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HEAVY MINERAL ANALYSIS OF THE MOLASSE SEDIMENTS, TRANS INDUS RANGES, KOHAT, PAKISTAN

IFTIKHAR AHMAD ABBASI & M. ASIF KHAN

Department and NCE in Geology, University of Peshawar

ABSTRACT

The molasse sediments in the Kohat plateau comprise two coarsening upward sequences, the Rawalpindi and Siwalik Groups, which are further subdivided on the basis of their lithological characteristics into a number of formations. Correlation of these formations across different areas becomes very difficult due to their time transgressive nature. Heavy minerals are a useful tool for such correlations, as each formation is characterized by a particular heavy mineral suite. The Murree Formation of the Rawalpindi Group contains a simple association of heavy minerals, and epidote constitutes bulk of the heavy mineral suite. The epidote content decreases upsection with a corresponding increase in the contents of other minerals and also by the appearance of new minerals. The Kamlial Formation is characteristically rich in tourmaline and garnet. The Siwalik Group, particularly the Shakardarra Formation of the Miocene age, is marked by the introduction of high grade metamorphic and igneous minerals such as amphibole, staurolite and kyanite. Amphibole constitutes the bulk of heavy minerals in the Indus Conglomerate Formation (Miocene- Pliocene age) besides pyroxene, kyanite and staurolite.

The mineral chemistry of amphibole and garnet shows that the amphibole was derived mainly from the igneous and metamorphic belts of the Kohistan island arc. The major source of garnet in the molasse sediments is interpreted as the metamorphic belts of the Indian plate exposed along its northern margin. Some garnet in the Indus Conglomerate Formation may have been derived from the Kohistan island arc terrain.

INTRODUCTION

Heavy minerals are commonly used for the identification of source areas and establishing stratigraphic correlations among different formations. This technique was first applied to the molasse sediments in the Himalayan foreland basin by Krynine

(1937). Subsequent studies, however, ignored the heavy minerals, and mainly concentrated on sedimentology (Behrensmeyer & Tauxe, 1982; Nio & Hussain, 1984), biostratigraphy (Raza, 1983), magnetostratigraphy (Khan, 1984; Johnson et al., 1985), and petrography (Abid et al., 1983; Abbasi & Friend, 1989). With the availability of an adequate data on mineral chemistry from the Himalayan orogenic belt in N. Pakistan (Jan, 1977; Jan & Howie, 1980, 1981, 1982; Bard, 1983; Khan, 1988; Jan, 1988; Jan et al., 1989; Khan et al., 1989; Treloar et al., 1989a, 1989b; Williams, 1989; Jan & Windley, 1990), it is now possible to compare the heavy minerals in the molasse sediments from the foreland basin to exactly locate the source terrain for each stratigraphic level. In this paper we present data on heavy minerals from the molasse sediments exposed in the Kohat foreland basin (Fig. 1), in terms of their modal abundance and composition, and attempt to interpret the nature of their source terrain. The molasse sediments in the Kohat foreland-basin are over 6 km thick and comprise two coarsening upward sequences (Fig. 2); a basal Rawalpindi Group consists of the Murree and Kamlial formations, while the Siwalik Group comprises the Chinji, Shakardarra (stratigraphically equivalent to the Nagri Formation in the Potwar area) and the Indus conglomerate Formations (stratigraphically equivalent to the Dhok Pathan Formation in the Potwar area). Sandstone constitutes a major proportion (about 70%) of the molasse sediments, with subordinate siltstone and conglomerates in the study area. For the purpose of heavy mineral separation and their chemical (microprobe) analysis, ten sandstone samples were selected from the Hukni section around Shakardarra area (Fig. 1), where a stratigraphically continuous molasse succession is well exposed.

PROCEDURE

The heavy minerals were separated from the lighter fraction in the sandstone by using heavy liquids. Calcite cement was removed from the disaggregated sandstone with the help of 1M HNO_3 and washed with water at least twice, and dried. It is commonly observed that heavy minerals are concentrated in the finer sand fraction (Lindham, 1987). The sand fraction between 250 μm and 63 μm was selected for heavy mineral separation. The heavy minerals were separated from the sand fractions by using acetylene tetrabromide (sp.gr. 2.96) in a centrifuge. The minerals of higher density than acetylene tetrabromide constitute the heavy mineral fraction used in this study.

In order to study the heavy minerals with greater accuracy and confidence, and to carry out microprobe analyses, the heavy-mineral separates were impregnated to prepare polished thin-sections. The chemicals used for impregnation were "araldite AY18 bisphenol-A-epoxy resin" and "hardener HZ18 4,4-diamodiphenyl methane".

