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Geochemical and petrological characteristics of xenoliths in Mansehra Granite, NW Himalaya, Pakistan: implications for petrogenesis and tectonic settings

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Mansehra Granite (MG) is massive and sheared which contains light-gray to jet-black schistosed and light-gray micaceous quartzite restites. The later possess relatively higher quartz as compared with mica contents whereas the former has predominant quartz and feldspar. Enclosure of apatite and zircon in micas and absence of sillimanite in schistosed and non-foliated facies suggest that these rocks are restite in nature. Presence of abundant and larger mica flakes at contact of restites with MG indicates exposure of these flakes at relatively higher temperature of granitic melt (623.7–886.6 °C) particularly at their margins. However, central part of restites remained unaffected due lesser impact of elevated temperature. Schistose and surmicaceous restites show crenulation cleavage and preserve structural antiquity during amalgamation in felsic melt. Geochemically, restites and Tanawal Formation indicate calc-alkaline to high K calc-alkaline domain with orogenic syn-collisional settings. Geochemical characteristics and modal mineralogy of restites and Tanawal Formation are similar. This study suggests that former has been derived from the later and their field relationships and geochemical signatures provide credible evidence in favour of S-type trait of Mansehra Granite. In geochemical diagrams, MG portrayed calc-alkaline, peraluminous S-type nature and its magma was generated from heterogeneous Tanawal Formation via fractional crystallization.

Introduction

The Mansehra Granitic Complex (MGC) is exposed in the Lesser Himalaya, NW of Pakistan (Fig. 1). The Mansehra Granite, a main member of the MGC, occurs as sub-concordant to discordant batho-

lith which covers an area of 100 km². The granite is generally massive but sheared at places due to ductile deformation (Shams, 1961). The Mansehra magmatic body is calc-alkaline and peraluminous having S-type traits formed through the anatexis of the Precambrian Tanawal Formation (Jan et al., 1981). The granite is intruded by basic dykes (Shams, 1967a). It is a binary mica and porphyritic granite which has K-feldspar phenocrysts. Apart from phenocrysts, the Mansehra Granite also contains light-gray to dark-gray as well as jet black xenoliths of varying size which may represent rock fragments entrapped during emplacement of magma or remnants of un-melted protolith. In particular, xenoliths are foreign rock fragments found in rocks having diverse composition from the enveloping rock which may indicate enclaves or restites (Vernon, 1983; Bacon, 1986). Study of xenoliths in granites provides valuable perception about magmatic evolution that may deliver credible evidence about petrogenetic processes (Didier and Barbarin, 1991; Waight et al., 2001). Although the derivation of xenoliths is still an issue of debate, however, it has been acknowledged that the xenoliths convey an exclusive opportunity to constrain the petrogenesis and provide valuable facts regarding the tectonic settings that prevailed during their genesis (Sarjoughian et al., 2017).

Granitic rocks of the Mansehra area has been investigated by many workers (e.g. Calkins and Matin, 1968; Honegger et al., 1982; Chaudhry et al., 1989; Ashraf, 1992). Earlier workers have presented general description of the rocks of the area. However, Shams (1961) carried out first systematic study on the granitic and associated metasedimentary rocks of the Mansehra area. Later, Shams (1971) undertaken detailed geological work and presented classification of rocks of the Mansehra. Naeem et al. (2016) carried out geochronological study of the Mansehra Granite and presented age of 516 ± 16 Ma based on Rb/Sr method. The Mansehra Granite contains xenoliths of varying size and composition that necessitates to investigate their nature and mode of occurrence which has a significant bearing on the petrological aspects of the MGC magmatic rocks. Hence, there is a dire need to carry out a thorough investigation of these xenoliths. Field relation-

Figure 1. Map shows location of study area and main tectonic sub-division of Himalaya (modified after Ganser, 1964; Sorkhabi and Arita, 1997; Paudel and Arita, 2000).

ships augmented with petrography and geochemistry of these xenoliths integrated with previous findings of the MGC rocks will furnish the credible evidence regarding petrogenesis of the xenoliths and Mansehra Granite. In the present research, we aim to provide new geochemical data and deliver insights into: (1) petrogenesis and compositional characteristics of xenoliths and Mansehra pluton (2) their tectonic implications.

Geology of the Area

The Himalayan mountain range, resulted from collision between the Indian and Eurasian plates, has been sub-divided into four major tectonic elements from north to south including Sub-Himalaya, Lesser Himalaya, Higher and Tethys Himalaya (Ganser, 1964; Le Fort, 1975; Hodges, 2000). The Lesser Himalaya is demarcated by the Main Central Thrust (MCT) in the north while delineated by Main Boundary Thrust (MBT) in the south. In Mansehra area, the Lesser Himalaya consists of igneous and metamorphic rocks constituting the Mansehra Granitic Complex (MGC) which is surrounded by metasediments of the Tanawal Formation, comprised of pelite, psammite, phyllite, quartzite and schists (Fig. 2). The MGC is principally composed of several plutonic bodies including medium to coarse-grained, binary mica, porphyritic and massive to sheared Mansehra Granite and poorly porphyritic to non-porphyritic tourmaline bearing massive Hakale Granite.

In addition, fine-grained microgranites, massive to sheared leucogranites and associated tabular as well as pod-like pegmatitic and aplitic bodies are also exposed (Ashraf and Chaudhry, 1976a, b; Naeem et al., 2016). Mansehra Granite is the main member of this complex which contains variety of xenoliths. Field description of xenoliths and enclosing Mansehra Granite is given below.

Along the Susalgali-Khaki (S-K) traverse, the sheared Mansehra Granite has microcline phenocrysts with groundmass. The sheared granite contains 1 to 5% K-feldspar phenocrysts having length ranging from 0.5 to 3 cm (Fig. 3a). Lenticular to elongated xenoliths found in the granite have light-gray to jet-black rusty colour (Fig. 3b-c). Size of these xenoliths varies between 2.5×2 and 12×10 cm. Light-grey oval xenoliths reveal abundant K-feldspar phenocrysts with parallel alignment (Fig. 3d). In contrast, elongated and sub-rounded xenoliths contain hematite and show reddish-brown colouration due to oxidation of iron around their margins (Fig. 3e). Lenticular xenoliths are fractured at places. Mineralogically, xenoliths contain quartz, feldspar, biotite, muscovite and rusty brown hematite. These xenoliths represent diffused, irregular and sharp contacts with the granitoid host.

Along the Oghi-Darband traverse (western part of the granite, Fig. 2), the Mansehra Granite is massive having microcline phenocrysts with weak flow-foliation. Scarce microcline crystals exhibit augen structure. Alignment of tadpole-shaped phenocrysts is also perceived at number of places. The granite comprises 1–15% K-feldspar phenocrysts from 0.6 mm to 7 cm in size. The granite contains light-gray to jet-black,

Figure 2. Geological map of Mansehra area showing samples location (modified after Calkins et al., 1975).

rounded to angular as well as lenticular xenoliths (Fig. 3f-g). K-feldspar crystals in the granite are aligned parallel to the margins of light-gray and jet-black xenoliths. Sizes of the xenoliths range from 3×2.8 to 12×8 cm which contains quartz, feldspar, biotite and muscovite. These xenoliths reveal sharp, irregular and diffused contact with the host Mansehra Granite (Fig. 3g).

In Mansehra area, the granite is massive which contains K-feldspar phenocrysts along with xenoliths at the contact between the granite

and Tanawal Formation. These xenoliths are light-gray to jet-black, rounded to oval in shape. Size of these xenoliths ranges from 4.5×2 to 15×7.5 cm. Jet black xenoliths are either devoid of or contain scarce (1–2%) K-feldspar crystals aligned parallel around the rim of these xenoliths (Fig. 3h). At places, rim of these xenoliths depicts rusting due to oxidation of iron-bearing minerals. Light to dark-gray xenoliths encompasses 20% K-feldspar crystals having 0.5×0.3 cm size. Phenocrysts aligned around their border have size range 3–0.5 cm.

