Chapter 7
Mode of Emplacement and some Petrogenetic Aspects

Various theories have been advanced by a number of workers in order to decipher the mode of emplacement of ring complexes.

Classical models have been given by Clough, Maufe and Bailey (1909); Smith and Bailey (1968) and Anderson (1936). The author intends to mention some general geological aspects of the mode of emplacement.

- Ring dykes fill transverse fractures that form in overlying rock cover when the magmatic pressure drops and a block from the cover founders; the fractures are projected upwards as subhorizontal tension faults.
- Radial dykes are emplaced into vertical tension fractures of hydraulic origin which are formed periodically by upwardly directed pulses of magma.
- Cone sheets fill shear fractures caused by the pressures that result from the rapid expansion of retro-boiling magma.

7.1 Chapman's Model

In order to explain the close association in space and time between basalt and gabbro, syenite and trachyte, riebeckite or arfvedsonite granite and rhyolite, Chapman (1966, 1976) has invoked the concept of polymagmatic chamber
(Fig. 7.1). According to this model, two magmas, basaltic and granitic could have formed at nearly the same time but at different levels in the earth, or the granitic magma could have been formed by selective melting of crustal material by the hot basaltic magma. Mainly because of its high viscosity and low density, much felsic melt would escape mixing and rise as liquid globs to the top of the magma chamber. Once a thin layer of granitic melt had formed above the mafic melt, it would develop its own pattern of thermal convection, which would operate in harmony with that established in the mafic melt beneath. Heat from the cooling mafic melt would be transferred upward through the granitic magma by tandem convection, and the processes of melting of the roof rocks could continue. The granitic melt would possess considerable superheat for some time, because its temperature would be maintained at roughly that of the mafic magma below. Presumably while the cap of granitic melt was still forming, the basalt melt was crystallizing, and the heavy minerals that formed early collected, with the xenolithic material, at the base of the magma chamber and built up on the floor. Melting by the granitic liquid, when deprived of its superheat became negligible, but stoping remained active in the more brittle and easily fractured sialic crust. During differentiation, the capping reservoir of the granitic liquid would grow in size and ultrabasic cumulate will be
Fig. 7.1 The polymagmatic chamber model with layers of enclaves (Chapman, 1966).
developed at the chamber base and during the cauldron subsidence process, the acid liquid form granite and syenite. The mixing of acid and basic magma is inhibited by the block faulting or extensional tectonic regime (Cf. Eichelberger and Gooley, 1977). Fig. 7.2 summarises the model of the evolution of silicic igneous complexes: (a) basalt from the upper mantle heats the crust (b) partial melting of the lower crust produces rhyolitic liquid which gathers into diapirs reach the upper crust rapidly, and little mixing occurs.

Chapman's hypothesis, developed from field data gathered from the different levels of ring complex formation, match perfectly the data from the various levels of cross sections through the magmatic chambers of the outcrops of Precambrian anorogenic batholith complexes in the United States, e.g. Pikes peak Colorado (Barker et al., 1975); Wolf River, Wisconsin (Van Schmus et al., 1975); Wichita, Oklahoma. In the Appalachians the examples are of upper Devonian age, e.g. Bays of Maine (Chapman, 1962); Saint-George, New Brunswick (Martin, 1970). All involve the stratiform association of gabbros with hypersolvus granites which intrude the roots of ring complexes and acid volcanics.

The Goliya Bhaylan area is characterised by the close association of trachytes (syenites), basalt with alkali granites. In the adjoining Mokalsar area, the

Fig. 7.2 Negligible Mixing, Short Crustal Residence

CRUST
MANTLE

Basalt Magma
Rhyolite Magma

Fig. 7.2 A model for evolution of Silicic igneous complexes (Eichelberger and Gooley, 1977).
peralkaline granites are closely associated in space and time with trachyte flows (Vallinayagam, 1988). In the adjoining Gura Nal area, the peralkaline granites are closely associated in space and time with gabbro (Chellasamy, 1990). From the Mokalsar area, Vallinayagam (1988) has reported peraluminous acid volcanics. Peraluminous rhyolites from Siwana has also been reported by Srivastava (1989). The peraluminous nature of these acid volcanics may be due to deuteric alteration.

In the Jalor area, the peralkaline-peraluminous granites are closely associated in space and time, with gabbro and basalt flows (Kochhar and Dhar, 1988; 1992). In view of the association of trachyte, basalt and gabbro, with the hypersolvus, subsolvus granite of the Malani area, it is suggested that the Chapman model (1966, 1976) of the polymagmatic chamber as outlined above can be applied to the area under study.