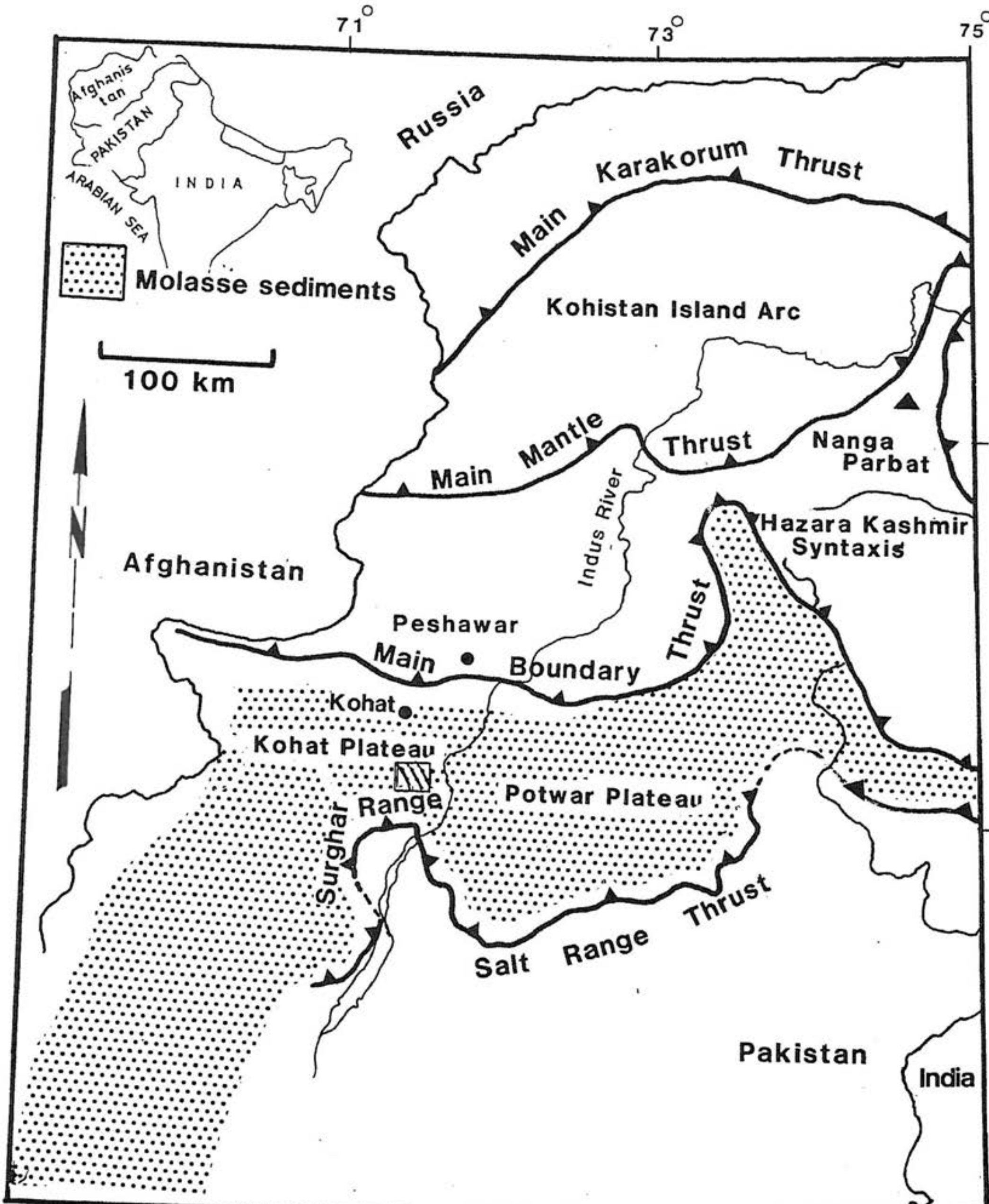


Fig. 1. Location map of northern Pakistan showing molasse distribution. Study area around Shakardarra is shown by a rectangle, regional map at top left corner.

Mineral identification and the determination of modal abundances were done with a petrographic microscope using a "sweep method". All the grains encountered on a given traverse were counted. An interval of one unit on the lateral axis was found sufficient to avoid recounting.