Figure 3. (a-k) represents field characteristics and features of xenoliths in Mansehra Granite exposed in diverse areas of NW Himalaya. (a) Sheared granite indicating deformed K-feldspar phenocrysts in Susalgali-Khaki area (b,c) Lenticular rusty jet-black and elongated inset bearing dark-gray xenolith in Mansehra Granite, Susalgali-Khaki area (d) Light-gray oval xenolith revealing parallel alignment of tadpole-shaped K-feldspar phenocrysts, Susalgali-Khaki area (e) Light-gray, elongated xenolith showing rusting at border and diffused contact with sheared Mansehra Granite, Susalgali-Khaki area (f,g) Light-gray, angular and lenticular xenoliths showing irregular contact with sheared Mansehra Granite, Susalgali-Khaki area (h) Minute K-feldspar phenocrysts around the rim of jet-black angular xenolith in massive Mansehra Granite, Mansehra area (i) K-feldspar insets bearing dark-gray rounded xenolith in massive Mansehra Granite, Mansehra area (j) Lenticular xenolith depicting diffused contact with host massive Mansehra Granite, Mansehra area (k) Jet-black xenolith in massive Mansehra Granite with diffused contact, Chitta-Batta area (l) Dark-gray, oval xenolith in massive Mansehra Granite, Phulra area.

Dark-gray rounded xenoliths contain microcline crystals with 2×1 cm size (Fig. 3i). Microcline phenocrysts with size (2–5 cm) are aligned along the margins of dark-gray, sub-rounded xenoliths. Apart from these, dark-gray xenoliths found in massive Mansehra Granite reveal schistosity. Mineralogically, xenoliths are comprised of quartz, feldspar, biotite, muscovite, K-feldspar phenocrysts and hematite. Xenoliths signify irregular and diffused contact with Mansehra Granite (Fig. 3j).

In Chitta-Batta, massive Mansehra Granite contains 3% K-feldspar phenocrysts having maximum length of 2 cm. The granite is massive, which contains dark-gray to jet-black, lenticular to oval xenoliths of 8×4 cm size (Fig. 3k). Field observation reveals that the xenoliths are composed of quartz, feldspar, biotite and muscovite. The xenoliths display irregular and diffused contact relations with granitoid host.

In Phulra area, Mansehra Granite is massive, medium-grained with weak to no flow-foliation. The granite contains angular to oval, dark-gray to jet-black xenoliths (Fig. 3l). Size of the xenoliths ranges from 4×2 to 13×12.5 cm. Megascopically, these varieties of xenoliths contain quartz, feldspar, biotite and muscovite and show irregular to diffused contact relationships with the Mansehra pluton (Fig. 3l).

Materials and Methods

Fieldwork of the Mansehra area was carried, and representative xenoliths samples, enclosed in Mansehra Granite and a small number of samples from Tanawal Formation were collected from various localities (Fig. 2). In total, 81 samples were crumpled by jaw crusher at Pakistan Council of Scientific and Industrial Research Laboratories Complex (PCSIR), Lahore. Dust was removed from the surface of the fragments and kept at a temperature of 110°C to remove moisture content. Roll crusher was used to further reduce the size of these samples. The pulverized material was distributed over splitter to obtain representative fraction of each rock type. TEMA mill was used to get passing 200 g of 300 mesh powder that was stored in plastic bottles for chemical analysis of the samples. Moisture content of the samples was removed at 110°C . For determination of loss on ignition, 5.0 g of every sample was taken in Platinum crucible and animated in furnace for 6–8 hours at 1050°C . X-ray Fluorescence (XRF) method at Pakistan Atomic Energy Commission (PAEC) was used to determine major, minor and trace elements of the Mansehra Granite, xenoliths and Tanawal Formation. Fused lithium tetraborate discs were prepared to determine major and minor elements. Moisture-free 12 g powdered samples were mixed with lithium tetraborate in 1:5 proportion for the trace elements determination. Fusion machine was used to prepare pressed pellets, which analyses through X-ray Fluorescence spectrometer (model Pw 4400/24 Axios, PANalytical, Netherlands). Required corrections for matrix effect and the spectral overlapping were applied. In terms of RSD, the XRF data analytical accuracy was $\leq 2\%$. The results of major, minor and trace element concentrations are presented in Tables 2 and 3.

Petrography

In total, 66 thin sections were prepared for petrography analysis of

xenoliths, associated Mansehra Granite, and the Tanawal Formation. The comprehensive description is presented below.

Light-gray Xenoliths

Light-gray schistosed xenoliths found in massive granites of Oghi-Darband, Mansehra area, Chitta-Batta in addition to Phulra and sheared granites of Susalgali-Khaki area primarily consist of hypidiomorphic to allotriomorphic quartz and feldspar with subsidiary mica. The accessory phases include specifically zircon, apatite and magnetite. The rock is foliated, displays lepidoblastic texture (Fig. 4a) and asymmetrical crenulation cleavage occasionally. Most of the quartz grains are extremely strained. Few fractured quartz grains show sutured contacts. Muscovite and biotite flakes show preferred orientation and parallel to sub-parallel alignment (Fig. 4b). Biotite and muscovite show foliation, which contains apatite and zircon crystals (Fig. 4a, b). These schistosed xenoliths are augmented in micas, especially biotite and muscovite, therefore, can be considered as surmicaceous (Fig. 4a, b). Presence of surmicaceous enclaves in Mansehra Granite implies restite character of these xenoliths (White et al., 1991). Likewise, occurrence of zircon, apatite and absence of sillimanite suggest them restites rather than xenoliths (Pupin, 1980; Clemes and Wall, 1981; Pitcher, 1993; Fig. 4a, b). At places, biotite shows pinch and swell structure, indicating the effect of the strain. Subhedral to anhedral magnetite grains occur in dispersed form.

In comparison, light-gray micaceous quartzite xenoliths restricted in sheared Mansehra Granite (Susalgali-Khaki area), are mainly comprised of subhedral to anhedral quartz with subsidiary feldspar, biotite, muscovite and accessory zircon, apatite as well as magnetite. Quartz grains are strained and show strong undulatory extinction and sutured contacts (Fig. 4c). Quartz grains associated with broken muscovite and biotite flakes specify mylonization. Subhedral to anhedral plagioclase shows polysynthetic twinning and microcline depicts sericitization (Fig. 4c). Zircon and apatite are enclosed in biotite (Fig. 4d). Disseminated magnetite reveals presence of euhedral to subhedral crystals. Zircon and apatite found in micaceous quartzite indicates restite character of the xenoliths (Pupin, 1980; Pitcher, 1993; Fig. 4d). Meanwhile, absence of sillimanite and surmicaceous character of the rock also provides strong clue about restite nature of these xenoliths (Clemes and Wall, 1981; White et al., 1991; Fig. 4c, d). Modal mineralogical composition is revealed in Table 1.

Dark-gray Xenoliths

Massive and sheared Mansehra Granite contains dark-gray schistose xenoliths which principally comprised of subhedral to anhedral quartz and feldspar with subordinate biotite and muscovite. Zircon, hematite, apatite and magnetite occur as accessory minerals. At places, quartz grains are highly strained and have inclusions indicating sieve texture of the rock. Plagioclase and microcline occurs as subhedral to anhedral crystals. Biotite comprises of zircon surrounded by dark halos (Fig. 5a). Muscovite often indicates preferred alignment with parallel to sub-parallel pattern (Fig. 5b). Occurrence of zircon, surmicaceous nature and the absence of sillimanite in schistose rock specify them as restite (Pupin, 1980; Clemes and Wall, 1981; White et al., 1991; Pitcher, 1993; Fig. 5a, c).

Figure 4. Microphotographs 4a-d depict various microscopic features of light gray restites: (a,b) Schistose restites sample MR-7 indicating schistosity, apatite (Ap) and zircon (Zrn) presence in biotite (Bt) and muscovite (Ms). (c) Micaceous quartzite restite MR-26 representing abundance of strained sutured quartz (Qz) and presence of sericitization (Ser) in plagioclase. (d) Zircon and apatite occurrence in quartzite restite (MR-43).

The xenoliths show irregular and sharp contact with the enclosing Mansehra Granite manifested by marginal mylonization, abundance of sericitization, enrichment of deformed as well as larger biotite flakes, muscovite and development of myrmekites suggesting slow cooling of magma in compressional tectonic settings (Fig. 5d, e). At the contact of the xenoliths with the enclosing granite, mica shows bending and augen structure, which indicates the impact of deformation (Fig. 5f). The rock is foliated, which reveals conspicuous lepidoblastic texture and interpreted with noticeable symmetrical to asymmetrical crenulation cleavage (Fig. 5g). In addition, hydrous mineral biotite was melted, re-crystallized and swirled and its core contains unmelted part at the contact, which can be typified as restite (Fig. 5h). Meanwhile, deformed biotite comprising zircon and associated with tinny quartz bands are stressed, which denotes tectonic impact (Fig. 5i). Modal mineral composition of the xenoliths is exhibited in Table 1.

