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HIGH PRESSURE (ECLOGITE FACIES) METAMORPHISM IN THE INDIAN PLATE, NW HIMALAYA, PAKISTAN

D.A. SPENCER[1], J.G. RAMSAY[1], C. SPENCER-CERVATO[1], U. POGNANTE[2], M.N. CHAUDHRY[3] & M. GHAZANFAR[3]

[1]Swiss Federal Institute of Technology, Zurich, Switzerland

[2]University of Torino, Italy

[3]University of the Punjab, Lahore, Pakistan

ABSTRACT

A zone of high pressure (eclogite facies) metamorphism, characterized by eclogites with an assemblage of omphacite - garnet - quartz - rutile ± phengite, has been recognized in the higher Himalaya in the Indian Plate of NE Pakistan. This suggests that the Upper Kaghan Nappe is the deepest derived part of the Indian Plate to have been subducted and subsequently uplifted along the whole length of the Himalaya. Mineral chemistry by microprobe analysis suggests that the eclogites formed at temperatures of 650±50 °C and pressures of 13-18 kbar, suggesting depth of eclogite formation at 60 km. The eclogites show an incipient decompressional re-equilibration which probably occurred at decreasing temperatures.

INTRODUCTION

Eclogites and eclogite facies metamorphism have been recognized for the first time in the Indian plate of the Himalayan belt. The findings of eclogites in thrust tectonic regimes are of special interest because of their relation to subduction processes and that they may help in the reconstruction of the early stages of orogeny. The significance of this find is of utmost importance in the study of Himalayan tectonics, as a pressure derived metamorphic assemblage, such as blueschists and eclogites, can be used to interpret the depth of formation of lithology, which, in terms of Himalayan tectonics is the depth of subduction of the Indian plate beneath the Kohistan Island arc and Asian plate.

The Himalayas are the classic example of the continent-continent collision zone yet, unlike in the European Alps, high pressure assemblages are not common. The Alps contain the blueschist and eclogite facies rocks affecting both the ophiolitic and continental rocks (Droop et al., 1990). However, in contrast, the recognition of high pressure assemblages has been confined to the blueschists of the ophiolitic sutures (Shams, 1972; Honegger et al., 1989) and the garnet-granulites of the Jijal Complex in Pakistan and the low- and medium-P metamorphism in the calc-alkaline magmatism in Tibet, Kohistan and Ladakh (Jan, 1991). This paper describes a high pressure assemblage in the continental type rocks of the Indian plate.

GEOLOGY OF THE KAGHAN VALLEY

Kaghan valley in the North West Frontier Province of Pakistan, can now be regarded as a classic section for the study of Indian plate geology (Fig. 1). The 165 km valley gives an unparalleled cross-section through the Indian plate and the tectonic units that it is composed of (Spencer et al., 1991). In summary, the Sub-, Lesser-, Higher- and Tethyan- Himalayan tectonic units, as well as the Kohistan Island Arc, are all exposed in one single cross-section along the Kunhar River. Associated with these major units are the Himalayan thrusts that separate them: Main Boundary Thrust, Panjal Thrust, Main Central Thrust and the Indus Suture or the Main Mantle Thrust. The Higher Himalayan Crystalline and the Higher Himalayan Tethyan Units are included in one nappe: the Upper Kaghan Nappe which lies between the Main Central Thrust and the Indus Suture. This nappe can be subdivided into three units, all of which are separated by unconformities: the Higher Himalayan Basement which consists of metagranites of probable Lower Paleozoic age which have intruded into a meta-pelitic unit of possible Precambrian age. This basement is unconformably overlain by sediments and intrusions (derived from the Tethyan ocean) which are unmetamorphosed along the length of the Himalayan belt. However, in the NW Himalaya, they are caught up with the subducting Indian plate and are taken down to depths of amphibolite and eclogite facies formation. There are two recognizable units of the Higher Tethyan Himalaya (so called to distinguish them from the unmetamorphosed Tethyan Himalaya) found in the Upper Kaghan Nappe: a lower metamorphic cover of metagraywacke of Lower Paleozoic age and upper metamorphic cover consisting of the Permian Panjal Trap Volcanics, associated syn-volcanic marine deposits (marbles) and a subsequent Triassic Sedimentary Series (marbles, micaschists and dolomites).

