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Basic rocks of Manipur Ophiolite in the Indo-Myanmar hill ranges, NE India and the petrotectonic significance

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ABSTRACT

The basic rocks of Manipur Ophiolite Mélange Zone occur as sporadic diabasic dykes (in ultramafics and pelagic sediments), sills (particularly in chert and cherty shale) and also as exotic blocks of diabase and pillow lavas. Occurrence of these basic rocks including pillows appears to be very much less than 10% of the total exposed ophiolitic rocks. Petrography, mineralogy and mineral chemistry of the main phases of the basic rocks indicate that they have undergone incipient thermal metamorphism of greenschist facies. The major and minor element oxides and various chemical plots indicate that these rocks are of alkali basalt lineage and have not experienced considerable fractional crystallisation and subsequent operation of crystal-liquid separation. The plot of Ce versus Nd of samples of basic rocks against predetermined standards reveals partial melting range of approximately 3-20%. When compared the trace element and REE variations of the basic rocks of Manipur Ophiolite with those of upper continental crustal rocks, lower continental crustal rocks and MORB with 15% contamination by upper crustal rocks, for signature of contamination, it is found that the melts of the basic rocks of Manipur Ophiolite have derived from upper mantle rocks metasomatised and contaminated by upper continental crust. Thus, the melts of the basic rocks of Manipur Ophiolite were derived from differential partial melting of enriched upper mantle rocks at depths of about 25-50 km in a slow spreading tectonic regime where no considerable magma chamber has been formed leading to the absence or rare occurrence of ideal gabbroic rocks.

Keywords: Diabasic dyke, sill, pillow, greenschist facies, Manipur Ophiolite

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INTRODUCTION

The fragments of ancient oceanic lithosphere, associated sediments and upper mantle material, when thrusted over or into the continental consuming plate margins, then their on land exposures are known as the Ophiolites (Coleman 1971, Dewey and Bird 1971, Davies 1971, Church 1972). The assembly of the different tectonic blocks of various litho-units of an ophiolite sequence occurring in a jumbled manner constitutes the Ophiolite Mélange Zone. The Manipur Ophiolite Mélange Zone (MOMZ) is such an assembly of various blocks of ophiolitic rocks in the Indo-Myanmar Hill Ranges in the north eastern corner of India bordering Myanmar.

The Manipur Ophiolite Mélange Zone is found to have quite a few number of diabasic dykes the widths of which range generally between 5-8 meters within the host of either peridotitic serpentinites (Fig. 1a) or within pelagic shale (Fig. 1b); and also found to occur occasional sill like bodies (thicknesses ranging between 1-8 meters) within chert and cherty shale (Fig. 1c). The diabasic rocks are also found as numerous exotic blocks floating mostly on pelagic shale (Fig. 1d), most abundantly along the western and eastern margin of the mélange zone. These exotic blocks are generally small (diameters of few meters only) and commonly have flat surfaces. From the consideration of not only their shape, size, and other field settings but also from the mineralogical and textural point of view the exotic diabasic rocks are inferred to be the pieces of dykes and sills, which have been displaced and injected as broken masses during the tectonic emplacement of the ophiolite belt.

The unique feature of the dykes in the common ophiolite sequences is that they consist of 100% dyke rocks without intervening older country rock screens (Coleman 1977). But the dykes of Manipur Ophiolite are only few meters thick and are very widely separated (in terms of hundreds of meters). Moreover, in the Manipur Ophiolite Mélange Zone no coarse grained basic rocks having evidences of gradual transition from the ultramafic bodies is encountered so far. There is also no exposure of monotonous very coarse grained basic rock bodies. It is found that the field characteristics and the textural features of the various samples of basic rocks collected from different parts of the mélange zone do not indicate evidences of being ideal gabbros. Therefore, it

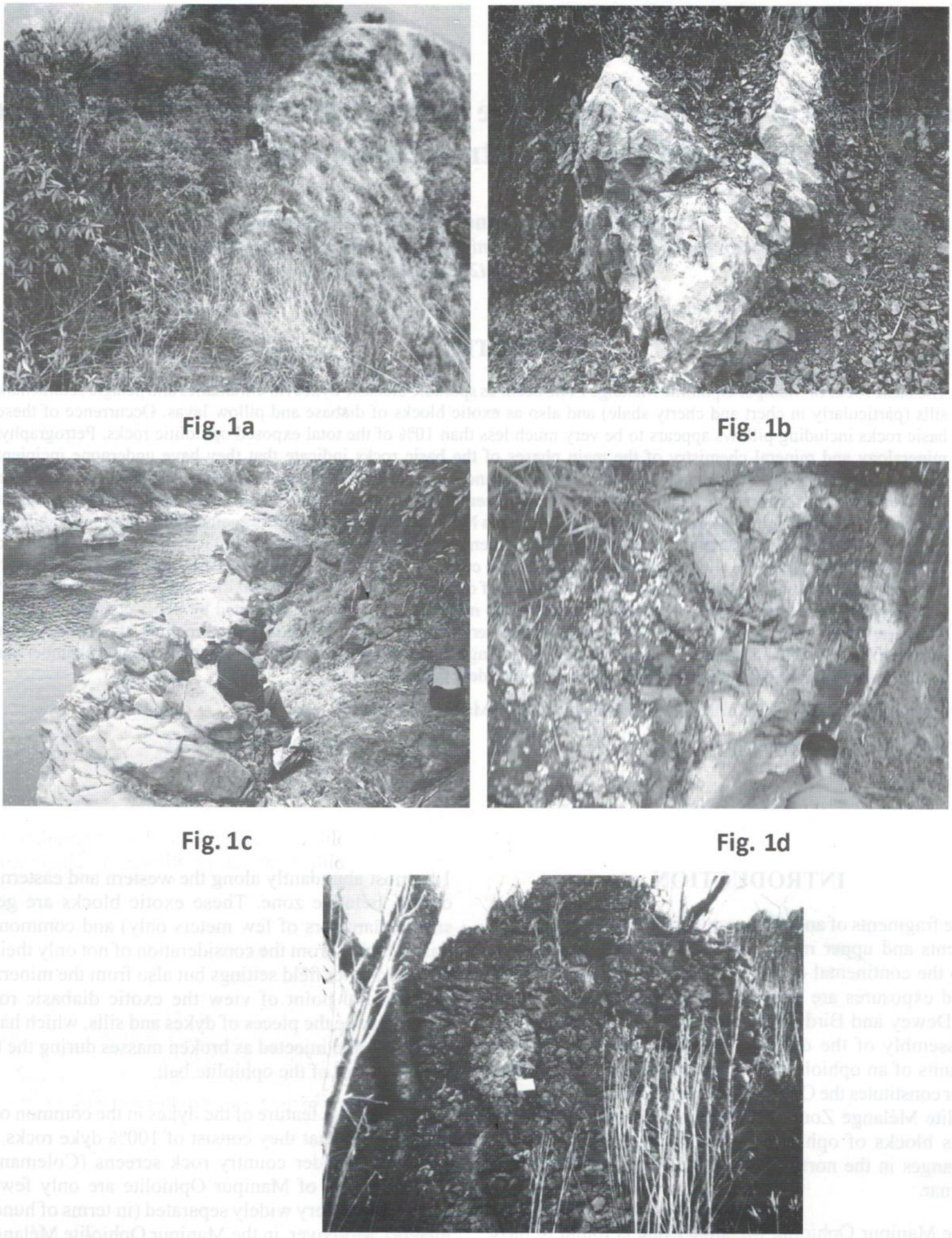

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

Fig. 1e

Fig. 1: Various forms and nature of basic rocks of Manipur Ophiolite Mélange Zone. (a) An exposure of basic dyke intruded in the ultramafic rock of Siroi peak, Ukhrul District, (b) A basic dyke intruded in the pelagic shale, near Nungbi, NH-150, (c) Sill like igneous intrusion within the beds of pelagic chert, Lokchao river bed Moreh, Chandel District, (d) Exotic block of basaltic rock exposed in the host pelagic shale, near Kangkhui village, Ukhrul District, (e) Fractures and cracks developed on the numerous individual pillows giving rise to the appearance of pillow breccias in pillow hill near Ukhrul town.

appears that gabbro is either absent or exceedingly rare in Manipur Ophiolite Mélange Zone. But, there are reports of occurrence of gabbro in Nagaland sector in the northern part of the belt (Ghose and Fareeduddin 2011).

Even though there are some sporadic and camouflaged (with host shale) occurrences of very few isolated pillows as sub-spherical exotic blocks within pelagic shale, good exposures of pillow lavas are not very frequent. But a very well preserved exposure of interconnected pillows found in the form of a hillock (Fig. 1e) was discovered at a distance of about 2.5 km in the south-eastern part of Ukhrul town (25°05′15′′N and 94°22′40′′E approximately) by the authours.

In the common complete ophiolite sequences, the basic volcanics of pillowed lavas and sheeted dyke complex (layer 2) is about 1-2.5 km thick, and the gabbroic layer (layer 3) with upper massive and lower stratified sub-layers, has a thickness of about 4 km. Thus out of the total maximum thickness of about 13 km of a common complete ophiolite sequence, the basic volcanics and the plutonic gabbros generally constitute about 35-40% (Gass 1980, Mason 1985). But in Manipur Ophiolite the occurrence of basic rocks including pillows appears to be very much less than 10% of the total exposed ophiolitic rocks, whereas the ultramafics are much greater than 90%.

In this paper, the authours taking into accounts of the facts of the field setting, petrography, mineralogy, mineral chemistry and bulk rock geochemistry mainly of the dyke and sill rocks, try to work out a scheme that could shed some light on the petrotectonic significance of the ophiolite belt of the Indo-Myanmar Ranges (IMR) in general and that of Manipur in particular.