Mansehra Granite

Enclosed Mansehra Granite is composed of feldspar, quartz and mica with accessory zircon, apatite and magnetite. Quartz grains occur

in anhedral form, which are often strained and indicate undulose extinction (Fig. 5j). Muscovite occurs both in primary and secondary form in the granite. Coarse flakes indicate that muscovite is of primary nature, while minute flakes are indicative of secondary one in granite (Fig. 5j). So, textural characteristics discriminate primary and secondary muscovite (Saavedra, 1978; Zen, 1988). Subhedral to anhedral microcline indicates well-developed cross hatch twinning and comprises of stringlets however, fine to medium-grained, subhedral albite depicts polysynthetic twinning as well as sericitization (Fig. 5k). More importantly, quartz crystals coupled with deformed mica flakes designate process of mylonization (Fig. 5l). Pleochroic biotite occurs as arbitrarily oriented flakes having dark halos. Mica flakes are pinched and swelled occasionally which signifies tectonic foliation. Biotite commonly contains zircon and apatite inclusions (Xiang et al., 2006). Magnetite is infrequently present in euhedral form. In the meantime, tourmaline and hematite are identified sporadically. Petrographic studies reveal that the granite is augmented in Al-rich minerals, especially muscovite and indicates absence of allanite and titanite, which is suggestive of S-type character of this pluton (Saki, 2010). Modal mineralogical composition of the granite is displayed in Table 1.

Figure 5. Microphotographs 5a-l portray diverse petrographic features of dark gray restites and Mansehra Granite: (a,b) schistose restite MR-10 signifies zircon (Zrn) halo in biotite (Bt) and presence of muscovite (Ms) sheets (c) Sample MR-16 specifies zircon (Zrn) with dark halo in schistose restite (d,e) Abundance of larger biotite (Bt) flake and marginal mylonization at the contact between schistose (Sch) restite and Granite (Grnt) respectively in sample MR-27 (f) Muscovite (Ms) flakes swirled around feldspar (Fsp) due to stress at the contact between schistose restite and Mansehra Granite (MR-27) (g) Lepidoblastic texture and noticeable crenulation cleavage in schistose restite, sample MR-27 (h) MR-30 indicates muscovite (Ms) and biotite (Bt) flake swirled around unmelted core of feldspar (Fsp) at the contact between schistose restite and Mansehra Granite (i) Tectonic bending in biotite (Bt) comprising zircon (Zrn) at the contact between schistose restite and Mansehra Granite in MR-30 (j,k) Mansehra Granite presenting strained quartz (Qz), primary (coarse) and secondary (smaller) muscovite (Ms) flakes and plagioclase (Pl) sericitization, twinning in MG-8,11 respectively (l) Deformed muscovite (Ms) and anhedral strained quartz (Qz) in Mansehra Granite MG-15.

Table 1. Modal mineralogical composition (%) of rocks from Oghi-Darband, Susalgali Khaki, Mansehra, Chitta-Batta and Phulra areas

Sample No.	Quartz	Feldspar	Biotite	Muscovite	Tourmaline	Zircon	Apatite	Magnetite	Garnet	Hematite	Rock Name
MR-06	65	11	14	6	-	0.5	0.5	3	-	-	Dark-gray schistose restite
MG-06	39	49	7	3	-	0.4	0.6	1	-	-	Granite
MG-07	40	46	8	5	-	0.3	0.4	0.3	-	-	Granite
MR-07	58	20	7	9	-	1	2	3	-	-	Light-gray schistose restite
MG-08	42	45	9	3	-	0.7	0.3	-	-	-	Granite
MG-09	41	49	4	3	-	1.5	0.5	1	-	-	Granite
MG-10	43	45	7	4	-	0.4	0.3	0.3	-	-	Granite
MR-10	50	21	16	6	-	1	1	3	-	2	Dark-gray rusty restite
MG-11	45	34	10	7	2	0.5	0.5	1	-	-	Granite
MG-12	47	40	6	5	-	0.4	0.6	1	-	-	Granite
MR-13	57	20	13	8	-	0.5	0.5	1	-	-	Dark-gray pear shape restite
MG-14	44	43	6	6	-	0.6	0.3	0.1	-	-	Granite
MG-15	40	41	10	6	1	0.5	0.5	1	-	-	Granite
MR-16	54	20	12	11	-	0.5	0.5	2	-	-	Dark-gray schistose restite
MG-17 (a)	48	36	5	8	-	0.3	0.7	2	-	-	Granite
MG-17 (b)	46	38	6	7	-	0.6	0.4	2	-	-	Granite
MR-19	68	11	10	9	-	0.5	0.5	1	-	-	Dark-gray schistose restite
MR-23	57	19	7	13	-	0.5	0.5	3	-	-	Light-gray quartz mica schistose restite
MR-26	87	7	3	-	-	0.5	0.5	2	-	-	Light-gray elongated micaceous quartzite restite
MR-27	51	15	16	14	-	1	-	3	-	-	Dark-gray schistose restite
MG-27	41	40	9	8	-	0.8	0.2	1	-	-	Granite
MR-28	53	21	13	9	-	1	-	3	-	-	Dark-gray schistose restite
MG-28	47	35	8	9	-	0.3	0.4	0.3	-	-	Granite
MR-30 (a)	63	10	13	8	-	1	1	3	-	1	Dark-gray rusty schistose restite
MG-30 (a)	43	42	7	7	-	0.5	0.4	0.1	-	-	Granite
MR-30 (b)	62	15	12	5	-	1	1	4	-	-	dark-gray schistose restite
MG-30 (b)	47	31	8	9	-	0.5	0.5	4	-	-	Granite
MG-33	42	44	7	5	-	0.4	0.6	1	-	-	Granite
MR-33	49	20	18	7	-	1	1	4	-	-	Jet-black schistose restite
MT-34	58	20	7	11	-	1	-	3	-	-	Quartz-mica schist, Tanawal Formation
MT-35	56	22	5	12	-	0.5	0.5	4	-	-	Mica schist, Tanawal Formation
MT-36	62	15	10	9	-	1	1	-	2	-	Garnet-mica schist
MT-39	59	13	9	12	-	1	1	2	3	-	Garnet-mica schist
MR-40	57	18	12	5	-	1	1	4	-	2	Dark-gray restite
MG-40	42	36	11	8	-	0.5	0.5	2	-	-	Granite
MR-41	60	13	14	7	-	1	1	4	-	-	Dark-gray restite
MG-41	40	48	7	3	-	-	1	1	-	-	Granite
MR-43	80	9	6	3	-	0.5	0.5	1	-	-	Light-gray quartzite restite
MR-45	62	20	11	3	-	0.5	0.5	3	-	-	dark-gray schistose restite
MR-47	70	8	7	11	-	-	1	3	-	-	Light-gray schistose restite
MR-48 (a)	48	30	10	6	-	0.5	0.5	5	-	-	Dark-gray schistose restite
MR-48 (b)	61	18	10	6	-	1	1	3	-	-	Dark-gray schistose restite

