Rifting, subduction and collisional records from pluton petrogenesis and geochronology in the Hindu Kush, NW Pakistan

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Abstract:

New U-(Th)/Pb geochronology and geochemical analyses of plutonic bodies in the Hindu Kush range, NW Pakistan, provide insight on the crustal growth and tectonic evolution of the southern Eurasian margin. These new data outline a protracted magmatic history that spans the Cambrian to the Neogene (ca. 538 to 23 Ma) and record a variety of petrogenetic associations variably influenced by within plate, volcanic arc, and collision tectonic environments. The Kafiristan pluton (538 ± 4 to 487 ± 3 Ma) yields geochemical signatures consistent with extensional plutonism and rifting of the Hindu Kush terrane from Gondwana. The Tirich Mir (127 ± 1 to 123 ± 1 Ma) and Buni-Zom (110 ± 1 to 104 ± 1 Ma) plutons have geochemical signatures that can be attributed to a subduction related continental volcanic arc system that developed along the southern margin of Eurasia in the Mesozoic. The Garam Chasma pluton, the youngest body in the study area (27.3 ± 0.5 to 22.8 ± 0.4 Ma), yields a geochemical signature consistent with widespread anatexis during crustal thickening related to the development of the Himalaya. The present geochemical and geochronological analysis from the Hindu Kush have produced important new constraints on the timing of tectonic events and variable tectonic settings along the south Eurasian margin before and after the continued India-Asia collision.

Key words: Hindu Kush, Eurasia, pluton petrogenesis, geochemistry, U-(Th)/Pb geochronology, tectonomagmatic evolution, Himalayan orogenic history.

1. INTRODUCTION

The NE-SW trending Hindu Kush range stretches for more than 600 km from northwestern Pakistan into adjacent Afghanistan (Figs. 1 and 2). The geology of the range

records a complex history of magmatism, deformation, and metamorphism spanning the early Paleozoic to the present day (Debon et al., 1987; Hildebrand, 1998; Zanchi and Gaetani, 2011; Faisal et al., 2014). Because the Hindu Kush records evidence of the evolution of Eurasia prior to continental collision (Zanchi et al., 2000; Hildebrand et al., 2001; Zanchi and Gaetani, 2011; Faisal et al., 2014), which is not well preserved in other parts of the orogen, the geologic history of the Hindu Kush is important for our understanding of the tectonic, magmatic and metamorphic evolution of the southern Eurasian margin.

The Hindu Kush terrane, which comprises most of the study area, was detached from Gondwana in the Paleozoic (Zanchi and Gaetani, 2011; Angiolini et al., 2013) and accreted to the southern margin of Eurasia in the Late Triassic (Faisal et al., 2014). Its accretion was followed closely by the collision and accretion of the Karakoram terrane in the Early Jurassic (Zanchi et al., 2000; Faisal et al., 2014). Continued northward subduction of the Paleotethys from the Middle Jurassic to the Early Cretaceous along the southern margin of Eurasia resulted in the intrusion of plutonic bodies in the Tirich Mir-Wakhan and Karakoram belts in an Andean-style margin (Searle et al., 1989, Hildebrand et al., 2001; Searle et al., 2010). The Kohistan island arc is interpreted to have developed within the Paleotethys sometime in the Mesozoic above a northward-dipping subduction zone (Tahirkheli et al., 1979) and was accreted to Eurasia in the Late Cretaceous (Pettersen et al., 1991; Fraser et al., 2001; Faisal et al., 2014). Continued subduction thereafter resulted in the development of a second Andean-style margin marked by the intrusion of the Kohistan Batholith (Pettersen and Windley, 1991). Ultimately, the Kohistan island arc was sandwiched between India and Eurasia during the Cenozoic initiation of their collision (Beck et al., 1995).

While timing constraints on accretion events and metamorphism now exist for the Hindu Kush (Zanchi et al., 2000; Hildebrand et al., 2001; Heuberger et al., 2007; Faisal et al., 2014) relatively little is known about the various plutonic bodies that intrude the region. There have been no systematic geochemical studies of the plutons of the Pakistani Hindu Kush, and therefore, the geochemical characteristics, potential sources, and the tectonic evolution of the Kafiristan, Tirich Mir, Buni-Zom (exposed along Golen Gol) and Garam Chasma plutonic bodies (Fig. 2) remain poorly constrained. Their occurrence has been variably attributed to subduction and/or collision-related crustal thickening processes (e.g. Desio, 1964; Debon et al., 1987; Hildebrand 1998, Hildebrand et al., 2000; Hildebrand et al., 2001; Zafar et al., 2000; Zanchi et al., 2000; Heuberger et al., 2007). This study examines the petrogenesis and tectonic significance of the Kafiristan, Tirich Mir, Buni-Zom and Garam Chasma plutons based on new major, trace and rare earth element (REE) data and integrated U(Th)-Pb (zircon/monazite) geochronology. This work contributes to the record of major tectonic events in the Hindu Kush and helps improve our understanding of the evolution of the southern margin of Eurasia, subduction dynamics of the Tethys, and the evolution of the Himalaya-Karakoram-Tibetan orogenic system.

1.1. Background Geology and Existing Chronology

The present work is focused on the Hindu Kush in the Chitral region, NW Pakistan (Fig. 1). The geology of the area is characterized by multiply deformed, variably metamorphosed, Paleozoic to Mesozoic sedimentary rocks intruded by the elongate Kafiristan, Tirich Mir, Buni-Zom, Kesu-Kohuzi and Garam Chasma plutons (Calkins et al., 1981; Hildebrand et al., 2000; Fig. 2). The plutonic bodies typically form physiographic

peaks in the region, which reach elevations of 7700 + m locally.

