U-Pb geochronology and petrogenesis of peraluminous granitoids from northern Indian plate in NW Pakistan: Andean type orogenic signatures from the early Paleozoic along the northern Gondwana

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Abstract

The pre-Himalayan peraluminous magmatic event along the northern margin of Indian plate in north-western Pakistan has been investigated leading to a correlation with the magmatic evolution in other Himalayan and northern Gondwana regions. The two mica granites from Utla and Mansehra regions of NW Pakistan are dominantly megacrystic, strongly peraluminous (A/CNK > 1.1) and intruded by aplitic dykes and quartz rich veins. U-Pb zircon dating by SIMS reveals their emplacement during the early Paleozoic, ranging from 476 Ma to 480 Ma. These granites are enriched in light rare-earth elements (LREEs) and show similar REE patterns with negative Eu anomalies. Geochemical modelling indicates that these granites were derived mainly from the partial melting of pelitic sources followed by the evolution of melt via fractional crystallization of feldspars, biotite, muscovite, apatite, and/or zircon, with the aplite dykes representing the very last fractionation product. Based on their compositions, source rock characteristics and U-Pb geochronology, we assign these to the regional association of other Cambro-Ordovician granitoids from the Himalayas and northern Gondwana terranes. Due to these similarities alongside other metamorphic, stratigraphic and geochemical evidence, an early Paleozoic Andean-type orogenic event is proposed for the genesis of these granitoids where the process could have been initiated by the subduction of the Proto-Tethys oceanic lithosphere beneath the northern Gondwana continental margin.

Key Words:

U-Pb Geochronology; Geochemistry; Early Paleozoic Utla granites; Andean-type orogeny; Northern Indian plate; NW Pakistan

1. Introduction

The northern Indian plate has experienced multiple tectonic regimes during its geological history. In the early Cenozoic, it records convergent tectonic conditions during the Himalayan orogenic episodes initiated by the intra-oceanic subduction of the Tethys Ocean (Searle et al., 2009; Jagoutz et al., 2011; Burg, 2011). Preceding this, it had been subjected to extensional settings during the late Paleozoic as indicated by the presence of rift-related alkaline lithologies (Kempe and Jan, 1970; Garzanti et al., 1999; Noble et al., 2001). Recent research has highlighted the role of magmatism as part of widespread tectonothermal activity during the early Paleozoic of the Himalaya (Gehrels et al., 2006a, 2006b; Cawood et al., 2007) as well as the other regions of northern Gondwana (DeCelles et al., 1998, 2000, 2004; Booth et al., 2004; Hu et al., 2013; Wang et al., 2013; Ding et al., 2015; Li et al., 2016).

The mechanism of early Paleozoic events are poorly understood as pre-Himalayan events are commonly overprinted by pervasive and extreme Tertiary tectonism. Pre-Himalayan rocks are generally associated with Pan-African orogenesis in response to the final accretion of the Gondwana continents (Murphy and Nance, 1991; Meert and Van der Voo, 1997; Miller et al., 2001; Liu et al., 2012; Yang et al., 2012). In contrast, an Andean type orogeny has been proposed for these rocks due to the subduction of proto-Tethyan oceanic lithosphere under the northern Gondwana continents (Cawood et al., 2007; Dong et al., 2013; Spencer et al., 2012; Hu et al., 2013; Wang et al., 2013; Li et al., 2016).

Research on the northern margin of the Indian plate has commonly focussed on the Cenozoic Himalayan uplift and related tectonism, metamorphism and magmatism, however, the pre-Himalayan details are relatively scarce. In this paper, we aim to help fill this knowledge gap by using a comprehensive geochemical and geochronological dataset to improve the understanding of pre-Himalayan events. Pre-Himalayan granites are exposed in various regions in NW Pakistan (i.e. Utla, Mansehra and Swat, Fig. 1). New U-Pb zircon ages of different units from the Utla and Mansehra granitoids are presented here and these confirm the broader petro-tectonic significance of these rocks. The Mansehra granite previously yielded a whole rock Rb-Sr age of 516 ±16 Ma (LeFort et al., 1980) which is also considered to be the age of Swat granite based on their similar field and petrological character (Anczkiewicz et al., 1998; DiPietro and Isachsen, 2001). These granites are associated with the early Paleozoic tectonic activity reported from the northern Indian plate on regional scale (LeFort et al., 1980; Pogue et al., 1992a; DiPietro and Isachsen, 2001; Cawood et al., 2007). An investigation of the petrogenetic history of these granitoids, their precise radiometric dating and regional tectonic correlations provide important information for unravelling the tectono-magmatic evolution of northern margin of the Indian plate during the early Paleozoic.

2. Regional Geology

The Indian plate, Kohistan Island Arc (KIA) and Eurasian plate are the three principal tectonic domains present in north-western Pakistan. The KIA originated as a result of intra-oceanic subduction within the Tethys Ocean which collided with the Indian plate along a regional fault zone known as Main Mantle Thrust (MMT) (Fig. 1) (Searle and Treloar, 2010; Burg, 2011). The northern Indian plate is divided into three tectonic units known as the Lesser Himalayan sequence (LHS), the Greater Himalayan Sequence (GHS) and the Tethyan Himalayan sequence (THS) which are separated by two regional fault systems: the Main Central Thrust (MCT) and South Tibetan Detachment system (STDS) (Fig. 1). Different granitic suites have been identified in Himalayan terrane i.e. early Cenozoic linked to Himalayan collision (e.g. Searle et al., 2009; King et al., 2011), rift related late Paleozoic (e.g. Noble et al., 2001; Ahmed et al., 2013) and early Paleozoic due to accretionary orogenesis (e.g. LeFort et al., 1986; Schelling, 1999; Cawood et al., 2007; Wang et al., 2013). The early Paleozoic granitic rocks intrude different GHS and LHS lithologies as confirmed by several geochronological investigations (e.g. Girard and Bussy, 1999; Miller et al., 2001; Gehrels et al., 2006a).

The study area in this paper is located in the Peshawar basin, which lies south of the MMT within the northern portion of the Indian plate (Fig. 1), today forming a portion of the Himalayan zone. The Precambrian and early Paleozoic stratigraphy of the study region is summarized in Figure 2. The Precambrian Tanawal formation is unconformably overlain by Cambrian Ambar formation (equivalent of Abbottabad formation in Hazara region). The stratigraphic contact is marked by an angular pebble conglomerate containing quartzite clasts from the Precambrian Tanawal formation

(Pogue et al., 1992b; 1999), which contains quartzites and meta-pelites and served as the country rocks for the emplacement of the Utla and Mansehra granites (Fig. 1). The Swat granite is hosted by Manglaur formation, which is considered as the lateral correlative of the Tanawal formation (DiPietro et al., 1993). The current investigation is largely based on the samples from the Utla granites, which we compared with our new as well as the already published data from the Mansehra granites (Le Fort et al., 1980; DiPietro and Isachsen, 2001).

