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Mineralogical Variations in the Delakhari Sill, Deccan Trap Intrusion, Central India *

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Abstract. The Delakhari sill (maximum thickness cf. 200 m) is the most extensive Deccan Trap instrusion which occurs in central India, between longitutdes 78°38′35″ to 78°22′40″ and latitudes 22°26′ and 22°22′30″. Based on petrographic examination, the sill is divided, from bottom to top, into (1) the Lower Chilled Zone (LCZ), up to 8 m thick, marked by abundant interstitial glass and an overall fine grain size, (2) the Olivine-Rich Zone (ORZ), 27 m thick, enriched in olivine (relative to the other zones in the sill), (3) the Central Zone (CZ), 70 m thick, marked by depletion in olivine and overall coarse grain size, (4) the Upper Zone (UZ), 55 m thick, marked by the presence of two chemically and morphologically distinct olivine types and abundant interstitial granophyre, and (5) the Upper Chilled Zone (UCZ), 10–25 m thick, marked by abundant interstitial glass.

Compositions of the pyroxenes and olivines show an overall increase in Fe/Mg with crystallization, but extensive interzonal and intrazonal variations and overlaps exist. Olivine ranges from Fa_{24} (ORZ) to Fa_{95} (UZ). In the UZ and inner UCZ, an equant (Fa_{44-50}, called type-A olivine) and interstitial skeletal olivine (Fa_{70-95}, called type-B olivine) occur together. Compositions of the Ca-rich and Ca-poor pyroxenes fall in the range $Wo_{38}En_{34}Fs_{28}$ to $Wo_{33}En_{8}Fs_{59}$ and $Wo_{14}En_{41}Fs_{45}$ to $Wo_{16}En_{19}Fs_{65}$, respectively. Overall, the two pyroxene trends converge with Fe-enrichment except for one anomalous sample from the UZ which contains a Ca-rich ($Wo_{34}En_{8}Fs_{58}$) and a Ca-poor ($Wo_{10}En_{18}Fs_{72}$) pyroxene well within the 'Forbidden Zone' of Smith (1972).

Compositions of coexisting oxide minerals indicate that the sill crystallized at oxygen fugacities from 10^{-10} atm (ORZ) to 10^{-13} (UZ). The magma prior to intrusion appears to have been derived from a more primitive melt from which a considerable amount of olivine and plagioclase have fractionated out. A model of open, interrupted fractional crystallization in the sill is proposed to explain the compositional variations exhibited by the major mineral phases.

A previous study (Crookshank 1936) concluded that the sill is actually a multiple intrusion and has given rise to the lowermost (flow I) and the topmost (flow III) lava flows in the neighboring area around Tamia (78°40′15″, 22°20′35″). The olivines of flows I and III have compositions Fo_{87} and Fo_{88} respectively, and are much more Mg-rich than the maximum Mg-rich olivine (Fo_{76}) of the Delakhari sill, refuting the possibility of the sill being the 'feeder' of the lava flows I and III.

* Geosciences Department, University of Texas at Dallas Contribution No. 338

Introduction

The Deccan Trap intrusions in central India are located mainly in the Chhindwara district of Madhya Pradesh, and some of them are evidently the feeders of the extensive lava flows which occupy a vast area of central India (Crookshank 1936). From a review of published literature (e.g., West 1958; Ghose 1976; Krishnamurthy and Cox 1977) on the Deccan Traps, it is evident that data on these intrusions are sparse. This is due mainly to the location of these intrusions in an inaccessible area of dense jungle. The area is extensively faulted with vertical scarps up to 350 m high. The intrusions occur within the Gondwana sediments, which are mostly soil-covered.

The Delakhari sill is the most extensive Deccan Trap intrusion in central India (Fig. 1). Only the western part of the sill was mapped (Fig. 1) and nearly sixty samples were collected in the present study. Location of some important samples (discussed in the

