CHAPTER V

PETROGENESIS
Petrologists working on mafic-ultramafic layered complexes have been confronted with a number of problems. Foremost among these are the nature of parent magma, the characteristics of source rocks, the factors responsible for magma generation, the mode of emplacement, the conditions of crystallization and the tectonic environments.

In this chapter an attempt is made to answer some of these questions, in the light of the data presented in the earlier chapters and on the basis of the information available in the literature. It may be pointed out though, that precise evaluation of some of these problems was not possible due to the constraints of systematic chemical data. In addition to the basic problems addressed above, the genesis of chromite has been discussed.
Parent Magma

The rocks of the Bondla mafic-ultramafic complex are cumulates. Therefore, the chemical data, although can be used to decipher the magmatic process and to underline the compositional differences and the relationship of rocks with each other, they will have to be utilised with caution to determine the composition of the parent magma. The difficulty is further aggravated by the absence of either a chilled margin or closely related mafic dykes. Thus there is no direct evidence of the composition of the parent magma.

In such cases the parent magma composition can be estimated by application of mineral-melt partition coefficient to the most primitive cumulates. Such an approach was adopted by DeBari (1994) in case of the Fiambala gabbroic intrusion, northwest Argentina. She made use of FeO/MgO olivine-liquid partition coefficient \([K_d(ol/liq)=0.30]\) of Roeder and Emslie (1970) and concluded that the most primitive olivine from the ultramafic cumulates (Fo90-91.5 and 0.40 NiO) crystallised from a liquid with Mg # between 0.73 and 0.74. As the Fo con-
tent of the olivines from the troctolites of the Lower Zone at Bondla is very close to the olivines from the Fiambala intrusion, by analogy it is inferred that the troctolite (BT2) with whole rock Mg # between 0.73 and 0.74 (MgO 12.5 wt.%) may represent the most primitive parent magma of the Bondla mafic-ultramafic complex. Moreover primary magmas in equilibrium with typical mantle mineralogies should have high Mg #, Cr and Ni values. The Bondla rocks have Mg # between 0.72 to 0.74, Cr more than 400 ppm. Ni about 370 ppm. and SiO2 between 50 and 51 wt %. These values lie within the ranges generally accepted for primitive and even primary magmas (Rhodes, 1981) except for Ni values which are slightly lower.

Magma Type

The sequence of crystallisation is olivine ± spinel, pyroxene and plagioclase. Olivine and spinel (Cr-Al) are cotectic phases as observed in Hawaiian tholeiitic basalts. Pyroxenes from basaltic rocks have been studied in an effort to relate compositional trends and the magma type. The nature of pyroxene assemblage is considered to be one of the criteria for the recognition of the parental
affinity of basaltic rocks although this has been questioned by Barberi et al., (1971).

The tholeiitic magma type is mainly characterised by two pyroxene assemblages (one Ca-rich pyroxene and the other Ca-poor) both commonly show exsolution lamellae and crystallise together in the early and middle stages of differentiation of tholeiitic magma (Carmichael, 1960; Brown and Vincent, 1963; Brown, 1967; Atkins, 1969).

Pyroxenes from the Bondla gabbroic rocks are also characterised by two phases Ca-rich pyroxene in the sub-calcic-augite-augite range and Ca-poor pyroxene in the bronzite-pigeonite range. Both these show variation in iron content, and frequently contain exsolution lamellae and coexist with olivine suggesting a tholeiitic magma. The crystallisation trend of coexisting pyroxenes show a trend of iron enrichment, however, it is noteworthy that these pyroxene pairs are somewhat different than those from Skaergaard (Brown and Vincent, 1963) and Bushveld (Atkins, 1969). The wollastonite content of Ca-rich pyroxene is higher than that of Skaergaard and Bushveld, and Fe
and Ca content of the Ca-poor pyroxenes are lower than those of the equivalent pyroxenes from the mentioned intrusions. This may be due to the difference in crystallisation conditions (e.g. lower equilibration temperature and possibly a slower cooling rate). The Bondla pyroxenes are poorer in alumina and titania and richer in silica than those from the above intrusions. The concentration of Al in tetrahedral sites (Al\textsubscript{2}) is relatively low and typical of tholeiitic type pyroxenes.