Table 1. Continued

Sample No.	Quartz	Feldspar	Biotite	Muscovite	Tourmaline	Zircon	Apatite	Magnetite	Garnet	Hematite	Rock Name
MG-49	46	31	10	8	2	0.7	0.3	2	-	-	Granite
MR-50	52	24	13	5	-	1	1	4	-	-	Dark-gray schistose restite
MT-51 (a)	61	18	10	7	-	0.6	0.4	3	-	-	Tanawal Schist
MT-51 (b)	57	18	12	8	-	0.8	0.2	4	-	-	Tanawal Schist
MR-52	42	31	19	3	-	1	1	3	-	-	Jet-black schistose restite
MR-53	63	11	11	10	-	1	1	3	-	-	Dark-gray schistose restite
MT-54 (a)	81	8	7	2	-	0.6	0.4	1	-	-	Tanawal Formation, micaceous quartzite
MT-54 (b)	86	8	4	-	-	0.5	0.5	1	-	-	Tanawal Formation, micaceous quartzite
MG-55	41	48	3	6	-	0.5	0.5	1	-	-	Granite
MR-56	60	13	13	9	-	1	1	3	-	-	Dark-gray schistose restite
MG-56	52	35	8	2	-	1	-	2	-	-	Granite
MR-58	59	13	13	10	-	1	1	3	-	-	Dark-gray schistose restite
MR-62	59	20	13	4	-	-	1	3	-	-	Dark-gray schistose restite
MG-62	59	14	15	9	-	0.5	0.5	2	-	-	Granite
MG-63	35	55	5	4	-	-	0.5	0.5	-	-	Granite
MR-65	53	25	12	5	-	1	-	4	-	-	Dark-gray schistose restite
MT-66 (a)	83	6	4	5	-	0.6	0.4	1	-	-	Tanawal Formation, micaceous quartzite
MT-66 (b)	59	16	11	10	-	0.5	0.5	3	-	-	Tanawal Formation, mica schist
MT-66 (c)	57	23	9	8	-	0.7	0.3	2	-	-	Tanawal Formation, mica schist
MT-66 (d)	81	6	5	6	-	0.5	0.5	1	-	-	Tanawal Formation, micaceous quartzite
MR-67	61	16	11	6	-	1	1	4	-	-	Dark-gray schistose restite
MR-70	58	22	10	5	-	1	1	3	-	-	Dark-gray schistose restite
MG-70	47	38	5	7	1	1	1	-	-	-	Granite
MR-71	57	23	8	9	-	0.5	0.5	2	-	-	Dark-gray schistose restite

Jet-black Xenoliths

Jet-black xenoliths enclosed in Mansehra Granite are primarily comprised of hypidiomorphic to allotriomorphic quartz and feldspar with minor biotite, muscovite as well as accessory zircon, apatite and magnetite. The xenoliths depict lepidoblastic texture along with asymmetrical crenulation cleavage and foliation (Fig. 6a). Quartz grains reveal sutured contacts and are associated with mica at places (Fig. 6a). Anhedral feldspar shows sericitization. Meanwhile, magnetite occurs in distributed form having idiomorphic to allotriomorphic crystals and occasionally replaces muscovite (Fig. 6a). Moreover, mica reveals parallel to sub-parallel alignment with occurrence of euhedral zircon (Fig. 6b). It is worth stating that presence of euhedral zircon, lack of sillimanite and surmicaceous nature suggests the restite character of these xenoliths (Pupin, 1980; Clemes and Wall, 1981; White et al., 1991; Pitcher, 1993; Fig. 6b). Modal mineralogical composition of the jet-black xenoliths is revealed in Table 1.

Tanawal Formation

Schists of Tanawal Formation are predominantly comprised of sub-

hedral to anhedral quartz and feldspar with subordinate mica and accessory apatite, magnetite and zircon. Textural characteristics reveal that the rocks are foliated and lepidoblastic (Fig. 7a). Quartz grains are patchily strained, interlocked and exhibit mosaic texture. Fine-grained muscovite substitutes quartz sporadically at number of places (Fig. 7a). Further, muscovite and biotite flakes reveal preferred orientation. Stressed muscovite symbolizes tectonic bending (Fig. 7a). Fine-grained quartz associated with broken mica suggests marginal mylonization (Fig. 7b). Meanwhile, mica associated with thin quartz bands are pinched and swelled, which characterizes tectonic foliation (Fig. 7b). Disseminated magnetite having euhedral to subhedral crystal shape replaces muscovite at number of places. Apart from these features, porphyroblasts of garnets are rarely found in the rocks (Fig. 7c). In contrast, micaceous quartzites of Tanawal Formation contain anhedral vastly strained quartz, feldspar with minor biotite, muscovite and accessory magnetite, zircon in addition to apatite. The rock is non-foliated that exhibits granular texture. Biotite and muscovite flakes enclose zircon and apatite while magnetite occurs in disseminated form in these bodies. Mineralogical composition of samples of Tanawal Formation is expressed in Table 1.

Figure 6. Microphotographs 6a-b portray lepidoblastic texture, magnetite (Mag) and euhedral zircon (Zrn) with dark halo in jet black schistose restite (MR-33, 52).

Figure 7. Microphotographs 7a-c signify microscopic features of Tanawal Formation in MT-34, 35 and 36: (a) tectonic bending in muscovite, quartz (Qz), feldspar (Fsp). (b) pinched and swelled muscovite (Ms) augen representing tectonic foliation. (c) garnet (Grt) presence in schist of Tanawal Formation.

Analytical Results and Geochemistry

Major, minor oxides and trace elements contents of eighty-one representative samples including xenoliths, Mansehra Granite and Tanawal Formation were determined through XRF. The results of various oxides (wt%) and trace elements (ppm) contents of the analyzed samples are presented in Tables 2 and 3.

The geochemical data of Mansehra Granite as interpreted in R_1 - R_2 and total alkali vs. SiO_2 diagrams, principally placed MG in granite field (Fig. 8a, b). The chemical data of the xenoliths, Tanawal Formation and Mansehra Granite was plotted on geochemical classification diagrams. AFM diagram of the xenoliths and Tanawal Formation depicts calc-alkaline compositions except one sample, which indicates tholeiitic

nature owing to relatively higher iron content (Fig. 9a). Nevertheless, all samples of MG exhibit calc-alkaline character in terms of AFM diagram (Fig. 9b). Likewise, SiO_2 - K_2O plot placed the samples of xenoliths and Tanawal Formation in calc-alkaline, high K calc-alkaline and shoshonite series (Fig. 10a). In contrast, SiO_2 - FeOt/MgO plot portrayed that these xenoliths and Tanawal Formation are calc-alkaline in nature, and some of the samples reveal tholeiitic behavior (Fig. 10b). Based on A/CNK vs. ANK , SiO_2 vs. K_2O , $(\text{Al}_2\text{O}_3 + \text{CaO})/\text{FeOt} + \text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. $100 (\text{MgO} + \text{FeOt} + \text{TiO}_2)/\text{SiO}_2$ and SiO_2 vs. FeOt/MgO , the geochemical data of MG reveals calc-alkaline and strongly peraluminous nature (Fig. 11a-d).

Further, chemical data of the xenoliths and Tanawal Formation plotted on geotectonic discrimination diagram displays that samples of xenoliths and Tanawal Formation fall in syn-collisional field of R_1 -