7.2 PETROGENESIS OF A-TYPE GRANITES

The following characteristics of A-type granite are as follows:

1. They are usually true granites in the classification of Streckeisen (1973).
2. They occur in anorogenic settings and commonly in tensional regimes where they postdate the intrusion of other sorts of granites.
A-type commonly form subvolcanic plutons or occur as lava flows; ash flows are less common. This contrasts with both I- and S-types which mostly occur as large plutons forming huge batholiths. S- and I-type volcanics are usually ash flows. Typically, A-type granites and rhyolites are metaluminous and calcium poor but have elements such as Sr, Rb, Ba in abundances similar to those in unfractionated S- or I-type granites. However, these metaluminous A-type are commonly associated in space and time with peralkaline A-type granites. Also many peraluminous granites are anorogenic.

Typical rock associations that include A-type are (1) granites (including peralkaline granites), syenites, gabbros and anorthosites (e.g., Pikes peak, Colorado, Barker et al., 1975); (2) bimodal suites of granites (all metaluminous), rhyolites, gabbros and basalts (e.g., Southeastern Australia, Collins et al., 1982).

7.3. CHEMICAL CHARACTERISTICS

A-type granites exhibit chemical features, namely high SiO₂, Na₂O+K₂O, Fe/Mg, Ga/Al, F, Zr, Nb, Ga, Sn, Y, Zn and REE (except Eu) and low CaO, Ba and Sr (Loiselle and Wones, 1979; Collins et al., 1982; White and Chappel, 1983). They exhibit a characteristic mineralogy consisting of iron rich mafic silicates (annite, ferrohedenbergite,
ferrohastingsite and fayalite) and in peralkaline suites alkali-rich mafic silicates (aegirine, arfvedsonite and riebeckite) and perthitic feldspars. Peraluminous and mataluminous granites of A-type granite suite exhibit relatively little variation in Zr, Nb, Ce, Y, Zn and Ga/Al, e.g. the Gabo and Mumbulla A-type suites of Lachlan fold belts. Suites of more alkaline phases contain distinctly high concentration of Zr, Nb, Ce, Zn and Ga/Al (Whalen et al., 1987).

7.4 CHARACTERISTICS OF GOLIYA BHAYLAN GRANITES

Although A-type granites are volumetrically insignificant compared with the vast amount of S- and I-type granites, in various parts of the world, their genesis are of particular interest since Mo, Sn, W, Nb, Ta, REE, Be and Li mineralisation (Collins et al., 1982; Pitcher, 1983) is commonly associated with A-type or fractionated granites.

The Goliya Bhaylan granites have the following characteristics typical of A-type rocks:

1. The granites are high level, subvolcanic and intrude their own ejecta.
2. They occur in anorogenic setting i.e within plate tectonic environment.
3. They show bimodal suites of granites, rhyolites, trachytes and basalt.
4. They are felsic, metaluminous but peralkaline according to anapaitic index.
5. They are hypersolvus granite crystallized from relatively dry, high temperature, completely molten (i.e. restite free) magma.

6. Mineralogically, these granites have characteristic alkali-rich mafic silicates i.e. aegirine, arfvedsonite and riebeckite.

7. These granites are low in CaO, MgO, high in SiO₂, Na₂O + K₂O, Fe/Mg, Zr, Nb, REE (except Eu) and very low in Co, Cr, Ni and Sr. These granites characteristically have enriched relatively flat to somewhat HREE depleted (La/Yb : 5.25) chondrite normalised REE pattern with significant Eu anomaly (Cf. Collins et al., 1982; Jackson et al., 1984).

From the above mentioned characteristics, there is no doubt that these granites are clearly anorogenic using the currently extant classifications. Thus, the Goliya Bhaylan granites are classified as A-type and their petrogenesis is presumably similar to that of other A-type granites.

Any theory on the petrogenesis of these A-type granites needs to explain:

1. The origin of peralkalinity.
2. Petrographic evidence that these granites crystallised from relatively dry, high-temperature, completely molten (i.e., restite free), Cl- and F-rich magmas.
3. High absolute abundances of a number of incompatible and high-field-strength (HFS) elements.

In broad terms, theories on the petrogenesis of alkaline granites fall into three categories:

1. Alkalinity developed by metasomatism of more normal magma, either early (e.g. Bailey, 1978; Currie et al., 1986) or late (e.g. Taylor et al., 1980) in its development.

2. Alkalinity developed as a consequence of fractionation (e.g., Currie (1976), usually assumed to involve either plagioclase or an aluminous amphibole.

