CHAPTER VI
PETROGENESIS

The data accruing from the field, petro-mineralogical and chemical investigations have been used in this chapter to discuss and establish the petrogenesis of the Kargil igneous complex. From these studies, it is evident that at least four phases of igneous activity have been witnessed by the area.

PHASE-I

The first phase of igneous activity is marked by the extensive outpour of basaltic-andesitic lava. These volcanics have been epidotized and chloritized showing thereby a low grade of metamorphism. Moreover, along their contacts with tonalites and granite, these have been transformed into amphibolites. The talc schist occurring near Chubuk, west of Kargil and also in the north of Shamsha, may be an altered products of originally ultrabasic rocks. According to Wadia (1937), this first phase probably occurred during the Upper Cretaceous to Lower Eocene times.

PHASE-II

The large scale intrusions of composite hornblendite-pyroxenite and norites followed by emplacement of gabbros
represent the second phase of igneous activity in the area - composite hornblendite-pyroxenite and norites being earlier than the gabbros. It is also presumed that composite hornblendite-pyroxenite and norites are contemporaneous in age.

PHASE-III

Tonalites and granite form the third and the last phase of large scale magmatic activity in the area. The granite, restricted in occurrence, is later than tonalites in its emplacement.

PHASE-IV

The dyke swarm cutting across all the rocks of the area (except Tertiaries) represents the end phase of magmatic activity in the Kargil area. It is significant that these dykes varying widely in their composition give an evidence for the existence of both basic and acidic magmas. The sequence of magmatic cycles in the area can, thus, be summarized as follows:

First Phase: Outpour of basaltic and andesitic volcanics - basic to intermediate magma

Second Phase: a) Emplacement of composite hornblendite-pyroxenite, norites

b) Emplacement of gabbros

Third Phase: Emplacement of tonalites and granite - acidic magma
Fourth Phase: Intrusion of a swarm of basic and acidic dykes - both basic and acidic magmas

The petrographic and petrochemical evidences witnessed in field have been found helpful in establishing the genesis of the igneous rocks discussed in the following pages.

FIELD EVIDENCES

The various field characters, such as intrusive contact, contact effect, shape of the body, xenoliths, dykes and apophyses, the nature of the body and association are of fundamental importance in deciphering the genesis of the intrusive rocks.

The base of the meta-volcanics (2,500 m) is not exposed anywhere in the area under investigation. Therefore, it is difficult to decipher the nature of the country rocks over which these volcanics were extruded. Nevertheless, stray blocks of metamorphic rocks and crystalline limestone (sometimes interbedded with slate) occur as rafts in the metavolcanics. Nearly parallel arrangement of these beds, at places, indicates their movement in a particular direction. The metavolcanics are composed of tuffs and basic flows.

The contacts of the intrusive rocks are sharp, nearly vertical (85° to 90°) and either straight or irregular.
The contact of norites with other intrusive rocks of the complex is not discernible except in tonalites. To the south and in the southeastern part of the area, norites are overlapped by younger sediments of Kargil basin which are of Miocene to Pleistocene age (Tewari, 1964). The vertical disposition of metamorphic rocks near the contacts might be due to a forceful injection of the igneous rocks. The zig-zag contact margins of these rocks may be due to small scale irregular fractures that developed locally during the course of intrusion. The tonalites are the typical younger intrusives. Their contacts with older metamorphites, metavolcanics and basic intrusives are sharp and irregular. Numerous dykes, tongues and apophyses of tonalites cut across the metamorphites, metavolcanics and the basic rocks. Similarly, the granite bodies also have sharp contacts with tonalites and amphibolites. The dykes of granite cut through amphibolites near Chubuk village.

The dykes, apophyses and tongues are of great significance in establishing the origin and sequence of intrusion. In the present area, gabbroic apophyses and dykes impregnate the adjacent metamorphites. Tonalite penetrates in the form of dykes and tongues into metamorphites, metavolcanics and amphibolites, norites and gabbros, whereas the granite dykes cut across amphibolites only. The study of these tongues, apophyses and dykes shows that the grain size
and the texture of these minor bodies remain nearly the same as that of parental rock. The relationship of these minor intrusions with larger rock masses indicates that the composite hornblendite-pyroxenite and norites are the earliest intrusions which were followed by emplacement of gabbros, tonalites and granite. The cross-cut relation also suggests that all the above mentioned rocks have crystallized from magma/magmas.

Occurrence of xenoliths in the Kargil igneous rocks clearly demonstrates igneous origin of these rocks. Further, these xenoliths also throw light on the age relationship and sequence of emplacement of these intrusives. Though the basic rocks, i.e., gabbros, are poor in xenoliths yet the occurrence of a few norite xenoliths in them is a clear indication of an earlier basic magmatic activity which formed norite in the area. Again, tonalites are quite rich in different kinds of xenoliths (Chapters II and III) which indicate a much later phase of acid igneous activity which took place after the emplacement of basic plutons. Wadia (1937) has described the occurrence of epidiorite xenoliths in hornblende granite (tonalite) from Burzil section lying to northwest of the present area which also contains xenoliths of amphibolites. Both granite and tonalites contain intrusive breccia (Pl. 1f) near their margins - a case similar to magmatic stoping indicating a forceful
The rarity of xenoliths in the gabbros indicates a low viscosity and high temperature of the magma and also sinking of xenoliths to a greater depth. These factors would explain the absence of xenoliths in the central part of the gabbros where complete digestion must have taken place because the constituent minerals of xenoliths and the mineral being crystallized from gabbros belong to the same group of reaction series. Occurrence of a few xenoliths of norites near the peripheral zone also indicates lower temperature and comparatively rapid cooling along the magma chamber walls. In the case of tonalites and granite, which are characterized by diverse type of xenoliths, the magma appears to be more viscous and of lower temperature where incorporation of foreign material had been incomplete. Further, these xenoliths contained minerals of higher group of Bowen's reaction series (1928) whereas acidic magma must have been crystallizing sodic plagioclase and quartz, and, therefore, the acidic magma was saturated with minerals of higher reaction series. Any change that has taken place in these xenoliths must have followed reciprocal reaction principle (Read, 1935).

