1.1 Flood basalts in relation to the Upper Mantle

Lakagigar eruption that took place in Iceland in 1783 is regarded as being similar to the Flood eruptions that in the past, have covered vast areas of the continents (Thorarinsson, 1969). These Flood basalts (Plateau Basalts) are believed to have erupted through fissures without explosive violence. "Their great number, regular alignment over large areas, individual continuity over distances of many miles and generally undisturbed condition, convey a vivid picture of basic magma welling up from the depths in a continuous flood along tension fractures, some of which must have extended deep into the crust to tap so copious a supply of basic magma" (Turner and Verhoogen, 1962, p.203).

Kuno (1969) listed the dimensions and ages of different Cenozoic plateau basalts (Table 1.1).

The characteristic vast plateaus which are the common topographic features of these flood basalts are, however, not noticeable among flood basalts belonging to older ages (Karroo basaltic province of southern Africa, Triassic dolerites of New Jersey, Triassic/Jurassic lavas of Parana
TABLE 1.1

DIMENSIONS AND AGES OF GENOZOIC PLATEAU BASALTS

<table>
<thead>
<tr>
<th>Name and location</th>
<th>Area km²</th>
<th>Thickness (km.)</th>
<th>Volume km³</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plateau around Baekdoosan (Hakuto-san) volcano, Manchuria-Korea border</td>
<td>22,000</td>
<td>0.5 (average)</td>
<td>11,000</td>
<td>Miocene (?) to Recent</td>
</tr>
<tr>
<td>Plateau south of Tungning, eastern Manchuria-Soviet border</td>
<td>5,340</td>
<td>0.015-0.150</td>
<td>415</td>
<td>Miocene or Pliocene</td>
</tr>
<tr>
<td>Columbia river plateau, N.W. United States</td>
<td>220,000</td>
<td>1</td>
<td>195,000</td>
<td>21.3-12.1 m.y. B.P.</td>
</tr>
<tr>
<td>Deccan Plateau, India</td>
<td>518,000</td>
<td>1.0</td>
<td>518,000</td>
<td>Late Cretaceous to early Eocene; duration 15 m.y. (?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>777,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
<td>1,036,000</td>
<td></td>
</tr>
</tbody>
</table>

basin in Southern Brazil, early Triassic lavas of Siberia. This may be due to deep burial in younger sediments or extensive erosion. Based on the petrographic and chemical characteristics of plateau basalts, Kennedy (1933) distinguished two types: tholeiitic and alkali basalts (referred to as 'alkali olivine basalt' by Tilley, 1950). The differences in mineralogy, petrology and chemistry of these two types have been discussed by various workers (Turner and Verhoogen, 1962;
Kuno, 1960; Brown, 1967; Wilkinson, 1967; Manson, 1967; Prinz, 1967). A third variety called high-alumina basalt has also been distinguished (Kuno, 1960), which is present as a group intermediate between the two, among the basaltic rocks of circum-pacific volcanic belt. "However, high-alumina basalt is not entirely absent among plateau basalts" (Kuno, 1969, p. 497).

The problem of the origin of different types of basalts has been much debated, and many hypotheses have been propounded as to their origin (Kennedy, 1933; Tilley, 1950; Turner and Verhoogen, 1962; Yoder and Tilley, 1962; O'Hara, 1965; Green and Ringwood, 1967; Kuno, 1968; Gast, 1968b).

Temperature vs. depth curves in the crust and the upper mantle (Clarke and Ringwood, 1964) point out that the temperature necessary for the production of basaltic magma is reached below the Mohorovicic discontinuity. Seismic evidence of the movement of basaltic magma (Eaton and Murata, 1960) indicate the depth of its origin to be 50 - 60 kms. Lovering (1968) and Kennedy (1959) consider that the Mohorovicic discontinuity (in seismic velocity and in density) reflects the change of basaltic rock (from the crustal gabbroic material assemblage) to a mantle eclogite material assemblage.