3. The initial melt was alkaline due to peculiarities of the source (e.g., Collins et al., 1982).

7.5 DIFFERENTIATION MODEL

The role of fractional crystallization in producing alkaline to peralkaline compositions has been debated for decades (Currie, 1976). The phases most often cited are plagioclase and aluminous amphiboles. Most A-type granite complexes are comprised of large volumes of felsic rocks lacking associated intermediate rocks and plutons seem to lack significant internal differentiation according to standard indices (K/Rb, K/Ba, Rb/Sr, Rb/Ba) (Anderson 1983; Collins et al., 1982; Jackson et al., 1984).
For the Goli a Bhaylan rocks, the absence of restite in the A-type granites implies that there is no petrographic evidence against fractional crystallization. The high concentration of elements such as Nb and the low abundance of Ca is consistent with a fractional crystallization model. However, such a process cannot occur in the enrichment of elements like Zr, Zn and depletion of Sr. Moreover, differentiation would produce minor volumes of granite with a partial A-type signature.

7.6 PARTIAL MELTING MODEL

If direct partial melting is a viable process for the formation of A-type melts, the only constraints that can be placed on the nature of the source are that (a) it must contain quartz + K-feldspar + plagioclase either as separate phases or as normative components necessary to form any granite and (b) it must be fluorine and/or chlorine-rich but poor in water. This source composition may be satisfied if the source rock has already a granitic magma extracted from it. A residual source was suggested by Barker et al., (1975) for the Pikes peak batholith of Colorado.

This model is able to predict many of the characteristics of A-type granites:

1. Some A-type granites have higher contents of F and low interpreted magmatic water contents than other granites. Collins et al., (1982) explained these features by proposing that after the first melting
event, residual biotite and amphibole are F-rich and the granulite residue has a low water content. These characteristics are inherited by A-type granites produced from this residual source.

2. The enrichment in high field strength elements (HFSEs) such as Zr, Nb, Y and REE's is explained by the higher temperature required for the second partial melting compared to that for original protolith. Under these higher temperature conditions, the solubility of accessory phases such as zircon and apatite may be high, and the solubility of zircon is enhanced by the high alkalinity of A-type granite magmas, thus contributing HFSEs to the melt (Watson and Harrison, 1984). Collins et al., (1982) also suggested that high F may promote high HFSE contents in the melt through complexing effects.

3. Most A-type granites are generated late in the magmatic or orogenic cycle of any particular crustal province, after the production of other granite types.

Though most of the characteristics of the Goliya Bhaylan granites can be explained with this model, the following factors do not favour the application of the partial melting of the depleted granulitic source for the Goliya Bhaylan granites:
A more detailed geological, geochemical and geochronological study is required to know the granite type and geochemistry in and around the Malani igneous suite, like the study done in Lachlan fold belt, Southeastern Australia (Collins et al., 1982). Only such a study will allow the comparison of the chemistry of first formed I-type and later formed A-type granite.

Recently Creaser et al., (1991) have argued that A-type granites are unlikely to be produced from a felsic granulite source rock that had previously generated an I-type granite. Their objection centre mainly upon the expected mineral content and geochemistry of this residual source and its ability to yield partial melts with A-type geochemical characteristics. They have presented experimental and natural data arguing convincingly against a "residual-source model".

Creaser et al., (1991) state that "we agree with Collins et al., (1982) that the source of A-type granites contains quartz, alkali feldspar and plagioclase, but disagree that this mineral assemblage is the result of previous generation of I-type granites".

Chapell and Stephens (1988) suggested that restite-free granite magmas, as well as those containing restite, may inherit the geochemical characteristics of their
sources if crystal fractionation or restite separation was not extensive. According to Creaser et al., (1991) a residual source will be enriched in Ca and Al (in plagioclase) and Mg and Fe (in pyroxenes + amphibole) and depleted in K and Si relative to the original protolith. The residual granulite of Rudnick and Taylor (1987) shows these characteristics with very low SiO₂ (43%) and K₂O (0.2%) abundances together with high Al₂O₃ (19%), MgO (7%), FeO (15%) and CaO (9%) abundances. So, we can see that the A-type geochemical characteristics are exactly opposite to that of the residual source geochemical characteristics.

Creaser et al., (1991) have suggested that A-type granites can be derived by partial melting of tonalitic to granodioritic compositions (Anderson, 1983). The source rocks have not undergone prior melt depletion and have not necessarily experienced granulite facies metamorphism prior to A-type granite generation.

Their source rocks of tonalitic to granodioritic composition forms a logical extension to the model suggested by Chapell and Stephens (1988) for the origin of I-type granites. According to Chapell and Stephens (1988) the partial melts of primitive addition to the continental crust (M-type granites) may yield I-type (tonalite) granites, which may in turn generate more potassic I-type granodiorites when they are themselves partially melted. A-type granites may be the final link in this progressive
model, a suggestion that is in accord with their enrichment in lithophile elements over granites.

