Oxidation and reduction conditions during crystallization of a magma have been considered as important factors influencing the formation of mineral assemblages (Eugster, 1959). Their significant roles during crystallization of rocks can be evaluated from the chemical analyses, specific mineral assemblages like pyroxene, olivine, and iron-titanium oxides, which may indicate the nature of oxidation conditions during crystallization.

In the context of chemical analyses, the effect of oxidation state of iron on crystallization trend of basaltic magma may be discussed. That the trend of differentiation of a magma, is also affected by the oxygen fugacity \((f_{O_2})\) existing in the crystallising magma was postulated by Kennedy (1955) and Osborn (1959, 1962). At a low value of \(f_{O_2}\), iron is not oxidised to form magnetite; but remains longer in the melt as \(Fe^{2+}\) to continue the crystallization of iron-rich silicates to a later stage and the crystallising magma ultimately becomes enriched in iron. Such an environment may arise when a magma is emplaced at shallow levels and subsequently water is lost to form lower \(f_{O_2}\) values. In the environment of high \(f_{O_2}\) iron is oxidised and thereby being removed as magnetite continuously during crystallization of the magma, the residual magma finally becomes silica-rich.

The oxidation ratio of iron during the course of differentiation of basaltic magma can be interpreted from the chemical analyses of the rocks of a particular suite. The trend in variation of oxidation ratio may give an approximate idea as to the prevailing nature of oxygen fugacity \((f_{O_2})\), but no direct correlation is possible. The oxidation ratio is defined in this case as
In the present rock analyses, the ferroaugite granophyre (Sp. No. 31/12, referred to in Chapter V) shows a low oxidation ratio of 28 which can be compared with the ratio of 20 found in basalts of the Deccan Traps in the stage of their maximum (16 percent) iron enrichment (De, 1964). The aegirine-augite granophyre (Sp. No. 21/9C, referred to in Chapter V) with a very high oxidation ratio of 78 with a minimum iron enrichment of 4.89 percent is responsible for the formation of alkali-pyroxene. The alkali-hedenbergite bearing rhyolite (Sp. No. 4/14.2, referred to in Chapter VIII) shows a high oxidation ratio of 66.94 with iron enrichment of 5.7 percent; the alkali content of hedenbergite and high maghematisation of titanomagnetite can be explained by the high oxidation condition during crystallization. The granodiorite porphyry (Sp. No. 30.0/90.8, referred to in Chapter XII) has a low oxidation ratio of 22.11 with iron enrichment of 9.06 percent; and it indicates its crystallization under low oxidation condition which is evident by the occurrence of diopside-augite and homogeneous titanomagnetite. In this context, it is to be mentioned that the intermediate members of Deccan Trap Series show a low oxidation ratio (De, 1964). The fayalite bearing acid rock (Sp. No. 8b/22.10, referred to in Chapter IX) from Ghumli area, shows the strongest iron enrichment of 12.99 wt. percent with an oxidation ratio 37.77, which indicates the crystallization of fayalitic-olivine under reducing conditions. The pitchstone rock (Sp. No. 5a/18.10.70, referred to in Chapter IX) from Talara talao shows an oxidation ratio of 39.50 at 12.61 weight percent iron enrichment, which is closely comparable with these values of fayalite-bearing acid rock.

The above mentioned variations are shown in figure-67 from which it can be observed that there is a gradual increase of oxidation ratio from granodiorite porphyry to aegirine-augite granophyre through ferroaugite-granophyre, fayalite-bearing acid rock, pitchstone and alkalic-hedenbergite-bearing rhyolite. The
iron-enrichment increases from granodiorite porphyry to fayalite-bearing acid rock and then decreases gradually towards aegirine-augite granophyre through pitchstone and rhyolite. It is noteworthy that there are distinctly lower oxidation ratios in the basic members of the Deccan Trap series (De, 1964). The contents of iron oxides and oxidation indices of these acid subvolcanic rocks show a parallelism with the same curve for the Deccan Trap series (De, 1964), with the exception that in these subvolcanic rocks the highest iron enrichment occurs at a slightly higher oxidation ratio of 38 in place of 20 as in the Deccan Trap basalt and the iron enrichment is also much lower in amount.

**PYROXENE TRENDS**

Clinopyroxene in the acidic rocks of the present area, occurs in a wide range of composition from augite to aegirine-augite and acmite, through the intermediate stages of ferrosalite, ferroaugite and hedenbergite (Figs. 54, 55). Pure acmite appears to be restricted mainly in the miarolitic and submiarolitic areas of granophyre. The clinopyroxene in the coarse varieties of granophyre are in some cases rimmed by alkalic pyroxene.

The range in composition of clinopyroxene has been observed as augite (Ca$_4$Mg$_2$Fe$_{26}$) --- Ferrosalite (Ca$_{46.5}$Mg$_{18.5}$Fe$_{35}$) --- Ferroaugite (Ca$_{32.5}$Mg$_{21}$Fe$_{40.5}$) --- Hedenbergite (Ca$_{48.5}$Mg$_{9}$Fe$_{43}$) --- Aegirine-Augite (CaMgFe$^{++}$)$_{78}$ (NaFe$^{+++}$)$_{22}$ --- Pure acmite. This range in pyroxene-composition is indicative of differentiation in the magma. It is evident that the course of crystallization led to a substantial decrease of magnesia and consequent enrichment of iron and alkalies together with slight increase in calcium content.