Based on geological, geophysical, chemical and isotopic studies and from experimental evidence, two types
of probable mantle compositions have been suggested.

1. Eclogite mantle (Fermer, 1913; Holmes, 1927; Lovering, 1958; Kennedy, 1959; Gangadharam and Aswathanarayana, 1971).

Green (1968) while reviewing the arguments about the probable mantle material for the origin of basaltic magmas, propounded the existence of a peridotite mantle. "Basaltic magmas must derive from this (peridotite) either by partial melting of peridotite, yielding a basalt liquid and residual refractory dunite and peridotite, or by complete melting of possible eclogite lenses and patches. The occurrence of such eclogite lenses within peridotite presumably result from fractional melting of the peridotite so that both processes require the fractional melting of the peridotite to produce basaltic magmas".

"Considering the degree of crystallization of primary magmas necessary to produce the plateau basalt magmas and also the proportion of the primary magmas to be produced by partial melting of mantle peridotite, the volume of mantle material involved in the formation of plateau basalts can be estimated. For the Columbia river basalt it would be
equivalent to a plateau about 80 km thick underlying the
area covered by basalt. This thickness is a small fraction
of the mantle" (Kuno, 1969).

1.2 Distribution of Deccan Traps

The Deccan Trap lava flows constitute one of the
largest continental flood eruptions. They occupy an area of
5 x 10^5 sq. kms. in the western and central India (Fig.1).
Apart from this main outcrop, they are found as far as Belgaum
in the south, Rajahmundry in the south-east, Siriguja, Jashpur
and Amarkantak in the east and Kutch in the north west. It
is reasonable to believe that the traps may have occupied
the gaps between the main outcrops and the outlying patches
including that of Sind. Thus the total volume of basaltic
lava poured out initially must have been enormous.

1.3 Geologic setting and general description

The traps have been divided into three groups, Upper
Middle and Lower, with infra-trappean beds or Lameta beds at
their base (Infra-trappean: Danian; Lameta-Turonian; Bagh
beds-Cenomanian). Wadia (1967) has given an excellent account
of the stratigraphy of the Deccan traps (vide Table 1.3 below):

<table>
<thead>
<tr>
<th>TABLE 1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Eocene</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>
Distribution of Deccan basalts in India showing location of Sagar the main area of study.
**Upper Traps:** of Bombay and Kathiawar; 500 metres thick, flows interbedded with numerous ash beds.

**Middle Traps:** of Malwa and Madhya Bharat; lavas and ash beds amounting to 1,250 metres in the thickest part of the series; no fossiliferous intertrappean beds.

**Lower Traps:** of Madhya Pradesh, Narbada, Berar and eastern India; 150 metres thick with fossiliferous intertrappeans but rare ash beds.

--- Slight Unconformity ---

Genomanian Lametas, Bagh beds, Jabalpur beds and older rocks.

The basalt pile is considerably thicker in the west. Around Bombay, it is more than 1,830 metres, the average thickness of an individual flow being 50 metres. Away from the western edge, the thickness diminishes in every direction. Over a greater part of the area, the Traps show an amazing monotony in their petrography, with a succession of tholeiitic basalts characterised by a remarkable horizontality and a great lateral extent. However in the western part, a considerable variety of rock types and structures are noticeable. This is particularly true of the faulted west coast and
Narbada-Son and Cambay grabens. Here pyroclastic and ash beds and also massive intrusions of gabbro and granophyre are locally abundant. Within this division one also finds carbonatites and differentiated rocks of acid and undersaturated compositions. The basalts of the Upper traps dip westward near Bombay; in contrast the flows of Lower traps are mostly horizontal. According to Bose (1972), "The diversification of the magma to the west is associated with the thickening of the lava pile and increase of the heat flow. The ultrabasic flows (picrite basalts) are products of fractionation of source magma of olivine tholeiite composition. The minor acid variants (e.g. rhyolites, pitchstones, felsites etc.) are possibly residual liquids of the ascending magma".

