olivine-clinopyroxene boundary surface, the suggested 1-atmospheric phase relations (i.e., moderate range of olivine crystallization before the entry of clinopyroxene) does not tally with the observed phenocrysts. This flow contains phenocrystal clinopyroxene in considerable excess over olivine, a feature which cannot apparently be explained in terms of atmospheric pressure (or very low pressure) crystallization alone.

Summarising the atmospheric pressure phase relations and the observed phenocrystal assemblages of the petrographic types, the Oceanitic types of picrite basalts and basalts could have formed under conditions analogous to the low pressure phase diagrams, as portrayed in the diagrams (Fig. 6-2a and -2b) while some of the ankaramitic types of the picrite basalts cannot be satisfactorily explained by such low pressure crystallization alone. Attempts are next made to see whether the postulation of crystallization at pressures higher than atmospheric can be more successful in explaining the phenocryst assemblages.

6:4 Effect of elevated pressures on the nature of phenocryst phases:

Conditions of crystallization at pressures higher than atmospheric can be portrayed in the anhydrous, pseudo-quarternary $CaO-MgO-Al_2O_3-SiO_2$ (CMAS) system, following the methods of O'Hara (1968). The method involves sub-projections within the system, usually from a mineral, on to the various compositional planes. The following two projections have been used to portray the effects of polybaric crystallization.

a) sub-projection from olivine on to CS-MS-A (Fig. 6-3a)

b) sub-projection from diopside onto C_3A-M-S (Fig. 6-3b).

The following points emerge from the study of the projected data into these polybaric phase diagrams.

1. The bore hole flows, comprising alkali basalts, olivine-tholeiites and tholeiites, straddle the olivine-gabbro thermal divide (Yoder and Tilley, 1962) which is operative up to 8 Kb. Therefore, if these flows are mutually related, - as they appear to be - they had probably attained their respective SiO_2-saturated and undersaturated characters before reaching a depth of ~25 Km.

2. Some of the <u>basalts</u> (see Fig. 6-3b) have compositions whose phenocryst assemblages appear to be fairly critically dependent on pressure. With increasing pressure, say ~5 Kb, the primary phase volume of orthopyroxene increases and which might cause the appearance of orthopyroxene in place of olivine. However, there is no orthopyroxene amongst the phenocryst assemblages of these flows, which indicates that the phenocrysts of these flows have originated at rather low pressures.

3. In some of the picrite basalts, three-phenocryst basalts and basalts, particularly those belonging to the olivine-tholeiite group, compositions are such that considerable amount of pressure i.e. 10-15 Kb would be necessary in the dry system to prevent the appearance of olivine and clinopyroxene as the first two phases to crystallize on cooling, and replace one of them by orthopyroxene. Here also, none of the flows contain any orthopyroxene which suggests only that these flows have crystallized at pressures of less than about 15 Kb.

Projections of the compositions of the bore hole flows in the $CaO-MgO-Al_2O_3-SiO_2$ (CMAS) pseudo-quarternary system (after O'Hara, 1968).

$C = (\text{Mol. prop. } CaO-3\frac{1}{3}\ P_2O_5+2\ Na_2O + 2\ K_2O) \times 56.08$

$M = (\text{Mol. prop. } FeO + MnO + NiO + TiO_2) \times 40.31$

$A = (\text{Mol. prop. } Al_2O_3 + Cr_2O_3 + Fe_2O_3 + Na_2O + K_2O + TiO_2) \times 101.96.$

$S = (\text{Mol. prop. } SiO_2 - 2\ Na_2O - 2\ K_2O) \times 60.09$

Fig. 6-3a: Sub-projection from olivine onto CS-MS-A (in wt.%). Phase boundaries at various pressures from 1 atm to 30 Kb are shown (after O'Hara, 1968, Fig. 4).

OP is plagioclase-olivine piercing point.

Note: The elongation trend of the plotted compositions is the result of distortion caused by obliquity of the plane to the olivine projection line (see insert).

Fig. 6-3b: sub-projection from diopside onto C_3A-M-S (in wt.%). Phase boundaries at various pressures from 1 atm to 30 Kb are shown (after O'Hara, 1968, Fig. 6).

DP is diopside-plagioclase piercing point.

Symbols used as in Fig. 2-2.

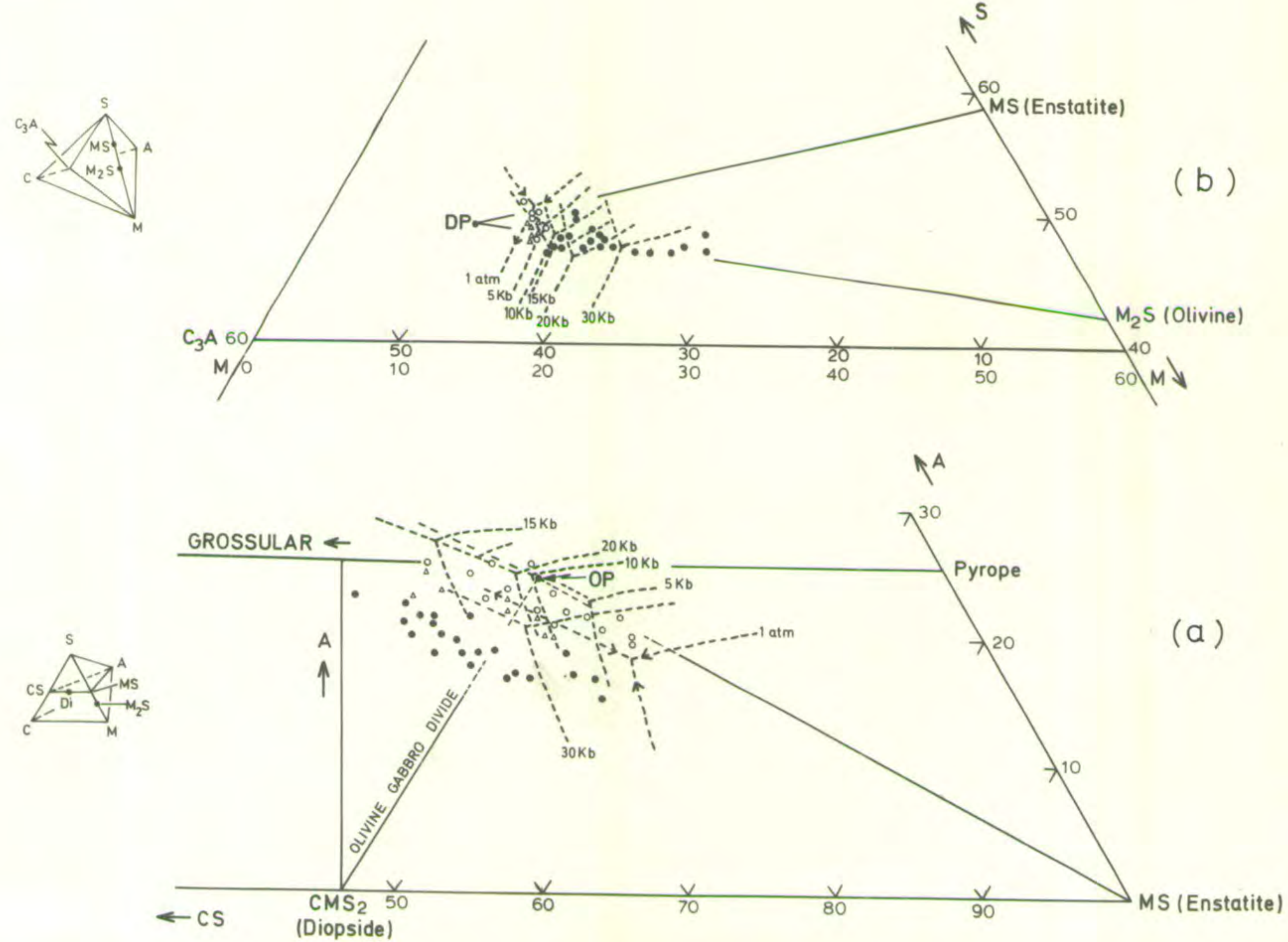

S
MS (Enstatite)
M2S (Olivine)
C3A
M
(b)
DP
1 atm
5Kb
10Kb
15Kb
20Kb
30Kb
60
50
40
50 10
40 20
30 30
20 40
10 50
60
0
C3A
S
MS
A
C
M2S
M
A
Pyrope
GROSSULAR
OP
15 Kb
20 Kb
10 Kb
5 Kb
1 atm
30 Kb
(a)
A
OLIVINE GABBRO DIVIDE
CMS2 (Diopside)
CS
MS (Enstatite)
30
20
10
50
60
70
80
90
S
A
CS
MS
Di
M2S
C
M

Fig. 6-3

4. There are some picrite basalts (especially the ankaramitic types), three-phenocryst basalts and basalts (which belong to the alkali basalt group) for which pressure increases >15 Kb cannot bring about the appearance of orthopyroxene (see Fig. 6-3a).

However, with reference to points (2) and (3) it is possible that with increasing pressure, the primary phase volume of clinopyroxene increases relative to olivine (see O'Hara, 1968, Fig. 5), which may therefore lead to the appearance of clinopyroxene either alone or along with olivine. That at least some of the clinopyroxene in the ankaramites is inherited from higher pressures must remain a distinct possibility.

In summary, considerations of high pressure crystallization enable us to conclude that the phenocrysts in the basalts may have originated at low pressures, while the phenocrysts in the picrite basalts may have originated at any pressures between 1 atmosphere and say 30 Kb. On the other hand it seems likely that the clinopyroxene phenocrysts in at least some of the ankaramites (e.g. specimen No. 244) cannot have originated at low pressures and therefore must be derived from considerably higher pressures, which on present data, however, it is not possible to specify.

6:5 Compensated crystal settling and selective fractionation:-

Two mechanisms of low pressure fractionation namely "compensated crystal settling" and "selective fractionation" have been proposed by Cox and Bell (1972) to account for the discrepancy between the observed phenocryst phases and the compositional variation, in the rocks of the New Georgia Group. According to them, in a side cooling, dyke-like magma chamber, a unique zone (see Cox and Bell, 1972, Fig. 6a and 6b) represents compositions of parental or original liquids, inspite of their strong porphyritic character. The character of the zone is achieved by virtue of its position in such a side-cooling, dyke-like magma chamber. To quote... "Zone B; uniform porphyritic magma, having approximately the same composition as the parent. This is the zone of compensated crystal settling, all crystals lost to the zone below being replaced by crystals received from above." This zone is alleged to have supplied the strongly porphyritic picrite basalts and pyroxene-olivine basalts of the New Georgia Group.

The mechanism can satisfactorily explain those strongly porphyritic rocks, alleged to result from non-fractional or quasi-equilibrium crystallization which are otherwise difficult to envisage because of the tendency of crystals to sink, particularly during the earliest stages of crystallization in basaltic, or picritic liquids.

Therefore, it is possible that a mechanism akin to compensated crystal settling may have operated to produce the strongly porphyritic picrite basalts in the present case. The only effective test of this mechanism would involve the study of a complete series of magmas erupted in rapid order and strict time sequence from the fractionating chamber. It would then be possible to test the predictions of the model fully. With the present data this is not possible, but the hypothesis is retained as a means of explaining why the bore hole magmas appear to have undergone relatively advanced quasi-equilibrium crystallization before eruption.

6:6 Appearance of plagioclase on the liquidus in atmospheric pressure melting experiments and possible mechanisms of plagioclase fractionation:-

One atmosphere phase relations do not allow residual liquids from magmas equilibrating with olivine to enter the plagioclase field. Three of the melted samples have plagioclase on the liquidus and a few other basalts suggest similar behaviour from consideration of their plotted positions (see Fig. 6-2a and -2b). Therefore, it is necessary to consider the causes which could make plagioclase appear on the liquidus.

The appearance of plagioclase as a liquidus phase, has been attributed to several of the following factors:

1. The nature of the Fe_2O_3:FeO ratio in the sample and the nature of oxidising (fo_2) conditions during the melting experiments or during the crystallization of basalts in nature. The stronger the oxidising conditions, the lesser the chance of olivine or clinopyroxene appearing on the liquidus, as compared with plagioclase. Secondary alteration of iron, after consolidation of the samples could complicate the melting pattern at laboratory conditions (Tilley et al., 1965).

2. Original calc-alkaline or alumina-rich character of the parental basalts (Yoder & Tilley, 1962; Tilley et al., 1965, p.201).

3. Plagioclase crystals could be xenocrystal or inherited (Tilley et al., 1965).

4. Plagioclase crystals could be enriched in the residual liquid either by positive upward flotation (Tilley et al., op.cit.) or by selective fractionation of phases sinking at different rates (Cox and Bell, 1972). Plagioclases probably sink more slowly than ferromagnesian minerals and thereby become enriched in the higher levels of a magma chamber (Cox and Bell, op.cit.). This may be thought of as relative flotation.

5. Plagioclase phenocrysts in the lavas crystallized under the influence of higher pressures under appreciable P_{H_2O}, where the precipitation temperature of plagioclase is lower (Yoder, 1969), but when such samples are melted under dry atmospheric pressure conditions they would show comparatively higher temperatures of appearance (Thompson, 1972).

It is not certain how much possibility No.5 has influenced the appearance of plagioclase on the liquidus in these samples. However, when considered in the light of the cotectic character of plagioclase in Sample No. 219, it is unlikely that P_{H_2O} played any significant role during the crystallization of the flows, and hence in the early appearance of plagioclase.

The oxidised nature of the melted flows can be clearly seen from the Table 5-1. As was noted in the section on the mineralogy of the basalts, some basalts do contain scarce xenocrystal plagioclase as calcic as An_{82}. Therefore, possibilities (1), (3) and (4) could collectively explain the appearance of plagioclase on the liquidus in some of the flows. However, factor (4), i.e. flotation or selective enrichment appears to be important from the following considerations.

a) Plagioclase appeared only in the three samples, in spite of the oxidised nature of all the melted samples and the high fo_2 (10^{-7} to 10^{-10}) buffer used during the runs.

b) Plagioclase was found to be cotectic with olivine and clinopyroxene in the least porphyritic basalt (No. 219 containing 6% felspar and insignificant amounts ofolivine and clinopyroxene; see Table 5-4).

c) The three samples in which plagioclase appeared on the liquidus contain larger amounts of modal phenocrystal plagioclase (12 to 26%).

Thus it is not unlikely that the strongly porphyritic felspar rich basalts, could have resulted through enrichment of plagioclase by some such process as selective fractionation of phases sinking at different rates.

6:7 Observed sequence of eruption, their petrographic characters and the implications on possible low pressure fractionation mechanisms in the light of the data presented so far:-

Attempts are made in this section to interpret the sequence of eruption and their petrographic characters, in the light of the postulated schemes of fractionation presented thus far. The porphyritic character of the rocks appears to suggest that prior to the eruption, the primitive or parental liquid has probably paused in the near surface environment, presumably in a plexus of magma chambers or conduits. It is possible that such a primitive magma may have contained at least phenocrysts of olivine and/or olivine + clinopyroxene (in the case of some ankaramitic flows) depending upon the degree of crystallization and fractionation en route, and may have been supplied to the same conduit at different times, or to different conduits at the same time.

The extent of low pressure crystallization and fractionation can be imagined to be largely controlled by the rate of cooling as well as the time of pause, prior to eruption. Eruption might be controlled by fluctuations in the magma pressure, and may also depend upon the local tectonic conditions. The occurrence of volcanic agglomerates and presence of red bole between flows suggest breaks in the sequence of eruption, and might be taken as evidences for longer periods of pause of the primitive liquid in the low pressure environment, providing opportunities for further diversification.

In general it is probably true that picritic types with varying amounts of phenocrysts of olivine and clinopyroxene result from small amounts of heat loss during short periods of stay in the low pressure environment, while moderate to excessive heat losses (which consequently may imply longer period of pause), might result in the production of evolved basalts at the top of the magma chamber, in which plagioclases might have become enriched either by selective fractionation or flotation. Mechanisms, akin to compensated crystal settling may be important in the intermediate levels of the chamber, while magmas which show a net gain or enrichment in crystals might form at the lower levels of the system.

A brief account of the probable scheme of low pressure evolution as inferred from the order of eruption and the nature of the petrographic types is given in Table 6-2.

Table 6-2

Sequence of eruption,and the nature of the petrographic types.
Subscripts to flow numbers, such as a, b, c etc. indicate the sub-cycle within a volcanic cycle (see text, Section 4:8, Fig. 4-6a, Chapter 4).
B = Basalt TPB = Three-phenocryst basalt. PBO = Picrite basalt Oceanite type PBA = Picrite basalt Ankaramitic type

Volc. Cycle	Flow No.	Rock Type	Vol. % Phenocrysts*			Implications regarding relative heat loss and time of pause in possible low pressure environments.
			Ol	Cpx	Plag	
A. DHANDHUKA BORE						
4	37	B	1.7	0.7	23.5	Picritic types may have paused for a short period with slight heat loss; some of the picritic types may have paused relatively longer with moderate to strong heat loss producing basalts; in some flows such as Nos. 33, 35, 36 and 37, plagioclases may have been selectively enriched.
	36	B	1.9	1.6	22.2	
	35	B	4.1	3.3	21.3	
	34	TPB	5.4	8.4	7.5	
	33	B	7.7	0.5	15.5	
	32	PBO	14.2	3.7	-	
	31	TPB	1.1	2.5	5.3	
	30	PBO	15.6	7.7	-	
	29	B	0.5	0.9	12.3	
	28	B	0.1	0.1	13.4	
	27	B	0.2	1.1	15.2	
	26	B	0.6	0.5	13.8	
	25	B	-	0.8	16.2	
	24	B	-	-	8.7	
3	23	B	0.4	0.3	15.8	Moderate to strong heat loss; time of pause probably maximum; plagioclase may have been selectively enriched in strongly felspar phyric basalts.
2	22 b	B	No sample			- do -
	21 h	B	0.6	0.5	23.2	
	20 h	B	0.5	1.1	19.0	
	19 h	B	0.5	0.4	13.2	
	18 h	TPB	1.1	0.4	7.5	
	17 h	B	0.5	-	5.3	
	16 g	TPB	0.9	2.9	-	Slight heat loss; time of pause probably short; phenocrysts in flow No. 12 are about 6 times that of flow No. 16, and therefore may represent crystal enriched lower portions of the system.
	15 g	PBO	5.2	4.6	-	
	14 g	PBO	2.3	1.7	-	
	13 g	PBA	6.8	11.9	-	
	12 g	PBA	9.5	14.3	-	
	11 f	PBO	19.7	6.2	-	Very slight heat loss; time of pause probably small. Flow No. 10 may be from crystal impoverished upper part while flow No. 11 may have gained some crystals.
	10 f	PBO	4.3	1.1	-	
	9 e	PBA	3.6	4.1	-	Very slight heat loss; flow No. 6 has just over three times of phenocrysts than flow No. 9, and is also relatively MgO rich. Relative crystal movements appear to be significant. Flow No. 6 may represent lower portions of the maga chamber
	8 e	PBA	2.8	6.1	-	
	7 e	PBA	8.3	11.3	-	
	6 e	PBA	11.2	13.9	-	
	5 d	PBA	5.7	5.5	-	Very slight heat loss
	4 c	TPB	1.1	3.8	0.5	Moderate to small amount of heat loss
1	3 b	TPB	0.5	3.9	0.4	- do -
	2 a	TPB	1.3	1.5	1.5	Flow No. 1 is the lowermost flow of the sequence. Moderate amount of heat loss; time of pause probably not long
	1 a	TPB	2.8	6.0	4.0	
B. BOTAD BORE						
	Top					
	6 b	PBO	9.8	4.6	-	Slight heat loss
	5 a	PBO	20.3	5.7	-	Very slight heat loss and hence probably paused for a short while
	4 a	PBO	23.8	4.0	-	
	3 a	TPB	3.7	4.9	3.9	Moderate to strong heat loss; in flow No. 2 plagioclase may have become selectively enriched
	2 a	TPB	2.3	4.9	10.7	
	1 a	PBO	20.8	4.8	-	Slight heat loss and probably paused for a very short time.
	Base					
C. WADHWAN JUNCTION BORE						
	Top					
	5	PBO	28.1	10.2	-	Picrite basalts may have paused for a short while without appreciable heat loss; three-phenocryst basalts probably resulted from a longer pause of the primitive liquid plagioclase may have been selectively enriched in them.
	4	TPB	1.2	2.0	10.9	
	3	TPB	3.4	4.5	11.2	
	2	PBO	25.7	11.0	-	
	1	PBO	26.2	6.8	-	

* Average mode of the flow.

CHAPTER VII

PETROGENESIS: MAGMA GENERATION

7:1 Introduction:-

Petrogenetic aspects of the bore hole flows are discussed in this chapter, in the light of the data presented so far. Genetic considerations of basaltic rocks generally involve two important but intricate processes, namely the generation of magma from an appropriate source rock and its subsequent evolution prior to eruption. The mechanisms of these processes are very poorly known and therefore the petrogenetic postulations are highly subjective and speculative. Nevertheless, in the light of data from experimental petrology an approach can be made to understand these processes. Possible mechanisms of differentiation, mainly in a low pressure environment, have already been discussed [in the previous chapter] and an attempt is made in this chapter to seek the origin of the flows, particularly the parental magmas.

7:2 Parental magma for the bore hole flows:-

The following facts provide evidence suggesting the possible parental nature of the picrite basalts.

1. The picrite basalts differ from the associated basalts* in containing Mg rich olivines (Fo_{90-86}) and diopsidic pyroxenes ($Ca_{46-43}Mg_{51-44}Fe_{11-5}$) and therefore, it is very unlikely that they could be produced by cumulus enrichment of olivine and/or clinopyroxene from the basalts. On the other hand it is possible to derive the basalts

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* This includes basalts associated with the picrite basalts in the bore holes as well as the most common Deccan basalt which is an over-saturated quartz-tholeiite (see Tables 1-2 and 3-7).

from the picrite basalts by processes of crystal fractionation, as outlined in the previous chapter.

2. In abundance <u>within the bore holes</u>, i.e., taking the number of flows and their bulk thickness, the picrite basalts constitute the largest group (see Table 7-1). However, this consideration may be of secondary importance, since it assumes that none of the volcanic sequence has been lost by erosion, and/or all magmas were erupted to the surface in correct quantities, both of which may be questioned.

Table 7-1

Type of flow	No. of flows	Bulk thickness in feet
Basalts	16	512
Three-phenocryst basalts	12	339
Picrite basalts	20	1043

However, selection of the most probable parental picrite basalt in the present case is beset with difficulties, because aphyric rocks are absent and porphyritic character appears to be the rule. The least porphyritic picrite basalt (No. 259, Table 4-2) has 10.4% MgO and contains 2.8% of phenocrystal olivine and 1.5% of phenocrystal clinopyroxene in the mode. Even provided with such nearly aphyric rocks, one has to exercise caution in assuming it as a possible parent, because such an aphyric character could result from the removal of crystals from a still more picritic parental liquid. The best approximation of the probable parental compositions appear to be provided by the estimates based on the following three considerations, and are given in Table 7-2.

1. The most basic and the least porphyritic picrite basalt.

2. The weighted average of all the analysed flows in the bore hole sequence, and

3. The most basic groundmass composition amongst the picrite basalts.

It can be seen from Table 7-2, that there is a fair amount of agreement between the different estimates and all of them tend to suggest only the least basic possible parental liquid. It is not unlikely that the parental liquid may be more basic than those presented in Table 7-2. The mildly alkaline and/or the olivine-tholeiitic character of the parental compositions can be clearly seen from their norm, as also their richness in normative diopside components.

7:3 Evidences for possible variations in the parental magma compositions:-

1. K_2O/Na_2O and K/Rb ratios.

K_2O/Na_2O ratios should remain substantially constant in any series of liquids produced by more or less closed system fractionation of minerals such as olivine and clinopyroxene as none of these minerals remove any significant amount of K_2O or Na_2O, with the exception of small amounts of Na_2O in the clinopyroxenes. Therefore, one would normally expect the K_2O/Na_2O ratios of the picrite basalts to remain fairly constant, since their evolution is largely controlled by olivine and/or clinopyroxene. Any significant changes in the K_2O/Na_2O ratios, therefore, may suggest changes in the original

Table 7-2: Possible parental picritic compositions.

No.1 Least porphyritic picrite basalt.
Specimen No. 259, Table 4-2.

No.2 Weighted average of all the analysed flows (weighted according to thickness).

No.3 Most basic groundmass composition among the picrite basalts.
Specimen No. 391, Table 4-2.
Composition estimated assuming
Groundmess = whole rock - Phenocrysts.
The modal estimate of the phenocrysts in Vol. % in the analysed specimens were converted into wt.% by using the following densities. Olivine = 3.3.
Clinopyroxene = 3.25. Groundmass = 2.85.
Wherever possible, in the estimation of the composition of the phenocrysts, analysed minerals have been used. In the absence of analysed minerals, average values have been utilised.

Table 7-2

Wt %	1	2	3
SiO_2	46.38	48.04	47.45
TiO_2	2.45	2.24	2.38
Al_2O_3	12.20	10.10	12.22
Fe_2O_3	1.78	1.86	1.77
FeO	10.03	10.56	10.01
MnO	0.17	0.20	0.18
MgO	10.74	12.80	11.75
CaO	12.50	11.52	10.95
Na_2O	2.15	1.85	1.98
K_2O	1.15	0.51	0.98
P_2O_5	0.36	0.32	0.33
Total	100.00	100.00	100.00
In ppm			
Ba	545		395
Zr	185		171
Sr	400		342
Rb	33		21
Y	27		26
La	25		29
Ce	70		47
Ni	231		365
Cr	509		879
V	327		248
Nb	50		35
Zn	76		107
Cu	109		102

	1	2	3
CIPW Norms			
Qz	-	-	-
Or	6.74	3.01	5.79
Ab	11.77	15.65	16.75
Ne	3.44	-	-
An	20.27	17.74	21.56
Di	31.81	30.13	24.71
Hy	-	9.85	4.20
Ol	17.65	15.91	19.12
Mt	2.57	2.70	2.57
Il	4.81	4.25	4.52
Ap	0.85	0.76	0.78

Fig. 7-1: Plot of Na_2O/K_2O vs. MgO. in the picrite basalts to illustrate their variation. Plotted positions of three-phenocryst basalts and basalts are also indicated.

Symbols as in Fig. 2-2.

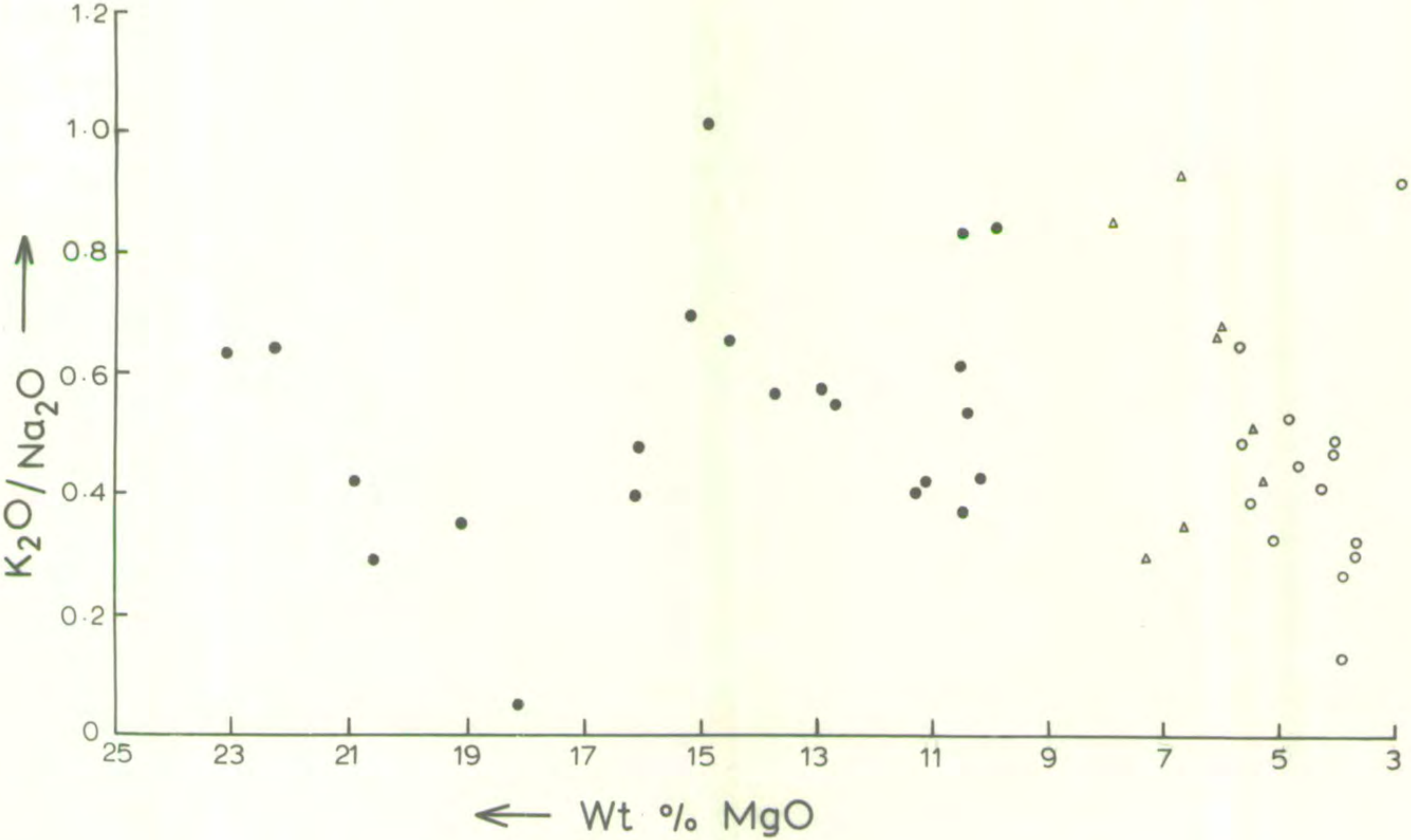

Fig. 7-1

liquid or parental magma compositions, assuming that there has been no influence by volatile transfer or thermal diffusion. A study of the K_2O/Na_2O ratios of the picrite basalts (Fig. 7-1), however, shows wide variations, and such a feature might be taken as evidence of possible variability of the parental magma compositions. K/Rb ratios also show some fluctuations (see Table 4-8 and Fig. 4-4b) between 271 and 498.

This evidence of variation in parental magma compositions has important petrogenetic implications, since it may be related to

a) Variations in the immediately parental material whether magmatic or solid,

b) Changes in the degree of partial melting (Gast, 1968),

c) Possible variations in the depth of origin (Kuno, 1959; Kushiro, 1968), and

d) Possible processes of high pressure crystal fractionation such as eclogite fractionation (O'Hara and Yoder, 1967).

7:4 Origin and Derivation of the Parental picritic liquids:-

Assuming that the parental picritic magmas originate as a result of partial melting in the mantle or upper mantle, a knowledge of two important things, namely

1) the nature of the source rocks at that depth, and

2) the physico-chemical conditions during melting,

are necessary, in order to postulate the probable formation of the parental magmas.

7:4a Source Rocks:-

The nature of the source rocks for basalts at mantle or upper mantle depths has been the subject of continued discussion and controversy (O'Hara and Mercy, 1963; Ringwood, 1966; Harris et al., 1967; White, 1967; Mason, 1966; Press, 1969; Kuno and Aoki, 1970; and see reviews by Wyllie, 1970 and 1971). The evidence collected by these various workers and others, lead us to the belief that the upper mantle may not be homogeneous and might comprise the following rock types, the peridotitic types being probably preponderent (c.f. Wyllie, op.cit.)

1. Original undepleted peridotites
2. Residual or depleted peridotite either because of magma extraction or removal of minor elements by other magmas passing along the primitive compositions.
3. Peridotitic, pyroxenitic and eclogitic rocks precipitated from possible earlier partial melting and high pressure crystallization events.

Only peridotitic compositions are considered here as possible source materials for it is unlikely that eclogitic and/or pyroxenitic types could give rise to picritic liquids on partial melting.

Table 7-3 gives the major oxides of the postulated peridotitic compositions (both primitive and residual) of the upper mantle by different workers and there is no compelling reason to reject any one in favour of the other. The author favours the view that compositions analogous to garnet-peridotite nodules - not necessarily belonging to any one unique environment - may probably represent the most appropriate primitive upper mantle compositions. The

Table 7-3

Postulated primitive and residual upper mantle compositions
(Major and some minor oxides)

	1	2	3	4 (10)	5 (25)	6 (15)	7 (4)
SiO_2	45.16	44.5-47.9	46.10	44.31	44.26	44.08	43.54
Al_2O_3	3.54	1.09-3.06	2.16	2.37	2.59	1.63	0.82
Fe_2O_3	0.46	5.89-8.39	2.42	2.13	1.64	1.44	1.20
FeO	8.04		4.40	8.84	7.25	6.95	6.47
MgO	37.47	37.68-45.74	41.95	38.31	40.55	43.10	47.29
CaO	3.08	0.86-3.50	1.64	2.12	2.44	1.53	0.11
Na_2O	0.57	0.06-0.40	0.17	0.39	0.23	0.13	0.07
K_2O	0.13	0.00-0.35	0.15	0.12	<0.03	<0.04	0.02
H_2O+	-	- -	-	0.67	0.31	0.39	0.21
H_2O	-	- -	-	0.16	0.06	0.17	0.04
TiO_2	0.71	0.02-2.30	0.26	0.24	0.15	0.12	0.07
P_2O_5	0.06	0.00-0.05	0.02	<0.04	<0.01	<0.06	0.00
MnO		0.09-0.15	0.11	0.15	0.14	0.13	0.12
Cr_2O_3	0.43	0.21-0.52	0.35	0.30	0.38	0.35	0.38
NiO	-	0.25-0.43	0.31				
TOTAL			100.04	100.11	100.00	100.02	100.34
MgO/ΣFeO				3.0-3.99	4.0-4.99	5.0-5.99	6.0-6.99

Index to numbers:

1) Pyrolite III (Ringwood, 1966).