The present distribution of xenoliths in various rock types indicates deep erosion. Much of the cover or the
roof of these plutons has been removed by a long cycle of weathering processes. This also explains the restricted occurrence of xenoliths along peripheral part of the igneous bodies. Further, it appears that intrusion of basic rocks must have taken place at comparatively greater depth than the acidic ones. From the study of xenoliths in various rock types, it is indicated that intrusion followed a certain sequence (as discussed later on) and the intrusions had been forceful in the case of acid magma.

The contact effect of the various intrusive bodies on their surrounding rocks is well exhibited. The metamorphites around gabbros and tonalites show recrystallization. The metavolcanics around the tonalites and granite have been thermally metamorphosed to form amphibolites which show foliated nature near the contact with intrusive bodies. Further, composite hornblendite-pyroxenite, norites and gabbros in contact with the country rocks or the tonalites show addition of quartz.

The ultrabasic-basic-acidic association of plutonic rocks and the dyke swarm of Kargil area are typical of an igneous rock suite. Wadia (1937) has described similar association from Astor-Burzil section. The author has also observed such an association at Dras, about 30 km west of the present area. Association of tonalite with basic rocks has also been observed around Leh and Upshi (to the east of
Leh). Gansser (1964) has described the presence of ophiolite belt from the east of Nanga Parbat passing through the present area up to Hanle (to the east of Leh). The association of these rocks indicates that the region was magmatically active for a long period.

PETROGRAPHIC EVIDENCES

Petrographic study along with other characters provides more information regarding the origin of the igneous rocks. The study is based on important textural and mineralogical features of the rocks.

The basic rocks - composite hornblendite-pyroxenite, troctolite and olivine gabbro - are coarse to very coarse grained. Their origin or crystallization must have taken place under high temperature, i.e., at a deeper level of the crust whereas medium to coarse grained norites and acid rocks indicate relatively higher level in the crust where crystallization of minerals must have been controlled by comparatively lower temperature and pressure. The tonalites appear to be the products of forceful intrusion which is revealed by the gneissose texture, embayment of felspar phenocrysts on the peripheral zone and shattering of the wall rock.

The composite hornblendite-pyroxenite and gabbros, at times, show heterogeneous texture thereby indicating a
normal crystallization of basic magma. Olivine in gabbros must have crystallized first along with basic plagioclase and has partially/-separated by crystal settling. Pyroxene and less basic plagioclase were formed after the removal of olivine. Thus, partial fractional crystallization caused segregation of olivine gabbro/within the gabbro thereby showing contrasted composition in the same igneous mass.

The development of composite hornblendite-pyroxenite mass is of great interest. It appears that the pyroxenes crystallized at depth in the initial stage but at later date the whole mass (magma containing both crystal and liquid phases) was uplifted causing paramorphism of pyroxene to hornblende under reduced temperature, pressure and addition of water from the country rocks.

The paragenesis of minerals observed in the Kargil rocks conform well to the sequence of fractional crystallization of a basaltic magma. The development of perthite, myrmekite and appearance of microcline in the granite suggest probably a lower temperature conditions for the formation of this rock. The existence of orthopyroxene (hypersthene) along the borders of gabbros flanking the metamorphites in the south of Chhainigund is probably due to assimilation. The development of orthopyroxene along the border of gabbro in the Le Pallet, France, has been described by Lacroix (vide Shand, 1950) where the gabbro
mass is intrusive into a mica schist and the margin of gabbro has been transformed into micaceous norite. Similarly, Watt (1914) and Read (1923) have cited examples of gabbro having a border of norite in the northeast of Scotland. Hence the formation of orthopyroxene at the border of gabbros in the present area is also considered to be as a result of assimilation.

Plagioclase is a common and at times a dominant mineral constituent in the Kargil rocks. The complex twinning is very common in these plagioclases. A combination of more than two laws is also present (Pls. 16e; 17d, e, f; 18a and b). These twin laws and combination of more than two twin laws are characteristics of igneous rocks which have crystallized from a melt. The same condition is confirmed by the synneuses twinning along with oscillatory and patchy zoning of the plagioclase.

The common occurrence of hornblende in the Kargil igneous complex indicates that the magma(s) was containing water which favoured the formation of hornblende rather than pyroxenes.

The freshness of the texture and mineral constituents in most of these rocks indicate that there has been little deformation of these rocks during the Himalayan orogeny.
GEOCHEMICAL EVIDENCES

The major chemical characters of the igneous rocks have already been described in chapter V. In the present section, only a passing reference to these characters has been made. The variation trends in various oxides, Niggli numbers and cations are represented in three diagrams (Figs. 5; 8a, b, c, d; 7a, b, c and d). All the variations are regular, well marked and follow the trends of magmatic differentiation. The plots of Differentiation Index Vs oxides, AFM diagram and Mafic Index Vs Felsic Index show that the basic rocks of the area are the products of middle stage differentiates whereas the acidic rocks are the products of late stage differentiates. The nature of the basic magma from which these basic rocks of the area crystallized is testified by AFM, Al₂O₃/SiO₂ Vs MgO, 'S' Vs SiO₂ and SiO₂ Vs total alkali diagrams and also by 'e' values and in all the cases, basic rocks of the present area fall in the tholeiitic field. The magma(s) for the various rock types has been discussed in the following pages. The geochemical behaviour, different kinds of indices and parameters calculated from the chemical analysis (Chapter V) provide valuable information regarding the origin and evolution of the Kargil complex.

From the genetic point of view, the igneous rocks are grouped in various series on the basis of their distinct
Brogger (1890) was the first to propose a two-fold classification of igneous rocks into 'alkaline' and 'non-alkaline' series. In the course of time, the term 'alkalic' more or less retained its use whereas the 'non-alkalic' series was variously termed as subalkalic, calc-alkalic, calcic, etc. Difference of opinion regarding the nomenclature of this series reflects the complexity associated with it.

Bowen (1928) pointed out that in non-alkalic series SiO₂, K₂O and Na₂O increase and total iron, MgO and CaO decrease with the fractionation in the magma. This gives rise to basalt-andesite-dacite-rhyolite series of rocks which are characteristics of an orogenic belt. The compositional variations are such that a series can be expressed with the help of Harker's diagram by plotting different oxides against SiO₂ content. The variation diagram (Fig. 5) based on oxides as above indicates that the Kargil igneous suite - a part of Himalayan orogenic belt - belongs to 'non-alkalic' series.