On AFM plot an iron enrichment trend characteristic of tholeiitic basalts is shared by the mafic-ultramafic rocks and the associated metabasalts. Enrichment of ferrous iron during late to intermediate stages of magmatic differentiation is best exemplified by the mafic and ultramafic rocks of the complex as there is a complete spectrum of rocks from ultramafic to leucograbbroic which evolved from a tholeiitic basalt magma with subalkaline affinities (Irvine and Baragar, 1971). The iron enrichment trend shown by the rocks is more iron-rich compared with a typical tholeiite and slightly less iron-rich than the liquid trends of Skaergaard layered intrusion (Wager and Brown, 1967) which illustrates the extreme case of iron
enrichment. The iron-rich character of the mafic rocks is accompanied by slightly higher silica content. The silica saturated nature of the rocks is reflected in their quartz normative compositions in early differentiates indicating that the magma evolved from the tholeiitic side of the thermal barrier. Low silica and high iron are features typical of Fenner trend of crystallisation (Fenner, 1929).

In addition to high iron, the mafic rocks also contain higher alumina concentrations. Some of the samples are fairly high in Al₂O₃ (16.5 wt.%) to be classified as high-alumina basalts. However, the enrichment in alumina is due to plagioclase accumulation. The samples are compared with field defined for high-alumina and high-iron basalts from the Archaean Blake River Group, Canada. The high-iron rocks are more alumina-rich than are typical Fe-basalts (Pearce and Birkett, 1974) and Fe-Ti basalts (Christie and Sinton, 1981) and the high-alumina rocks have more iron than typical high-alumina basalts (Kuno, 1960).

The crystallisation sequence olivine, pyroxene,
plagioclase is characteristic of tholeiitic melt and results in the formation of large amounts of pyroxene-rich ultramafic cumulates and gabbronorites very conspicuously seen in the Bondla complex.

The REE content of the Bondla rocks progressively increases from the Lower Zone ultramafics to the Upper Zone gabbros which is a consequence of olivine dominated crystallisation which causes the REE and the La/Lu ratio to increase with progressing fractionation. It is also supported by absence of Eu anomaly in the Lower Zone rocks whereas the overlying gabbros exhibit a small positive Eu anomaly due to the accumulation of plagioclase. In the case of large intrusive complexes such as Skaergaard, Bushveld, Stillwater etc. the early cumulates tend to have a positive Eu anomaly and smaller La/Lu ratio than the presumed parent melts of the chill zone gabbro (Haskins and Haskin, 1968). The REE increases progressively in the stratigraphic sequence which could be ascribed to clinopyroxene crystallisation at low pressure (Cullers and Graf, 1984).
Nature of Source Rocks

The major and the trace element geochemistry indicate that the Bondla magma was tholeiitic in character and that it originated at mantle depths. It is generally agreed that tholeiitic magmas originate at the upper plagioclase stability limits. The Bondla magma can be modelled as a low-Ti, high-Mg basaltic magma. It is widely accepted that the generation of such a magma requires melting of a severely depleted residual mantle source. Experimental petrology arguments restrict the genesis of low-Ti basalts and boninites to high degree (25-35%) of water saturated melting of peridotitic mantle (Serri, 1981; Sun and Nesbit, 1978) at low pressures of less than 10 kb. However, the MgO content of the Bondla magma is rather low to be the product of partial melting of a primitive undepleted mantle source.

Mysen and Kushiro (1977) showed that melts produced by extensive partial melting of lherzolite contain about 20% MgO. High pressure melting experiments on peridotitic komatiite by Bickle and Ford (1977) also suggest that liquids in equilibrium with olivine and orthopyroxene
(residue of extensive partial melting) at 10 kb contain 18-19 % MgO. If the Bondla rocks had generated by extensive partial melting their MgO should have been higher which is not the case. Furthermore extensive partial melting should produce LREE-depleted melts unlike the LREE-enriched melts found at Bondla. This is because LREE decrease with increasing degree of partial melting while the HREE remain constant (Nicholls and Harris, 1980). The Bondla rocks also show low concentrations of High Field Strength Elements (HFSE). Sun and Nesbit(1978) suggested that the low content of HSFE is due to remelting of a mantle source already depleted in these elements. It is suggested that the low-Ti magmas at Bondla involved the remelting of a residual depleted mantle source with fractional crystallisation of derivative melts prior to magma emplacement. Such a model would explain the relatively high Cr, Ni and high Mg #s of olivine, Ca-poor - and Ca-rich - pyroxene in the Bondla rocks and also allows for somewhat lower levels of these elements than would be expected of partial melting of a primitive mantle source.