2) Composition range in 15 analysed garnet-peridotite nodules from Kimberlite (Carswell and Dawson, 1970, Table 3).

3) Average of No. 2.

4) 5) 6) and 7) are average compositions of lherzolite nodules (including garnet-lherzolites) grouped on the basis of MgO/FeO + Fe_2O_3 x 0.19 (Kuno and Aoki, 1970, Table 16).

Number of analyses indicated in brackets.

concentration levels of the trace elements (including K_2O, and volatiles(?)) of such primitive upper mantle compositions are less precisely known than the major elements because their amounts can be seriously affected by secondary alteration and contamination from the host rocks of the nodules. Therefore, concentration levels of K, Ba, Rb and Sr estimated by Griffin and Murthy (1969), for an average garnet-peridotite (after Harris et al., 1967; comprising 65% olivine, 12% clinopyroxene, 13% orthopyroxene and 10% garnet) from concentration levels of these elements in individual minerals are accepted as a first approximation and are given in Table 7-4. According to Griffin and Murthy (1969, p. 1399) anhydrous mantle compositions are unsatisfactory, as they fail to explain neither the observed Sr^{87}/Sr^{86} ratios of the erupted basalts, nor the observed heat flow on the continents and the ocean basins. Therefore, hydrous upper mantle compositions with trace amounts of amphibole and/or phlogopite have been suggested by Griffin and Murthy (1969), a view proposed earlier by Oxburgh (1964) and Kushiro et al., (1967). Therefore, concentration levels of K, Rb, Ba and Sr in phlogopite bearing garnet-peridotites are also included in the Table 7-4. However, it must be stressed that given a constant source composition the stability fields of amphibole and/or phlogopite depend upon P, T and P_{H_2O} (c.f. Green 1973). In general, the stability field of amphibole is restricted to pressures < 25-30 Kb, compared with phlogopite, which is stable over a wide range of pressure and temperature (Kushiro, op.cit.).

Table 7-4

Trace element concentrations in the postulated garnet-perido~~d~~tite upper mantle

A. Anhydrous mantle

Element	Conc. in ppm.	Reference
K	106	Griffin and Murthy (1969, Table 6)
Rb	0.84	
Sr	15.0	
Ba	14.0	
Zr	30.0	Vinogradov (1962)
Zn	30.0	
Cu	20.0	

B. Hydrous mantle

Element	With 0.2% phlogopite conc. in ppm.	With 0.5% phlogopite	Reference
K	248	464	Griffin and Murthy (1969, Table 7)
Kb	0.98	1.76	
Sr	15	17	
Ba	15	21	

7:5 Partial melting of the mantle peridotite and the derivation of the parental magmas:-

Introduction:-

Experimental petrological studies in recent years, by a number of workers, on natural and synthetic compositions analogous to the postulated upper mantle, (as in Table 7-3), under controlled conditions of P, T and P_{H_2O} have provided important guide lines and limitations to petrogenetic postulations, such as the derivation of magmas and their primary or evolved character. The experimental approach has been to seek the composition of the primary or initial liquid produced at the minimum melting temperature, under higher pressures in peridotitic compositions (O'Hara, 1963; Ito and Kennedy, 1967; Kushiro, 1972, 1968; Kushiro et al., 1968 and 1972) or to seek the nature of the erupted basalts of different compositions and their melting and phase relations at higher pressures so as to see whether or not they are capable of being in equilibrium with peridotitic compositions (Green and Ringwood, 1967; Bultitude and Green, 1971; Ito and Kennedy, 1968).

From these studies, several important conclusions have been drawn, which have direct bearing on the genesis of basaltic and other magmas. The composition of the initial or primary liquid was found to be dependent critically on at least four factors (cf. Wyllie, 1971);

1. the mineralogy of the source rock which varies with pressure
2. the depth of formation
3. the degree of partial melting which is controlled by the temperature interval above the solidus, and

4. anhydrous or hydrous conditions during melting which depends on the presence or absence of water or hydrous minerals. If present the vapor-absent ($P_{H_2O} \leq P_{TOTAL}$) or vapor-present conditions ($P_{H\,O} > P_{TOTAL}$) are critical (Kushiro, 1972; Green, 1973).

The composition of the initial partial melt produced under anhydrous or vapour-absent conditions from peridoditic compositions at upper mantle depths have been found to be picritic* and not basaltic. Hydrous or vapor-present conditions favoured the production of silica over-saturated liquids according to Kushiro et al., (1972) and Kushiro (1972) while silica-undersaturated (nephelinitic) liquids are produced according to Green (1969). Higher degrees of melting (say > 20%), irrespective of the conditions of melting, tend to produce increasingly picritic liquids, approaching the composition of the source rock. With these points in mind, attempts are now made to seek the origin of the parental picritic liquids arrived at earlier and also to assess the consequences of assuming different parental compositions.

7:5a Derivation of the parental picrite basalts:-

Figures 7-2a and -2b (after O'Hara, 1968, Fig. 6) may be used to portray the probable scheme of derivation of the parental picrite basalts from a source rock analogous to a garnet peridotite or garnet-lherzolite. All the picritic compositions have been plotted in Fig. 7-2a, while the least basic parental compositions inferred earlier (see Table 7-2) are shown in Fig. 7-2b. Some of the

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[*] Both Ol + Hy normative picrites (O'Hara and Yoder, 1967) and Ne-normative picritic liquid (Kushiro et al., 1972) have been postulated.

Fig. 7-2a. Sub-projections from diopside onto C_3A-M-S (in wt.%) within the CMAS system of all picritic compositions from the bore hole flows. Phase boundaries shown for various pressures excluding the 25 Kb one (which has been extrapolated) are from O'Hara (1968, Fig. 6). The enclosed area around the 25-30 Kb pseudo-invariant points include picritic compositions with c. 16-18 wt.% MgO. Some of the postulated upper mantle compositions (both primitive and residual) as given in Table 7-3 are also shown. Filled square represents the plotted position of the average olivine phenocryst (average of 8) from the picrite basalts as in Fig. 4-2.

Fig. 7-2b. Similar to above, but only the least basic picritic parental compositions, as given in Table 7-2 are plotted.

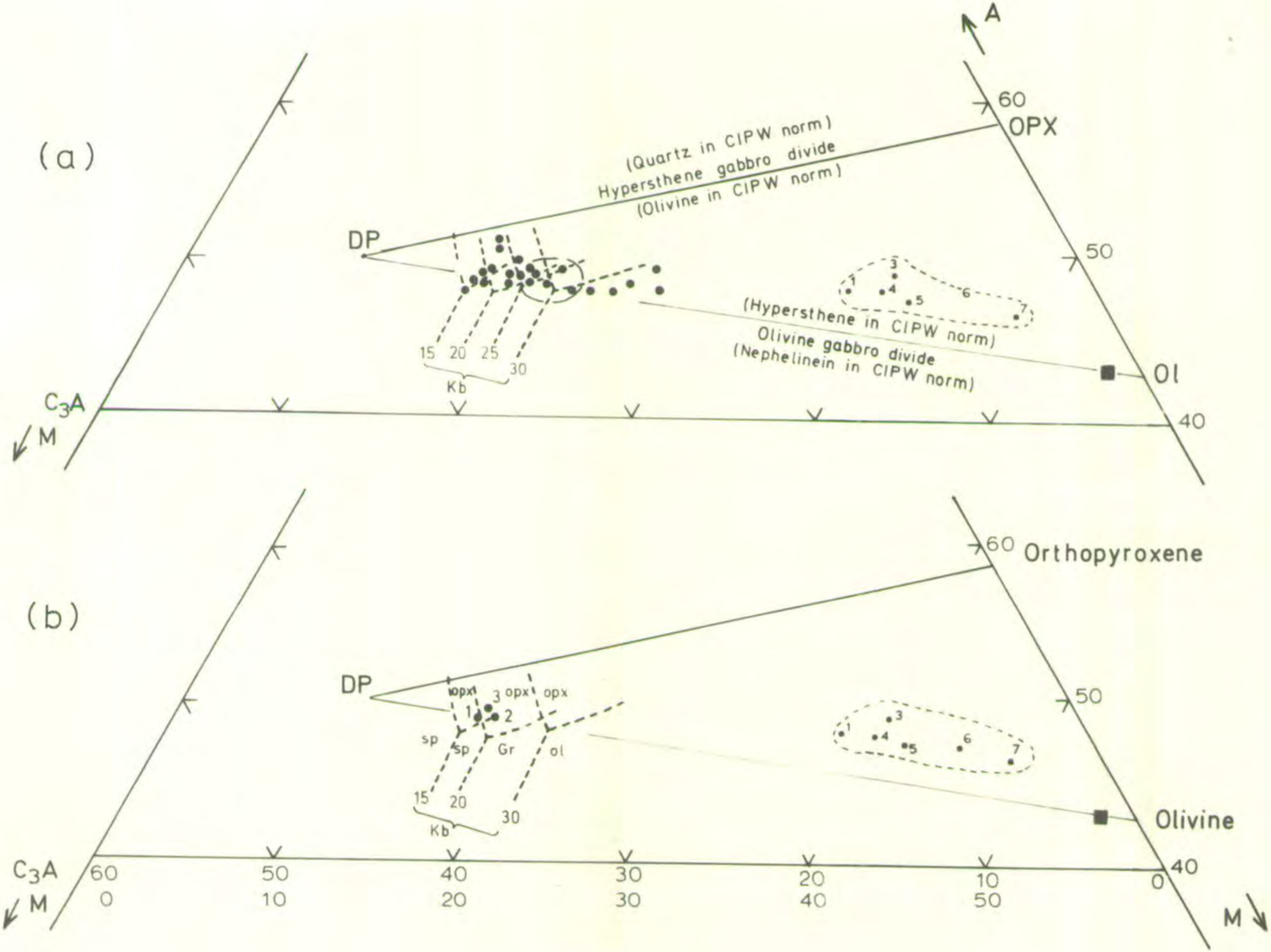
(a)
A
60
OPX
(Quartz in CIPW norm)
Hypersthene gabbro divide
(Olivine in CIPW norm)
DP
50
1
3
4
5
6
7
(Hypersthene in CIPW norm)
Olivine gabbro divide
(Nephelinein in CIPW norm)
Ol
15
20
25
30
Kb
C3A
M
40
(b)
60 Orthopyroxene
DP
opx
3
opx
opx
1
2
sp
sp
Gr
ol
50
1
3
4
5
6
7
15
20
30
Kb
Olivine
C3A
M
60
0
50
10
40
20
30
30
20
40
10
50
0
40
M

Fig. 7-2

postulated primitive upper mantle compositions are also indicated in the figures. It can be seen from Fig. 7-2a that some of the picritic compositions, particularly those with about 16-18% MgO and 70-76 Mg x 100/Mg + Fe^{2+}, approximate in projection with the position of the 25-30 Kb pseudo-invariant point i.e. the composition of the liquid in equilibrium with the four-phases of the source peridodite (Ol + Cpx + Opx + Gr) or with Ol + Opx - the residual minerals of fairly advanced stage partial melting (cf. O'Hara, op.cit.).

According to Ito and Kennedy (1967, p. 534) ..."picritic basalts can be expected as surface flows only where lava travels from very great depths to the surface at very high speeds" ... because during slow uprise, the steady precipitation of olivine, (as a result of cooling) causes the magnesium content of the liquid to drop rapidly. Therefore, in order to retain the picritic character of the parental liquids in the present case, it becomes necessary to postulate rather a rapid ascent to them from their place of formation. With regard to the origin of the parental magmas of the bore hole flows, the following possibilities seem plausible.

a) If the least basic picritic liquids (as in Table 7-2 and Fig. 7-2b) represent parental compositions, it is probable that they are derived from more primitive picritic liquids formed at c. 30 Kb through loss of some olivine en route.

b) On the other hand, if picritic compositions more basic than the least basic picritic liquids, analogous to those with about 16-18% MgO, represent parental liquids, then it is probable that such compositions may approximate initial or primary liquids formed at c. 25-30 Kb in conformity with the phase diagram (Fig. 7-2a). In such a case, fairly rapid ascent of the initial partial melts from upper mantle depths to shallow level magma chambers or conduits is implied. The porphyritic character of these flows, however, suggests that they might have paused for a short time with slight heat loss, in the low pressure environment prior to eruption. Examples of such rapid transport of primary or primitive picritic liquids have been reported from Baffin Bay in West Greenland (Clarke, 1970) and Nuanetsi in Southern Rhodesia (Jamieson, 1966).

An additional possibility is that the least basic picritic liquids may even represent direct partial melts, probably at pressures < 30 Kb, i.e. at depths < 100 Km. Cox and Jamieson (in press) from high pressure experimental studies postulate, that Karroo picrite basalts equilibrated with Ol + Opx at pressures as low as c. 10 Kb, which implies very high local thermal gradient. From high pressure melting experiments on a parental picritic liquid from Northern Skye (with 11.08% MgO), Thompson (1973) has postulated that such a liquid could remain in equilibrium with a lherzolitic source with an Mg x 100/Mg + Fe^{2+} ratio of 85 at pressures c. 16.5 Kb (55 Km). In other words, these picritic liquids - analogous to the least basic parental picritic compositions of the bore hole flows - are possibly primary liquids. Therefore, the possibility of the least basic picritic liquid being direct partial melts cannot be ruled out at this stage. High pressure experimental work may shed some light on this aspect. Nevertheless, postulation (a) is tentatively retained here, in the discussions to follow.

However, the primitive or primary character of the picritic basalts suggested from their major element chemistry and phase equilibria considerations, is not supported by their trace element concentrations, particularly by the "incompatible" elements (Ringwood, 1966). Therefore, it becomes necessary to consider the various postulated processes which are alleged to increase the incompatible elements in erupted basaltic and picritic liquids. Concentration levels of trace elements in the primitive upper mantle source, and the partition coefficients of these incompatible trace elements between crystals and liquids at higher pressures are very poorly known. Nevertheless, a brief attempt is made in the following section with regard to the processes which may enrich the concentrations of incompatible elements in the picritic liquids.

7:6 Potassium and Associated elements:-

This group of elements termed the "incompatible" elements comprise K, Ba, Sr, Rb, P, Zr, Ti, U, Th and Pb, and are largely rejected by the major minerals of the upper mantle source rock i.e. garnet-peridotite (Griffin and Murthy, 1969). However, some of these elements may be held in trace amounts of amphibole (Oxburgh, 1964; Lambert and Wyllie, 1968), phlogopite (Kushiro et al., 1967) apatite and zircon. Because of chemical discrimination by the major silicate phases, these elements will be concentrated in the initial liquid phase formed as a result of partial melting, and will remain in the residual liquid during any subsequent high pressure fractionation. A number of hypotheses, such as a) the degree of melting (Gast, 1968; O'Hara, 1968), b) high pressure fractionation (O'Hara and Yoder, 1967; Green and Ringwood, 1967) and c) wall rock reaction, including "zone refining" (Harris, 1957; Green and Ringwood, op.cit.) have been attributed to the enrichment of the incompatible trace elements in various basaltic types, and these are briefly considered with reference to the parental picritic basalts in the following section. The importance and efficacies of these different processes have been reviewed by a number of workers (Bell and Powell, 1969; Jamieson and Clarke, 1970; Appleton, 1972). However, it must be stressed that criteria with which one can distinguish these processes are either lacking or absent.

7:6a Degree of partial melting:-

According to Harris (1967, p. 312) the majority of the K and associated elements enter the initial liquid phase, their concentrations being inversely proportional to the degree of melting, a view supported by Gast (1968) and Griffin and Murthy (1969). Assuming total element incompatibility, the relation between the degree of partial melting and the subsequent enrichment factor can be expressed by the following equation:

$$E = 100/V$$

where E = Enrichment (E) factor for a particular element

$$= \frac{\text{Concentration of a particular element in the specimen}}{\text{Concentration of the element in the upper mantle}}$$

and V = volume % of the liquid produced after partial melting or remaining after a particular process of crystal fractionation of the initial melt.

Table 7-5

Enrichment (E) factors* of the minor and trace elements for the least porphyritic and most basic picrite basalt (No. 1 of Table 7-2)

A. Anhydrous mantle

Element	Conc. in the mantle[a]	Conc. in the sample	E factor
K	106.00	9544	90
Rb	0.48	33	69
Sr	15.00	400	27
Ba	14.00	545	39
Zr	30.00	185	6
TiO_2	0.26	2.54	10
Na_2O	0.17	2.15	12
P_2O_5	0.02	0.36	18

E factor mean[b] = 28

E factor mean[c] = 56

B. Hydrous mantle with 0.2% phlogopite

K	248.00	9544	28
Rb	0.98	33	34
Sr	15.00	400	27
Ba	17.00	545	22

E factor mean[c] = 28

C. Hydrous mantle with 0.5% phlogopite

K	464	9544	21
Rb	1.76	33	19
Sr	15.00	400	27
Ba	21.00	545	26

E factor mean[c] = 23

* E factors rounded off to the nearest whole number

a = Concentration of elements in ppm and oxides in wt.%.
b = Excluding Zr only
c = K, Rb, Ba and Sr only.

Based on the above equation, E factors have been calculated for the most basic and the least porphyritic picrite basalt parental composition, as this might provide the upper limit for the E factors, in such compositions, and are presented in Table 7-5. It can be seen from the table that, depending upon the initial concentration levels of the source rock, a wide range of E factors are possible. Griffin and Murthy (1969, Table 10, p. 1405) provide concentration levels of K, Rb, Ba and Sr in initial partial melts for different degrees of partial melting from both anhydrous and hydrous upper mantle compositions. Using these values, and the above equation, E factors for various degrees of partial melting have been calculated and are presented in Table 7-6.

Table 7-6
Enrichment (E) factors for different degrees of partial melting

	% Melt		
Element	5	10	20
K	18	10	5
Rb	16	9	4
Ba	18	9	5
Sr	17	9	5
Mean	17	9	5

Magma extraction is considered to be very unlikely when the degree of melting is less than 5%, which in the present case gives an initial maximum %, E factor of 17. However, it is doubtful that such a low degree of partial melting can give rise to either the least basic parental picritic composition or a more basic parental picritic type than the least basic one.

According to Green and Ringwood (1967, p. 161) moderate to high degree of melting (c. 20 to 40% by volume) is necessary to produce picritic liquids which can fractionate subsequently to give derivative magmas. It is assumed here that <u>at least</u> about 20% melting (giving an initial E factor of 5) is necessary to produce liquids analogous to those primitive picritic liquids of the bore holes which approximate in projection with the 30 Kb pseudo-invariant point, i.e., picritic compositions of about 16-18% MgO. Independent estimates* of the degree of melting for a picritic liquid of such a composition gave a value of 21% (see Table 7-7), thus giving an initial E factor of 5, for the probable primary liquid, and which appears to support the assumption made previously. Thus it can be seen that in the present case degree of melting alone cannot satisfactorily account for the E factors of either the least basic parental picrite basalt or the postulated primary liquid, from which the least basic parental liquid is probably derived. Therefore, it becomes necessary to postulate additional mechanisms of enrichment, such as high pressure crystallization and/or wall rock reaction.

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* Computer estimates based on the assumption that the liquids are primary and related as follows:
Possible primary liquid + possible residual upper mantle = Possible primitive upper mantle.

Table 7-7

	No.1	No.2	No.3	Weight	Calc.	Diff.	Extract
SiO_2	43.50	45.94	44.43	1.00	44.01	0.41	45.94
Al_2O_3	0.82	10.46	2.60	1.00	2.85	-0.25	10.46
Fe_2O_3	1.20	1.66	1.65	1.00	1.30	0.35	1.66
FeO	6.46	9.36	7.28	1.00	7.07	0.20	9.36
MgO	47.25	16.48	40.70	1.00	40.76	-0.05	16.48
CaO	0.11	11.87	2.45	1.00	2.59	-0.14	11.87
Na_2O	0.07	1.41	0.23	1.00	0.35	-0.12	1.41
K_2O	0.02	0.55	0.03	1.00	0.13	-0.11	0.55
TiO_2	0.07	1.62	0.15	1.00	0.40	-0.25	1.62
P_2O_5	0.00	0.25	0.04	1.00	0.05	-0.01	0.25
MnO	0.12	0.20	0.15	1.00	0.14	0.01	0.20
Cr_2O_3	0.38	0.21	0.30	1.00	0.34	-0.04	0.21
SOLUTION	78.90	21.10					21.10
SENSITIVITY	0.08	-0.04					

SUM OF SQUARES OF RESIDUALS = 0.509

No.1 Possible upper mantle residue as in column No.7, Table 7-3.
No.2 Picrite basalt, specimen No. 129, Table 4-2 (calculated H_2O free)
No.3 Possible upper mantle source material as in column No.5 Table 7-3.

Note:- Source and residual materials, other than the ones used here give large amounts of sum of squares of residuals.

7:6b High pressure fractionation:-

High pressure eclogite fractionation has been proposed by O'Hara and Yoder (1967) as an effective process for increasing the incompatible trace elements in the residual liquids, without affecting the major element chemistry. Subsequent olivine fractionation of the initial liquid (up to 40%) en route has also been postulated by O'Hara (1968), to enhance the enrichment of the incompatible elements. Certain combinations of eclogite fractionation and olivine fractionation (up to a maximum of 40%) as postulated by O'Hara (op.cit.) are shown in Table 7-8, which are necessary if the E factors have to be accounted for by closed-system crystallization alone. It can be seen that fairly large amounts of crystallization are required for producing the E factors obtained assuming a anhydrous upper mantle when compared with E factors obtained assuming a hydrous mantle (say with 0.5% phlogopite).

Large amounts of crystallization invoked to account for the enrichment of the incompatible elements has been criticized by Gast (1968), because they imply large reductions in the volume of the initial partial melt. The efficacy of eclogite fractionation has been further doubted by Bultitude and Green (1971) on the grounds that

a) the crystallizing pyroxene is not omphacitic as in the case of a typical eclogitic pyroxene, but an aluminous sub-calcic type, and

b) large amounts of crystallization are necessary to increase the initial enrichment factors even by small amounts.

Table 7-8

Enrichment (E) factors based on different degrees of eclogite and olivine fractionation, assuming an initial E factor of 5 after C.20% partial melting

% Melting	% Eclogite fract.	% Olivine fract.	Resulting E Factor
20	50	40	17
20	50	-	10
20	-	40	8
20	60	40	22
20	70	40	28

Average E factors for the least porphyritic and most basic picritic basalt is as follows (Data from Table 7-5).

a) Assuming anhydrous mantle
  i) 28^b
  ii) 56^c

b) Assuming hydrous mantle with 0.5% phlogopite
  i) 23^c

Harris (1967) has pointed out that large amounts of eclogite fractionation might produce residual liquids with unusually high Fe/Mg and Na/Ca ratios.

An additional point to be borne in mind in the present case is that the rapid transport of the initial picritic partial melt, - a pre-requisite necessary for the retention of the picritic character of the parental flows - may not have been conducive to any significant high pressure fractionation mechanisms to set in.

Nevertheless, there is some evidence for the operation of eclogite fractionation from the variations of the K_2O/Na_2O ratios of the bore hole suite, particularly in the primitive picrite basalts. Because of the preferential entry of Na in omphacitic pyroxenes (?), eclogite fractionation, had it been operative, should show an increase in the K_2O/Na_2O ratio when plotted against K_2O, assuming that no other processes are influencing the variation. A plot of the K_2O/Na_2O Vs. K_2O (Fig. 7-3), though scattered, shows a general increase, particularly among the picritic basalts, and such a feature might be taken to support the possibility of some eclogite fractionation. But the process may not have been significant enough to account for the bulk of the 5 to 11 fold increase in the enrichment factors. Large amounts of olivine fractionation of the primary or primitive liquid is also unlikely, for it will produce residual liquids, which may not resemble the least basic picrite basalts. Assuming an initial partial melt of about 16% MgO, c. 15% of olivine fractionation is possible, so that the residual liquids resemble the least basic picrite basalt. Therefore, considerations of an additional process of trace element enrichment

Fig. 7-3: Plot of K_2O/Na_2O vs. K_2O (wt.%).

Symbols as in Fig. 2-2.

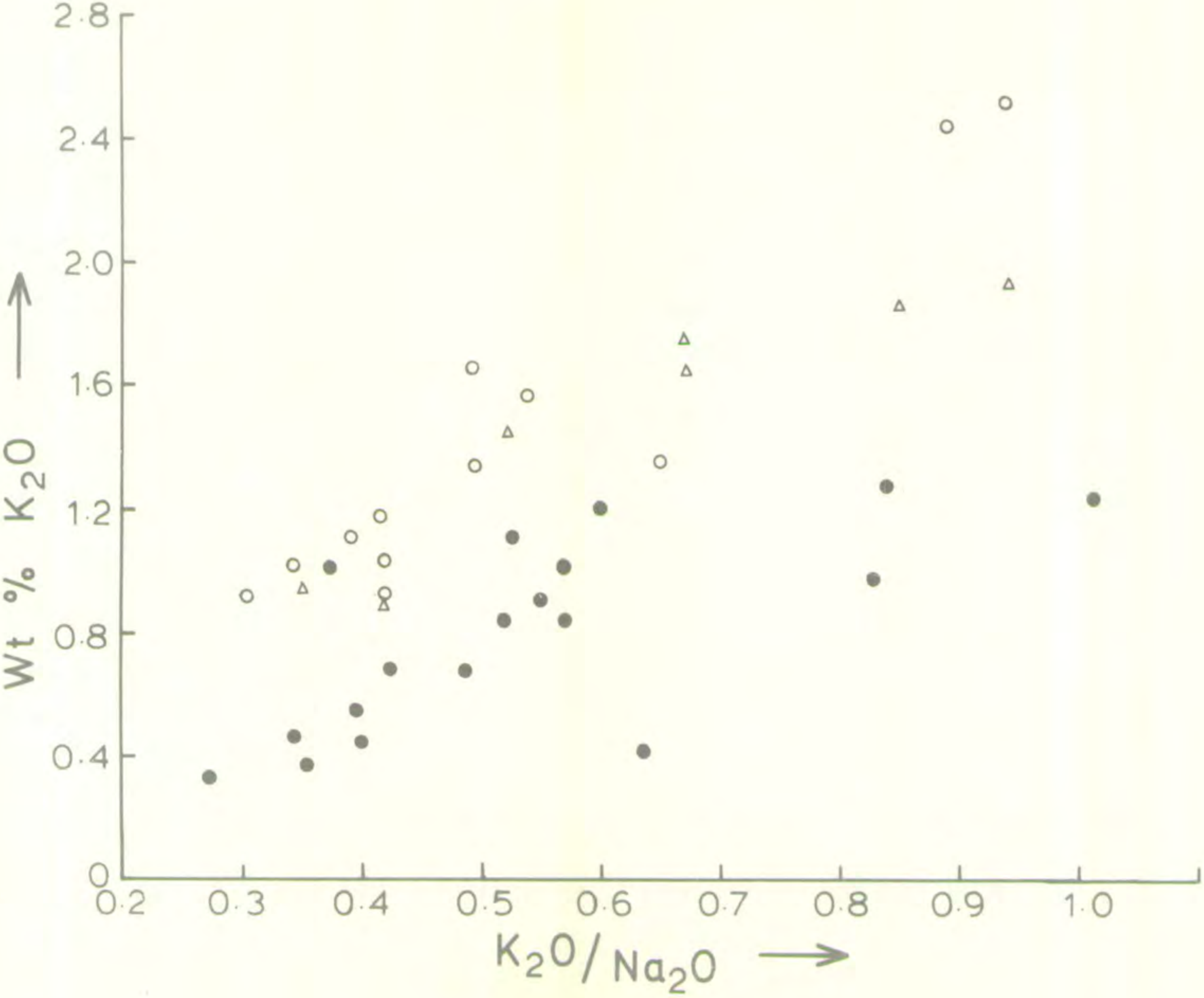


Fig. 7-3

i.e. wall rock reaction becomes necessary.

7:6c Wall-rock reaction:-

The nature of wall-rock reactions (Green and Ringwood, 1967) are difficult to quantify, but nevertheless it is possible to imagine the operation of such a process, at least in the early batches of magmas. Considering the point that the bore hole flows appear to be the earliest products of eruptions in this part of the basalt plateau, wall-rock reaction may not be totally ruled out. Green and Ringwood (op.cit.)have used the K/Sr and Rb/Sr ratios of the parental basalts to distinguish the approximate depth of wall-rock reaction, since Sr behaves as a compatible element (held in plagioclase) at lower pressures (<15 Kb). The K/Sr and Rb/Sr ratios of the parental picritic basalts (Table 7-9) compare closely with those rocks alleged to have achieved their incompatible element enrichment at upper mantle depths. However, the ratios at hand are slightly higher than those reported. Nevertheless, the importance of the process may have to be limited, considering the faster rate of ascent, implied by the picritic character of the parental liquids.

7:7 Summary:-

It is difficult to decide between the different mechanisms which have probably contributed to the enrichment of K and associated elements, because of the assumptions that have to be made regarding the trace element content of the source rock, the distribution of these elements, the behaviour of the elements during partial melting and the stability fields of minerals such as phlogopite and amphibole, which are thought to carry these trace elements.

Table 7-9

Range of observed K/Sr and Rb/Sr ratios of the picrite basalts compared with mantle- and crust-contaminated rocks.

Type of rock	K/Sr			Rb/Sr		
	Min.		Max.	Min.		Max.
Picrite basalts (bore hole flows)	7	-	35*	0.03	-	0.11*
Mantle-contaminated lavas^x	10	-	22	0.015	-	0.07
Crust-contaminated lavas^x	31	-	88	0.12	-	0.4

x After Green and Ringwood (1967, Table 21).

* A single specimen (No. 381) gave 58 of K/Sr and 0.158 of Rb/Sr, but this differs from the rest in having vein-like plagioclase segregations as well as resorbed phenocrysts of olivine.

Additional problems are imposed by the probable mantle inhomogeneity (Kay <u>et al</u>., 1970; Frey <u>et al</u>., 1968; Schilling, 1971) and the evidence for the presence of a "low velocity zone" in the mantle at ~ 100 to 200 kms (Anderson, 1962) because of the presence of a fluid phase (partial melt (?), H_2O, $\pm$ CO_2 (?)) which in turn according to Green (1971), may permit selective migration and enrichment and hence chemical zoning in the uppermost part of the low velocity zone.

Nevertheless, partial melting processes of a phlogopite bearing source rock, i.e. garnet-peridotite appears to pose fewer problems of enrichment than those without it. Additional processes such as high pressure eclogite fractionation and/or wall rock reaction may have played a less significant role in enriching the initial concentration levels.

7:8 Petrogenetic Summary:-

In the light of the evaluations of petrography, mineralogy, chemistry and phase equilibria considerations dealt with so far, the following petrogenetic scheme may be envisaged to have operated in the evolution of the bore hole flows.

1. Partial melting of an upper mantle composition analogous to a garnet-peridotite, probably with trace amounts of phlogopite at c. 25-30 Kb (c. 75 to 100 km) with the production of c. 20% primary picritic liquid. Compositions analogous to such a liquid - at least with regard to the major elements - may be represented by some of the picritic liquids of the bore hole sequence.

2. Fairly rapid ascent and supply of such a liquid to plexus of shallow level magma chambers or conduits in the crust with or without immediate eruption. Such a liquid may have lost some olivine and clinopyroxene (?) en route to produce compositions analogous to the least basic picritic parental liquids.

3. Depending upon the time of pause and rate of heat loss, in the low pressure environment, differentiation of the primitive picritic liquid ensued, mainly through fractional crystallization of olivine, clinopyroxene and plagioclase. However, the mechanisms of crystal fractionation may not have been simple.

4. The primitive picrite basalts, particularly the strongly porphyritic types, may have suffered from low pressure crystal fractionation mechanisms akin to compensated crystal settling, while the ankaramitic types may have been influenced by some high pressure crystallization. In some of the residual liquids, i.e. basalts,

plagioclase may have been selectively enriched to produce the strongly porphyritic, felspar rich types.

5. Enrichment of trace elements in the primitive picrite basalts pose considerable problems.

Enrichment of the incompatible trace elements in the primitive picrite basalts were probably largely achieved as a result of partial melting of the phlogopite bearing source rocks. Small amounts of high pressure eclogite fractionation and wall rock reaction may have enhanced the concentration of the incompatible trace elements to a small extent, and also probably account for the variations observed in the parental liquids.

PART II

CHAPTER VIII

WESTERN PARTS OF THE RAJPIPLA HILLS, BROACH DISTRICT, GUJARAT STATE

8:1 Introduction:-

The area studied covers the western parts of the Rajpipla hills, just south of the Narmada river (see Fig. 1-1) and lies between Longitude 73°15' - 73°20' East - Latitude 21°40' - 21°45' North, in the survey of India toposheet No. 46 G/6. A brief account of the previous studies of the area by different workers has already been given (see Chapter 1; Section 1:2). The author's work during 1967-70, has brought to light the following points with regard to the basaltic rocks of the area.