GEOLOGICAL AND TECTONIC SETTING

The geological and tectonic setting of the westerly arcuate Indo-Myanmar Ranges (IMR) in general and its constituent Manipur hills in particular is attributed to the geological conditions of the extensional basin (Indo-Myanmar Ocean?) and the subsequent tectonic inversion leading to the subduction of the Indian plate beneath the Myanmar (Burma) plate thereby causing the consequent orogenesis of the IMR. The IMR comprising of the Naga-Patkai Hills, Manipur Hills, Mizo-Chin Hills and Arakan-Yoma is believed to be the northern extension of the Indonesian-Andaman arc linking with the eastern Himalaya, probably along the Tidding Suture zone. Almost all along the eastern margin of the IMR, ophiolites of late Mesozoic do occur as a long and narrow belt, which is commonly called as the Naga-Manipur-Chin Hills Ophiolite (NAMCHO) belt as an obducted remnants of the then oceanic crust. The Manipur Hills, having a general topographic trend of NNE-SSW, occur between the NE-SW trending Naga-Patkai Hills in the north and N-S trending Chin-Mizo Hills in the south forming an integral part of the IMR of the Northeast India.

The rock formations in Manipur are principally made up of turbiditic flysch sediments, mainly of Tertiary age, which constitutes about 65% of the total area. The flysch sediments are characterized as the Disangs (Mallet 1876) and the Barails (Evans 1932). The age of the Disangs is assigned to be Eocene to Upper Cretaceous while that of the Barails to be Oligocene to Upper Eocene. Disangs are a group of monotonous sequence of dark grey to black splintery shales which has sometimes intercalations of siltstone and fine to medium grained sandstones of light to brownish grey. Barails are predominantly arenaceous sediments characterized by light grey to brown, fine to medium grained sandstones with minor to considerably thick interbands of shale. The Barails are unconformably overlain by the molasse sediments characterized as the Surmas (Evans 1932) and Tipams (Mallet 1876), whose age is mainly Miocene but may extend upto upper Oligocene. The Manipur Ophiolite Mélange Zone (MOMZ), in which the present study is carried out, overthrusts the Disang-Barail flysch belt. The MOMZ is again overthrusted by an exposure of metamorphic rocks having a very limited extent on the extreme eastern part of the state. The metamorphic complex known as the Naga Metamorphics is principally composed of low to medium grade phyllitic schists, quartzite, marble, granite-gneiss, etc. Brunnschweiler (1966) assigned them Pre-Mesozoic or older age. Acharyya et al. (1986) however, assigned them Proterozoic age. The different litho-units in this region are intensely deformed and juxtaposed against each other as an imbricate thrust system having NNE-SSW trend in this part of the IMR, in such a way that the younger ones are on the west while the older ones are on the eastern side (Soibam 2000, Soibam and Pradipchandra 2006, Soibam and Khuman 2008). The general geological, structural and tectonic features of Manipur are shown in Fig. 2.

The Ophiolite Belt in Manipur consists predominantly of the main ophiolitic body (ultramafic suite), pelagic sediments and various blocks of exotic rocks. The ultramafics having sporadic diabasic dykes cutting across them are found to have been sandwiched with pelagic shale, and generally occupies the central portion of the belt and very few of the exotic rocks are found in this horizon. The ultramafic suite is flanked in the western and eastern margins by the exposure of a mixture of pelagic sediments – shale, chert and limestone, and associated exotic rocks. The host pelagic shale and cherty shale exposed along the outer margins has small intrusions in the form of dykes and sills. Of the pelagic sediments, shale is exceedingly predominant and sometimes mixed with flysch like sediments, which could be of Lower Disang. The associated exotic rocks in the host of mostly of pelagic shale include a number of blocks of variable dimensions of diabasic dyke, pillow lava, conglomerate, gritty sandstone and rocks kindred with lava extrusion. The assembly of the different tectonic blocks of the whole range of the litho-units comprising of the ultramafic suite, pelagic sediments and exotic rocks of various kinds constitute the Manipur Ophiolite Mélange Zone. The ophiolite mélange zone in Manipur sector is wider on the northern side, which gradually tapers towards the south. The ophiolite suite

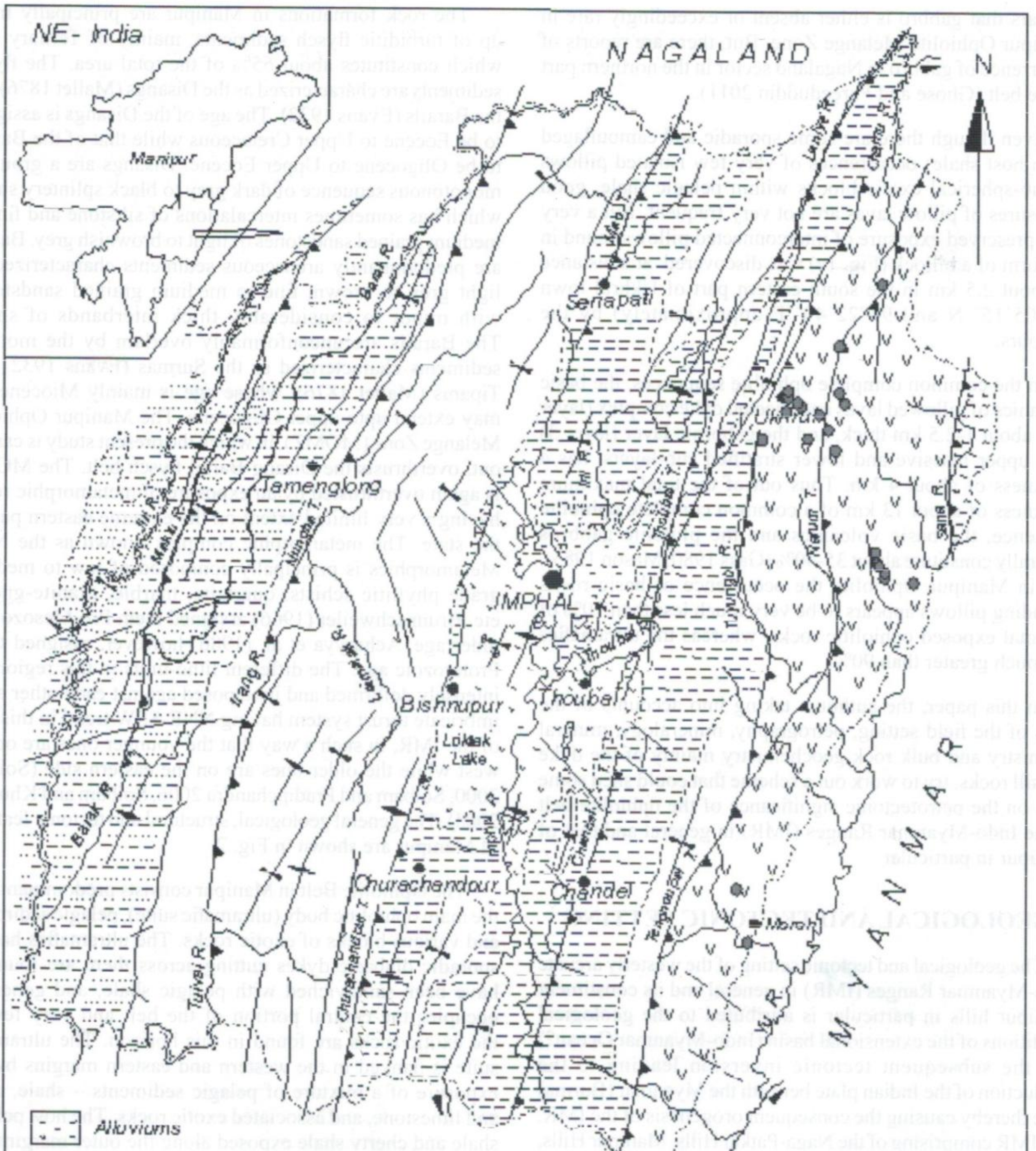

Fig. 2: Geological and structural map of Manipur (modified after Soibam 1998)

extends more than 100 km long as an almost continuous body in the NNE-SSW trend from the border of Nagaland state on the north upto Moreh on the south eastern part of Manipur. On the southern sector this ultramafic suite is exposed as isolated blocks upto the south eastern extremity of the state and beyond (in Myanmar). The peridotites are mainly of metamorphic harzburgite and lherzolite (Khuman and Soibam 2010) with sporadic podiform chromite occurrences. Exposures of exotic blocks of pillow lavas floating on pelagic shale are more predominant on the western margin than on the eastern margin and are better preserved (sometimes in the scale of a small hillock) and more frequent on the northern side where the MOMZ is wider. Although most of the exotic rocks float over pelagic shale, some smaller blocks of gritty sand are observed to float over the ophiolitic ultramafics as well, particularly on the eastern margin of the MOMZ. The radiolarian chert exotic blocks found on the western margin is sometimes intensely folded. On the eastern margin of the MOMZ the radiolarian chert exposures are found to be less deformed and intruded by occasional sills. They are either found juxtaposed along reverse faults with ultramafics or inter-bedded with pelagic shale.

Most of the earlier workers feel that the Nagaland-Manipur ophiolite belt is a dismembered one (Acharyya et al. 1986, Vidyadharan et al. 1986), thereby making the different units of the ophiolite sequence not exposed together at the same place. It may be argued that the cumulate basics (gabbros) could have not been scraped off in the process of obduction and remained buried; but in this respect the question, why much of the heavier ultramafics are brought up but not the lighter gabbros, remains unresolved. Therefore, considering the field setting, the authours are of the opinion that representative proportions of all the units of the ophiolite sequence are obducted as different blocks but in a jumbled manner so as to give rise to the MOMZ, where the not so well developed basic rocks have been represented poorly.