Our study region is mainly affected by regional Barrovian metamorphism that resulted from the Tertiary collision of the Indian plate with KIA (Treloar, 1997). The systematic study of metasedimentary units indicates an increase in metamorphic grade from chlorite to sillimanite grade towards the collision boundary (Treloar et al., 1989a). Pre-Himalayan deformation along with tectonism in the early Paleozoic have been identified in the region as shown by the metamorphic overprint of Proterozoic strata (i.e. Hazara and Manglaur formations, Baig et al., 1988; Williams et al., 1988) and unmetamorphosed Paleozoic sequence (Pogue et al., 1992b). Analogous pre-Himalayan tectonism has also been recorded in other Himalayan regions from NW India and Nepal (Gehrels et al., 2006a, b).

3. Field features

A sharp intrusive contact of the Utla and Mansehra granites with Precambrian Tanawal formation has been observed (Fig. 3A). On the basis of the field features, the Utla granites can be divided into mega-porphyritic granites (MPG), aplite dykes having granitic compositions with fine to medium grained texture (AMG) and quartz rich veins (QRV) (Fig. 3B-D). The Mansehra granites exhibit similar field characteristics to Utla granites (MPG). The mineralogical composition and field characteristics of the Utla intrusive units are summarized in Table 1. QRV contain < 5% feldspars and range in thickness from a few up to several centimetres. Apart from the textural differences, the dark minerals content is less in the AMG than MPG units. Dykes of a basic composition also cross-cut the host granites. Most of the granites are fresh and compact, however, foliation can be found in some areas and this is particularly so adjacent to shear zones. In some places the surfaces of granitoids show intense weathering leading to a dark brown colour. Tourmaline rich veins cross cut both the MPG and AMG (Fig. 3E) and tourmaline nodules have also been observed in certain areas (Fig. 3F).

4. Laboratory Methods

4.1. Zircon Separation

We generated zircon concentrates by crushing, grinding and sieving of hand samples followed by magnetic and heavy liquid separation. The samples were initially crushed and ground using a jaw crusher and grinder. The resulting material was passed through 350 µm sieve to remove the coarser fragments. A Wilfley table was used to separate the heavy minerals from the less dense phases. The heavy mineral fractions were processed through a Frantz magnetic separator, which eliminated the magnetic fraction. The remaining fractions were passed through heavy liquid (Di-iodomethane, ρ = 3.32 g/cm^3) to obtain highly concentrated zircon separates. Around 100 zircon grains from each sample were embedded in a 1-inch diameter, round epoxy block, after which the individual grains were imaged in both back scattered electron (BSE) and Cathode Luminescence (CL) modes using a scanning electron microscope. These images revealed the internal growth zoning of the many grains, allowing a better targeted selection of spots for U-Pb isotope determination.

4.2. U-Pb isotopes analysis

U-Pb isotopes analyses were conducted by Secondary Ion Mass Spectrometry (SIMS) using the CAMECA 1280-HR instrument at GFZ Potsdam in Germany. The analyses employed a 10 nA, $^{16}O^{2-}$ shaped primary ion beam resulting in a beam diameter of 25 µm at the sample's surface. Positive secondary ions were extracted using a +10 kV potential as applied to the sample holder. Each analysis was preceded by a 10 nA, pre-sputtering lasting 120 seconds and employed a 25 µm raster. Oxygen flooding was used to enhance the lead sensitivity. The data were acquired using an ETP electron multiplier operating in mono-collection mode. A single analysis consisted of 16 cycles of the peak stepping sequence: $^{90}Zr_2\,^{16}O$ (1 second integration time per cycle), $^{92}Zr_2\,^{16}O$ (1s), 200.5 (4s), $^{94}Zr_2\,^{16}O$ (1s), ^{204}Pb (6s), ^{206}Pb (4s), ^{207}Pb (6s), ^{208}Pb (2s), $^{177}Hf\,^{16}O_2$ (1s), ^{232}Th (2s), ^{238}U (2s), $^{232}Th\,^{16}O$ (2s), $^{238}U\,^{16}O$ (2s) and $^{238}U\,^{16}O_2$ (2s). Thus, including pre-sputtering, a single analysis lasted approximately 16 minutes.

The software package Isoplot (Ludwig, 2012), was used to display the data using the decay constants recommended by the IUGS sub-commission on geochronology (Steiger and Jäger, 1977). Our common lead correction was based on the observed ^{204}Pb counts in conjunction with the modern common lead compositions from the model of Stacey and Kramers (1975).

The reference material (RM) zircon 91500 ($^{206}Pb/^{238}U$ age: 1062.4 ± 0.4 Ma; $^{207}Pb/^{206}Pb$ age: 1065.4 ± 0.3, Wiedenbeck et al., 1995) was used both as primary U-Pb calibration material and to establish the repeatability of the analytical method. The RM zircon Temora 2 ($^{206}Pb/^{238}U$ age: 416.78 ± 0.33 Ma, Black et al., 2004) was used as a quality control to evaluate data accuracy. The analysis of one or two RMs was regularly interspersed after every four unknown points during data collection. The analyses were carried out in two sessions (Appendix-1). In the first session, eleven determinations of RM 91500 yielded a Concordia age of 1063.6 ± 4.8 Ma (2s) and a $^{206}Pb/^{238}U$ age of 1063.2 ± 14.4 Ma (2s), respectively. The respective ages obtained during the second analytical session (n = 16) were 1063.4 ± 2.5 Ma (2s) and 1062.9 ± 8.4 Ma (2s). Figure 4a presents the collective concordia age distribution of RM 91500 for both sessions (1063.4 ± 2.3 Ma); the respective $^{206}Pb/^{238}U$ age is 1063.0 ± 10.8 Ma (2s). On the basis of the 91500 results the repeatability of our concordia and $^{206}Pb/^{238}U$ age determinations are estimated to be better than 0.5 % and 1.5%, respectively.

Ten analyses of zircon RM Temora 2 obtained during the two sessions yielded a mean concordia age of 414.3 ± 2.6 Ma at the 95% confidence level (Fig. 4b) and a mean $^{206}Pb/^{238}U$ age of 413.1 ± 8.5 Ma (2s). These ages are around 0.6% and 0.9% lower, respectively, than the assigned values reported by Black et al. (2004). This slight offset may reflect instrumental bias and/or sample heterogeneity. Overall, the repeatability of the U-Pb calibration on 91500 zircon as well as results of Temora 2 suggest that the data are reliable to better than ± 2%.

4.3. Mineral Chemistry

The chemical composition of minerals from representative rock samples were determined using a JEOL JXA-8200 Superprobe at Camborne School of Mines (CSM), University of Exeter, UK. An accelerating voltage of 20 kV, beam current 10 nA and beam diameter of 5 µm were used for analysis of all mineral phases. The instrument was calibrated (elements and X-ray lines shown in parentheses) using orthoclase (SiKα, KKα), almandine (FeKα, AlKα), albite (NaKα), wollastonite (CaKα), periclase (MgKα), rhodonite (MnKα), rutile (TiKα), tugtupite (ClKα) and fluorite (FKα) calibrants. Mineral formulas were calculated on the basis of stoichiometry and charge balance.