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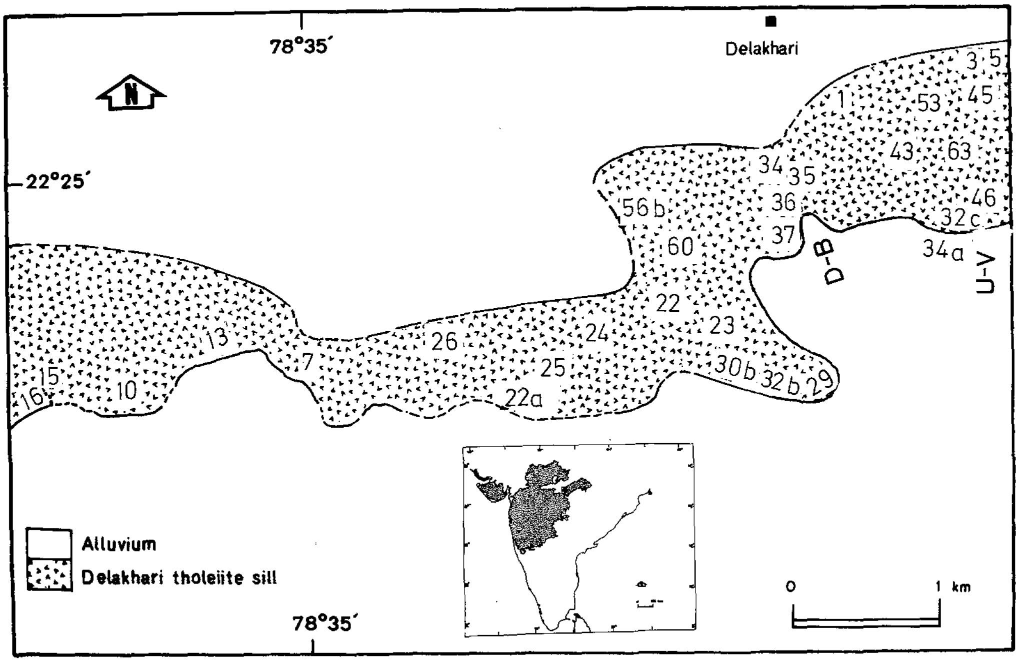

Fig. 1. Map of the Delakhari sill showing some of the typical specimens. The inset shows the distribution of the Deccan Trap lavas in India: the sill occurs in the enclosed square area. (*D-B:* Delakhari-Banjarigurhi road section; *U-V:* Umaria village section)

unpublished M. Sc. thesis of the author) is shown in Fig. 1. The sill thins to the west of the mapped area and finally merges with a composite dyke composed of dolerite and granodiorite-porphyry (Sen 1973). To the east, the sill appears to thicken considerably, and has been reported to merge with the lava flows around Tamia (78°40′15″, 22°20′35″; Crookshank 1936). The maximum thickness of the sill in the mapped area is about 200 m.

In the field, the lower boundary of the sill is marked by a thin (up to 8 m thick) chilled zone against the Gondwana sediments (upper Palaeozoic to lower Cretaceous, Krishnan 1956). Exclusive of a thick (10–25 m) chilled zone at the top, the grain size of the sill increase upward. The upper part contains patchy occurences of pegmatitic, lensoidal, bodies rich in granophyre which are about 0.5 m thick and 1 m long.

Method of Study

The present study is based mainly on samples from two field sections, namely "Umaria village secion" and "Delakhari-Banjarigurhi road section" (Fig. 1). Detailed petrography and chemistry of some of the samples will be published elsewhere.

Preliminary estimation of olivine and pyroxene compositions was done from 2V and refractive index measurements, and plagioclase compositions were estimated by the symmetrical extinction method on a universal stage. Optically estimated compositions of plagioclase and olivine are reasonably close to those determined by electron microprobe (±5%), but optically estimated pyroxene compositions do not cover the same range as that defined by the microprobe analyses.

Electron microprobe (ARL model EMX–SM) study of some typical samples of the sill was carried out at the University of Texas at Dallas. Operating conditions were 15 kV accelerating potential, 0.5–0.15 microamp beam current, and 150 microamp emission current. The olivines and pyroxenes were analyzed against an augite standard, and the plagioclases and Fe–Ti oxide minerals against plagioclase and ilmenite standards, respectively. A finely focussed beam (0.3 μm) used to analyze the silicate minerals, and a defocussed beam (beam diameter ~ 15 μm) and higher beam current (0.5 microamp) to analyze the Fe–Ti oxide minerals. The raw data were corrected for mass absorption, fluorescence, dead time, and atomic number effects using the EMPADR VII correction program of Rucklidge and Gasparrini (1969).

Petrography and Zonation

The sill rocks, in general, have the mineralogy of olivine tholeiite; Plagioclase, augitic and pigeonitic pyroxenes, and variable proportions of olivine and Fe–Ti oxide minerals comprise the bulk of the sill, with subordinate amounts of quartz, alkali feldspar, apatite, and tridymite (inverted to quartz). The modal proportions change from the bottom to the top of the sill (Fig. 2), as do the textures. Based on such variations, the sill is divided into the Lower Chilled Zone (abundant interstitial glass), the Olivine-Rich Zone, the Central Zone (depletion in olivine and overall coarse grain size), the Upper Zone (enrichment in interstitial micropegmatite and occurence of interstitial olivine), and an Upper Chilled Zone (abundant interstitial glass).