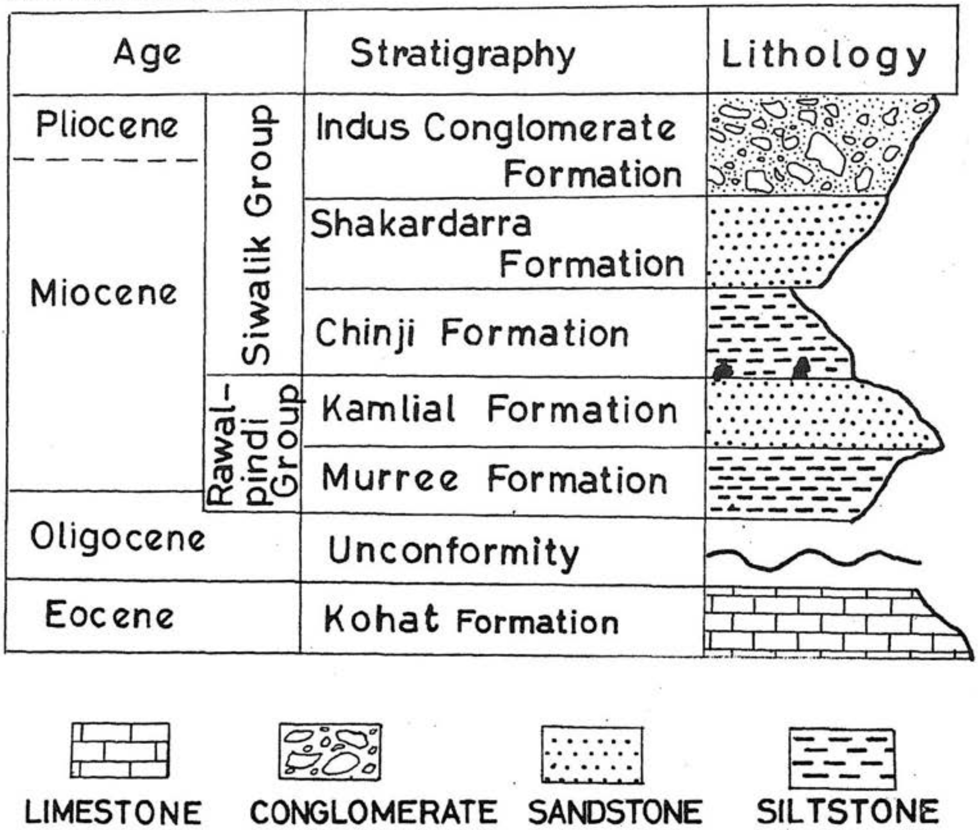


Fig. 2. Neogene stratigraphy around Shakardarra area.

About 250 to 300 non-opaque grains were counted from each sample. The opaques were counted as one class. The percentage of each fraction was calculated relative to the total number of transparent grains and presented in Table 1.

The mineral analyses were carried using a JEOL 733 electron microprobe, using olivine and cobalt as standards.

HEAVY MINERAL ANALYSIS

The common heavy minerals in the sediments of the Rawalpindi and Siwalik groups are epidote, garnet, tourmaline, zircon, mica, amphibole, kyanite and staurolite. Spinel, pyroxene, sphene and rutile are found in traces in a few samples.

TABLE 1. MODAL ANALYSIS OF HEAVY MINERALS

Sample No.	Epi.	Gar.	Tour.	Zr.	Staur.	Mica	Ky.	Horn.	Pyr.	Spn.	Oth.	Opaq/ N-Op.
Murree Fm.												
M1	63	6	1.5	11	-	15	-	-	-	-	3	3
M3	62	13	4	13	-	4	-	-	-	-	5	1.5
Kamlial Fm.												
K1	50	12	10	10	-	15	-	-	-	-	3	4
K4	32	36	9	12	-	7	-	-	-	2	2	3
Chinji Fm.												
C3	45	12	4	12	-	16	2	tr.	-	tr.	4	3.5
C4	55	11	4	11	-	14	tr.	-	-	tr.	3	6
Shakardarra Fm.												
S3	28	15	2	8	-	7	3	30	-	tr.	7	2
S4	29	6	2	7	2	9	3	31	-	-	12	24
Indus Cong. Fm.												
I1	14	7	tr.	6	1	16	5	45	2	tr.	7	19
I3	15	5	tr.	2	2	9	9	53	1	-	4	19

Epi-Epidote, Gar-Garnet, Tour-Tourmaline, Zr-Zircon, Staur-Staurolite, Ky-Kynite, Horn-Hornblende, Pyr-Pyroxene, Spn-Spinel, tr-Traces, Fm-Formation, Cong-Conglomerate, Oth-Others, Opaq/N-Op-Opaque/Non-opaque ratio.