Published constraints on the age of plutonic rocks in the Hindu Kush vary considerably. Existing whole rock Rb-Sr data from the Kafiristan and Tirich Mir plutons outline ages of 483 ± 21 Ma (Debon et al., 1987) and 115 ± 4 Ma (Desio, 1964) respectively. U-Pb Isotope Dilution Thermal Ionization Mass Spectrometry (ID-TIMS) analysis on monazite and uraninite grains from a pegmatite dyke in the Tirich Mir fault zone, thought to be related to the main Tirich Mir plutonic body, yielded a discordant, interpreted intrusion age of 114 ± 2 Ma (Hildebrand et al., 2000). More recently, zircon grains analyzed from a different specimen of the Tirich Mir body yielded two concordant analyses interpreted to comprise an age of 121 ± 1 Ma (Heuberger et al. 2007). Both U-Pb age estimates for the Tirich Mir pluton are consistent with a 110.6 ± 3.2 Ma post-magmatic ^{39}Ar - ^{40}Ar (muscovite) date (Heuberger et al., 2007). A specimen of the Buni-Zom plutonic body collected to the northeast of study area yielded a U-Pb (zircon; ID-TIMS) age of 103.79 ± 0.27 Ma defined by two concordant data points (Heuberger et al., 2007). Finally, U-Pb ID-TIMS analyses on monazite and xenotime grains from a specimen collected from the Garam Chasma pluton yielded a discordant age of 24 ± 0.5 Ma (Hildebrand et al. 1998). This is consistent with 18-20 Ma K-Ar (biotite) dates from the same body if they are interpreted to represent cooling and not crystallization (Zafar et al., 2000).

2. PLUTON DESCRIPTIONS

Plutonic rocks are a major constituent of the eastern Hindu Kush comprising ~35% of the bedrock in the region (Fig. 1). The grayish white (fresh) Kafiristan pluton exposed along the Bomborate and Rumboor valleys (Fig. 1) is foliated and is characterized by a porphyritic

texture with K-feldspar megacrysts ranging in size from 3–4 cm. The matrix minerals consist of $Qz + Kfs + Pl + Bt \pm Hbl$ and accessory $Zrn + Tur + Ap + Ep$ (Fig. 3A and B). The alkali feldspar and plagioclase locally display perthitic and myrmecitic textures respectively. Minor sericitization is observed in one specimen of the Kafiristan pluton (S60; Fig. 1). Initial petrographic observation indicates the pluton includes at least two phases; a $Bt + Hbl$ bearing phase along the Bomborate valley and a Hbl free phase exposed along the Rumboor valley (Fig. 1).

The grayish white and pinkish (fresh) Tirich Mir pluton is foliated and porphyritic with K-feldspar megacrysts ranging in size from 4–5 cm. The Tirich Mir intrusive has abundant $Qz + Kfs + Pl + Bt + Ms, \pm Grt$, and accessory $Zrn + Ap$ (Fig. 3C and D). Hbl has been reported from Tirich Mir pluton (Searle et al., 2001), but it was not observed in this study. Perthite, myrmekite, and zoned Pl are common locally. Petrographically, the Tirich Mir pluton can be divided into at least three phases (1) $Ms + Bt$ (2), $Ms + Bt + Grt$, and (3) $Ms + Tur$.

Previous studies have mapped the Buni-Zom and Kesu Kohuzi plutons as separate bodies (e.g. Aslam et al., 2007). Fieldwork in the Golen Gol area during this study, however, shows that the Buni-Zom pluton extends much farther southwest than previously thought, almost to the Kesu Kohuzi body. In this study the Buni-Zom and Kesu Kohuzi are considered as part of the same plutonic body (Fig. 1). For simplicity, they are collectively referred to as ‘Buni-Zom’ here forward. The dark gray to white (fresh) Buni-Zom plutonic body, which crops out along the Golen Gol, consists of $Afs + Pl + Hbl + Bt$ with accessory Ttn, Zrn, Ap and opaques (Fig. 3E and F). Plagioclase crystals are generally zoned and perthitic textures are observed in alkali feldspar locally. Petrographically, the Buni-Zom pluton can be divided

into two phases: (1) biotite + feldspar + titanite, and (2) biotite + hornblende.

The leucocratic fresh Garam Chasma pluton consists of Afs + Pl + Ms + Bt and subordinate Grt + Sil bearing leucogranite (Fig. 3G and H) with accessory Tur + Zrn + Xtm + Urn + Mzn + Ap. Rare sericitization of alkali feldspar is observed. The leucocratic Garam Chasma pluton occurs as a single phase.

3. WHOLE ROCK GEOCHEMISTRY

Specimens from the Kafiristan, Tirich Mir, Buni-Zom, and Garam Chasma plutons were analysed for whole rock major and select trace element compositions through X-Ray fluorescence (XRF) on pressed pellet using a Bruker S8 TIGER instrument at the Saskatchewan Research Council (SRC) Geoanalytical Laboratories, Saskatoon, Canada. Additional trace and REE concentrations in select specimens were determined by lithium metaborate fusion – inductively coupled plasma mass spectrometry also at the SRC.

3.1. Kafiristan Pluton

Two specimens from the Kafiristan pluton (S60 and S81) were analyzed for major, trace and REE. Chemically, the specimens plot across the alkali granite and granitic fields of the Cox et al. (1979) classification diagram (Fig. 4). The two specimens have variable SiO₂ (67.9–75.9 wt.%), Al₂O₃ (13.1–14.4 wt.%), MgO (0.16–0.9 wt %), P₂O₅ (0.09–0.25 wt%), CaO (0.6 –1.92 wt%) and Fe₂O₃ (1.29–4.76 wt%), and high K₂O (4.48–5.70 wt.%) relative to Na₂O (2.53–3.26 wt.%). Harker plots of major elements within the two analyzed specimens from the Kafiristan pluton show a significant difference in K₂O, Na₂O, CaO, MgO, Al₂O₃, TiO₂, Fe₂O₃, and P₂O₅ contents between specimens when plotted against SiO₂ (Fig. 5).