Gravity studies in the Deccan trap region by Kailasam et al. (1972) indicate the existence of two major lineaments, one along the west coast and another along the 21st parallel (Narmada-Son lineament). "The gravity anomalies are everywhere negative, as is normally to be expected over a continental crust, except in strips in the west coast surrounding Bombay and Surat" (Kailasam et al., 1972). On the basis of gravity studies, Krishna Brahman and Negi (1973) postulated the existence of Koyna and Kurduvadi rifts in the Deccan Traps of Maharashtra.
1.4 Time and mode of eruption and possible relation to 
Mid-Indian Oceanic ridge

It is widely believed that Deccan traps have poured 
out from fissure eruptions. But, there are remarkably few 
genuine examples where dyke and lava flows are visibly 
joined. Features brought to light by the detailed field 
work of Agashe and Gupte (1970) in western Maharashtra 
demand more careful consideration. The many supposed feeders 
of the flows may turn out to be hypabyssal intrusions. Until 
central type of volcanoes and explosion products are found 
in abundance in the bulk of Deccan province, the obvious 
explanation seems to be that the welling out of the enormous 
lava flows came from a great number of fissures which 
probably, came into being when the crust was in a state of 
tension during the break-up of Gondwanaland. In the case of 
Sagar, the nearest dyke (feeder) is at least 100 km. away, 
which would mean that the flows now seen must have flowed 
a long distance from where they originated.

Regarding the age of Deccan traps, Oldham (1833) 
concluded, on geological grounds, that "the traps commenced 
to be poured out in the uppermost Cretaceous, continued 
throughout the gap of time marked in Europe by the unconformity 
between the Mesozoic and the Tertiary and in North America, 
by the Laramide Orogeny, and extended perhaps well into 
the Eocene".
Reported K-Ar ages of the Deccan Traps range from 65-37 m.y. The K-Ar and palaeomagnetic work has led some to believe that Deccan traps might have been extruded during Cretaceous-Eocene transition (Wellman, 1968), between 60 and 65 m.y. ago (Wellman and McElhinny, 1970; Kaneoka and Haramura, 1973; Molnar and Francheteau, 1975). While this may be true for the western margin (the dated sample are from this region), it does not seem probable that the extrusion of the entire Deccan Traps took place in just 5 m.y.

Volcanic eruptions may appear to have occurred at random but a detailed examination of the stratigraphic distribution of the volcanic rocks shows that there is a pattern in their distribution in space and time. Today in igneous petrology, the concept of sea floor spreading and plate tectonics has greatly illuminated the understanding of the larger volcanic episodes that occurred on earth. Continental tholeiitic provinces comprising tholeiitic flood basalts and intrusive equivalents are closely related to the rifting of the continental plates preliminary to accelerated drift. Deccan traps are no exception to this general model.

The Traps have been fairly extensively sampled for palaeomagnetic studies. Studies on the remanent magnetism
of the flows and their ages are largely consistent with interpretations drawn from the recent researches on the origin and nature of mid-Indian Oceanic ridge (McKenzie and Sclater, 1971; Vinogradov, et al, 1969). From these studies a genetic relationship between the northward drift of the Indian plate, the Himalayan upheaval, Deccan volcanism and the evolution of Indian ocean and mid-oceanic ridge is evident. Vinogradov et al (1969) believe that the mid-oceanic rift zone of the Indian and Atlantic oceans originated in a continental type crust. There are good reasons to accept such an idea when one considers that:

(i) the Seychelles have a continental crust,
(ii) to the south of de Malha bank are volcanic features (Shor and Pollard, 1963),
(iii) the oldest ages for the Deccan traps and the Seychelles bank are similar, i.e. Palaeocene (Davies, 1968),
(iv) the coast of north-west India and Pakistan are approximately parallel to the Carlsberg ridge and to the Seychelles shelf and
(v) shelf edges of India and the Seychelles bank are parallel in a Mercator projection based on the proposed pole of rotation (Le Pimhon, 1968).
According to Davies (1968) the rupture of the Seychelles and India occurred at the latitude 30°S in the early Palaeocene, and this model is consistent with the coming into existence of the Carlsberg ridge, the initiation of Deccan volcanism and the development of the Indian ocean magnetic anomaly pattern.