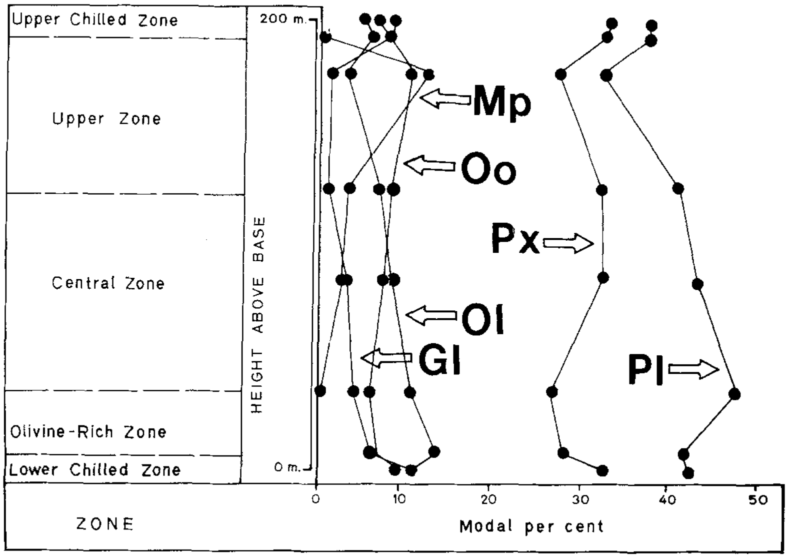

Fig. 2. Modal percent of the constituent minerals (*Mp*: micropegmatite; *Gl*: glass; *Oo*: Fe–Ti oxide minerals; *Ol*: olivine; *Px*: pyroxene; *Pl*: plagioclase) in the Umaria village section

Lower and Upper Chilled Zone (LCZ and UCZ)

The rocks are characterized by phenocrysts of olivine and plagioclase in a groundmass consisting predominantly of plagioclase, pyroxene, and glass. Quartz and alkali feldspar occur in the groundmass of some rocks. The olivines are usually euhedral and are enclosed by either plagioclase or pyroxene. In the inner part of the UCZ, some olivine grains are notably skeletal ("spinifex" type) and Fe–rich (Fa_{80}). Many grains are partially or wholly altered to an iddingsitic material. Plagioclase phenocrysts are generally tabular with some oscillatory zoning and are enclosed by pyroxene and olivine. Clinopyroxene grains are usually granular to subprismatic and exhibit well developed, wavy and sectoral extinction. Among the Fe–Ti oxide minerals, skeletal laths of ilmenite are dominant. Titanomagnetite grains are mainly skeletal and restricted to the groundmass glass areas. A few round specks (less than 0.8 μm in diameter) of chalcopyrite are present. The relative proportions of glass, plagioclase, pyroxene, and Fe–Ti oxide minerals vary to some extent along the length of the sill (Sen 1973). The texture varies from intergranular-intersertal to ophitic-subophitic.

Olivine-Rich Zone (ORZ)

The olivine grains vary in shape from euhedral to rounded, and their size ranges from 0.5 × 0.3 to 0.3 × 0.2 mm. Pigeonite reaction rims around olivine are common. Plagioclase exhibits a seriate variation of grain size. Large (2 × 1.2 mm) megacrysts showing oscillatory zoning are common in the top part of this zone. Normal zoning is more commonly shown by smaller plagioclase laths (0.4 × 0.1 mm). Pyroxene grains are subprismatic to prismatic (0.7 × 0.6 to 0.5 × 0.3 mm) and show normal zoning, sector zoning, and wavy extinction. Titanomagnetite, ilmenite, chalcopyrite, pyrite, pyrrhotite, and pentlandite occur in minor amounts. The high-temperature sulphides: pyrite, pyrrhotite, and pentlandite, occur only in this zone. The interstitial material is composed of glass (generally altered to palagonite), plagioclase laths, pyroxene granules, some spherulitic intergrowths of alkali feldspar and quartz, and small round chalcopyrite grains. The texture is ophitic to subophitic.

Central Zone (CZ)

The rocks of this zone are coarse-grained and the base is marked by a sudden depletion in olivine (Fig. 2). Plagioclase laths show a seriate variation in size from small (0.2 × 0.1 mm) laths to coarse, tabular (2 × 1 mm) ones. Normal and oscillatory zoning is common. Olivine grains are mostly altered to iddingsite. Augite forms plates (3 × 2.5 mm), usually mauve to deep brown in colour. Pigeonite forms faint-brown coloured, small (0.75 × 0.5 mm) grains. Titanomagnetite and ilmenite form fairly coarse (0.5 × 0.4 mm), somewhat skeletal grains, and commonly enclose each other. Coarse trellis lamellae of ilmenite, possibly formed by oxidation-exsolution of titanomagnetite, occur commonly in two and three sets in titanomagnetite. The interstitial materials include palagonite (secondary glass), plagioclase laths, Fe–Ti oxide minerals, granophyre, and apatite. The texture is ophitic to subophitic.