Similarly, differences between specimens also exist in trace element concentration (e.g. Rb, Sr, Ba, Zr and Th) vs. SiO₂ plots (Fig. 5).

MORB-normalized spider plots of the Kafiristan pluton specimens show relative enrichment in Large Ion Lithophile Elements (LILE: e.g. Rb) compared to High Field Strength Elements (HFSE: e.g. Nb), with pronounced negative anomalies in Sr and enrichments in Th (Fig. 6a). While on chondrite-normalized REE plots, S60 shows a moderate negative Eu anomaly and depleted heavy REE (Fig. 7a), whereas S81 has a 'V' shaped REE pattern and a pronounced negative Eu anomaly (Fig. 7a).

3.2. Tirich Mir Pluton

The five specimens of the Tirich Mir plutonic body (S24, S26, S28, S29 and S62) generally have restricted range in SiO₂ (70.0–73.9 %) and Al₂O₃ contents (14.4–16.2 wt%), and wide ranges in K₂O (2.17–6.22 wt%), Na₂O (2.18–4.83 wt%), P₂O₅ (0.17–0.28 wt%), MgO (0.09–0.82 wt%) and Fe₂O₃ (0.59–2.32 wt%) (see Table 1). With the exception of S62, which has an affinity more toward alkali granite, the Tirich Mir specimens plot in the granite field of the Cox et al. (1979) K₂O + Na₂O vs SiO₂ classification diagram (Fig. 4). Major element Harker plots show generally negative slopes in K₂O, MgO, Fe₂O₃ and TiO₂ when plotted against SiO₂; Na₂O has a positive slope (Fig. 5). Furthermore, trace element Harker plots of Ba, Sr and Zr show negative relationships with SiO₂ while Th has a variable relationship (Fig. 5).

On MORB-normalized trace element diagrams, S24, S28, and S62 have similar LILE and HFSE values, with relative enrichment in Rb, Th, and variably negative Sr and Nb anomalies (Fig. 6b). Chondrite-normalized spider plots of the Tirich Mir specimens show

relative enrichment in light REE ($(\text{La/Yb})_N = 8\text{--}14$), depletion in heavy REE and moderate negative Eu anomalies (Fig. 7b).

3.3. Buni-Zom Pluton

The three specimens analyzed (S47, S95 and S96) from the Buni-Zom pluton show a wide compositional range in SiO_2 (57.1–71.8 wt%), MgO (0.91–3.82 wt%), P_2O_5 (0.2–0.43 wt%), CaO (2.1–7.12 wt%), and F_2O_3 (2.27–8.65 wt%). Na_2O within a specimen is typically higher than K_2O . The Buni-Zom specimens variably plot within the diorite and granite fields of Cox et al. (1979) (Fig. 4). Major-element Harker diagrams show negative relationships for CaO , MnO , P_2O_5 , TiO_2 , MgO , Fe_2O_3 with increasing SiO_2 (Fig. 5). In contrast, Sr shows a positive relationship with SiO_2 ; a similar, though weaker, relationship may exist with Ba and Rb (Fig. 5).

MORB-normalized trace element plots for the Buni-Zom specimens show some variation in LILE and HFSE (Fig. 6c; Table 1). The specimens show generally similar distributions of LILE with a pronounced negative Sr anomaly, however, specimen S95 shows more enrichment in Th and less depletion in Nb compared to S47 and S96. The chondrite-normalized REE pattern of the two specimens analysed have uniform negative slopes with minor positive Ho anomalies (Fig. 7c), however, specimen S96 ($(\text{La/Yb})_N = 9$) is more enriched in heavy REE than S95 ($(\text{La/Yb})_N = 17$).

3.4. Garam Chasma Pluton

The four specimens analyzed from the Garam Chasma pluton have a narrow range of compositional variation in SiO_2 (72.2–75.0 wt%), MgO (0.11–0.24 wt%), P_2O_5 (0.08–0.17

wt%), CaO (0.69–1.32 wt%), F₂O₃ (0.63–1.41 wt%); K₂O (4.11–5.39 wt%) and Na₂O (2.61–3.79 wt%). Compositionally, the Garam Chasma specimens plot in the alkali granite and granite fields of the Cox et al. (1979) discrimination diagram (Fig. 4). The only trends apparent on major element Harker plots are negative relationships between Na₂O and Al₂O₃ against SiO₂ (Fig. 5).

The MORB-normalized spidergram of specimens S9A, S9B, S10 and S10B from the Garam Chasma pluton show similar concentrations in LILE with strong negative Sr anomalies. Moreover, Th shows moderate enrichment in the specimens while Nb shows minor relative depletion (Fig. 6d). The two specimens, S9A and S10B, of the Garam Chasma pluton analyzed for REE concentrations show enrichment in light REE ((La/Yb)_N = 29–56)), with similar decreasing slopes towards heavy REE on chondrite-normalized plots (Fig. 7d).

4. INTERPRETATIONS AND PETROGENESIS

4.1. Kafiristan Pluton

Though only constrained by two specimens, apparent decreasing K₂O, CaO, MgO, Al₂O₃, TiO₂, Fe₂O₃, and P₂O₅ with increasing SiO₂ in the Kafiristan pluton (Fig. 5) are consistent with fractionating of hornblende, plagioclase, and potentially biotite (e.g. White and Chappell, 1983). In addition, decreasing Sr, Ba, and Zr and increasing Rb contents from S60 to S81 are also consistent with a fractionating plutonic body (Crawford and Searle, 1992; Chappell and White, 1992; King et al., 1997; Dostal and Chatterjee, 2000; Liu et al., 2012). Moreover, the overall negative anomalies of Eu, Sr, and Nb in spidergrams of the two specimens (Fig. 7) may indicate significant fractional crystallization of plagioclase and

titanite/ilmenite minerals (Wu et al., 2003). Enrichment of the Kafiristan specimens in heavy REE relative to chondrite may be attributed to the dissolution of either garnet/monazite and or allanite thereby liberating these elements (Crawford and Searle, 1992; Zhang et al., 2014).