1. The lowermost flows of the area are sub-alkaline, and tholeiitic in composition analogous to those commonly found over most of the Deccan basalt plateau.

2. These are overlain by flows and/or cut by minor dykes of a mildly alkaline, moderately potassic suite comprising predominantly porphyritic basalts and porphyritic trachybasalts, with small amounts of ankaramitic basalts, felspar phyric basalts and oligoclase basalts and trachyte, the last one being represented by a single dyke. Thus the alkaline suite appears to form a differentiated series ranging from alkali basalts to trachyte.

3. Small plug like masses of potassic rhyolites (those referred to as "trachytic plugs" by earlier workers) cut both (1) and (2) and may be genetically related to the alkalic suite.

4. Both (1), (2) and (3) are in turn cut by major, sub-alkaline tholeiitic dolerite dykes with a NE and ENE trend.

K-Ar dating of a porphyritic basalt belonging to the alkalic suite gave an age of 60 ± 5 Ma (Lower Eocene; N.J. Snelling, personal communication).

The present chapter is mainly concerned with the evolution of the alkalic suite from a chemical and mineralogical point of view. The geological map of the area is given in Fig. 8-1 and some aspects of classification, petrography and mineralogy are briefly considered before discussing the variations in chemistry and their implication on the genesis of the suite.

8:2 Classification:-

According to the simple chemical classification based on total alkalies vs. silica (Fig. 8-2), the differentiated suite belongs to the alkalic group, following the boundary line used by Macdonald and Katsura (1964). The tholeiitic nature of the earliest flows of the area and the youngest dolerite dykes are very clear from their plotted positions. However a norm based classification after Yoder and Tilley (1962) indicates that the differentiated series in fact comprises all the three following types:-

1. Alkali basalts (nepheline normative; nepheline <5% in the norm).

2. Olivine-tholeiite (Ol + Hy normative).

and 3. Quartz-tholeiites (Hy + Qz normative).

Coombs (1963) has shown that the oxidation state of iron can influence the appearance of normative nepheline, olivine, hypersthene and quartz of an analysis, and therefore its plotted position in the basalt tetrahedra (Yoder and Tilley, op.cit.) and its classification.

Fig. 8-1: Geological map of the western portions of Rajpipla hills, Broach district, Gujarat state, India.

GEOLOGICAL MAP OF THE WESTERN PARTS OF RAJPIPLA HILLS, BROACH DISTRICT, GUJARAT, INDIA

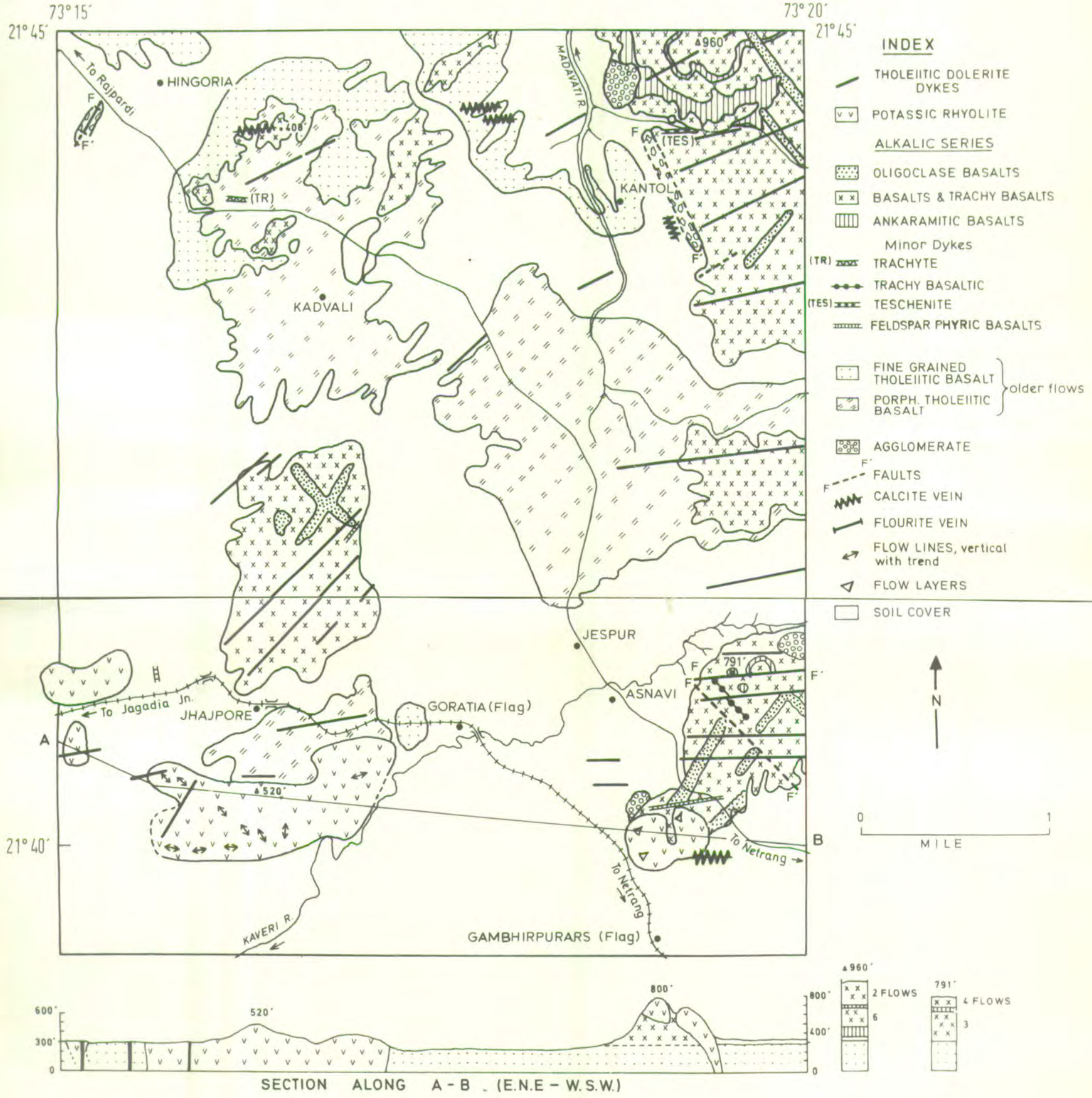


Fig. 8 -1

Fig. 8-2: Plot of total alkalies vs silica for the rocks from the western parts of Rajpipla hills. The boundary between the tholeiitic and alkalic rocks are after Macdonald and Katsura (1964, Fig. 1)

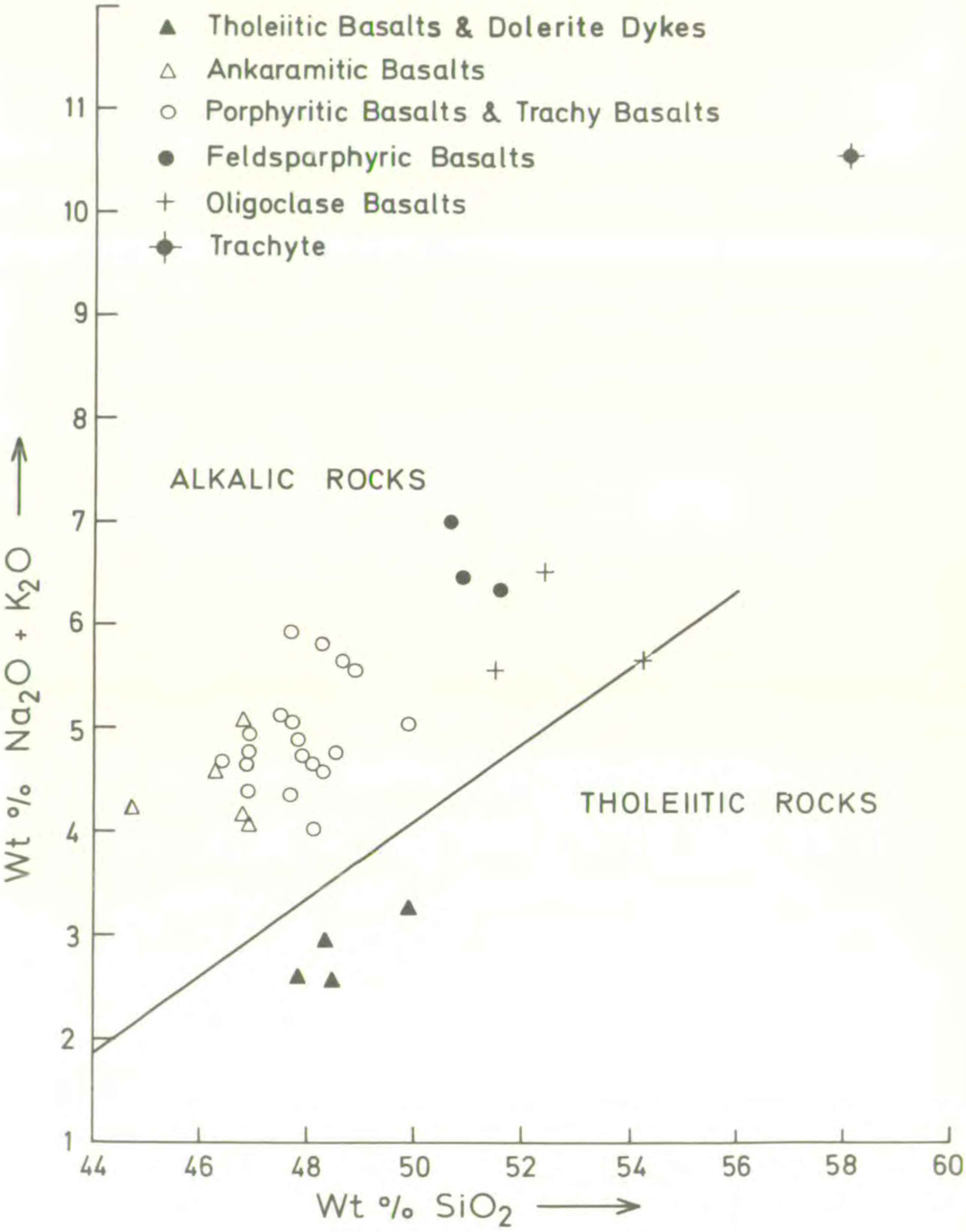

▲ Tholeiitic Basalts & Dolerite Dykes
△ Ankaramitic Basalts
○ Porphyritic Basalts & Trachy Basalts
● Feldsparphyric Basalts
+ Oligoclase Basalts
Trachyte
ALKALIC ROCKS
THOLEIITIC ROCKS
Wt % $Na_2O + K_2O$
Wt % SiO_2
1
2
3
4
5
6
7
8
9
10
11
44
46
48
50
52
54
56
58
60

Fig. 8-2

The alkali basalts on the whole are highly oxidised and altered for their uncorrected Fe_2O_3 x 100/FeO + Fe_2O_3 ranges widely from 30 to 83%, compared with the tholeiitic basalts and dykes which show a narrow range from 26 to 28%. The oxidised nature of the differentiated suite is probably a reflection of the intrinsic alkaline character of the rocks and thus appears to be in conformity with the observations made on such group of rocks from a number of localities (Manson, 1967). Therefore, standardisation of the Fe_2O_3:FeO ratios of the analysed flows has been done, taking a Fe_2O_3 x 100/Fe_2O_3 + FeO ratio of 30%, given by the freshest sample (Specimen No. R-19, Table 8-7). In spite of such a normalisation of the Fe_2O_3/FeO ratios, the normative character of the flows do not change very much, except for the fact that the number of flows belonging to each group changes, as shown below.

Rock types. Based on normative minerals After Yoder and Tilley (1962)	Prior to standardisation of the Fe_2O_3/ FeO + Fe_2O_3 ratio.	After standardisation of the Fe_2O_3x100/FeO + Fe_2O_3 to 30%.
Alkali basalts <5% nepheline in the norm	2	7
Olivine-tholeiites	4	14
Quartz-tholeiites	31	16

Therefore, the differentiated series appears to belong to the "mildly alkaline" or "transitional" group, of Coombs (1963), and in <u>this</u> respect resembles those found in Easter Island (Bandy, 1937), Banks Peninsula (Benson, 1941), Tutuila (Daly, 1924), Ascension

Island (Daly, 1925; Coombs, 1963), Skye (Thompson et al., 1972), the differentiated series of Reunion (Upton and Wadsworth, 1972), the older series of Mauritius (Baxter, 1973), the peralkaline volcanic suite of Aden (Cox et al., 1970), and Gough Island (Le Matre, 1962).

However, the mildly alkaline series of the Rajpipla area appears to be richer in potassium than any other documented alkali basalt-trachyte association (see Fig. 8-3). In having such high potassium some of the members of the differentiated series show similarities to the absarokite-shoshonite association (Joplin, 1968) as well as to the low K series of the Roman province (Appleton, 1970,1972). However, as will be shown later, there are essential differences in the contents of TiO_2, total iron etc. between the present suite and those mentioned above. The potassic character of the suite also poses problems in the nomenclature of the flows.

8:3 Nomenclature:-

The whole scheme of nomenclature of the Rajpipla rocks is summarised in Table 8-1).

8:4 Petrography:-

Petrographic descriptions of all the analysed specimens would be highly repetitive. Therefore, a generalised account of the petrographic features of each group is given in summary form in the following section. Individual descriptions of the analysed samples are given in Appendix B (Table B-2)

Fig. 8-3: K_2O vs. Na_2O plot of the samples of the Rajpipla alkalic series from basalt to trachyte, compared with other suites. (Potassic rhyolites of the Rajpipla area (open squares) have also been included.)

<u>Explanations</u>:

Hawaii, B-B = Hawaiian alkalic series from basalt to benmoreite (Macdonald, 1968)

Skye, B-B = Skye main lava series, from basalt to benmoreite (Thompson <u>et al</u>., 1972).

Skye, B-T = Skye main lava series from basalt to trachyte (Thompson, <u>et al</u>., <u>op.cit</u>.)

East Otago, M-POT = Moderately potassic, under-saturated lavas of East Otago (Coombs and Wilkinson, 1969)

Gough Island B-T = Gough Island alkalic series from basalt to trachyte (Le Maitre, 1962)

L-K Series = Low potash series, Roman Province (Appleton, 1970)

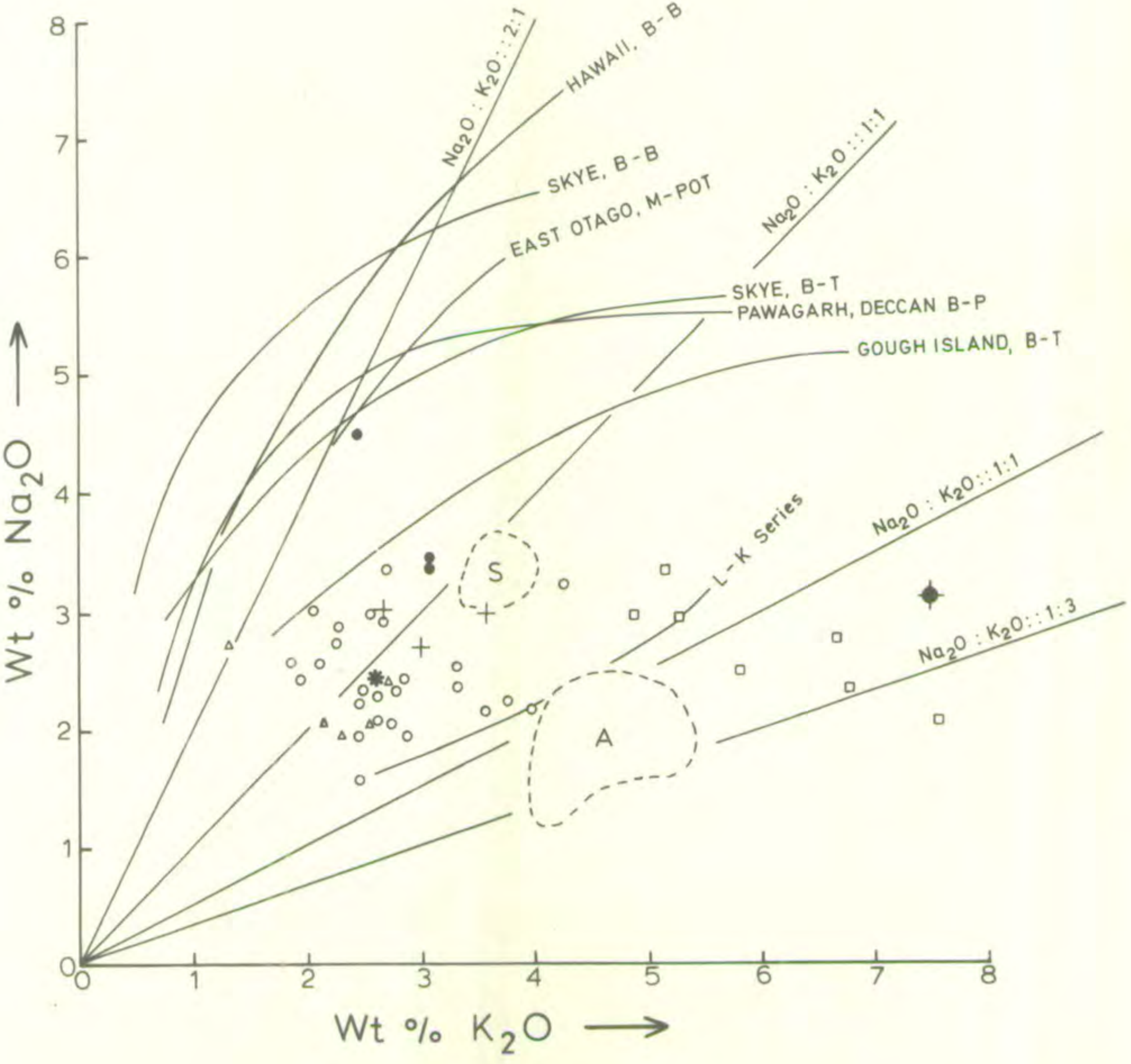
B-P = Basalt-pitchstone series from Pawagarh (Tiwari, 1969).

A = Field of absarokites (Joplin, 1968)

S = Field of shoshonites (Joplin, <u>op.cit</u>.)

Asterisks indicate the Na_2O and K_2O values of the parental basalt of the Rajpipla alkalic suite.

Other symbols as in Fig. 8-2.



8
7
6
5
4
3
2
1
0
Wt % Na_2O →
0
1
2
3
4
5
6
7
8
Wt % K_2O →
$Na_2O : K_2O :: 2:1$
HAWAII, B-B
SKYE, B-B
EAST OTAGO, M-POT
$Na_2O : K_2O :: 1:1$
SKYE, B-T
PAWAGARH, DECCAN B-P
GOUGH ISLAND, B-T
S
L-K Series
$Na_2O : K_2O :: 1:1$
$Na_2O : K_2O :: 1:3$
A

Fig. 8 - 3

Table 8-1

Summary of Nomenclature of the Rajpipla rocks

Rock types	Wt.% MgO	Differentiation Index	Phenocrysts	Remarks
Ankaramitic basalt	>7.96 <8.41	27 to 35	Abundant Cpx always > olivine in the mode	
Porphyritic basalt	>5.00 <6.15	31 to 42	olivine + clinopyroxene + plagioclase + Ore	Groundmass alkali feldspar scarce
Porphyritic trachy basalt	>4.0 <5.0	35 to 45	olivine + clinopyroxene + plagioclase + Ore	Groundmass alkali feldspar normally present
Feldspar phyric basalts	1.7 to 3.4	49 to 54	Dominantly plagioclase; scarce olivine, clinopyroxene and Ore	$Na_2O:K_2O$ <2:1 Modal plagioclase more calcic than andesine (An_{50-60})
Oligoclase basalt	2.7 to 3.6	47 to 54	Scarce microphenocrysts of oligoclase; very scarce olivine, Cpx and Ore	Qz-normative
Trachyte	0.82	71	Albite (Ab_{97}) Cpx + Kaersutite + Ore	Rather potassic; $K_2O/Na_2O = 2.38$
Potassic rhyolite	<0.7	87 to 95	Orthoclase-microperthite + albite Resorbed biotite + amphibole?	Average $K_2O/Na_2O = 2.19$
Teschenite	5.77	30	Titan-augite olivine. Ore	Rather potassic; Glenmurite type
Tholeiitic basalt and tholeiitic dolerite	4.87 to 6.46	25 to 27	Generally aphyric. Some may have scarce plagioclase and/or altered olivine phenocrysts	Plots in the tholeiitic field of total alkali-silica Diagram (Fig. 8-2)

8:4a Tholeiitic basalt (Plate 8-1)

Flows of this group form the base of the volcanic sequence exposed. In hand specimens they are melanocratic, dense, fine-grained, and generally aphyric. In thin sections, they are micro-crystalline with a few phenocrysts (up to 1.25 mm) of olivine completely altered to yellowish brown, feebly pleochroic iddingsite. Microlites of plagioclase (An_{65-70}) average 0.15 mm x 0.025 mm in size, and commonly twinned on albite law, and forms triangular networks. Granules of augite ($Z\wedge c = 43^{\circ}$; $2V_{r} = 52$) in between the plagioclase; grains of magnetite and ilmenite are common accessories. Scarce patches of yellowish coloured chlorophaeite, apparently after the alteration of the glass are not uncommon. Micro-vesicles may contain quartz and/or calcite. A few flows of this type (as in Specimen No. T-2) may have phenocrysts of plagioclase (An_{65-70}).

8:4b Ankaramitic basalt

Flows of this type are of minor occurrence (4 flows; 10-50' thick), and scarcely dykes of this type have been found. In hand specimens, they are melanocratic, dense and porphyritic. Phenocrysts are dominantly composed of euhedral to sub-hedral (up to 1 cm long) colourless to mauve-coloured, non-pleochroic to very feebly pleochroic augite ($Ca_{52-44}Mg_{45-37}Fe_{13-11}$; Table 8-3). Normal zoning and twinning on (100) are frequently seen (Plate 8-2); glomeroporphyritic groupings of the clinopyroxenes rather common. Olivine phenocrysts (up to 5 mm) are subordinate to the clinopyroxenes; majority of them are iddingsitised (Plate 8-3). Modal phenocrystal clinopyroxenes (in vol. %) range from 19 to 28%, while that of olivines range from 2 to 3%. Groundmass is generally fine-grained (<0.1 mm) to crypto-crystalline, when crystallized, grains of augite, iddingsitised olivine and microlites or micro-phenocrysts of plagioclase (An_{65}) and titano-magnetite have been noticed. Palagonite and/or calcite may be present occasionally in the micro-vesicles.

8:4c <u>Porphyritic basalts</u> (Plates 8-4, 8-5 and 8-6)

Together with the trachy basalts, these flows constitute the largest group of flows within the differentiated series, and range in thickness from 50 to 250 feet. Minor dykes of these types are not uncommon. In hand specimens they are black to brownish-black in colour, and are invariably porphyritic with varying amounts of phenocrysts of olivine, clinopyroxene, plagioclase and ore. In thin sections these phenocrysts are frequently seen in glomero-porphyritic aggregates. The following range of modal variation in the amounts of phenocrystal minerals has been observed within this group:

	In Vol. %		
	Min.	Max.	Average (11 samples)
Olivine (altered to iddingsite or hematite; up to ~4mm x 1mm in size but averages ~1mm x .25mm)	0.3	5.0	2.7
Clinopyroxene (augite; fresh and commonly in glomero-porphyritic groupings; individual crystal may be up to ~7mm x 3 mm but averages ~2mm x .5mm)	5.7	18.8	10.4
Plagioclase (An_{65-50}; rarely up to ~1cm long in parallel groupings; scarcely in stellate groups)	0.3	13.7	6.5
Ore (titano-magnetite and ilmenite, measuring up to 3 mm^2 plates; commonly altered and oxidised to hematite and ilmenohematite)	0.7	6.3	2.8

Groundmass is generally very fine-grained (<.1mm), rather dirty brown in colour and may be altered in some samples. Plagioclase microlites are dominant and generally less calcic than the phenocrysts. Other minerals include grains of clinopyroxene, scarce altered olivine, and plenty of granular and dusty iron ore. Scarce flakes of phlogopite are not uncommon. In some flows, alkali felspar microlites may be present. Micro-vesicles, when present, may be infilled with secondary minerals such as calcite, chalcedony, palagonite and zeolites.

8:4d Porphyritic trachy basalts (Plates 8-7 and 8-8)

These occur as flows, ranging from 50-200 feet thick, in close association with the porphyritic basalts. They resemble the porphyritic basalts and it is difficult to distinguish them by petrography alone. In general flows of this group tend to contain plagioclase phenocrysts which are slightly less calcic than those present in the porphyritic basalt types (i.e. An_{60-45}). In addition they may also contain microlites of alkali feldspar in the groundmass and flakes of phlogopite. The following range of modal variation in the amounts of phenocrystal minerals has been noticed within this group.

	In Vol.%		
	Min.	Max.	Average (12 samples)
Olivine	-	9.6	2.9
Clinopyroxene	-	15.1	8.3
Plagioclase	1.1	16.0	8.0
Ore	1.0	5.5	3.0

8:4e Feldspar phyric basalt (Plate 8-9)

A single flow (~50 feet thick) and several minor dykes of this type have been found to be present. In hand specimens they are greyish black in colour, and strongly porphyritic with dominant phenocrysts of plagioclase, with scarce olivine, clinopyroxene and ore. In thin sections, plagioclase (An_{60-50}) tends to show parallel groupings (up to 12 mm x 3 mm) and may exhibit fluidal pattern. A few of them show feeble zoning and corrosion of the borders. Twinning after albite and albite-carlsbad law are common. Staining and refractive index studies indicated the presence of potash feldspars, especially in the groundmass. There is a paucity of mafic minerals, which when present include non-pleochroic augite ($2V_\gamma$ 55°; $Z \wedge C$ 43°) and olivine completely altered to pseudomorphs of iron ore. Accessories include plates of ores and flakes of biotite. The groundmass is dirty brown and finely crystalline with microlites of feldspar and dusty iron ore.

8:4f Oligoclase basalt

A single flow of this type and several minor dykes, the latter occupying at times fault lines, have been noticed. In hand specimens, the rock is ash grey to brownish black, with occasional small crystals of pyroxene and olivine, set in dense matrix. Amygdales with calcite may be present in some. In thin section the microphenocrysts are seen to include colourless augite ($2V\gamma$ 53°; $Z \wedge C$ $.41^\circ$), olivine thoroughly altered to iron ores and plates of primary ore. Microphenocrysts and/or microlites of median olivoclase in the groundmass show fluidal pattern (Plate 8-10), especially around the microphenocrysts of the ferromagnesian minerals. The groundmass is finely crystallined (<0.05 mm) with dominant microlites of oligoclase, some potash feldspar (indicated by staining) and dusty iron ore. Scarce flakes of biotite and needles of apatite may be present in some.

8:4g <u>Trachyte</u> (Plate 8-11)

A single dyke (20' x 70') of this type has been found to be present within the area of study. It is light coloured, porphyritic with phenocrysts of prismatic, brown coloured amphibole (< 5 mm long), greenish coloured pyroxene (< 4 mm long), and white to pink coloured feldspar laths, set in a dense matrix. In thin section the texture is feebly trachytic and the minerals identified include kaersutite (Table 8-5), augite ($Ca_{48}Mg_{38}Fe_{14}$; Table 8-3), plagioclase (Ab_{97}; Table 8-4), and ore. Groundmass is finely crystallined and dominantly composed of microlites of feldspar, much of it is potassic. Grains of ore are peppered throughout the groundmass, while needles of apatite are occasionally seen. Quartz is modally absent.

8:4h <u>Teschenite</u>

A single dyke (50' x 400') of this type has been found. Texturally it belongs to the porphyritic type of Walker (1923, p. 243) characterised by fine to medium grained nature, with phenocrysts of fresh pyroxene forming glomeroporphyritic aggregates (Plate 8-12). Phenocrysts are dominantly of mauve coloured, feebly pleochroic titan-augite ($Ca_{48}Mg_{40}Fe_{12}$), minor iddingsitised olivines, and titano-magnetite. Analcite of natrolitic composition (R.I. = 1.492 ± 0.002) occurs as irregular, interstitial patches in the groundmass, enclosing crystals of clinopyroxene, altered olivine and granules of titano-magnetite. Microlites of plagioclase in groundmass are partly analcitised. Iron ore, phlogopite and needles of apatite are also present in the groundmass. Micro-vesicles, infilled by chabazite has been noticed.

8:4i Potassic rhyolites (Plate 8-13)

These occur as small plug like intrusions (Kariadongar) or tongue like protrusions (Varadiadongar) amidst the basalts of the area (Fig. 8-1). Flow structure is commonly seen in these masses. In hand specimens, the rock is leucocratic and porphyritic with phenocrysts of pinkish coloured, squarish to tabular crystals (3 mm x 2 mm) of feldspar and scarce ferromagnesian minerals set in a very dense matrix. A few samples show banding in hand specimen level. In thin section the feldspar phenocrysts are mostly of orthoclase-microperthite ($Or_{83}Ab+An_{17}$ to $Or_{45}Ab+An_{55}$) while scarce phenocrysts of plagioclase (Ab_{90}) also occur. Mafic minerals are in very small amounts comprising resorbed biotite, and amphibole(?). Quartz has not been found as a phenocrystal mineral. Groundmass is fine grained (< 0.1 mm) and is mainly composed of potassic feldspars (sanidine) and grains of quartz. The groundmass textures range from mosaic aggregates to granophyric and/or spherulitic. In some quartz may be found in vugs or in vein like form. Occasionally crystals of apatite and zircon have been found.

PLATE: 8-1

Specimen No. 1-T Tholeiitic basalt showing intergranular to intersertal texture, with an iddingsitised olivine phenocryst in the middle.

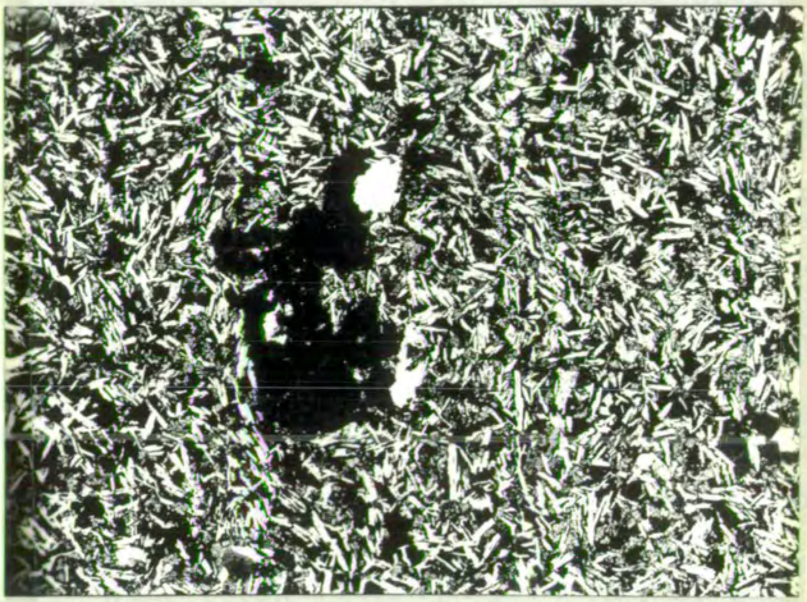
X 22 Plane polarised light.

PLATE: 8-2

Specimen No. R-9 Ankaramitic basalt

Clinopyroxene phenocryst showing zoning.

X 15 Crossed Nicols.



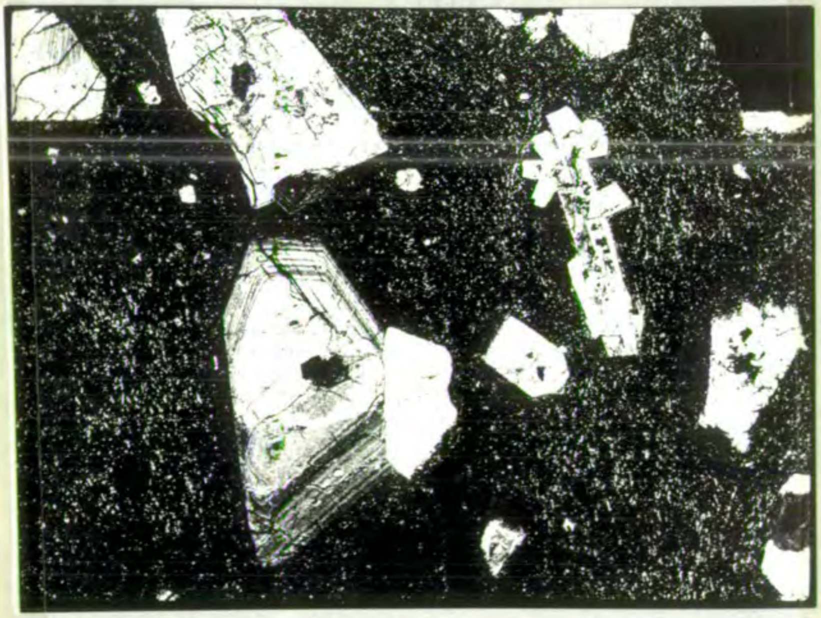


PLATE: 8-3

Specimen No. R-2 Ankaramitic basalt

Phenocrysts of olivine (iddingsitised), augite and microphenocrysts of labradorite (showing flow pattern) and ore in a fine grained groundmass.