This model of Creaser et al. (1991) also explains many characteristics of A-type granite:

1. Granites derived from vapour-absent partial melting of felsic and tonalitic and granodioritic rocks that have not been metamorphosed to granulite facies conditions prior to A-type granite generation also have low water contents, because the amount of water structurally bound in amphibole and biotite in these source rocks is small.

2. During partial melting of tonalites and granodiorites, essentially all F will be partitioned into the melt because only modally minor apatite + titanite can accept F in the residue. The high contents of HFSEs in A-type granites are explained by the solubility relations of accessory phases, together with the high F contents of the melts. The low contents of ferromagnesian trace elements V, Cr, Co and Ni in A-type granites relative to I-type granites (Collins et al., 1982) are consistent with the derivation of A-type granites from sources more felsic than those involved for I-type granites.
Thus, it is possible to conclude that partial melting of crustal igneous rocks of tonalitic to granodioritic composition can be one possible candidate for the origin of A-type Goliya Bhaylan granites.

**7.7 METASOMATIC MODEL**

Metasomatism could be of three types (i) metasomatism of magma by an extraneous fluid, (ii) auto-metasomatism of a magmatic body in situ without intervention of an extraneous fluid phase, (iii) metasomatism of solids.

Metasomatism of magma by an extraneous fluid leading to peralkaline rocks appear to be rare process. Currie et al., (1986) described an example where an alkali gabbro pluton interacted with brine, producing peralkaline syenite. The brecciated character, depleted REE signature, very high Cl and Br content, and disturbed Sr isotope signature of the peralkaline rocks of Mont Saint Hilaire unmistakably indicate the former presence of a free brine phase. The Siwana ring complex exhibits large scale homogeneity in peralkaline magma and there is no doubt that such a local process of metasomatism of magma by an extraneous fluid need not be involved for the Goliya Bhaylan rocks.

"Gas streaming" hypothesis have been suggested in the literature on alkaline rocks as a method of producing peralkaline patches in subalkaline plutons by subsolidus reactions (Taylor et al., 1980; Martin and Bonin, 1976). The
operation of hydrothermal solutions in peralkaline rocks can be readily demonstrated by the study of feldspar (Martin and Bonin, 1976), but if peralkalinity was due to these hydrothermal processes, it would be expected that the distribution of peralkalinity would be patchy and related to fluid migration channels. Then, obviously the present model can be excluded for the Goliya Bhaylan granites.

Alkali metasomatism of solid rocks (fenitization) is a common process at shallow to moderate crustal levels (for example Beach, 1973; Semiatkowska and Martin, 1975; Currie and Ferguson, 1971) which produces metasomatic peralkaline rocks, commonly along cracks and fissures surrounding alkaline complex. Fenitization can produce an alkaline or peralkaline protolith to serve as a source of future magma.

Metasomatism of the upper mantle and lower crust to produce materials enriched in alkalies and incompatible elements as a protolith for extraction of alkaline or peralkaline magma has been much discussed in recent literature (Hawkesworth and Norry, 1983; Bailey, 1987).

The mineral chemical data discussed previously have shown the presence of highly evolved alkali amphiboles and pyroxenes. The high FeO, Na₂O and low CaO contents of these minerals indicates that significant fractionation of mafic silicates did not occur prior to the emplacement of magma (cf. section 4.1 and 4.2). The trace element data are
consistent with the fractionation of feldspar and amphibole from the magma after its emplacement into the upper crust. The low concentrations of Sr and marked negative Eu anomaly (Eu/Eu* ratios of 0.32-0.36) are consistent with feldspar fractionation. Thus, the data discussed above do not support differentiation of this peralkaline magma from a less alkaline magma through crystal fractionation, leading to the conclusion that the chemical characteristics was established at the time magma was generated. It is possible that the magma was derived from metasomatized crust. If this magmatic activity could be related to a mantle plume as suggested by Kochhar (1984), Eby and Kochhar (1990), then the fluids moving upwards from this plume could metasomatize lower crustal material thus providing a chemically anomalous region characterized by the high HFS and LIL elements, in which the melt is generated. The fluids could be from the basalts and gabbros occurring in the area and possibly from the mantle (?) to provide a chemically anomalous region. Pending the acquisition of isotopic data it is not possible to quantify the input from the mantle.

In conclusion, the derivation of magma by partial melting of crustal igneous rocks of granodioritic to tonalitic composition is one possible model, another possible model which deserves serious consideration is that the magma was derived from metasomatized crust.