Table 2a. Major and minor oxides (percent) in xenoliths and Tanawal Formation

Sample No.	Petrology	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	MnO	LOI
MR-2	Restite	62.16	16.85	6.51	1.99	2.49	2.31	2.86	0.27	0.96	0.08	1.85
MR-3	Restite	62.53	15.9	5.52	2.67	2.07	2.61	2.28	0.31	0.86	0.07	1.83
MR-7	Restite	62.98	16.98	6.58	2.02	2.52	2.32	2.9	0.27	0.96	0.08	2.05
MR-12	Restite	60.76	16.81	5.53	2.93	2.37	2.74	2.43	0.3	0.74	0.07	1.88
MR-18	Restite	81.98	10.1	1.27	2.23	0.41	1.29	0.5	0.11	0.17	0.08	1.76
MR-20	Restite	60.8	18.32	5.26	0.81	1.01	1.24	6.1	0.07	0.76	0.08	2.09
MR-22	Restite	64.66	16.05	5.1	2.2	1.56	3.19	2.42	0.31	0.65	0.07	1
MR-23	Restite	64.4	17.54	4.98	0.77	1.68	1.28	4.63	0.08	0.66	0.07	2.03
MR-26	Restite	63.63	15.53	5.39	2.61	2.02	2.55	2.22	0.3	0.84	0.06	1.19
MR-29	Restite	61.76	18.19	5.23	0.8	1.03	1.26	6.11	0.07	0.76	0.08	2.63
MR-30	Restite	65.69	17.85	5.09	0.78	1.72	1.31	4.72	0.19	0.68	0.08	1.13
MR-31	Restite	62.63	17.32	4.73	0.6	1.54	1.03	7.38	0.12	0.71	0.07	1.33
MR-32	Restite	65.13	16.43	5.12	2.2	1.55	3.19	2.42	0.32	0.65	0.06	1.05
MT-34	Tanawal Formation	62.97	19.06	3.02	0.3	0.59	1.58	7.82	0.07	0.31	0.06	1.2
MT-35	Tanawal Formation	62.33	18.83	3.01	0.29	0.59	1.59	7.75	0.07	0.31	0.06	1.77
MR-38	Restite	59.91	16.34	6.13	1.5	2.57	3.04	3.09	0.25	0.53	0.1	2.51
MR-41	Restite	63.45	17.03	5.05	2.25	2.01	3.69	2.2	0.32	0.79	0.08	1.77
MR-42	Restite	62.76	16.82	4.98	2.2	2.02	3.66	2.18	0.32	0.79	0.07	1.9
MR-43	Restite	61.73	17.08	5.62	2.98	2.4	2.78	2.47	0.31	0.75	0.07	2.37
MR-44	Restite	65.64	16.5	5.71	2.41	1.08	2.09	2.81	0.25	0.82	0.08	1.62
MR-45	Restite	65.33	17.73	5.02	0.75	1.69	1.31	4.68	0.19	0.68	0.08	1.66
MR-48	Restite	81.04	9.99	1.25	2.2	0.4	1.27	0.49	0.11	0.17	0.08	1.09
MR-50	Restite	65.86	16.35	5.19	2.24	1.59	3.25	2.47	0.32	0.66	0.07	1.56
MR-52	Restite	60.65	18.17	7.11	3.71	2.25	1.95	2.31	0.41	1.12	0.1	1.3
MR-54	Restite	63.88	16.11	5.02	2.16	1.52	3.13	2.38	0.31	0.63	0.06	2.36
MR-56	Restite	62.98	15.83	5.48	2.31	1.04	2.01	2.7	0.24	0.79	0.08	1.62
MR-57	Restite	62.5	16.14	3.38	2.18	1.69	3.97	2.02	0.24	0.48	0.07	2.3
MR-59	Restite	59.39	17.76	6.99	3.6	2.21	1.93	2.27	0.4	1.08	0.09	1.87
MR-60	Restite	62.02	15.73	5.44	2.63	2.03	2.56	2.23	0.3	0.84	0.05	1.67
MT-64	Tanawal Formation	64.88	16.47	5.7	2.75	2.12	2.69	2.34	0.32	0.88	0.06	1.6
MT-66	Tanawal Formation	78.59	9.67	1.24	2.08	0.38	1.22	0.47	0.11	0.17	0.08	1.51
MR-67	Restite	77.79	13.49	1.22	2.06	0.38	1.21	0.46	0.11	0.17	0.08	1.54
MR-68	Restite	60.63	16.94	5.71	2.26	1.48	3.29	2.3	0.33	0.62	0.08	2.64
MR-69	Restite	61	16.94	5.44	2.87	2.33	2.74	2.52	0.3	0.76	0.08	2.31
MR-72	Restite	62.71	17.48	5.61	2.96	2.41	2.82	2.6	0.31	0.78	0.08	1.9
MR-73	Restite	61.41	17.01	5.78	2.25	1.49	3.3	2.33	0.34	0.63	0.08	1.71
MR-74	Restite	64.81	16.65	3.49	2.25	1.74	4.1	2.08	0.25	0.5	0.07	1.52
MR-75	Restite	60.33	17.88	5.95	1.65	1.31	1.95	3.38	0.21	0.51	0.1	2.39
MR-78	Restite	61.81	18.35	6.1	1.69	1.33	1.98	3.45	0.21	0.55	0.11	1.99

Table 2b. Trace elements (ppm) in xenoliths and Tanawal Formation

Sample No.	Petrology	Zr	La	Ce	Th	V
MR-2	Restite	149	33	16	27	6
MR-3	Restite	196	33	24	28	7
MR-7	Restite	71	25	8	26	7
MR-12	Restite	148	30	11	28	4
MR-18	Restite	74	32	9	13	9
MR-20	Restite	75	18	12	24	12
MR-22	Restite	122	25	16	17	14
MR-23	Restite	120	29	15	14	8
MR-26	Restite	74	19	8	26	6
MR-29	Restite	194	21	16	28	5
MR-30	Restite	76	28	9	21	9
MR-31	Restite	223	22	16	23	10
MR-32	Restite	122	26	12	25	8
MT-34	Tanawal Formation	146	29	15	22	22
MT-35	Tanawal Formation	77	27	18	19	4
MR-38	Restite	148	17	15	16	24
MR-41	Restite	76	21	9	13	5
MR-42	Restite	147	18	8	25	6
MR-43	Restite	148	24	11	27	7
MR-44	Restite	120	20	7	14	9
MR-45	Restite	147	19	13	27	3
MR-48	Restite	196	23	14	29	5
MR-50	Restite	148	25	12	18	6
MR-52	Restite	149	22	9	15	10
MR-54	Restite	122	28	12	21	8
MR-56	Restite	120	13	17	23	12
MR-57	Restite	148	17	18	20	8
MR-59	Restite	145	15	19	18	9
MR-60	Restite	196	19	22	16	11
MT-64	Tanawal Formation	148	22	12	25	5
MT-66	Tanawal Formation	74	21	9	18	8
MR-67	Restite	74	24	8	15	4
MR-68	Restite	72	18	10	18	6
MR-69	Restite	148	8	17	14	12
MR-72	Restite	74	16	12	19	9
MR-73	Restite	124	23	16	24	7
MR-74	Restite	148	21	13	21	6
MR-75	Restite	121	19	15	26	10
MR-78	Restite	149	24	21	19	9

Table 3a. Major and minor oxides (percent) in Mansehra Granite

Sample No.	Petrology	SiO ₂	K ₂ O	Na ₂ O	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	FeO	TiO ₂	MnO	P ₂ O ₅	LOI
MG-06	Massive Granite	70.03	4.07	4.17	1.21	15.45	0.83	1.49	2.15	0.78	0.07	0.29	0.21
MG-07	Massive Granite	71.15	3.73	4.05	1.39	15.11	0.85	1.19	1.75	0.57	0.04	0.23	0.33
MG-08	Massive Granite	71.7	3.16	3.15	1.61	14.08	2.47	1.19	1.16	0.57	0.09	0.3	0.65
MG-09	Massive Granite	72.06	4.25	2.65	1.31	16.25	0.43	0.59	1.71	0.45	0.02	0.19	0.25
MG-10	Massive Granite	73.15	3.75	2.78	1.14	15.33	0.44	0.73	1.46	0.43	0.12	0.17	0.34
MG-11	Massive Granite	68.75	4.17	3.16	1.22	15.39	1.59	0.79	1.29	0.43	0.08	0.23	2.04
MG-12	Massive Granite	71.02	3.17	2.59	1.31	14.23	0.68	0.79	2.79	0.41	0.07	0.18	2.05
MG-13	Massive Granite	71.16	2.49	3.49	0.7	16.27	0.18	1.85	1.18	0.66	0.04	0.23	1.03
MG-14	Massive Granite	70.35	2.43	3.14	1.59	15.63	2.13	1.41	0.87	0.65	0.06	0.25	0.95
MG-15	Massive Granite	69.95	3.23	3.05	1.53	14.57	2.15	1.29	1.29	0.59	0.14	0.22	1.83
MG-16	Massive Granite	71.05	3.57	3.03	1.41	14.03	0.52	0.89	1.81	0.43	0.07	0.16	2.41
MG-17a	Massive Granite	73.79	2.69	2.27	1.25	15.79	0.69	0.77	1.03	0.29	0.09	0.17	1.02
MG-17b	Massive Granite	72.65	3.89	2.79	1.27	15.29	0.43	0.89	1.23	0.49	0.07	0.16	0.87
MG-19	Massive Granite	69.03	4.85	3.73	1.03	17.55	0.58	0.85	1.03	0.37	0.09	0.25	0.63
MG-23	Sheared Granite	70.28	2.43	4.15	0.63	17.93	0.13	0.26	1.67	0.65	0.07	0.28	1.53
MG-27	Sheared Granite	73.06	3.55	3.03	1.13	15.49	1.31	0.59	1.69	0.35	0.06	0.18	0.26
MG-28	Sheared Granite	73.39	3.49	3.01	1.15	15.65	1.3	0.64	0.91	0.34	0.08	0.21	0.34
MG-30a	Sheared Granite	70.75	5.28	2.78	1.12	14.19	1.19	0.57	1.03	0.31	0.16	0.16	2.35
MG-30b	Sheared Granite	68.35	3.5	2.63	1.57	15.13	2.5	1.29	1.9	0.69	0.06	0.17	1.87
MG-33	Sheared Granite	69.85	4.43	3.32	0.89	15.23	0.34	0.69	1.28	0.34	0.08	0.18	2.65
MG-40	Sheared Granite	68.75	4.59	2.65	1.61	16.59	1.85	1.13	2.03	0.58	0.09	0.23	0.27
MG-42	Sheared Granite	70.85	4.36	2.53	1.23	14.29	0.31	0.61	1.89	0.34	0.12	0.12	2.63
MG-43	Sheared Granite	67.5	3.75	3.73	1.5	16.89	0.79	0.93	1.75	0.43	0.11	0.26	1.83
MG-44	Sheared Granite	69.55	3.65	3.48	1.09	15.24	0.74	0.86	1.85	0.42	0.06	0.25	2.11
MG-46	Sheared Granite	68.5	3.69	2.5	1.73	15.32	0.76	1.16	1.89	0.51	0.05	0.23	2.69
MG-49	Massive Granite	73.09	3.79	3.59	0.43	15.27	0.13	0.23	1.59	0.59	0.07	0.26	0.88
MG-64	Massive Granite	73.17	3.35	0.25	1.07	16.08	0.89	1.6	0.86	0.89	0.06	0.05	1.13
MG-65	Massive Granite	72.25	3.13	3.13	1.47	14.29	1.23	2.03	1.03	0.65	0.13	0.39	0.41
MG-67	Massive Granite	68.75	4.03	3.19	1.23	14.13	1.41	1.89	1.88	0.79	0.09	0.35	1.89
MG-68	Massive Granite	70.55	3.29	3.81	0.54	15.78	0.38	1.12	1.18	0.54	0.08	0.25	1.9
MG-69	Massive Granite	71.15	3.08	2.79	1.88	16	0.49	1.3	0.91	0.78	0.06	0.19	1.37
MG-70	Massive Granite	69.07	3.12	2.89	1.79	17.8	0.66	1.39	1.25	0.77	0.05	0.23	1.14
MG-71	Massive Granite	73.17	3.03	2.61	1.52	15.9	0.49	1.08	0.89	0.51	0.08	0.07	0.64
MG-72	Massive Granite	70.59	4.41	4.17	0.52	15.57	0.45	0.12	1.05	0.44	0.01	0.3	1.95
MG-73	Massive Granite	68.47	4.84	3.73	0.93	17.39	0.31	0.63	1.59	0.26	0.05	0.4	0.86
MG-74	Massive Granite	71.77	3.27	3.35	0.89	16.4	0.29	0.65	0.88	0.23	0.04	0.27	1.78
MG-75	Massive Granite	71.04	3.96	2.61	1.47	16.75	0.47	1.05	0.84	0.54	0.09	0.17	1.01
MG-76	Massive Granite	69.49	5.35	2.23	1.19	15.05	0.43	0.81	1.15	0.51	0.05	0.14	2.61
MG-77	Massive Granite	68.35	4.3	3.52	1.73	15.68	0.57	1.2	1.24	0.59	0.06	0.28	1.71
MG-78	Massive Granite	72.55	3.57	2.69	1.19	15.39	0.73	0.79	2.05	0.43	0.12	0.17	0.69
MG-79	Massive Granite	71.15	3.86	3.19	1.43	17.19	1.2	0.62	1.51	0.34	0.08	0.2	0.14
MG-80	Massive Granite	69.05	3.37	2.39	1.59	15.27	2.15	1.28	2.08	0.68	0.09	0.22	1.34