X 15 Plane polarised light.

PLATE: 8-4

Specimen No. R-12A Porphyritic basalt

Glomeroporphyritic aggregate of clinopyroxenes along with ore, and phenocrysts of labradorite (to the right).

X 14 Plane polarised light.

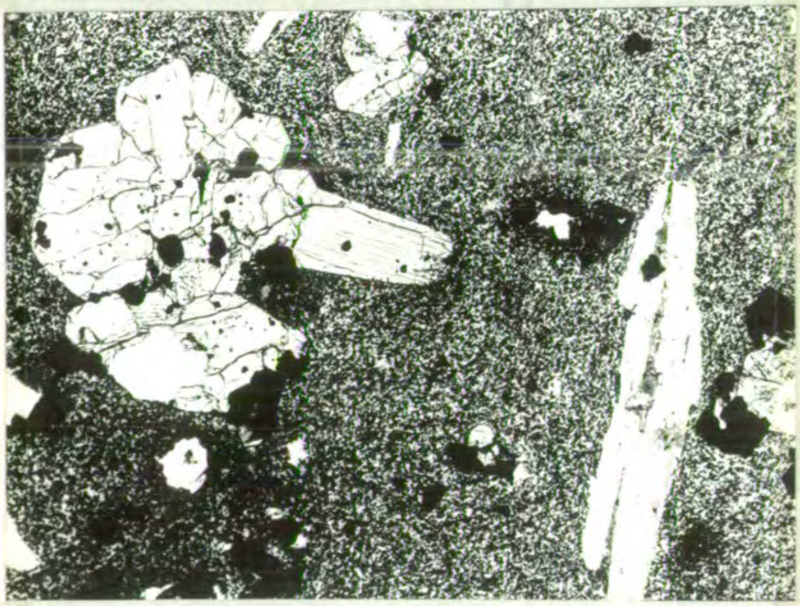


PLATE: 8-5

Specimen No. R-24 Porphyritic basalt

Phenocrysts of plagioclase (labradorite), and altered olivine in a matrix of clinopyroxene, plagioclase and ore.

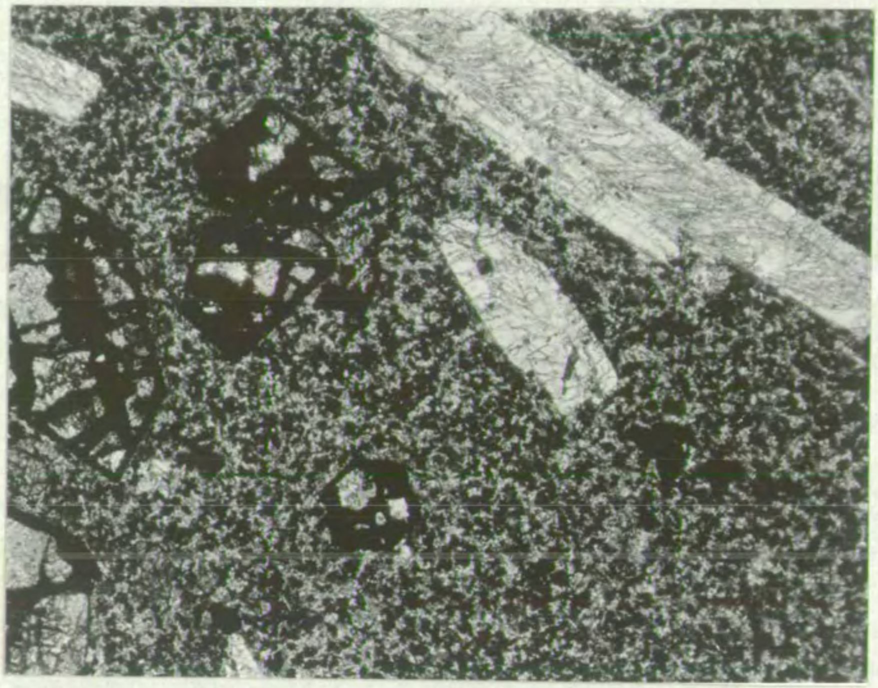
X 25 Crossed Nicols.

PLATE: 8-6

Specimen No. R-12B Porphyritic basalt

Glomeroporphyritic aggregate comprising dominantly clinopyroxenes and ore with minor amounts of plagioclase (white).

X 25 Plane polarised light.



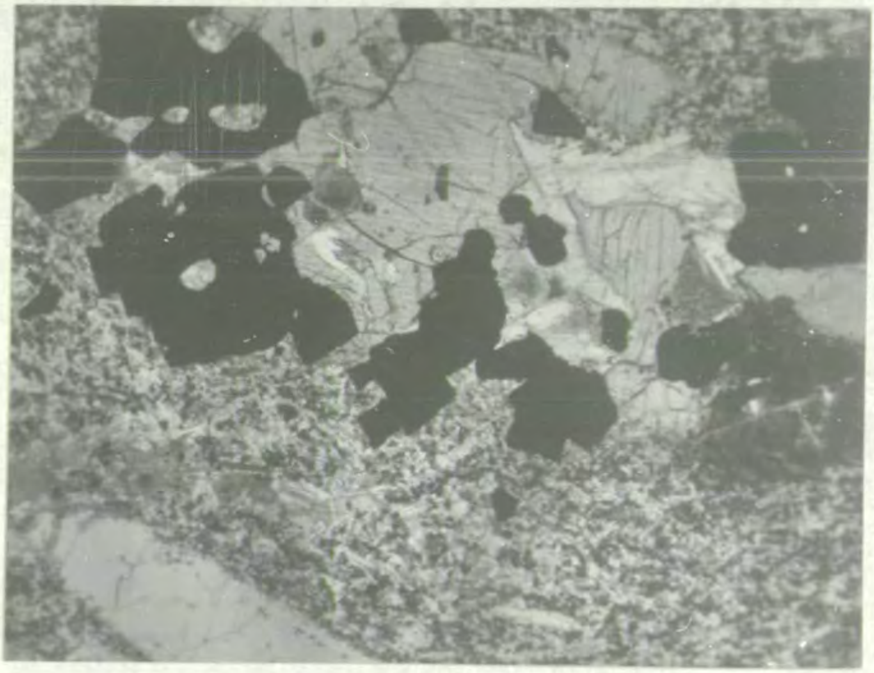


PLATE: 8-7

Specimen No. R-16 Porphyritic trachy basalt

Euhedral to subhedral phenocrysts of clinopyroxene, plagioclase (some with stellate groupings), altered olivine and ore.

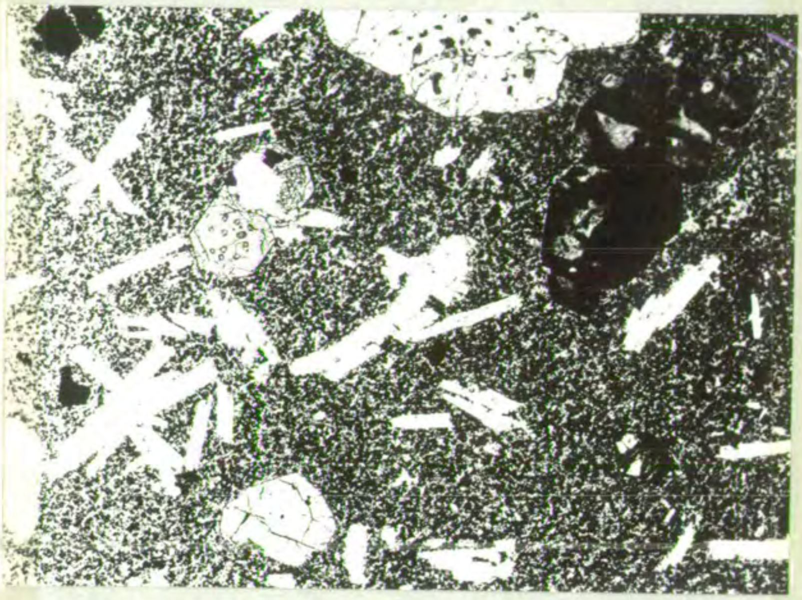
X 13 Plane polarised light.

PLATE: 8-8

Specimen No. R-15A Porphyritic trachy basalt

Phenocrysts of augite (top left hand side) and plagioclase the latter showing fluidal pattern.

X 11 Crossed Nicols.



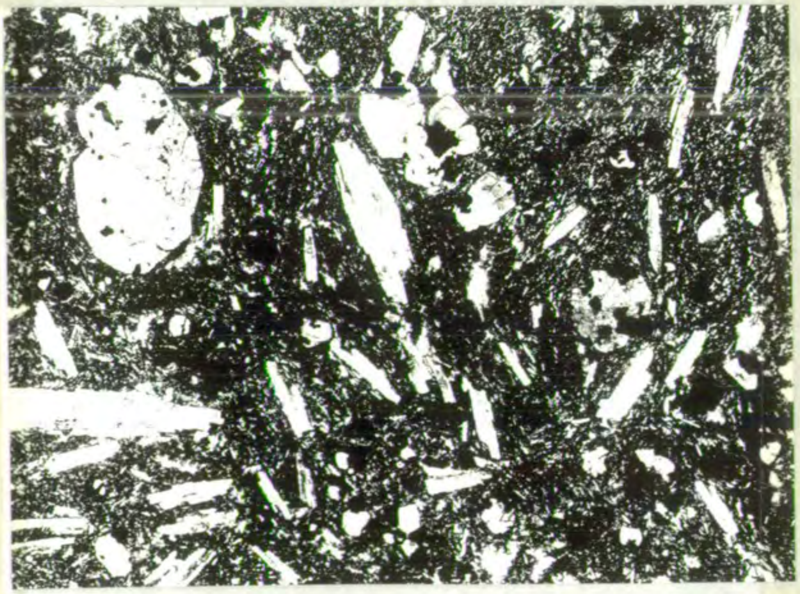


PLATE: 8-9

Specimen No. R-31 Feldspar phyric basalt

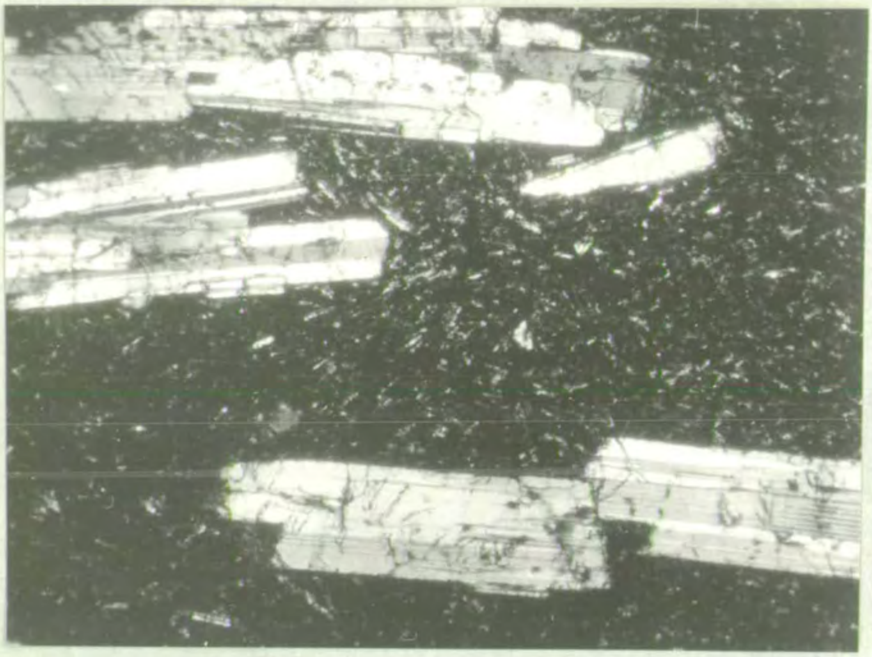
X 25 Crossed Nicols.

PLATE: 8-10

Specimen No. R-35 Oligoclase basalt

Microlites of oligoclase showing fluidal pattern.

X 25 Crossed Nicols.



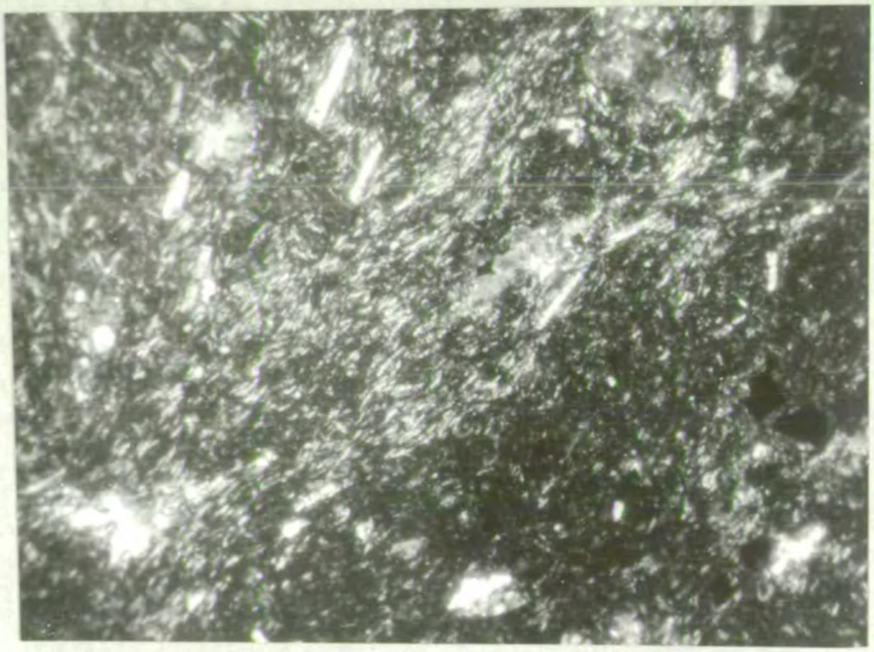


PLATE: 8-11

Specimen No. R-37 Trachyte

Phenocrysts of kaersutite (black and dark brown), augite (light grey with cleavage) feldspar (white, showing parallel growth) and ore in a finely crystalline groundmass.

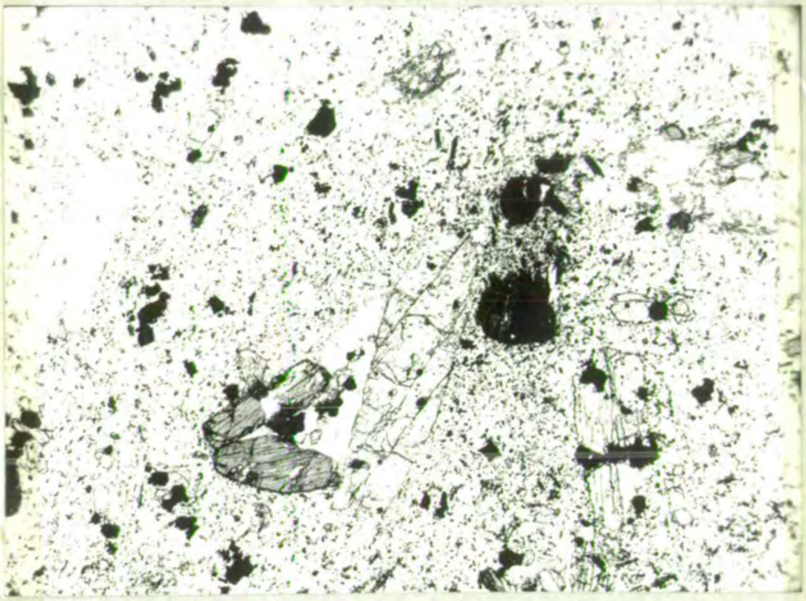
X 15 Plane polarised light.

PLATE: 8-12

Specimen No. R-1 Teschenite

Phenocrysts of euhedral to sub-hedral clinopyroxenes and irregular patches of analcite with inclusions of titano-magnetite and clinopyroxenes.

X 20 Plane polarised light.



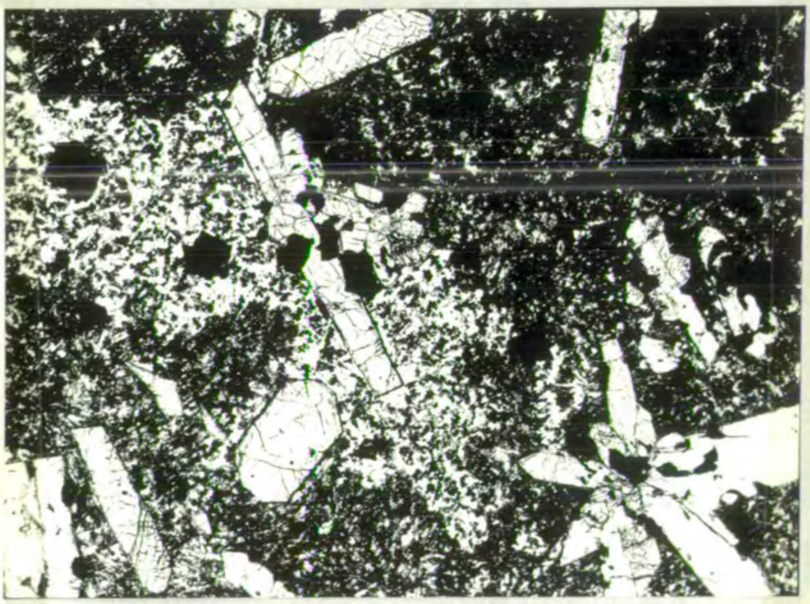


PLATE: 8-13

Specimen No. R-40 Potassic rhyolite

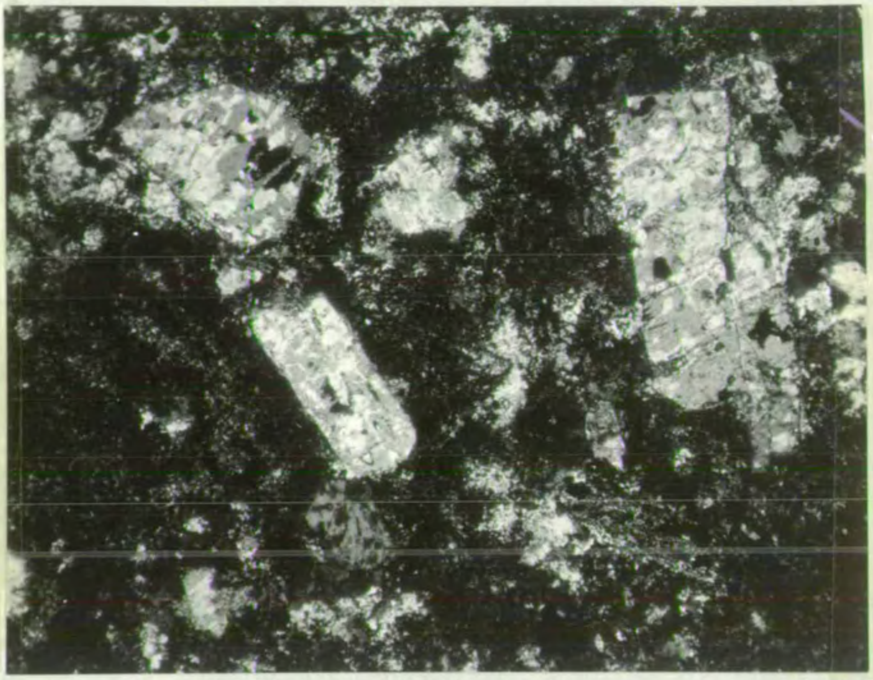
Phenocrysts of orthoclase-microperthite in a fine grained groundmass composed of alkali feldspar and quartz.

X 25 Crossed Nicols.

PLATE: 8-14

Specimen No. 4-T-1 Tholeiitic dolerite dyke

X 25 Plane polarised light.



8:4j Tholeiitic dolerites (Plate 8-14)

They represent the youngest intrusive phase of the area and comprise the NE and ENE trending major dykes (Fig. 8-1). In hand specimens they are melanocratic, medium to fine-grained, the interiors of some thick dykes (~100′ across) are micro-gabbroic in appearance. In thin section, the normal type shows an ophitic to sub-optitic texture with dominant plagioclase (An_{65-55}), and augite ($2V\gamma$ 42; $Z\wedge C$ 44); scarce iddingsitised olivines may be present in some. Titano-magnetite and ilmenite are important minor minerals. Needles of apatite may be found as a minor accessory. A few samples have a pale brownish yellow coloured, altered glass in the interstices between pyroxenes and feldspars.

8:5 Mineralogy

Analyses of clinopyroxenes, plagioclases, mica and amphibole are presented in Table 8-3, 8-4, and 8-5 respectively. The mineralogical details of the individual group of rocks are summarised in Table 8-2. The salient mineralogical features of the alkalic series are as follows:

1. Although olivine is ubiquitous as a phenocryst and groundmass phase in the basaltic rocks of the area, it is always subordinate to the clinopyroxenes and plagioclases, and mostly altered. Attempts to determine olivine composition throughout the series by universal stage techniques were unsuccessful because of the rareness of fresh material. Iddingsitised olivines are minor compared to those altered to hematite, the presence of the latter appears to suggest high temperature oxidising conditions of alteration

(Baker and Haggerty, 1967). However, enstatite (Baker and Haggerty, op.cit.) and/or silica (Champness, 1970) associated with the hematite have not yet been found, for the materials associated are completely altered and are too small to identify by ordinary microscopic methods.

2. The clinopyroxenes are fresh throughout and are abundant in the ankaramitic basalts. They range in composition from $Ca_{52}Mg_{37}Fe_{11}$ to $Ca_{42}Mg_{37}Fe_{17}$. Normal zoning in the phenocrysts are frequently seen, as in R-15, Table 8-3. In the analysed clinopyroxenes, Al and Ti show sympathetic variation while Al and Si show the opposite. The rims of the phenocrysts and the pyroxenes of the groundmass appear to be richer in TiO_2 and Al_2O_3 compared with the cores and phenocrystal pyroxenes.

3. Plagioclase feldspars show a fairly continuous variation from An_{65} to An_3, the extremely sodic type occurring in the trachyte (see Table 8-4).

4. With the exception of the potassic rhyolites, none of the rocks carry potash feldspar phenocrysts, although potash feldspar has been observed in the groundmass of some basaltic rocks, particularly in the trachy basalts.

5. Ore minerals, comprising homogeneous titano-magnetite, ilmenite and magnetite are conspicuous as phenocrysts in the basaltic rocks, particularly in the porphyritic basalts and porphyritic trachy basalts where they occur up to 7% by volume. An important feature of the ore minerals is their oxidation characters, indicated by their alteration to hematite, ilmeno-hematite and (?) maghemite.

Table 8-2

Mineralogy of the alkalic suite

Minerals		Ankaramitic basalts	Porphyritic basalts	Porphyritic trachybasalts *	Oligoclase basalts	Trachyte	Potassic rhyolite
Olivine	P	Minor amounts commonly iddingsitised	Present, subordinate to Cpx; iddingsitised or altered to hematite	As in porphyritic basalts. Scarcer in felspar phyric basalts	Very scarce, altered to hematite	Absent	Absent
	GM	Present, iddingsitised or altered to Ore	Present altered	Present altered; rather scarce	Present altered; rather scarce	Absent	Absent
Clinopyroxene[b]	P	Dominant and fresh; $Ca_{52-44}Mg_{45-37}Fe_{13-11}$	Dominant as in Ankaramitic basalts	Common $Ca_{45-42}Mg_{41-40}Fe_{17-15}$ scarcer in felspar phyric basalts	Minor amounts	Minor amounts $Ca_{48}Mg_{38}Fe_{14}$	Absent
	GM	Present $Ca_{45}Mg_{41}Fe_{14}$	Present	Present	Scarce crystals	Rare	Absent
Plagioclase[c]	P	Absent; scarce as micro-phenocrysts. An_{65}	Common An_{65-50}	Present An_{60-45} Abundant in felspar-phyric types	Scarce; An_{40-30}	In parallel groups An_{2-10}	Scarce An_{10}
	GM	Present	Present; normally less calcic than phenocrysts	Present	Mainly as microlites An_{35-25}	Present	Absent(?)
Ore[d]	P	Scarce. micro-phenocrysts of titano-magnetite + ilmenite	Titano-magnetite + ilmenite oxidised	As in porphyritic basalts	Scarce. plates of titano-magnetite + ilmenite oxidised	Scarce plates	scarce mainly after biotite
	GM	As grains	Present	Present	Present	Present	Present as grains
Potash feldspar[e]	P	Absent	Absent	Absent	Absent	Absent	Present approx. composition $Or_{83-45}(Ab+An)_{17-55}$ Orthoclase-microperthite
	GM	Absent(?)	Scarce	Present	Present as microlites	Present	Present
Mica[f]		scarce wisps	not uncommon as flakes	frequently seen in the groundmass	scarce wisps	Absent	Present resorbed to Ore
Amphibole[f]		Absent	Absent	Absent	Absent	Kaersutite phenocrysts	Absent

P = Phenocrysts. GM = Groundmass b = Based on XRF and Probe analyses (see Table 8-3)
c = Probe analyses (Table 8-4) and optical; the latter for plagioclase through universal-stage techniques from extinction angles in the zone $(\bar{0}10)$, after Naidu (1959); for alkali-felspars from $2V\alpha$ using curves of Tuttle (1952)
d = From reflected-light studies. e = Presence ascertained through staining with sodium-cobaltic nitrite (Rosenblum, 1956)
f = Probe analyses (one phlogopite and 2 Kaersutite analyses, see Table 8-5)
* = Includes felspar phyric basalts.

Table 8-3

Clinopyroxene analyses

	Ankaramitic basalts					Teschenite	Porphyritic basalts Porphyritic trachybasalts					Trachyte
Specimen No.	R-19 P	R-26 P	R-9 P	R-9a P	R-9a GM	R-1 P	R-17 P	R-15a P	R-15a P_C	R-15a P_R	R-15 P	R-37a P
Wt.%												
SiO_2	50.80	48.60	51.40	50.70	48.24	49.00	49.20	49.95	50.44	49.02	49.81	50.76
TiO_2	1.74	2.13	1.22	1.51	2.31	2.51	1.22	1.42	1.38	1.68	1.56	0.99
Al_2O_3	3.98	5.04	3.19	2.84	4.38	5.53	3.67	3.14	2.75	3.85	3.80	2.69
Fe_2O_3	1.78	2.40	2.71	3.22	3.48	1.98	4.88	2.01	1.90	2.02	1.64	
FeO	6.62	6.30	4.27	5.10	5.48	5.32	6.11	7.50	7.08	7.54	7.35	8.90
MnO	0.11	0.14	0.17	-	-	0.17	0.17	-	-	-	0.14	-
MgO	14.58	13.11	15.52	14.98	13.81	13.28	14.38	13.76	14.22	13.64	13.41	13.08
CaO	20.93	21.53	21.73	21.24	21.51	22.20	20.09	20.84	20.89	20.99	20.39	22.27
Na_2O	0.47	0.25	0.41	-	-	0.59	0.47	0.32	0.42	0.39	0.48	0.70
K_2O	0.09	0.03	0.01	-	-	0.02	0.06	0.01	0.02	0.01	0.05	0.002
P_2O_5	tr	tr	tr	-	-	tr	tr	-	-	-	tr	-
Cr_2O_3	0.08	0.05	0.23	-	-	0.03	0.10	-	-	-	0.04	-
Total	101.18	99.58	100.86	99.30	98.89	100.75	100.43	98.94	99.10	99.14	98.76	99.41
ppm												
Ba	71	70	59			85	52				63	
Zr	75	125	<10			235	75				90	
Y	11	25	11			26	18				23	
Cl	22	40	<10			16	36				24	
La	11	18	<10			26	38				64	
Sr	110	150	105			260	110				100	
Zn	51	52	66			50	61				64	
Cu	60	66	103			70	78				62	
Ni	118	107	169			68	123				83	
Cr	538	334	1550			172	648				245	
V	397	374	216			307	284				319	
Atomic %												
Ca	45.1	51.9	44.8	43.9	45.3	48.1	41.6	43.6	44.0	44.3	44.5	47.6
Mg	43.8	37.10	44.5	43.2	40.5	40.0	41.4	40.2	41.5	40.1	40.6	37.9
Fe*	11.1	11.0	10.7	12.9	14.2	11.9	17.0	16.2	14.5	15.6	14.9	14.5

* $Fe^{2+}+Fe^{3+}+Mn$

P = Phenocrysts (separates)

P_C = Phenocrysts core

P_R = Phenocrysts rim

GM = Groundmass crystal

a = Probe analyses. Fe_2O_3:FeO corrected according to those analysed wet chemically, except R-37

Table 8-4

Plagioclase analyses

	Trachybasalts					Trachyte
Specimen No.	R-7w	R-8w	R-15a	R-15a	R-15a	R-37a
Wt.%						
SiO_2	55.43	56.08	55.48	54.84	54.88	68.15
TiO_2	0.18	0.31	0.16	0.04	0.12	0.04
Al_2O_3	27.43	26.47	26.92	27.71	27.95	20.41
Fe_2O_3	1.84	1.94	0.55	0.75	0.78	0.01
CaO	10.61	10.06	10.19	10.51	10.78	0.20
Na_2O	4.79	4.48	5.15	5.25	5.09	10.86
K_2O	0.71	0.83	0.90	0.77	0.75	0.42
Total	100.99	100.21	99.35	99.87	100.35	100.09
ppm						
Ba	560	470				
Zr	130	125				
Y	6	7				
Cl	40	42				
La	31	40				
Sr	2060	1680				
Rb	9	29				
Composition Mol %						
An	52.7	52.5	49.4	50.1	51.6	1.1
Ab	42.9	42.2	45.1	45.6	44.1	96.7
Or	4.4	5.3	5.5	4.3	4.3	2.2

w = Plagioclase separates. Analyses by XRF

a = Probe analyses, in which FeO is converted into Fe_2O_3

Table 8-5

Phlogopite and Kaersutite analyses

	Phlogopite	Kaersutite		
Specimen No.	R-15	R-37	R-37	R-37
Wt.%				
SiO_2	40.67	40.05	40.54	40.74
TiO_2	4.19	5.74	5.37	5.65
Al_2O_3	12.07	11.53	11.26	10.70
FeO	8.61	12.57	12.26	12.72
MgO	19.41	12.51	12.64	12.61
CaO	0.01	11.55	11.45	11.41
Na_2O	0.85	2.60	2.67	2.69
K_2O	8.32	1.33	1.30	1.38
Total	94.12	97.88	97.49	97.94
MgO/FeO	2.25			

R-15 Trachybasalt

R-37 Trachyte

6. Minor amounts of wisps or flakes of phlogopite have been noticed in the groundmass of many basaltic rocks (Table 8-5). In certain flows the mode of occurrence of phlogopite around the margins of clinopyroxenes appears to suggest that they probably resulted through reaction between the clinopyroxene and the potassium rich groundmass liquid.

7. The appearance of Kaersutite (Table 8-5) as a phenocryst phase in the trachyte is indicative of the importance of the hydrous conditions with increasing magmatic evolution.

8. Quartz is never found as a phenocryst phase either in the trachyte or in the potassic rhyolites.

8:6 Geochemistry

The distribution of analysed samples between the different rock types are as follows:

1. Tholeiitic flows.	2	(Table 8-6)
2. <u>Alkalic suite</u>		
a) Ankaramitic basalts	5	Table 8-7
b) Porphyritic basalts	11	
c) Porphyritic trachy basalts	12	
d) Feldspar phyric basalts	3	
e) Oligoclase basalts	3	
f) Trachyte	1	
g) Teschenite	1	
h) Groundmass analyses	6	(Table 8-8)
3. Potassic rhyolites	7	(Table 8-9)
4. Tholeiitic dolerite dykes	2	(Table 8-10)

Table 8-6

Analyses of Tholeiitic basalts

			CIPW Norms		
Specimen No.	1-T	2-T		1-T	2-T
Wt.%					
SiO_2	47.80	48.34	Qz	4.74	1.03
TiO_2	3.23	2.25	Or	3.01	2.27
Al_2O_3	14.85	16.70	Ab	18.00	21.74
Fe_2O_3	3.96	3.36	An	30.19	33.42
FeO	10.24	8.50	Di	11.66	14.58
MnO	0.17	0.14	Hy	19.36	17.13
MgO	5.67	5.86	Mt	5.84	4.93
CaO	9.31	10.54	Il	6.24	4.32
Na_2O	2.09	2.54	Ap	0.94	0.57
K_2O	0.50	0.38	H_2O	1.89	2.58
H_2O+	1.89	2.58			
P_2O_5	0.35	0.24			
Total	100.12	100.33			
D.I.	25.04	25.75			
In ppm					
Ba	300	160			
Zr	205	112			
Nb	32	10			
Sr	280	305			
Rb	7	6			
Y	35	24			
La	25	15			
Cl	55	25			
Ni	90	67			
Cr	173	87			
V	430	334			
Zn	122	202			
Cu	101	176			

[illegible]

Table 8.7.