Epidote is one of the most common and abundant minerals throughout the succession. Its abundance decreases up-section from 63% (sample M1) to 14 % (sample I1) (Table 1). Epidote grains are commonly fractured and have an irregular outline with some unfractured grains. A number of epidote grains display a brown surface coating, probably iron-oxide. In a few grains, authigenic overgrowth at the grain edges was observed indicating *in situ* precipitation of epidote probably due to feldspar dissolution within the basin of deposition. In a few cases epidote is found occurring as inclusions in quartz and feldspar grains. In the Indus Conglomerate Formation, particularly in the sample I1, one amphibole-epidote schist and one quartz-epidote-mica schist rock fragments were observed. Clinozoisite is also abundant.

Garnet occurs consistently throughout the succession. It is irregular in outline and often pitted. Some finer grains are well rounded. Dark brown to black staining is common on the surface of several garnet grains in the Indus Conglomerate Formation.

Tourmaline of brown, pleochroic variety is abundant with occasional blue tourmaline. The tourmaline grains are irregular in shape, sometimes in the form of prismatic subhedral grains.

Zircon commonly occurs as minute well rounded grains, but prismatic euhedral crystals are also present.

Amphibole appears in the Siwalik Group as small flaky grains. Its grain size increases (within the range 250-63 μm) up-section with large amphibole grains found in the Indus Conglomerate Formation. The amphibole is chemically the blue-green hornblende called tschermakitic hornblende and magnesio-hornblende (Abbasi & Friend, 1989). It commonly exhibits well developed cleavage and is strongly pleochroic. It is usually in the form of elongated flakes, with irregular broken edges. The appearance of blue-green hornblende at the base of the Nagri Formation (equivalent to the Shakardarra Formation) has also been reported from Potwar (Johnson et al., 1985) and Surghar Range (Abid et al., 1983).

Kyanite occurs as elongate, evenly fractured grains, some of the Kyanite grains are distinctly curved and sheared. Staurolite occurs as rounded or irregularly shaped grains. Rectangular grains of pyroxene with well developed cross-cleavage are also present in the upper part of the succession.

Mica grains are coated (iron xide) in all the formations except the Shakardarra and Indus Conglomerate formations. In the Indus Conglomerate Formation, unaltered biotite grains are dominant with subordinate muscovite grains. Opaque minerals are dominantly hematite, magnetite and probably ilmenite.

STRATIGRAPHIC REVIEW OF THE HEAVY MINERALS

The Murree Formation contains a comparatively simple association of heavy minerals compared to other formations. Among the heavy mineral fraction, epidote constitutes the major fraction (63%), with garnet (av. 10%), zircon (av. 11%), tourmaline (av. 3%) and mica (av. 9%) present in subordinate amounts (Table 1). One sphene and two glauconite grains were also found in sample M1. The opaque to non-opaque ratio varies from 1.5 to 3.

The heavy mineral assemblage of the Kamlial Formation is characteristically richer in tourmaline (av. 9.5%) than the other formations. Epidote (av. 41%), garnet (av. 24%) and zircon (av. 11.5%) are other common constituents. Garnet is most abundant in sample K4 (36%) (Table 1), also at least 2% of spinel was found in this sample, which is unusual in the rest of the molasse sequence. The heavy mineral suite of the Kamlial Formation resembles the Central Potwar assemblages in respect of the high tourmaline content, but differs in epidote content which is absent in the Central Potwar (Gill, 1952), as compared to 41 % in the study area.

Although the Murree and Kamlial formations appear similar in their heavy mineral constituents, the two can be differentiated on the basis of their heavy mineral frequency. The Murree Formation is rich in epidote (av. 63%) as compared to the Kamlial Formation (42%), and the Kamlial Formation has a high tourmaline content (9.5%), as compared to the Murree Formation (3%).

The Chinji Formation is characterized by the appearance of high grade metamorphic minerals such as blue-green hornblende and kyanite, although in traces. Within the heavy mineral assemblage, epidote constitutes the bulk (av. 50%) of the heavy minerals. Garnet (av. 11.5%), zircon (av. 11.5%), tourmaline (av. 4%) and mica (av. 15%) constitute the rest of the heavy mineral populations (Table 1), with sphene and spinel in traces. The opaque to transparent ratio varies from 3.5 to 6.

The Shakardarra Formation is characterized by the predominance of blue-green hornblende which constitutes about 30% of the heavy mineral content particularly in its upper part. The kyanite content amounts to 3% with elongate, large grains. Staurolite also appears in the upper part of the Shakardarra Formation (2% in sample S4). The epidote content decreases to 28%, zircon to 7% and tourmaline to only 2% (Table 1). The garnet content is consistent with respect to the underlying formations (av. 10%), whilst sphene, spinel and glauconite are present in traces (one or two grains).