As steatisation is observed to take place in the ultramafic rocks overthrusting the water rich pelagic sediments and which have experienced considerable displacement and shearing in some of the faulted contacts in Manipur Ophiolite Mélange Zone, and since a wide horizon of talc schist is well developed along the Tengnoupal-Tuyungbi Thrust (Fig. 2) at the western margin of the main ophiolitic body (ultramafic suite), particularly in the northern side of the belt where the ophiolite body is thicker, this thrust could be considered as the mantle rooted Ophiolite Thrust (cf. Moores 2002). Considerably large displacement of the faulted blocks must have taken place overriding the Ophiolite Thrust thereby causing much of the lower ocean floor fragments (ultramafics) were obducted surpassing the overlying sediments. This could explain the predominance of the ultramafics in the horizon of the main ophiolite suite on the eastern side of the Ophiolite Thrust and also the reason of producing a wide zone of steatisation in the ultramafics exposed along the thrust plane. It appears that the displacement along the other reverse/thrust faults gradually decreases as one moves away from the Ophiolite Thrust, and hence, the upper units of the ophiolite sequence like the pillow lavas, dykes intruded pelagic shale and other associated sediments like chert, pelagic limestone, etc., are usually found more abundantly in the host of pelagic shale beyond the main ophiolite suite. There is limited and occasional occurrence of the ultramafics on the eastern and western margins of the ophiolite mélange zone.

PETROGRAPHY

Most of the samples of dyke rocks except very few are light green in colour with macroscopically visible leucocratic grains of plagioclase laths embedded within greenish masses. The sill rocks are also identical. In some samples the colour is dark green and sometimes appears almost black. The basic rocks are fine (<1 mm) to medium (1-5 mm) grained. And these rocks are found to be generally diabasic (doleritic) in the dykes/sills and basaltic in the pillow lavas. Three groups of samples having different characteristics are noticed in the dyke/sill and exotic diabasic rocks of the Manipur Ophiolitic Mélange Zone. The exposures of greenish coloured samples are very widespread and from the petrographic point of view, two different varieties are noticed in such samples. The samples of the third group are almost leucocratic with patches of dark green phases and their occurrence in the mélange zone is very restricted.

The samples of the first variety are found to be composed of earlier formed crystals, predominantly of olivine, orthopyroxene, clinopyroxene; and later crystallized phases of larger plagioclase laths and intersertal to intergranular partly or wholly altered pyroxene grains (Figs. 3a, 3b, 3d, and 3e). The earlier formed grains of olivine and pyroxene are mostly euhedral to sub-hedral and are generally least altered; and their sizes range from 0.2-0.5 mm diameter in various samples. These grains constitute about 15-20% modal proportions. The sub-hedral plagioclase grains are cloudy or dirty albite and consist of minute crystals of epidote (Fig. 3b); and constitute about 60-65% modal proportions. The lengths of the laths generally range from 0.5-5 mm. The later formed sub-hedral to anhedral and intergranular pyroxene grains are found to have been variably altered to actinolite (green amphibole), chlorite and epidote, the mixture of which is known as uralite (cf. Deer et al. 1978); and these later crystallized grains including the uralites (Fig. 3b) constitute about 15-20% modal proportions. In few samples some of the earlier formed pyroxenes are also partially uralitised. The olivine grains show no zoning, but occasionally found to consist of pyroxene layers at the outer margins enclosing them. As minute magnetite grains are also found along with the enclosing pyroxenes, the pyroxenes appear not to be coronas developed during peritectic crystallisation. On account of addition and dissociation of water, the oxygen content of the melt could have caused oxidation of ferrous iron in olivine, after the phases having been developed. Ferric iron could not be accommodated in the olivine structure. This in turn caused a relative increase in the Si/(Mg, Fe) ratio in olivine, and thus resulted in conversion of some of olivine

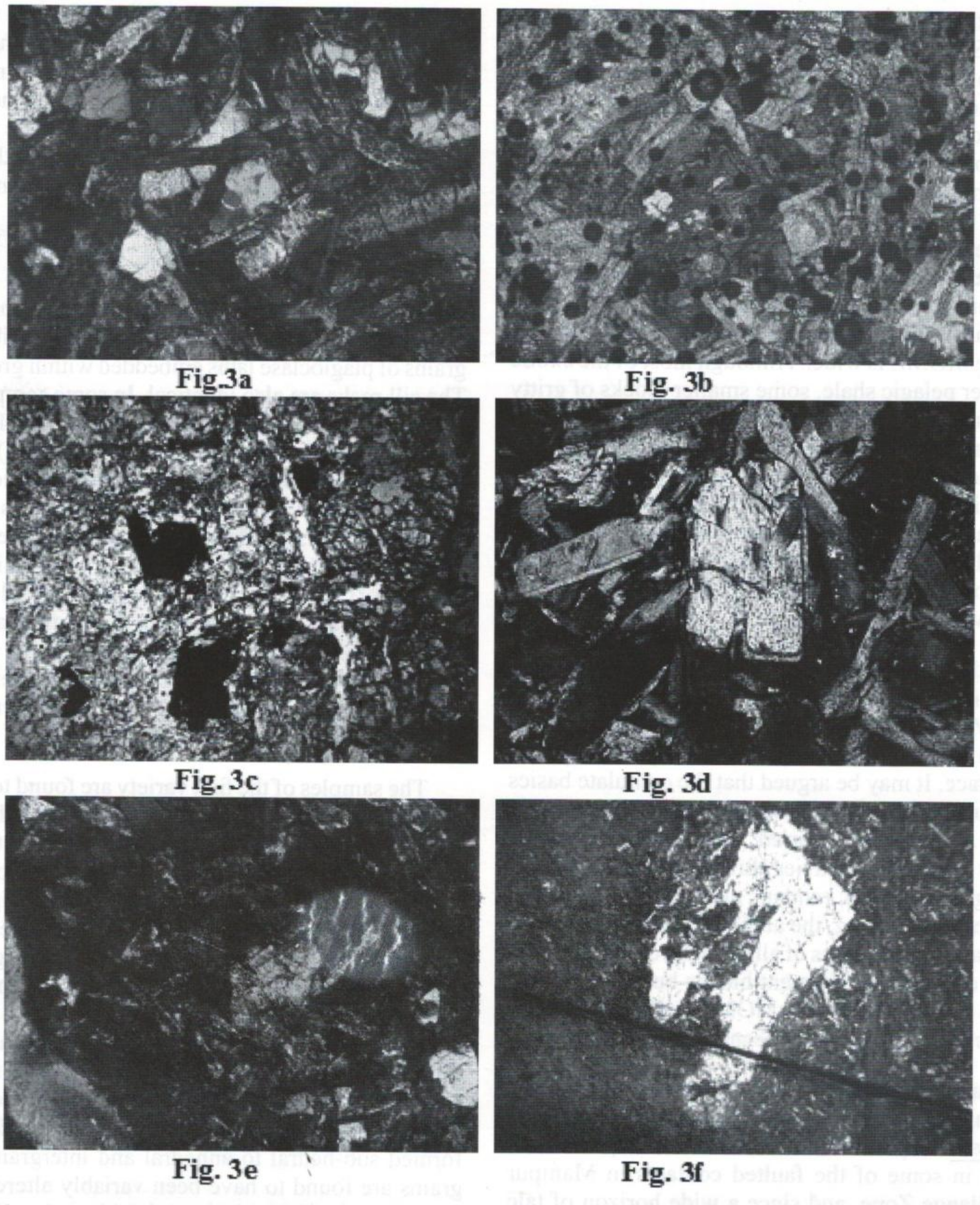
Fig.3a
Fig. 3b
Fig. 3c
Fig. 3d
Fig. 3e
Fig. 3f

Fig. 3: Photomicrographs showing different textural features of dyke and sill rocks. (a) Earlier formed pyroxene and olivine grains (10x cross), (b) Uralitised inetrgranular pyroxene and cloudy dirty albite laths (10x pol), (c) Pseudomorphs of magnetite after mafic phases and segregated patches of serpentinised phases in dyke rock. The width of the photo is 0.8 mm (20x pol), (d) Unzoned earlier formed olivine crystal over which plagioclase is epitaxially grown. The width of the photo is 0.8 mm (20x cross), (e) Twinned clinopyroxene and another similar grain showing sub-ophitic texture (10x cross), and (f) A very large plagioclase grain (4x cross) in dyke rock. The width of the photo is 4 mm.

to pyroxene (Ehler and Blatt 1987). The clinopyroxene crystals, some of which are twinned (Fig. 3e), also show partially altered margins, which could have been caused by later reactions in the oxygen enriched environment. The pyroxene grains are generally unzoned.

In the second group of the samples, earlier formed crystals of olivine and pyroxenes are almost absent and the main phase is found to be of cloudy albitic plagioclase (Figs. 3b, 4a and 4b). There are some equidimensional plagioclase phenocrysts as large as 5 mm diameter (Fig. 3f). There are also some samples in which, the plagioclase laths show flow structures (Fig. 4a) and variolitic texture (Fig. 4b) as well. In some of the samples of this category of basic rocks, there are portions in which aggregates of larger epidote crystals are very well developed within a vein like mush of hydrothermal solution appearing flux (Fig. 4c). There are also samples in which calcite filled vesicles generally of 0.02-0.04 mm diameters are present (Fig. 4b); but few of which is as large as 0.1 mm.