In order to know the nature and the type of source rocks the chemical data were plotted in Al2O3 /TiO2 vs
TiO\(_2\) (Fig. 5.1a) and CaO/TiO\(_2\) vs TiO\(_2\) (Fig. 5.1b) binary diagram. In the Al\(_2\)O\(_3\)/TiO\(_2\) vs TiO\(_2\) diagram majority of the rocks show affinities towards arc- and MORB- type of source. In the CaO/TiO\(_2\) vs TiO\(_2\) diagram majority of the samples plot in the depleted arc- type of source. A few which have higher content of TiO\(_2\) as a result of magmatic differentiation, plot in the undepleted - MORB field. Thus it is clear that the chemical characteristics are more consistent with a depleted arc- type source.

Tectonic Analogies

In the earlier sections the nature of the parent magma and the source characteristics have been outlined. In this section it is attempted to identify the tectonic analogies of the Bondla magma with the help of High Field Strength Elements (HFSE). Discriminant diagrams based on less mobile elements such as Ti, Zr, Y, Hf, Nb, etc. are currently being increasingly used for identifying the tectonic environments of volcanic suites (Pearce and Cann, 1973; Floyd and Winchester, 1975). However, when these diagrams are used to interpret the tectonic environments of Precambrian rocks, it is necessary to take into account
Fig. 5.1a Plot of Bondla rocks in $\text{Al}_2\text{O}_3/\text{TiO}_2$ vs $\text{TiO}_2$ wt.% diagram [(after Sun and Nesbitt, 1978)].

Fig. 5.1b Plots of Bondla rocks in $\text{CaO}/\text{TiO}_2$ vs $\text{TiO}_2$ wt.% diagram [(after Sun and Nesbitt, 1978)].
the changes in chemistry the rocks have undergone due to secondary alteration and weathering. In fact most of these diagrams are based on and adopted for the Phanerozoic volcanic suites and their validity as discriminants particularly for the Precambrian plutonic rocks could be a matter of speculation and debate. Pharaoh and Pearce, (1984) discuss the efficacy of HFSE in characterisation of tectonic environments vis-a-vis mantle evolution and they conclude that even though time related changes occur in mantle evolution, they do not change the efficacy of the discriminant itself (also Condie, 1976b).

In the Ti vs V plot, most of the samples plot in the field of arc-tholeiites, and MORB and continental tholeiites (Fig. 5.2a). The Ti/V ratio is less than 10 which is typical of arc-tholeiites (Shervais, 1982). The V/Ti ratio of igneous rocks reflects the oxygen fugacity of the magma (Shervais, 1982). In general the oxygen fugacity of arc-tholeiites is higher than that of MORB and continental tholeiites. In the Zr vs TiO₂ diagram (Fig. 5.2b) majority of the analyses occupy the field of arc-tholeiites. Two samples plot in the overlapping field of arc-tholeiites and MORB. In the Zr-(Ti/100)-(Yx3) tecton-
Fig. 5.2a Plots of Bondla rocks in 1000xTi wt.% vs V (ppm) [after Shervais, (1982)].

Fig. 5.2b Plots of Bondla rocks in TiO$_2$ wt.% vs Zr (ppm) [after Pearce and Norry (1979), Pearce (1979)].
ic discriminant diagram (Fig. 5.3a) (Pearce and Cann, 1973) majority of the Bondla rocks plot in the ocean floor basalt (OFB) and low-K tholeiite fields. Similarly in Zr/4-2Nb-Y triangular plot (Fig. 5.3b), the Bondla rocks either plot in the N-type MORB field or lie in the vicinity of it. From the various discriminant diagrams it is apparent that the Bondla magma is identical to an arc-tholeiite having some similarities to MORB.

Chemical characteristics of the Bondla complex provide further evidence for an island-arc type of magma. The island-arc rocks are typically characterised by enrichment of LILE over MORB. These enrichments are not dependent on any prior fractionation of parent magma (De Bari, 1994). In comparison with MORB the island-arc rocks show depletion in HFSE. The trace element patterns of the most primitive Bondla rock (BT2) is depicted in a MORB normalised pattern (Fig. 5.4). The pattern of a typical island-arc basalt from Talkeetna is also shown for comparison. The Bondla rock shows a characteristic arc-like signature with enrichment in LILE and depletion in HFSE relative to MORB. It is seen that the LILE concentrations in the most primitive Bondla rock are higher than average
Fig. 5.3a Plots of Bondla rocks in Zr-(Ti/100)-(Yx3) diagram [after Pearce and Cann, (1973)]. WPT-Within Plate tholeiites, OFB-Ocean floor basalts.