Fenner (1929) has pointed out that residual magmas after the fractional crystallization of basaltic magmas are generally enriched in iron. Wager and Deer (1939) also observed enrichment of iron in the olivine gabbro-gabbro-ferrogabbro series of Skaergaard complex. In the present study, iron enrichment has been found to occur up to the
middle stage of differentiation. The sudden enrichment in SiO₂ is either indicative of a marked change in the chemical composition of the magma or suggestive of a different magma.

It is evident from the literature that non-alkaline magmas followed two distinct trends of differentiation. Such trends have been well recognized by many workers (Nockolds and Allen, 1953, 1954, 1956; Kuno, 1959, 1968a, b; Miyashiro, 1974 and others). Nockolds and Allen (1953, 1954, 1956) recognized two series, one as 'calc-alkaline' in which iron depletion and alkal enrichment takes place, the second one as 'tholeiitic series' where iron enrichment is characteristic. Further, three trends of evolution of magmatic rocks have been well recognized (Nockolds and Allen, 1953, 1954, 1956; Taylor and White, 1965; Jakes and White, 1965, 1972; Jakes and Gill, 1970 and others). However, Kuno has distinguished three types of magmas.

The Kargil igneous complex can be classified as belonging to partly tholeiitic and partly calc-alkalic series. Such association has been described from island arcs (Rittmann, 1953; Kuno, 1960, 1968b; Sugimura, 1968; Katsui, 1961; Dickinson, 1968; Dickinson and Hatherton, 1967; Jakes and Gill, 1970; Jakes and White, 1972; Miyashiro, 1974). It has been observed that in the early stages of magmatic activity, the crystallization in basaltic magma...
takes place in following order, basalt-andesite representing tholeiitic series. However, near the continental margin, the magma follows calc-alkalic trend (Miyashiro, 1974). Crystallization differentiation has been observed in cases of well matured island arcs.

The Kargil rocks are dominantly constituted by sodic, intermediate and calcic plagioclase, hornblende and/or augite, hypersthene and olivine. Such mineral association is said to be typical of calc-alkalic series. However, such a criterion is misleading. Therefore, the author has based his conclusion on chemical data (cf. Peacock, 1931).

The Kargil igneous complex characterized by composite hornblendite-pyroxenite, norites, gabbros, tonalites and granite appears to be the product of differentiation (cf. Kennedy, 1933). Moreover, the extensive intrusion of tonalite (= andesite) at a last stage of magmatic activity is commensurate with the observations of Tilley (1950). Therefore, it may be concluded that igneous rocks of the map area belong to the tholeiitic and calc-alkalic series.

Kuno (1960, 1965) has advocated three parent magmas, viz., alkali-olivine basalt, tholeiite basalt and high alumina basalt for the origin of igneous rocks whereas
Chayes (1965) recommended the use of 'sub-alkaline basalt' in place of 'tholeiite basalt'. Based on the presence of normative orthopyroxene in the rocks, Tilley and Muir (1967) stressed on the use of term 'tholeiite basalt'. The characteristic feature of tholeiitic and calc-alkalic series is the presence of normative orthopyroxene and quartz.

Normative orthopyroxene is present in these basic rocks as well as in tonalites. However, quartz is present in a few norms of the basic rocks. Hence, the rocks of the area belong to tholeiite and/or calc-alkaline series.

The rocks of the Kargil igneous complex have been classified, according to Irvine and Baragar (1971), Miyashiro (1974) and others, into tholeiitic and calc-alkalic series. The nature and origin of these rocks are discussed in the following pages of this chapter.

The low K_2O and total alkalies (Na_2O + K_2O) in the basic rocks of the area are characteristic of tholeiitic magma. The acidic rocks are characterized by moderate to high Al_2O_3 as well as total alkalies and K_2O with low MgO and TiO_2 contents. Accordingly, these rocks form a calc-alkaline suite of Trans-Himalayan orogenic belt.

Figure 24a is the plot of total alkalies (Na_2O+K_2O) Vs SiO_2. The rocks of the area fall in a sub-alkaline series of Irvine and Baragar (1971). Miyashiro (1974) does not
FIG. 24a ALKALIES-SILICA PLOT FOR INTRUSIVE ROCKS OF KARGIL
(AFTER IRVINE & BARAGAR, 1971)

FIG. 24b O1'-Ne-Q PLOT FOR THE INTRUSIVE ROCKS OF KARGIL
(AFTER IRVINE & BARAGAR, 1971)
recommend the use of alkalies or $K_2O$ as a safe guide for the demarcation of the calc-alkalic series from tholeiitic one because of the fact that there are calc-alkalic series which are poor in alkalies and $K_2O$ contents. Hence, in case of the Kargil igneous suite, other significant and more reliable parameters and variation diagrams have been used.

The AFM diagram (Fig. 12b) plotted and discussed in chapter V is suitable for distinguishing the trends of tholeiite and calc-alkaline series (Kuno, 1968a). The hypersthene and pigeonite rock series of Kuno corresponds to calc-alkalic and tholeiitic series of Miyashiro (1974) respectively. The diagram (Fig. 12b) for the Kargil rocks shows that the magma responsible for basic rocks had been tholeiite as the trend for these rocks runs parallel to FM line which corresponds to the Skaergaard trend - a tholeiitic trend. However, the trend for acidic rocks becomes calc-alkaline occupying mainly the hypersthene field.

This variation in composition from tholeiitic to calc-alkalic magma can be explained in more than one way. A general consensus is that there was a single parent tholeiitic magma which during the early stages of crystallization caused the removal of mafic minerals thereby impoverishing the mafic constituents and simultaneously bringing about enrichment in alkalies in the residual magma, or, after the crystallization of the basic constituents,
the magma might have got mixed up with the crustal rocks of acidic composition. Though there is some evidence of assimilation in the present area yet the intrusion of tonalites and granite cannot have taken place by these processes on a regional scale. In the Kargil area, the surface volume of basic and acidic rocks is nearly equal in proportion which cannot be explained by differentiation from a single magma. Hence, we have to look for more than one magma for the origin of Kargil igneous complex.