Upper Zone (UZ)

In the 50 m thick UZ, two distinct types of olivine occur: one type (A) as equant, subhedral grains (0.7 × 0.5 mm), and the other (B) as elongated skeletal grains (0.8 × 0.1 mm) in the interstices in association with granophyric materials. The skeletal type is more Fe–rich (Fa_{70-95}) than the equant type (Fa_{50-64}). The pyroxenes vary from coarse prismatic to long bladed grains. The bladed grains are usually twinned with conspicuous zoning and exhibit interfingering intergrowths with ilmenite and titanomagnetite. The plagioclase grains vary from coarse tabular to lath-shaped, and most are zoned (normal). Titanomagnetite and ilmenite from coarse skeletal grains. Sandwich and a few trellis lamellae of ilmenite in titanomagnetite are notable. Also, the titanomagnetite is extensively transformed to maghemite. Vermicular intergrowths of ilmenite with glass and pyroxene are usually present. The interstitial materials consist of granophyre, apatite, and tridymite (inverted to quartz), together with palagonitized glass. Ophitic-subophitic and gabbroic textures are dominant.

Compositional Variations in Olivine

Extensive variation in composition (Fig. 3, Table 1), in terms of Fe/Mg, is apparent within and between

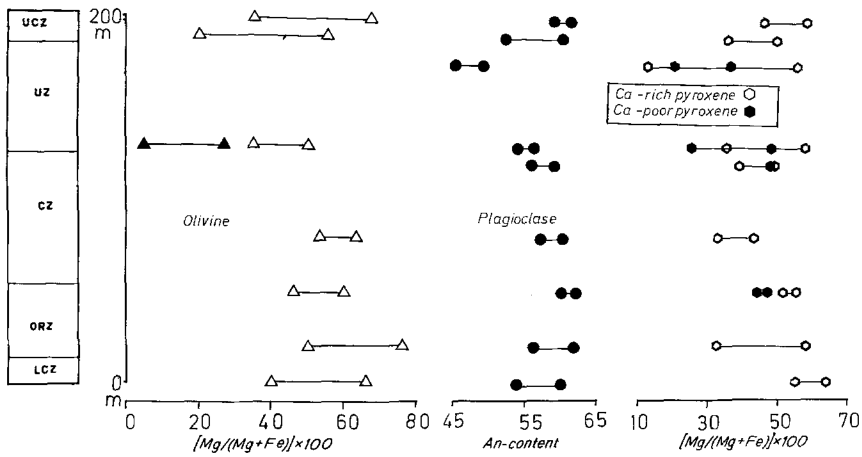

Fig. 3. Variations in the compoisitions of major minerals in the Delakhari sill from the Umaria village section (*unfilled triangles:* equant olivine; *filled triangles:* skeletal interstitial olivine; *circles:* An-content in plagioclase; *unfilled hexagons:* Ca-rich pyroxene; *filled hexagons:* Ca-poor pyroxene)

Table 1. Representative parial analyses of olivine

	1	2	1	2	1	2	3
SiO_2	38.41	32.43	39.89	35.60	38.41	30.53	29.84
FeO*	30.76	51.56	16.24	37.36	30.76	65.31	65.43
MgO	31.10	15.58	43.10	26.50	31.10	3.25	4.42
CaO	0.24	0.45	0.20	0.25	0.24	0.53	0.47
TiO_2	0.02	0.03	–	0.02	0.02	0.15	0.12
Al_2O_3	–	0.01	–	–	–	0.06	0.06
Total	100.53	100.06	99.43	99.73	100.63	99.87	100.34
Number of cations for four oxygens							
Si	1.029	0.988	0.992	1.001	1.003	1.005	0.982
Fe**	0.689	1.366	0.338	0.878	0.705	1.799	1.792
Mg	1.242	0.707	0.608	1.106	1.271	0.159	0.216
Ca	0.006	0.008	0.005	0.005	0.007	0.016	0.018
Ti	0.000	0.000	–	0.000	0.000	0.002	0.007
Al	–	0.000	–	–	–	0.003	0.001
Sum	2.996	3.017	2.993	2.990	3.003	2.996	2.990
Mole% Fa	36	65	27	54	50	91	88
Position	Chilled zones		ORZ		type-A olivine	type-B UZ olivine	

FeO*: Total iron oxide as FeO; Fe**: Total Fe as Fe^{2+}

each zone. The olivines of the LCZ and the outer UCZ fall in the range Fa_{33-65} and are much more Fe–rich than those (Fa_{15}) of the "three-phenocryst basalts" of the Deccan Traps (Krishnamurthy and Cox 1977), indicating relatively more differentiated nature of the sill magma. In the ORZ, CZ, and UZ, the olivines fall in the ranges Fa_{24-54}, Fa_{40-63}, and Fa_{50-95} respectively (Fig. 3). Thus, there is a considerable overlap of olivine compositions between different zones.