1.5 Geologic setting of the Sagar flows investigated

1.5.1 Sagar:

The Deccan traps in the neighbourhood of Sagar (23°56' N : 78°38' E) immediately overlie the denuded surface of Vindhyan sediments. At a few places (like the site of Bore hole 3), Vindhyans are overlain by sedimentary beds of upper Cretaceous age (Lameta beds) which are predominantly, friable sandstones and limestones. The Deccan lavas blanket these older units and gave rise to the major topographical features of the area, namely, flat-topped hills and step-like terraces (Figs. 2 & 3). This topography is the result of the variation in the hardness of different flows and of parts of the same flow. The flows are uniformly horizontal (although dips up to 2° are not uncommon) and often are separated by a sedimentary horizon such as cherty limestone or clay bed. Two such prominent sedimentary breaks are present in the bore hole sections; one above the 4th flow and the next above the 5th flow. Laterite and alluvium
FIG. 2 A part of geological section, 5 km S.W. of Sagar showing relationship of higher flows (4-6-9) to the older rock.

FIG. 3 A part of geological section showing relationship of the lower flows (1, 2 and 3) to the older rocks near the site for bore-hole BH-3

Approximate Scale for both the sections 1 cm = 150 metres (Vertical) and 1 cm = 1 km (horizontal)
A part of the Geological Map around Sagar; the width of the Intertrappean limestone outcrops is exaggerated.
constitute the upper-most and youngest unit of the area under study. Table 1.5.1 gives the geological formations in the order of superposition.

**TABLE - 1.5.1**

<table>
<thead>
<tr>
<th>Pleistocene and Recent</th>
<th>Upper Cretaceous</th>
<th>Precambrian</th>
</tr>
</thead>
<tbody>
<tr>
<td>- - - - - unconformity</td>
<td>Deccan trap lava flows with intertrappean beds of limestone and clay.</td>
<td>Vindhyan sandstone-quartzite.</td>
</tr>
</tbody>
</table>

1.5.2 **Vindhyan sandstone-quartzite**:

The Vindhyan formation exposed around Sagar belongs to the upper Rewa Sandstone group which is exclusively arenaceous, consisting of unfossiliferous medium-grained sandstones. The grains are almost rounded and invariably cemented by ferruginous material. The more compact and hard variety is usually called quartzite, although the effects of metamorphism are absent. The Vindhyan sandstones are generally undisturbed and almost horizontal, with local dips up to 2°- 5° being not uncommon. Presence of abundant ripple marks and current bedding suggest their deposition in shallow agitated waters.
In two of the boreholes (BH 1 and BH 2) at the contact of sandstone-quartzite and basal flows, an indurated layer is found. This is clearly due to the effect of hot lava flowing over the country rocks. Due to the refractory nature of the sandstone-quartzite and possibly, rapid flow of the lavas, this zone is not very thick. In the case of borehole 1, the layer attains a thickness of a few centimetres only.

1.5.3 Lameta beds (roughly Turonian according to Von Huenae and Matly, 1933):

The Lameta beds, also known as Infratrappean, are the fluviatile or esturine beds occurring below the Traps. In the present study, they are found only in borehole 3, underlying flow 1. These are mainly impure limestones with subordinate sandstones and clays. Limestones are arenaceous but at a few places, the pure variety is also found. Their thickness varies from place to place depending upon the original Vindhyan topography. At the site of borehole 3, they attained a thickness of 21 metres, when the boring was stopped. Rarely they contain good determinable fossils, although Molusca, Fishes and dinosaurian reptiles have been found in the type area of Lametas from Jabalpur (Krishnan, 1968).
1.5.4 Intertrappean sediments:

These sedimentary beds sandwiched between the lava flows, indicate that a considerable time elapsed between successive eruptions. A number of these beds are fossiliferous indicating that the time gap was large enough for the development of an environment capable of supporting plant (mostly palms) and animal life. The fauna is unmistakably estuarine. Physa principii is one of the most characteristic species in the lower intertrappaeans at Sagar. Plant fossils at Sagar and other parts of Central India have distinct Eocene affinities.