The blue-green hornblende content increases greatly in the Indus Conglomerate Formation (av. 49%), and is in the form of large, pleochroic grains. Pyroxene grains also appear in this formation and form up to 2% of the heavy mineral population. The kyanite content increases to 9% (av. 7%), whereas staurolite remains the same (av. 2%) as in the Shakardarra Formation. The epidote content decreases to 14.5%, zircon to 4%, garnet to 6% and tourmaline is in traces. Some of the garnet grains have a black coating on their surfaces.

Some of the heavy mineral grains are fairly strained, particularly the kyanite grains. One or two amphibole-epidote schist fragments are also present. Mica grains are unaltered and are composed of biotite with occasional muscovite. One or two grains of quartz containing inclusions of rutile needles were also observed. The opaque to non-opaque ratio increases to 22. Predominant blue-green hornblende, abundant kyanite, appearance of pyroxene, little or no locally derived sedimentary lithics and high grade metamorphic lithics are characteristics of the Indus Conglomerate Formation.

MINERAL CHEMISTRY

Garnet and amphibole from the molasse sediments were analyzed for comparison with the data on these minerals available from the Himalayan orogenic belt. Garnet occurs in fairly constant amount across the molasse succession suggesting a regular supply from the source terrains. Amphibole appears in minor amounts at the base of the Shakardarra Formation and gradually increases up-section constituting a major proportion of the heavy-mineral suite in the Indus Conglomerate Formation.

In Fig. 3 microprobe analysis of the detrital amphibole grains from the Shakardarra and Indus Conglomerate formations are plotted against amphibole analysis from the Kohistan island arc (Khan, 1988). According to the classification of Leake (1978), the amphiboles from the study area together with those of the Kohistan arc are calcic, and fall in the field of tschermakitic-hornblende and magnesio-hornblende with one analysis being tschermakite. This close resemblance suggests that the most probable source for the detrital amphibole in the molasse sediments is the Kohistan arc sequence in N. Pakistan, where amphibole-bearing gabbronorites and amphibolites are exposed over a large area (> 8000 km^2).

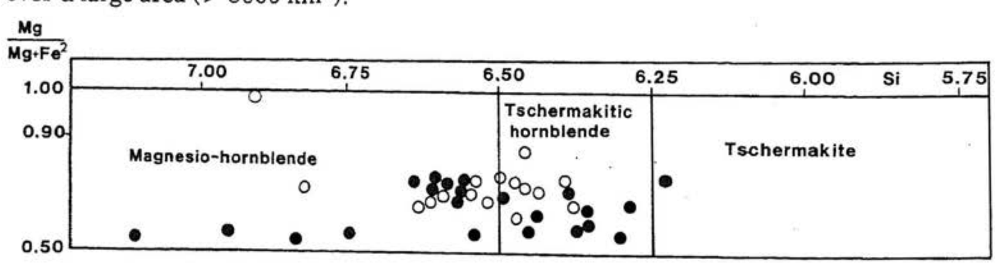
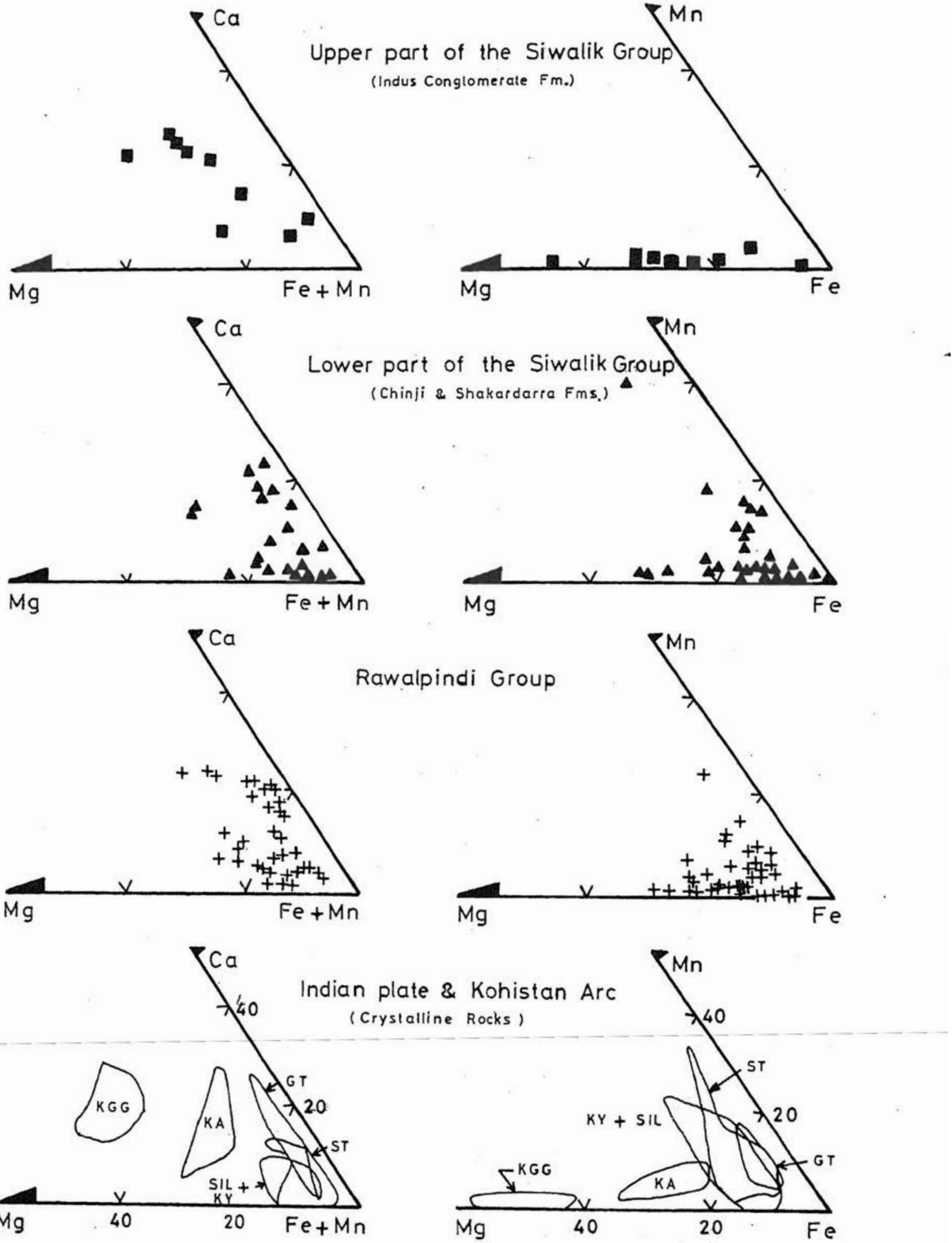