Analyses of Rajpipla rocks (Alkalic series)

	Ankaramitic basalts					Porphyritic basalts										
Specimen No.	R-9	R-2	R-10	R-19	R-70	R-5	R-8	R-11	R-12	R-13	R-14	R-20	R-24	R-27	R-28#	R-18
SiO_2	46.98	47.95	46.30	46.80	44.73	46.96	46.85	47.65	48.16	46.94	48.09	47.50	47.75	46.45	48.25	47.74
TiO_2	3.10	3.11	3.26	3.50	3.46	3.02	3.87	3.67	4.12	3.00	3.56	3.85	3.39	3.78	3.04	3.32
Al_2O_3	12.50	12.25	10.68	10.49	10.21	15.85	13.38	12.50	14.45	14.25	12.13	11.02	12.35	13.75	13.01	15.25
Fe_2O_3	3.70	4.90	3.58	3.82	3.86	3.75	4.01	3.84	3.61	4.06	3.74	3.90	3.74	4.20	3.43	4.04
FeO	8.64	7.73	8.36	8.85	9.00	8.76	10.66	8.98	8.83	9.53	8.74	9.09	8.70	9.81	8.01	9.42
MnO	0.15	0.17	0.17	0.20	0.21	0.18	0.20	0.18	0.17	0.18	0.16	0.19	0.14	0.14	0.17	0.18
MgO	8.19	8.22	8.41	7.96	8.30	5.34	5.86	5.75	6.43	5.42	6.09	6.15	6.01	5.00	5.74	5.44
CaO	10.63	10.38	10.32	10.38	12.57	8.83	8.68	10.07	8.77	8.48	10.05	9.52	8.43	7.91	9.33	8.28
Na_2O	2.73	2.01	2.01	2.40	1.94	2.23	2.71	1.95	1.56	2.58	2.58	2.87	2.23	2.16	2.03	2.30
K_2O	1.31	2.13	2.56	2.71	2.26	2.43	2.28	2.44	2.44	1.81	2.11	2.23	3.74	3.92	2.55	2.76
H_2O^+	2.08	1.67	2.79	1.50	2.25	2.40	2.80	2.48	1.94	1.78	1.56	1.99	2.24	2.33	1.90	1.74
P_2O_5	0.33	0.38	0.57	0.49	0.57	0.58	0.64	0.46	0.45	0.45	0.60	0.49	0.60	0.64	0.54	0.42
Total	99.91	100.90	99.01	99.10	100.09	100.33	100.62	99.97	100.93	98.51	99.02	98.80	99.32	99.36	98.83	100.84
D.I.	29.37	30.14	33.39	35.23	26.98	34.55	36.70	32.53	30.80	33.63	35.03	38.47	42.16	42.31	36.03	35.98
					Trace elements (in ppm)											
Ba	961	1138	1299	920	1345	1238	1455	1580		1900	1245	980	1810	2280		1745
Zr	261	344	302	292	260	323	330	328		305	310	362	300	350		330
Nb	41	63	50	54	40	49	54	51		61	49	73	64	63		54
Sr	680	697	1000	946	830	883	860	780		700	680	735	805	1045		915
Rb	72	74	66	75	72	63	47	107		70	67	58	82	74		100
Y	30	29	32	30	25	35	34	32		31	32	37	31	35		38
La	71	70	70	60	60	59	85	75		75	75	80	70	85		80
Ce	135	155	175	144	145	148	220	170		160	180	225	190	200		175
Ni	139	91	90	83	107	63	67	46		88	96	72	65	58		65
Cr	511	278	308	222	184	149	62	64		171	142	93	95	98		25
V	345	346	405	376	429	326	425	454		353	470	440	372	415		418
Zn	103	111	104	105	113	114	126	136		118	122	125	104			125
Cu	193	155	116	170	149	170	113	90		113	133	112	70			114
		CIPW Norms														
Q	-	-	-	-	-	-	-	0.84	2.91	-	-	-	-	-	2.77	-
Or	7.77	12.82	15.72	16.40	13.75	15.80	13.58	14.78	14.56	11.05	12.73	13.53	22.74	23.67	15.54	16.41
Ab	19.92	17.32	17.67	16.50	8.91	18.75	23.12	16.91	13.33	22.57	22.29	24.94	19.42	18.61	17.72	19.58
Ne	1.68	-	-	2.33	4.33	-	-	-	-	-	-	-	-	0.03	-	-
An	17.89	18.45	13.05	10.09	12.84	30.56	17.76	18.60	25.47	22.70	15.61	12.29	13.01	16.60	19.45	23.27
Di	27.02	25.25	29.10	31.67	38.22	8.44	17.54	24.17	12.49	14.53	25.49	26.78	21.30	16.03	15.58	13.43
Hy	-	9.12	0.51	-	-	4.36	4.35	10.73	16.97	14.38	8.11	1.41	1.98	-	14.59	9.07
Ol	13.05	4.99	10.72	9.34	8.04	9.34	8.84	-	-	1.69	1.87	6.54	7.88	9.95	-	5.00
Mt	5.35	5.11	5.39	5.67	5.76	5.40	5.86	5.71	5.29	6.09	5.54	5.81	5.58	6.22	5.13	5.89
Il	5.87	6.02	6.43	6.81	6.76	5.98	7.41	7.14	7.90	5.89	6.90	7.51	6.63	7.33	5.95	6.34
Ap	1.46	0.92	1.40	1.19	1.39	1.37	1.53	1.12	1.08	1.10	1.45	1.19	1.46	1.55	1.32	1.00
H_2O	2.08	1.67	2.79	1.50	2.25	2.40	2.80	2.48	1.94	1.78	1.56	1.99	2.24	2.33	1.90	1.74

$Fe_2O_3^*$ = Recalculated to give Fe_2O_3 x 100/FeO + Fe_2O_3 = 30
(except in the case of R-37)

D.I. = Differentiation Index
# includes 0.83% CO_2

Table 8.7 (Contd.)

Specimen No.	Porphyritic trachy basalts												Felspar phyric basalts			Oligoclase basalts			Trach-yte	Tesch-enite
	R-3	R-6	R-7	R-15	R-16	R-17	R-21	R-22	R-23	R-25[b]	R-29	R-30[c]	R-32	R-33	R-31	R-35[a]	R-36[≠]	R-34	R-37	R-1
SiO_2	48.60	46.90	46.40	48.28	47.85	49.99	48.50	49.60	48.88	46.35	47.90	46.75	50.98	51.65	50.72	52.41	54.21	51.54	58.07	43.92
TiO_2	3.79	2.99	4.14	3.56	3.36	2.88	4.57	3.40	4.54	3.90	3.23	3.99	2.58	3.05	2.20	2.32	2.25	3.00	1.20	3.40
Al_2O_3	13.40	14.50	14.26	14.16	16.80	16.40	12.28	13.54	12.26	13.29	13.01	12.93	17.88	15.59	17.95	15.85	17.10	16.25	18.75	14.05
Fe_2O_3	3.95	3.99	3.93	3.67	3.64	3.35	4.28	3.64	4.47	3.93	3.66	4.11	2.67	3.24	3.04	3.19	2.65	3.11	3.00	4.19
FeO	9.21	8.30	9.17	8.56	8.49	7.81	9.99	8.16	10.42	9.16	8.53	9.59	6.25	7.55	7.08	7.44	6.19	7.24	4.59	9.76
MnO	0.15	0.18	0.20	0.18	0.18	0.16	0.16	0.14	0.17	0.15	0.16	0.15	0.04	0.14	0.04	0.18	0.10	0.17	0.11	0.22
MgO	4.20	4.79	4.16	4.79	3.76	3.75	3.92	3.86	4.50	4.22	4.65	3.98	2.67	3.38	1.70	3.39	2.74	3.55	0.82	5.77
CaO	8.38	9.76	8.28	8.32	7.85	7.51	8.26	8.45	7.01	9.04	10.02	7.89	7.13	7.27	6.95	5.89	6.32	6.46	3.43	10.15
Na_2O	2.15	2.30	2.94	2.51	2.29	2.99	1.91	2.40	2.99	2.34	2.04	3.36	3.43	3.44	4.59	3.00	2.70	2.94	3.12	3.64
K_2O	3.51	2.48	2.62	3.29	2.59	2.07	2.82	2.81	2.53	3.29	2.71	2.66	2.99	3.04	2.43	3.54	2.98	2.64	7.42	1.99
H_2O^+	2.38	2.36	2.81	1.69	1.70	1.83	2.41	2.64	2.50	2.03	2.90	2.78	1.60	1.20	1.88	2.08	1.80	1.68	tr	1.67
P_2O_5	0.59	0.53	0.69	0.65	0.57	0.62	0.55	0.56	0.56	0.64	0.57	0.54	0.65	0.68	0.72	0.65	0.72	0.82	0.25	0.60
Total	100.31	99.08	99.60	99.66	100.88	99.36	99.65	99.20	100.80	99.03	99.38	99.72	98.86	99.03	99.30	99.94	100.38	99.40	100.76	99.36
D.I.	40.88	53.69	35.24	41.66	41.48	41.57	39.49	42.29	42.77	40.72	35.84	45.27	49.19	48.69	54.30	54.24	51.30	46.93	71.42	30.30
Ba	1380	1630	1500	1730		1545	1250		1350	1570	1325	1340	1890	1945		1740			3065	1930
Zr	355	328	342	348		320	340		312	325	305	352	355	350		365			575	345
Nb	75	53	58	73		75	64		60	61	41	66	62	56		62			109	65
Sr	1160	798	850	800		1160	725		840	845	895	1095	1225	760		930			635	1005
Rb	117	122	65	97		117	74		71	80	90	77	76	~~78~~		83			273	202
Y	43	40	34			43	31		34	32		34	34	37		36			51	22
La	75	65	80	75		70	80		95	70	60	75	85	75		80			100	110
Ce	190	170	210	190		190	210		165	185	155	175	205	220		215			235	245
Ni	39	59	43	49		39	48		54	64	74	29	32	22		22			< 10	60
Cr	42	121	99	46		42	89		31	44	165	15	60	28		31			< 10	116
V	414	324	420	392		414	345		536	479	355	380	243	221		246			138	456
Zn	114	127	131	121		114	117		128	131	119	128	110	102		126			76	117
Cu	67	80	162	100		67	134		103	141	77	94	64	56		52			60	153
C	1.16	-	-	-	1.14	3.15	5.75	4.09	1.87	-	1.38	-	1.23	1.22	-	6.94	10.27	5.54	1.92	-
Or	21.16	15.14	15.98	19.82	18.75	12.52	17.12	17.18	15.19	20.17	16.59	16.37	18.15	18.12	14.72	21.37	17.86	15.95	43.48	12.03
Ab	18.56	20.11	25.68	21.66	20.15	25.90	16.61	21.02	25.71	20.54	17.88	28.06	29.81	29.36	39.31	25.93	23.17	25.44	26.12	13.52
Ne	-	-	-	-	-	-	-	-	-	-	-	0.84	-	-	0.27	-	-	-	-	4.75
An	16.88	22.64	18.55	18.00	18.93	25.81	17.05	18.50	12.76	16.62	18.99	12.85	25.22	18.27	21.73	19.74	23.05	23.87	15.08	16.50
Di	17.91	19.60	15.91	16.35	18.39	7.29	17.72	17.42	15.68	21.11	23.56	20.09	5.78	11.53	7.84	4.49	-	2.98	0.12	25.31
Hy	9.72	6.74	2.59	7.05	8.82	13.27	9.10	8.28	12.10	1.31	8.36	-	9.22	9.30	-	6.54	12.65	13.82	6.41	-
Ol	-	2.63	5.61	3.23	-	-	-	-	-	5.08	-	6.36	-	-	5.59	-		-	-	8.62
Mt	5.84	5.98	5.88	5.43	5.49	4.97	6.38	5.46	6.59	5.91	5.50	6.21	3.98	4.74	4.52	8.41	3.90	4.60	4.13	6.22
Il	7.34	5.87	8.12	6.89	6.93	5.60	8.92	6.68	8.76	7.68	6.35	7.89	5.03	5.84	4.28	4.50	4.33	5.83	2.25	6.61
Ap	1.43	1.30	1.69	1.57	1.40	1.50	1.34	1.37	1.35	1.57	1.40	1.33	1.58	1.62	1.75	1.57	1.73	1.99	0.59	1.45
H_2O	2.38	2.36	2.81	1.69		1.83	2.41	2.64	2.50	2.03	2.90	2.78	1.60	1.20	1.88	2.08	1.80	1.60	-	1.67

b = includes 0.69% CO_2

c = includes 0.99% CO_2

≠ Includes 1.12% Corrundum in the norm.

a = Includes 0.50% hematite.

tr = traces.

Table 8-8

Groundmass analyses

	Ankaramitic basalts		Basalts and Trachybasalts			
Specimen No.	R-9	R-26	R-5	R-17	R-28	R-30
SiO_2	46.50	46.71	51.50	51.97	48.07	48.09
TiO_2	5.02	4.10	3.69	3.10	4.99	4.19
Al_2O_3	12.19	12.70	14.44	14.46	12.44	14.08
Fe_2O_3*	4.09	4.29	3.35	2.28	4.60	4.28
FeO	9.55	10.00	7.82	8.64	10.73	9.99
MnO	0.21	0.17	0.14	0.15	0.15	0.13
MgO	5.70	4.62	3.29	3.52	3.80	2.73
CaO	8.69	7.65	7.04	7.01	8.12	5.76
Na_2O	2.55	3.16	2.51	2.95	3.13	3.01
K_2O	2.67	2.81	3.87	3.46	3.22	3.34
H_2O+	2.64	2.46	1.76	1.60	1.02	2.79
P_2O_5	0.72	0.83	0.81	0.91	0.74	0.69
Total	100.53	99.52	100.22	100.05	99.84	99.08
		CIPW NORMS				
Q	-	-	4.62	2.51	-	1.64
Or	16.11	17.10	23.22	20.76	19.02	20.49
Ab	22.03	27.54	21.56	25.34	26.48	26.44
An	14.22	12.53	16.96	16.24	10.38	15.62
Di	20.17	17.17	10.74	10.80	20.62	7.80
Hy	6.73	1.40	8.91	12.82	1.10	11.61
Ol	3.20	7.81	-	-	4.51	-
Mt	6.06	6.41	4.93	3.36	6.67	6.44
Il	9.74	8.02	7.11	5.98	9.47	8.26
Ap	1.74	2.02	1.95	2.19	1.75	1.70
H_2O	2.64	2.46	1.76	1.60	1.02	2.79
D.I.	38.14	44.64	49.40	48.61	45.50	48.57

* Recalculated to give 30% of $\frac{Fe_2O_3 \times 100}{FeO + Fe_2O_3}$

Table 8-9. Analyses of Potash Rhyolites

Specimen No.	R-38	R-40	R-41	R-42	R-43	R-44	R-45
Wt.%							
SiO_2	74.14	70.40	70.05	72.32	74.85	72.77	72.33
TiO_2	0.20	0.25	0.36	0.33	0.32	0.33	0.31
Al_2O_3	13.65	14.38	16.73	13.55	12.37	12.92	14.06
Fe_2O_3	2.25	2.01	1.53	1.51	1.79	1.04	1.74
FeO	0.29	0.30	0.43	0.49	0.35	0.92	0.29
MnO	0.06	0.41	0.11	0.14	0.05	0.11	0.06
MgO	trace	0.77	trace	0.40	0.29	0.63	trace
CaO	0.41	1.16	0.62	0.71	0.07	0.24	0.20
Na_2O	2.33	2.96	3.35	2.73	2.95	2.49	2.05
K_2O	6.78	4.86	5.10	6.60	5.24	5.78	7.58
H_2O+	0.49	1.52	2.18	1.60	1.50	1.85	1.70
P_2O_5	0.29	0.18	0.04	0.06	0.02	0.02	0.02
Total	100.89	99.68	100.51	99.85	99.80	99.10	100.22
D.I.	91.10	87.23	93.50	91.22	94.65	92.31	94.30
Trace elements (in ppm)							
Ba	505	485	500	450	375	495	440
Zr	355	380	330	360	295	355	372
Nb	110	128	124	110	113	111	126
Sr	95	108	116	107	95	90	235
Rb	271	264	289	248	313	399	290
Y	65	49	61	53	57	63	60
La	85	80	75	80	85	85	90
Ce	195	240	210	235	200	220	210
V	10	8	6	9	10	10	14
Zn		162	93	114	102	140	92
Cu		43	49	47	55	56	52
CIPW Norms							
Qz	38.81	32.20	31.08	33.79	37.75	35.52	31.34
Or	32.48	29.40	31.54	33.82	31.50	35.12	45.38
Ab	19.81	25.64	29.67	23.61	25.39	21.66	17.57
An	0.67	4.69	3.27	3.20	0.22	1.09	0.87
Cr	3.67	2.60	1.65	1.89	1.80	2.24	2.20
Di	-	-	-	-	-	-	-
Hy	1.25	1.96	-	1.02	0.73	2.12	0.15
Mt	0.55	1.62	0.73	1.10	0.37	1.55	0.24
It	0.38	0.49	0.72	0.64	0.62	0.64	0.60
Ap	0.50	0.44	-	0.15	0.05	0.05	0.05
He	1.88	0.94	1.35	0.78	1.57	-	1.60
H_2O	0.49	1.52	2.18	1.60	1.50	1.85	1.70

D.I. = Differentiation Index

Table 8-10

Tholeiitic dolerite dykes

				NORMS	
Specimen No.	4-T	5-T		4-T	5-T
SiO_2	48.55	49.93	Q	5.52	1.17
TiO_2	2.56	1.80	Or	1.63	5.10
Al_2O_3	16.20	13.30	Ab	19.80	20.63
Fe_2O_3	3.50	2.65	An	33.84	23.37
FeO	9.78	10.99	Di	7.33	19.39
MnO	0.22	0.20	Hy	20.27	22.39
MgO	4.87	6.46	Mt	5.18	3.90
CaO	9.10	9.61	Il	4.86	3.47
Na_2O	2.29	2.40	Ap	1.34	0.58
K_2O	0.27	0.85	H_2O	1.75	1.00
H_2O+	1.75	1.00			
P_2O_5	0.51	0.24			
Total	99.10	99.43			
D.I.	27.22	26.90			
Ba	255	300			
Zr	205	174			
Nb	27	20			
Sr	226	160			
Rb	8	10			
Y	32	35			
La	30	25			
Ce	55	65			
Ni	74	18			
Cr	56	31			
V	398	388			
Zn	131	134			
Cu	142	55			

8:6a Major oxide variation:-

Major oxide variations of the alkalic suite, i.e. from the ankaramitic basalt to trachyte, are shown in Fig. 8-4 where the wt.% of MgO in the samples are plotted against other oxides, for MgO shows a fairly continuous and gradational variation compared with SiO_2. The following features can be noticed in the variations of the major oxides.

1. Certain of the plots (i.e., FeO + Fe_2O_3, TiO_2, SiO_2) show a prominent slope change at ~4-5% MgO which approximately corresponds with the appearance of plagioclase and ore as phenocrysts.

2. Al_2O_3 shows a steady increase with decreasing MgO. The scatter in the Al_2O_3 values between 6 to 4% of MgO is probably related to the presence of varying amounts of plagioclase phenocrysts in the basaltic rocks.

3. CaO shows a steady decrease with decreasing MgO, but the rate of decrease is rather faster from about 6% MgO.

4. SiO_2 remains fairly constant between about 8 to 6% MgO, and thereafter increases sharply.

5. Both total iron (FeO + Fe_2O_3) and TiO_2 tend to remain constant between ~8 to 4% MgO, or with a slight increase, followed by a steady decrease. The scatter in the values of total iron and TiO_2 between 6 to 4% MgO, is probably related to the varying amounts of phenocrysts of ore phases.

6. Na_2O and K_2O show a gradual increase with decreasing MgO, but K_2O shows a rather steep increase from about 4% MgO, when compared with Na_2O, if it is assumed that the solitary trachyte is representative of the more silica-rich end of the trend.

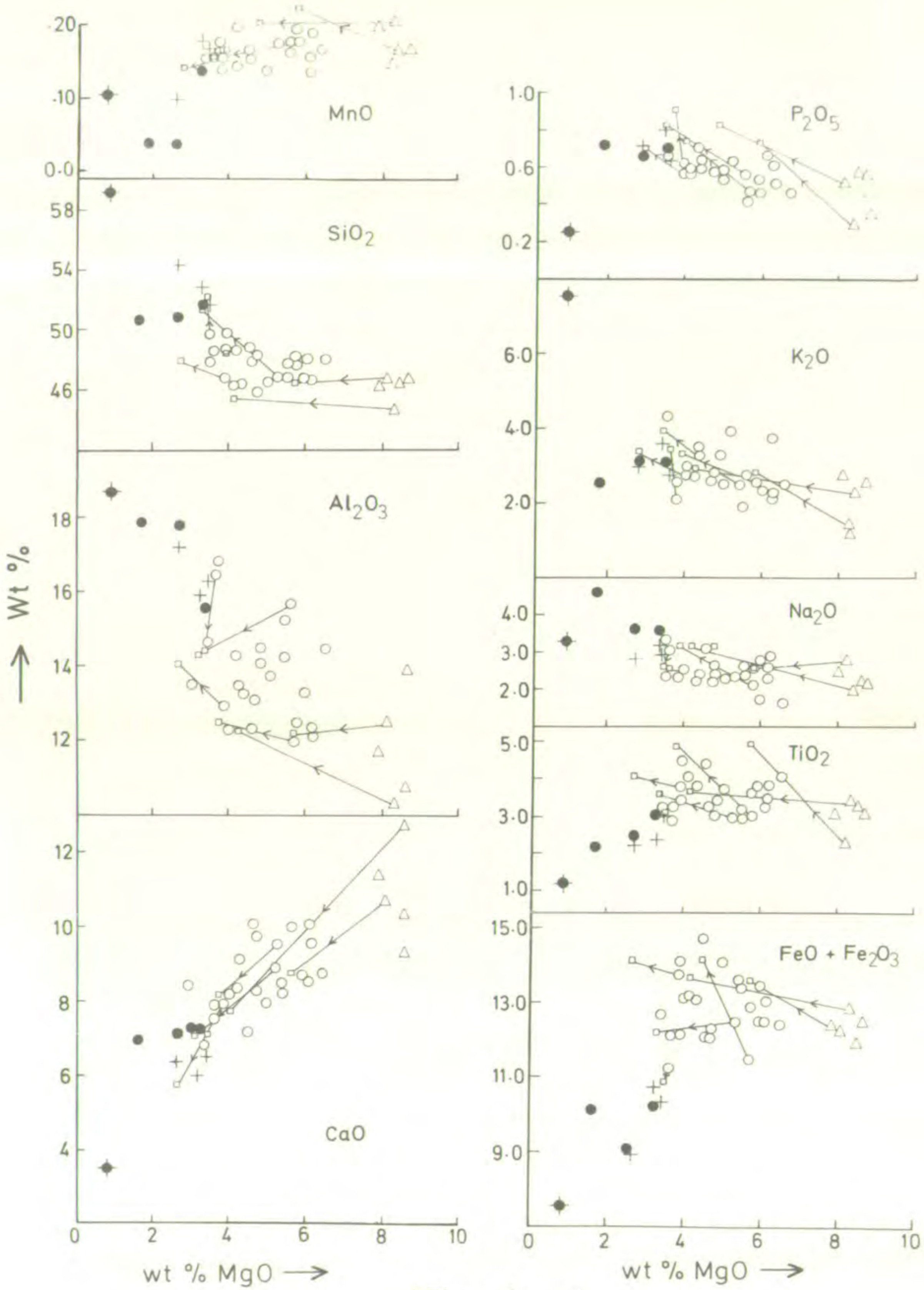
Table 8-11

Compositional range observed in the porphyritic basalts and possible parental magma composition

Wt.%	Minimum	Maximum	Mean	Anhydrous mean	CIPW Norm	
SiO_2	46.45	48.25	47.48	48.59	Qz	0.00
TiO_2	3.00	3.87	3.51	3.59	Or	15.77
Al_2O_3	11.02	15.85	13.45	13.77	Ab	19.88
Fe_2O_3	3.43	4.20	3.85	3.93	Ne	-
FeO	8.74	10.66	9.15	9.36	An	19.13
MnO	0.16	0.20	0.17	0.17	Di	18.47
MgO	5.00	6.43	5.75	5.88	Hy	10.22
CaO	7.91	10.07	8.94	9.15	Ol	2.74
Na_2O	1.56	2.87	2.30	2.35	Mt	5.70
K_2O	1.81	3.92	2.61	2.67	Il	6.82
H_2O+	1.56	2.80	2.11	-	Ap	1.28
P_2O_5	0.42	0.64	0.53	0.54		
Total			99.85	100.00		
ppm						
Ba	1238	2280	1581	1581		
Zr	310	362	326	326		
Nb	49	73	58	58		
Sr	680	1005	838	838		
Rb	47	107	74	74		
Y	31	38	34	34		
La	59	85	76	76		
Ce	148	200	185	185		
Ni	46	96	69	69		
Cr	25	149	100	100		
V	326	470	403	403		
Zn	104	136	121	121		
Cu	70	170	114	114		

Fig. 8-4: Variation diagram for the major oxides with MgO of the Rajpipla alkalic suite from basalt to trachyte.

Symbols as in Fig. 8-2.



MnO
SiO2
Al2O3
CaO
P2O5
K2O
Na2O
TiO2
FeO + Fe2O3
Wt %
wt % MgO
wt % MgO
.20
.10
0.0
58
54
50
46
18
16
14
12
12
10
8
6
4
1.0
0.6
0.2
6.0
4.0
2.0
4.0
3.0
2.0
5.0
3.0
1.0
15.0
13.0
11.0
9.0
0
2
4
6
8
10

Fig. 8 - 4

7. P_2O_5 shows a gradual increase with decreasing MgO throughout the series but is much depleted in the trachyte where scarce needles of apatite can be seen.

8. MnO in general, tends to follow total iron and TiO_2.

8:6b Trace element variation:-

As in the case of the major oxides, the trace element variation of the alkalic suite has been studied by plotting them against the wt.% of MgO (Fig. 8-5) and the following points have been noticed, in the variations of the different elements.

a) Nickel and chromium:-

Cr normally substitutes for Fe^{+3} sites in the clinopyroxenes, while Ni substitutes for Mg^{+2} in the olivines (Prinz, 1967). With decreasing MgO, both Ni and Cr show a steady decrease, and appears to suggest fractionation of both olivine and clinopyroxene. Cr shows a fair amount of scatter and is possibly due to the varying amounts of clinopyroxene phenocrysts in the basaltic rocks and their rather variable Cr content (see Table 8-3).

b) Vanadium:-

V seems to follow total iron ($FeO + Fe_2O_3$) for it remains constant or (?) increases between 8 to 6% MgO, and thereafter decreases steadily. The scatter in the V contents of the samples particularly between 6 to 4% MgO, is probably related to varying amounts of ore phases and clinopyroxenes, for the latter contains from about 200 to 400 ppm of vanadium (see Table 8-3).

c) Strontium:-

Sr can substitute for Ca sites in clinopyroxene, plagioclase, and apatite (Prinz, 1967) but it appears to prefer the Ca sites in

Fig. 8-5: Variation of trace elements with MgO from basalt to trachyte. Trace elements concentrations of some of the potassic rhyolites (open squares) have also been indicated.

Symbols as in Fig. 8-2.

the plagioclase feldspars in the early stages (Taylor, 1965). Sr attains maximum concentrations in the basaltic rocks between 5 to 3% MgO, particularly in the feldspar rich types, since in the two analysed feldspars (see Table 8-4) Sr varies from 1680 to 2060 ppm. The scatter in the Sr values are apparently related to the varying amounts of plagioclases in these rocks, which vary from about 1 to 25% by volume. Sr values in the analysed clinopyroxenes range from 80 to 260 ppm.(see Table 8-3), which might also have enhanced the scatter.

d) Barium and Rubidium:-

Both Ba and Rb show an increase with decreasing MgO, the increase being rather steep from about 4% MgO. Both these show a close correlation with potassium, as observed by Prinz (1967) and others. The scatter of these two elements are therefore related to the varying potassium contents of the suite.

e) Zirconium and Niobium:-

Both Zr and Nb show a general increase from the basalts to the trachyte as these two elements are largely rejected by the fractionating minerals (Prinz, 1967), and thereby get enriched in the residual liquids.

f) Lanthanum, Cerium and Yttrium:-

Both individually and collectively (i.e. Σ La + Ce + Y) they show an increase with decreasing MgO, and thereby appears to be enriched in the residual liquids.

g) Copper and Zinc:-

Cu^{2+} and Zn^{2+} can substitute for Fe^{2+} in the late sites (Taylor, 1965), while Cu^{1+} may substitute for Na^{1+} (Taylor, op.cit.)

Cu shows a fairly steep decrease with decreasing MgO from about 8 to 4% and thereafter remains steady at ~60 ppm level. Therefore, the variation of Cu is not fully consistent with that of Fe. On the other hand, Zn shows a slight initial increase with decreasing MgO from about 8 to 5% and then decreases, and appears to follow the variations of total iron.

8:7 Differentiation:-

Several of the following lines of evidence appear to support the view that the observed diversity from basalt to trachyte, has resulted through a process of crystal fractionation - presumably through a simple process of crystal settling - from an initial, mildly alkaline, moderately potassic basalt.

8:7a Chemical and mineralogical evidence:-

There is fairly close correlation between the chemical variation and the nature of the phenocryst phases present in the rocks. The observed chemical variation when considered in conjunction with the phenocrystal minerals appears to be consistent with the following order of mineral controlled evolution (see Fig. 8-4).

a) Flows with >6% MgO lie on an Ol + Cpx control line and therefore, their evolution is controlled by the fractionation and/or accumulation of a mixture of olivine and clinopyroxene, the latter preponderating, and is in conformity with the anakaramitic nature of the basalts (see Fig. 8-6).

b) For flows with about 5% MgO or less, the evolution is controlled by the fractionation and/or accumulation of an ore mineral, along with olivine and clinopyroxene. The fairly steep

Fig. 8-6. Plot of MgO vs. CaO and Al_2O_3 (in wt.%).

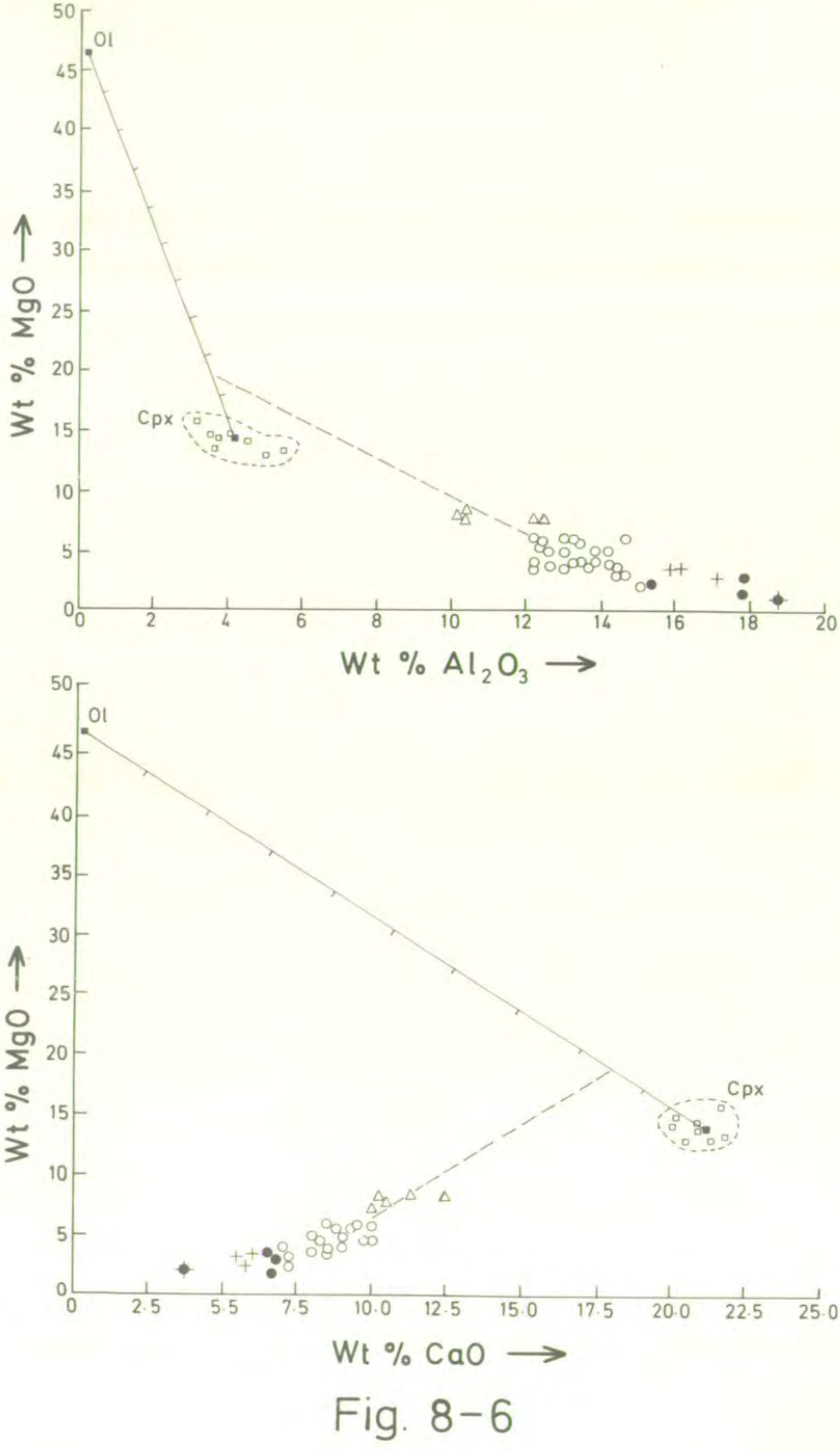
Solid lines are Ol-Cpx tie lines.

Dashed lines are "control lines" from average olivine/augite phenocryst ratio in ankaramitic basalts.