In the three borehole sections there are two prominent intertrappean horizons overlying the 4th and 5th flows. The lower horizon consists of a chocolate-coloured clay bed with a thickness of 7 metres. This horizon seems to be fairly uniform in its horizontal extent. The higher sedimentary horizon consists of a cherty limestone with intermixed clay.

Although in the borehole sections only two sedimentary horizons could be recognised, elsewhere in the field there are intertrappean beds between nearly every pair of flows (Fig. 4). The thickness of these varies from a few centimetres to a few metres and there is always a great variation in their lateral extent and lithology. One of
Lava flows and the intertrappean sediments, a generalised section. This is based upon geological studies over a wide area around Sagar and may not be true for every location. The thickness of intertrappean sediments (blue bands) is exaggerated.
the common minerals in the limestones is aragonite, which often occurs as thin layers or nodules. Figure 4 gives a diagramatic representation of number of intertrappean beds occurring around Sagar. The sequence is generalised on the basis of observations in different localities, and it shows that the time gap between successive flows was variable.

1.5.5 Laterite and Alluvium:

Not all the flows have a laterite cover. However, the tops of 7th and to a lesser extent the 5th, 6th and 8th flows, have disconnected lateritic covers. A uniform thick cover is not usual; huge rounded boulders are more common. In composition these are invariably ferruginous, red to brown in colour and often pisolitic. It is interesting to note that only 100 km. east of Sagar there are extensive economic Bauxite deposits derived from Deccan traps but for some unknown reason, aluminous Laterites are completely missing from around Sagar.

Alluvial cover in the area is extensive, ranging up to 10 metres in thickness but usually of limited extent. The hill tops and plateaus are normally covered with lateritic soils. As a result of weathering, the traps at lower elevations have given rise to 'Regur' or black cotton soil rich in plant nutrients such as lime, magnesia, iron and alkalis.
1.6 Previous works

In the section of "Plateau Basalts" of the XXII International Geological Congress, New Delhi, 1964, and in the Proceedings of the International Symposium on "Deccan Traps and other flood eruptions", Sagar, 1969, several papers of geochemical interest have been presented. The earlier geochemical work was restricted to major element analysis. Later some trace element studies (based on emission spectrographic or x-ray fluorescence methods) have been reported. Only recently, limited REE and Sr isotopic studies on the Deccan Traps have been performed (part of it under collaboration between the Geological Survey of India and the Geological Survey of Japan).

The important contributions to the geochemistry of the Deccan Traps are as follows:

1.6.1 Petrography and Chemistry of the Flows:

The first systematic study of Deccan traps was made by Washington (1922) who studied the twenty-two specimens of Deccan Traps, sent to him. He drew attention to the uniformity of their chemical characters and described them as tholeiitic basalts.

The chemistry of Deccan basalts from different locations has been studied subsequently (Krishnan, 1926;
Fermor, 1934; Kalapesi and Dalal, 1942). Vemban (1947) for the first time made an attempt to group together all the then available chemical analyses of the Deccan traps. Based on the interpretation of the analyses of fifty-five samples, he concluded that the original magma was picritic in composition and both the lines of differentiation i.e. calc-alkaline and alkaline, are discernible. On the basis of the high quality analysis of 73 samples for the basalts of Bombay region, Sukheswala and Poldervaart (1958) concluded that lavas of intermediate compositions are rare in Deccan province and that iron enrichment is generally more pronounced than alkali enrichment.