Fig. 5.3b Plots of Bondla rocks in Zr/4-2Nb-Y diagram [after Meschede, (1986)]. WPT-Within plate tholeiites, WPA-Within plate alkali, P- p-type MORB, N-N-type MORB.
Fig. 5.4 MORB normalised incompatible element pattern of troctolite and gabbro from Bondla and of island arc basalt, Talkeetna [from De Bari, (1994)].
whereas the HFSE are typically lower. Basalts erupted in continental margin arcs exhibit similar patterns as their oceanic counterparts but have higher absolute trace element abundances. They are also richer in HFSE. These features have been attributed to their derivation from metasomatised subcontinental lithosphere (Pearce, 1983). Although this interpretation could be valid in case of Bondla, it seems more likely that the higher concentrations could have been developed by a combination of progressive crystal fractionation and replenishment during in situ crystallisation of magma. Thus it can be concluded that the most primitive of the Bondla magma closely resembles a typical primitive island arc-type tholeiitic magma. The magma generated in continental environments, and evolved from a primitive tholeiite with island-arc-type trace element characteristics.

Mode of Emplacement

The Bondla mafic-ultramafic complex shows a close similarity to the Great Dyke complex of Zimbabwe as far as the layered sequence is concerned. At Bondla the Lower Zone is made up of ultramafic rocks (olivine- chromite
cumulates) and the Upper Zone of gabbros and norites (plagioclase, clinopyroxene cumulates). The two zones are distinctly separated by a horizon of pyroxenite and troctolite although these are laterally not persistent in all sections. Texturally all rocks are cumulates and no chilled margin has been observed along the contacts of the intrusion. The ultramafic zone is best exposed in the NW where the layering dips northeasterly by about 30 to 35°. The gabbronorites are exposed both in the north and south, however, they are better exposed in the south where isomodal layering is seen. This indicates that the complex is made up of two subchambers which were interconnected.

The western contact of the complex with Precambrian metasediments is marked by a fault zone (zone of mylonite) whereas, the eastern margin is largely concealed under laterite. Along the western contact small coarse grained gabbro bodies are locally intruded along the fault zone. This bears testimony to the layered rocks being uplifted to their present position subsequent to consolidation. Subsequent tilting towards southeast and erosion has exposed the deeper ultramafic part of the layered series in the northwest. The absence of thermal metamorphic
effects in the vicinity of the fault zone suggest that the country rock metasediments must have been well above the immediate roof of the intrusion. Hence the uplift of the layered rocks must have been considerable.

Sequence of Crystallisation

The Bondla parent magma is a low-Ti, high-Mg tholeiitic in composition. Such a magma is capable of precipitating olivine, chrome-spinel, pyroxene and plagioclase. Olivine and chrome-spinel are likely to have crystallised slightly earlier than pyroxene and plagioclase. Stratigraphy shows that the latter two minerals are absent from the Lower Zone ultramafites. The layering could be explained as due to mechanical sorting. However, the difficulty is of the size of the chrome spinels relative to density due to which they would not be expected to sink faster than pyroxene. Secondly the size and density of pyroxene is similar to that of olivine yet they do not occur as cumulate phases along with olivine. This suggests that the order of crystallisation rather than mechanical sorting was the prime factor responsible for the formation of
macro-units. The distribution of minerals, repetition of layers in relation to stratigraphy, presence of a thick chromitite layer, reversal of cryptic variation in chromites all point to there being an underlying set of causes which were repeated many times during the process of crystallisation. The conditions necessary for the development of repeated units were initiated by periodic replenishment of the magma chamber by a fresh pulse of genetically related basaltic magma from a deeper source (Irvine, 1977; von Gruenewaldt and Worst, 1987; Eales, 1987; Hatton and von Gruenewaldt, 1987; Eales et al., 1990).

The Ni, and Cr vs Mg # correlation is consistent with the early fractionation of olivine and chromite from the magma (that resulted in low concentration of these elements in later differentiates) in the initial magma pulse at the same time driving the magma towards silica saturation which led to the precipitation of Ca-poor pyroxene in preference to Ca-rich pyroxene. Normally mantle derived magmas should crystallize Ca-rich pyroxene before Ca-poor pyroxene at crustal pressures (Campbell, 1985). The prevalence of Ca-poor pyroxene over Ca-rich pyroxene in the ultramafic part of the Bushveld has been
ascribed to elevated SiO$_2$ at the time of emplacement, as a result of pre-emplacement crustal contamination (Campbell 1985, Barnes, 1989) although continental boninite associations have been suggested. In the present case, however, the increase in silica is ascribed to olivine separation. The presence of Ca-poor pyroxene also indicates the anhydrous nature of the melt at this stage.