The Kafiristan pluton specimens have generally high $\text{Na}_2\text{O} + \text{K}_2\text{O}$, Fe/Mg ratios show pronounced negative Sr anomalies (Figs. 5, 6). These signatures, along with high Rb (Fig. 6) and high total REE (Table 1) with significant negative Eu anomalies (Fig. 7) are consistent with geochemical signatures of plutonic bodies that have evolved from the partial melting of lower crust from a basaltic source (White and Chappell, 1983; Whalen et al., 1987; Eby 1990; Whalen et al., 1997; Wu et al., 2002; Li et al., 2007; King et al., 1997; Yang et al., 2011). Furthermore, high LILE/HFSE, Y/Nb (2.13–2.70) and Yb/Ta (1.37–1.96) ratios, and with strong fractionation of Ba, Sr and Eu are also consistent with derivation from a basaltic source (Figs. 5 and 7; Table 1; Eby, 1990; Li et al., 2013). The two specimens of the Kafiristan pluton are, therefore, interpreted to have resulted from the variable fractionation of magma from basaltic source in an anorogenic, perhaps rift-type, environment.

4.2. Tirich Mir Pluton

Minor sericitization was observed in specimens S24 and S62 from the Tirich Mir pluton, and minor chloritization was also noted in specimen S24. In both specimens the alteration typically follows fractures in alkali feldspar. In specimens S28 and S29, fractures in plagioclase crystals variably contain secondary calcite and/or chlorite minerals. The affect of chloritization and sericitization appear to be minor, as these specimens do not show any significant alteration trend and generally plot within range of an average fresh granitic body (Fig. 8). All specimens are, therefore, considered for interpretation below.

The general trends of decreasing K₂O, Fe₂O₃, MgO, and TiO₂ with increasing SiO₂ in the Tirich Mir pluton is consistent with crystal fractionation of K-bearing Fe-Mg rich minerals (biotite or perhaps hornblende as reported by Searle et al., 2001), and plagioclase (White and Chappell, 1983; Li et al., 2007). Moreover, the negative Ba and Sr anomalies also indicate removal of a K-bearing phase by fractionation crystallization (Rex et al., 1988; Guillot and Le Fort, 1995; Liu et al., 2012). The negative Eu anomalies in the Tirich Mir specimens are consistent with plagioclase-controlled magmatic fractionation or occurrence in the residuum. The higher light REE relative to heavy REE in the Tirich Mir specimens may indicate accessory mineral, such as monazite/allanite, fractionation and retention of garnet in the residue (Rex et al., 1988).

Most of the Tirich Mir specimens generally have high K₂O (Na₂O/K₂O <1), low heavy REE, are associated with a moderately negative Eu anomaly, and low Sr/Y and Nb/Ta ratios, all consistent with derivation from partial melting of mafic/ultramafic lower crustal and upper mantle (mantle wedge) material in a continental arc setting (White and Chappell, 1983; Li et al., 2007; Zhang et al., 2014). Moreover, the high LILE/HFSE ratios with notable negative Nb anomalies of the Tirich Mir specimens are characteristic of subduction-related melting (Li et al., 2007; Zhang et al., 2014). This interpretation is also supported by a pronounced negative Sr anomaly and more moderately negative Ba and Eu anomalies, indicative of fractionation of arc magmas (Li et al., 2007; Yang et al., 2010; Ji et al., 2009; Zhang et al., 2014). The Tirich Mir pluton is, therefore, interpreted to have evolved from a fractionated, subduction-related igneous magma source with variable contribution from sedimentary/crustal rocks through assimilation.

4.3. Buni-Zom Pluton

Major element composition, hand specimen, and petrographic examination outline two distinct phases in the Buni-Zom pluton: 1) a low silica phase and 2) a high silica phase. The low silica phase specimen (S96) is dominated by Pl, Afs, Bt, Hbl, and Ttn, while the high silica phase specimen (S95) has a similar mineralogy but lacks hornblende. The relatively low ASI values 0.7-1.1 (Table 1), wide ranging compositions, and presence of Hbl and Ttn (accessory) are characteristic of intrusive rocks generated from an igneous protolith (White and Chappell, 1983; Chappell and White, 2001). Major-element Harker diagrams show negative relationships between CaO, MnO, P₂O₅, TiO₂, MgO, and Fe₂O₃ with SiO₂ while K₂O shows the opposite, consistent with a fractionation of minerals such as hornblende, biotite, and plagioclase. Moreover, the amphibole free specimen (S95) has higher alkali, LILE and HFSE also consistent with a fractionating magmatic source (Whalen et al., 1987; Crawford and Windley, 1990; Chappell, 1999; Chu et al., 2009; Deng et al., 2011).

Chondrite-normalized REE patterns have fairly uniform negative slopes with the less evolved diorite, specimen S96, showing more enrichment in heavy REE ((La/Yb)_N = 9) than the more evolved S95 ((La/Yb)_N = 17)), consistent with fractional crystallization of magma. The absence of a Eu anomaly and the high Sr (663–826 ppm) content of the Buni-Zom specimens are compatible with plagioclase incorporated into the melt or a plagioclase-free source. The depletion in Nb and Ti and very low Nb/Ta ratios (0.1–0.7) indicates that the

protolith to the Buni-Zom pluton has amphibole, titanite and/or rutile in the residuum (Mahoney et al., 1998; Zhang et al., 2014).

4.4. Garam Chasma Pluton

Harker plots of the Garam Chasma pluton are typically scattered, however, Na₂O has a negative relationship with SiO₂, consistent with the fractionation of plagioclase. Such an interpretation is consistent with higher K₂O (5.4–4.1 wt%) over Na₂O (3.3–2.6 wt%), and high Rb, as well as the presence of aluminous phases such as garnet and sillimanite in the Garam Chasma specimens (e.g. Chappell and White, 2001; Villaros, 2010).