4.4. Whole rock geochemistry (Major and trace elements)

Whole rock major element compositions were determined using the Bruker S4 Pioneer wavelength dispersive X-ray fluorescence (XRF) spectrometer at CSM on fused disks. Reference materials (SARM-1 and DNC-1) were run at the start and at the end of each batch to monitor both drift and the stability of the instrument during data acquisition. For sample preparation, fresh rock samples were crushed and ground using an agate mill. The relative analytical uncertainty on the total concentration of each element is <1% for SiO_2, Al_2O_3, Na_2O and K_2O, <2% for CaO, Fe_2O_3 and TiO_2 and <10% for MgO, MnO and P_2O_5.

Trace elements, including rare earth elements (REEs) were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at CSM. Four acids including HF, HNO_3, $HClO_4$ and HCl were used to digest the rock powder in Teflon tubes for analysis following the procedure of Yu et al., (2001). Two blanks and two reference solutions (Sarm-1: granite and DNC-1; Dolerite) were prepared and analysed during each analytical run to assess the elemental contamination and precision. A reference solution, with a known concentration of elements, was also analysed after each six unknowns to observe instrumental drift. The precision is <5 % for all the element except for La, Ce and Zr which is <10%.

5. Results

5.1. Petrography and mineral chemistry

MPG constitutes the major portion of Utla granites, having both plagioclase and alkali feldspar (including both orthoclase and microcline) as phenocrysts. Plagioclase is mostly cloudy, displaying partial to complete alteration to sericite and clay minerals. It occurs as phenocrysts as well as forming part of the MPG groundmass. Some of the phenocrysts display distinct zoning (Fig. 5a). The albite content of zoned plagioclase grains systematically increases from core to margin (Core: An_{36}, Margin: An_{16}) (Appendix-2) elaborating the fractional crystallization of the melt. Alteration to clay minerals and sericite in the core domain (Fig. 5a) reflects higher Ca content as calcic plagioclase is more susceptible to alteration than sodic. Plagioclase in the ground mass is mostly uniform in composition ranging from An_{23} to An_{11} (Fig. 5b). In comparison, plagioclase from AMG is mostly unzoned and has a high albite content ($An_{0.22}$-An_6) (Fig. 5b). Alkali feldspar, including both orthoclase and microcline, occur as phenocryst as well as groundmass in the MPG. Perthite exsolution is observed in orthoclase grains, suggesting their crystallization under sub-solidus conditions. Feldspars from the AMG samples do not show exsolution, implying a faster cooling rate as compared to MPG.

Micas (both biotite and muscovite) and tourmaline are commonly occurring accessory minerals as well as lesser amount of rutile, garnet, apatite and andalusite. Rounded to sub-rounded nodules formed by accretion of dark coloured tourmaline is observed in AMG. In addition to quartz and minor amounts of feldspar, QRV also contain well developed coarse grained (up to 1cm long) dark tourmaline grains.

The chemical variations in the micas provide an excellent opportunity for distinguishing between the various phases of magmatism. The Fe+Mn+Ti–Al^{VI} vs Mg–Li plot (Tischendorf et al. 2001) groups the analyses into two clusters and thus effectively separates MPG and AMG biotites (Fig. 5c). Magnesian siderophyllite (Fe biotite) dominates in the MPG samples; in contrast the composition changes towards siderophyllite in the AMG. The concentration of F is relatively higher in the MPG than in the AMG biotites (Appendix-2). The analyses of muscovite from both the rock types fall mostly in the region of muscovite, however some of the MPG data points approach the ferroan muscovite field (Fig. 5c).

5.2. U-Pb Zircon Geochronology

Zircons separated from the Mansehra (M-5) and Utla granites (UT-69) and the cross cutting aplite dyke (UT-44) show a large range in morphology and size (Fig. 6). Most zircons occur as subhedral, short-prismatic to oval, < 20-120 µm long crystals. Cracks, holes, mineral inclusions are common, limiting considerably the number of possible SIMS analytical spots. Most of zircons have old and partly metamict cores surrounded by young rims which we believe to represent the crystallization age of the granitic hosts. Fig. 6 show the CL images of representative zircons with position of the analytic spots. Appendix-1 enlists the zircon U-Pb ages of all the samples obtained by SIMS.

5.2.1. Utla Granite (MPG, UT-69)

$^{206}Pb/^{238}U$ ages of MPG zircons range from 894 to 458 Ma (Appendix-1). At least two major crystallization events are recognizable. Proterozoic crystallization at ≈ 1100-800 Ma is documented by inherited cores (Fig. 6). In contrast, a young event at around 485 to 470 Ma is documented in the zircon rims, thus documenting the crystallization of the Utla granite. The average concordia age of all rim analyses younger than 500 Ma is 478.8 ± 2.3 Ma (2s; Fig. 4c). $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data younger than 480 Ma average at 473.2 ± 8.3 Ma (1s, n=7) and 474.2 ± 4.5 Ma (1s, n=8), respectively.

The crystallization of MPG zircons appear to have lasted a protracted time frame having ended at around 474 Ma.

5.2.2. Utla Granite (AMG, UT-44)

The age spectra of granite UT-69 and aplite dyke UT-44 overlap, thus suggesting a common genesis mechanism. Again, inherited cores are Proterozoic in age (with a single sample even being as old as 1700 Ma). Concordia ages of the rim domains < 500 Ma suggest a slightly younger crystallization age of dyke UT-44 as compared to cross cut granite UT-69, averaging at 476.6 ± 4.1 Ma (2s; Fig. 4d). A roughly 2 Ma younger age is also indicated by the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ data younger than 480 Ma, which average at 471.2 ± 2.3 Ma (1s, n=5) and 472.9 ± 5.8 Ma (1s, n=5), respectively. Note however that within 2s uncertainties, the ages of MPG and AMG rocks overlap and are indistinguishable.

5.2.2. Mansehra Granite (M-5)

Most inherited cores in M-5 zircons range between around 600 and 1315 Ma in age, with a single concordant sample being as old as 2000 Ma (Appendix-1). In marked contrast to the Utla rocks, rim domains of Mansehra zircons form reverse discordant correlation lines in both the conventional and the Tera-Wasserburg Concordia diagrams (Fig. 4e-f). Strongly reverse discordant $^{206}Pb/^{238}U$ zircon ages have also been documented for 2700 Ma old zircons from the Murchison Province of Western Australia (Wiedenbeck 1995) and for 180 Ma old zircons from the Tasmanian dolerites (South-East Australia; Williams and Hergt, 2000; White and Ireland, 2012). In both cases, the zircons are characterized by high uranium contents of up to 3400 µg/g (Wiedenbeck, 1995) and 12000 µg/g (White and Ireland, 2012) and display correlations between U concentration and apparent $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages. Wiedenbeck (1995) explains this effect by exclusively natural processes involving mobilization and redistribution of labile Pb, while White and Ireland

(2012) argue for instrumental (tuning) and analytical causes (matrix effect). Rims of M-5 zircons are significantly higher in uranium (1300 to 9600 µg/g) as compared to UT-69 and UT-44 zircons (< 1000 µg/g) and a rough correlation between U content and apparent Pb/U ages is observed (not shown). We therefore hesitate to use these Pb/U data to derive a crystallization age for the Mansehra granite. Instead, we suggest that the Discordia-Concordia intercepts at 479.5 ± 5.8 Ma (Fig. 4e and 4f) date the formation of the M-5 rock, which is statistically indistinguishable from those of the Utla granites.