Similar overlaps and reversals in olivine and plagioclase composition have been observed in the Rhum layered intrusion (Brown 1956; Dunham and Wadsworth 1978). An open, interrupted fractional crystallization process affected by multiple intrusive phases, has been invoked (Wager and Brown 1968) to explain such compositional behaviour in that intrusion and it is suggested that such a process may have been operative in the Delakhari sill.

The olivine with maximum Fe (Fa_{70-95}) occurs intertitially as elongated, skeletal crystals in the UZ and inner UCZ rocks *only*. Such extremely Fe–rich olivines have not previously been reported from any Deccan Trap rock. Henceforth these olivines of the UZ and inner UCZ will be called type-B olivines, and the coarse equant Mg–rich (Fa_{50-64}) ones of the UZ and inner UCZ (see "Petrography and Zonation") will be called type-A olivines. It is interesting that the Delakhari sill does not apparently show a pause in olivine crystallization, as observed experimentally (Bowen and Schairer 1935) and in most layered tholeiitic intrusions, e.g., the Skaergaard intrusion (Wager and Brown 1968). A compositional gap, however, appears to exist between the type-A (Fa_{50-64}) and type-B (Fa_{70-95}) olivines of the UZ, and these two olivines could not have crystallized in equilibrium with each other. The difference between Fa_{64} (type-A olivine) and Fa_{70} (type-B olivine) could be a result of insufficient data, but if it is real, two possible explanations are: (1) a highly fractionated Fe–rich silicate liquid (from which the type-B olivine crystallized) carrying some xenocrysts of early crystallized type-A olivines from an underlying differentiating magma chamber, was emplaced at the level of the UZ and inner UCZ (i.e., multiple intrusion); (2) type-B olivines could have crystallized from a late stage interstitial immiscible Fe–rich silicate liquid, with the other alkali-rich immiscible liquid part giving rise to some of the interstitial granophyres (note that the modal content of interstitial granophyres is excessively high in the UZ-Fig. 2) in the UZ and inner UCZ.

In regard to the second explanation, it should be mentioned that Philpotts (1979), in his study of immiscibility in Jurassic basalts of Connecticut and the standard diabase W-1, did not observe any fayalitic olivine in association with the immiscible Fe–rich silicate glasses. Also, olivine was not a liquidus phase in the basalts studied by Philpotts (he found a very few *altered* olivines); whereas it is an abundant phase in the Delakhari sill rocks. Thus, the Delakhari sill rocks are compositionally different from the rocks studied by Philpotts, and his evidence on the existence of immiscible liquids may not apply to the Delakhari sill.

The occurence of a few reverse-zoned pyroxenes (rims with 15 mole percent higher En than the cores), and general compositional overlaps seem to support the multiple intrusion hypothesis. However, even though no direct morphological evidence such as globular shapes of interstitial immiscible liquid glasses (De 1974; Philpotts 1979) could be found, the second hypothesis cannot be refuted, especially in view of De's (1974) finding of extensive silicate-liquid immiscibility in the Deccan Trap lavas. Extensive alteration of the interstitial areas is present and may mask textural evidence of immiscibility.

Composition of Plagioclase

Partial analyses of cores of plagioclase grains with respect to the elements Ca, Na, Al, and Si have been carried out using the microprobe. The core-compositions of plagioclase phenocrysts in the sill show, in spite of interzonal and intrazonal compositional overlaps, a progressive decrease in An-content from An_{62} in the ORZ to An_{45} in the UZ only in the "Umaria village" section (Fig. 3). In the same field section, the modal content of plagioclase also decreases from 48% in the ORZ to 32% in the UZ (Fig. 2), suggesting settling of plagioclase in this field section. However, no such systematic variation has been observed in the "Delakhari-Banjarigurhi road" section (Sen 1973), where the sill is much narrower. Thus, plagioclase-settling seems to have been controlled by the thickness of the sill.

It is interesting that the most calcic plagioclase (An_{62}) of this sill is poorer in An than those of the "normal basalts" (An_{57-66}), "picrite basalts" (An_{74-88}), and the "three phenocryst basalts" (An_{72-88}) of the Deccan Traps (Krishnamurthy and Cox 1977). The more sodic nature of the sill plagioclases suggests a relatively differentiated nature of the first emplaced sill magma (as compared to the lavas), a feature that is corroborated by the relatively Fe–rich nature of the olivine phenocrysts of the sill.

Composition of Iron-Titanium Oxide Minerals

Many of the titanomagnetite and ilmenite grains (Table 2) are sufficiently homogeneous to permit the use of the $f_{O_2}-T-X$ diagram of Buddington and Lindsley (1964), p. 316; the revised diagram of Lindsley 1977, has been used here). However, in some cases where perfectly homogeneous grains were not present, titanomagnetite grains in coarse sandwich intergrowth with ilmenite were used for compositional determinations. Volumetric considerations indicate these intergrowths to be primary and not produced by oxidation-exsolution of titanomagnetite (see also Haggerty 1976).