The rocks of the area are also classified into 'sub-alkaline' series by using the normative $O_1' - Ne' - Q'$ triangular diagram (Fig. 24b) where

$$O_1' = \text{Olivine} + \frac{3}{4} \text{orthopyroxene}$$
$$Ne' = \text{Nepheline} + \frac{3}{4} \text{albite}$$
$$Q' = \text{Quartz} + \frac{2}{3} \text{albite} + \frac{1}{4} \text{orthopyroxene}$$

The two 'critical planes of silica saturation' are also marked after Yoder and Tilley (1962) and Irvine and Baragar (1971) in the diagram. The Kargil rocks fall within the sub-alkaline field except those samples which are rich in plagioclase (i.e., troctolite and porphyritic dolerite). The rocks of the area are of sub-alkaline nature and can be further subdivided into tholeiitic and calc-alkaline types as suggested by Irvine and Baragar (1971).
Figure 25a is a plot of weight percent $\text{Al}_2\text{O}_3$ against the normative plagioclase composition which is calculated as:

$$\text{Normative plagioclase composition} = \frac{\text{An}}{\text{An} + \text{Ab} + \frac{5}{3}\text{Or}}$$

The diagram (Fig. 25a) shows concentration of points along and on both the sides of the dividing line between the tholeiitic and calc-alkaline fields. Data for basic rocks fall within the tholeiitic field whereas the quartz bearing basic rocks fall near or over the dividing line. Further, the acidic rocks occupy the calc-alkaline fields. This also indicates that the basic rocks are the derivatives of tholeiite magma which may have incorporated some crustal rocks to form quartz bearing basic varieties. Moreover, these basic rocks must have changed in their composition on the peripheral zone due to intrusive effect of acidic rocks. Further, acid rocks have been formed by calc-alkaline magma. However, it has been observed that troctolite and some of the plagioclase rich dyke rocks occupy calc-alkaline field. This disharmony is noteworthy and can be explained as due to high percentage of plagioclases in these rocks (cf. Irvine and Baragar, 1971). The diagram shows a close association between the rocks of tholeiitic and calc-alkaline series.

The above conclusion for the Kargil rocks is further
FIG. 25a PLOT OF Wt% $\text{Al}_2\text{O}_3$ Vs NORMATIVE PLAGIOCLASE COMPOSITION FOR INTRUSIVE ROCKS OF KARGIL
(AFTER IRVINE & BARAGAR, 1971)

FIG. 25b PLOT OF NORMATIVE COLOUR INDEX Vs NORMATIVE PLAGIOCLASE COMPOSITION FOR INTRUSIVE ROCKS OF KARGIL
(AFTER IRVINE & BARAGAR, 1971)
supported by plotting SiO$_2$, FeO$^+$ (total iron as FeO+0.9 Fe$_2$O$_3$), TiO$_2$ and normative quartz (only those rock analyses are plotted which have normative quartz) against FeO$^+$/MgO as suggested by Miyashiro (1972, 1974). The above mentioned oxides have been plotted against FeO$^+$/MgO in the figures 27a, b, and c along with various well established trends. The boundary between calc-alkaline and tholeiitic fields is a marked one. These diagrams also show a similar nature of the two rock types as discussed in the case of figure 25a. All these diagrams show a close association between tholeiitic and calc-alkaline series for the Kargil igneous complex.

The author has also tried to study the Kargil igneous rocks on the basis of normative colour index (olivine + ortho- and clino-pyroxenes + magnetite + ilmenite + haematite) plotted against normative plagioclase. An examination of the diagram shows that basic rocks fall within the basaltic field and tonalites in the andesitic field. However, a few points for tonalites fall either in tholeiite-andesite or dacite fields. The granite of the area lies in the dacite and rhyolite fields. The acidic dykes occupy both the dacite and rhyolite fields. This study indicates a close agreement with mineralogical classification of these rocks. A similar result is also obtained by plotting the data in An - Ab' - Or triangular diagram.
FIG. 26a PLOT OF An-Ab-Or IN CATION PERCENT FOR THE INTRUSIVE ROCKS OF KARGIL (AFTER IRVIN & BARAGAR, 1971)

FIG. 26b PLOT OF FeO/MgO Vs SiO₂ FOR THE INTRUSIVE ROCKS OF KARGIL (AFTER MIYASHIRO, 1974)
FIG. 27 PLOT OF FeO/MgO Vs FeO (a), TiO₂ (b) AND NORMATIVE QUARTZ (c) FOR THE INTRUSIVE ROCKS OF KARGIL (AFTER MIYASHIRO, 1974)
The rocks of the area fall in all the three fields, i.e., 'K-poor', 'common' or 'average' and 'K-rich' ones, but it shows maximum concentration in 'common' field. This also confirms that igneous rocks of the map area belong to tholeiitic and calc-alkaline series.

**GENESIS OF AMPHIBOLITES**

Based on the petrochemical and other characteristics, it has been ascertained that the amphibolites occurring at the contact of tonalites and granite and within the metamorphites are ortho-amphibolites and genetically related to the metavolcanics. The amphibolitic rocks, under discussion include metavolcanics, amphibolites and xenoliths of gabbro. Though these rocks differ either in their field or mineralogical and textural characters yet chemically they have a common parentage. From the different variation diagrams (Figs. 19b, 21b, 22b, 22c and 23a), it is concluded that these rocks exhibit a differentiation trend similar to that of Karroo dolerites and Connemara amphibolites (Chapter V) and correspond with the general trend shown by tholeiitic igneous rocks (Nockolds and Allen, 1956).

The origin of amphibolites has been a burning problem in geology and much work has been done in this field without any consensus evolving on the issue. Attempts have
been made to find out reliable criterion to distinguish between the two types of amphibolites. Para-amphibolites are generally the result of high grade metamorphism of impure calcareous sediments whereas ortho-amphibolites are completely recrystallized metadolerites, metabasalts or metabasic tuffs. The banded nature of amphibolites and their association with carbonate rocks are the important criteria to distinguish between para-amphibolites and ortho-amphibolites (Wilcox and Poldervaart, 1958; Walker, et al., 1960; Heier, 1962). Several workers have advocated that differences between ortho- and para-amphibolites exist definitely in the proportion of their major elements (Lapadacu-Hargues, 1953; Engel and Engel, 1951; Evans and Leake, 1953; Leake, 1964). In most of the cases, it has been found that a clear-cut distinction cannot be made. No definite and precise parameter has been evolved so far to solve this genetic problem. Nevertheless, a number of characters taken together may help in understanding the processes of formation of this rock.