5.3. Whole rock major and trace elements geochemistry

The concentration of major and trace elements in representative whole rock samples is presented in Table 2 (complete data set is available Appendix-3). Generally, samples from both the MPG and AMG are strongly per-aluminous as suggested by high A/CNK values (> 1.11; Fig. 7), which is also supported by the mineralogical characteristics described earlier. Likely, all the samples are predominantly sub-alkaline as described in total alkalis vs. silica plot (Fig. 7). Samples from Mansehra granite were also analysed during the current investigation (Appendix-3) and their data is presented (Fig. 7). They show similar petrographic and geochemical behaviour to that seen for the Utla granites (MPG) i.e. megacrystic, strongly peraluminous, sub-alkaline. The variation plots of major elements are presented in Fig. 8. A decreasing trend in Al_2O_3, MgO, Fe_2O_3 and CaO against SiO_2 points to fractionation of plagioclase and biotite. A negative correlation between P_2O_5 and CaO with SiO_2 indicates the fractionation of apatite. Inclusions of apatite in biotite further support this observation. TiO_2 shows a negative relationship with increasing SiO_2 content.

A curve trend has been observed in the plot of Rb/Sr (differentiation index) against Fe_2O_3, mainly due to an enrichment of Rb in AMG (Fig. 8). Both rock types show LREE enriched patterns with negative Eu anomalies (Fig. 9). However, the total REE content of MPG (ΣREE = 89.2 µg/g) is greater than AMG (ΣREE = 36.2 µg/g) (Appendix-3). The Eu anomaly is much stronger in the case of AMG (Eu/Eu*=0.23) than is seen in MPG (Eu/Eu*=0.42) (Fig. 9). The trace elements normalized to primitive mantle reveal a similar pattern for both MPG and AMG (Fig. 9), showing an enrichment of Rb, Th, U and Pb and a depletion of Ba, Sr, Ti, Zr and Nb.

6. Discussion

6.1. Fractional crystallization and Source rock characteristics

The evolution of the Utla granitoids via fractional crystallization is visible on Harker plots (Fig. 8) and is also suggested by the observed mineralogical compositions. The fractionated phases mainly include feldspars (plagioclase and orthoclase), biotite, apatite and zircon. A normal zoning (i.e. increasing Ab content from core to rim) observed in plagioclase from MPG and an enrichment in the albite content of plagioclase in AMG relative to MPG strongly indicates plagioclase fractionation. Furthermore, AMG samples plot towards the higher silica content relative to MPG, implying a more evolved character (Fig. 8). Despite such a strong evidence for fractionation process, the total REE content of AMG is less than MPG. This can be explained by the fractionation of REE bearing phases in MPG, including zircon and apatite, which are most likely hosts for REEs. The presence of these minerals as inclusions in biotite supports this interpretation.

The negative Eu anomaly in the chondrite normalized REE pattern also supports the fractionation of plagioclase as Eu^{2+} normally substitute for Ca in feldspar lattice (Rollinson, 1993). The observed negative Eu anomalies could also reflect the fractionation of other minerals including hornblende, titanite, garnet; however this would result in the opposite trend to that of feldspar. The observed higher LREE/HREE ratio is very typical of granitic systems and is commonly caused by the fractionation of zircon from the magma (Rollinson, 1993).

The negative Ba, Sr, Nb and Ti anomalies (Fig. 9) also points to a highly fractionated nature of the studied granites (Chappell, 1999). Fractionation of Ti bearing phases (e.g. rutile, ilmenite and sphene) normally results in a negative Ti anomaly. Negative Sr and Ba anomalies are indicative of plagioclase and orthoclase fractionation, respectively (e.g., Miller, 1985; Patiňo Douce et al., 1990; Wu et al., 2003; Healy et al., 2004; Li et al., 2015). The identical geochemical behaviour of Utla and

Mansehra granitoids (Fig. 7 and 9) show their origin related to a single coeval magmatism (Sajid et al., 2014).

Various experiments have been performed for the estimation of source rock features of peraluminous granites (e.g. Patino Douce and Johnston, 1991; Chappell and White, 1992; Skjerlie and Johnston, 1996; Sylvester, 1998). The source characteristics of studied granites have been interpreted using the plots of experimental data (based on Rb/Sr, Rb/Ba, CaO/Na_2O, FeO, MgO, Al_2O_3, TiO_2) gathered in these investigations. The Al_2O_3/TiO_2 and CaO/Na_2O ratios from the Utla (MPG and AMG) and Mansehra granites point to a pelitic source (clay-rich, plagioclase-poor) for their parental melt (Fig. 10). The molar $Al_2O_3/(MgO + FeO_T)$ vs. $CaO/(MgO + FeO_T)$ of Altherr et al. (2000) diagram also suggests a similar source rock composition for these granitoids (Fig. 10).

6.2. Comparison with other granitic suites

Granites with analogous geochemical signatures in similar tectonic regimes exist in other Himalayan regions (e.g. LeFort et al., 1986). In NW India several peraluminous granitic plutons with similar mineralogical and geochemical characteristics were reported (e.g. Jispa granites; Islam and Gururajan, 1997), Tso Morari granite (Girard and Bussy, 1999), Rakcham granite (Kwatra et al., 1999) and Mandi granites (Miller et al., 2001). Similar granitic suites from Nepal include Simchar granite (LeFort et al., 1983), Palung granite (Gehrels et al., 2006a) and Kathmandu (Gehrels et al., 2006b). Paleogeographic reconstructions indicate a juxtapositioning of the southern China blocks (e.g. Baoshan block) to the northern Indian plate in early Paleozoic time (Metcalfe, 1996, Fig. 11). The granitic plutons in SW China also show similar geochemical characteristics (Wang et al., 2010, 2013; Dong et al., 2013) to the Utla and Mansehra granites as well as to other Himalayan granites described above (Fig. 7). The origin of these granites has been related to a melting of a metasedimentary source rock (Fig. 10) followed by the fractional crystallization of feldspar and biotite (Dong et al., 2013; Wang et al., 2013). The whole rock geochemical data from the Tso-Morari and Mandi pluton from NW India (Girard and Bussy, 1999; Miller et al., 2001, respectively) and from the Baoshan and Shan-Thai block (Fig. 11) from SW China (Dong et al., 2013; Wang et al., 2013) are presented for comparison (Fig. 7 and 10). Apart from geochemical similarities, these granites yield early Paleozoic emplacement ages ranging from ~460 to ~530Ma (Fig. 11) as documented by extensive geochronological Rb-Sr (e.g. LeFort et al., 1980; Debon et al., 1981; Trivedi, 1990; Einfalt et al., 1993) and U-Pb (e.g. Gehrels et al., 2006a; Dong et al., 2013; Wang et al., 2013) studies. The geochemical and geochronological similarities of Utla and Mansehra granites, as well as other granites from the Himalayan terrane along the northern margin of Gondwana suggest an extensive orogenic thermal activity during early Paleozoic (Girard and Bussy, 1999; Miller et al., 2001; Cawood et al., 2007).