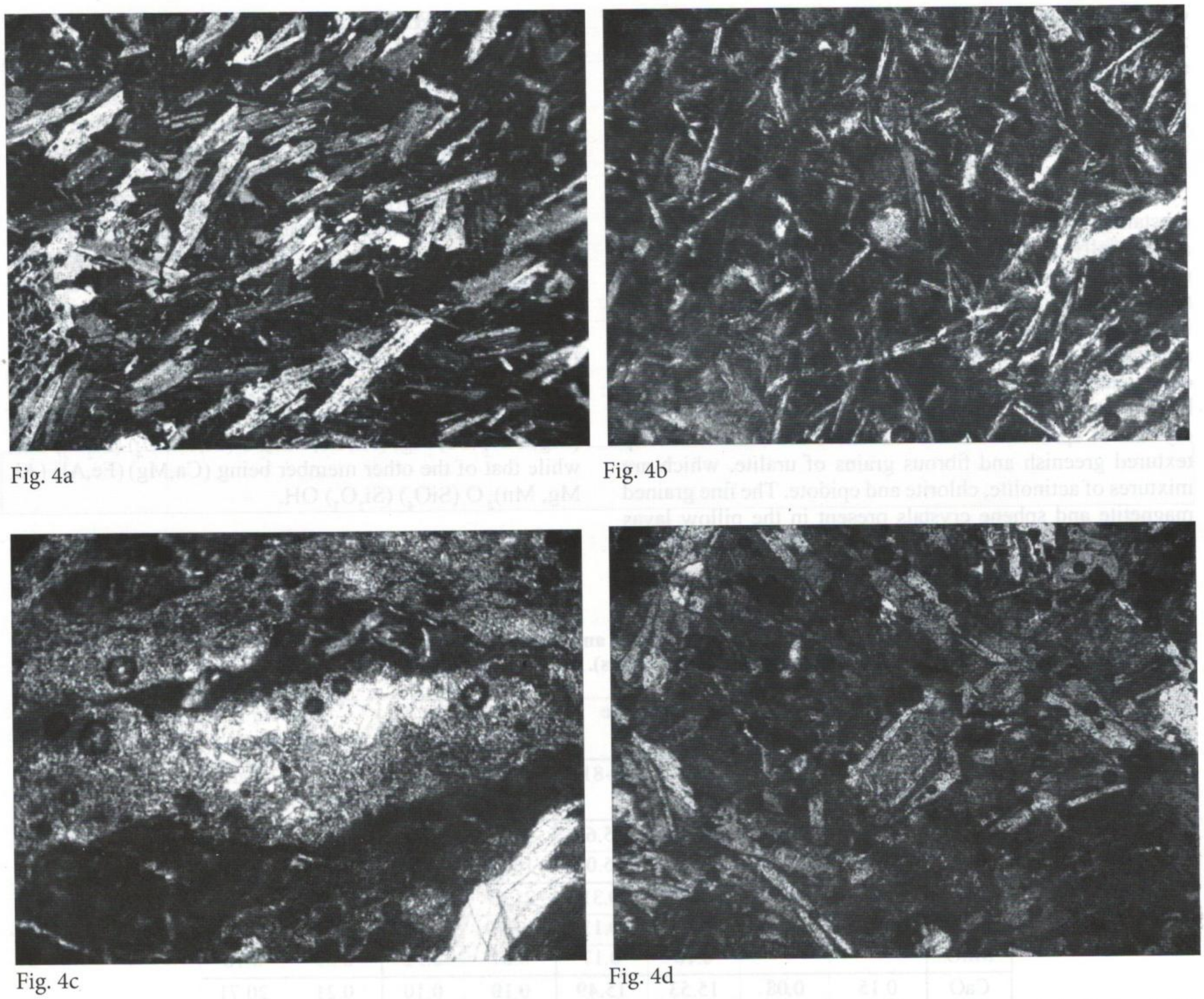
Fig. 4a
Fig. 4b
Fig. 4c
Fig. 4d

Fig. 4: Photomicrographs showing different textural features of dyke, sill and volcanic rocks. (a) Flow structure of plagioclase laths. The width of the photo is 1.6 mm (10x cross), (b) Variolitic texture with vesicle (10x pol), (c) Aggregate of larger epidote crystals within a veinlike mush of hydrothermal flux (10x pol), and (d) Epitaxial growth of plagioclase over uralitised pyroxene (10x pol).

The third group of basic rocks is found to be principally composed of plagioclase and serpentine (Fig. 3c). A number of magnetite grains are also present as pseudomorphs (Fig. 3c) after equidimensional as well as elongated crystals, possibly of the earlier formed mafic phases. The pseudomorphs of magnetite could be attributed to the change in the activity of oxygen as a result of which Fe^{+2} in olivine are converted to Fe^{+3} at the sub-ocean floor environment leading to the crystallization of secondary magnetite. Even though the sizes of the plagioclase laths are variable they have comparatively grown larger. There are laths as long as 3-4 mm, but in the average, their lengths range 0.5-0.8 mm. The segregated patches of serpentine have various sizes sometimes as large as 3mm diameter. The serpentine patches could have been derived from olivine. It appears that partial segregation of plagioclase and olivine has taken place indicative of crystal settling in very few selected samples. The plagioclase laths are, as in the other categories of basic rock samples, altered to albite with inclusions of minute epidote crystals.

In some of the samples of all the categories of dyke and sill rocks, there are plagioclase grains grown epitaxially over olivine and pyroxene (Figs. 3d and 4d.). And in most of the samples, particularly more in the second category, some of the plagioclase laths are replaced by secondary quartz pseudomorphing after them. Some of the plagioclase grains are also altered to calcite; and a number of crystals of calcite which are not pseudomorphs after plagioclase are also present. Some of them are as large as 1mm diameter. Few very fine grained (<0.02 mm) secondary quartz grains are also present. Some of the samples contain xenoliths of small pieces of chert, the outer margin of which have been melted to quartz, but the smallest pieces are completely melted to quartz grains. Such quartz grains are generally either corroded at their margins or found having reaction zones. It is also observed that in few of the samples there are phenocrysts of pyroxene found enclosing sub-ophitic plagioclase microlites (Fig. 3e). These pyroxene grains are again enclosed within larger plagioclase laths giving rise to the opposite diabasic texture (Fig. 3a).

The pillow lavas are found to consist mainly of plagiocase crystallites and intersertal minute grains of pyroxene, which are partially or wholly uralitised. The slender plagioclase crystallites have random to radial orientation giving rise to typical variolitic textures (Fig. 4b). There are some larger phenocrysts of pyroxene, major portions of which are uralitised. EPMA data (Table 1) and petrographic examination indicate that plagioclase crystallites are found to be of albite composition and associated with myriad minute crystals of epidote, and also that there are intersertal felty textured greenish and fibrous grains of uralite, which are mixtures of actinolite, chlorite and epidote. The fine grained magnetite and sphene crystals present in the pillow lavas appear to be of secondary origin, which could have been related with the alteration of the mafic phases.

MINERAL CHEMISTRY

The EPMA analysis of representative samples of dyke and pillow lava of Manipur Ophiolite has been carried out at the Institute Instrumentation Centre (IIC), Indian Institute of Technology (IIT), Roorkee using JEOL-JXA-8600. The probes were run under the operating conditions of a probe current of 20 nA, an acceleration voltage of 15kV and beam diameter of 0.5 µm. From the data (Table 1) the plagioclase of dyke and pillow lava are found to be albite with the chemical composition of $(Na, Fe, Ca, K) Al (Si, Al)_3 O_8$. Whereas the chemical composition of actinolite present in uralite is found to be $Ca_2 (Al, Na, Ca, Fe, Mg, K, Cr)_5 Si_8 O_{22} (OH)_2$ and that of chlorite is calculated as $(Mg, Fe, Al, Mn)_6 (Si, Al)_9 O_{10} (OH)_8$. And, epidote of the uralite is found to have two end members, one with composition of $(Mg, Ca)_2 (Fe, Mg) (Al, Fe, Mn)_2 O (Si, Al, O_4) (Si_2O_7) OH$, while that of the other member being $(Ca,Mg) (Fe,Al) (Al, Mg, Mn)_2 O (SiO_4) (Si_2O_7) OH$.

Table 1: Microprobe analysis of Plagioclase, Actinolite, Chlorite and Epidote of the representative samples of dyke (Sc-10kw) and pillow lava (Su-81A) of Manipur Ophiolite (n= number of points).

Major Oxides	Plagioclase (n=9)		Actinolite (n=4)		Chlorite (n=3)		Epidote (n=3)	
	Sc-10kw	Su-81A	Sc-10kw	Su-81A	Sc-10kw	Su-81A	Sc-10kw	Su-81A
SiO_2	67.48	67.22	56.99	55.65	30.13	31.23	35.39	36.22
Al_2O_3	19.73	18.69	15.23	16.00	16.63	16.76	17.54	20.04
FeO	0.67	1.25	0.33	0.31	21.67	22.00	20.50	9.54
MgO			0.12	0.11	17.79	17.91	19.16	2.17
MnO			0.16	0.17	0.61	0.52	0.33	0.16
CaO	0.15	0.08	15.53	15.49	0.10	0.10	0.21	20.71
Na_2O	11.76	12.03	7.16	6.90	0.30	0.03	0.04	
TiO_2					0.02	0.01	0.04	
Cr_2O_3			0.01		0.03	0.03	0.01	0.04
K_2O	0.10	0.04	0.13	0.12				
Total	99.89	99.31	95.66	94.70	87.28	88.59	93.22	88.88
Cation	8-Oxygen basis		24-Oxygen basis		18-Oxygen basis		13-Oxygen basis	
Si	2.97	2.98	8.28	8.20	3.05	4.08	2.87	2.87
Al	1.02	0.98	2.61	2.68	1.95	2.58	1.68	2.10
Fe	0.03	0.05	0.04	0.04	1.83	2.40	1.39	0.49
Mg			0.03	0.03	2.68	3.39	2.30	0.32
Mn			0.02	0.03	0.06	0.08	0.02	0.20
Ca	0.01		2.42	2.41			0.02	2.00
Na	1.00	1.03	2.02	2.00				
Ti								
Cr								
K	0.01		0.01					

Table 2: Major and minor elements oxides in percent (XRF data) and CIPW norms of basic rocks of Manipur Ophiolite.