Table 3b. Trace elements (ppm) in Mansehra Granite

Sample No.	Petrology	Y	Sr	Rb	Nb	Zr	U	Ba	Th	Ce	Nd	La
MG-06	Massive Granite	28	59	249	13	141	12	245	47	123	45	33
MG-07	Massive Granite	29	49	287	17	123	25	248	53	65	23	36
MG-08	Massive Granite	34	78	228	15	179	13	275	51	149	39	34
MG-09	Massive Granite	14	27	151	12	234	15	1621	39	89	2	37
MG-10	Massive Granite	30	47	263	15	121	11	259	50	155	21	45
MG-11	Massive Granite	28	58	253	16	146	14	277	45	112	21	39
MG-12	Massive Granite	26	56	235	13	125	12	206	52	147	42	46
MG-13	Massive Granite	10	38	21	18	166	13	92	55	112	7	11
MG-14	Massive Granite	31	67	279	17	143	23	249	49	72	39	29
MG-15	Massive Granite	27	55	243	13	129	16	348	48	66	3	52
MG-16	Massive Granite	25	63	247	16	127	14	279	53	118	28	39
MG-17a	Massive Granite	17	73	125	11	104	14	239	43	92	4	49
MG-17b	Massive Granite	29	64	235	14	125	15	351	46	143	36	46
MG-19	Massive Granite	33	61	261	14	151	15	281	55	133	27	48
MG-23	Sheared Granite	24	48	289	14	87	10	221	45	137	19	34
MG-27	Sheared Granite	33	75	199	15	165	13	349	55	125	29	47
MG-28	Sheared Granite	24	49	248	16	115	14	2429	41	165	27	32
MG-30a	Sheared Granite	25	51	255	14	106	17	339	44	69	5	51
MG-30b	Sheared Granite	19	162	139	17	124	11	211	45	189	26	36
MG-33	Sheared Granite	22	45	235	15	91	15	278	42	117	25	25
MG-40	Sheared Granite	27	76	227	17	161	13	371	53	139	53	47
MG-42	Sheared Granite	25	64	191	10	107	12	319	47	137	39	43
MG-43	Sheared Granite	21	41	225	15	99	11	179	42	125	25	29
MG-44	Sheared Granite	23	49	276	16	112	15	349	53	111	53	38
MG-46	Sheared Granite	19	46	326	14	88	24	181	47	65	18	27
MG-49	Massive Granite	23	73	185	11	149	13	362	48	88	28	23
MG-64	Massive Granite	32	75	186	14	178	14	261	49	75	18	31
MG-65	Massive Granite	34	61	235	16	156	10	235	52	73	5	47
MG-67	Massive Granite	25	56	231	15	134	13	238	52	12	5	33
MG-68	Massive Granite	18	8	372	17	25	11	23	33	63	17	13
MG-69	Massive Granite	47	105	206	21	276	21	532	54	110	19	53
MG-70	Massive Granite	34	75	191	18	185	18	415	49	74	32	37
MG-71	Massive Granite	43	63	205	19	312	21	366	63	123	38	61
MG-72	Massive Granite	11	9	192	9	15	25	28	34	23	13	12
MG-73	Massive Granite	32	35	345	19	89	24	182	49	69	36	23
MG-74	Massive Granite	24	48	243	12	105	25	265	44	55	32	18
MG-75	Massive Granite	31	59	209	19	181	21	229	57	125	47	42
MG-76	Massive Granite	32	56	219	18	161	24	325	51	53	23	37
MG-77	Massive Granite	5	15	47	6	32	23	55	34	48	7	14
MG-78	Massive Granite	27	54	261	15	119	12	279	51	127	42	33
MG-79	Massive Granite	22	51	181	8	83	17	235	43	92	8	31
MG-80	Massive Granite	31	86	205	17	204	15	325	56	97	21	27

Figure 8. Binary plots of geochemical data of Mansehra Granite in geochemical classification diagrams indicating granitic fields (after Cox *et al.*, 1979 and De la Roche *et al.*, 1980); (a) SiO_2 vs. total alkalis (b) Plot of R_1 vs. R_2 .

Figure 9. AFM diagram (Irvin and Baragar, 1971) of restites, Tanawal Formation and Mansehra Granite. (a) plot of restite and Tanawal Formation indicating their calc-alkaline character; (b) Mansehra Granite (MG) representing calc-alkaline nature.

R_2 diagram (Fig. 12a). Likewise, geochemical data of the MG plotted on triangular tectonic discrimination diagrams denote syncollisional orogenic settings of the pluton (Fig. 12b-d).

Chemical data of xenoliths and Tanawal Formation plotted on Harker's variation diagrams express negative trends with SiO_2 (Fig. 13a-c). Geochemical plots of various oxides with SiO_2 show scattering on account of irregular distribution of minerals and heterogeneity in the protolith (Fig. 13). Likewise, in variation diagrams of Mansehra Granite, major oxides also reveal negative correlation with SiO_2 (Fig. 14). Meanwhile, the trace elements Zr, Sr, Nb, Y and Th exhibit significant positive variations and relationships (Fig. 15a-d, f). Rb however, varied inversely with Sr (Fig. 15e) and exhibited negative correlation (Fig. 15e). These significant binary plots of major and trace elements

describe scattering in Mansehra Granite.