The very high LILE/HFSE (high Rb/Nb+Y ratios) and LREE/HREE ratios in the specimens (La/Yb = 41.94–81.82), and a relatively pronounced negative Nb anomaly are consistent with a magma from a crustal source (Chappell, 1999; Chu et al., 2009; Deng et al., 2011). Relative depletion of heavy REE and the absence of a negative Eu anomaly indicates that REE-bearing phases such as garnet/monazite/allanite remained in the source while and plagioclase was either absent in the source or contributed to the melt. Trace element abundances of Rb, Ba and Sr define an array of strongly increasing Rb/Sr with decreasing Ba (Fig. 10) indicative of vapor-absent incongruent melting of muscovite (Harris and Inger, 1992; Inger and Harris, 1993). Similar vapor-absent melting of a muscovite-bearing protolith has been found to be associated with decompressional melting along the Himalayan orogen (Langtang, Fig. 10; Harris and Massey, 1994; Prince et al., 2001; Searle et al., 1999; King et al., 2011; King and Harris, 2013). The geochemical and geochronological (discussed below) similarities of the Garam Chasma specimens to the Baltoro (Karakoram; Searle et al., 1989), Bhagirathi leucogranite (Garhwal, India; Stern et al., 1989), and Manaslu (Nepal; Guillot

and Le Fort, 1995) plutons of the Himalaya, and North Himalayan decompression-related plutons: Gomdre, Kouwu and Majia (King et al., 2011) and Leo Pargil dome (NW India; Lederer et al., 2013), indicate that the Garam Chasma leucogranite may have evolved through a similar processes of crustal anatexis during collisional orogenesis.

5. GEOCHRONOLOGY

Considerable variation is observed in published data, with a wide range of variably concordant dates for specimens from the Tirich Mir, Buni-Zom and Garam Chasma plutonic bodies. Published ages are typically interpreted based on only a few concordant analyses or extrapolated from arrays of data variably affected by Pb loss (Hildebrand et al., 1998; Hildebrand et al., 2000; Heuberger et al., 2007); moreover, there is no previous record of U-Pb geochronology from the Kafiristan pluton. New U-(Th)/Pb geochronology data were acquired using laser ablation paired with a multicollector inductively coupled plasma-mass spectrometer (LA-MC-ICP-MS) at the University of Santa Barbara, California (for detailed methodology see Cottle et al., 2011; 2013). This approach to dating specimens collected from the Hindu Kush allows specific domains of zircon and/or monazite, imaged through cathodoluminescence (CL) and/or electron backscatter imaging, to be targeted avoiding potential problems associated with mixing of distinct age domains.

Isoplot v2.4 (Ludwig 2000) was used to calculate both Tera–Wasserburg concordia diagrams (Fig. 11) for Kafiristan, Tirich Mir, Buni-Zom and Garam Chama pluton using the ^{238}U , ^{235}U and ^{232}Th decay constants of Steiger and Jäger (1977).

5.1. Kafiristan Pluton

The LA-MC-ICP-MS results for two specimens, S80 and S60, from the Kafiristan pluton are reported along with isotopic ratios and calculated ages in Table 2. Zircon grains from the two specimens of the Kafiristan pluton are euhedral and typically show oscillatory zonation under CL consistent with the zircon grains being magmatic (Corfu et al., 2003; Fig. 11). The rims of the grains were the primary targets during analysis to avoid any potential inherited domains. Forty analyses were obtained while targeting the outer rims of thirty-seven zircon grains from S80. Two anomalously young zircon ages (S80_04 and S80_31) and a single spot missing the target (S80_35) were excluded from interpretation (Table 2). Tera–Wasserburg concordia (uncorrected for common Pb) exhibit a broad dispersion between 495–525 Ma (Fig. 11). While most of the data are concordant, some show a slight discordance consistent with a minor common Pb component (Fig. 11). The youngest concordant age from S80 is 492 ± 3.2 Ma, which is taken as the minimum crystallization age of this specimen.

Thirty analyses were obtained from an equal number of zircon grains separated from S60. The dates from this specimen are generally concordant and spread between ~487 Ma and 525 Ma (Fig. 11), with a minimum crystallization age of 486.7 ± 5.4 Ma. Some of the analyses are slightly discordant suggestive of minor common Pb or minor Pb loss (Fig. 11).

The two analyzed specimens of the Kafiristan pluton outline a protracted magmatic history spanning between ca. 488–525 Ma. Dates from both specimens (representing geochemical distinct phases in the Kafiristan pluton as observed above) overlap and are, therefore, interpreted to indicate that the two phases are the result of a single protracted magmatic event. The new dates obtained are within uncertainty of a previous whole rock Rb/Sr crystallization age of 483 ± 21 Ma (Debon et al., 1987).

5.2. Tirich Mir Pluton

U-Pb (zircon) dating was carried out specimen on S24 of the Tirich Mir specimen. CL images of euhedral zircon from the Tirich Mir specimen display undisturbed oscillatory patterns indicating that the zircon grains are magmatic (Fig. 11). Fifteen analyses were obtained from eight zircon grains (Table 2). Two of the analyses (S24_007 and S24_012) were excluded as they yield anomalously older ages (early Paleozoic and Mesoproterozoic, respectively) than most of the specimen (Early Cretaceous). The two old analyses may reflect detrital/inherited zircon components. The remaining analyses from specimen S24 spread between ca. 123 and 127 Ma (Fig. 11). Most of the data acquired are concordant but three spots suggest the presence of some common Pb (Fig. 11).

The spread in dates from the Tirich pluton specimen is interpreted to indicate continuous crystallization from ca. 123–127 Ma with a final crystallization age of 123.7 ± 0.7 Ma. This minimum age is similar to, but somewhat older than, the previously published date of Heuberger et al. (2007), 121 ± 1 Ma, and significantly older than the 114 ± 2 Ma date of Hildebrand et al., (2001), indicating that crystallization/magmatism within the pluton may have a protracted history.