FIELD OCCURRENCE OF THE ECLOGITES

Eclogites have been found and recognized in two units of the Upper Kaghan Nappe: the Higher Himalayan basement and the Upper Higher Himalayan Tethyan

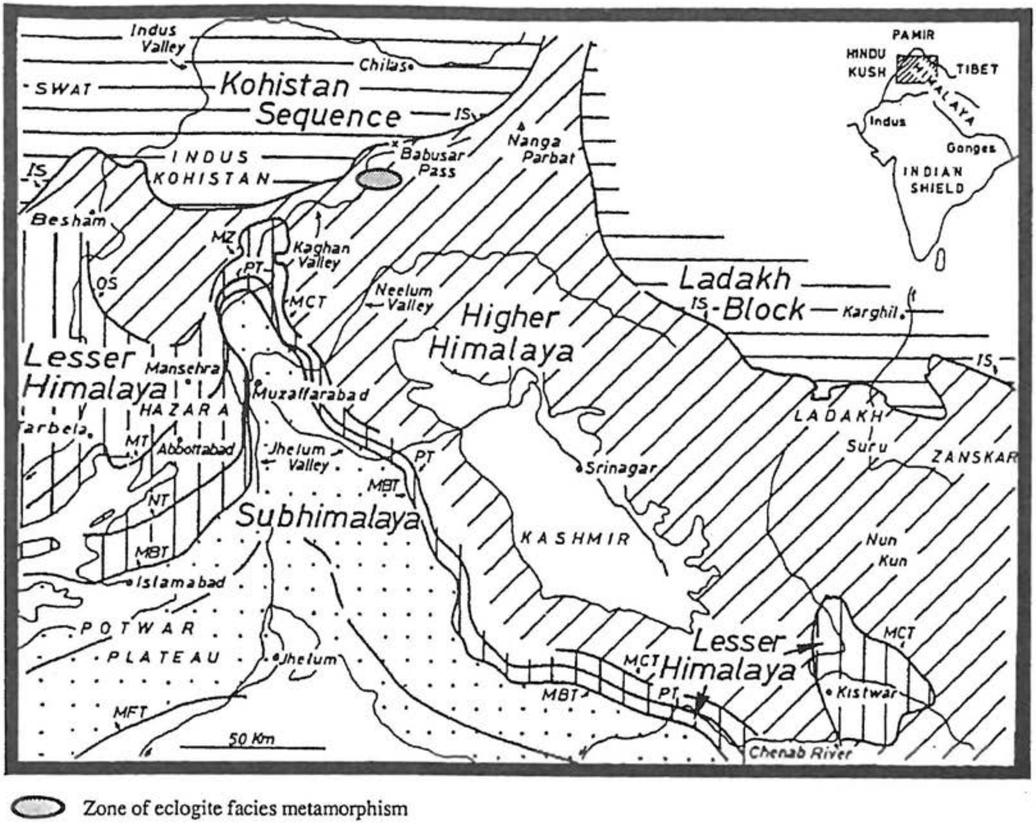


Fig. 1. Tectonic map of NW Himalaya (redrawn after Greco, 1989) to show the approximate location of the eclogite facies metamor phism in northern Pakistan reported in detail in Figure 2.

cover. Chaudhry et al. (1987) were the first to recognize an unusual rock in the basement unit of the Higher Himalaya. They described the rock as:

"....ultramafic, garnet - amphibole - pyroxene rocks occurring as xenolits and small screens in granite. These rocks have a distinctively higher specific gravity than the ordinary amphibolites. They are multicoloured red, bright green and black with granoblastic to sub-porphyroblastic textures. The individual minerals may show some segregation and at places, the lenses are composed of up to 80% garnet. At other places, pyroxene and amphibole show segregation. The screens and xenoliths, at places, along contacts with granite gain a little quartz, feldspar and even mica. While the surrounding granite becomes rich in garnet, amphibole and at places biotite".