Subsequent to the crystallisation of pyroxenites the water content in the magma increased due to which olivine got stabilised relative to pyroxenes which led to the formation of the troctolite layer. The anorthitic nature of the troctolite plagioclase can also be attributed to the presence of water in the melt during crystallization (Helz, 1973).

The later more primitive pulse mixed with the resident magma (from the previous unit) to give a homogeneous liquid. A part of the residual magma may have been extruded from the chamber as lava at a surface volcano to form the metabasalts associated with the mafic-ultramafic rocks.
This situation was operational in the deeper northwestern magma sub-chamber which gave rise to the olivine chromite cumulates. This seems to be more likely because in the early stages of magma chamber formation the tectonic conditions may have been unstable and resulted in periodic flooding of the chamber with fresh supplies of more primitive magma. Such a process of magmatic integration has been suggested by Wager and Brown (1967) in case of the Bushveld Complex of South Africa. Towards the close of the integration stage a magma replenishment occurred that gave rise to the main chromitite layer. Further differentiation occurred by crystal fractionation and gravity separation with the development of more regular cryptic layering and subdued rhythmic layering. This is observed in the southern magma sub-chamber where more regular cryptic variation is seen in the gabbro, gabbronorite and leucogabbro (Fig.5.5).

The southern sub-chamber was relatively shallow as deduced from the dominance of medium grained rocks. Lower MgO content of the rocks and greater degree of LREE enrichment than the rocks of the northwestern sub-chamber indicate more fractionated nature of the magma in the
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Fig. 5.5 A schematic stratigraphic column (not to scale) showing variations in mineral composition and whole-rock Zr content of representative rocks from Bondla.
southern sub-chamber. In this zone the plagioclase and the pyroxenes show a trend of crystallisation towards low temperature compositions. The magma became progressively richer in iron probably accompanied by increase in oxidation state leading to the precipitation of titaniferous magnetite. The melanocratic layers grade upwards into felspar-rich layers indicating rhythmic layering. Fractionation led to precipitation of plagioclase of andesine composition, Ca-rich pyroxene to ferroaugite composition and Ca-poor pyroxene to ferropigeonite. Upwards the rocks become leucogabbros with occasional granophytic textures.

Role of Water during Crystallisation

Several features of the Bondla intrusion indicate that the parent magma was hydrous in nature but it was not water saturated. This is supported by co-existence of olivine which is stable under hydrous conditions and orthopyroxene which is unstable under water saturated conditions. Continued crystallisation of anhydrous minerals may have led to water enrichment in the magma which stabilised anorthitic plagioclase. A minimum water content
can be inferred from the work of Holloway and Burnham (1972) who showed that amphibole will only crystallise from a basaltic melt that contains more than 3 wt.% water at the time of crystallisation. As amphibole is absent in the Bondla rocks it may be inferred that water content was much less than 3 wt.% originally, but may have increased at the time of plagioclase crystallisation.

Crystallisation Temperatures

The crucial factor in understanding the evolution of the rock suite is the knowledge regarding the temperature conditions under which the rocks crystallised. The only evidence of this is provided by the minerals contained in the rocks. Here it is considered that coexisting mineral phases are in the equilibrium, in the absence of evidence to the contrary. Although the estimated temperatures may not be exactly those at which the minerals crystallised, it is not unreasonable to consider them at least as lower limits at which the minerals crystallised or re-equilibrated.

It has been attempted here to make qualitative...
assesment of the temperatures of crystallisation of the gabbroic rocks from the Bondla complex from the chemistry of pyroxenes. The efficacy of coexisting Ca-rich and Ca-poor pyroxenes to provide temperature information is well recognised. However, the lack of directly measured Fe$^{2+}$ and Fe$^{3+}$ creates a problem while using these geothermometers. The problems involved in applying experimental data from simple synthetic systems to complex natural mineral assemblages have been reviewed by Boyd (1973).