5.3. Buni-Zom Pluton

The U-Pb analytical results on two specimens, S92 (intermediate phase) and S95 (high SiO₂ phase) of the Buni-Zom body are given in Table 2. Zircon from both specimens are typically elongate and euhedral with oscillatory zoning, consistent with a magmatic origin (Fig. 11). A total of Forty analyses were obtained from the rims of thirty-four grains

from S92. Three of the analyses (S92_004, S92_023 and S92_033) yielded anomalous ages and were excluded from further interpretation. Two of the excluded zircon ages, 119 ± 0.8 Ma (S92_004) and 115.8 ± 1 Ma (S92_023), may be associated with earlier magmatism in an Andean-type setting along the southern margin of Eurasia (discussed below), while 727 ± 6 Ma (S92_033) is considered an inherited age. The remaining concordant dates spread between ~ 102 and 110 Ma (Fig. 11), with a minimum age of 101.8 ± 0.6 Ma. Similarly, Forty spot ages were obtained from targeting the rims of thirty-six zircon grains from specimen S95 (Table 2). The data acquired from these analyses yield dates that spread between ~ 105 and 109 Ma (Fig. 11), yielding a minimum date of 104.7 ± 0.7 Ma.

The ages from the two specimens of the Buni-Zom representing geochemically distinct phases overlap entirely and are interpreted to have evolved in a nearly continuous magmatic spanning for ca. 8 Ma years. The previously reported 103.8 ± 0.27 Ma crystallization age from the Buni-Zom (Heuberger et al., 2007) is in general agreement with the range of new data presented herein.

5.4. Garam Chasma Pluton

Monazite U-Th-Pb dating of the Garam Chasma leucogranite was performed on specimen C65 (Table 3). Because $^{207}\text{Pb}/^{235}\text{U}$ dates are relatively imprecise in young monazite, $^{208}\text{Pb}/^{232}\text{Th}$ dates are reported (Fig. 11). Most of the monazite dates are concordant, however, some reverse discordance is apparent in the $^{208}\text{Pb}/^{232}\text{Th}$ vs. $^{206}\text{Pb}/^{238}\text{U}$ plot indicating unsupported ^{206}Pb from the decay of ^{230}Th (Schärer, 1984). Specimen C65 of the Garam Chasma pluton yields two apparent age populations: the older age population yields a weighted mean age ($^{208}\text{Pb}/^{232}\text{Th}$) of 27.1 ± 0.3 (MSWD 0.6) and younger age population with

a weighted mean $^{208}\text{Pb}/^{232}\text{Th}$ date of 23.6 ± 0.1 Ma (MSWD 0.8). These two populations may indicate an episodic emplacement history. The dominant phase outlined in this study is consistent with the age of ca. 24 Ma interpreted by Hildebrand et al (1998) from discordant monazite and uraninite dates.

6. DISCUSSION AND TECTONIC SIGNIFICANCE

Recent metamorphic monazite ages from the Hindu Kush range (Faisal et al., 2014), along with sedimentary records from the nearby Pamir (Angiolini et al., 2013) outline a protracted tectonic history for the southern Eurasian margin in the region involving terrane accretion, plutonism, and related mountain building processes from the Mesozoic to the Cenozoic. The present study builds on this earlier work and outlines four distinct magmatic events in the Hindu Kush area spanning the Cambrian–Early Ordovician to the late Oligocene with affinities to a) intraplate extension/rifting, b) subduction-derived melts into a continental arc and c) synorogenic crustal anatexis. These magmatic episodes outline the regional magmatic and metamorphic history of the Hindu Kush and aid in a broader understanding of Himalaya geology and the tectonic evolution of the southern margin of Eurasia.

Geochemically, the Kafiristan pluton is ferroan, calc-alkalic to alkali-calcic, and weakly peraluminous to peraluminous consistent with generation in anorogenic extensional tectonic environment (Fig. 12a). The crystallization ages from the two specimens examined are indistinguishable, which indicates that the two phases of the pluton were part of the same magmatic event between 538 and 487 Ma. Such an event may reflect post-collisional rifting of the Gondwana supercontinent during the Paleozoic (e.g. Dèzes, 1999; Fernández et al.,

2012) with the Kafiristan pluton intruded as the Cimmerian terranes, including the Hindu Kush and Karakoram, rifted and drifted away from peri-Gondwana toward Eurasia (Sengör, 1979; Rogers et al., 1995; Gaetani, 1997; Heuberger, 2004; Zanchi and Gaetani, 2011). Similar Cambro-Orographic plutons interpreted to be related to the same rifting event have been identified in the nearby Zaskar (Dèzes, 1999), Karakoram (Le Fort et al., 1986; Noble and Searle, 1995; Rolland et al., 2002; Zanchi and Gaetani, 2011) and Wakhan (Debon et al., 1987) regions.

The continued subduction of Paleotethys oceanic lithosphere beneath the Hindu Kush-Karakoram led to the intrusion of the Tirich Mir and Bun-Zom plutons in the Cretaceous (Fig. 12d). U-Pb zircon geochronology from the Tirich Mir pluton outlines a magmatic event spanning 123 to 127 Ma, coeval with subduction-related magmatic activity and the intrusion of the Karakoram batholith farther east (Searle et al., 1989; Hildebrand et al., 2001; Heuberger et al., 2007 and references therein).

While like the Tirich Mir specimens, the Buni-Zom rocks show geochemical signatures of a plutonic body generated above a subduction zone, the absence of trends in Al_2O_3 , Na_2O , P_2O_5 , CaO and MgO in Buni-Zom specimens when plotted against SiO_2 (Fig. 4), indicate that its source is less evolved. Moreover, high molecular Mg content as well as a close association with the calcic to calc-alkalic boundary on the MALI (Figs. 9a and b) compared to the calc-alkalic to alkali-calcic nature of Tirich Mir specimens indicates that the Buni-Zom plutonic body was located farther toward the oceanic portions of the Andean –Arc related belt. This is consistent with their relative proximity to the paleo-Eurasian margin (to the SE of the field area) in the Cretaceous.