6.3. Tectono-magmatic Implications

The Himalayan region of NW Pakistan was part of the northern Gondwana supercontinent during late Precambrian and Paleozoic times, constituting the Indian passive continental margin prior to collision with Eurasian continent in early Cenozoic (Brookfield, 1993; Cawood et al., 2007; Wang et al., 2013). The large volume of Cambro-Ordovician (~530-470Ma, Fig. 11) granitoids intruding in LHS and GHS (DeCelles et al., 1998, 2000, 2004; Godin et al., 2001; Gehrels et al., 2003; Booth et al., 2004; Lee and Whitehouse, 2007; Quigley et al., 2008) indicate an early Paleozoic orogenic event in the Himalayan terrane.

6.3.1. Evidence of early Paleozoic orogenesis

The existence of this orogeny is supported by a break in the stratigraphic record (Garzanti et al., 1986; Le Fort et al., 1994; Valdiya, 1995; Liu et al., 2002; Zhou et al., 2004; Qasim et al., 2017), by detrital zircon age distributions from sedimentary strata (Hodges, 2000; Kusky et al., 2003; Zhang et al., 2008a, b; Dong et al., 2009; Myrow et al., 2010; Spencer et al., 2012) and coeval metamorphism (e.g. Argles et al., 1999; Catlos et al., 2000, 2002; Godin et al., 2001; Gehrels et al., 2003, 2006a, 2006b; Kohn et al., 2004) across wide regions of the Himalayas.

The unconformable contact marked by conglomeratic beds between the Cambro-Ordovician strata with older rocks in Himalayan terrane provide strong evidence for a major period of erosion and uplift associated with an orogenic event during the early Paleozoic (e.g. Garzanti et al., 1986; Brookfield, 1993; Qasim et al., 2017). An important observation is that lower Ordovician basal conglomerates unconformably overly the Cambrian strata in Kathmandu, Nepal (Kumar et al., 1978; Funakawa, 2001; Gehrels et al., 2003). Similarly, in the Spiti and Zanskar regions of NW India, the Cambrian lithologies are unconformably overlain by coarse Ordovician conglomerates (Hughes, 2002; Myrow et al., 2006a, b). The U-Pb chronology and Hf isotopes of detrital zircons from sedimentary strata led Spencer et al. (2011, 2012) to propose that sediment input in GHS was prompted by orogenic activity in the early Paleozoic. A similar interpretation was also made through the comparison of U-Pb age of detrital zircons representing a particular time span from the broad geographic range covering around 2000 km along the length of Himalayan orogen from Pakistan to Bhutan (Myrow et al., 2010). Evidence for early Paleozoic deformation and metamorphism include regional folding and metamorphism (up to garnet grade) of Neoproterozoic Bhimphedi group rocks prior to the deposition of overlying Ordovician strata (Gehrels et al., 2006a). All these observation points to an early Paleozoic orogenic phase in the northern Gondwana that extended at least from NW India to the Namche Barwa region in southern China (Wang et al., 2013).

The early Paleozoic stratigraphy of eastern Peshawar basin in NW Pakistan is summarized in Fig. 2. The Precambrian Tanawal formation is unconformably overlain by Cambrian Ambar formation. The contact is marked by angular pebble conglomerate containing quartzite clasts from the Tanawal formation (Pogue et al., 1992b; 1999). In certain regions (i.e. northern Swabi close to Utla area) the Ambar formation is completely eroded and Tanawal formation is directly overlain by the Ordovician Misri Banda quartzites (Pogue et al., 1999). The Abbottabad formation is the lateral equivalent of Ambar formation in Hazara region east towards the Indus river (Fig. 1). The unconformable contact between Abbottabad and Tanawal formation is noticed, however, in certain regions, Tanawal formation is eroded and Abbottabad formation directly overlain the Precambrian Hazara formation through an angular unconformity marked by conglomeratic bed containing angular clasts (Calkins et al., 1975; Baig et al., 1988; Pogue et al., 1999; Palin et al., 2018). The growth of new metamorphic mica along with the presence of a pronounced cleavage has been noticed in the Hazara formation, which has been metamorphosed up to the greenschist facies (Baig et al., 1988). Metamorphism of Tanawal formation has also been reported in the recently investigated U-Pb monazite geochronology (482.4 ± 7.9 Ma and 464.5 ± 4.0 Ma, Palin et al., 2018). No evidence of deformation and metamorphism is observed in either the conglomeratic bed marking the unconformity nor in the overlying Abbottabad formation. These indications imply a tectonothermal event during the early Paleozoic times, which deformed and metamorphosed the Precambrian strata. The intrusion of peraluminous Utla and Mansehra granites (478.8 ± 2.3 Ma and 479.5 ± 5.8 Ma respectively) in this region is consistent with the existence of such an event.

6.3.2. Tectonic model

Our U-Pb zircon dating documents the crystallization of the peraluminous Utla and Mansehra granites between 470 and 480Ma (Fig. 4 and 6). Similar aged rocks are also present in other Himalayan regions, including both NW India (e.g. Miller et al., 2001) and Nepal (e.g. Gehrels et al., 2006a). Based on the tectonic position, age, geochemistry of studied granites and the earlier mentioned evidences of orogenesis, we propose a hypothetical tectonic model. It elaborates the origination of granites from the melting of metasedimentary rocks due to the large scale thermal activity triggered by the collision of the northern margin of Gondwana with southward subducted oceanic lithosphere of the proto-Tethys (Fig. 12). The outlines of the events proposed are described as under:

1. The integration of current geochemical and geochronological data with the existing data set indicates a convergent margin setting of northern Indian plate in the early Paleozoic (Cawood et al., 2007). At that time the Prototethyan oceanic crust was subducted beneath northern Gondwana, which produced the extended back-arc basin due to roll-back of the

subducted plate (Wang et al., 2013), leading to sediment accumulation in a back-arc basin setting (Palin et al., 2018). Pogue et al. (1992b) and Qasim et al. (2017) presented the regional scale Proterozoic and early Paleozoic stratigraphy of Hazara and Swabi region, north Pakistan. The constituent lithologies mainly include argillites, quartzites and carbonates which shows the existence of back-arc basin and subsequent sediment build-up (Palin et al., 2018).

2. The existence of magmatism along the traverse of Himalayan orogen (around 700km, Cawood et al., 2007) requires large scale crustal anataxis, which could not have been induced by a simple magmatic arc. This suggests the crustal melting in the extensive back-arc region induced by the high heat flow. The evidence of coeval mafic magmatism has been highlighted by earlier workers (e.g. Miller et al., 2001). The Mandi mafic rocks in GHS of NW India yielded 496 ± 14 Ma (Sm-Nd isotopes) age and exhibit convergent margin geochemical signature (Miller et al., 2001). The cumulated gabbros (473 ± 3.8 Ma) from Baoshan block (Wang et al., 2012) and associated synchronous I-type granites are believed to be the product of the subduction of the Prototethyan Ocean (e.g. Zhang et al., 2008; Liu et al., 2009; Zhu et al., 2012). The similar aged basic magmatism in the region suggests a heat input from a mafic magma underplating the lower crust; such a heat source might have been responsible for the large scale anatexis.
3. The orogenesis was related to the ongoing plate subduction followed by the accretion of an isolated block onto the continental margin (Fig. 12). Different terranes or geological blocks including Lhasa, Qiantang and Helmand along the Indian plate margin are recognized as part of the reconstruction of northern Gondwana (Fig. 11) in the early Paleozoic (Sengor et al., 1988; Metcalfe, 1996). Detrital zircon ages of early Paleozoic strata from the western Qiangtang also indicate its juxtaposition to the Himalayan terrane in the early Paleozoic (Zhu et al., 2013). The vicinity of these block to the Indian plate is also supported by paleoclimatic and palaeontological records presented in Metcalfe (1996).