Fig. 3. Amphibole microprobe analysis from the Indus Conglomerate Formation and Kohistan Island Arc (Khan, 1988). (Filled circles, Indus Conglomerate Formation, open circles, Kohistan Island Arc). The analyses are plotted according to amphibole classification of Leake (1978). Amphiboles from both areas are calcic and out of 25 classes of calcic amphibole, plot in the field of tschermakitic-hornblende and magnesio-hornblende. (From Abbasi & Friend, 1989).

Garnet in the studied molasse sediments is highly variable in composition. As expected in the case of detrital minerals, there are grain-to-grain variations even within the limits of one thin section. Between the various levels of the molasse succession {i.e., Rawalpindi Group, lower (Chinji and Shakardarra Formations) and upper (Indus Conglomerate Formation) parts of the Siwalik Group}, the garnet compositions show a considerable overlap (Fig. 4). The majority of the garnet in all the stratigraphic levels of the molasse succession is almandine in composition with minor grossular, spessertine and pyrope components. Particularly, the sandstones in the Rawalpindi and in the lower part of the Siwalik groups are more or less identical in terms of ranges in the composition of the garnet. This is comparable to the garnet composition reported for the molasse sediments from the Potwar area by Bajwa et al. (1987). A more or less similar range of garnet composition is reported from the crystalline Indian-plate basement rocks in the Hazara, Swat and Besham areas in the northern Pakistan (Treloar et al., 1989a, b; Williams, 1989), which shows a wide range in metamorphic grades (including garnet, staurolite, kyanite and silliminite). A few of the more pyrope-grossular-rich garnets in this lower to intermediate part of the molasse succession have compositions which are similar to those found in the Kamila Amphibolites of the Kohistan arc sequence in N. Pakistan. In the Indus Conglomerate Formation, which represents the uppermost molasse succession in the studied area, a relatively much broader range of garnet compositions is encountered, with a greater number of grains with higher pyrope and grossular components. None of the garnets in the Indian-plate basement rocks, even from the highest metamorphic grades contain comparable pyrope-grossular rich garnets. Such garnets are, however, common in the Kohistan arc sequence (Jan, 1977; Jan & Howei, 1981; Bard, 1983), particularly in the southern, stratigraphically basal parts of the Kohistan arc (the Jijal Complex, and the Kamila amphibolites). On the basis of these comparisons we conclude that the garnet for bulk of the molasse sequence was derived from the Indian plate; and that deep-seated, high- grade basement rocks of the Indian plate were already exposed prior to the deposition of even the stratigraphically most basal part of the molasse sequence in the studied area. There might have been minor contributions from the Kohistan sequence as early as during the deposition of the lower to middle parts of the molasse succession, but the basal parts of the Kohistan succession started contributing detrital garnet only when the uppermost part of the moalsse succession (Indus Conglomerate Formation) started accumulating. This would indirectly imply that the garnet-bearing rocks in the Kohistan Island Arc were uplifted much later than the amphibole bearing rocks.