Subsequently several analyses of Deccan basalts were published, notable among which are eight chemical analyses of normal and picritic basalts from Saurashtra (West, 1968), seven chemical analyses from Pavagarh hill (Chatterjee, 1964) and eleven from Girnar Complex (Subbarao, 1964). West (1968) on the basis of his study on the petrography and petrogenesis of forty-eight flows from Saurashtra proposed a parent tholeiitic magma from which the early-formed olivines and pyroxenes got separated and formed cumulates, and the whole mass then froze. Lavas of different compositions would then be available on subsequent remelting.
Ghose (1971) studied the chemical characteristics of basaltic rocks of different ages in India and pointed out that rocks of Pavagarh, Girnar, Rajmahal, Mundwara, Guddapah and Panjal traps constitute more or less independent magmatic series of the mixed type, and are different from Deccan basalts.

Prasad (1971) found that the tholeiitic flows of Linga, Chindwara District, M.P. have slightly more FeO, MgO and Al₂O₃ than most tholeiitic basalts.

An examination of the petrochemistry of the Deccan traps around Tandur by Rao et al (1971) demonstrated that the Tandur basalt tend to be poorer in silica and richer in iron, magnesium, phosphorous and titanium relative to the normal basalts. The authors also suggested that the high Fe₂O₃/FeO (1.07) could be either due to extrusion under oxidising conditions or due to excess of water in the magma.

Viswanathan et al (1971) from their study on the tholeiitic basalt sequences around Malape, Mumba and Kalyan in western India showed that the lavas exhibit lateral inhomogeneities, limited differentiation, hyper-ferric iron enrichment, similarity to Hawaiian trend and an alkalic and high-alumina basalt nature.
Deccan basalts of Mahabaleshwar have been investigated by Konda (1971) who showed that the basalts in all the twenty-two flows analysed are silica-saturated tholeiites. There are minor gradual variations with the order of eruption, which has been ascribed to magmatic differentiation somewhat similar to that found in the case of the Skaergaard intrusion.

Mishra (1972) studied the basalts from the area between Chalisgaon and Igatpuri. From petrographic and geochemical study he concluded that the parent magma was tholeiitic.

The studies cited above clearly indicate that the Deccan traps are not chemically uniform and it is not correct to group the entire Deccan traps under the tholeiites. Obviously, there are areas that form sub-provinces in the main Deccan basalt province.

1.6.2 Geochemistry-Major oxides and Trace element studies

Sinha and Karkare (1964) furnished the first systematic account of the behaviour of major and trace elements in the lower, middle and upper Traps. Their study reveals that in spite of the similarity in the mineral composition, there are diagnostic chemical variations both laterally and vertically. They concluded that the trap horizons show progressive decrease in water and alkalis and progressive increase in lime and magnesia, from the lower to the upper trap horizons.
Major and trace element geochemistry of the rocks of Pavagarh has been reported by Sinha and Tiwari (1964). They delineated the sequence of separation of trace elements from the crystallising magma and concluded that Pavagarh rocks provide a good example of the co-existence of both olivine basalt and tholeiitic magma types.

Variation of both major and trace elements in the igneous complex of Mount Girnar has been investigated by Bose (1973). He showed that the alkalinity in the suite increases with fractionation of magma and concluded that history of fractional crystallisation has been influenced by growing water content of the magma followed by depletion of water in the final residual liquid.

Krishnamurthy (1974) provided major and trace element data for 101 rocks besides 125 partial or complete mineral analyses, in respect of the basaltic and associated rocks from several localities in western India. He demonstrated that basalts from western India show considerable variety in their chemistry. He could show that the E-W trending Narmada lineament has rocks of extreme diversity along with normal basalts. (Rajpipla in the western part being mildly alkaline, in contrast to the Ambadongar in the eastern part which is strongly potassic and sodic in composition). Alkaline rocks are also present in the Cutch region but are scarce in Bombay region.
1.6.3 REE and Strontium isotopic studies:

Studies in the abundance of rubidium and strontium and the magnitude of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the oceanic and continental basalts have been found to provide useful information on the petrogenesis of the latter. For example, such studies have been used to investigate the possible similarity of the Mesozoic tholeiites of Tasmania, Antarctica, South America and South Africa (Compston et al, 1968). Such data are very few for the Deccan basalts. Faure and Hurley (1963) reported the first ever strontium isotopic ratio for the Deccan basalts of Bombay region (average of $0.7039 \pm 0.0002$) and remarked that (as in the case of continental basalts from other regions) this ratio appear to be slightly higher than that of the oceanic basalts.