Chaudhry et al. (1987) further went on to speculate that they look like garnet retrogranulites and retroeclogites.

Subsequent reexamination of these locations described by Chaudhry et al. (1987) confirmed that these unusual lithologies did exist and further locations were discovered in Basel area of the Kaghan Valley. The first petrological recognition of the eclogites (C. Spencer-Cervato) was difficult due to the amount of retrogression that the eclogites had undergone in the Upper Himalayan Tethyan Cover and their sporadic occurrence in the Higher Himalayan Basement. Detailed mapping of the metamorphic assemblage has now distinguished a zone of eclogite facies metamorphism within the previous known zone of amphibolite facies metamorphism (Chaudhry et al., 1986).

The zone of eclogite facies metamorphism is concentrated in an oval shape around the village of Basel in Kaghan valley (Fig. 2). Due to reasons of retrogression they are best recognized in the basement unit where the water necessary for the equilibrium hydration reaction of eclogite to amphibolite facies was less prominent. The best location for the recognition of the unretrogressed eclogites are between Kaar and Khanka Deri in the Purbinar valley, near Basel. Other locations include the area between Lalia Di Baihk and Khaida Baihk in the Gittidas Nala valley, near Gittidas, the entrance to Lhyalul Nar, near Gittidas and along the Kaghan Valley road below Basel di Mahli.

The eclogites are discordant to the surrounding host rocks in the Higher Himalayan Basement and are concordant to the surrounding host rocks in the Higher Himalayan Tethyan Cover. From this field observation, it is suggested that the eclogites in the basement are the feeder dykes to the eclogites and Panjal Trap layers in the Upper Higher Himalayan Tethyan Cover.

In the basement, the eclogites occur as lens-like bodies which vary from a few meters lens thickness and tens of meters in length. The contact of the country rock with the lenses was regular enough to get structural measurements of the lens orientation: Purbinar Lens: 67 NE/150; Gittidas lens: 28 SW/168. In contrast, the eclogites in the Upper Higher Himalayan Tethyan Cover extend within the Panjal Trap layers hundreds of meters in length with varying thicknesses of some one to twenty meters.

PETROLOGICAL DESCRIPTION

Eclogites from the basement unit are those that show the least amount of retrogression and so were the best to analyse.

In hand sample, the specimen consists essentially of a fine to medium grained rock characterized by the assemblage: Na-pyroxene and almandine garnet, quartz, rutile $\pm$ phengite. The garnet can sometimes make up to 80% of the rock, with a granoblastic texture. A foliation or a venule, corresponding to a compositional layering is often present, which is probably due to metamorphic differentiation and is defined by the preferred orientation of the Na-pyroxenes ± rutile.

Fig. 2. Geological map of Kaghan Valley, northern Pakistan (modified after Greco, 1 8) to show the zone of eclogite facies metamorphism in the Higher Himalayas.

In thin sections, the eclogite has: essential minerals: omphacite - colourless to pale green (40-50%), almandine garnet - isotropic (40-80%); minor minerals: rutile - occurring as small subidiobatic to idiobatic crystals (~5%); quartz - forms xenoblastic intergranular crystals (5%); amphibole - retrogressed product of the omphacite (10%); no plagioclase is found.

The texture is granoblastic, with a slight elongation of the omphacite grains and with interlocking polygonal aggregates of pyroxene and garnet. The grain boundaries between the crystals tend to be straight, although the garnets tend to form crystal faces. Minor retrogression has occurred to the pyroxene with a "kelyphitic" alteration. This forms rims around the grains. Minor reaction between the garnet and the pyroxene occurs to give reaction rims and irregular symplectic intergrowths. Early growth of amphibolite and epidote are also associated with the post- eclogite recrystallisation.