Dotted area included analysed clinopyroxenes from ankaramitic basalts and basalts and the average.

solid square = olivine composition (Fo_{84}) taken from a three-phenocryst basalt flow of the bore hole sequence (specimen No. $126-P_1$ Table 3-1)

Other symbols as in Fig. 8-2.



Ol
Cpx
Wt % MgO →
Wt % Al$_2$O$_3$ →
0
2
4
6
8
10
12
14
16
18
20
5
10
15
20
25
30
35
40
45
50
Ol
Cpx
Wt % MgO →
Wt % CaO →
0
2.5
5.5
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0

Fig. 8-6

decrease in the amounts of total iron, TiO_2 and V, coupled with an increase of SiO_2 are consistent with such a hypothesis. Many of the flows in this range contain phenocrysts of all these phases.

c) Whether plagioclase has effectively fractionated at any stage is debatable. There is no clear evidence of anything other than a steady rise in Al_2O_3 throughout the series. This is coupled with a general tendency for the plagioclase phenocryst content to increase, suggesting that although plagioclase crystallizes freely in the trachy basalts it is probably not removed. This may be due to a lack of sufficient density contrast between the plagioclase and the liquid (cf. Cox and Bell, 1972).

d) Apatite may have crystallized as a phase at ~2.5% MgO, for P_2O_5 shows a decrease after an initial build up. In fact, needles of apatite can be seen in the trachyte.

e) Evidence is also provided by the enrichment of certain elements such as Ba, Rb, Zr, Y, La and Ce which are strongly rejected by most of the fractionating phases, and which show maximum enrichment in the trachyte.

8:7b <u>Bulk rock-Groundmass relations</u>:-

The model of mineral controlled evolution and consequent changes in the residual liquid compositions, outlined in the previous section, are further supported by a study of the whole rock-groundmass relations (Table 8-8 and Fig. 8-4). The groundmass composition of the ankaramitic basalts correspond with the whole rock composition of the porphyritic basalts or trachy basalts, while that of the basalts or trachy basalts approximate the whole rock compositions of the oligoclase basalts or compositions lower in the fractionation series. Such a feature clearly indicates the progressive change in the liquid composition as a result of crystallization and fractionation.

However, the following two important features support the contention that the ankaramitic basalts are in all probability the result of the early settling of olivines and clinopyroxenes from a basaltic magma (with ~5–6% MgO) undergoing crystallization at fairly low pressures, presumably in a plexus of shallow magma chambers.

1. The clinopyroxenes of the ankaramitic basalts although slightly magnesium-rich on the average, resemble those present in the porphyritic basalts. The nature of the olivines is not certain, for in both types they are completely altered.

2. The ankaramitic flows and/or dykes are subordinate in amounts to the porphyritic basalts of the area and are invariably present as minor flows and dykes (4 flows and a few minor dykes; 10 to 50 feet thick) interlain with the dominant basalts (23 flows; 50 - 250 feet thick).

The most probable scheme of differentiation for the alkalic suite is summarised in Fig. 8-7.

8:8 <u>Compositional gap between the trachyte and the potassic rhyolite and possible genetic relations of the rhyolites to the alkalic series</u>:-

There is a fairly large compositional gap, represented by ~12% SiO_2 between the trachyte and the rhyolite and intermediate compositions are absent. This might cast doubt on a possible direct genetic link between the alkalic series and the rhyolites.

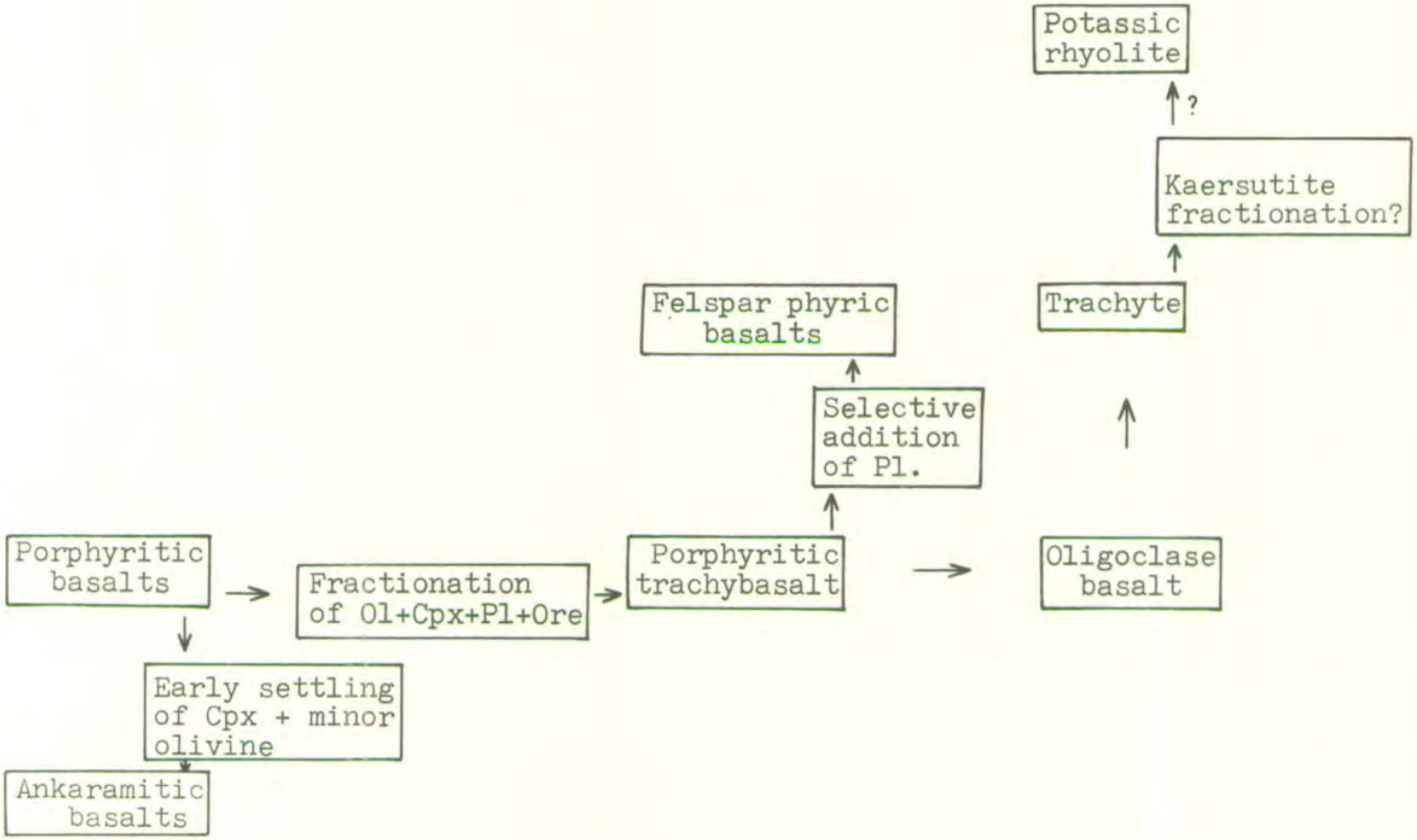


Fig. 8-7. Schematic diagram of the petrographic evolution of the Rajpipla alkalic series.

However, the following mineralogical and chemical features may be taken tentatively as evidences for the existence of a probable genetic relation through fractional crystallization, although additional processes such as sialic contamination and silicification might have also contributed to their origin.

1. As has already been shown (see Section 8:2 on Classification) the alkalic series from basalts to trachyte is moderately potassic in nature and the rhyolites also exhibit a similar character.

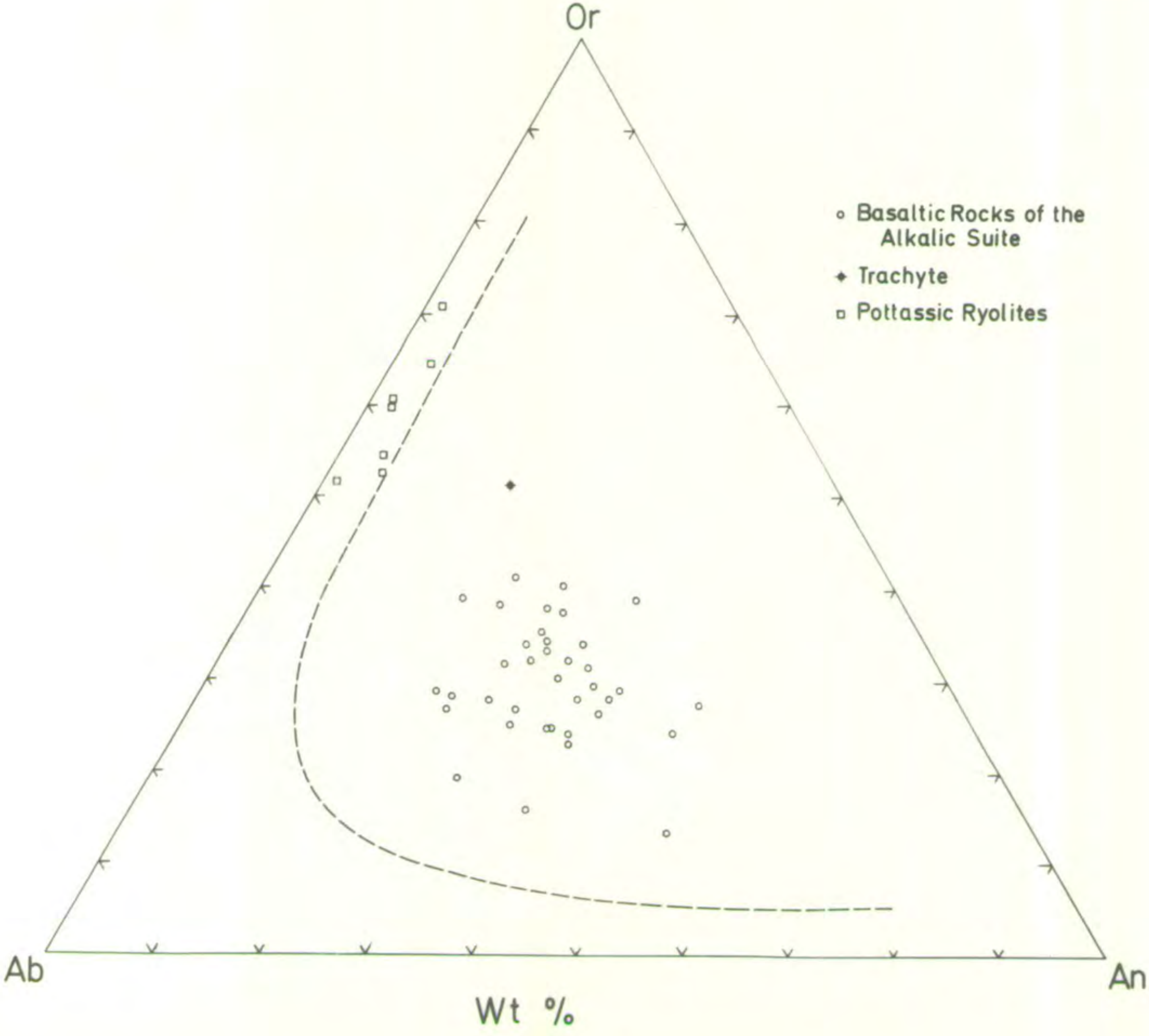
2. Major oxides such as Al_2O_3, Na_2O and K_2O show a decrease from trachyte to rhyolite, which appear to be related to the crystallization and fractionation (?) of sodic plagioclase and potash feldspar both of which are present in the rhyolites. Precipitation of amphibole (Kaersutite) in the trachyte, may also have increased the SiO_2 content of the residual liquid.

3. Trace elements such as Ba and Zr which show a continuous increase in the alkalic series from basalt to trachyte, decrease sharply (particularly Ba) and appears to be consistent with the crystallization of potash feldspar and zircon, the latter mineral found as an accessory in the rhyolites (see Fig. 8-5).

4. The composition of the normative feldspars (Ab-An-Or, Fig. 8-8) of the alkali series plot in the two feldspar field, and such suites may fractionate to rhyolites with two feldspars (cf. Carmichael, 1963).

5. The normative salic constituents of the alkaline series and the rhyolites, when plotted in the system Ab-Or-Qz-H_2O system (Tuttle and Bowen, 1958; Luth, Jahns and Tuttle, 1964) clearly illustrates the potassic nature of the suite and appears to progress

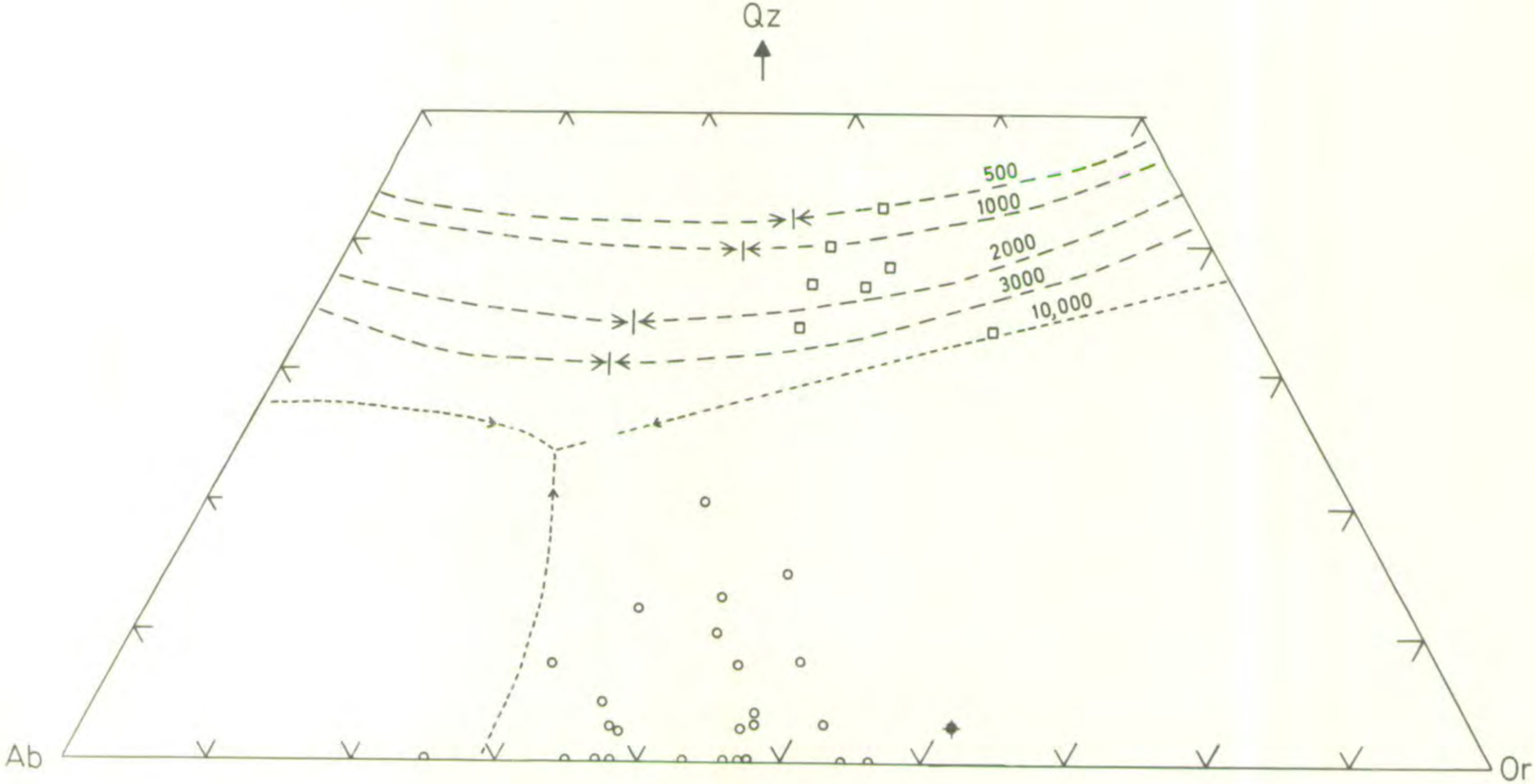
Fig. 8-8. Normative feldspar composition of the rocks of the alkalic series of Rajpipla in the system albite-anorthite-orthoclase (in wt. %). The composition of the feldspars in the potassic rhyolites are also indicated. The limit of solid solution in natural feldspars (shown in dashed line) is taken from Tuttle and Bowen (1958).



Or
Ab
An
○ Basaltic Rocks of the Alkalic Suite
✦ Trachyte
□ Pottassic Ryolites
Wt %

Fig. 8-8

Fig. 8-9: The salic normative constituents of the Rajpipla alkalic series plotted in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. The boundary curves and minima at 500, 1000, 2000, 3000 (Tuttle and Bowen, 1958) and 10,000 Kg/cm^3 (Luth, Jahns and Tuttle, 1964) water-vapour pressure are indicated.



Wt PERCENT

Fig. 8-9

towards the low on the alkali feldspar-quartz boundary, but is rather shifted towards the orthoclase-quartz boundary (Fig. 8-9).

8:9 Origin of the parental basalt of the alkalic suite:-

It was shown in the preceding sections that differentiation of a parental alkali basalt of moderately potassic nature can account for the observed diversity from basalts to trachyte. Attempts are made in this section to seek the origin of such a basalt. The average of 11 porphyritic basalts with MgO > 5% and < 6.5% has been taken as the most likely parental magma and is given in Table 8-11. It's olivine-tholeiitic character is clear from the norm, and hence also its slightly-undersaturated character. The potassium content of the parental basalt is rather high when compared with flows at comparable stages of evolution (see Fig. 8-3). Because of the following reasons, it is considered highly unlikely that such a mildly alkaline, moderately potassic parent magma is directly related to the tholeiitic basalts of the area, which occur at the base of the succession.

1. The alkaline and tholeiitic basalts differ in their K/Rb ratios (as shown below), and such a feature, suggested by Gast (1968), indicates the improbability of deriving the alkali basalts from the tholeiites by fractional crystallization.

	K/Rb ratio
Tholeiitic basalts	526 to 593
Alkali basalts	189 to 440

2. Estimated liquidus temperatures of the tholeiites are lower than that of the alkali basalts (see Table 8-12), and they also

Table 8-12

Atmospheric pressure melting and crystallization relations under Ni/NiO (fo_2 10^{-7}-10^{-10}) buffer.

Rock type	Highest temperatures of crystallization of major phases (in ^{o}C)
<u>Alkali series</u>	
Ankaramitic basalt	
R-9	(1248) Ore + glass;
	(1200) Ol + Cpx [illegible] ore disappears;
	(1114) Ol + Cpx + Plag + Ore.=
Porphyritic basalt	
R-8	(1197) Glass;
	(1175) Ol + Cpx + Plag;
	(1160) - do -
	(1140) Ol + Cpx + Plag. + Ore.
<u>Tholeiitic rocks</u>	
1-T	(1170) Glass;
	(1166) Plag;
	(1150) Plag. + Ol + Cpx;
	(1127) Ore.
2-T	(1186) Glass;
	(1180) Plag;
	(1160) Ol + Cpx;
	(1127) Ore.
4-T	(1170) Glass;
	(1166) Plag + Cpx + Ol(?);
	(1127) Ore.

appear to differ from the alkali basalts in having plagioclase and plagioclase + clinopyroxene as the liquidus phase.

3. Thermal divides (see O'Hara, 1968) place further restrictions on postulations of assimilation and contamination of the tholeiitic basalt by crustal material to derive the alkali basalts.

Therefore, it becomes necessary to postulate an independent origin for the parental basalt of the alkalic suite and its potassic nature. The origin and evolution of such a liquid may be considered with respect to the following points.

1. Partial melting.

2. Crystal-liquid fractionation at higher pressures en route,

and 3. Mantle wall-rock reaction.

8:9a Partial melting:-

Experimental petrological studies (as mentioned in the previous chapter, Section 7:5) have indicated that under anhydrous or vapour-absent conditions, it is highly unlikely that basaltic magmas with an Mg x 100/Mg + Fe^{2+} ratio of c. 65 or less can co-exist in equilibrium with an upper mantle (either primitive or residual peridotite whose Mg x 100/Mg + Fe^{2+} ratio is of the order of c. 90 (cf. Green, 1971). On the contrary, picritic magmas with an Mg x 100/Mg + Fe^{2+} ratio of c. 70 or more can remain in equilibrium with possible peridotitic upper mantle compositions. Therefore, it is probable that the parental basalt or basalts of the Rajpipla alkalic series, with an average Mg x 100/Mg + Fe^{2+} ratio of 54, may have been derived from a more primitive, possibly picritic liquid formed at upper mantle depths. It is assumed here that about 20% initial melting of a garnet-peridotite source gives a primary picritic liquid, analogous to the one postulated in the case of the bore hole flows, dealt with in the previous chapter. Accepting such a hypothesis, it becomes necessary to postulate the probable mechanisms through which one can obtain the compositions approximating the parental basalt.

Both high pressure crystallization and fractionation at *specific depths* has been proposed by Green and Ringwood (1967), Green (1970), and O'Hara (1965, 1968), for the derivation of different types of magmas from an initial picritic or olivine-tholeiitic partial melt. Olivine and aluminous enstatite fractionation has been advocated by Green (*op.cit.*), while continuous olivine fractionation (up to 40%), which may or may not be preceded by variable eclogite fractionation (at depths >25 Kb) has been proposed by O'Hara (1968).

Bulk of the enrichment in the "incompatible" trace elements in the derivative basalts are as a result of wall-rock reaction in the scheme of Green and Ringwood (*op.cit.*) while in O'Hara's scheme (*op.cit.*) it is mainly through the closed system high pressure eclogite fractionation and subsequent olivine fractionation en route.

Since it is likely that picritic partial melts will fractionate *at least* olivine during ascent (Davies and Schairer 1965; Ito and Kennedy, 1967), it is probable that the parental basalts were derived from more primitive picritic liquids at depths through loss of olivines en route, before reaching the volcanic sub-stratum.

8:9b Enrichment factors and the nature of evolution:-

Enrichment (E) factors for certain trace and minor elements in the parental basalt are given in Table 8-13, assuming both an anhydrous and hydrous upper mantle. These have been found to range (in average) from 133 for an anhydrous upper mantle to 55 for an hydrous upper mantle with 0.5% phlogopite taking enrichment factors of K, Rb, Ba and Sr.

Based on the different degrees of partial melting and the resulting concentration levels given by Griffin and Murthy (1969, Table 10, p. 1405), enrichment factors have been calculated for K, Rb, Ba and Sr (see Chapter 7, Table 7-6). On this basis, enrichment factors have been calculated assuming

a) degree of partial melting alone (Table 8-14a),

b) degree of partial melting + olivine fractionation up to a maximum of 40% as suggested by O'Hara (1968)(Table 8-14b),

and c) partial melting + olivine fractionation (up to 40%) + eclogite fractionation (up to 50% or more) (Table 8-14c).

These are presented in Table 8-14, and their role in enriching the concentrations of the "incompatible" elements are briefly considered.

Assuming that the parental basalt is derived from an initial picritic melt (say after 20% melting) it can be seen from Table 8-14b that melting + subsequent olivine fractionation (up to a maximum of 40%) gives only an E factor of 8 in the residual basalt and thus cannot account for the observed E factors. Lower degrees of melting (say 5 or 10%) and subsequent olivine fractionation increases the E factors only slightly, but according to Green and Ringwood (cf.

Table 8-13

Enrichment factors for the postulated parental basalt

E* = as defined in Chapter 7, Section 7:6a

Element	Concentr. in Upp. mantle	Concentr. in the basalt	E*
a) Assuming anhydrous mantle**			
K	106	22157	209
Rb	0.48	74	154
Sr	150	838	56
Ba	14.0	1581	113
Zr	30.0	326	11
Zn	30.0	121	4
Cu	20.0	114	6
TiO_2	0.26	3.59	14
P_2O_5	0.02	0.54	27
Na_2O	0.17	2.35	14
b) Assuming hydrous mantle with 0.5% phlogopite**			
K	464	22157	48
Rb	1.76	74	42
Sr	15.0	838	56
Ba	21.0	1581	74
		Mean	55

E Mean (a) = 74 (excluding Zn and Cu) } for anhydrous mantle
E Mean (b) = 133 (K, Rb, Ba and Sr only) } for anhydrous mantle

** Values for anhydrous and hydrous upper mantle taken from Griffin and Murthy (1969, Table 6, p. 1399 and Table 7, p. 1402 respectively)

Table 8-14

Enrichment (E) factors based on melting alone and melting + crystallization

a) Melting alone

% Melting	E* factor
5	17
10	9
20	5

Average enrichment factor for the parental basalt (K, Rb, Ba, Sr, only)

1) Assuming anhydrous upper mantle = 133

2) Assuming hydrous upper mantle = 55

E* = As in Table 8-13.

b) Melting + 40% olivine crystallization enroute

% Melting	% Crystallization	Resulting E Factor
5	40	28
10	40	15
20	40	8

c) Melting + eclogite fractionation + up to 40% olivine fractionation enroute

% Melting	% Eclogite fractionation	Ol Fractionation	Resulting E factor
10	50	40	30
10	73	40	55
20	50	40	17
20	70	40	28
20	80	40	42

1967) low degrees of melting may not produce picritic partial melts to start with. Therefore, it becomes necessary to invoke additional high pressure processes for the enrichment of the incompatible elements. Two such processes, namely eclogite fractionation (O'Hara and Yoder, 1967; O'Hara, 1968) and wall-rock reaction, including "zone refining" (Green and Ringwood, 1967; Harris, 1957) have been attributed to the enrichment of the incompatible trace elements in various basaltic types.

According to O'Hara and Yoder (op.cit.) eclogite fractionation is alleged to increase the concentrations of elements such as K, Ti, Ba, Rb etc. for these elements do not take part in the fractionating eclogitic mineral phases. Accordingly, the enrichment factors in the residual liquids depend upon the amount of fractionation which the initial liquid has suffered. Because of the preferential entry of Na in the eclogitic pyroxene, the K_2O/Na_2O ratio tends to show an increase in the residual liquids resulting from eclogite fractionation. The K_2O/Na_2O ratios of the porphyritic basalts, which have been averaged to give the most probable parental composition, show a slight increase in their K_2O/Na_2O ratios, with increasing K_2O (Fig. 8-10). Such a feature may be taken as evidence to support the possibility of some eclogitic fractionation at depth, in the parental picritic liquid, before it commenced its journey to reach the volcanic sub-stratum. Both harzburgite (Ol + Opx) and or lherzolite (Ol + Opx + Cpx) fractionation are implicit in O'Hara's (1968) scheme, while a pyroxenite stage (Opx + Cpx) has been postulated by Tilley and Yoder (1964) before the onset of eclogite fractionation.

Fig. 8-10: Plot of K_2O/Na_2O vs. K_2O (wt.%) in the ankaramitic basalts and basalts (excluding trachybasalts) of the Rajpipla alkalic suite.

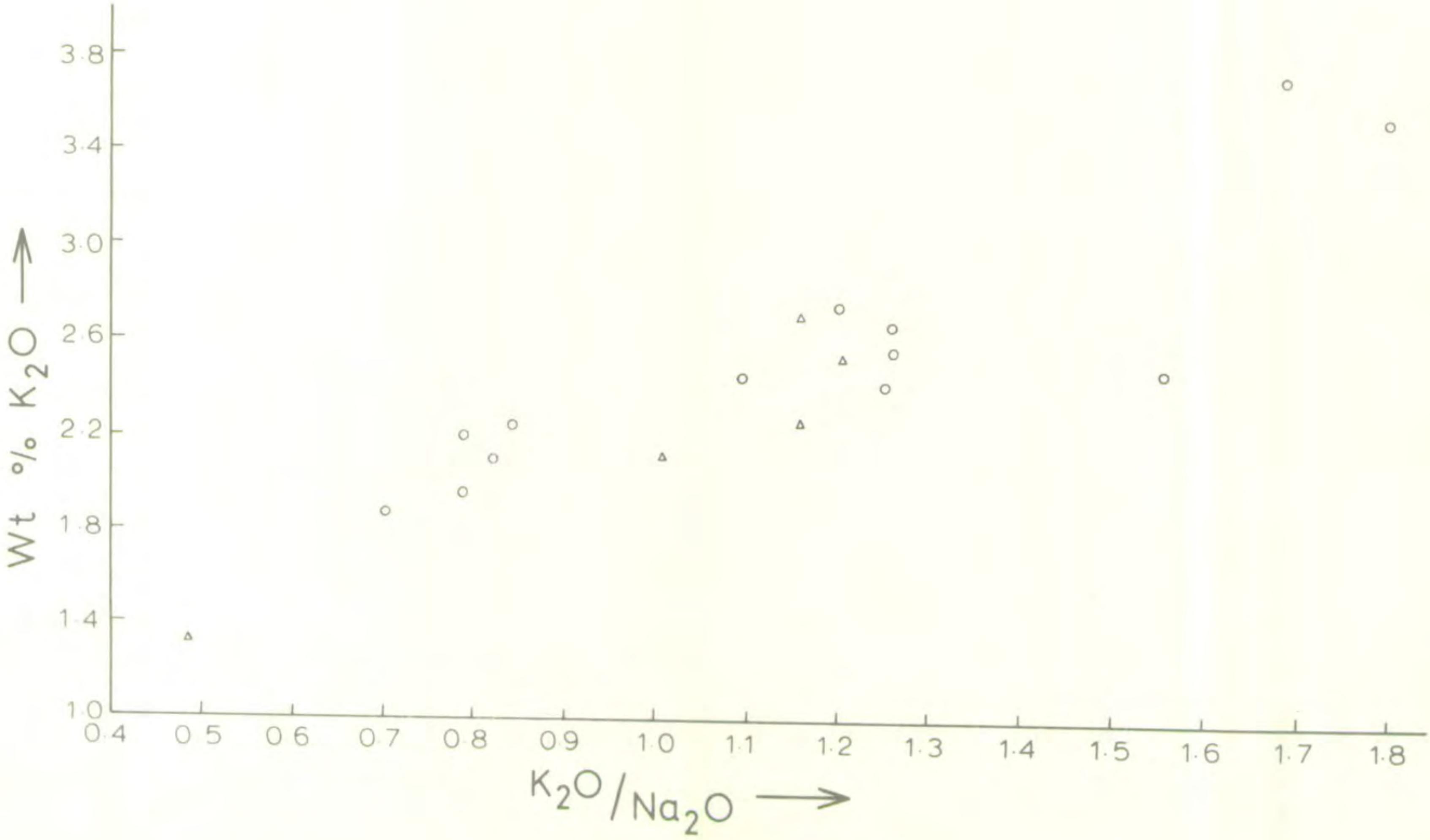

Wt % K_2O →
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
K_2O/Na_2O →

Fig. 8-10

However, in the present case, even large amounts of eclogite fractionation (say to 70 or 80%), followed by a maximum of 40% olivine fractionation cannot account for the observed E factors obtained assuming a hydrous upper mantle. E factors of 133, obtained assuming an anhydrous mantle seems to require still larger amounts of fractionation. Such <u>large</u> amounts of eclogite fractionation are probably unlikely and hence additional mechanisms of incompatible element enrichment is needed.

The whole concept of closed system fractionation is criticized by Gast (1968) because of the large scale volume reductions implied in such models. As an alternative, Gast (<u>op.cit</u>.) proposed a direct partial melting model of different source regions, in order to account for the high and variable trace element contents observed in different types of basalts. For alkali basalts he proposed 3 to 7% melting from a fertile mantle. If eclogite fractionation (at least up to <u>50%</u> on the initial picritic liquid) is not assumed, then it becomes necessary to advocate either

a) considerable amounts of wall-rock reaction as suggested by Green and Ringwood (1967) and/or

b) a variable source composition with comparatively higher amounts of incompatible elements than the one assumed here, namely the one with <u>0.5%</u> phlogopite.

Although accepting the principle of eclogite fractionation, Green (1971) and Bultitude and Green (1971) refute the efficacy of <u>large scale</u> operation of such a process because

a) the clinopyroxene of the alleged eclogite extract is not "omphacitic", and

b) excessive eclogite fractionation, according to them, tends to produce residual liquids which are not only strongly nepheline-normative, but also low in Mg x 100 / Fe^{2+} ratios.

It is possible that the strongly alkaline rocks such as nephelinites and ijolites in and around Ambadongar (Sukeshwala and Avasia, 1969; Udas, 1969), which lies about 50-60 miles ENE of the area, may be related to such a process at depths.

In summary, assessment of the mechanisms of incompatible element enrichment in the parental basalt poses considerable problems. It is difficult to distinguish or to quantify the different high pressure processes which can contribute to the trace element enrichment in the parental basalt. In this context, upper mantle compositions with slightly higher levels of initial incompatible element concentrations (say with 0.5% phlogopite) appear to pose problems of lesser magnitude than those based on anhydrous compositions.

8:10 Petrogenetic summary:-

1. Partial melting of c. 20% of garnet peridotite (probably with 0.5% phlogopite) producing an initial picritic liquid.

2. Extensive high pressure fractionation (say up to 50% of eclogite) followed by olivine fractionation, producing compositions analogous to the parental, mildly alkaline, moderately potassic, olivine-tholeiites. Wall-rock reaction may also have played a significant role in enriching the incompatible elements of the parental basalts.

3. Supply of such a liquid to shallow level magma chambers or

conduits, where fairly simple processes of crystal fractionation appear to have produced the observed diversity from basalts to trachyte.