The most important features, which point to the ortho-parentage of Kargil amphibolites, are summarized as below:

1) Relic igneous texture, i.e., ophitic and subophitic.
2) Relic pyroxene in amphibole

3) Schiller inclusions in amphiboles.

4) Presence of plagioclase with complex twinning (Carlsbad twinning)

5) Plagioclase inclusions in plagioclase

6) Low $K_2O$ content and Niggli $k$-values. These are considered to be characteristic of ortho-amphibolites (Leake, 1964). Low $K_2O$ and $k$ are characteristic of tholeiitic basalts (Miyashiro, 1974)

7) Absence of crundum in the norm

8) Presence of olivine in the norm from 6.9 to 16.2

9) Presence of ilmenite in all the analysed samples

10) Various ratios, i.e., $Na_2O/K_2O$, $FeO/Fe_2O_3$ and $FeO/MgO$, also indicate the igneous parentage to these amphibolites.

In the field, the amphibolites of the investigated area are schistose at the contacts but massive and compact in the inner parts. The contacts between schistose and massive amphibolites are always gradational. Massive amphibolites grade into metavolcanics without any marked boundary.
Metavolcanics are epidotized and chloritized. The foliation in the vicinity of intrusive body has developed parallel to the contacts. The contacts of limestone, slates and gneisses, which occur as patches in these amphibolites, are sharp and smooth.

Banding in the amphibolites is regarded as a criterion for their sedimentary origin, e.g., the 'Feather amphibolites' of Poldervaart (1953) and the 'Layered amphibolites' of Wilcox & Poldervaart (1958) which have been considered as para-amphibolites whereas the massive types are considered as ortho-amphibolites. The amphibolites of the Kargil area do show banding and/or layering. This banding structure is not of sedimentary origin but it represents compositional difference in the original volcanic flows as preserved and recorded in the metavolcanics. Evans and Leake (1960) have suggested that the banding or stripped nature of the amphibolites may also be due to metamorphic differentiation. The typical para-amphibolites of Eckelmann and Poldervaart (1957) and Wilcox & Poldervaart (1958) have been considered as ortho-type by Kamp (1939).

Most of the workers are of the opinion that chemical analysis of major and trace elements are capable of giving sufficient information regarding the parentage of these rocks (Engel and Engel, 1951, 1962; Evans and Leake, 1960; Leake, 1964; Kamp, 1968, 1969). The major oxides determined
from Kargil amphibolites have been plotted in different variation diagrams (Figs. 9b to 23g). These diagrams clearly show that the amphibolites of the Kargil area falls in middle stage differentiation of a tholeiite magma.

From all the above mentioned characters, it is inferred that amphibolites of the area are of igneous parentage. This is further confirmed by the plots of major oxides where these rocks fall in a middle stage of differentiation of a basaltic magma. From the comparison of chemical trends of these amphibolites with those of basic intrusive rocks of the area, it is clear that these rocks are genetically related to the basic intrusives of the area.

DISCUSSION

The origin and evolution of the magma(s) for Kargil igneous complex is directly related to the nature and relationships of the tholeiitic and calc-alkalic suites of rocks. The tholeiitic series is represented by metavolcanics (including amphibolites, discussed separately), composite hornblendite-pyroxenite, norites, gabbros, dolerites and lamprophyres whereas calc-alkalic series is represented by tonalites, granite and quartzo-felspathic dykes. The two main series differ in their silica and alkali contents along with mafic constituents. Hence, the two series probably differ in their genesis. The author feels that these rocks
are possibly the products of fractional crystallization of a tholeiitic and calc-alkalic magmas.

The origin of tholeiitic and calc-alkaline magmas in Kargil area is discussed here on the basis of field and laboratory evidences. Unfortunately, trace element and isotopic analyses could not be carried out which otherwise would have thrown more light on this problem. However, advantage has been taken from the published literature on these aspects.

The two series of rocks recognized in the Kargil area represent large volume in each category which cannot be easily explained by simple differentiation from a single magma. It is possible that the two series of rocks might have originated at two different levels in the crust of the earth or in the upper mantle by different complex processes.

In the map area, the basalt-andesite volcanics, which represent the first phase of igneous activity, are altered and metamorphosed. Therefore, it has become difficult to decipher their true nature and original composition. Nevertheless, in the near vicinity of Minjigon and Chubuk (Fig. 3), these volcanics are relatively fresh and reveal their basaltic-andesite nature. The chemical characters and genesis of these rocks have been discussed separately under the amphibolites. The andesitic flows of
limited extent occur near Chubuk where these flows are younger than the basaltic flows as is evident from their stratigraphic position as well as their freshness. The basalt volcanics are considered to be the products of a tholeiitic magma. The presence of andesite volcanics with basaltic rocks, which are characteristic of calc-alkaline series, are debatable. However, Jakes and White (1973) hold that the fractionation of hornblende from the tholeiite basalt can give rise to andesitic magma. Hence, basaltic and andesitic volcanics were generated from a single tholeiite magma in the early stage of its ascent. It is presumed that some part of this basic magma formed local chambers at depths which finally gave rise to other basic intrusive rocks of the area. The basalt-andesite volcanism took place in the Upper Cretaceous-Lower Eocene times coinciding more or less with the first phase of the Himalayan orogeny. Therefore, orogenic environment for the basalt-andesite volcanism in the Kargil area is obvious.

Tholeiitic magma, which gave rise to the various basic rocks of the area seems to have been saturated in terms of silica (except amphibolites). Majority of the basic rocks are free from olivine in the modal composition. None of these rocks contain nepheline. However, there is normative olivine ranging from 1.6 to 22% in gabbros. The high normative olivine may be due to crystal accumulates of
olivine and calcic plagioclase in the initial stage of crystallization in the basic magma. As discussed earlier in this chapter, there is normative quartz also in some of the basic rocks. However, hypersthene is common in all the basic rocks. The presence of troctolite and pyroxenite is suggestive of an original magma which might have been more basic than the tholeiite, possibly olivine tholeiite or akin composition. Therefore, it can be inferred that the tholeiitic series might have been derived from the olivine tholeiite parent magma which after removal of olivine and some pyroxene gave rise to normal gabbro.