Samples / Major oxides	Sc10(KW)	Su29(X_2)	Su-43(B)	Su-66	Su-77(A)	Su-81(A)
SiO_2	50.41	47.22	44.73	45.19	51.19	48.00
Al_2O_3	13.17	13.22	13.32	13.36	13.38	15.67
Fe_2O_3(T)	7.77	9.81	9.18	10.92	13.11	11.05
MnO	0.11	0.12	0.11	0.15	0.11	0.28
CaO	6.35	4.82	8.53	5.96	5.83	3.29
MgO	7.14	6.22	5.37	4.59	3.99	6.42
Na_2O	6.22	6.12	6.48	3.51	4.76	4.57
K_2O	0.59	0.16	0.09	0.06	0.10	0.14
TiO_2	0.99	1.22	1.38	1.15	1.19	1.30
P_2O_5	0.17	0.19	0.42	0.01	0.02	0.11
LOI	7.30	11.01	11.06	15.37	6.20	9.58
Total	100.22	100.11	100.67	100.27	100.68	100.41

*NORMS

Quartz	-	-	-	4.55	5.46	4.02
Orthoclse	3.34	1.11	0.55	0.55	0.55	0.55
Albite	41.37	47.16	28.56	29.87	40.40	38.77
Anorthite	6.39	8.06	6.95	20.29	14.73	8.89
Nepheline	5.96	2.25	14.34	-	-	-
Corundum	-	-	-	-	-	4.79
Diopside	19.33	53.21	26.29	4.29	8.37	-
Hypersthne	-	-	-	15.87	12.65	24.28
Olivine	10.38	23.95	7.98	-	-	-
Ilmenite	0.30	2.28	2.58	2.13	3.80	0.30
Apatite	0.34	0.33	1.01	-	-	3.02

*Norms calculated on conversion of all Fe_2O_3 (T) to FeO (T) and deletion of volatiles

BULK ROCK GEOCHEMISTRY

Six representative samples of the basic rocks found in different locations in Manipur Ophiolite Mélange Zone, were analyzed using X-Ray Fluorescence (XRF) spectrometer with recommended matrix corrections at the Department of Instrumentation and USIC, Gauhati University, Guwahati, for 10 major and minor element oxides. The major and minor element oxides data are shown in Table 2. In addition to the XRF analysis, 5 out of the 6 representative samples were also analyzed for selected trace elements and REE's by the ICP (MS) at IIC, Indian Institute of Technology, (IIT) Roorkee, the result of which is enumerated in Table 3.

Major and minor element oxides (XRF data) geochemistry

Out of the 10 major and minor element oxides (compositions) of the various representative samples of the basic rocks including pillows, only Al_2O_3 and MnO values are found to be consistent throughout the samples without much variation except one or two in each case. All other oxides are considerably variable. SiO_2 proportions in the basic rocks are widely variable ranging from about 45-51%.

The clustering of Al_2O_3 values in all the samples except in one (Su 81, which is a pillow) at around 13% indicates that there has been very little effect of contamination and magmatic differentiation on the alumina content. Very little fractionation of Al-bearing phase (plagioclase) which attributed to make alumina content of not much variation in all the samples is evident from the fact of having almost similar modal proportion of plagioclase in all the samples of the basic rocks. MnO values also cluster at around 0.11% in almost all the samples with the exception of that of the sample (Su 81A) in which Al_2O_3 value is also found comparatively higher than the common values. It, therefore, appears that the same principle assumed for Al_2O_3 also holds well in the case of MnO.

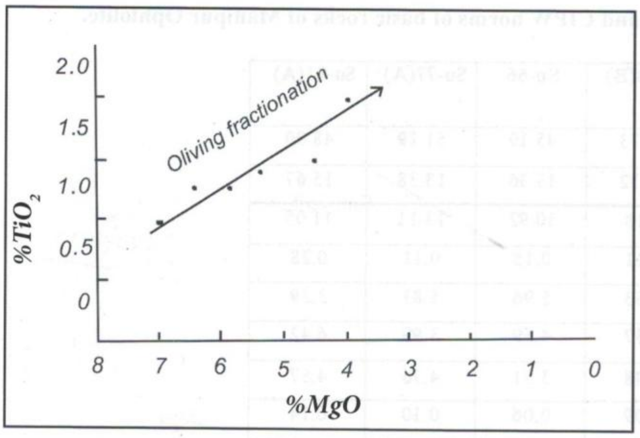

Fig. 5: Harker type variation diagram of wt % MgO vs wt % TiO_2 showing the trend of olivine fractionation (adopted from Pearce and Cann 1971).

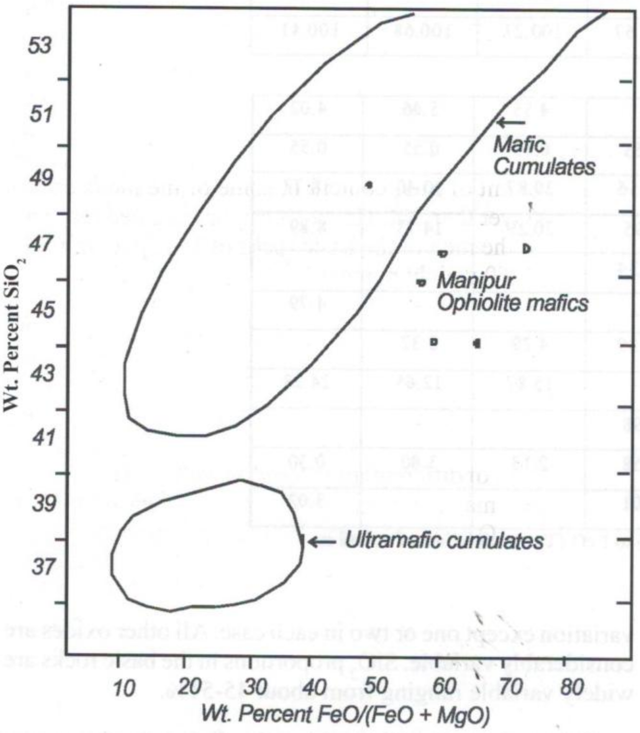

Fig. 6: Plot of wt. % SiO_2 vs wt. % FeO/(FeO + MgO) showing the fields of Ophiolite cumulate rocks. Almost all of the basic rocks of Manipur Ophiolite are beyond the field of mafic cumulates (adopted from Coleman 1977).

TiO_2 values as in the case of MgO, show a gradational variation which appear to have been caused by magmatic differentiation trend. Moreover, the TiO_2 content of most of the basic rocks shows much less spread values and, therefore, may be representative of the primary igneous values (cf. Pearce and Cann 1971). Therefore, a Harker-type variation diagram in the form of two element plot (Fig. 5) is drawn to examine the trends of fractional crystallization of mafic phases and crystal-liquid separation during magmatic evolution. As the diagram shows no segmented trend or any inflection, there has not been marked fractional crystallization of mafic phases like crystal settling and the subsequent operation of crystal-liquid separation.

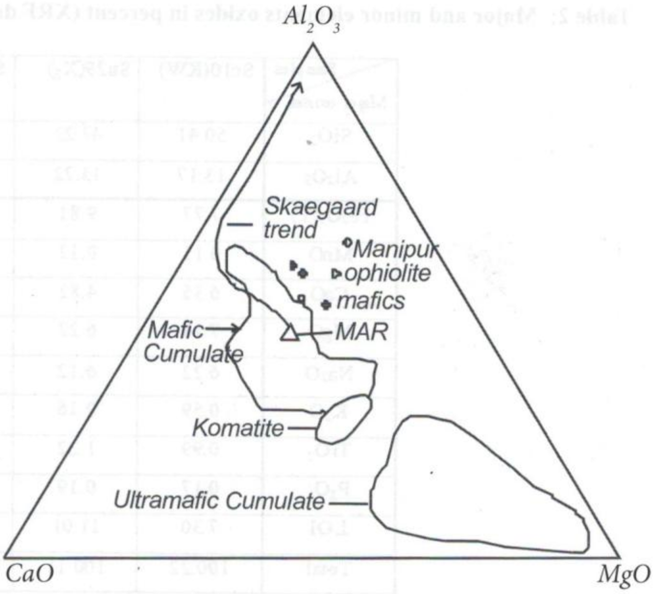

Fig. 7: Triangular diagram of MgO-CaO-Al_2O_3 showing field of Ophiolite cumulate rocks. The basic rocks of Manipur Ophiolite are beyond the field of mafic cumulate (adopted from Coleman 1977).

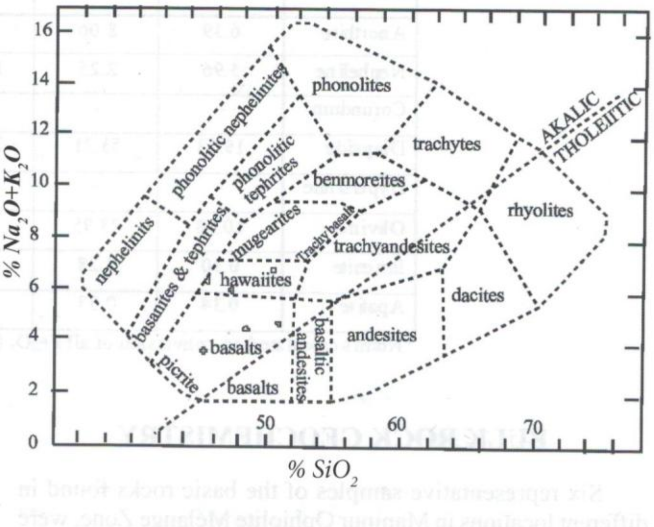

Fig. 8: Total alkali (wt % Na_2O+K_2O) vs wt % SiO_2 diagram. The basic rocks of Manipur Ophiolite are of alkali basalt lineage (adopted from Cox et al. 1979, and McDonald and Katsura 1964).