4. The peraluminous signature of most of granitic plutons in the northern Indian plate (e.g. Girard and Bussy, 1999; Miller et al., 2001; Wang et al., 2013; current study) support the accretion of one or more outboard blocks with the continental margin (Fig. 12), which led to significant crustal and sediment thickening in the back-arc basin, which along with the mafic underplating, would have been responsible for crustal melting and generation of granitic melts. The prime factor for generating the peraluminous S-type granite is the melting of meta-sedimentary source, most likely due to deep burial caused by continent-continent collision (Harris et al., 1986; Tingyu et al., 1995). The collision of an outboard block with the continental margin provided a similar environment that led to the formation of peraluminous melts (Fig. 12).
5. The partial melting and roll back of subducted oceanic lithosphere and the subsequent slab break-off also induced mantle convection, which result in the formation of coeval calc-alkaline volcanic rocks (Miller et al., 2001; Visona et al., 2010). The involvement of mantle in the orogenic process is also shown by the presence of cumulate gabbros in the Qiangtang (467 Ma) and Baoshan (473 ± 3.8 Ma) blocks (Zhai et al., 2009; Wang et al., 2012 respectively). Cambrian volcanic rocks include volcanic tuffs, basalts, andesites and felsic volcanic rocks in the western Tethyan Himalaya (e.g., Brookfield, 1993; Garzanti et al., 1986; Valdiya, 1995). The occurrence of an extensive subduction zone magmatism along the Indian margin of Gondwana is shown due to the presence of basalts and basaltic andesites from different regions of GHS including Mandi pluton, western Himalayas (Miller et al., 2001) and Kharta region, central-eastern Himalayas (Visona et al., 2010). Late Cambrian (~492Ma) bimodal volcanic rocks have been identified in the central Lhasa block which relate to an active continental margin (Ji et al., 2009; Zhu et al., 2012). Subduction related late Cambrian (499.2 ± 2.1 Ma) mafic lavas have also been reported in Gongyanghe Group in Baoshan block (Yang et al. 2012) overlain by lower Ordovician basal conglomerate (Wang, 2000).

The existing U-Pb geochronology data set reveal the emplacement of the majority of granitic plutons during 470-490Ma span (e.g. Debon et al., 1981; Trivedi et al., 1986; Girard and Bussy, 1999; Gehrels et al., 2006a) which marks the active span for crustal melting and granite emplacement. However, relatively few ages have been reported between 500-530Ma (e.g. Lee et al., 2004, 2006), which most probably was the time of onset of tectonic activity (Cawood et al., 2007). According to petrological data of the studied granites in combination with the model presented here, an Andean type orogeny along the northern margin of the Gondwana supercontinent took place during the early Paleozoic.

6.3.3. Other Tectonic models

On the basis of available Rb-Sr and K-Ar ages of rock suites in Africa, Kennedy (1964) for the first time introduced the concept of the Pan-African orogeny. This includes thermo-tectonic events occurring around 500Ma, during which several mobile belts formed around the periphery of the older cratons. This concept was extended to all the regions of Gondwana, which also include the Indian plate. The western end of Indian plate was attached to present day Somalia and Kenya with Madagascar in between (Smith et al., 1981; Dalziel, 1992; Unrug, 1996). The existence of analogous geological features confirms the pan-African events in Madagascar and Southern India, which includes the occurrence of major shear zone having >100km sinistral displacement and analogous podiform chromite deposits in ultramafic lenses (Kroner and Stern, 2004).

However, the similar aged magmatism of the northern Indian plate and its relationship with pan-African orogenesis is unclear. Girard and Bussy (1999) relate the A-type magmatism in Kaghan granite (Pakistan) and Rupshu granite (Ladakh, India) with the youngest A-type activity from the Arabian-Nubian shield in the Pan-African belt. This comparison seems uncertain due the subtle age differences (Trivedi et al., 1986; Windley et al., 1996) in both events. Kwatra et al. (1999) described the geochemical and geochronological features of early Paleozoic Rakcham granitoids from Sutlej valley in NW India. Based on similar tectonic settings and similar trace element discrimination diagrams, they include the Cambro-Ordovician granitic suites (including Mansehra granite) of the northern Indian plate with the Pan-African magmatic belt.

In contrast, Stern (1994) clearly shows that the early Paleozoic granites in NW Himalayas post-date the collision and major thermal events of the Pan-African belt. Only the southern part of the Indian plate is affected by these events, as revealed by their paleogeographic reconstruction (Stern, 1994). Furthermore, in most of the Pan-African suites (e.g. Mali, southern Brazil) a general magmatic evolutionary trend is observed with subduction related rocks (Bonin et al., 1998). The alkaline magmatism during similar time span also forms a common observation in these belts. Although having a roughly similar crystallization age to the Utla-Mansehra granites (and other Cambro-Ordovician GHS and LHS granites), the convincing evidence for their association with Pan-African event is lacking due to the absence of any evolutionary imprints from mafic magma and lack of synchronous alkaline magmatism.

The early Paleozoic magmatism was related to a non-arc extensional setting (Miller et al., 2001). The granites studied here fall in the field of syn-collisional to volcanic arc settings based on Nb vs Y and Rb vs Y+Nb discrimination diagrams (Fig. 13). Moreover, these granites are depleted in Ba, Nb and Sr but enriched in Rb, Th and U (Fig. 9), indicative of continental volcanic arc settings (Brown et al., 1984). This geochemical evidence contradicts an extensional non-arc setting in favour of a magmatic arc environment, which was most probably associated with subduction and collision along the northern margin of Gondwana. This interpretation is supported by the widespread existence of volcanic rocks, including acid and basic tuffs and andesites in the western Tethyan Himalayas (Garzanti et al., 1986; Valdiya, 1995) and Lhasa terrane (Zhu et al., 2012).

6.3.4. Implications for Late Proterozoic magmatism in northern Indian plate

The concordant core ages from the studied zircons (both Utla and Mansehra Granites) mostly ranges between 813 Ma to 893 Ma. Similar U-Pb zircon ages have been reported from Black

Mountain Complex (DiPietro and Isachsen, 2004) and Chingalai Gneisses (Ahmed et al., 2013). The Black Mountain Complex is present along the eastern bank of Indus River mainly composed of equigranular fine-grained biotite-quartz-feldspar orthogneisses and intruded by Mansehra Granite (DiPietro and Isachsen, 2004). Other subordinate lithologies include biotite and garnet bearing gneisses, migmatites and mafic rocks. Zircon from the main lithology yielded an age of 823 ± 2 Ma (DiPietro and Isachsen, 2004). The Chingalai Gneisses are present on the western side of Indus River and mapped as south-eastern extension of Swat Granite by DiPietro et al. (1998). The U-Pb zircon age of 816 ± 70 Ma has been reported from these gneisses (Ahmed et al., 2013). Similar range of these ages and ages obtained from zircon cores in current investigation points towards the occurrence of small scale magmatism in late Proterozoic time in the northern Indian plate. DiPietro and Isachsen (2004) and Ahmed et al. (2013) relate these rocks with Malani magmatism, which show the age range between 750 and 850 Ma on the Aravalli craton exposed on the Rajasthan platform of northern India.