In addition, petrographic observation and chemical data illustrate the presence of zircon in the xenoliths found in Mansehra Granite. Zircon saturation behaviour is a powerful tool to evaluate temperature of the xenoliths, metasediments and melts (Watson and Harrison, 1983; Montel, 1993; Miller *et al.*, 2003; Janousek *et al.*, 2006). Zircon saturation thermometry of both rocks determined through GCDKIT software shows that zircon temperatures of xenoliths and Tanawal Formation range from 734.8 to 850 °C and 753.1 to 808.6 °C, respectively. However, zircon saturation temperatures of the Mansehra Granite vary from 623.7 to 886.6 °C. The temperature results are presented in Tables 4 and 5.

Figure 10. shows geochemical series of restites and Tanawal Formation: (a) SiO_2 - K_2O plot (after Peccerillo and Taylor, 1976) indicating calc-alkaline to High-K calc-alkaline nature; (b) SiO_2 - FeO/MgO plot (after Miyashiro, 1974) exhibiting calc-alkaline to tholeiite series.

Figure 11. Plot of chemical data of Mansehra Granite reveals calc-alkaline and strongly peraluminous nature a) A/CNK vs. ANK (Shand, 1943); (b) SiO_2 vs. K_2O (after Peccerillo and Taylor, 1976); (c) $(Al_2O_3 + CaO) / (FeO + Na_2O + K_2O)$ vs. $100(MgO + FeO + TiO_2) / SiO_2$ (Sylvester, 1998); (d) SiO_2 vs. FeO/MgO (after Miyashiro, 1974).

Figure 12. (a) R_1 - R_2 diagram (Batchelor and Bowden, 1985) of xenoliths and Tanawal Formation showing orogenic syn-collisional settings; (b) Triangular Plot representing orogenic settings of Mansehra Granite (Pearce et al., 1977); (c, d) Tectonic discrimination diagrams signifying syn-collisional tectonic settings of Mansehra Granite (Pearce et al., 1984).

Discussion

Field Characteristics and Geochemical Attributes of Xenoliths in Mansehra Granite

Light-gray to jet-black xenoliths are found in Mansehra Granite in Oghi-Darband, Susalgali-Khaki, Chitta-Batta, Phulra and Mansehra areas. Light-gray xenoliths are non-foliated and contain relatively higher concentration of quartz as compared with mica contents and classified as micaceous quartzite. Whereas, light-gray xenoliths, which are principally comprised of quartz and feldspar with relatively lower mica contents, are classified as schistosed xenoliths (Fig. 3d, g). These schistosed xenoliths have tadpole-shaped K-feldspar phenocrysts with parallel alignment around their borders, suggesting the impact of stress and flow of Mansehra Granitic magma in a viscous state (Fig. 3d). Jet-black xenoliths contain relatively higher biotite contents as compared with dark-gray variety (Fig. 3b). These xenoliths are randomly distributed throughout the mass of Mansehra Granite which is contrary to the observation of Shams (1961) who proposed that these

xenoliths are abundant near the contact of the granite with the Tanawal Formation.

Geochemically, lower Na_2O values in xenoliths correspond to its lesser albite contents. The K_2O constituents in xenoliths are 0.46–7.38%, which relate to their modal K-feldspar contents. On the other hand, lesser K_2O level in xenoliths suggest lower modal microcline contents. The overall subordinate CaO and Na_2O level relative to K_2O represent lower modal plagioclase and higher microcline, whereas the smaller value of MgO is due to scarcity of chlorite. Relatively higher or lower levels of TiO_2 and MnO in samples of xenoliths suggest augmentation or deficiency of biotite and garnet constituents.

Implications on Petrogenesis and Tectonic Settings of Xenoliths

Geochemical classification diagrams of light-gray to jet-black xenoliths and metasediments of the Tanawal Formation placed these rocks in calc-alkaline to high K calc-alkaline fields (Fig. 9a; 10a). Both xenoliths and metasediments of Tanawal Formation lie in syn-collisional

Figure 13. Harker's variation plots (Harker, 1909) between various oxides and SiO_2 in xenoliths and Tanawal Formation. a) SiO_2 - Na_2O b) SiO_2 - K_2O c) SiO_2 - MgO d) SiO_2 - TiO_2 e) SiO_2 - P_2O_5 f) SiO_2 - Al_2O_3 g) SiO_2 - Fe_2O_3 h) SiO_2 -Zr.

Figure 14. Harker's variation diagrams (Harker, 1909) between major oxides in Mansehra Granite: a) CaO vs. SiO_2 b) Fe_2O_3 vs. SiO_2 c) SiO_2 vs. K_2O d) Na_2O vs. SiO_2 e) SiO_2 vs. $\text{Na}_2\text{O}+\text{K}_2\text{O}$ f) P_2O_5 vs. SiO_2 .

Figure 15. Harker's variation diagrams (Harker, 1909) between trace elements in Mansehra Granite: a) Nb vs. Zr b) Rb vs. P_2O_5 c) Zr vs. Y d) Th vs. Zr e) Rb vs. Sr f) Sr vs. Ba.

sional orogenic domain of the tectonic discrimination diagrams (Fig. 12a), implying that these rocks are linked with orogenic syn-collision tectonic settings. In the meantime, orogenic syn-collisional tectonic setting in tectonic discrimination diagram also suggests that petrogenesis of these rocks is associated with compressional regime. Likewise, both these rocks have comparable modal mineralogical and geochemical composition (Tables 1 and 2). The light-gray to jet-black xenoliths and Tanawal Formation shared common features in variation diagrams (Fig. 13). These rocks also have comparable zircon saturation temperatures (Table 4). In view of the resemblance of geochemical signatures, geotectonic features and petrographic characteristics of the xenoliths and the metasediments of the Tanawal Formation, it can be inferred that the former has been derived from the later. These xenoliths now may be referred to as restites, which substantiate the hypothesis of anatexis nature and S-type trait of the Mansehra Granite. Occurrence of zircon and apatite in schistosed xenoliths is pointer of restites (Pupin, 1980; Pitcher, 1993). Enclosure of apatite and zircon in non-foliated micaceous quartzite xenoliths of the Mansehra Granite suggests the restite nature of these rocks. Meanwhile, presence of surmicaceous enclaves in Mansehra Granite also proposed the restite character of these rocks, which is similar to the findings of White et al. (1991).

Metasedimentary xenoliths present in S-type Mansehra Granite are restites which are analogous to conclusions of White et al. (1991) and Wyborn et al. (1991). Lack of sillimanite in metasedimentary xenoliths of S-type granite is pointer of restites (Clemens and Wall, 1981). The absence of sillimanite in schistosed rocks of the Mansehra area proposed the restite nature of xenoliths. In addition, xenoliths of S-type granites of the Lachlan fold belt, Australia deliver confirmation

of the restite and these S-type granites are formed by anatexis of enclosing metasedimentary protolith (Chappell and White, 1974; Thompson, 1982; Le Fort et al., 1986; Clemens and Vielzeuf, 1987; Barbey et al., 1990; Holtz and Barbey, 1991; Inger and Harris, 1993; Albarede, 2003; Best, 2003). Likewise, we propose that the xenoliths of S-type Mansehra granites provide evidences of the restite and the Mansehra pluton is developed by anatexis of enclosing metasedimentary Tanawal Formation which is also consistent with the findings of Jan et al. (1981). In view of these findings, it can be inferred that the anatexis nature and S-type character of the Mansehra Granite suggests the enclosing Tanawal Formation as the probable protolith for the granitic melt of the pluton. The restite nature of the xenoliths found in the granite furnishes credible evidence in favour of the generation of Mansehra Granitic magma through partial melting of metasediments of the Tanawal Formation.

Association of larger biotite flakes at the contact of these restites with Mansehra Granite (Fig. 5d) points out that these restites represents non-melted fragments of the Tanawal Formation which were exposed to relatively higher temperature during anatexis of the protolith. Mean crystallization temperature of the Mansehra Granite ranged from 623.7 to 886.6 °C. The restites most probably exposed to these higher temperatures, particularly at the margins and induced recrystallization and relatively larger flake size as compared with the central part of these restites due to lesser impact of elevated temperature.