Moreover, the basic rocks of the Manipur Ophiolite when plotted in terms of SiO_2 and FeO/(FeO+MgO) are found not to be consistent with the field of the mafic cumulates of ophiolitic rocks (Fig. 6). Similarly, the triangular diagram of MgO-CaO-Al_2O_3 (Fig. 7), also shows that they are beyond the field of mafic cumulates.

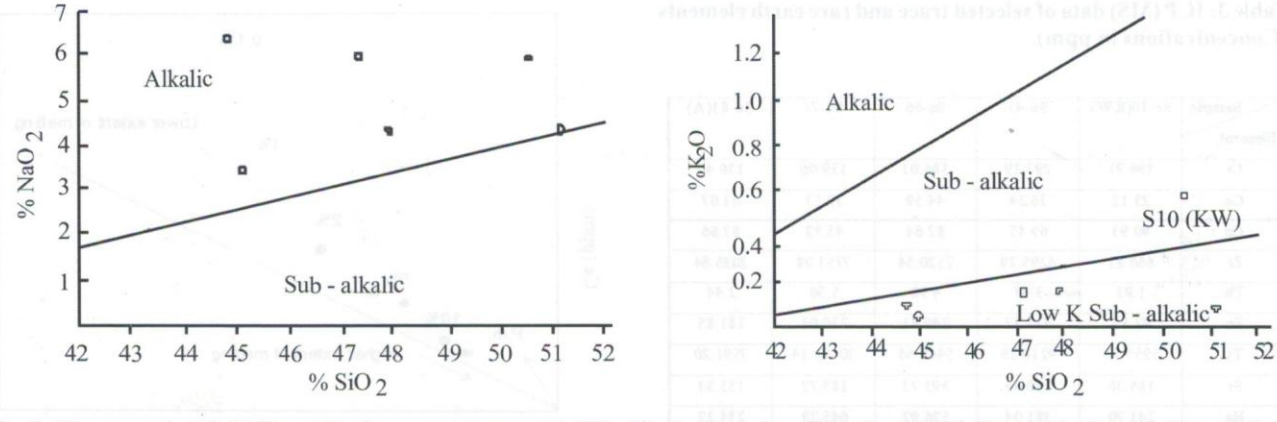

Fig. 9: Diagram of wt% K_2O and Na_2O separately vs wt% SiO_2. The basic rocks of Manipur Ophiolite plot in the alkali basalt field in 'a' (wt% Na_2O) and in the sub-alkali basalt field in 'b' (wt% K_2O) (adopted from McDonald and Katsura 1964).

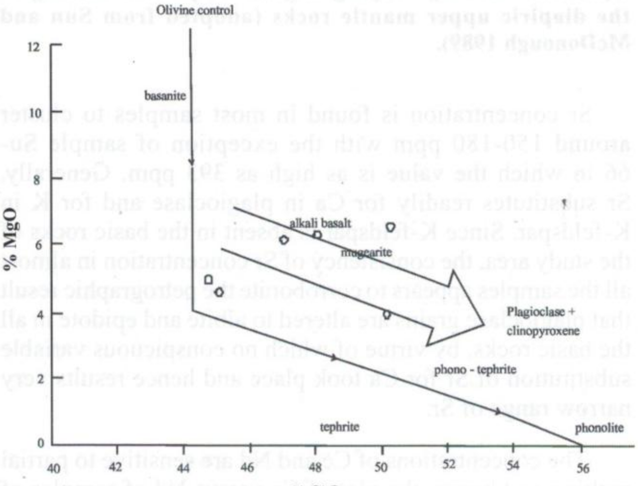

Fig. 10: Variation of wt % MgO vs wt % SiO_2 for alkali basalt-mugearite series that could be derived from the basanitic parent magma. The basic rocks of Manipur Ophiolite appear to be close to alkali basalt-mugearite series (adopted from Wilson 1989).

From the CIPW norms (Table 2), it is also perceived that some samples are undersaturated (normative nepheline) while the others have normative quartz (<5%). The samples of the basic rocks are found to have 44.73-51.19 weight percent of SiO_2. Moreover, the sample S10 (KW) having the highest SiO_2 content out of the undersaturated samples is happened to be the one of the least contaminated samples with considerable amount of olivine crystals (from petrographic examination). It is, therefore, reasonable to assume that the silica content of some of the original undersaturated melts could be as high as 50%; and sample Su 43(B) having as high as 14.3% normative nepheline contains 44.73% SiO_2. On the other hand sample Su-66 having 4.5% normative quartz contains 45.19% SiO_2. As Su 66 contains lower Na_2O content (also for all other samples having normative quartz), the sample has been contaminated by silica and therefore, extra SiO_2 have been added to that of the original melt. Considerable assimilation of silica is evident from petrographic examination in this sample. But the extra SiO_2 cannot be very large because sample Su 43(B) having 44.73% SiO_2 is still undersaturated. Thus, only few percent which may be about 2-3% of SiO_2 must have been added to the undersaturated melts to become saturated. Therefore, the lower limit of SiO_2 content in some of the melts cannot be much lower than 3%. Hence, it can be assumed that SiO_2 contents of the melt of the basic rocks of Manipur Ophiolite is about 43-50 weight percent.

Considering the possible variation of SiO_2 contents within a range of 43-50% and since, the weight percents of SiO_2 of all the samples of the basic rocks are also well within this range even after considerable assimilation with silica in some of the samples, SiO_2 variation could be used, for interpretation of differentiation trend as well as classification of the type of magmatic lineage. Therefore, when total alkalis (% Na_2O+K_2O) versus silica (% SiO_2) are plotted (Fig. 8) over the fields of non-potassic volcanic rocks nomenclature as given by Cox et al. (1979), the basic rocks of Manipur Ophiolite are found to have been pigeonholed in the fields of alkali basalt and hawaiites. From the diagram of weight percent K_2O and Na_2O separately versus weight percent SiO_2 (Fig. 9), it is found that the basic rocks of the study area plot in the alkali field in one diagram (% Na_2O) and in the sub-alkali field on the other (% K_2O). Such rocks are termed as transitional basalts (Middlemost 1975). Moreover, the variations of MgO with SiO_2 (Fig. 10) also indicate that the basic rocks appear to be of alkali basalt-mugearite series. Formation of mugearite by fractionation of alkali basalt is established by MacDonald and Katsura (1964).

Trace and rare earth elements geochemistry

The trace element and REE data are used as an important tool in deciphering the conditions of the formation of the basic rocks and the subsequent changes in due course of the evolution of the Ophiolite in Manipur. Cr content in the basic rocks of the study area is low ranging from about 140-380 ppm. The variation appears not showing any significant trend which may suggest any conspicuous fractionation. Generally,

Table 3: ICP (MS) data of selected trace and rare earth elements (Concentrations in ppm).

Sample / Element	Sc-10(KW)	Su-43	Su-66	Su-77	Su-81(A)
Cr	196.91	297.29	386.01	139.66	136.46
Co	23.12	36.24	44.59	32.13	63.67
Cu	40.93	69.45	82.64	45.32	87.66
Zr	866.82	4295.79	7520.54	7751.98	2095.64
Th	1.93	3.47	4.96	5.36	2.44
Zn	82.85	417.77	240.81	230.03	181.85
Ti	3955.53	9216.29	5409.56	10482.14	7591.20
Sr	184.38	170.46	393.73	183.72	153.33
Ba	243.70	381.04	526.92	645.29	234.22
Sm	2.07	4.71	3.73	6.16	2.97
Eu	0.71	1.61	1.47	2.11	1.05
Tb	0.38	0.90	0.66	1.28	0.58
Ho	0.63	1.62	1.25	2.49	0.85
Tm	0.26	0.68	0.53	1.04	0.34
Lu	0.37	0.93	0.97	1.42	0.40
Gd	1.87	4.02	3.64	5.85	2.65
Yb	2.67	6.01	4.58	9.67	5.35
Y	16.41	41.12	30.17	66.71	22.11
La	7.73	16.40	17.37	24.70	9.85
Ce	14.46	31.48	32.86	54.17	18.87
Pr	1.98	4.29	4.04	6.19	2.59
Nd	7.88	17.24	14.86	24.00	10.53
Tb	0.33	0.75	0.57	1.07	0.49
Dy	2.73	6.61	4.68	9.30	3.96
Nb	1.97	4.16	5.78	6.30	4.22
Ta	0.29	0.47	0.65	0.74	0.44

decrease in Co content through a rock series suggests olivine fractionation. The Co variation of the basic rocks of Manipur Ophiolite (23-63 ppm) shows no significant reflection of such a fractionation.

The basic rocks of the study area are found to have high concentrations of Ti, ranging from about 4000-10000 ppm. As the basic rocks consist of very limited grains of primary magnetite, this element could have been mostly present in secondary spinel. Concentration of Zr, which is a classic incompatible element not readily, substituting in the major mantle phases, is very high ranging from about 800-7500 ppm. The high concentration of Zr may suggest substitution for Ti in accessory secondary phases in due course of metasomatism or in due course of interaction of the mantle rocks with the continental rocks at the time of diapiric ascent.