7. Conclusions

- The Utla granites intrude Precambrian metasedimentary rocks of the northern Indian plate, NW Pakistan. The granites are megacrystic and contain biotite, muscovite, tourmaline, garnet, epidote and apatite as accessory phases. Fine to medium grained aplite dykes and coarse-grained quartz rich veins cross cut the megacrystic granites.
- The granitoids are S-type and strongly peraluminous (A/CNK values > 1.11). Fractional crystallization is indicated as the dominant evolutionary process due to the change in composition of plagioclase from megacrystic granite to aplite dykes, zoned plagioclase megacrysts and higher silica content in the aplite dykes. Major and trace elements geochemistry imply the origin of these granites is related to the melting of a pelitic source.
- The early Paleozoic 478.8 ± 2.3 Ma emplacement age of megacrystic Utla granites is shown by U-Pb zircon geochronology followed by the intrusion of aplite dykes in 476 ± 4.1 Ma. The mineralogically and geochemically similar Mansehra granites show a statistically synchronous emplacement time i.e.

479.5 ± 5.8 Ma.

- The composition and geochronology of the studied plutons suggest their association with other early Paleozoic granitoids from northern Gondwana. The origin of these granitoids in an arc setting related to subduction of the Proto-Tethys Ocean beneath the northern Gondwana supercontinent in early Paleozoic has been modelled, which is supported by the several metamorphic and stratigraphic arguments as well as by the observed trace element characteristics.
- The concordant core ages (813 Ma to 893 Ma) of zircons from both the Utla and Mansehra granites agree with published data and point towards a late Proterozoic magmatic event along northern Indian plate.

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Figure Captions

Fig. 1. A) Geologic map of the Himalayan terrane (redrawn after Kohn 2014), star showing location of Fig. 1B, B) Regional tectonic map of NW Pakistan elaborating the major granitic suites, inset showing the geological map of the study area

Fig. 2. Precambrian and Paleozoic stratigraphy of Peshawar basin after Pogue et al., (1992b; 1999). H = Major Hiatus

Fig. 3. Field photographs: A) Sharp contact between Utla granite and Tanawal formation, B) Feldspar megacrysts in Utla granites, C) fine grained aplite in MPG D) cross cutting QRV, E) tourmaline vein in Utla granite, F) nodular tourmaline in Utla granites, inset showing close-up of polished tourmaline nodule

Fig. 4. U-Pb Concordia plots of reference materials and zircons from studied granites. The data acquired from zircon rim domains of studied zircons is shown

Fig. 5. A) Micrograph showing zoned plagioclase phenocryst, B) Composition of plagioclase, symbols: Ab: albite, Olig: Oligoclase, And: Andesine, Lab: Labradorite, Byto = bytownite, An: Anorthite, C) classification of biotite and muscovite after Tischendorf et al. (2001)

Fig. 6. Cathode Luminescence (CL) images showing the internal structure of representative zircon grains and their respective ages in Ma. Circles show the position of analytical spots

Fig. 7. Classification of Utla granitoids, MPG and AMG show peraluminous and sub-alkaline signature (A) Al_2O_3/ ($CaO+Na_2O+K_2O$) versus $Al_2O_3/(Na_2O+K_2O)$ (Maniar and Piccoli, 1989) B) Alkalis vs SiO_2 plot after Miyashiro (1973). The corresponding data of Mansehra granites (this study), Baoshan Block, SW China (Dong et al., 2013), Shan-Thai block, SW China (Wang et al., 2013), Tso Morari granites (Girard and Bussy, 1999) and Mandi Granite (Miller et al., 2001) is also shown for comparison

Fig. 8. Major element harker diagrams of MPG and AMG. Symbols are same as in Fig. 7

Fig. 9. A) Chondrite normalized REE pattern show stronger Eu anomaly in AMG, normalized data from McDonough and Sun (1995), B) Primitive mantle-normalized multi-element diagram, normalized data

from McDonough et al. (1992). The trend of Mansehra granite samples (blue line) analysed in this study showing the average values (n = 9) is also presented along the MPG samples

Fig. 10. Interpretation of source rock composition A) Al_2O_3/TiO_2 versus CaO/Na_2O, field of strongly peraluminous rocks from Sylvester (1998) (B) Rb/Ba versus Rb/Sr diagram, calculated source composition after Sylvester, 1998, C) molar $Al_2O_3/(MgO + FeO_T)$ vs. $CaO/(MgO + FeO_T)$, source fields after Altherr et al. (2000). Data source of other mentioned plutons are same as in Fig. 7.

Fig. 11. Early Paleozoic reconstruction map of the India–Australia prototethyan margin showing paleogeographical locations of the microcontinents (revised after Cawood et al., 2007 and Wang et al., 2013). The ages and location of coeval granitic pluton along the northern Gondwana margin are also shown.

Fig. 12. Sketch showing the tectonic model of early Paleozoic orogenesis (not to scale), A) subduction of Prototethyan oceanic lithosphere beneath northern margin of Indian plate. Initiation of extended back-arc basin due to mantle convection and slab bending for sediment accumulation. Mafic and calc-alkaline subduction related magmatism also initiate with slab bending, (B) Collision of external geological block with continental margin. Crustal thickening along with mafic underplating cause partial melting of lower crust to generate peraluminous melt

Fig. 13. Studied granites show volcanic arc to syn-collisional tectonic settings on trace elements discrimination plots (after Pearce et al., 1984). VAG=volcanic arc granites, WPG= within plate granites, ORG=ocean ridge granites, Syn-COLG= syn-collisional granites

Table 1. Field and mineralogical features of Utla granites

Magmatic Unit	**Field characteristics**	**Major Minerals**	**Minor assemblage (dominant minerals in bold letters)**
Mega-porphyritic granite (MPG)	K-feldspar and plagioclase phenocrysts, medium to coarse grained groundmass, tourmaline and biotite recognisable in field, foliated along shear zones	Plagioclase, K- feldspar (orthoclase and microcline), quartz	**Tourmaline, biotite, muscovite**, andalusite, apatite, rutile, ilmenite, zircon, beryl
Fine to medium grained aplite dykes (AMG)	Texturally homogenous, nodular tourmaline in places	Plagioclase, orthoclase, quartz	**Tourmaline, biotite, muscovite, epidote, garnet,** rutile, zircon
Quartz rich veins (QRV)	Coarse grained, extremely fresh and white in colour	Quartz, feldspars (<5%)	**Tourmaline**

Table 2. Whole rock major (wt.% age) and trace (µg/g) element concentration of representative samples from studied granites