Temperature estimates were computed using the empirical geothermometers on experimentally determined Ca-Mg-Fe pyroxene phase relations following Lindsley (1983). The clinopyroxene mole fractions have been plotted in the experimentally contoured pyroxene quadrilateral (Lindsley, 1983) at 5 kb and 10 kb (Fig. 5.6a and Fig. 5.6b). The Ca-rich pyroxenes from troctolites (BT1) indicate temperatures between 1000 to 1200°C whereas, Ca-poor pyroxenes give temperatures between 1200 and 1300°C. The Ca-rich pyroxenes from gabbro (GS23) give temperatures of about 1000°C.

Textural evidence indicates that the cumulates in
Fig. 5.6  Plot of Ca-poor and Ca-rich pyroxenes from Bondla rocks in pyroxene quadrilateral contoured at 100°C interval for use in geothermometry [Lindsley, (1983), (a) 5kb, (b) 10kb].
gabbroic rocks (GS23) crystallised very close to the inversion temperature of pigeonite. The orthopyroxene formed by apparent inversion of pigeonite with a Mg # varying between 0.6 to 0.7. It has been shown by Barnes and Hoatson (1994) in case of the inverted pigeonites of the Munni Munni complex, Western Australia that orthopyroxene with Mg # in the range of 0.60 to 0.63 correspond to crystallisation temperature of 11000°C (Lindsley, 1983). BaIhaus and Glikson (1989) in Wingellina Hills intrusion, Central Australia suggest that olivines with Fo89 should have a melt with Mg # 0.72 and estimate the liquidus temperature of the parent melt at about 13500°C. By similar reasoning, it may be suggested, that the liquidus temperature of the primitive melt (BT2) at Bondla may have been approximately between 1200 and 13000°C, at pressures approximately 6-10 kb. These values appear to be fairly in conformity with most basaltic compositions.

**Depth of Crystallisation**

Tholeiitic magmas in general originate at the upper plagioclase stability limits which broadly correspond to a
pressure of about 10 Kb. Low-Ti basalts and boninites under water saturated melting conditions originate at low pressures of less than 10 Kb (Serri, 1981; Sun and Nesbitt, 1978). The crystallisation in the northwestern sub-chamber may have taken place approximately at 10 Kb. However, in the southern sub-chamber the crystallisation possibly occurred at a pressure of less than 10 kb, as plagioclase - the dominant phase of this zone, becomes unstable at 10 kb (Kushiro and Yoder, 1966; Green and Hibberson, 1970). Experimental studies on the system anorthite-potassium feldspar at 10 kb by Ai and Green (1989) showed that maximum solubility of K-felspar in plagioclase is about 18% at 10 kb. As the plagioclase at Bondla contains about 0.2 mole % K-felspar, it is contented that they are of low pressure origin.

Heat Source for Magma Generation

It has been shown that the Bondla magma was generated by partial melting of depleted mantle pyrolite source, in the shallower part of the mantle where the water content is sufficient to induce melting.
For melting to occur at relatively low pressures it is necessary that the geothermal gradient should be fairly steep and temperatures of about 1300°C be attained. Hence, it is essential to define the source of heat. From the currently available data on heat flow measurements from the Indian shield, it is possible to have a rough estimate of the conditions prevailing during Archaean. Heat flow in the Dharwar area is approximately $1 \times 10^{-6}$ cal/cm²/sec and it increases in the northern part to 1.5 to $2 \times 10^{-6}$ cal/cm²/sec (Naqvi and Rogers, 1987). Average heat flow from the Indian peninsula appears to be slightly higher than other Archaean shields (Jessop and Lewis, 1978). If this difference is valid then it can be explained that the heat production in the crustal rocks may have been higher in the Archaean rocks in India than in similar rocks elsewhere (Rao et al., 1976). If these gradients have persisted for large part of geologic time then it can be visualised that enhanced melting might have taken place in the mantle (Naqvi and Rogers, 1987) during the Archaean. The close spatial association of rocks of komatiitic chemistry also hints at the unusually high geothermal gradient in the upper mantle before 2,500 Ma (Srikantappa et al., 1984).
A high geothermal gradient and a crustal thickness of about 35-40 km in Peninsular India (Naqvi and Rogers, 1987) could have supplied the required heat to bring about melting.