DISCUSSION

Although the heavy mineral assemblage appears fairly similar across the molasse succession, there is a marked change in the relative abundance of different minerals at


Upper part of the Siwalik Group
(Indus Conglomerate Fm.)
Lower part of the Siwalik Group
(Chinji & Shakardarra Fms.)
Rawalpindi Group
Indian plate & Kohistan Arc
(Crystalline Rocks)
Ca
Mn
Mg
Fe+Mn
Fe
40
20
KGG
KA
GT
ST
SIL + KY
KY + SIL

various stratigraphic levels. Also a number of new minerals appear in different formations, e.g., amphibole, pyroxene, staurolite and sillimanite occur in the Siwalik Group, but are absent in the Rawalpindi Group. In essence, the sediments of the Siwalik Group, particularly those of the Shakardarra and Indus Conglomerate formations, are characterized by the appearance of minerals derived from high-grade metamorphic and igneous rocks.

The introduction of blue-green amphibole during Miocene times in the molasse sediments of Potwar and the Surghar range (Abid et al., 1983; Johnson et al., 1985), is rather unique to this part of the Himalayan foreland basin. Elsewhere, for instance in the part of the foreland basin exposed in India, there is a complete absence of amphibole in the molasse sediments (Chaudhri, 1971, 1972; Raiverman et al., 1983). Indeed, the heavy-mineral suite of the molasse sediments in India is much different from that found in the molasse sediments of the present study (Fig. 5). In the Indian molasse sediments, zircon, garnet, tourmaline and staurolite constitute the bulk of the heavy-mineral fraction with subordinate amounts of epidote (Chaudhri, 1972). Hornblende and pyroxene are either not present (Chaudhri, 1972) or, if found, are fairly uniformly distributed (Raiverman et al. , 1983) across the succession. These differences in the heavy minerals in the Kohat-Potwar area and Indian part of the foreland-basin suggest different provenance and different catchement areas for the river systems. The molasse sediments in the Indian part of the foreland-basin were probably deposited by a river system similar in source to the present-day Ganges River (Fig. 5), but very different from that of the palaeo-Indus River.

Of all the heavy minerals found in the molasse sediments in the Kohat foreland basin, garnet and amphibole are particularly important because of their abundance in particular parts of the Himalayan orogenic belt. For instance, amphibole is amongst the major constituent minerals of the metabasic igneous rocks in the Kohistan island arc terrain, which is now accreted with the Indian plate at its northern margin (Tahirkheli et al., 1979; Coward et al., 1986). Garnet, on the other hand, is more common in the basement metamorphic rocks in the Indian plate than in the Kohistan arc. A greater abundance of garnet of almandine composition in the Rawalpindi Group, and its consistent presence in the entire molasse succession, suggests that the deep-seated Indian- plate basement rocks were exposed even prior to the onset of deposition in the foreland basin, and were the main source of the detrital material throughout the depositional history of the basin. As far as the contribution from the Kohistan arc sequence is concerned, it can be monitored on the basis of both amphibole and garnet

Fig. 4. (Facing page) Garnet microprobe analysis from the molasse sediments of the Rawalpndi and Siwalik Groups compared with those of the Indian Plate and the Kohistan Island Arc terrains. Most of garnet in the molasse sediments was derived mainly from the rocks of the Indian Plate. KGG- Kohistan garnet granulite, KA- Kohistan amphibolites, Ky- Kynite grade, SIL- sillimanite grade, ST- staroulite grade, GT- garnet grade.