Kurasawa (1972, personal communication to Aswathanarayana) analysed several Deccan basalts for their strontium isotopic ratios. He is of the view that the Deccan tholeiites in general are comparable to the oceanic ridge and Izu-Oshima basalts of Japan in $K_2O/(K_2O + Na_2O)$ ratios but contain higher strontium isotopic ratios in the range of oceanic island basalts.

A few REE data are available for Deccan basalts. The first ever reported REE abundance of Deccan basalts is from Western India (Frey et al, 1968). REE abundances of ten
basalts of Mahabaleswar, have been studied by Nakamura and Masuda (1971) and exhibit good linearity, and the chondrite-normalised REE pattern is quite different from that of the REE pattern for abyssal tholeiites, in spite of the similarity between the two in terms of major element composition.

Recently, Mirali (1974) has furnished comprehensive geochemical data on the Girnar igneous complex covering not only major and important trace elements but also strontium isotopic ratios and REE abundances. He points out that the basalts of Girnar are different from continental basalts and resemble the oceanic island basalts. The concentration of K, Rb, Cs, REE, Th, U and Pb and Rb/Sr ratios, when interpreted in the light of the recent contributions from seismic and magnetic anomaly studies, have led him to believe that Mount Girnar may be a continental analogue of Iceland and may be related to the Mid-Indian oceanic ridge in the same manner as the Reykjanes ridge is related to Iceland today.

Paul et al. (to be published) in their geochemical study of the Girnar complex suggested a continuous evolution in the complex. The K/Rb and Th/K ratios are shown to have crustal values. Rare-earth elements increase in abundance from gabbro to syenite and become increasingly fractionated. The initial $^{87}$Sr/$^{86}$Sr ratios of the rocks are shown to have a bimodal distribution. Variation in isotopic ratios in
gabbro-syenite group is inferred to be related to crustal contamination.

1.6.4 K-Ar Studies:

Compared to the vast extent and enormous volume of Deccan basalts, the reported K-Ar ages are limited in number. The majority of them are whole-rock ages of samples drawn mostly from western India.

The K-Ar ages of Deccan flows and dykes reported by Rama (1964) suggested two episodes of extrusion of Deccan traps i.e. one around 42-45 m.y. and the other around 60-65 m.y. ago. Wellman and McElhinny (1970) rejected this idea because they got several ages concordant at 60-64 m.y. on the basis of carefully chosen samples. They concluded that the traps were extruded over a period of the order of 5 m.y.

Kaneoka and Haramura (1973) reported K-Ar ages of rocks from flow sequences at Mahabaleshwar and Amboli and also from localities investigated by earlier workers (i.e. Pavargarh, Girnar and Bombay). The ages reported by them range from 40-66 m.y. The younger ages were considered unreliable, which led the authors to conclude that the ages of the flows investigated are about 60-65 m.y.

More recently Agrawal and Rama (1976) have reported
K-Ar ages of a number of samples from Rajmahal and Deccan traps and from basaltic dykes of Gondwana. Their ages for Rajmahal agree fairly well with the ages reported earlier by McDougall and McElhinny (1970). K-Ar ages of the samples from Bhor Ghat and Satara sections fit into the 60-65 m.y. time scale. The authors are of the view that the Deccan Trap activity started in Gujarat-Kathiawar and spread over almost the entire area in the next 5-7 m.y. However, they recognise that the traps in the north-eastern region around Chhindwara and Amarkantak may be younger (around 47.0 ± 1.5 m.y. B.P.) and may have been extruded in the middle of Eocene. K-Ar ages of the dykes suggest the persistence of the hypabyssal activity upto 34 m.y. They accept the possibility that there may have existed still younger flows which might have been since eroded away.