The mole percent ulvośpinel and hematite in titanomagnetite and ilmenite, respectively, were determined by assuming a perfect stoichiometry of the phases. In Fig. 4, the plots of the coexisting titanomagnetite and ilmenite are compared with the FMQ-buffer curve and with the $f_{O_2}-T$ path followed by the Skaergaard intrusion. The primary compositions of the oxide phases in the Delakhari sill appear to have been unchanged by subsequent, subsolidus alteration.

The temperature of emplacement of the sill magma appears to be 1,150° C (±30°) and the temperature of final solidus crystallization, 900° C (±30°).

Table 2. Representative magnetite and ilmenite analyses

	ilm.	tmgt-1	tmgt-2	tmgt-3	ilm.	tmgt-1	tmgt-2
MgO	0.25	0.12	0.30	0.30	0.51	0.23	0.38
TiO_2	49.47	21.30	20.30	21.15	47.69	25.72	28.44
Al_2O_3	0.41	0.19	0.20	n.d.	0.39	0.24	0.25
FeO*	50.78	74.50	68.91	75.15	46.97	67.21	63.18
Total	100.91	96.11	89.71	96.53	95.57	93.40	92.25
Fe_2O_3	4.78	26.93	24.22	27.43	3.49	15.71	9.29
FeO	46.48	50.27	47.12	50.47	43.83	53.08	54.82
%USP.		60.99	60.36	60.38		76.18	85.45
%Hem.	4.78				3.49		
Zone	Upper zone				Olivine-rich zone		

(Note: FeO*: total iron oxide as FeO)

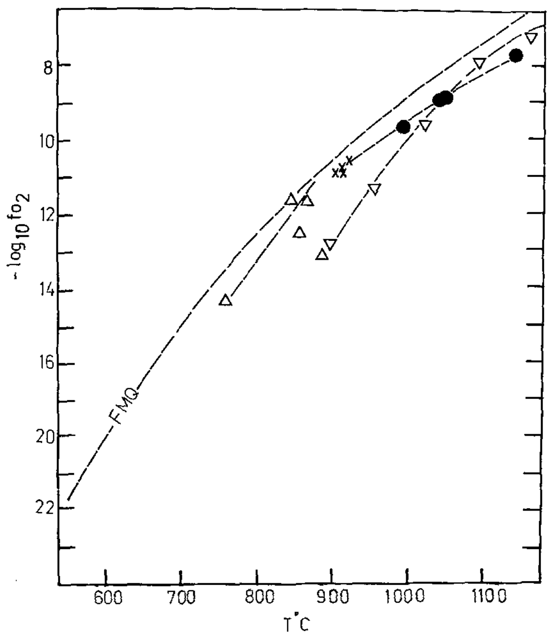

Fig. 4. Composition of coexisting titanomagnetite and ilmenite in $f_{O_2}-T-X$ space (*solid circles*: ORZ; *crosses*: UZ; *upright triangle*: plots of coexisting Fe–Ti oxides, and *inverted triangles*: values deduced from silica activity for the Skaergaard intrusion: cited by Haggerty 1976)

It may be pointed out that the temperature of final solidus crystallization is in accord with that determined from the quartz = tridymite inversion point (inverted tridymite plates occur interstitially in the UZ). The limiting oxygen fugacities during the crystallization of the sill magma are 10^{-10} and 10^{-13} atm. The maximum temperature and oxygen fugacity values are compatible with the estimates of De (1964) for the Deccan Trap lavas.

Figure 4 also demonstrates that the $f_{O_2}-T$ path followed by the Delakhari sill magma is analogous to that of the Skaergaard intrusion as determined from silica activity (e.g., Haggerty 1976), and both follow the FMQ-buffer curve closely. The lower values of f_{O_2} and T shown by the coexisting Fe–Ti oxide compositions of the Skaergaard intrusion are possibly due to subsolidus effects.

Compositional Variations in Pyroxenes

In the Delakhari sill, two pyroxenes, one Ca-rich (augitic-ferroaugitic) and the other Ca-poor (pigeonitic-ferropigeonitic) occur. Extreme variations in the composition of the two pyroxene types is notable in all the samples of the sill (Fig. 5). The most maganesian Ca-rich pyroxene ($Wo_{33}En_{55}Fs_{12}$) and Ca-poor pyroxene ($Wo_{11}En_{55}Fs_{34}$) occur in the LCZ and ORZ respectively; however, cores of zoned pyroxene grains of comparable compositions occur in the CZ and UZ also (Fig. 3). These Mg-rich pyroxene cores of the UZ and CZ may have crystallized from minor replenishments of somewhat undifferentiated magma (therefore, Mg-rich) from a magma chamber at depth. The Fe-rich rims of these zoned pyroxenes of the UZ and CZ later grew from a mixture of Fe-rich liquid produced by differentiation of the first emplaced sill magma and the minor Mg-rich replenishments.