In summing up it is suggested that, the Bondla mafic-ultramafic complex represents an open system magma chamber which was periodically replenished by pulses of fresh primitive melt from below with concurrent fractionalation at a pressure of approximately 10 kb. The complex comprises two subchambers, the northwestern and the southern. The northwestern chamber is deeper, wider and represents the main chamber (conduit). The southern chamber is shallower, narrower, and represents a higher level of the magma chamber. The main chamber shows rhythmic layering marked by olivine and chromite with a main chromitite horizon at the top of the ultramafic pile. In the southern chamber a layered gabbro sequence developed by convection and gravitational differentiation of a more evolved magma at a more shallow level after the stabilisation of the magma chamber.

The parent magma is a low-Ti, high-Mg tholeiitic
magma that was generated from a slightly metasomatised subcontinental lithosphere having trace element characteristics similar to continental arc-type lavas.

**Genesis of chromite**

In discussing the genesis of chromites some of the features appear to be significant. (i) The chromites occur as layers 0.5 to 5 cm in thickness which alternate with olivine-rich layers. (ii) Towards the top of the ultramafic pile the chromite occurs forming a thick chromitite layer 300 m wide (iii) Cr # of chromite increases from peridotite chromite to chromitite chromite and an opposite behaviour is shown by Mg #. Cr # shows inverse relationship with Al #. (iv) Fe+3 increase from peridotite chromite to chromitite chromite to troctolite chromite.

The Cr/(Cr +Al + Fe+3) ratio of Bondla chromites increases from peridotite chromite to chromitite chromites and then decreases further up in the troctolite chromite. The upward increase in Cr # could be related to enrichment of Cr+3 in the magma brought about by replenishment in the magma chamber. It could also be related to early clinopy-
roxene crystallisation which decreases the Cr/(Cr+Al) of the associated chromites as Cr/Al of clinopyroxene is higher than that of the melt (Roeder and Reynolds, 1991). This could also explain the absence of chromites in the gabbro pile above the troctolites. The absence of chromites in the gabbros in one sense is comparable to the stratigraphic gap observed in the Bushveld complex where no chromites are recorded.

Further upward decrease in Cr # from the chromitite chromite to troctolite chromite is largely dependent on the available Cr+3 in the magma. Fisk and Bence (1980) have shown that the Cr/(Cr+Al+Fe+3) ratio of chromite co-precipitating with olivine decreases with decreasing temperature and that this trend may be related to a gradual decrease of Cr+3 in the magma with continued spinel crystallisation.

A different behaviour is however, shown by Fe+3#. It increases progressively upwards from peridotite chromite to chromitite chromite to troctolite chromite and also shows an inverse relationship with Mg #. In general chromites that crystallise early from basaltic magmas in
nature generally have Fe$^{3+}$ # below 0.15 (Roeder and Reynolds, 1991) which is also the case with the Bondla chromites. The upward increase in Fe$^{3+}$# need be explained. Roeder and Reynolds (1991) have experimentally shown that ferric content of chromites increases with increasing $f_{O_2}$. The upward increase in Fe$^{3+}$# shown by Bondla chromites could be related to increase in $f_{O_2}$ brought about by the fresh pulse of magma, however, such a conclusion has to be taken with considerable reservations owing to the altered nature of the chromites.

Increase in $f_{O_2}$ promotes crystallisation of spinel at the expense of silicates (Yoder and Tilley, 1962). Hill and Roeder (1974) have experimentally shown that increase in $f_{O_2}$ promotes crystallisation of spinel however, Al$_2$O$_3$ content, Cr/Fe and Mg/R$^{+2}$ ratio decreases at the same time as also seen in case of Bondla chromites. The decrease of Cr # of chromites is slightly affected by falling temperature because although total Cr content of basaltic melt is very sensitive to $f_{O_2}$ the composition of coexisting chromites is relatively insensitive to $f_{O_2}$ value near and below that of FMQ buffer (Roeder and Reynolds, 1991). The reason being that Cr$^{+3}$ content of the melt controls
chromite composition and not the total Cr dissolved in the melt. Experimental studies (Elthon et al., 1982) and petrological investigations (Bodimier, et al., 1987; Suen and Frey, 1987) suggest that under sufficiently high pressure, pyroxene, olivine and spinel crystallise from basaltic magma to the exclusion of plagioclase. Thus Elthon et al., (1982) concluded that ultramafic cumulates in the North Arm Mountain massif of the Bay of Island ophiolite crystallised at pressure of >10 kb. DeBari and Coleman (1989) reported a thick sequence of ultramafic rocks overlain by cumulate gabbros from Tonsina, Alaska. They have also been interpreted as high pressure cumulates. Some analogies with these rocks could be drawn in explaining the crystallisation of the Bondla rocks. It is tempting to suggest that the Bondla ultramafic pile with the chromite layers represent high pressure crystallisation (>10 kb) of a basaltic magma. This is supported by experimental observations of Roeder and Reynolds (1991) wherein they have shown that increasing pressure leads to decrease in stability of plagioclase with a consequent increase of alumina both in the melt and coexisting chromites. Thus the chemical variation shown by chromites is not due to solubility of Cr in basaltic melts but it is the effect of
Al\textsubscript{2}O\textsubscript{3} content of the melt and are not direct effects of pressure on the chromite–melt equilibrium as also shown by Fugi and Scarfe (1985) and Fallon and Green (1987).