Macdonald (1968) postulated the origin of the Hawaiian tholeiitic series by crystallization of olivine tholeiite magma in shallow magma chambers. He stressed that majority of tholeiitic lavas do not represent the parent tholeiitic magma which generates in the mantle. The depth of formation of magma in the case of Hawaiian tholeiitic rocks has been estimated to be 60 km, that is, the upper mantle (Eato and Murata, 1960). Bowen (1928), O'Hara (1965) and Battey (1966) contended that the silica-saturated tholeiites are the products of fractionation of olivine tholeiite magma during its ascent. The various stages of partial melting of garnet peridotite could produce different types of magmas. The tholeiitic basalts are formed at an early stage of partial melting(O'Hara and Yoder, 1967). Gast
(1968), Philipotts and Schnetzler (1970b) advocated that the extensive fusion of garnet peridotite or eclogite gives rise to tholeiitic basalts. Still others (Kuno, et al., 1957; Kuno, 1959, 1966; Kushiro and Kuno, 1963; O'Hara, 1965; Cann and Vine, 1966; Green and Ringwood, 1967; Anmento, 1967; Gast, 1968; McGregor, 1968; Miyashiro, et al., 1969b; Robinson, 1969; Hawkins, 1970; Leeman and Rogers, 1970) considered the formation of tholeiites due to partial melting of mantle under low pressure and high temperature conditions. Various workers have emphasized that the fractionation of this parent basalt could produce both alkaline olivine basalt and tholeiitic basalt depending on the depth and pressure which seem to play a significant role (Powers, 1955; Yoder and Tilley, 1962; O'Hara, 1965, 1968; Webber, 1966; Mc Birney and Williams, 1969; Peterman and Hedge, 1971). The origin of tholeiite basalts can also be explained as a result of deep-seated fractionation of a parental picrite liquid and silica-poor alkali liquids. In this case, the fractionation of olivine occurs during the uprise of magmas (O'Hara, 1965; Yoder, 1967; Ito and Kennedy, 1967).

Recently, attempts have been made to correlate the generation of magma(s) in mobile belts with the help of plate tectonics. It has been postulated that in seismic zone, differential melting of the upper mantle, which gently dip under the continents near the plate margins, could produce
magma, which on fractional crystallization, depending on the depth of crystallization, can give rise to different types of magmas (Kuno, 1959, 1966; Yoder and Tilley, 1962; Kushiro and Kuno, 1963; O'Hara, 1965; Dickinson and Hatherton, 1967; Smith and Carmichael, 1968; Gorshkov, 1969). The above process is considered to be more effective in hydrous conditions (Hamilton, 1964, 1966; Green and Ringwood, 1967; Ringwood, 1974). Another mechanism related to plate tectonics is the melting of oceanic crust going down under the continental plates (Coats, 1962; Gilluly, 1969, 1971; Press, 1969; Hamilton, 1969; Green and Ringwood, 1969; Souther, 1970; Dickinson, 1969, 1970a). The tholeiitic magma might have generated by direct partial melting of pyrolite at depth up to 70 km and at 20 kb pressure (Ringwood, 1974). Ringwood (1974) concluded that the saturated tholeiite and olivine tholeiite could possibly be generated by partial melting under water saturated conditions at depths between 70 and 100 kms.

From the above discussion, it becomes evident that the tholeiitic magma is generally derived from a parental olivine tholeiitic magma which is generated by partial melting of the peridotite-eclogite layer in the upper mantle or by melting of the oceanic crust in zones of subduction under the continental margin at shallower depths.
The basic rocks of Kargil may, thus, be regarded as formed from tholeiitic magma which might have been derived from a parental olivine tholeiitic magma generated by partial melting of the upper mantle. The low K₂O content of these rocks (Tables 18.19) also indicates a shallower depth of origin possibly between 70-100 km as suggested by Dickinson (1968) and Ringwood (1974). The sedimentary prism in the Trans-Himalayan zone is said to be 60-80 km thick. This may have an important bearing on the generation of the magma.

Formation of orthopyroxene in the Kargil norites is of particular significance because the formation of hypersthene in basic rocks is a much debatable question. Kuno (1959) suggested that hypersthene, which is a characteristic mineral in the groundmass of the calc-alkaline volcanic series of Hawaiian Island, was formed at the cost of augite. On the other hand, Yoder and Tilley (1962) are of the opinion that hypersthene is not a characteristic mineral in the calc-alkaline series and thus it may appear in tholeiitic magma most probably by assimilation of country rocks. In the present case, co-existence of ortho- and clino-pyroxenes (hypersthene and augite) is noteworthy as both the pyroxenes show independent formation (Chapter IV). However, the dolerite dyke within the gabbro (which is noritic in composition) indicates the formation
of augite from the orthopyroxene. Moreover, hypersthene has been reported to occur in the tholeiitic rock series. As such, Kuno's (1959) observations are not applicable to the present case. It is most probable that hypersthene in Kargil norites is the result of assimilation of the country rock at depths by tholeiitic magma during its ascent. Although no xenolith of the country rock has been found in norites to give direct evidence of assimilation yet this contention is supported by the fact that hypersthene appears in the gabbros in the contact zone with the metamorphites in the south of Chhainigund. Similarly, the presence of hypersthene in dolerites of the area can be explained by applying assimilation hypothesis.

In conclusion, the origin of Kargil norite, occurrence of hypersthene in the peripheral part and its sporadic occurrence in dolerite dykes is due to assimilation of foreign rocks by the invading tholeiitic magma from the depth. It is also presumed that at a certain depth, a secondary magma chamber might have been formed as a result of assimilation of the crustal rocks which gave rise to norites.