4. Crystal settling of early formed olivines + clinopyroxenes from the basalts appear to have produced the minor ankaramitic basalts.

5. Strongly oxidising conditions appear to have prevailed during the evolution of the suite under low pressure conditions which has caused the early appearance of ore, and consequently rapidly enhanced the silica enrichment of the suite.

6. The rhyolites share the potassic character of the alkaline suite and thus may be genetically related to them through processes of crystal fractionation.

PART III

CHAPTER IX

OTHER AREAS AND SOME GENERAL OBSERVATIONS ON THE CHEMISTRY OF THE DECCAN BASALTS AND THE AGE AND DURATION OF THE VOLCANISM.

9:1 Introduction:-

Chemical analyses carried out on miscellaneous samples from areas such as Pawagarh, Ambadongar, Panwand, Kawant and Dedan (see locality map Fig. 1-1) are presented in Table 9-1. These have been used along with published analyses of Deccan basalts from the various parts, in order to assess the general chemical nature of the basalts of western India and to compare them with the rest of the Deccan.

The samples have been grouped into the following regions:

a. Central India, which covers the north-eastern part of the basalt plateau.	Eastern portions of the basalt plateau.
b. South-eastern margin of the basalt plateau.	
c. Bombay-Poona region	Western portions of the basalt plateau/Basalts of Western India.
d. Narmada region	
e. Kathiawar or Cutch region	

Fig. 9-1 indicates the localities included under the different regions.

It is fairly well established from previous work (referred to in the introductory section of Chapter I) that the rocks of the eastern part of the Deccan traps i.e. from Central India, comprise fairly uniform tholeiitic basalts without much variation, while those from western India, show considerable variety. However, no attempt has to date been made to investigate regional variations

Fig. 9-1. Names of the localities included under the different regions.

Central and Eastern India

1. Mandla
2. Seoni
3. Chhindwara
4. Betul
5. Rajamundri

Western India

a) Bombay-Poona region

6. Kolhapur
7. Mahabaleshwar
8. Poona
9. Igatpuri
10. Bombay

b) Narmada region

11. Rajpipla
12. Ambadongar
13. Pawagarh.

c) Cutch region

14. Dhandhuka)
15. Botad) Bore hole samples
16. Wadhwan Junction)
17. Mount Girnar
18. Barda Hills
19. Panandrao
20. Dedan.

Note: See Caption to Fig. 9-2 for the references from where the analyses used in the present study were taken.

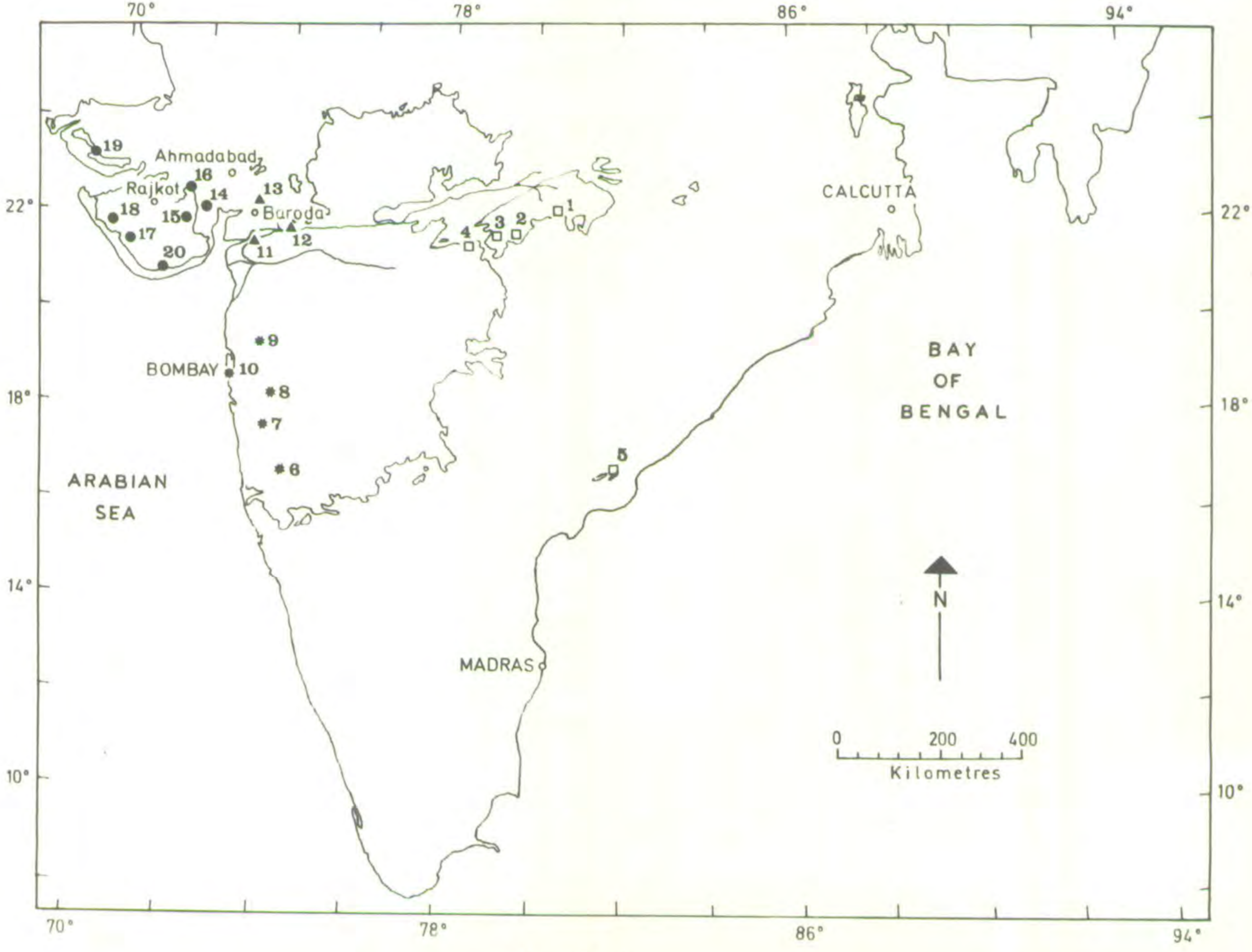

70°
78°
86°
94°
22°
18°
14°
10°
19
Ahmadabad
Rajkot
16
13
14
18
15
17
20
Baroda
12
11
1
2
3
4
CALCUTTA
9
BOMBAY
10
8
7
6
5
BAY
OF
BENGAL
ARABIAN
SEA
N
MADRAS
0
200
400
Kilometres

Fig. 9-1

Table 9-1

Analyses from other areas

	Dedan		Pawagarh						Ambadongar, Panwad and Kawant						
Spec. No.	A-78-TK	A-64	TK-A-31	PA-17	P.13-18	P.B-36	P.B-39	P.B-52	320	ANK-K	355	193[a]	47	P1-K	A.D.-10
Wt.%															
SiO_2	46.60	47.25	47.85	48.55	46.40	47.60	47.45	45.35	49.73	45.33	46.75	50.28	47.85	41.10	49.06
TiO_2	0.96	1.25	0.92	2.83	2.08	1.71	1.64	1.61	3.01	1.16	1.87	1.52	0.89	3.18	0.97
Al_2O_3	11.19	11.99	10.26	14.92	12.54	9.83	9.59	9.65	13.27	12.67	11.39	18.86	14.00	10.59	14.46
Fe_2O_3	5.82	2.76	2.26	4.69	5.75	3.78	4.95	4.47	2.82	1.88	3.04	2.76	5.60	4.97	6.19
FeO	5.91	8.55	8.19	6.76	5.89	7.90	5.57	6.75	10.87	7.58	7.86	2.95	2.01	6.35	1.70
MnO	0.18	0.16	0.18	0.17	0.18	0.17	0.17	0.18	0.18	0.17	0.18	0.18	0.32	0.21	0.29
MgO	15.48	12.76	12.69	5.32	9.18	14.08	14.40	16.78	4.54	12.09	12.31	1.58	1.77	7.39	1.23
CaO	8.61	9.59	11.84	10.57	11.72	11.16	11.46	9.41	9.40	14.78	11.68	5.61	11.79	13.49	8.59
Na_2O	1.53	1.46	0.98	2.70	1.82	1.56	1.45	1.48	2.54	1.68	1.71	6.21	7.60	2.30	8.13
K_2O	0.50	0.21	0.85	1.39	0.64	0.76	0.66	0.50	0.92	0.80	0.56	4.74	0.33	3.21	1.35
H_2O+	2.60	3.14	4.29	1.88	3.78	1.88	1.78	2.44	1.87	1.59	2.77	4.18	5.23	2.26	5.00
P_2O_5	0.12	0.15	0.16	0.45	0.23	0.21	0.27	0.25	0.36	0.31	0.29	0.36	0.65	1.11	0.54
CO_2	-	-	-	-	-	-	-	0.24	-	-	-	-	2.32	4.60	1.85
Total	99.50	99.27	100.47	100.23	100.21	100.64	99.39	99.11	99.51	99.83	100.41	99.23	100.36	100.76	99.36
In ppm															
Ba	359	171	220	655	245	255	280	275	394	1115	259	2106	1421	1455	2340
Zr	107	84	65	175	124	110	110	115	234	155	128	512	959	409	1117
Nb	21	<10	<10	38	28	28	27	28	18	21	17	134	236	75	275
Sr	160	194	159	505	310	245	245	280	340	810	255	1544	1342	1353	1320
Rb	4	5	10	37	14	22	8	7	23	5	13	165	25	84	43
Y	37	25	30	30	25	24	22	22	36	26	15	33	35	33	35
La	24	18	20	124	10	16	16	22	52	34	26	136	214	28	182
Cl	92	94	80	120	106	102	95	98	65	118	96	220	425	260	330
Ni	483	367	215	49	192	430	453	612	36	280	284	9	16	85	13
Cr	1140	691	772		437	1161	1142	1737	22	689	841	19	<10	133	<10
V	177	198	210	317	292	265	241	230	395	228	260	125	200	396	258
Zn	79	82	77	89	83	75	80	84	123	104	89	90	230	82	235
Cu	78	78	53	80	90	92	100	100	147	97	109	46	41	102	50
CIPW Norms															
Q	-	-	-	1.88	0.91	-	-	-	4.52	-	-	-	-	-	-
Or	3.05	1.29	5.22	8.37	3.92	4.55	3.99	3.10	5.57	5.00	3.39	29.46	2.05	19.25	8.45
Ab	12.36	12.85	8.62	23.28	15.97	13.36	12.57	13.14	22.01	4.19	14.82	22.34	45.84	16.25	46.09
Ne	-	-	-	-	-	-	-	-	-	5.11	-	17.84	11.77	1.89	13.40
An	22.90	26.57	21.92	24.31	25.05	17.79	18.14	19.10	22.62	24.74	22.27	10.08	3.27	9.22	-
Di	16.06	17.59	30.59	20.91	26.56	29.38	30.12	22.25	18.89	37.68	28.08	10.83	9.99	17.23	7.00
Hy	25.43	29.48	21.35	7.76	14.28	13.20	18.02	11.55	15.48	-	10.47	-	-	-	-
Ol	8.33	5.22	6.68	-	-	12.38	5.95	20.24	-	12.30	12.12	-	-	9.43	-
Mt	8.71	4.16	3.41	6.93	8.64	5.55	7.35	6.80	4.19	22.78	4.51	4.21	5.19	7.31	3.83
Il	1.88	2.47	1.82	5.48	4.10	3.29	3.19	3.21	5.85	2.28	3.64	3.04	1.78	6.13	1.95
Ap	0.29	0.37	0.39	1.09	0.56	0.50	0.66	0.62	0.87	0.72	0.70	0.90	1.62	2.67	1.36
H_2O	2.60	3.14	4.29	1.88	3.78	1.88	1.78	2.44	1.87	1.59	2.77	4.18	5.23	2.26	5.60
Hm	-	-	-	-	-	-	-	-	-	-	-	-	2.30	-	3.29
Ct	-	-	-	-	-	-	-	-	-	-	-	-	5.54	10.61	4.46
Ac	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.80

a = Includes 1.3% Wollostonite

within the western area.

9:2 Chemical variation:-

The chemical nature of the basalts from these different regions has been studied by plotting them in two simple diagrams, namely:

1. Wt. % of total alkalies vs. wt.% SiO_2 (Fig. 9-2)
2. Wt. % of MgO vs. wt.% other oxides (Fig. 9-3).

The samples included in the plot generally satisfy the "chemical screen" of basaltic rocks proposed by Manson (1967).

9:2a Total alkalies vs. Silica:-

This diagram (Fig. 9-2) has been used mainly to group the basalts into either alkaline or sub-alkaline (tholeiitic) types, taking the Hawaiian boundary line (Macdonald and Katsura, 1964) as a gauge. The following points emerge from a study of the plotted data:

a) Without exception the basalts of the eastern area are tholeiitic in nature.

b) Basalts from western India comprise both alkalic and tholeiitic flows.

These two points substantiate what has already been observed by earlier workers. However, within the western region, the plotted data indicate the following features:

i) Majority of the basalts of the Bombay-Poona area are tholeiitic while alkaline types are scarce, and when alkaline types do occur they are comparatively less alkaline than those present, in

Fig. 9-2. Plot of total alkalies vs. Silica for basaltic rocks from the different parts of the Deccan. The analyses plotted in this figure and in Fig. 9-3 are taken from the following sources:

Central and Eastern India:

Washington (1922) and Fermor (1934)

Western India:

a) Bombay-Poona region

Konda (1971); Sukeshwala and Poldervaart (1959); Viswanathan *et al.*, (1969); Vemban (1949); Washington (1922); Noble and Sukeshwala (1967).

b) Narmada region:

Rajpipla area

Krishnamurthy (1969); and Present work.

Pawagarh Hills

Present work; Tiwari (1969)

Ambadongar

Present work; Udas (1969)

c) Cutch area

Present work; West (1958); Washington (1922); Krishnan (1925); Subba Rao (1964); Dave (1969).

Note:

The dashed line separates phonolitic and nephelinitic rocks and lamprophyres from the Ambadongar-Kawant area from the basaltic rocks. These samples have not been included in Fig. 9-3.

AVT = Average of all tholeiites; major oxides, n = 897.(Manson, 1967, Table VI, No. 17).

AVA = Average of all alkali basalts; major oxides, n = 661. (Manson, 1967, Table VI, No. 21).

The boundary line between the alkalic and tholeiitic rocks are after Macdonald and Katsura (1964, Fig. 1).

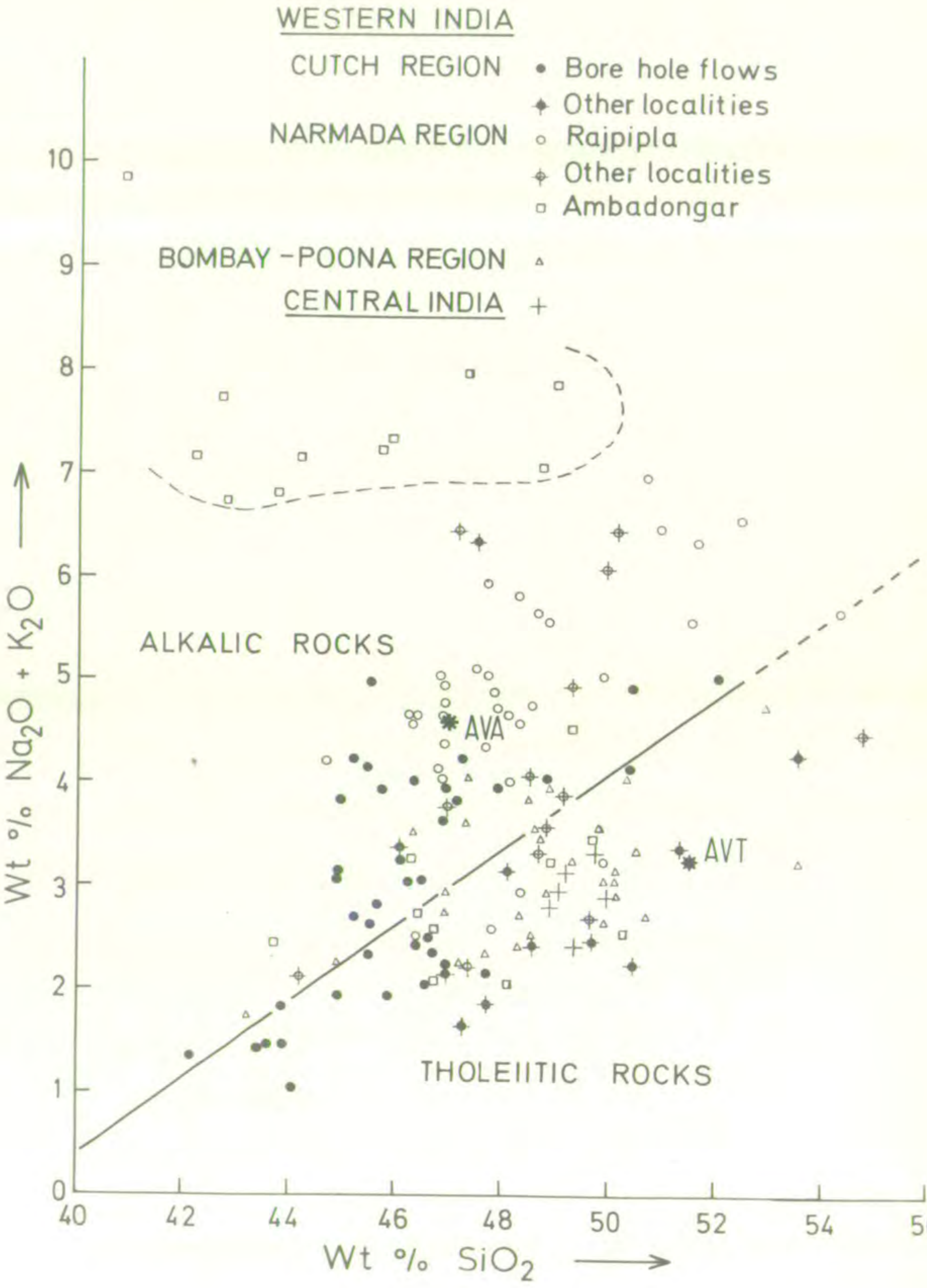

WESTERN INDIA
CUTCH REGION
● Bore hole flows
✦ Other localities
NARMADA REGION
○ Rajpipla
⊕ Other localities
□ Ambadongar
BOMBAY - POONA REGION △
CENTRAL INDIA +
ALKALIC ROCKS
THOLEIITIC ROCKS
AVA
AVT
Wt % Na2O + K2O
Wt % SiO2
0
1
2
3
4
5
6
7
8
9
10
40
42
44
46
48
50
52
54
56

Fig. 9-2

the Narmada region or in the cutch region.

ii) The Narmada region shows considerable variety for it contains not only strongly alkaline rocks such as nephelinites-ijolites (as at Ambadongar) but also appear to contain differentiated suite of rocks such as those present at Rajpipla (basalt to trachyte; present work) and at Pawagarh (Tiwari, 1969).

iii) Although the cutch region comprises rocks which are more alkaline than those present in the Bombay area, strongly alkaline rocks (with the exception of a single instance of analcitised-nepheline basalt (Bowen, 1927)) such as those available in the Narmada region are yet to be found.

Compared with the average tholeiite (Manson, 1967, Table VI, No.17) the Deccan tholeiites are in general slightly impoverished in SiO_2 and total alkalies, but they contain more SiO_2 and alkalies than the oceanic tholeiites of Engel et al., (1965, Table 3, No.1). The average alkali basalt (Manson, 1967, Table VI, No. 21) compares well with those reported from the Rajpipla area, while those from other areas are less alkaline.

9:2b MgO vs. other oxides (Fig. 9-3)

Table 9-2 summarises the variations observed in the plots of MgO vs. other oxides, from the different areas. The following is a summary of the overall variation observed in the different areas.

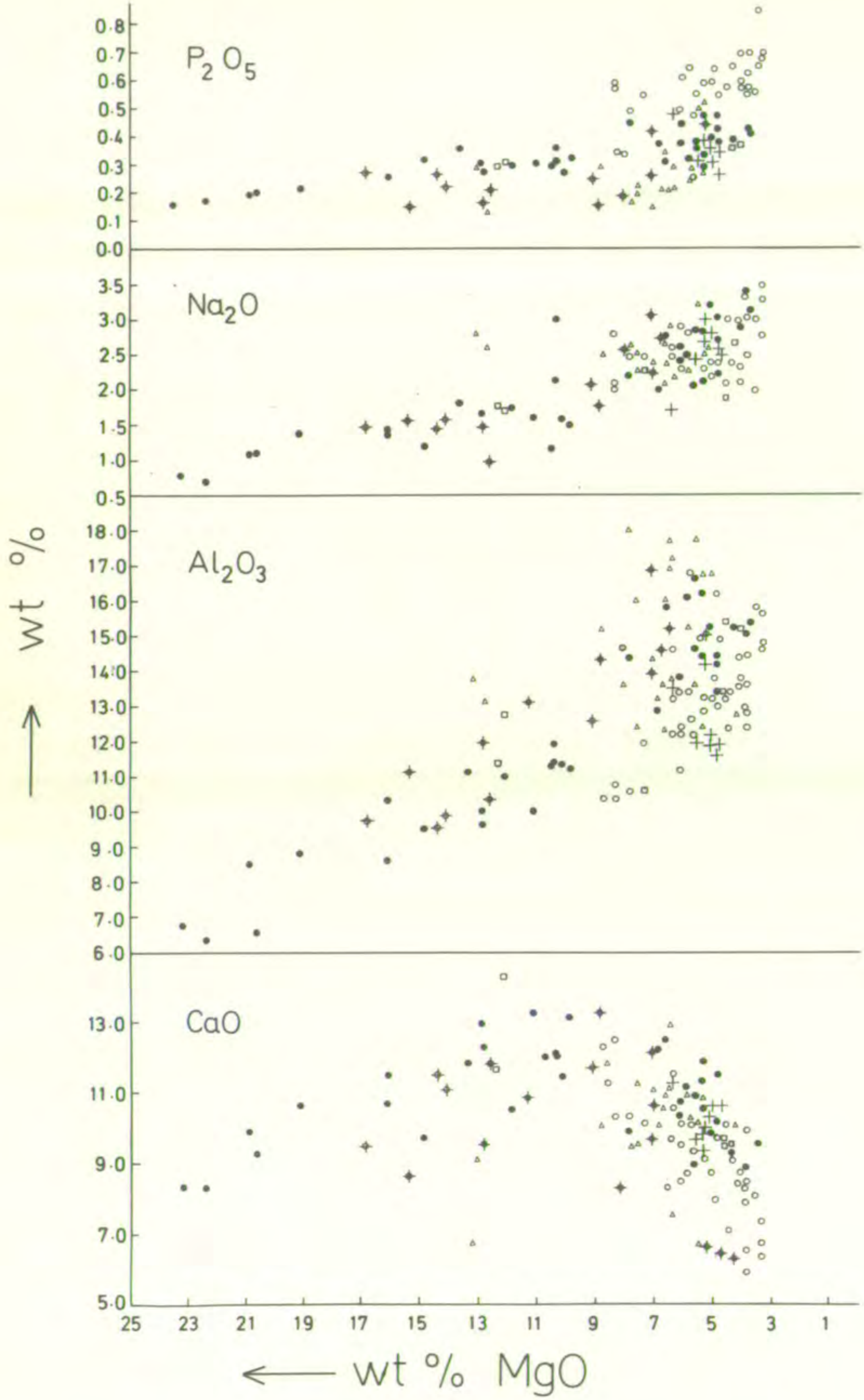
1. Narmada region

The E-W Narmada region appears to be unique for it contains rocks of extreme diversity. However, within the Narmada region, the western part comprising the Rajpipla area appears to be

Fig. 9-3: Plot of MgO vs. other major oxides for basaltic rocks from western and central India.

Symbols as in Fig. 9-2.

A few of the overlapping points have been omitted in order to keep clarity in the diagrams.



P2 O5
Na2O
Al2O3
CaO
wt %
wt % MgO
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1.0
1.5
2.0
2.5
3.0
3.5
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
5.0
7.0
9.0
11.0
13.0
25
23
21
19
17
15
13
11
9
7
5
3
1

Fig. 9-3

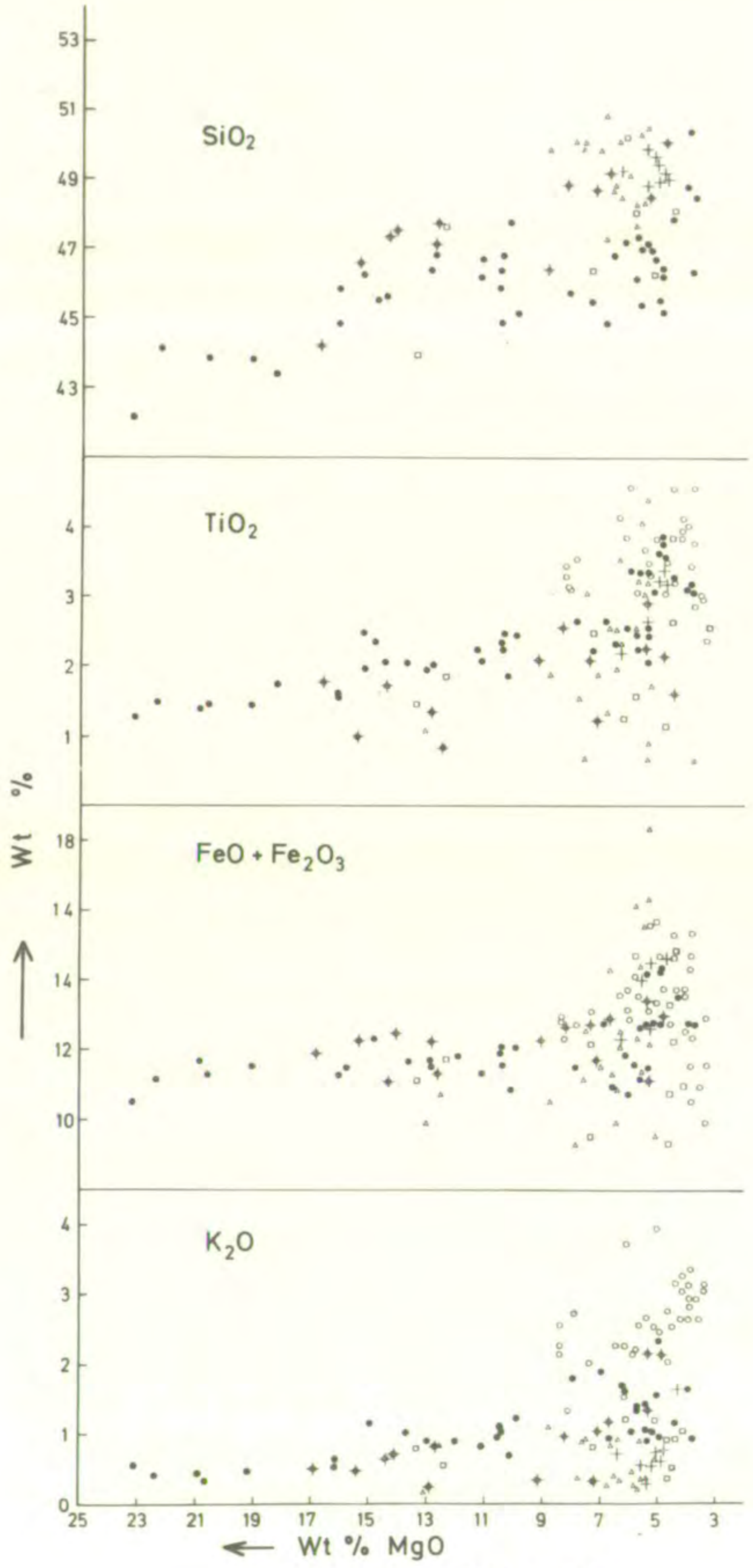

SiO$_2$
TiO$_2$
FeO + Fe$_2$O$_3$
K$_2$O
Wt %
Wt % MgO
53
51
49
47
45
43
4
3
2
1
18
14
14
12
10
4
3
2
1
0
25
23
21
19
17
15
13
11
9
7
5
3

Fig. 9–3 (Cont.)

Table 9-2

Comparative summary of the chemical features of the different parts of the Deccan basalt plateau, as observed in the MgO Vs Oxides plot (Fig. 9-3)

	WESTERN INDIA					CENTRAL INDIA (C.I.)
	BOMBAY-POONA AREA	RAJPIPLA AREA	PAWAGARGH HILLS	AMBADONGAR-PANVAD-KAWANT	KATHIAWAR OR CUTCH REGION	
SiO_2	Shows fair amount of scatter, but appear to contain higher values than any other area.	Fairly limited amount of variation; impoverished than Bombay or Central India basalts, even with tholeiitic rocks	Values lower than Bombay area	Shows a fair amount of scatter but generally lower than Bombay area	As in the case of the Rajpipla area	Uniform, without much variation
TiO_2	Shows wide variation from c. 0.6% to 4% in the basalts at c. 5-6% MgO level	Consistently higher values; alkalic series max. TiO_2 enrichment than any other region of the Deccan	Limited amount of variation; compares with the basalts of the bore-holes	Exhibit's fair amount of variation; generally lower than the Rajpipla area	In general > 1.5% in the basalts.	Generally > 1.5%. < 3.3%
FeO + Fe_2O_3	Shows wide variation from samples with c. 9-10% to c. 18.5% at c. 5% MgO level	Moderate amounts; max. c. 15%	Moderate amounts; c. 12-13%	Fair amount of scatter	Generally lesser than any other region except for a few samples	Moderately rich c. 14.5% and limited variation
Al_2O_3	Widely varying from c. 12 to c. 18%; some of the aphyritic types with high Al_2O_3 may resemble high-alumina basalts of Kuno (1960)	Fair amount of variation; some of the high Al_2O_3 ones being strongly felspar phyric; Lower than Bombay area in general.	Higher than flows of the Rajpipla area in the case of basalts	Fair amount of variation but generally > flows from C.I. and Rajpipla	Higher than Rajpipla and C.I. flows; many of them porph. with plag. phenocrysts	Moderate to lower amounts c. 12-13%; the lowest Al_2O_3 values of all the areas with a few exceptions at c. 5% MgO level.
CaO	Fairly limited c. 9-11%.	Generally lower than other areas.	Values are lower than any other area.	Ranges between 9-14%, the higher values being in some ankaramitic types.	As at Ambadongar-Panwad-Kawant.	Limited variation c. 9-11%.
MgO	In general c.5-7%; picritic types scarce	4-6% dominant	5-6% common; picritic types are present as minor flows (see Table 9-1)	c. 5-7%; picritic types do occur (see Table 9-1)	Strongly to mildly picritic types with up to c. 24% MgO; basalts c. 7-4%	Limited variation c. 5-6%
Na_2O	Fairly uniform (c. > 2 - < 3%) for most of the flows in the c. 5-6% MgO range with the exception of some flows at Ambadongar, where not only basalts with lower values of Na_2O occur, but also where strongly alkaline nephelinitic types are present (see Fig. 9-2).					
K_2O	Appears to be of two groups: 1) low K c. < 0.5% 2) moderate K c. 0.9%	Moderate to strongly potassic than any other area of the Deccan	Compares with the bore hole flows	Rather varying from c. 0.6% to 1.2%	Generally higher than c. 1% at 5-6% MgO level, but lower than the Rajpipla area	Very limited variation; <0.8% >0.4%
P_2O_5	Least enriched	Maximum enriched	Higher than Bombay area	Shows scatter; generally > Bombay area	Lower than Rajpipla but higher than other areas	Higher than Bombay area

moderately-potassic while the eastern part constituting the Ambadongar-Panwad-Kawant area seems to be moderately to strongly sodic. The intervening area of about 50-60 miles is yet to be studied. The Pawagarh basic rocks in turn are mildly alkaline and appear to provide both alkaline and calc-alkaline trends of differentiation. (cf. Tiwari, 1969).

2. Bombay-Poona region

This region, although containing scarce alkaline rocks, seem to provide a wide variation in the tholeiitic rocks themselves for they show a wide variation in the TiO_2, Al_2O_3 and total iron.

3. Cutch region

This region is also rather mildly alkaline but appears to be comparatively more alkaline than the Bombay-Poona region. Taking the bore-hole flows as an example, it is possible that some of the picritic flows are primary liquids, apparently erupted during the earliest stages of the Deccan volcanic episode. The basalts are also slightly more potassic (but less so than the Rajpipla area) than the Bombay or the Ambadongar area.

9:3 Age and duration of the Deccan Volcanism:-

The Deccan basalts have been classified into three groups as follows (cf. Pascoe, 1964):

Upper Traps (1500 feet):	Bombay-Kathiawar; with numerous intertrappean horizons and layers of volcanic ash.
Middle Traps (4000 feet):	Central India and Malwa; with numerous ash beds above and devoid of intertrappeans.

Lower Traps (500 feet): Central Provinces and eastern area; with inter-trappean beds and rare occurrence of ash beds.