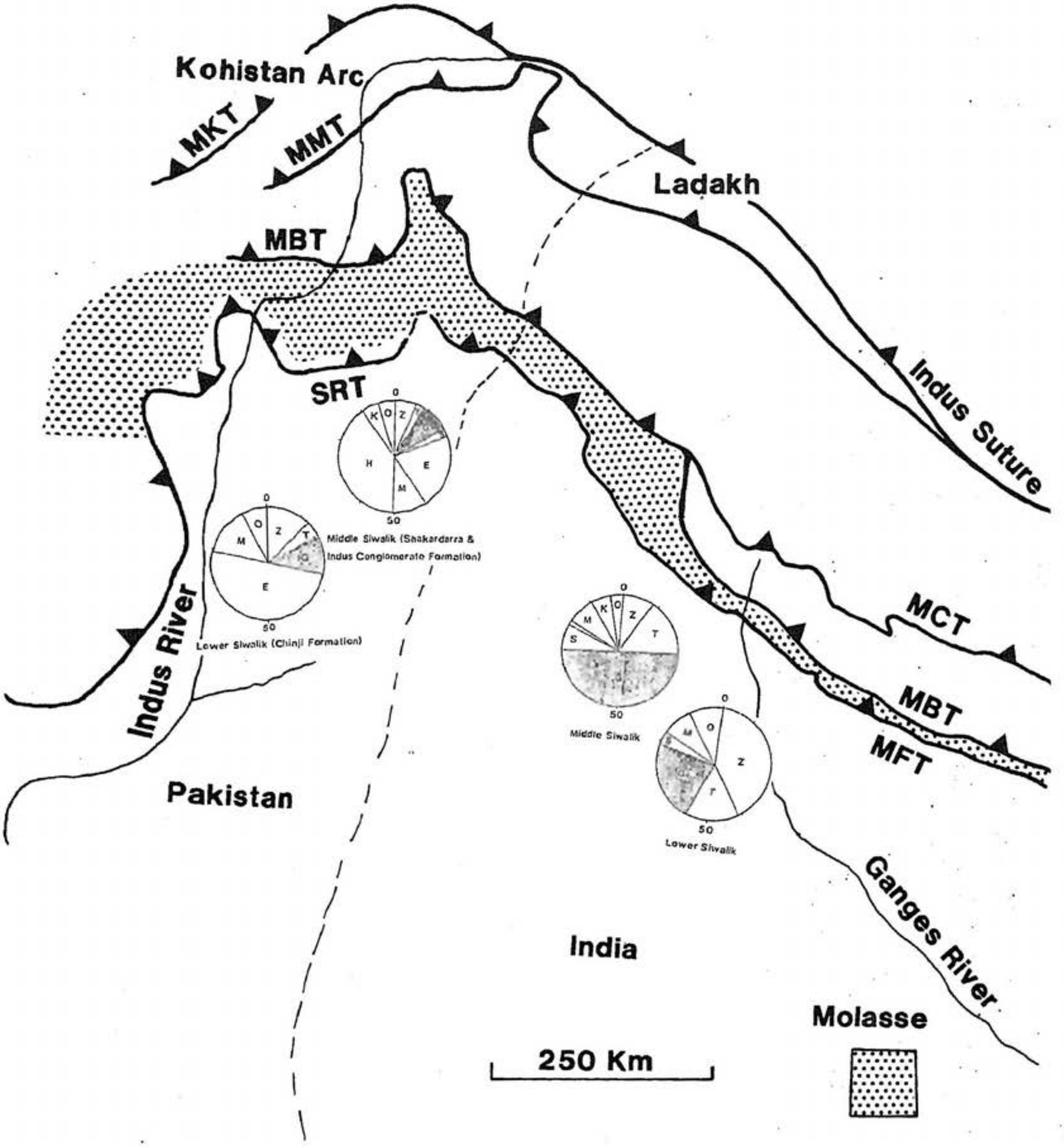


Fig. 5. Comparison of heavy mineral assemblages of the Siwalik Group in the Kohat-Potwar area and Indian part of the foreland-basin (Chaudri, 1972). The two areas show distinct assemblages suggesting probable different source areas. E epidote, G garnet, T tourmaline, Z zircon, S staurolite, K kyanite, H hornblende, M mica and O others. Garnet and zircon constitute the major proportion of heavy minerals in the Indian part of the foreland-basin, whereas, in the Kohat-Potwar area epidote is the dominant heavy mineral in the lower Siwalik and hornblende in the middle Siwalik.

(relatively richer in pyrope component than that of the Indian plate). These two minerals, however, do not appear simultaneously; amphibole starts appearing at the base of the Shakardarra Formation, whereas the pyrope-rich garnet is found mainly in the Indus Conglomerate Formation. This may be due to differences in the abundances of these minerals at different stratigraphic levels in the Kohistan arc sequence. Amphibole in the Kohistan arc is characteristically found in the intermediate to shallow level metabasic rocks, while the garnet-bearing rocks are restricted to intermediate to deep-crustal levels (e.g., Kamila amphibolite and the Jijal Complex). Appearance of the amphibole at the base of the Shakardarra Formation would record a metamorphic event responsible for the uplift and exposure of the upper to intermediate levels of the Kohistan arc crust. The appearance of pyrope-rich garnet in the uppermost molasse succession suggests exposure of the basal arc crust in Kohistan much later than the shallow to intermediate crustal levels.

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