The calc-alkalic series in the Kargil igneous complex is represented by tonalites, granite and quartzofelspathic dykes.
Tonalites (55-60% SiO₂) can be regarded as an intrusive equivalent of andesite. Hence, the genesis of tonalites will be discussed with respect to andesite. The granite and other acidic dykes must have also been derived from the same calc-alkaline magma. The relatively high percentage of K₂O in the granite and acidic dykes may be due to the extreme differentiation or modification by assimilation and this may not be related to the depth of generation of the magma. There are two main views regarding the origin of the calc-alkaline magma of andesite-dacite-rhyolite series. Many authors (Skhirtladze, 1958; Turner and Verhoogen, 1960; Gorskhov, 1969; McBirney, 1969) advocated the independent origin of andesitic magma with respect to basaltic magma. There are others who believe that the andesitic magma may originate from the basaltic magma after necessary modification by the addition of potash, silica, oxygen and hydrogen (Ashgirei, 1972). The processes responsible for the formation of the calc-alkaline magma is said to operate at a much deeper levels than the depth for the formation of basaltic magma (Blot and Frian, 1963; Wyllie, 1971, 1974). In a detailed investigation of this problem, Osborn (1969) proposed that the andesites of calc-alkaline series were produced by fractional crystallization of olivine basalt magma in orogenic regions under conditions of high oxygen fugacity, by flow of water from the surrounding
geosynclinal sediments into the magma and the migration of hydrogen. On the other hand, Taylor (1969), on the basis of isotope studies of igneous rocks, assumed that the andesites are derived from a parent basalt magma by differentiation. Similar observations were made by Katsui (1961) and Kuno (1968, 1969a), who emphasized that the varied andesites are the products of fractional crystallization of different basaltic magmas.

In the Cascade Range and northern California, large volumes of basaltic andesites were erupted during Cenozoic time. The hypersthene andesites of late Tertiary Feather River was said to have been derived from a tholeiitic basalt magma (Hietanen, 1972). Later, Hietanen (1973) gave a possible origin for all the continental andesites of calc-alkaline series by fractionation or contamination of basaltic magmas. However, the hypothesis of contamination of basaltic magma by sialic material failed to explain the common andesitic volcanism in the island arc where the crust is very thin. The study of trace elements of andesite along with $\text{Sr}^{87}/\text{Sr}^{86}$ ratio goes against the hypothesis of contamination (Taylor, 1969; Hedge, 1969; Hedge and Peterman, 1969). The source of andesitic and associated lavas in the island arcs where no continental crust is present, has been looked for in the mantle (Wyllie, 1971). Wilson (1959) considered that the andesites of island arcs were derived from the
partial melting of mantle peridotite between 70-100 km depths. Gorshkov (1969) suggested that the andesitic magma is generated in the upper mantle (asthenosphere).

In relation to the concept of plate tectonics, it has been suggested that all alkaline magmas originate due to subduction of oceanic crust and the continental margin along a plate. It has been contended that in Feather River area, the calc-alkaline andesitic magma was generated along a subduction zone above the Benioff zone and by partial melting of the mantle under anhydrous conditions (Hietanen, 1973). On the basis of experimental work, Yoder (1969) has pointed out that the calc-alkaline (andesitic) magma can be derived directly from the mantle peridotite in anhydrous conditions. In this case the water can be extracted from the descending slabs of the sialic material (Ringwood, 1974).

McBirney (1969) agreed to Yoder (1969) and suggested that for the generation of Cenozoic calc-alkaline lavas of Central America, necessary water was derived from the descending oceanic plate. It is, therefore, generally believed that the generation of calc-alkalic magma in island arcs and subduction of oceanic lithosphere along the inclined seismic zones are closely related (Dickinson and Hatherton, 1967; Isacks et al., 1969; Barazangi et al., 1970; Dickinson, 1970a). On the basis of this association, two possibilities
have been proposed. One possibility is that the partial melting of quartz eclogite took place at depths of 80-150 km, and the other is based on the partial melting of amphibolites and gabbros or fractional crystallization of hydrous basalts at depths of 30-40 km (Green and Ringwood, 1969; Ringwood, 1974). However, in the Tonga arc, the down-going plate has been traced as a rigid body from 350-700 km depths (Isacks et al., 1969; Barazangi et al., 1970). This limits the scope of generation of andesitic magma from the downgoing lithosphere. Yoder and Tilley (1962) regarded andesites as directly derived from tholeiite. Kushiro (1972) and Yoder (1969) proposed that the andesitic and dacitic magmas might be produced directly by partial melting of pyrolite under high water pressure at depth of 70-100 km (at 20-30 kb). Green (1973) and Nickolls & Ringwood (1973) agreed with this hypothesis.

The high temperature at shallow depths, which causes low pressure metamorphism, is created probably by the thermal effects of the rising aqueous fluids and/or magmas (Miyashiro, 1967; Hamilton, 1969). According to Miyashiro (1967) and Hamilton (1969), the convective and diapiric rise of peridotitic material through upper mantle, above the Benioff zone, would transport heat to induce partial melting of the subducting oceanic crust and cause the generation of new magma or magmas. This means that from
the same process of subduction of the oceanic lithosphere, two different magmas could be produced to form two quite distinct series of rocks. Magmas that originate in the Benioff zone can give rise to a calc-alkalic rock series which is mainly composed of andesite-dacite-rhyolite volcanic rocks or their intrusive equivalents. However, the magmas originated in convective and diapiric masses of the upper mantle lead to the formation of tholeiites, high-alumina basalts and alkali basalt along with their different derivatives (Ringwood, 1969, 1974; Miyashiro, 1974). The magma for granitic rocks is considered to have been originated from the mantle. This is based on Sr\textsuperscript{87}/Sr\textsuperscript{86} ratio (Hurley et al., 1962). There are two possibilities for the origin of granitic magma from the mantle. One of these is the remelting of the eugeosynclinal piles, containing much of mantle material to produce granitic magmas with Sr\textsuperscript{87}/Sr\textsuperscript{86} ratios equivalent to that of mantle material (Peterman et al., 1967). The other possibility for the generation of the granitic magma is that the descending oceanic crust along the Benioff zone may undergo phase transformation and partial melting (Green and Ringwood, 1968; Ringwood, 1969, 1974). Matsumoto (1965, 1968) has postulated another and a third possibility according to which the generation of granitic magmas is considered to be from deep mantle under high pressure conditions.
The calc-alkalic rock series of the Kargil area indicates contamination both in the field and in their chemical composition. A perusal of literature indicates that the magma responsible for the rocks of calc-alkaline series of which andesite is the most common member, originates in the mantle by more than one process, i.e., contamination of crustal material relatively at greater depth than the tholeiite basalt and a shallower depth than alkalic basalts.