Preservation of the eclogite differs relative to the host rock in which they are found. In the basement they are very well-preserved and in the Upper Higher Himalayan Tethyan Cover they are often very retrogressed. This is simply due to the fact that mafic eclogites, which consist primarily of omphacite and garnet, have to hydrate to equilibrate in the amphibolite facies during uplift. Therefore, a major factor that controls the rate of such equilibration is the availability and rate of supply of water from an external source during uplift. The supply of water was more readily available from the metapelites and marbles in the Upper Higher Himalayan Tethyan Cover than in the granites of the Higher Himalayan Basement. This reaction is one, of perhaps others that may be occurring, based on petrological observations:

Phengite + Paragonite + Garnet ------ Plagioclase + Biotite + Water

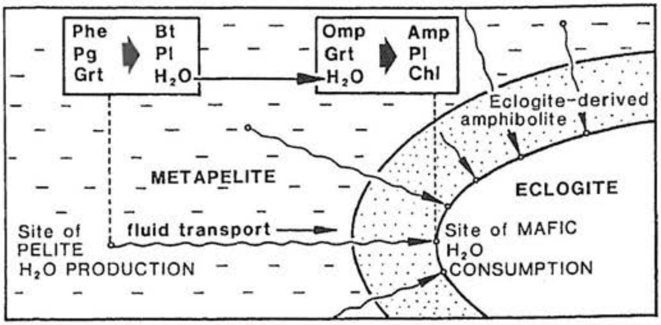
(Reaction 1)

In contrast, lenses of the mafic eclogite equilibrated in the amphibolite facies by the hydration reaction:

Garnet + Omphacite + Water ------- Hornblende + Plagioclase + Chlorite

(Reaction 2)

Alteration by reaction 2 developed initially at the margins of the eclogite bodies and concentric zones of symplectite eclogite and amphibole grew progressively inwards (Fig. 3). The progress of reaction 2 was evidently controlled by infiltration of hydrous fluid from the surrounding pelites. Dehydration of these pelites by reaction 1 was the source of these fluids. On the basis of widths of reaction zones and the likely permeability values (Rubie, 1986), it is estimated that fluid-present conditions in the pelites and amphibolisation of the mafic eclogites occurred over a relatively short time interval of Ma. Although the preservation of the eclogites depends primarily on the absence of hydrous fluid during uplift, the maintenance of a low or decreasing temperature is also important. If the temperature remains high, certain lithologies, such as metapelites in the Upper Higher Himalayan Tethyan Cover, may dehydrate and consequently act as a source of hydrous fluid. Similar reactions can be seen in the eclogites of the Adula Nappe in the Central Alps (Heinrich, 1982). Here, metapelites were in direct contact with the eclogites in the basement of the Adula Nappe. The eclogites underwent an eclogite to amphibolite facies transition during the Tethyan (Lepontine) metamorphism and in the metapelites this transition occurred by a similar dehydration reaction.



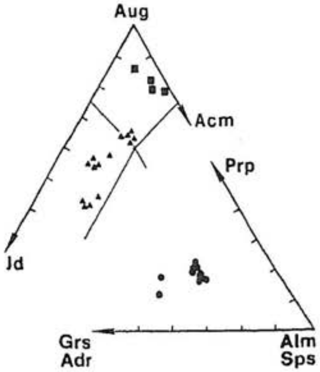


Fig. 3 (Left). Suggested explanation for the conversion of eclogites to amphibolites in the Upper Higher Himalayan Tethyan Himalaya Cover. The eclogite is being hydrated to amphibolite by the water released by the dehydration on the enclosing metapelites. Lack of substantial metapelites or dehydration reactions associated with the granites and granite-gneisses in the Higher Himalayan Basement, leads to the excellent preservation of the eclogites in the basement.

Fig. 4 (Right). Composition of pyroxenes in the augite (Aug) - jadeite (Jd) - aegirine (Aeg) diagram, and of garnets in the pyrope (Prp) - [grossular (Grs) + andradite (Adr)] - [almandine (Alm) + spessartine (Sps)] diagram. Squares: diopsides from symplectite reaction rims after Na-pyroxenes; Triangles: omphacites and sodian augites; Dots: garnets.