The protracted Andean-style magmatism in the Hindu Kush recorded during the Early Cretaceous intrusion of the Tirich Mir and Buni-Zom plutons ceased as the Kohistan Island arc docked along the southern margin of Eurasia during the Late Cretaceous (Petterson et al., 1991; Fraser et al., 2001; Faisal et al., 2014; Fig. 12e). The continued subduction of the Neotethys along the accreted Kohistan arc to Eurasia culminated with the collision of India and Eurasia in the Eocene (Patriat and Achache, 1984; Beck et al., 1995; Fig. 12). The crustal shortening and thickening of the Indian and Eurasian margins during collision led to widespread anatexis and the intrusion of the Garam Chasma pluton in the Hindu Kush region during the Oligocene/Miocene (Fig. 12f). The general similarity in the geochemistry and age of the Garam Chasma pluton with other Cenozoic leucogranites from the Himalaya, e.g. Langtang (Inger and Harris, 1993), Manaslu (Guillot and Le Fort, 1995), North Himalaya leucogranite (Gomdre, Kouwu and Majia, King et al., 2011) is consistent with regional scale anatexis across the Himalaya, Karakoram and Hindu Kush. The monazite dates from the Garam Chasm pluton are also consistent with published metamorphic monazite dates from the same area (Faisal et al., 2014) indicating that anatexis and metamorphism occurred synchronously in the Hindu Kush terrane during the Late Oligocene/Early Miocene.

7. CONCLUSIONS

The geochemical and geochronological data from the plutonic bodies of the Hindu Kush outline a protracted tectonomagmatic history of the southern margin of Eurasia that spans from the early Paleozoic into the Cenozoic. These data provide constraints on crustal

growth and paragenesis along the southern margin of Eurasia prior to Cenozoic initiation of continental collision with India.

1. The Kafiristan pluton is a Cambro-Ordovician body interpreted to be associated with the break-up of Gondwana.
2. Subduction of the Paleotethys beneath the southern Eurasian margin after the accretion of the Hindu Kush and Karakoram terranes developed an Andean-style margin resulting in the Cretaceous emplacement of the Tirich Mir and Buni-Zom plutons.
3. The origin of the Cenozoic Garam Chasma pluton is attributed to crustal anatexis associated with the India-Eurasia collision. The crystallization age of the Garam Chasma leucogranite is coeval with sillimanite-grade metamorphism and intrusion of leucogranite bodies within the nearby Karakoram, Himalaya and regions.

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Figure 1. Tectonic map of Northern Pakistan and surrounding regions. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MMT, Main Mantle Thrust; SS, Shyok Suture; TMF, Tirich Mir Fault Zone; EHK, East Hindu Kush; ACM, Alitchur mountains; RPZ, Rushan-Pshart Zone; WAS, Wanch-Ak Baital Suture; N-P, North Pamir; C-P, Central Pamir; SE-P, SE-Pamir; SW-P, SW-Pamir; WAZ, Waziristan; K, Kabul. 1, Quaternary; 2, Tertiary foredeeps; 3, Palaeozoic belts; 4,

Terranes of Gondwanan affinity; 5, Kabul Block; 6, Wasser-Panjao Suture; 7, Waziristan ophiolitic complex; 8, Kohistan- Ladakh arc terranes; 9, Himalaya. Heavy lines represent main sutures (Redrawn after Gaetani et al., 1996; Zanchi et al., 2000). Insert rectangle shows the location of Figure 2.

Figure 2. Geology map of the Chitral region showing Kafiristan, Tirich Mir, Bun-Zom and Garam Chasma with specimen locations used for geochemical and geochronological analyses noted.

Figure 3. Cross-polarized photomicrographs of the Kafiristan (A, B), Tirich Mir (C, D), Buni-Zom (E, F) and Garam Chasma (G, H). Mineral abbreviations after Whitney and Evans (2010).

Figure 4. The classification of the Kafiristan, Tirich Mir, Buni-Zom and Garam Chasma plutons in the SiO_2 vs. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram (after Cox et al., 1979).

Figure 5. Chemical variation Harker diagrams of the Kafiristan, Tirich Mir, Buni-Zom and Garam Chasma plutons.

Figure 6. MORB-normalized trace plots of the Kafiristan (a), Tirich Mir (b), Buni-Zom (c) and Garam Chasma (d) specimens (after Sun and McDonough, et al., 1989).

Figure 7. Chondrite normalized REE diagrams of the Kafiristan (a), Tirich Mir (b), Buni-Zom (c) and Garam Chasma (d) specimens. Normalizing values are from McDonough and Sun (1995).

Figure 8. Ternary plot of Al_2O_3 -($\text{CaO}+\text{Na}_2\text{O}$)- K_2O , showing common alteration trend of an average granitic composition. Data from the Hindu Kush plutons (Kafiristan, Tirich Mir, Buni-Zom and Garam Chasma) bodies generally cluster together (weathering trend and weathering data after Nesbitt and Young (1984; 1989). See text for discussion.

Figure 9. a) $\text{FeO}_{\text{tot}}/(\text{FeO}_{\text{tot}} + \text{MgO})$ versus weight per cent SiO_2 diagram showing the boundary between ferron (Kafiristan and Garams Chasma) and magnesian (Tirich Mir and Buni-Zom) plutons (after Frost et al., 2001). b) $\text{NaO} + \text{K}_2\text{O} - \text{CaO}$ versus weight per cent SiO_2 plot showing the compositional range of Kafiristan, Tirich Mir, Buni-Zom and Garam Chasma plutons (after Frost et al., 2001).