The end phase of igneous activity, as already described in the preceding pages of this chapter, is marked by the dyke swarm. The composition of these dykes varies from basic to acidic. The basic dykes are dolerites and lamprophyres. Among these, dolerites are the products of tholeiitic magma. However, there is a controversy over the origin of lamprophyres. Hence, the genesis of lamprophyres is discussed in brief as below.

Origin of lamprophyric dykes in the present area, in brief, may also be described here. The dykes of lamprophyres in the tonalites trend more or less parallel to those of dolerites. There is not much variation in their grain size, but phenocrysts of hornblende are characteristic of these rocks. These are predominantly composed of hornblende and plagioclase (An$_{45-60}$), with
pyroxene as a subordinate mineral constituent. Hornblende and pyroxenes are mostly fresh. No undersaturated mineral is present. Chemically, they are characterized by low K₂O and low total alkali and hence their affinity with the basic rocks of the area is obvious.

Hyndman (1972) has suggested an alkaline olivine basalt parentage for similar lamprophyres. In Kargil area, however, there is no evidence supporting such a relationship and it seems plausible that the lamprophyres of Kargil have been derived from a tholeiitic magma of a different phase under high oxygen pressure and in water saturated environment (cf. Lewis, 1973). This would also explain the formation of large phenocrysts of hornblende.

The mineralogical and geochemical characters of lamprophyres also indicate that these were derived from the tholeiitic magma saturated with water and at a high oxygen pressure. It is most probable that the temperature of crystallization was depressed by high water content in the magma, thus, crystallization of hornblende took place instead of pyroxenes (Barth, 1951, 1962). A similar process may have been responsible for the formation of hornblendite dykes in the gabbro.

The acidic dykes which follow the calc-alkalic trend as shown by tonalites and granite, must have been originated
from the calc-alkalic magma.

From the study of these dykes, it has become evident that both the magmas (i.e., tholeiitic and calc-alkalic) were present within the crust up to the end phase of igneous activity in the Kargil area.

In the Himalayan eugeosynclinal orogenic belt, the Kargil area lies close to the 'Indus Suture Line'. A zone said to be of active seismicity, some workers regarded the 'Indus Suture Line' as a zone of subduction where the Indian plate might have been consumed (Dewey and Bird, 1970; Burke and Dewey, 1973; Dewey and Burke, 1973). The significance of this major tectonic feature in the Himalaya is hitherto not understood clearly. The author feels that more work has to be done before one can arrive at a definite conclusion about the role of the 'Indus Suture Line'.

From the above discussion, it is evident that the Kargil igneous complex has been formed by more than one parent magma. Let us examine the events of magmatic history which may be summarized as: widespread volcanic activity in Upper Cretaceous to Lower Eocene. This was followed by:

a) Emplacement of composite hornblende-pyroxenite and norite plutons
b) Emplacement of gabros
c) Emplacement of tonalites and granite
d) Emplacement of dykes and veins
The close similarity, as indicated by various diagrams, between tholeiitic and calc-alkalic series of Kargil rocks suggests the generation of their parental magmas from the same mantle material. Tholeiitic magma possibly generated at relatively shallow depth and calc-alkalic magma at greater depth in accordance with the views put forward by Green and Ringwood (1968), Ringwood (1969, 1971), Miyashiro (1971) and Dewey and Burke (1973).

If the plate tectonics has been the mechanism of Himalayan uplift then possibly the volcanics and intrusive rocks of the Kargil igneous complex may be due to the subduction of the oceanic lithosphere into the mantle, beneath the Tethyan eugeosyncline, water contained in the geosynclinal sediments might have been squeezed into the mantle thereby lowering the melting point of the mantle peridotite. This may have caused the generation of various types of magmas along the Benioff zone. As the subduction and partial melting of peridotite above the Benioff zone continued, the basaltic magma of the tholeiite composition might have formed with intermediate andesitic magma. This is followed by the generation of calc-alkaline magma at a later stage of subduction. Further, fractionation, contamination by crustal rocks during the emplacement and formation of local chambers at a higher level in the crust might have given rise to different types of magmas that ultimately
produced variety of rocks of the Kargil igneous complex.

As has already been mentioned, it is also possible that the igneous rocks of the map area may be the products of contamination that took place at depth and the rocks of tholeiitic and calc-alkalic series originated in the mantle. It is also possible that tholeiitic basalt may have originated at a shallower depth in comparison to alkalic basalts.

No final hypothesis can be postulated at the present stage of the investigation yet it is believed that the present work may form a base for future investigations.

The emplacement history of the Kargil igneous complex is concerned with the mechanism, time and space of emplacement within a thick metasedimentary prism of the Tethys eugeosyncline (Pande, 1967). It is postulated that during the first phase of Himalayan uplift, widespread volcanic activity took place (Saxena and Pande, 1969). After outpour of lava, a number of small magma chambers were left behind at depth which later on formed the intrusive rocks.

The igneous complex was emplaced into a thick pile of metasediments and Upper Cretaceous to Lower Eocene volcanics which had erupted on the floor of the sea (Berthelsen, 1953; Gansser, 1959, 1964; Pascoe, 1964). The emplacement was at a high level in these metasediments.
volcanic pile. All the plutons are without a roof and are exposed at an height of 5,000 m or more. Though the actual thickness of the roof cannot be determined yet it is believed that it was of a huge thickness. The span of time over which the emplacement took place is yet unknown. However, it can be said that the various intrusions occurred between Lower Eocene (the upper age of the volcanics) and Oligocene, as during the Miocene to Pleistocene, the molasses were deposited over the tonalites and norites.

The most important feature which has a bearing on the emplacement of plutons is the relationship between the attitude of the contacts of the various plutons and the trend of the fractures in the country rocks. However, for the detailed study of the emplacement history, a detailed mapping on regional scale is required to ascertain the relationship between the plutons and the trends of fractures in the country rocks. The present study is confined mainly to the attitude of contacts between various plutonic bodies except that of norites. As referred to earlier, the contact between the plutons and the country rocks are rather sharp and the contact planes are nearly vertical. Cross-cut relation between them is very clear. The sharp and vertical contacts indicate that the plutons were emplaced along deep seated fractures. Most probably, the origin of deep seated fractures and generation of magmas were synchronous.