Occurence of a few reverse-zoned subcalcic ferroaugite (with rims containing 15 mole percent or more En than the cores) pyroxene grains in the UZ also supports the multiple injection hypothesis. Zoning in pyroxenes has only been studied in the UZ and ORZ in the present work. The proposed phenomenon of multiple injection interrupting the fractionation process in the first emplaced sill magma also explains the compositional overlaps in pyroxenes, ol-

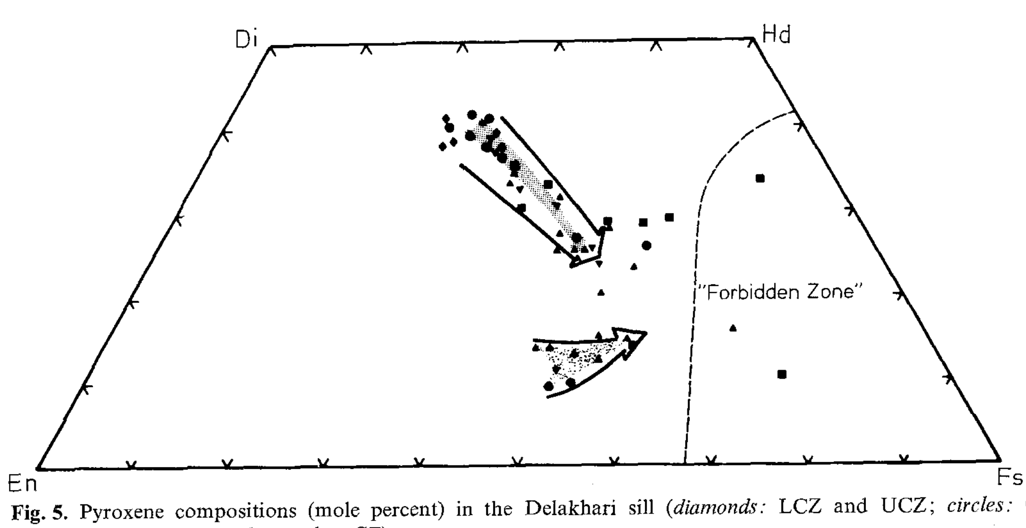

Fig. 5. Pyroxene compositions (mole percent) in the Delakhari sill (*diamonds*: LCZ and UCZ; *circles*: ORZ; *upright triangles* and *squares*: UZ, and *inverted triangles*: CZ)

Table 3. Partial analyses of the three Fe-rich pyroxenes

	1	2	3
SiO_2	45.83	48.61	48.08
FeO*	37.55	36.93	41.59
MgO	9.00	6.48	5.85
CaO	5.49	7.21	4.49
TiO_2	0.55	0.45	0.42
Al_2O_3	0.75	0.68	0.65
Total	99.17	100.36	101.08
Number of cations for six oxygens			
Si	1.946	2.000	1.996
Fe*	1.313	1.273	1.448
Mg	0.500	0.392	0.362
Ca	0.206	0.318	0.199
Ti	0.013	0.011	0.011
AlIV	0.018	0.000	0.014
AlVI	0.004	0.006	0.002
Sum	4.002	4.007	4.014
Mole percent			
Wo	11	16	10
En	26	20	18
Fs	62	64	72

(Note: FeO*: Total iron oxides as FeO; and Fe*: total Fe as Fe^{2+})

ivines, and plagioclases between each zone (Fig. 3). Three analyses of very Fe-rich pyroxenes, which occur interstitially in the UZ, have compositions (Table 3; Fig. 5) lying well within the experimentally determined "Forbidden Zone" at one atmosphere and 925° C (Smith 1972). No pyroxene can be stable within this "Forbidden Zone" at low pressures and at 925° C (Lindsley and Munoz 1969). Smith also determined that the area of the "Forbidden Zone" decreases with increasing pressure, but in view of the shallow depth of the sill, it is suggested that these pyroxenes may have formed metastably at low pressure from an interstitial Fe-rich silicate liquid, which may have been produced by simple differentiation or silicate liquid immiscibility.

Discussion and Conclusions

The olivine-tholeiitic nature of the sill magma is amply demonstrated by the abundance of olivine, and the coexistence of two pyroxenes. The occurrence of phenocrysts of plagioclase and olivine in the chilled margin rocks suggests that these two phases started crystallizing in the magma prior to emplacement.