Ba concentration in the basic rocks is found to range from about 240-650 ppm. It is an interesting observation that Ba concentration is found higher in samples which have higher modal proportion of uralite. As Ba substitutes for K in K-feldspar, amphibole and biotite, and since K-feldspar and biotite are absent in the basic rocks of Manipur, Ba must be mostly concentrated in the uralite grains and hence substitution for K during later metasomatism.

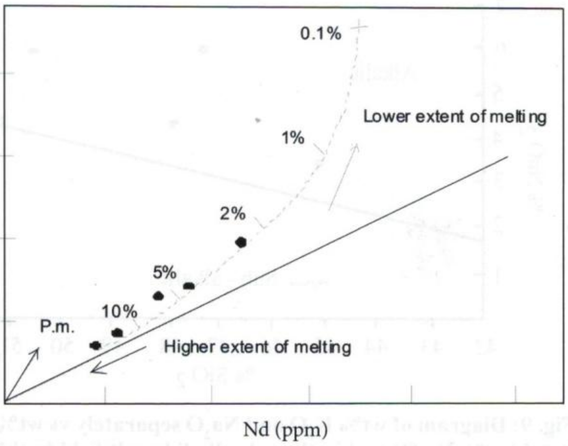

Fig. 11: Plot of Ce vs Nd for the basic rocks of Manipur Ophiolite showing varying degrees of partial melting of the diapiric upper mantle rocks (adopted from Sun and McDonough 1989).

Sr concentration is found in most samples to cluster around 150-180 ppm with the exception of sample Su-66 in which the value is as high as 393 ppm. Generally, Sr substitutes readily for Ca in plagioclase and for K in K-feldspar. Since K-feldspar is absent in the basic rocks of the study area, the consistency of Sr concentration in almost all the samples appears to corroborate the petrographic result that plagioclase grains are altered to albite and epidote in all the basic rocks, by virtue of which no conspicuous variable substitution of Sr for Ca took place and hence results very narrow range of Sr.

The concentrations of Ce and Nd are sensitive to partial melting and hence, the plot of Ce versus Nd of samples of basic rocks against predetermined standards generally reveals the varying degrees of partial melting of the diapiric mantle peridotitic rocks (Sun and McDonough 1989), which in case of Manipur Ophiolite is found to be ranging approximately within 3-20% (Fig. 11).

To understand the control of the composition of the melts by that of the host ultramafics and the change in the melt on account of fractional crystallization, chondrite normalized REE patterns of the ultramafics (averaged) and various basic rocks are plotted (Fig. 12). The data of the ultramafics are from Khuman (2009), while those of the basic rocks are given in Table 3.

Fig. 13a shows the spiderdiagram patterns for typical tholeiitic mid-oceanic ridge basalt (MORB); magma of tholeiitic origin with 15% contamination by upper crustal rocks; an upper crustal amphibolite facies gneiss; and a lower crustal granulite facies gneiss. MORB has been choosen to illustrate the trace element characteristics of a basaltic magma derived by partial melting of upper mantle rocks, which cannot have interacted with continental crustal rocks en route to the surface. Fig. 13b shows the spiderdiagram patterns of the basic rocks of Manipur ophiolite. The concentrations of

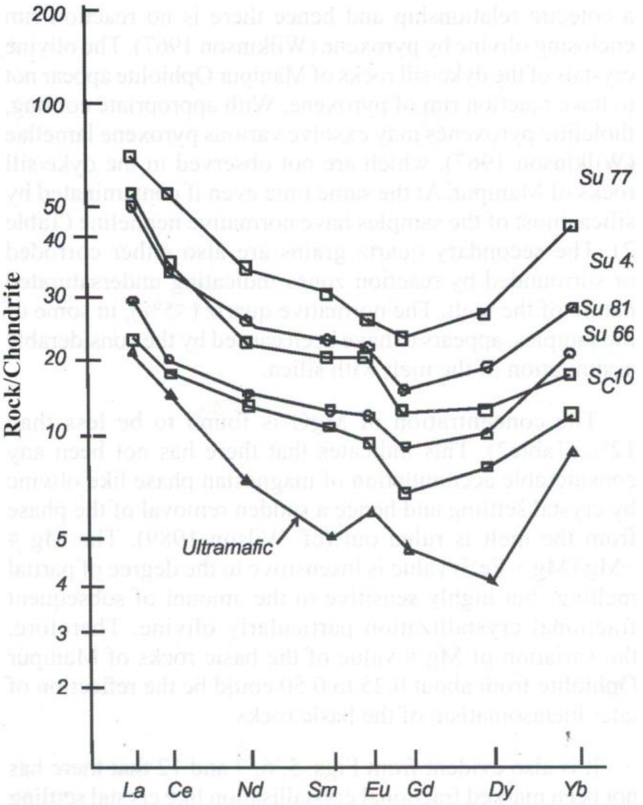

Fig. 12: Comparison of chondrite normalized REE patterns of ultramafic and basic rocks of Manipur Ophiolite.

K and P in these samples are calculated from XRF (percent) data, while those of the other elements are obtained from the ICP (MS) analysis data.

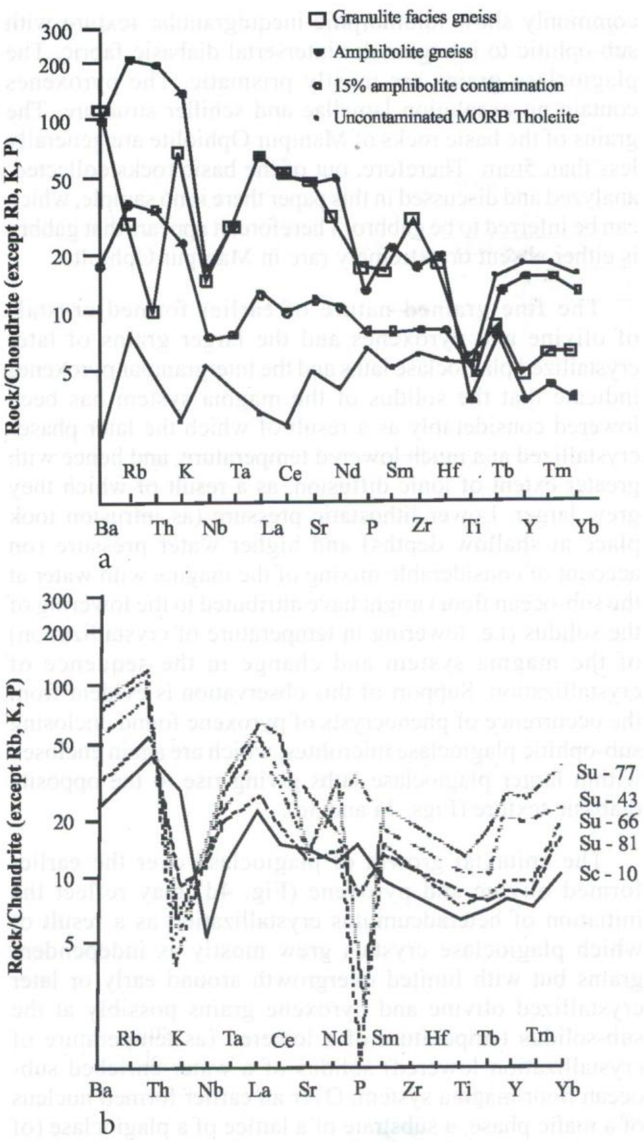

Fig. 13: (a) Spiderdiagram patterns of typical MORB, MORB (tholeiitic) with 15% contamination, amphibolite facies gneiss and granulite facies gneiss (adopted from Wilson 1989). (b) Spiderdiagram patterns of basic rocks of Manipur Ophiolite which appear to have been contaminated by upper crustal rocks (adopted from Wilson 1989).

DISCUSSIONS

From petrography and mineral chemistry it is established that all the samples of the dyke/sill rocks and pillow lavas of the Manipur Ophiolite Mélange Zone have undergone greenschist facies hydrothermal metamorphism, which is also known as spilitic metamorphism (cf. Gass and Smewing 1973). Coleman (1977), is of the opinion that spilitic metamorphism within the ophiolite sequence results from the interaction with hot circulating water within the upper part of the newly formed oceanic crust; and since the hydrothermal circulation cannot extend beyond 2-3 km depth on account of higher lithostatic pressure at such greater depths, the gabbroic rocks generally do not become spilites; and within the gabbroic horizon where the hydrothermal metamorphism dies out, calcic plagioclase persists and co-exists with actinolite and chlorite. As no basic rock having calcic plagioclase unaltered to albite and epidote could be explored, all the samples of the basic rocks collected so far from the Manipur Ophiolite Mélange Zone are found to be those which have either extruded to the ocean floor or intruded within peridotitic serpentinites and the pelagic sediments at shallow depths up to a maximum of about 3 km from the ocean floor. Moreover, Manipur Ophiolite dyke/sill rocks are found to consist of vesicles (Fig. 4b), which indicate shallow level of intrusion. Generally, gabbros are commonly hypidiomorphic equigranular, less commonly ophitic or sub-ophitic. Plagioclase is generally tabular in habit; and the pyroxenes frequently contain exsolution lamellae and often show well-developed schiller structure, arising from platy or needle shaped inclusions (Wilkinson 1967). Moreover, the gabbroic rocks are coarse-grained (5 mm - 3 cm). But the basic rocks of Manipur Ophiolite commonly show idiomorphic inequigranular texture with sub-ophitic to intergranular/intersertal diabasic fabric. The plagioclase grains are mostly prismatic. The pyroxenes contain no exsolution lamellae and schiller structure. The grains of the basic rocks of Manipur Ophiolite are generally less than 5mm. Therefore, out of the basic rocks collected, analyzed and discussed in this paper there is no sample, which can be inferred to be gabbro. Therefore, it appears that gabbro is either absent or extremely rare in Manipur Ophiolte.