Sample	UT-65	UT-66	UT-69	UT-40	UT-48	UT-27	UT-29	UT-30	UT-36	UT-44	M-5	M-11	M-17	M-22	M-27
Type	MPG	MPG	MPG	MPG	MPG	AMG	AMG	AMG	AMG	AMG	MG	MG	MG	MG	MG
SiO_2	71.38	68.87	71.89	75.12	71.26	76.77	77.01	74.32	76.02	76.30	70.05	72.57	69.37	69.81	71.66
TiO_2	0.61	0.49	0.35	0.24	0.69	0.14	0.14	0.12	0.10	0.11	0.56	0.21	0.66	0.53	0.46
Al_2O_3	13.97	14.04	14.73	13.03	14.29	12.49	12.82	13.87	12.96	13.34	14.86	14.47	15.00	15.15	14.17
Fe_2O_3	4.07	3.15	2.55	2.10	2.50	1.40	0.56	1.40	1.52	0.92	3.85	1.70	4.77	3.54	3.24
MnO	0.06	0.05	0.05	0.02	0.05	0.02	0.01	0.04	0.03	0.01	1.06	0.39	1.31	0.95	0.85
MgO	1.11	0.75	0.63	0.58	0.92	0.27	0.14	0.22	0.15	0.41	0.06	0.03	0.07	0.06	0.05
CaO	1.78	0.62	0.86	0.76	1.61	0.19	0.14	0.58	0.34	0.24	1.51	0.72	1.57	1.35	1.19
Na_2O	2.39	2.36	2.31	3.99	3.53	2.15	2.53	2.66	2.65	3.75	2.58	3.04	2.43	2.47	2.36
K_2O	3.55	5.30	5.15	3.22	2.87	5.33	5.97	5.58	5.42	4.11	4.15	5.28	4.12	5.02	4.31
P_2O_5	0.14	0.16	0.20	0.13	0.13	0.10	0.08	0.10	0.15	0.11	0.21	0.27	0.24	0.18	0.18
LOI	0.81	1.48	1.21	0.79	2.15	1.03	0.78	0.98	0.79	0.82	0.82	0.60	0.47	0.78	1.37
Total	99.90	97.36	99.96	100.04	100.02	99.88	100.18	99.88	100.14	100.11	99.74	99.31	100.04	99.91	99.88
Trace and REEs															
V	56.53	36.81	25.54	13.10	47.38	5.11	1.79	4.57	1.63	2.33	35.57	8.73	67.27	28.85	23.75
Cr	26.46	15.95	13.48	8.09	23.14	3.18	2.03	2.68	1.67	1.43	17.94	4.04	29.70	16.34	14.13
Rb	145.36	187.92	220.53	105.83	150.06	201.75	213.72	346.67	312.64	100.59	142.12	213.08	204.95	150.56	167.11
Sr	63.99	46.82	27.64	78.12	46.40	14.42	20.63	15.38	7.55	13.92	36.35	16.26	61.73	41.01	30.70
Y	19.85	12.89	14.53	18.60	47.53	10.25	6.99	20.74	21.71	9.40	16.10	8.61	19.89	11.79	17.70
Zr	2.98	2.56	13.91	6.21	2.44	11.18	11.07	21.57	16.33	22.93	8.14	11.74	7.95	5.47	13.68
Nb	16.02	13.53	15.39	8.70	12.49	8.46	10.33	8.55	8.54	5.81	14.52	12.97	22.89	12.52	12.47
Sn	6.74	10.71	13.59	4.41	5.47	19.84	17.63	10.20	10.16	10.54	5.41	8.96	7.06	5.35	9.71
Ba	372.39	701.82	209.83	389.49	178.11	134.46	74.78	100.85	14.91	100.49	271.88	157.35	433.17	443.72	235.13
La	35.21	17.07	17.92	16.86	72.65	6.28	3.85	11.25	6.37	5.13	23.95	15.59	58.34	23.22	20.41
Ce	65.24	30.88	25.27	26.15	126.70	12.27	6.35	22.46	11.79	7.51	46.85	34.76	127.61	46.91	46.50
Pr	8.94	4.55	4.69	4.47	17.68	1.83	1.06	3.12	1.95	1.33	6.99	4.35	15.34	6.56	5.69
Nd	33.84	17.26	17.86	16.57	65.44	6.90	3.86	11.45	7.15	4.85	27.52	16.52	58.99	25.81	22.23
Sm	7.07	3.84	4.13	3.98	13.65	1.85	1.06	3.00	2.29	1.35	5.89	4.03	12.04	5.29	4.95
Eu	1.04	0.83	0.66	0.49	1.59	0.13	0.09	0.29	0.06	0.13	0.73	0.35	1.03	0.75	0.55
Gd	5.97	3.52	3.64	3.65	11.93	1.73	1.02	2.88	2.45	1.30	4.84	3.25	9.09	4.19	4.16
Dy	4.29	2.95	3.14	3.84	10.09	2.03	1.36	3.92	3.84	1.61	3.68	2.22	5.32	2.94	3.55
Ho	0.75	0.56	0.56	0.74	1.80	0.40	0.26	0.80	0.78	0.32	0.64	0.34	0.79	0.49	0.67
Er	1.99	1.48	1.56	2.16	4.87	1.20	0.78	2.38	2.49	0.98	1.72	0.84	1.74	1.20	1.88
Tm	0.28	0.24	0.22	0.31	0.66	0.18	0.12	0.38	0.40	0.15	0.23	0.12	0.20	0.15	0.27
Yb	1.74	1.37	1.38	1.86	4.18	1.22	20.81	2.57	2.74	0.98	1.33	0.69	1.04	0.89	1.75
Lu	0.26	0.26	0.18	0.28	0.65	0.16	0.13	0.38	0.39	0.13	0.16	0.08	0.13	0.11	0.25
Hf	0.10	0.15	0.49	0.30	0.19	0.42	0.46	0.79	0.58	0.81	0.24	0.36	0.25	0.16	0.51
Ta	1.58	1.62	2.15	0.99	1.18	1.37	1.74	1.41	1.23	0.62	1.74	2.20	1.78	1.51	1.89
W	3.72	4.24	4.90	2.10	5.42	2.64	2.05	1.86	1.90	1.50	2.28	3.12	3.10	0.90	2.23
Pb	17.03	11.73	10.66	3.59	11.40	4.01	8.56	17.79	10.93	3.93	11.89	8.08	24.81	17.55	17.15
Th	15.51	8.77	8.88	8.81	16.92	6.22	4.62	10.90	8.01	3.08	16.25	12.37	30.70	14.55	14.15
U	4.52	0.86	1.71	1.09	1.88	2.07	2.64	1.78	2.97	0.56	1.46	1.32	2.94	0.93	1.94
ΣREE	166.62	84.81	81.19	81.35	331.89	36.19	20.77	64.88	42.69	25.78	124.52	83.14	291.67	118.53	112.85
A/CNK	1.27	1.31	1.34	1.14	1.21	1.29	1.18	1.21	1.19	1.21	1.29	1.20	1.32	1.27	1.32
Eu/Eu*	0.49	0.69	0.52	0.39	0.38	0.22	0.27	0.31	0.08	0.30	0.42	0.30	0.30	0.49	0.37

MPG and AMG = Utla granites, MG = Mansehra granites,

LOI = loss on ignition,

A/CNK = molar ratio Al_2O_3/ ($CaO+Na_2O+K_2O$),

$Eu/Eu^* = Eu_N/ (Sm_N*Gd_N)^{0.5}$