Schistosed restites are abundant and exhibits conspicuous lepidoblastic texture having discernible symmetrical and asymmetrical crenulation cleavage (Fig. 5g). These restites are surmicaceous containing zircon and apatite (Fig. 5a-g). Schistosed restites record defor-

Table 4. Zircon saturation temperatures of restites (MR) and Tanawal Formation (MT) samples from the Mansehra area

Sample No.	Zr Saturation Temperature °C
MR-2	807.9
MR-3	821.4
MR-7	744.5
MR-12	791.7
MR-18	762.0
MR-20	757.3
MR-22	779.3
MR-23	808.3
MR-26	739.1
MR-29	841.7
MR-30	768.3
MR-31	846.8
MR-32	781.2
MT-34	808.6
MT-35	753.1
MR-38	799.2
MR-41	737.9
MR-42	793.0
MR-43	791.7
MR-44	788.5
MR-45	827.2
MR-48	850.0
MR-50	796.1
MR-52	797.3
MR-54	781.0
MR-56	788.4
MR-57	789.7
MR-59	794.9
MR-60	822.3
MT-64	796.6
MT-66	763.3
MR-67	778.1
MR-68	736.1
MR-69	792.5
MR-72	734.8
MR-73	781.3
MR-74	789.8
MR-75	798.6
MR-78	817.9

Table 5. Zircon saturation temperatures of Mansehra Granite (MG) from Mansehra area

Sample No.	Zr Saturation Temperature °C
MG-06	779.1
MG-07	768.8
MG-08	810.5
MG-09	850.2
MG-10	790.3
MG-11	794.9
MG-12	792.1
MG-13	828.6
MG-14	804.5
MG-15	785.2
MG-16	781.8
MG-17a	792.7
MG-17b	789.7
MG-19	797.5
MG-23	770.6
MG-27	817
MG-28	786.3
MG-30a	759.8
MG-30b	785.9
MG-33	755.3
MG-40	805.5
MG-42	771.1
MG-43	760.1
MG-44	773.8
MG-46	756.9
MG-49	807.8
MG-64	865.5
MG-65	801.8
MG-67	779.7
MG-68	667.4
MG-69	864.6
MG-70	831.2
MG-71	886.6
MG-72	623.7
MG-73	753
MG-74	782.2
MG-75	827.6
MG-76	805.6
MG-77	666.2
MG-78	790.3
MG-79	754.9
MG-80	836.5

mations in the form of crenulations (Fig. 5g), and these metasedimentary restites preserve confirmation of structural antiquity at the time of their amalgamation in the felsic melt which is parallel to the conclusions of Fleming (1996).

In summary, this study suggests that these light-gray to jet-black restites have been derived from the Tanawal Formation, which is the protolith of the Mansehra Granite. Furthermore, these restites comprise fairly high SiO_2 contents comparable to Tanawal Formation, reflecting that the restites are derived from metasediments of Tanawal Formation. Field relationships coupled with modal mineralogical composition, geochemical signatures and geotectonic association of the restites and the metasediments of the Tanawal Formation provide credible evidence in favour of anatectic nature and S-type trait of the Mansehra Granite.

Petrogenetic and Tectonic Implications of Mansehra Granite

Based on petrographic studies, the host rock of the restites (Mansehra Granite) represents abundance of Al-rich minerals specifically muscovite (Fig. 5j) and absence of allanite and titanite suggesting anatectic and S-type character of this pluton which is consistent with the interpretations of Villaseca et al. (2007) and Saki (2010). Apart from this, the geochemical plotting constructed for the Mansehra Granite (MG) placed this pluton in strongly peraluminous and calc-alkaline domain (Fig. 11a-d), which also imply anatectic and S-type trait of the Mansehra pluton. Meanwhile, the sheared and massive granites are plotted in the identical area of geochemical diagrams, representing that the both varieties of pluton are generated from similar compositional phase, therefore, can be reflected as cogenetic (Fig. 8, 9b, 11a-d). Triangular plot (Pearce et al., 1977) and trace elements plots particularly of Y-Nb and Y+Nb-Rb (Pearce et al., 1984) denote that the samples of Mansehra pluton are clustered around triple point confluence of syn-COLG, VAG and WPG presenting orogenic syncollisional tectonic settings (Fig. 12b-d). Therefore, it can be deduced from these diagrams that the Mansehra pluton is linked with orogenic and syn-collisional settings. In terms of trace element geochemistry, the deficiency of Ba and Sr in MG may signify robust partitioning of Ba into feldspar and micas and Sr into feldspar which is consistent with the interpretation of Icenhower and London (1996) and Blundry and Wood (1991). Meanwhile, extremely greater concentration of Ba in number of samples possibly can be ascribed to local enrichment. Fairly greater concentrations of U (10–25 ppm) and Th (33–63 ppm) may propose that the MG is resulting from crystal fractionation of metasediments bearing Tanawal Formation, as argued by Azman (2005).

Harker's variation diagrams of the major oxides indicated negative correlations for Mansehra pluton (Fig. 14) which reflect crystallization of micas and feldspar in felsic melt of the granite. Parallel interpretations have also been demonstrated by Singh (2010). On the contrary, positive trend in the correlation of Ba vs. Sr (Fig. 15f) can probably depict feldspar fractionation in line with the conclusions testified by Janousek et al. (2002). Likewise, the positive relationship in plots of Zr with Nb, Th, Y advocate Th, Nb and Y accumulation in crystallized zircon of MG (Fig. 15a, c-d). Geochemically, zircon crystallization in MG is preferred in peraluminous felsic melt comprising lower amounts of CaO, which is parallel with the conclusions of Yurimoto et al. (1990).

Meanwhile, the decline of Zr and P_2O_5 with fractionation in MG most possibly exhibit zircon and apatite crystallization from the melt, as proposed by Nagudi et al. (2003). According to Chappell and White (1992), the positive correlation of P_2O_5 with Rb suggests that the felsic melt of granitic rock is resulting from metasediments. In the present study, the trend of P_2O_5 with Rb also exhibits positive correlation (Fig. 15b), implying that the felsic melt of Mansehra Granite is resulting from metasediments of Tanawal Formation. Therefore, in view of these grounds, it can be inferred that the silicic melt of the Mansehra pluton is resulting from Tanawal Formation. In contrast, the negative correlation of Rb with Sr (Fig. 15e) propose that during the MG melt evolution, fractional crystallization was possibly the key differentiation process in a close scheme, lacking significant contamination. This finding is comparable with the conclusions of Rapela and Shaw (1979). Based on these sights, it is worth stating that the plots of MG in variation diagrams indicate variability, reasonable correlations, and scattering in composition owing to heterogeneity in protolith (Tanawal Formation). Furthermore, the scattering in plots of major oxides may pertain to irregular minerals dissemination in the silicic melt of MG, as stated and testified by Sing and Kumar (2005).

Conclusions

Mansehra Granite contains light-gray to jet-black restites. Presence of zircon, apatite, surmicaceous nature and lack of sillimanite suggests that these rocks are restites which are erratically dispersed throughout the mass of Mansehra Granite rather than concentrated near the contact of the granite with the Tanawal Formation. Occurrence of abundant and relatively larger mica flakes at the contact of restites with Mansehra Granite revealed that due to exposure at higher temperature of the granitic melt prompted recrystallization and larger flake size as compared with the central part of restites owing to lesser impact of elevated temperature. Schistosed and surmicaceous restites depict crenulation cleavage which record deformations in the form of crenulations and preserve structural antiquity at the time of their amalgamation in the felsic melt.

Geochemical classification diagrams of light-gray to jet-black restites and metasediments of Tanawal Formation placed these rocks in calc-alkaline, tholeiitic and high K-calc-alkaline to shoshonite field and portrayed their compositional resemblance. The restites found in Mansehra Granite showed orogenic syn-collisional tectonic settings signifying their association with compressional regime. Similar mineralogical, geochemical composition and geotectonic signatures of light-gray to jet-black restites and metasediments of the Tanawal Formation represent derivation of the former from the later which reveals the anatectic nature and S-type character of the Mansehra Granite. Geochemical classification diagrams pertaining to massive and sheared Mansehra pluton place this granitic body in calc-alkaline domain with peraluminous S-type trait. Both, the sheared and massive S-type granites are generated from similar compositional phase, therefore, can be concluded as cogenetic. Trace elements plots of Mansehra pluton suggests association of MG with orogenic and syn-collisional settings. Careful interpretation of MG in Harker plots propose that the magma of this pluton was resulting from heterogeneous Tanawal Formation via process of fractional crystallization.

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