It is, therefore, obvious that the importance of water as a reaction catalyst in the retrograde reactions during the uplift of eclogites to the earth's surface is dependent on its availability. This availability is dependent on the surrounding lithologies and is fundamental in the recognition of well-preserved eclogites in the Higher Himalayan Basement and their retrogression in the Upper Higher Himalayan Tethyan Cover.

MINERAL CHEMISTRY

Pale green Na-pyroxenes occur in granoblastic aggregates or in small grains associated with garnet-rich or quartz-rich layers. They are sodian augites or omphacites (in different samples) (Table 1; Fig. 4) with slight irregular zoning and with the highest jadeite contents (X_{jd} = 0.42) in the quartz rich samples. In a few samples, Na-pyroxenes show symplectic reaction rims consisting of diopside (X_{jd} = 0.01-0.07) and albite (X_{ab} = 0.97- 0.99). Garnets form idioblastic or sub-idioblastic grains which are often concentrated in layers. They are rich in almandine (X_{alm} = 0.46-0.60), with lower grossular (X_{grs} = 0.15-0.33) and pyrope (X_{prp} = 0.12-0.22) contents (Fig. 2) and very low andradite (X_{adr} = 0.03-0.06) and spessartine (X_{sps} = 0.00-0.17) contents (Table 1; Fig. 3).

TABLE 1. REPRESENTATIVE MICROPROBE ANALYSES OF PYROXENES, GARNETS, AMPHIBOLE, PHENGITE AND EPIDOTE

Mineral Probed	Pyrox	Pyrox	Gar	Gar	Amph	Phen	Epid
Location	Rim	Core	Rim	Core	Core		
Sample number	89/88	88/129	88/88	88/129	88/88	88/129	88/88
SiO_2	52.94	[illegible].74	37.81	37.86	45.52	50.91	37.92
TiO_2	0.00	0.00	0.00	0.00	0.49	0.83	.0.00
Al_2O_3	5.47	10.65	20.90	21.41	10.20	25.03	24.85
Fe_2O_3	7.32	7.17	2.03	1.12	5.64	1.77	12.09
FeO	4.55	2.18	25.76	25.56	10.44	1.94	0.67
MnO	0.00	0.00	0.61	0.32	0.00	0.00	0.00
MgO	8.58	5.77	5.50	5.22	11.65	4.66	0.00
CaO	15.54	10.66	7.58	8.34	10.20	0.00	23.03
Na_2O	5.08	8.48	0.00	0.00	3.03	0.59	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	10.07	0.00
Total	99.48	99.65	100.19	99.83	97.17	95.80	98.56
Si	1.961	1.973	2.955	2.961	6.706	3.396	2.988
Al^{IV}	0.039	0.027	0.045	0.040	1.294	0.604	0.012
Al^{VI}	0.200	0.425	1.880	1.933	0.476	1.364	2.295
Ti	0.000	0.000	0.000	0.000	0.054	0.042	0.000
Fe^{3+}	0.204	0.194	0.119	0.066	0.625	0.890	0.717
Fe^{2+}	0.141	0.066	1.684	1.671	1.287	0.108	0.044
Mn	0.000	0.000	0.041	0.021	0.000	0.000	0.000
Mg	0.474	0.310	0.641	0.609	2.558	0.464	0.000
Ca	0.617	0.412	0.635	0.699	1.610	0.000	1.944
Na	0.364	0.593	0.000	0.000	0.866	0.076	0.000
K	0.000	0.000	0.000	0.000	0.000	0.857	0.000
Total	4.000	4.000	8.000	8.000	15.476	7.000	8.000

Structural formulae are calculated on the basis of 4 cations and 6 oxygens for pyroxenes, 8 cations and 12 oxygens for garnets, 13 cations (ncat-Ca-Na = 13) and 23 oxygens for amphibole, 7 cations and 12 oxygens for phengite, 8 cations and 13 oxygens for epidote..