However, the actual age and duration of the Deccan basalt volcanism has been and continued to be the subject of considerable debate and discussion (Pascoe 1964; McElhinny, 1968; 1970; Pal and Bhimasankaram, 1969). Geological data, summarised in Pascoe (op.cit.) suggest that the Deccan basalt eruptions commenced some time before the end of Cretaceous and continued across the Palaeocene into the epoch of Lower Eocene, thus bridging the gap between the Mesozoic and Tertiary eras. K-Ar dating of basaltic and some of the associated rocks [both extrusive basic and acidic rocks (e.g. Pawagarh) and intrusive plutonic rocks (e.g. Girnar)] by various workers (Rama, 1964; Deans and Powell, 1968; Wellman and McElhinny, 1970; Kaneoka and Haramura, 1973; Snelling (unpublished data)) indicate a range of ages from about 40 to 66 Ma*. Kaneoka and Haramura (op.cit.) report K-Ar ages of a lava pile at Mahabaleshwar which are discordant with the stratigraphy and the discrepancy has been attributed to Ar losses in the samples through alteration. Therefore according to them the K-Ar ages of about 60-65 Ma for the main Deccan basalt volcanism represents a minimum age of formation.

Since an intrusive diorite at Mt. Girnar gave an age of 65 Ma it was suggested by them that the flows being intruded are obviously older than 65 Ma.

---

* Ma = 10^6 years.

Based on paleomagnetic data, i.e. a one polarity reversal model, McElhinny (1970) proposed that the Deccan traps were probably erupted within a short span of about 5 Ma. (during the northerly migration of India when Madagascar parted company). However, other workers (Pal et al., 1971) have contested the short span of eruption proposed by McElhinny (op.cit.) and provide evidence for at least five polarity reversals, and hence a protracted period of volcanic activity from later upper Cretaceous (c. 65 Ma) to Late Eocene (c. 40 Ma).

According to McElhinny (1968; 1970) the main Deccan basalt eruptions are alleged to have occurred during the northerly migration of the Indian-Madagascar block, relative to Antartica, when India and Madagascar parted company, in late Cretaceous. Davies (1968) postulates that the separation of Seychelles and India caused the eruptions of the Deccan basalt.

According to McElhinny (1968; 1970) spreading from the Carlsberg ridge involved the separation of India on the one side and Madagascar and Seychelles on the other. Dietz and Holden (1970) propose that the Deccan volcanic eruptions ensued as a result of the Indian plate passing over a "thermal centre" which is also attributed to the formation of the Chagos-Laccadive ridge in the Indian ocean.

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APPENDIX A

SAMPLE PREPARATION AND ANALYTICAL METHODS

A:1 Sample preparation - crushing and grinding

A:2 Separation of phenocrystal minerals and groundmass

A:3 X-ray spectrographic analysis and electron probe microanalysis

A:4 Wet chemical analysis

A:5 Modal analysis

A:1 Sample preparation:-

Bulk rock powders:

The samples selected for analyses (generally from about 50g to 400g) were initially scrubbed and washed with a hard bristle brush under running water to remove any loose weathered material and/or dust. The samples were then washed in deionised water and dried. Then using a CUTROCK hydraulic splitter, the larger samples were reduced to C. 3-5 cm chips. At this stage weathered surfaces, if any, were discarded. The chips were then crushed using a Sturtevant Jaw Crusher, until the sample was reduced to about 36 mesh B.S. The material so obtained, was then reduced to -100 mesh size by repeated grinding (45 to 60 sec) and sieving in a Tungston Carbide TEMA disc mill, until the whole of the sample was reduced to -100 mesh B.S. The powdered samples were then bottled and dried for 24 hours at 110°C. Some of the Rajpipla samples were hand ground in India using a steel percussion mortar and pestle.

The only possible sources of contamination are W and Co from the Tungston Carbide TEMA disc mill and these were not determined.

The oxidation state of the samples that are ground in high velocity disc mills have been investigated by Fitton and Gill (1970). These authors have found that the amount of oxidation is dependent upon grinding time, sample weight and water content of the samples. Reference to Fitton and Gill (<u>op.cit.</u>, Table 2) shows that the grinding procedures used in the present study will produce negligible amount of oxidation.

A:2 Separation of Phenocrystal Minerals and Groundmass

Introduction:

In the case of the Rajpipla samples, separation of groundmass and phenocrystal plagioclase and clinopyroxene have been carried out. The following procedure is common up to a certain stage for the separation of the phenocrysts and the groundmass. Firstly the size of the phenocrysts to be separated were initially determined through a study of the hand specimen and the thin section. The samples were then crushed about ⅓ to ½ of the phenocryst sizes, so as to obtain a good yield of phenocryst only fragments. A size reduction up to -36 mesh B.S. was found to be satisfactory at this stage. Excess comminution of the sample was avoided by periodic sieving to remove the undersized before further reduction of the oversized material. The sample was then washed to remove the fine dust and dried at 105°C. The ore rich groundmass and the composite groundmass-phenocryst fragments were then removed by repeatedly passing the sample through Frantz isodynamic magnetic separator, vertically aligned, and at different field strengths, with the vibrating table removed. After this stage the following three crude concentrates (each about 60-80% pure) were obtained.

1. Plagioclase concentrates
2. Ferromagnesian mineral concentrates (mainly clinopyroxene)
3. Groundmass grains and composite grains comprising phenocryst + groundmass and some phenocrysts.

Further purification of these were done using Frantz isodynamic magnetic separator and heavy liquids.

a) Plagioclase felspars:-

The phenocryst concentrates of (1), obtained as above, were hand ground using a Protolite pestle and a flat tungsten carbide plate, so as to avoid excessive comminution, and passed through -100 mesh B.S., washed and dried. These were then repeatedly passed along the vibrating table of the Frantz isodynamic magnetic separator using different field strengths and inclinations. Generally an intensity of 0.65 to 0.85 ampere and inclination of 20°/22° was found satisfactory. This procedure effectively removed any remaining groundmass and also the magnetic ferromagnesian phenocrysts from the non-magnetic plagioclase. Final purification was done by floating off plagioclase (S.G. = 2.63-2.76) from impure fragments using ANALAR tetrabromoethane (S.G. = 2.964 at 20°C) which is diluted with Analar acetone, whereever necessary. In case, where the phenocrysts contained inclusions, the concentrates so obtained were ground to -125 to -200 mesh B.S. and the above procedure repeated. The purity was checked under the microscope, by point counting and the plagioclase concentrates were about 99.5 to 99.9% pure.

b) Separation of clinopyroxene:-

The ferromagnesian mineral concentrate obtained from the initial treatment largely consisted of clinopyroxene crystals, apart from some composite phenocryst + groundmass grains and scarce plagioclases. The concentrate was hand ground, so as to avoid excessive comminution, and passed through -100 mesh B.S., washed and dried. These were then repeatedly passed along the vibrating table of the magnetic separator using different field strengths. This procedure effectively removed some of the strongly magnetic composite groundmass grains and also some scarce altered olivine. Plagioclase felspars were removed by floating in Analar tetrabromoethane (S.G. = 2.964), which does not displace the much denser clinopyroxene (2.96 - 3.55) or olivine (3.22 - 3.49). The heavies were then washed and dried at 110°C. It was found at this stage that there were scarce crystals of olivine in some concentrates. Since the specific gravities of these two overlap, the purification of the clinopyroxene posed some problems. However, using Clerici's solution (S.G. = 4.00 at 10°C) and diluting it with deionised water, by trial and error, pure crops of clinopyroxene (99 to 99.5%) were obtained. The clinopyroxenes generally ranged in density from about 3.30 to 3.50, while the olivines tend to have higher densities. The samples were then thoroughly washed to remove traces of Clerici's solution and dried at 110°C for 24 hours.

c) Separation of the groundmass:

The separation of the groundmass was achieved by the following methods:

1. In the case of some strongly porphyritic types, such as sample R-26, thin slabs (about 1-2mm) were cut and both the phenocrysts and the groundmass drilled out using a hand drill.

2. By hand picking from the concentrates obtained after the initial treatment which largely consisted of groundmass grains, along with composite grains (i.e. phenocryst + groundmass) and some

phenocrysts. In addition the sample was hand ground and passed through -125 mesh B.S. The material was cleaned and dried at 110°C. Further concentration was done by passing the material through the Frantz isodynamic magnetic separator, keeping it vertical, without the vibrator, and with 0.05 to 0.1 A. This removed most of the small phenocrysts which are less magnetic than the "composite groundmass grain" comprising generally felspar microlites, groundmass ferromagnesian minerals, and groundmass ore. Further purification was done by passing the material along the vibrating table with low amperage, whereby, the strongly magnetic groundmass grains were separated from the weakly magnetic phenocrysts of plagioclase and/or clinopyroxene. The purity of the groundmass is about 98 to 99%.

A:3 X-ray Spectrographic Analysis:

The theoretical basis and general principles of x-ray spectrographic analyses are given by Jenkins and de Vries (1967) and Norrish and Chappel (1967). All the major and trace elements, with the exception of FeO, Na_2O, H_2O+ and Cr were determined by this method, using a Philips Automatic Spectrometer (PW 1212). Operating conditions during the analyses are summarised in Table A-1.

Major elements:

The method of sample preparation used here is similar to that developed by Rose et al., (1963). A fusion mixture comprising the sample, lanthanum oxide and lithium tetraborate in the ratio of 1:1:8 were used. In the case of whole rock analyses the ratio was

Table A-1

Operating Conditions for XRF analysis using PW1212 Automatic Spectrometer

Element & Line	Kv	mA	Crystal	Method	Counter	Time	Collimator	Vacuum	Remarks
Al Kα	60	24	PE	P	F	60	C	Y	
Ba Kα	80	24	LiF	P-B	S	30	F	N	
Ca Kα	40	24	PE	P	F	30	F	Y	
Ce Kα	80	24	LiF	P-B	F	300	F	Y	
Cu Kα	80	24	LiF	P-B	S	120	F	N	
Fe Kα	60	24	LiF	P	S	60	C	Y	
K Kα	60	24	PF	P	F	30	F	Y	
La Kα	80	24	LiF	P-B	F	300	F	Y	
Mg Kα	40	32	KAP	P-B	F	300	C	Y	Discriminate against KAP peak
Mn Kα	60	24	LiF	P-B	F	30	F	Y	
Nb Kα	80	24	LiF	P-B	S	60	F	N	
Ni Kα	80	24	LiF	P-B	S	120	F	N	
P Kα	60	24	PE	P-B	F	120	F	Y	
Rb Kα	80	24	LiF	P-B	S	60	F	N	
Si Kα	60	24	PE	P	F	60	C	Y	
Sr Kα	80	24	LiF	P-B	S	60	F	N	
Ti Kα	60	24	LiF	P	F	30	C	Y	
V Kα	80	24	LiF	P-B	F	120	F	Y	
Y Kα	80	24	LiF	P-B	S	60	F	N	Corrected for Rb Kβ
Zn Kα	80	24	LiF	P-B	S	120	F	N	
Zr Kα	80	24	LiF	P-B	S	60	F	N	Corrected for Sr Kβ

Tube = Cr (major elements); W (minor elements)

Discrimination = automatic except for Mg

Sample preparation = Fusion (major elements); compressed discs (minor elements)

Method
P = Peak
B = Background

Counter
F = Flow
S = Scintillation

Vacuum
Y = Yes
N = No

Time = counting time in seconds.

generally 1g:1g:8g while in the case of the mineral and groundmass analyses the ratio varied between 0.5g:0.5g:4g to 0.25g:0.25g:2g. After fusion in a muffle furnace at 1050°C the samples were cooled and the weight of the glass bead was made up with lithium tetraborate to maintain exactly the 1:1:8 dilution ratio. The glass beads were then crushed to -200 mesh in a tungston carbide ball mill and the powder dried at 110°C. Compressed discs (at 15 tons pressure for 45 seconds) with boric acid backing were prepared just before analysis. Care was taken to preserve a smooth, flat surface of the compressed disc, because of the shallow depth of penetration of characteristic radiation associated with the light elements (Mg, Al, Si). This preparation method produces a homogeneous sample and reduces matrix effects, so that there is a linear relation between concentration and fluorescent intensity for all major elements with $Z > 11$.

The results were calculated using a Major element Computer program available in the department.

Table A-2 shows the standards that were used during the course of the study.

<u>TABLE A-2</u>

Standards used for major element analysis

Wt %	BCR-1	GSP-1	PCC-1	DTS-1	QMC-I_1	QMC-I_2	99a	N-90	N-93
SiO_2	✓	✓	✓	✓	✓	–	✓	✓	–
TiO_2	✓	✓	✓	✓	✓	✓	–	✓	✓
Al_2O_3	✓	✓	✓	✓	✓	✓	✓	✓	–
Fe_2O_3	✓	✓	–	–	✓	✓	–	✓	✓
MgO	✓	✓	✓	✓	✓	–	–	✓	✓
CaO	✓	✓	✓	✓	✓	✓	✓	✓	✓
K_2O	✓	✓	✓	✓	✓	✓	✓	✓	–
P_2O_5	✓	✓	✓	✓	✓	✓	✓	✓	–

The recommended values of Flannagan (1969) were used for the USGS standards.

In order to estimate the precision of the XRF analytical methods, seven fusions of specimen No. R-2 were prepared. The results of this precision test are presented in Table A-3. The precision data is compared with that obtained by Rose *et al.*, (1963) using XRF methods.

Trace elements:

The following procedures were adopted in the preparation of the samples for trace element analysis:

About 4 to 5g of the sample powder (initially of -100 mesh B.S.) was ground for about 45 seconds in a tungsten carbide TEMA disc mill. Sieving test showed that the majority of the sample powder was -200 mesh B.S. after this operation. The powder was then dried at 110°C for one hour, and then compressed into discs (at 15 tons pressure for 45 sec.) using boric acid backing.

Mass absorption coefficients for the samples and the reference standards were determined following the methods of Reynolds Jr. (1963). The Peak-Background corrected counts for the samples and the standards were used in the determination of the trace elements of the samples, following the procedures of Reynolds Jr. (*op.cit.*). However, in the present case apart from W-1, other USGS standards such as AGV-1, GSP-1, G-2 and PCC-1 were also used.

Electron Probe Microanalysis:

All the mineral analyses of the bore hole samples and some of the Rajpipla samples were performed on Cambridge Instrument

Table A-3

Precision of XRF Major Element Analysis (Present work)

Wt. %	$\bar{x}$	R	s	C(%)
SiO_2	47.95	0.94	0.359	0.74
TiO_2	3.11	0.08	0.026	2.57
Al_2O_3	12.25	0.19	0.063	0.51
Fe_2O_3T	13.59	0.35	0.131	0.96
MgO	8.22	0.40	0.193	2.35
CaO	10.38	0.21	0.092	0.89
K_2O	2.13	0.03	0.010	0.47
P_2O_5	0.38	0.01	0.003	0.79

Rose *et al.*, (1963)

Wt. %	Comp. range	C(%)
SiO_2	50 - 75	0.50
TiO_2	0.1 - 2.0	2.14
Fe_2O_3T	10 - 20	1.02
MgO	0.4 - 10	2.07
CaO	1 - 12	0.97
K_2O	-	-
P_2O_5	-	-

$\bar{x}$ = Mean of 7 determinations (specimen No. R-2)

R = Range = Max. - Min. concentrations

s = Standard deviation

C(%) = Relative deviation ($100\ s/\bar{x}$).

Company's Geoscan and Microscan 5 at the Universities of Manchester and Edinburgh respectively. The methods of analyses and the correction procedures used are after Long (1969) and Sweatman and Long (1969).

A:4 Wet Chemical Analysis:-

$\underline{Na_2O}$ was determined using an EEL flame photometer following the methods of Vincent (1960). A double Na filter was used to minimise the interference of CaO.

FeO was determined by Wilson's (1955) cold solution method using PTFE crucibles.

The precision and accuracy of these two methods of analyses are shown in Table A-4.

Table A-4

	n	$\bar{\bar{x}}$	R	s	C(%)	Reference
Na_2O	7	2.72	0.15	0.046	1.69	Present work. Specimen No. R-3.
FeO	7	4.19	0.12	0.042	1.01	Appleton (1970, p.A-6).

$\underline{H_2O+}$ was determined gravimetrically following the methods of Shapiro and Brannock (1962).

$\underline{CO_2}$ was determined by the Pressometric method of Welcher (1963, p. 1191).

Cr: Because of the interference of V and Ti with Cr in the XRF method, Cr was determined using Atomic Absorption techniques, following the methods of Medlin *et al.*, (1969).

A:5. Modal Analysis:

Modal data was obtained by point counting on thin sections. Most of the thin section modal analyses were carried out by counting 600-1200 points on a Shadowmaster projection microscope. Several thin sections from the Rajpipla area were determined using the Swift point counter. The modal data is expressed as volume %.

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APPENDIX B

Modal data and petrographic notes of analysed specimens

Table B-1. Bore hole samples

Oc = Oceanite.
Ank = Ankaramite.
TPB = Three-phenocryst basalt.
B = Basalt.

Table B-2. Rajpipla samples

AB = Ankaramitic basalt.
PB = Porphyritic basalt.
PTB = Porphyritic trachy basalt.
FPB = Feldspar phyric basalt.
OB = Oligoclase basalt.
TR = Trachyte.
TESC = Teschenite.
P.RHY = Potassic rhyolite.
Th.B = Tholeiitic basalt.
Th.D = Tholeiitic dolerite.

Table B-3. Other areas

Ol = Olivine
Cpx = Clinopyroxene
Pl = Plagioclase
Ore = chromite/Titano-magnetite/Ilmenite
Ap = Apatite
Gl = Glass (normally altered to palagonite)
Af = Alkali feldspar
Bio = Mica (Phlogopitic in the basaltic rocks and biotitic in the potassic rhyolites)
\+ = Present
\- = Absent

TABLE B-1

22 22 N
071 59 E

Flow No.	Speci-men No.	Depth of specimen in feet	Rock Name	Vol. % Phenocrysts				Groundmass Mineralogy						Remarks
				Ol	Cpx	Pl	Ore	Ol	Cpx	Pl	Ore	Ap	Gl	
A. DHANDHUKA BORING														
37	2	294	B	3.3	1.7	31.3	2.7	+	+	+	+	+	+	Ol iddingsitised (Id); markedly Pl. phyric (An$_{68}$)
36	13	319	B	2.3	1.8	20.3	-	+	+	+	+	+	+	Ol altered to brown and green palag; Pl pheno An$_{69}$
35	19	340	B	4.0	4.9	25.7	-	+	+	+	+	-	-	Ol Id; Pl pheno An$_{66}$; Gl Pl An$_{61}$;
34	26	394	TPB	1.7	1.8	9.2	-	-	+	+	+	-	-	Ol altered to serpentine; Pl pheno An$_{70}$
33	27	400	B	7.7	0.5	15.5	-	+	+	+	+	-	-	Ol altered to serp; black opaque matrix with dusty Ore lacking Cpx
32	30	410	Oc	13.9	4.4	-	-	-	-	+	+	-	-	Ol abundant up to 4mm; altered to serp.
30	37	482	Oc	18.3	5.9	-	-	+	+	+	+	-	-	Ol up to 7mm; partly fresh:altered to carbonate and Ore;
29	41	523	B	-	2.7	15.1	1.7	-	+	+	+	+	+	Pl up to 6 mm; An$_{63-66}$; Gl abundant brownish isotropic charged with Ore and Ap
28	45	545	B	0.3	0.5	13.3	-	-	+	+	+	+	-	Pl pheno An$_{64}$; dirty brown gl.
27	50a	564	B	-	0.5	15.8	0.3	-	+	+	+	-	+	- do -
26	58	608	B	0.3	0.7	19.2	0.3	-	+	+	+	-	+	Ol altered; pl pheno An$_{61-65}$; dusty brown gl. some micro-vesicles with calcite or opal.
26	60	614	B	-	0.7	15.8	0.5	-	+	+	+	-	+	- do -
25	67	670	B	-	0.9	17.2	1.2	-	+	+	+	-	+	Pl pheno An$_{64}$; 2.5% vesicles with chalcedonyl palagonite
23	77	785	B	-	-	11.3	0.3	+	+	+	+	+	-	Pl up to 2 mm; An$_{62-64}$
21	84	1012	B	0.5	0.4	21.9	-	+	+	+	+	+	+	Pheno plag abundant;
20	90	1027	B	-	2.0	11.6	-	+	+	+	+	-	+	Pl up to 5 mm with ragged ends; isotropic dusty gl.
19	99	1100	B	1.2	-	22.0	3.2	-	+	+	+	-	-	Ol altered to dellesite; pl abundant slightly altered
18	108	1215	TPB	1.1	0.5	5.3	-	+	+	+	+	-	-	Contains 1.3% biotite and scarce hornblende
17	219	1245½	B	0.6	-	6.7	-	-	+	+	+	-	-	Ol altered; Gm altered, abundant vesicles filled with laumontite and dellesite.
16	222	1255	TPB	2.5	6.4	-	-	+	+	+	+	-	-	Lacks Pl pheno; Ol altered; transitional towards ankaramites
15	227	1274	Oc	10.3	5.3	-	2.3	+	+	+	+	-	-	Ol entirely altered
12	244	1345	Ank	3.3	21.8	-	-	+	+	+	+	-	-	Scarce wisps of biotite; Ol partly fresh Fo$_{87}$; glomero Cpx
11	252	1411	Oc	23.2	6.3	-	1.5	+	+	+	+	-	-	Wisps of biotite; Ol up to 6 mm;
10	259	1450	Oc	2.8	1.5	-	1.0	+	+	+	+	-	-	Nearly aphyric; scarce biotite; one rare Pl pheno.

Table B-1 (contd.)

Flow No.	Specimen No.	Depth of specimen in feet	Rock Name	Vol. % Phenocrysts				Groundmass Mineralogy						Remarks
				Ol	Cpx	Pl	Ore	Ol	Cpx	Pl	Ore	Ap	Gl	
9	266	1482½	Ank	1.9	6.9	-	-	+	+	+	+	-	-	Ol partly fresh
8	274	1503	Ank	2.6	6.6	-	-	+	+	+	+	-	-	Vesicular containing calcite, laumontite and palagonite
7	279	1523	Ank	5.3	21.0	-	-	+	+	+	+	-	-	Cpx pheno up to 1 cm; Ol entirely altered to Ore and Id
6	285	1557	Ank	15.5	10.1	-	-	+	+	+	+	-	-	Scarce biotite wisps; Cpx up to 7 mm; Fo_{89}
5	293	1582	Ank	5.4	6.5	-	-	+	+	+	+	-	-	Ol partly fresh (Fo_{87-86}); Gm lacks Pl
4	299	1612	TPB	0.6	5.3	1.6	-	+	+	+	+	-	+	Pl pheno An_{80}; scarce phlogopite
3	312	1660	TPB	1.2	1.6	-	-	+	+	+	+	+	-	Occasional crystals of hornblende in micro vesic; nearly aphyric
1	321	1675	TPB	2.6	12.4	1.0	-	+	+	+	+	+	-	Ol entirely altered; Cpx up to 7 mm; zoned (Ca_{44-41} Mg_{44-43} Fe_{12-16}
B. WADHWAN JUNCTION BORING 2209 N 7329 E														
5	391	222	OC	21.3	9.3	-	1.3	+	+	+	+	+	+	Glass divitrified; Pl scarce in the groundmass
3	387	268	TPB	9.8	2.8	12.8	2.0	+	+	+	+	-	+	Pl up to 3mm long (An_{86-89}); Ol comp alt
2	381	321	Oc	25.7	11.0	-	2.0	+	+	+	+	-	+	Ol up to 4 m.; Cpx pheno grades into Gm; Pl in gm. vein like; some Gl. divitrified
1	380	345½	OC	29.1	7.4	-	-	+	+	+	+	-	-	Gm; Pl scarce; Ol up to 5mm (Fo_{86})
C. BOTAD BORING 2210 N 7140 E														
6	111	25	OC	7.0	4.1	-	1.4	+	+	+	+	-	+	Groundmass Pl. An_{74}. Pheno Cpx has a thin dark rim, matching the Gm Cpx; Ol fresh (Fo_{88})
5	116	111	OC	28.3	6.3	-	0.5	+	+	+	+	-	-	Ol partly altered to serpent
4	119	146	OC	24.3	2.7	-	0.7	+	+	+	+	-	-	Ol fresh; Cpx pheno grade in size to gm scale
1	129	339	OC	21.7	4.5	-	1.0	+	+	+	+	-	+	Ol fresh up to 4 mm; some up to 9 mm; In gm Cpx Pl

RAJPIPLA
21 52 N
73 30 E

Table B-2

Specimen No.	Rock Type	Mode of Occ.	Vol. % Phenocrysts Oliv.	Cpx	Plag.	Ore	Groundmass mineralogy Oliv.	Cpx.	Plag.	Ore		Remarks
A. Alkalic rocks												
R-9	AB	Flow	3.1	20.5	-	0.6	+	+	+	+		Zoned Cpx: glomero groupings
R-2	AB	Dyke	2.2	27.8	4.6	3.0	+	+	+	+		Pl. micropheno. (An_{65}): iddingsitised Ol; wisps of mic
R-10	AB	Flow	1.9	19.4	-	0.5	+	+	+	+		Cpx. glomero groupings
R-19	AB	Flow	3.2	21.0	2.6	3.7	+	+	+	+		Mauve col. augite zoned: Ol iddingsitised; some isotropic patches in gm
R-26	AB	Flow	1.1	25.5	-	1.1	+	+	+	+		Cpx in stellate groupings: micro vesic. with green palagonite; rather altered gm.
R-5	PB	Flow	5.0	10.2	5.7	2.1	+	+	+	+		Pl pheno An_{60}; Ol alt. to Hm.
R-8	PB	Flow	3.3	9.8	8.0	3.6	+	+	+	+		Zoned Cpx; An_{53}
R-11	PB	Flow	0.3	8.8	5.7	1.7	+	+	+	+		Pl in groups (An_{55-60}); Cpx in glomero groups zoned; microvesicles with palag; rare mica
R-12	PB	Flow	3.5	13.5	7.6	3.1	+	+	+	+		Palagonite patches in gm; Ol altered to Ore; yellow green mass.
R-13	PB	Flow	2.1	17.5	2.5	1.9	-	+	+	+		Gm showing fluidal pattern; very fine grained
R-14	PB	Flow	3.8	18.8	5.0	5.2	+	+	+	+		1.3% mica as micro. pheno;
R-20	PB	Flow	2.0	6.6	0.3	1.0	-	+	+	+		Ol. iddingsitised: Ol+Cpx+Ore groupings; Ore skeletal
R-24	PB	Flow	1.4	5.7	7.4	1.2	+	+	+	+		Pl (An_{60-55})
R-27	PB	Flow	1.5	12.8	9.3	0.8	-	+	+	+		Pl pheno An_{55-50}; Zoned Cpx; dirty brown gm.
R-28	PB	Flow	2.3	6.3	13.7	0.7	-	+	+	+		Gm. microcrystalline: pl. rich (An_{55}); Ol→Ore
R-18	PB	Flow	2.7	7.5	1.1	6.3	-	+	+	+		Ol altered to Ore; An_{55}; Ore plates up to 3 mm.
R-3	PTB	Flow	0.7	9.2	2.7	5.5	-	+	+	+		Pl slightly altered (An_{60}) grouped
R-6	PTB	Flow	9.6	7.5	7.4	1.5	+	+	+	+		Microvesicles with palagonite
R-7	PTB	Flow	1.5	-	8.7	1.0	-	+	+	+		Pl. pheno An_{53}.
R-15	PTB	Flow	4.3	8.9	12.1	2.7	-	+	+	+		Pl. pheno. An_{55-60}; phlogopite (Table 8-5)
R-16	PTB	Flow	2.7	5.5	16.0	4.4	-	+	+	+		Scarce mica.
R-17	PTB	Flow	4.3	2.7	12.2	3.2	+	+	+	+		Pl. pheno An_{50-55}; tend to be grouped resorbed: natrolite in mic. vesi.
R-21	PTB	Flow	-	15.1	1.9	4.4	-	+	+	+		Glomero grouping of Cpx prominent
R-22	PTB	Flow	1.7	3.3	2.7	1.3	+	+	+	+		Gm. fine grained and altered; 3.6% micro. vesi.
R-23	PTB	Flow	0.3	7.8	1.4	3.5	-	+	+	+		Glomero. Cpx (2 mm x 1.6 mm) with
R-25	PTB	Flow	1.5	5.8	3.8	1.3	+	+	+	+		Micro-vesicles with palagonite
R-29	PTB	Flow	3.3	8.1	14.5	1.7	+	+	+	+		Ol altered; green-yellow patches in gm.
R-30	PTB	Flow	1.8	11.7	11.6	4.9	+	+	+	+		Pl slightly altered
R-32	FPB	Dyke	0.5	0.3	20.6	0.5	-	+	+	+		Wisps of mica in gm Pl. pheno An_{60-50}
R-33	FPB	Dyke	0.3	0.5	19.2	0.3	-	+	+	+		
R-31	FPB	Dyke	0.2	0.8	25.2	1.9	-	+	+	+		Wisps of mica in gm.
R-34	OB	Flow	-	3.6	2.5	2.8	-	+	+	+		Pl. as micro-pheno. scarce mica & alkali felspar
R-35	OB	Dyke	0.6	5.3	0.5	5.2	-	+	+	+		- do -
R-36	OB	Dyke	-	2.1	0.4	0.7	-	+	+	+		- do -
R-37	TR	Dyke	-	4.0	5.5	4.0	-	-	+	+		Pl. pheno Ab_{97}; 5.8% pheno of Kaersutite; Gm apatite
R-1	TESC	Dyke	0.6	23.8	-	6.5	-	+	+	+		11% of Gm analcite.
			Af	Pl	Biot.	Ore	Af	Biot.	Ore	Qz		
R-38	P.RHY	Tounge	13.2	0.4	1.5	3.5	+	+	+	+		Anhedral grains of Qz in gm.
R-45	"	"	8.0	-	2.0	0.5	+	-	+	+		- do - rare garnets; resorbed biotite
R-40	"	Plug	10.6	0.5	1.3	0.5	+	+	+	+		Portions of Af altered to calcite;
R-41	"	"	11.2	-	1.2	1.5	+	+	+	+		Spongy Ore
R-42	"	"	13.0	-	-	2.6	+	-	+	+		Anhedral grains of Qz in vug like cavities
R-43	"	"	12.5	0.5	1.3	0.5	+	+	+	+		Qz in veins and vermicular
R-44	"	"	13.1	0.2	0.9	2.4	+	-	+	+		About 78% Gm show graphic inter-growth
			Ol	Cpx	Pl	Ore	Ol	Cpx	Pl	Ore	Gl	
B. Tholeiitic Rocks												
1-T	Th.B	Flow	2.0	-	-	-	-	+	+	+	+	Ol iddingsitised: Gl altered
2-T	Th.B	Flow	-	-	-	-	-	+	+	+	+	Pl pheno (An_{65}) slightly altered
4-T	Th.D	Dyke										Fine grained margin of the dyke.
5-T	Th.D	Dyke										Coarse dolerite with ophitic to sub-ophitic textur

Table B-3

Other Areas

unknown

21 03 N
71 17 E

unknown

Specimen No./Name	Mode of Occ.	Rock type	Phenocrystal Mineralogy in Vol. %				Remarks
			Ol	Cpx	M	Ore	
1. PAWAGARH							
P.B-52	Flow	Oceanite	19.4	-	-	-	Fresh gm: crypto crystalline. Ol marginally altered to red brown iddingsite.
P.B-39	Flow	Oceanite	13.5	11.9	-	-	Gm nearly glassy, to crypto xalline.
P.B-36	Flow	Oceanite	15.6	9.4	-	-	Scarce micro.pheno.pl.
P.B-18	Flow	Basalt	3.0	17.0	20.3	-	Rather coarse, gabbroic; interstial gl. altered to yellow green palag.
P.A-17	Flow	Basalt	1.0	1.0	43.	-	Fresh gm with Pl. Cpx & Ore.
2. DEDAN							
A-64	Dyke	Picrite	13.2	-	2.0	-	Micro-crystalline: Ol altered along cracks gm with Cpx + Pl + Ore + Ol
TK-A-31	Dyke	Ankaramite	2.1	33.7	-	1.0	5 x 6 mm^2 glomero grouping of Cpx with scarce pl. gm finegrained.
A-78-TK	Dyke	Picrite	18.6	-	-	-	Cpx: Pl forming triangular network in gm; green palag. patches
3. AMBADONGAR-PANVAD-KAWANT							
355	Flow	Oceanite	10.2	4.1	-	1.8	Ol up to 3 x 2 mm^2; partly altered grades into gm xals; crypto. xalline gm, with micro. vesi.
ANK-KAV	Dyke	Ankaramite	14.1	32.4	-	-	Cpx clusters up to 4 mm^2; gm coarsely xalline with altered glo.
320	Dyke	Basalt	0.8	-	12.9	-	Big pl. xals (up to 2 cm long); micro vesi, with palagonite.
193	Dyke	Alkali Trachyte	-	6.7	-	2.2	Kaersutite pheno also present; Cpx is aegirine-augite (aeg-aug) to aegirine zoned; sphene present
Pl.Kar	Dyke	Lamprophyre	-	10.5	-	-	5.8% phlogopite; kersanitic; Cpx titan-augite; in gm some isotropic patches (?) analcite.
47	Dyke	Phonolitic rocks	-	1.8	-	-	17% nepheline altered to zeolites; minor sphene; 2.5% alkali felspar altered mainly to calcite; Cpx is aegirine-augite; 2% melanite garnet; altered gm
A.D.-11	Dyke	" "	-	4.3	-	-	14% nepheline and 4% alkalifelspar; 6% melanite garnet, otherwise similar to 47
A.D.-10	Dyke	" "	-	4.0	-	-	2% melanite garnet; Cpx is aegirine-augite; gm opaque looking to dirty brown.