The extremely differentiated nature of the sill magma prior to emplacement is indicated by the Fe-rich nature of the olivines and Na-rich nature of the plagioclase. Presnall et al. (1979) and Frey et al. (1974) have argued that some MOR tholeiites (e.g., certain FAMOUS tholeiites) closely approximate primary magma compositions. These primary tholeiites have olivine and plagioclase phenocrysts falling in the ranges Fo_{87-90} and An_{85-88} (e.g., Bryan and Moore 1977) respectively. Also, olivine and plagioclase phenocrysts of some primitive continental tholeiites (e.g., the "three-phenocryst basalts" of the Deccan Traps, West 1958) have compositions in the ranges Fo_{84-90} and An_{76-88} respectively. The olivines from "undepleted" mantle are also believed to fall in the range Fo_{86-88} (e.g., Carter 1970). Thus, even the maximum Mg-rich olivine (Fo_{76}) and maximum Ca-rich plagioclase (An_{64}) in the Delakhari sill do not come anywhere near the general ranges of compositions of olivines and plagioclase associated with primary tholeiites. It is probable, therefore, that the sill magma is not primary, and has undergone extensive fractionation at least of olivine and plagioclase before emplacement. Alternatively, a less likely possibility is that the sill magma had a much more Fe- and Na-rich source than the source for the tholeiites of the Deccan Traps and of the oceans.

Crookshank (1936) concluded from his study, based mainly on field observations that the sill is possibly multiple and a 'feeder' of the lava flows I (basal flow) and III (top most flow, Sen 1973) of the neighbouring area of Tamia (78°40′15″ E, 22°20′35″ N). The present author (Sen 1973) observed that (i) the chilled zone plagioclase phenocrysts in the sill are more sodic (An_{62}) than the maximum calcic plagioclase phenocrysts of the flows (e.g., flow I – An_{64}, flow II – An_{66}, flow III – An_{66}), (ii) the olivine phenocrysts of the flows (flow I – Fo_{87}, flow III – Fo_{88}) are much more magnesian than the maximum Mg-rich olivine of the sill (i.e., Fo_{76}), (iii) native copper occurs in association with chalcopyrite in flow III, whereas only chalcopyrite occurs in the sill. Thus, it appears that the sill magma was more differentiated than the flows I and III of that area, and the sill could not have been the 'feeder' of these lava flows.

The first emplaced sill magma has, evidently, undergone further differentiation through extensive settling of olivine in all field sections through the sill and both olivine and plagioclase in the "Umaria Village" section. Pyroxene settling has not occurred, and this is perhaps due to late appearance of this phase. The early settling of olivine and plagioclase has caused enrichment of the late liquid in alkalies, Fe, and SiO_2. This process of simple fractionation is believed to have been interrupted by minor epidosic intrusions of relatively less differentiated magma from

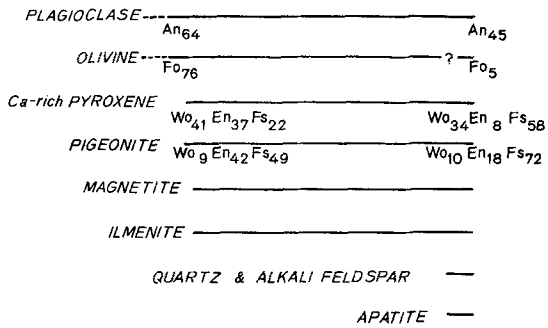

Fig. 6. Schematic diagram showing the sequence of crystallization of the minerals in the Delakhari sill

an underlying differentiating magma chamber, resulting in the overlaps in the composition of major mineral phases. The schematic diagram shown in Fig. 6 summarizes the sequence of crystallization of the mineral phases in the Delakhari sill. Only the extreme compositional limits of the silicate minerals are shown because the composition of each mineral phase has been episodically disturbed by multiple intrusion. Plagioclase and olivine started crystallizing in the magma prior to emplacement and were later joined by the pyroxenes, Fe–Ti oxide minerals and apatite in the approximate order as shown. The olivine compositional gap between Fo_{36} and Fo_{30} (shown in Fig. 6) is questionable, and has been discussed earlier. The sulphides have crystallized from minor immiscible sulphide liquid.

The nonequilibrium coexistence of type-A and type-B olivines in the UZ and inner UCZ rocks in this sill is, perhaps, unique. To the author's knowledge, such co-occurrence of compositionally and morphologically different olivine types in the same rock has not been observed in any other intrusion. Coarse and a small grain varieties of olivine do occur in the Mg-olivine layer ("Hyalosiderite dolerite", Walker 1969, p. 34, plate 5) in the Palisades sill. Microprobe analyses (Walker 1969, p. 62) indicate a general overlap of composition ranges (Fo_{69-77}) of the two groups, "though overall the large grains appear to contain somewhat more Fe than the small". Thus, the Palisades sill case is compositionally and morphologically quite different from the Delakhari sill as far as the two-olivine occurence is concerned.

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