They show only slight zoning with rims usually enriched in almandine and spessartine and depleted in grossular and pyrope relative to cores. In a few samples, they show an incipient transformation to Ca-amphibole, albite and Fe-oxides. Amphiboles form poikiloblasts including corroded grains of Na-pyroxene and garnet. According to the IMA classification (Leake, 1978) in the quartz poor samples they are green-coloured magnesio-hornblendes (Table 1) and ferroan pargasitic hornblendes characterized by high Al^{IV} (1.267-1.700 atoms per 13 cations and 23 oxygens), lower Al^{VI} (0.467-0.831), low Ti contents and irregular zoning patterns. In the quartz-rich samples, they are blue-green coloured magnesio-katophorite with intermediate Al^{VI} (0.999-1.040) and Al^{VI} (0.929-0.937), and low Ti contents. Phengites (Si=3.3-3.4 atoms per 11 oxygens) have been found only in the quartz-rich samples where they form large crystals rimmed by green biotite. Epidotes are secondary minerals and form poikiloblasts rich in inclusions of corroded garnet.

P-T CONDITIONS OF ECLOGITISATION

For the studied rocks, temperatures of eclogitisation have been measured on the basis of the garnet-clinopyroxene Fe-Mg geothermometer. The former gives T=650±50°C (mean 20 pairs) using the calibration of Ellis and Green (1979) and T=600±60°C using the calibration of Krogh (1988). The garnet-phengite thermometer gives T=600±35°C (mean of 10 pairs, using the calibration of Green and Hellman (1982). Omphacite, garnet and phengite do not show any significant zoning and the derived temperatures are rather consistent, lying within the range of the temperatures proposed for the sillimanite-kyanite bearing gneisses of the Upper Kaghan Valley by Greco (1989) and Treloar (1989). These lines of evidence suggest that the temperature values recorded by us do not reflect a marked readjustment of the Fe-Mg exchange equilibria and probably approach the peak temperatures of eclogitisation.

Considering pressure estimates, the presence of omphacite (X_{jd}=0.42) coexisting with quartz indicates pressure in excess of 13 kbar (at T=600°C) using the calibration of Holland (1983). An upper limit of 18 kbar (at 700°C (upper limit of maximum peak temperature); Holland, 1983) is suggested by the apparent lack, in the host gneisses, of jadeite-quartz assemblages. The Si content per formula unit of phengite (3.396 (in Table 1) and 3.504, 3.468, 3.382) suggest, at temperatures of 650°C, pressures of 12-15 kbar (Massone and Schreyer, 1987). Consequently, omphacite-garnet assemblages in metabasites and plagioclase-bearing assemblages in quartzofeldspathic rocks probably coexist in the Upper Kaghan Nappe. These pressure values are higher than the 11±2 kbar (at T=675±50°C) proposed for the Upper Kaghan Nappe by Treloar (1989). The derived pressures are also significantly higher than those estimated for more easterly parts of the Higher Himalayan Crystalline, for example in Zanskar (Pognante et al.,

1990) and Nepal (Brunel & Kienast, 1986; Hubbard, 1989) where occasional garnet-granulites occur instead of eclogites (Burg et al., 1987; Pognante and Lombardo, 1989).

Depth of formation of the eclogites can be made from the above estimates on a pressure - time - depth diagram (Fig. 5). They show that a depth of eclogite formation at around 45-65 km is evident, certainly confirming that Upper Kaghan Nappe, or at least that part of the nappe that now crops out near Basel, is the deepest derived nappe, known so far, in the Himalayan belt.