The fine grained nature of earlier formed crystals of olivine and pyroxenes and the larger grains of later crystallized plagioclase laths and the intergranular pyroxenes indicate that the solidus of the magma system has been lowered considerably as a result of which the later phases crystallized at a much lowered temperature, and hence with greater extent of ionic diffusion, as a result of which they grew larger. Lower lithostatic pressure (as intrusion took place at shallow depths) and higher water pressure (on account of considerable mixing of the magma with water at the sub-ocean floor) might have attributed to the lowering of the solidus (i.e. lowering in temperature of crystallization) of the magma system and change in the sequence of crystallization. Support of this observation is evident from the occurrence of phenocrysts of pyroxene found enclosing sub-ophitic plagioclase microlites, which are again enclosed within larger plagioclase laths giving rise to the opposite diabasic texture (Figs. 3a and 3e).

The epitaxial growth of plagioclase over the earlier formed olivine and pyroxene (Fig. 4d) may reflect the initiation of heteradcumulus crystallization as a result of which plagioclase crystals grew mostly as independent grains but with limited overgrowth around early or later crystallized olivine and pyroxene grains possibly at the sub-solidus temperature of a lowered (as temperature of crystallization lowered) solidus of a water enriched sub-ocean floor magma system. Over an earlier formed nucleus of a mafic phase, a substrate of a lattice of a plagioclase (of a definite composition) having susceptible atomic structure, might have grown epitaxially over it (cf. Best 2001).

The samples of the dyke/sill rock are found to have been assimilated considerably by silica. On the other hand, intrusion of the dykes must have not been in depths greater than 3 km. Consequently, the ultramafic rocks must have risen to the sub-ocean floor indicating that diapirism still continued even after partial melting of the rocks died out. The shallowness of the ultramafics in the ocean basin again implies that the mafic layer of the oceanic crust (Layer 2 and Layer 3) were exceedingly thin. This again supports the idea that Manipur Ophiolite Mélange Zone is either devoid or exceedingly rare of gabbro.

An essential and critical petrographic feature of magmas of tholeiitic lineage is the reaction relation between olivine and calcium poor pyroxene, often indicated by pyroxene riming olivine; and in strong contrast, olivine and calcium poor pyroxene belonging to the alkali basalt lineage show a cotectic relationship and hence there is no reaction rim enclosing olivine by pyroxene (Wilkinson 1967). The olivine crystals of the dyke/sill rocks of Manipur Ophiolite appear not to have reaction rim of pyroxene. With appropriate cooling, tholeiitic pyroxenes may exsolve various pyroxene lamellae (Wilkinson 1967), which are not observed in the dyke/sill rocks of Manipur. At the same time even if contaminated by silica, most of the samples have normative nepheline (Table 2). The secondary quartz grains are also either corroded or surrounded by reaction zones indicating undersaturated nature of the melt. The normative quartz (<5%), in some of the samples, appears to have been caused by the considerable assimilation of the melt with silica.

The concentration of MgO is found to be less than 12% (Table2). This indicates that there has not been any considerable accumulation of magnesian phase like olivine by crystal settling and hence a sudden removal of the phase from the melt is ruled out (cf. Wilson 1989). The Mg # =Mg/(Mg + Fe^{+2}) value is insensitive to the degree of partial melting but highly sensitive to the amount of subsequent fractional crystallization particularly olivine. Therefore, the variation of Mg # value of the basic rocks of Manipur Ophiolite from about 0.25 to 0.50 could be the reflection of later metasomatism of the basic rocks.

It is also evident from Figs. 5, 6, 7 and 12 that there has not been marked fractional crystallisation like crystal settling and the subsequent operation of crystal-liquid separation in the melts of Manipur Ophiolite. Therefore, no large magma chambers must have been developed and hence the Manipur Ophiolite must have been developed in a slow spreading centre (cf. Wilson 1989).

In Fig. 13a the continental crustal rocks (amphibolite gneiss) are variably enriched in the whole range of incompatible elements from Ba to Hf relative to MORB and variably depleted in the elements Ti to Yb. The spiderdiagram patterns of lower crustal granulite facies gneiss are remarkably similar from K to Yb but differ significantly for the elements Rb and Th, which are strongly concentrated in the upper crust. In comparison Fig. 13b with Fig. 13a, it is observed that most samples of the basic rocks closely approach the pattern of magma with 15% contamination by upper crustal rocks. The distinctive signature for the magma, which has been contaminated by upper continental crustal rocks, is the marked trough in the spiderdiagram pattern at Nb-Ta. It is observed that K and P are strongly depleted in most of the samples which are interpreted to have been caused by higher level of alteration in due course of interaction of the melt/rock with the percolating hot ocean water.

Fig. 13b as compared with Fig. 13a also reveals some important features concerning crustal contamination effects. The elements Ti, Tb, Y, Tm and Yb appear essentially unmodified, even at significant degrees of contamination. The marked deviation from unmodified nature of Ti, Tb, Y, Tm, and Yb in the basic rocks of Manipur Ophiolite may serve as an additional evidence to show that the original melts from which the rocks crystallized are not of tholeiitic lineage.

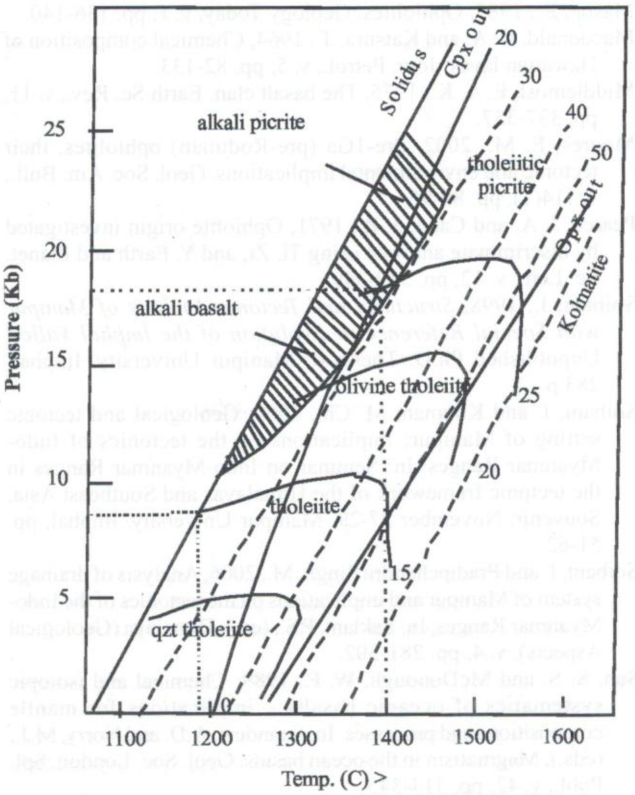

Fig. 14: Determination of the P-T conditions of magma generation of Manipur Ophiolite, from the experimentally determined partial melting characteristics of an enriched lherzolite source (adopted from Jaques and Green 1980).

It is found that the melts must have been contaminated by upper continental crustal (amphibolite gneiss) rocks. But, the spiderdiagram patterns of the basic rocks conform (sub-parallel) to that of the host ultramafics (Fig. 12). Therefore, the host rocks from which the melts derived must have already contaminated on account of interaction of the diapiric upper mantle rocks with the upper (continental) crustal rocks leading to considerable metasomatism.

For determination of the conditions for the generation of the melts, we make use of experimentally determined partial melting characteristics (after Jaques and Green 1980) of an enriched lherzolite source (Fig. 14). The ophiolitic ultramafics of Manipur Ophiolite are found to be of enriched continental source origin (Khuman and Soibam 2010). As contour of 8% normative olivine in the figure is well within the field of tholeiite (contrary to the alkalic basalt lineage of the basic rocks of Manipur Ophiolite), it is assumed that the minimum normative olivine of the parent basaltic melt should not be less than 15%. But, the upper limit of 24% is well in agreement with the possible maximum upper level of 25% of the general melts of alkali basalt composition generated from less than about 20% partial melting of enriched lherzolite source. Therefore, the range of normative olivine in the original melts of diabasic/basaltic rocks of Manipur Ophiolite is considered to be about 15-25%. For melts having 15% normative olivine the initiation of partial melting begins at a temperature of about 1185^{0}C with a corresponding pressure of about 8Kb. The maximum partial melting of Manipur Ophiolite is about 20% (Fig. 11), and there are no modal clinopyroxene in some of the ultramafic samples (Khuman 2009). Therefore, the point nearest to the line of 20% partial melting and the line of clinopyroxene out in the figure with that of the 25% normative olivine contour indicate the maximum temperature for production of the melt. This corresponds to a temperature of about 1400^{0}C and a pressure of about 18 Kb. Therefore, the temperature range for the generation of the basaltic rocks of Manipur Ophiolite is roughly within 1185-1400^{0}C, with the corresponding pressure range of about 8-18 Kb. Hence, the approximate depth range is about 25-50 km.

CONCLUSIONS

From the analyses and observations as discussed above, it can be brought to the conclusion that all the basic rocks: diabasic dykes/sills, exotic blocks of diabase and basaltic pillow lavas of Manipur Ophiolite have experienced spilitic metamorphic conditions. The melts are of alkali basalt lineage having transitional character. The melts must have been generated on account of partial melting of about 3-20% of the diapiric upper mantle rocks contaminated by upper continental crust in a slow spreading centre at a depth range of about 25-50 km. And normally oceanic crust formed at slow spreading centers has little or no well developed gabbroic layers (cf. Moores 2002). It is also observed that there have not been large magma chambers where considerable crystal-liquid separation was operational thereby resulting to the creation of a very thin oceanic crust where the cumulate rocks are either absent or considerably rare.

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