**Cyclicity of layering**

Cyclicity of layering could be considerably modified and diversified simply through the blending of batches of liquid of the same parentage at different stages of differentiation. Such a process can readily be visualised as occurring in subvolcanic intrusions and passageways through eruptive processes whereby fresh magma is repeatedly added to residues of earlier liquids that have been differentiated by partial crystallisation.

The dominant process of layer formation seems to have been sudden repetitive changes in supply of crystallisation products (settled crystals). It is essential, however, to explain the deposition of a thick chromitite layer. The petrogenesis of such a monomineralic layer of chromite remains a debated issue. One explanation is that the chromitite layer was formed by fractional crystallisation. Irvine and Smith (1969) explain that fractional
crystallisation by itself cannot yield a concentrated deposit of chromite once silicate minerals begin to form, but some additional process is required. Several hypotheses have been put forth by different workers to explain the mechanism for the origin of chromite-rich layers in stratiform intrusions.

On the basis of silicate inclusions in chromite from the Bushveld chromites, McDonald (1965) suggested the existence of a chrome-rich immiscible liquid. This interpretation was however, criticised by Jackson (1966) who argued that it is unlikely that such a liquid would form in a basic magma. Cameron and DesBorough (1969) and Ulmer (1969) explaining the chromitites of Bushveld critical zone suggested that an increase in oxygen fugacity brought about by the assimilation of wall rocks could be the responsible factor. Whereas, according to Cameron, (1977, 1978) tectonically induced changes in total pressure in the magma chamber could bring about deposition of chromitite layers of great extent.

Contamination of the parental magma with granite melt derived from salic roof rocks was proposed by Irvine
(1975) as a possible mechanism by which chromitites formed in the Muskox and other intrusions. In the case of Stillwater Complex, Campbell and Turner (1986) opined that early emplacement of magma brought about extensive melting of the floor leading to contamination of the magma which mixed with the following fresh input of a primitive magma to form the chromitite layer. Mixing between a relatively fractionated (evolved silicious) magma with a chromite-saturated primitive liquid is also suggested by Irvine (1977). The variation in chemistry exhibited by the Bondla chromitites is consistent more with the latter possibility.

**Syntering of grains**

One of the major problem concerning the origin of chromitite layers is how chromite cumulate with a calculated and experimentally determined porosity of 30 to 45% (Jackson, 1961; Cameron and DesBorough, 1969) became densified to form a massive chromitite with less than about 10% silicates. Various hypothesis have been proposed to explain this feature. Cameron and Emerson (1959) suggested partial melting of cumulus chromite. McDonald (1967) proposed the existence of chromite rich liquid.
Both possibilities were rejected by Jackson because a chromite-rich liquid would require a temperature of 1700 to 2000°C.

Spry (1969) points out that simplest mechanism of crystal enlargement is by annealing or synering of fine grained aggregates of strained grains to form a coarse grained aggregate of unstrained grains. The driving force for the growth being the lattice strain energy plus grain boundary energy. By this process polygonal texture can develop. The synering process is greatly enhanced by the presence of a capillary fluid. The presence of a liquid phase can enhance the rearrangement of the particles in the aggregate to get the most effective packing and can produce maximum number of grain boundary contacts. The weight of the overlying crystal mush can provide the desired pressure. The process in this case is referred to as pressure synering. Under thermodynamic equilibrium conditions the shape of the grains is polygonal with straight to slightly curved grains boundaries meeting in 120° at triple junctions. The development of polygonal grains with triple junctions in adcumulates such as chromitites was considered by Voll (1960) to be due to syner-
ing. Golding (1975) considers such a mechanism to explain chromitites in podiform chromites from the Coolec ultramafic belt in New South Wales. A similar process is considered by Reynolds (1985) to have caused the densification of the magnetite layers in the upper zone of the Bushveld complex.