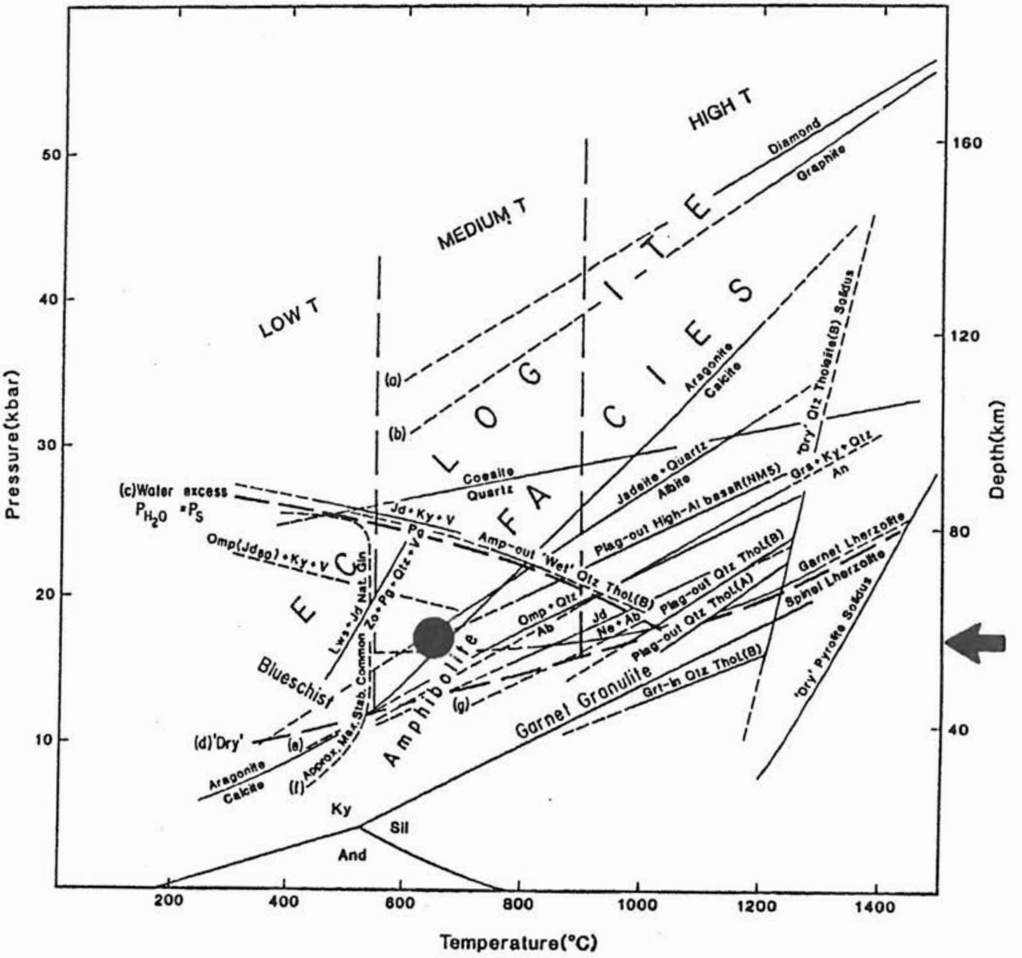


Fig. 5. Pressure (lithostatic confining pressure on solid aggregate of mineral grains) - Temperature - Depth petrogenic grid showing the conditions for the stability of eclogite facies assemblages. Pressure - temperature conditions of the basement eclogites for the Upper Kaghan Nappe are shown by the circular symbol and the extrapolated depth of formation shown by the arrow.

Although the eclogite assemblage of the studied rocks is very well preserved, it displays incipient transformation with the growth of secondary amphibole and epidote poikiloblasts and the formation of symplectic reaction rims of diopside and albite. These transformations should reflect a decompressional evolution eventually accompanied, during the growth of amphibole and epidote, by infiltration of a water-rich phase. Regarding the temperature conditions during decompression, the following considerations provide a few constraints:

a) The secondary formation of the hornblende, epidote, diopside and almost pure albite is usually ascribed to recrystallisation near the transition between greenschist facies and amphibolite facies (e.g. Winkler, 1974; Maruyama et al., 1983).

b) In the relics of garnet-granulites from the Zanskar region in Kashmir abundant hornblende, plagioclase (X_{Ab}= 79-66) and biotite (but neither epidote nor albite) formed during pressure drop at medium-high temperatures (Pognante and Lombardo, 1989). This kind of transformation was not observed in the Kaghan eclogites.

c) Petrographic observations in the gneisses of the Kaghan Nappe indicate the kyanite formed during the pressure peak and during the exhumation path (Greco, 1989). In the zone of eclogite facies metamorphism, kyanite also occurs in late stage pegmatite dykes, whilst sillimanite is lacking.