It is interesting to note that clinopyroxene shows iron enrichment and hence a lowering of Mg/Fe ratio in the course of differentiation. An
VARIATION OF OXIDATION RATIO AGAINST IRON ENRICHMENT IN THE IGNEOUS COMPLEX OF BARDA HILLS

1. Aegirine-augite granophyre
2. Alkali hedenbergite bearing rhyolite
3. Pitchstone
4. Fayalite bearing microgranite
5. Ferroaugite granophyre
6. Granodiorite porphyry

OXIDATION RATIO

IRON ENRICHMENT
increase in FeSiO$_3$ molecule is expected in pyroxene, when the condition of oxidation stays constant or decreases (De, 1964). A suggestion has been drawn by De (1964) that the oxygen fugacity (10$^{-10}$ atmosphere) remained more or less constant during the course of differentiation. This idea is also consistent with the enrichment of FeSiO$_3$ molecule in clinopyroxene.

The trend augite —— salite —— ferrosalite —— ferroaugite —— hedenbergite observed in the acidic rocks of the present investigation, is a characteristic for low oxygen fugacity condition, prevailing during the rapid cooling of acid subvolcanic magma (De and Bhattacharya, 1971).

The appearance of alkalic pyroxene indicates the change of oxygen fugacity (fO$_2$) condition. It has been observed (De and Bhattacharya, 1971) that the high oxygen fugacity and low temperature conditions are favourable for the formation of alkali pyroxene. Similarly a low oxygen fugacity and high temperature of volcanic environment may be responsible for the alkali content of pyroxene, even those with high soda content (Yagi, 1966). At the stage of crystallization of miarolitic granophyre, the second boiling point of acid magma was reached. During that boiling stage, there would be sudden appearance of H$_2$O gas phase in large volumes in the miarolitic and submiarolitic cavities. The dissociation of H$_2$O and escape of H$_2$ would cause high oxygen fugacity and low temperature condition in the miarolitic cavities, and this condition favours the formation of alkali pyroxene and alkali amphibole in the miarolitic areas of coarse granophyre. It is also noteworthy that any particular mineral assemblages can be stable at lower oxygen fugacity, if the temperature is lowered (Buddington and Lindsley, 1964). As a result, when the temperature drops during the crystallization and cooling of magma under the condition of constant or slightly lowered oxygen fugacity, while the previously crystallised primary pyroxene would be subjected to an oxidising environment to form an alkali-pyroxene rim.
IRON-TITANIUM OXIDE MINERALS

Titanomagnetite occurs as a major constituent of the opaques, in the forms of coarse subhedral, skeletal to fine disseminated grains. Coarser forms occur as intergrowths with the silicates. Magnetitisation and martitisation in the titanomagnetite are more intense in the coarse granophyre in comparison to those in the felsite and fine granophyre. Oxidation exsolution lamellae of ilmenite within magnetite have been frequently found in the granophyre rather than in the felsite. Discrete and euhedral laths of ilmenite, occur more frequently in the interstitial spaces of coarse granophyre rather than in the felsite. Primary intergrowths of ilmenite within magnetite have also been traced in the granophyre.

An oxygen fugacity $10^{-13}$ has been deduced at an assumed reasonable temperature of 900°C, for the fayalite - quartz - titanomagnetite mineral assemblage of ferrosalite - ferroaugite-bearing felsite of the present area, as it is also suggested by De and Bhattacharya (1971). The same conditions for the formation of fayalite-ferrosalite-bearing felsite can be correlated with the fayalite-ferrogabbro of Skaergaard (Buddington and Lindsley, 1964) and for the fayalite-clinopyroxene-bearing pitchstone of Arran Scotland and glassy acidic rocks of eastern Iceland (Carmichael, 1967). On the basis of phase diagram (Ernst, 1962) the assemblage riebeckite-acmite-magnetite-hematite-quartz indicates an oxygen fugacity value of $10^{-17.5}$ atmosphere at an inferred low temperature of 520°C. In view of that inferred low temperature, the oxygen fugacity $10^{-17.5}$ atmosphere is comparatively high than that of ferrosalite-fayalite mineral assemblage as referred earlier and that condition is responsible for the formation of alkali-pyroxene.

The titanomagnetite crystals in granophyre of the present area, have undergone exsolution and oxidation giving rise to oriented intergrowths of
ilmenite lamellae. The formation of such intergrowth structure can be best interpreted in terms of oxidation, concomitant with slow cooling, which affected titanomagnetite during crystallization. The oxidation index (Watkins et al., 1970) in the coarse granophyre has a range up to III; whereas in the felsites, the index is low order. The low oxidation product maghemite may be superimposed on the high temperature oxidation sequence. The oxidation of magnetite to maghemite has been reported to take place at a temperature as low as 200°C (Lepp, 1957, cited in Watkins et al., 1970).