1.6.5 Models and Reviews:

Bose (1972) reviewed the salient mineralogical and chemical characteristics of the Deccan basalts. He has suggested that the Deccan basalts like other quartz tholeiites have attained their composition, owing to olivine fractionation. He has ascribed the diversity of magma types in the western India to the thickening of the lava pile and the increase of heat flow. Ultrabasic flows are believed to be products of fractionation of the source magma of olivine tholeiitic
composition whereas minor acid variants are possibly residual liquids of the ascending magma.

On mineralogical, chemical and phase-equilibria considerations, Krishnamurthy (1974) has suggested that, for the rocks of the Dhandhuka, Wadhwan and Botad in Gujarat, the picritic rocks might be closest in composition to the parental liquids which in turn might have been derived from the partial melting of the garnet peridotite of the upper Mantle at c. 25-30 Kb with the production of c. 20% picritic liquids.

More recently, the composition and origin of Deccan basalts have been reviewed by Ghose (1976). He has attempted to correlate the physical and chemical characteristics of Deccan basalts with the observed seismic, gravity and palaeomagnetic data. He suggests that the earliest eruptions of quartz-tholeiitic compositions were derived by a high degree of partial melting of peridotite at moderate depths (37-41 km.) and that the undersaturated lavas were derived by low degree of partial melting of garnet peridotite in the low velocity zone along the tectonically active belts.

1.7 Objectives of the present study

The Deccan trap flows in western India tend to have in some cases, compound flows, diversity of rock types, association with carbonatite and alkaline rocks, post-trapp
dyke swarms, high heat flows, etc. In contrast, the Deccan traps around Sagar are characterised by simple flows with great lateral extent, and presence of a number of (fossiliferous) intertrappean beds. Petrographic variations are minor, and the tholeiitic rocks are low in potassium (about 0.1% K₂O in some flows). Dyke swarms absent pyroclastics and ash beds are absent. These features make the flows around Sagar a good subject for a detailed geochemical investigation. The objective of the present work is to generate a self-consistent model in respect of the nature of the magma, and time and mode of emplacement of the Sagar flows, in comparison with the flows of Dhanduka, western India, and Karroo basalts of Africa.

1.3 Scope of the present work

The quantum of field and laboratory work accomplished by the author in pursuance of the above objective is summarised below:

(i) Mapping an area of about 250 Km² around Sagar, collection of representative samples from the twelve flows and their general petrographic study.

(ii) Logging the three bore-hole sections (drilled by the Geological Survey of India) and sampling ten flows and three sedimentary beds.

(iii) Major element geochemistry of 60 basalt samples (by X-ray fluorescence method, and 10 samples by
wet chemical method also). Samples from few localities in western India (Kindly provided by Dr. W.D. West) and ten core samples of Karroo basalts (Kindly provided by Dr. P.H. Nixon) were analysed and used for comparison.

(iv) Trace element geochemistry of 60 samples by X-ray fluorescence method (Ba, Cu, Cr, Co, Pb^{Ni}, Rb^{Nb}, Sr, Zn and Zr). The following elements (Be, Co, Ga, La, Mo, Nb, Ni, Pb, Sn, V, Y, Yb & Zr) were also determined by emission Spectrography in 36 Sagar samples.

(v) Strontium isotopic data for 18 Deccan trap samples (Fourteen from Sagar, three from Dhandhuka and one from Pavagarh).

(vi) Rare-earth elements (by Neutron Activation Analysis) of 21 samples of Dhandhuka Flows (samples kindly provided by Dr. P. Krishnamurthy and Dr. K.G. Cox). A report on this which has been accepted for publication in "Lithos", 1977, No. 10, is kept in the pouch separately.

(vii) Whole-rock K-Ar dating of 14 samples of basalts from Sagar, Dhanduka, Koyna, Dohad, Pavagarh, Rajkot, and Pachmari.