All these considerations suggest a post-eclogite exhumation at more or less decreasing temperatures, in agreement with the cooling path already proposed by Greco (1989) for the Kaghan Nappe. A different exhumation history occurred in the Higher Himalayan Crystalline of India and Nepal Himalaya where the early decompressional paths occurred at uniform or, more likely, at increasing temperatures with extensive migmatisations and leucogranite formation (e.g. Le Fort, 1986).

CONCLUSIONS

Eclogites are stable below 700 °C and pressure above 10 kbar. This assemblage can, therefore, be related to a specific very high pressure-medium temperature environment for the metamorphism. The metamorphism in the Himalaya took place as a response of the Indian - Asian plate collision and the resulting crustal thickening. The highest grades of metamorphism reported so far were associated with the extensive migmatites and anatectic granites. To date, only blueschist, greenschist and amphibolite facies metamorphism were recognized in the Indian plate. The eclogite facies metamorphism recognized in the Kaghan Valley, therefore, represents the deepest derived rocks of the Indian Plate known so far and are the first record of true high-pressure assemblages of eclogite facies in the continental-type units of the Himalayan belt. They formed at $T=650\pm50$ °C and P=13-18 kbar and represent the deepest rocks derived from the Indian plate known so far. The eclogites apparently derive from the Panjal Trap Volcanics and feeder dykes of Permian age and are included in orthogneisses which suffered only the Himalayan metamorphism. Consequently, eclogitisation is tentatively ascribed to the early stage of the Tertiary Himalayan metamorphism which, on the basis of geochronological data, should be of Eocene - Oligocene age (Treloar et al., 1989).

The incipient re-equilibrations of the eclogitic assemblage reflect a pressure drop which probably occurred at decreasing temperatures. This suggests that the Kaghan Nappe of northern Pakistan followed an exhumation path different from the paths of the Higher Himalaya in India and Nepal. East of Pakistan, after occasional formation of garnet-granulites instead of eclogites, the early exhumation occurred at more or less increasing temperatures. Further differences along the Higher Himalayas are given by the geochronological data which indicate prevalent pre-Miocene ages in the northern Pakistan (Treloar et al., 1989) and Miocene ages more easterly (Le Fort, 1986).

In conclusion, subduction at very deep crustal levels with eclogite formation and rapid exhumation, probably along a cooling path, are apparently restricted to a part of the Higher Himalaya of northern Pakistan. In central and eastern Himalayas subduction and exhumation probably occurred at lower rates giving a relatively warm thickened crust which suffered extensive anatexis and formation of abundant leucogranites. The fact that these are the only recorded eclogites in the Indian Plate could also be used to indicate that there is a significant reason for this. Plate tectonic reconstructions of the Indian-Asian collision (Dewey et al., 1989) show that the promontory of the Indian plate was the first part of the plate to collide with the Asian Plate. This would, therefore, be the first part of the crust to subduct and, as such, would effectively go to the deepest level. As a result, it would attain the highest temperatures and the highest pressure for any part of the collision zone, as there is the likelihood that, after the "main" collision took place (i.e. the more substantial, "non-promontory" part of the Indian Plate), the level of subduction was not so deep. This recognition of eclogite facies has a direct influence on the understanding of the Himalayan metamorphic history and diverted PT-time trajectories, as well as the cooling-uplift rates suggested by various dating techniques.

As the metamorphic constraints on the thermal models for the tectonic environment have not included the possibility of eclogite facies metamorphism in the Himalaya, it is, therefore, considered that a modification is needed. The upper Kaghan Nappe may well represent the deepest level of subduction in the Indian plate and was probably the first part of the northward moving Indian Plate to collide with the Asian Plate. Thrusting along the Main Central Thrust combined with fold superposition, along with erosion are suggested to be the main methods of exhumation of the high pressure rocks as no evidence of any extension was found to suggest unroofing associated with normal faults. This will be discussed in detail in future publications as well as geochronological analysis of the eclogites.

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