Figure 10. Rb/Sr versus Sr and Ba diagram (after Inger and Harris, 1993) for Garam Chasma and Langtang (from Inger and Harris, 1993) leucogranites. Mu (VA)-vapour-absent muscovite melting; Bi (VA)-vapour-absent biotite melting. F=melt fraction.

Figure 11. Tera–Wasserburg concordia diagrams showing analytical data for zircons from Kafiristan, Tirich Mir and Buni-Zom plutons. Concordia diagram for Garam Chasma pluton specimen with $^{208}\text{Pb}/^{232}\text{Th}$ ratios along the x-axis. Note, the Garam Chasma data are shown as crosses because errors are not correlated. See text for details. Cathodoluminescence images of representative zircons from Kafiristan, Tirich Mir and Buni-Zom are shown with the relevant concordia plots along with a backscattered monazite image from the Garam Chasma pluton.

Figure 12. Schematic cross-sectional evolutionary model of the southern Eurasian margin. See text for discussion (modified after Hildebrand et al., 2001; Burg 2011; Zanchi and Gaetani 2011; Angiolini et al., 2013, Faisal et al., 2014). CP = Central Pamir, SP-HK = South Pamir – Hindu Kush, KK = Karakoram, NG = Northern Gondwana, KIA = Kohistan Island Arc, RPB = Rushan-Pshart Basin, RPS = Rushan-Pshart Suture, TWB = Tirich-Wakhan Basin, TMBZ = Tirich Mir Boundary Zone, PT = Paleotethys, NT = Neotethys, MKT (Northern Suture) = Main Karakoram Thrust, ISZ = Indus Suture Zone.

Table 1. Major elements (%), trace elements and rare-earth elements (ppm) of the plutonic bodies in the Eastern Hindu Kush, from the Chitral area, NW Pakistan.

Table. 2. LA-ICP-MS U-Pb geochronology data for spot analysis of zircon of the Kafiristan, Tirich Mir and Buni-Zom plutons.

Table 3. LA-ICP-MS U-Th/Pb geochronology data for spot analysis of monazite of the Garam Chasm pluton.

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Hindu Kush and Karakoram terranes detachment from the northern periphery of Gondwana and intrusion of Kafiristan pluton.

The Cimmerian orogeny continued with the accretion of the Karakoram terrane followed by northward subduction transforming the margin into a continental arc.

Denise of the Paleotethys with the docking of the KIA and intrusion of the subsequent intrusion of the Kafiristan batholith.

Subsequent to extension, the Hindu Kush terrane accreted to Eurasia during the first phase of Cimmerian orogeny.

Intrusion of the Tethyan Mir and Buni-Zom plutons in a continental arc setting.

Crustal thickening associated with the continued India-Eurasia collision results in crustal anatexis and the formation of the Garam Chasma pluton.

CP = Central Paropam, RPB = Ruzhen-Pishan Basin,
SP-HK = South Pamir - Hindu Kush, PT = Paleotethys,
KK = Karakoram, NG = Northern Gondwana, NT = Neotethys,
RPS = Ruzhen-Pishan Suture, TWB = Tethyan-Walshen Basin,
TMBZ = Tethyan Mir Boundary Zone, KIA = Kafiristan Island Arc,
MKT (Northern Suture) = Main Karakoram Thrust,
ISZ = Indus Suture Zone

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Table 1

Samples	Kafiristan		Tirich Mir					Buni-Zom			Garam Chasm		
	S-60	S-81	S-24	S-26	S-28	S-29	S-62	S-47	S-95	S-96	S-9A	S-9B	S-10
Na ₂ O	2.53	3.26	2.84	4.83	3.62	2.72	2.18	3.46	3.96	2.49	3.33	2.61	3.26
MgO	0.90	0.16	0.63	0.09	0.37	0.82	0.40	0.94	0.91	3.82	0.24	0.11	0.17
Al ₂ O ₃	14.4	13.1	14.6	16.2	14.4	14.8	18.4	14.4	15.0	14.4	14.3	14.6	15.5
SiO ₂	67.9	75.9	72.2	73.9	73.2	71.0	70.0	71.8	70.1	57.1	74.1	75.0	73.7
P ₂ O ₅	0.25	0.09	0.28	0.19	0.17	0.30	0.22	0.20	0.26	0.43	0.08	0.10	0.17
K ₂ O	5.70	4.48	4.57	2.17	4.57	5.04	6.22	3.55	3.14	2.08	4.11	5.39	4.59
CaO	1.92	0.69	1.37	0.60	1.50	1.61	0.55	2.10	2.98	7.12	1.32	0.69	1.09
TiO ₂	0.67	0.15	0.39	0.02	0.23	0.46	0.43	0.33	0.38	1.12	0.21	0.08	0.11
MnO	0.08	0.02	0.05	0.10	0.03	0.04	0.02	0.04	0.05	0.16	0.01	0.02	0.01
Fe ₂ O ₃	4.76	1.29	2.32	0.590	1.51	2.77	0.94	2.36	2.27	8.65	1.41	0.63	0.71
Total	99.1	99.1	99.3	98.7	99.6	99.5	99.4	99.2	99.1	97.4	99.1	99.2	99.3
S	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sc	7.90	3.10	5.10	1.50	1.50	7.80	5.70	2.50	4.00	22.0	1.50	4.60	1.50
V	44.0	0.80	19.6	0.50	5.40	26.3	16.2	26.4	32.1	191.8	0.80	0.50	0.50
Cr	18.2	12.4	10.9	43.8	19.4	24.7	23.3	16.9	31.1	22.2	17.9	6.6	17.2
Co	2.30	1.50	1.50	1.50	2.30	1.50	5.80	1.50	1.50	25.8	1.50	1.50	1.50
Ni	7.2	9.2	7.6	10.7	8.3	14.0	13.1	10.0	12.4	22.0	9.7	8.5	11.0
Cu	22.8	2.5	2.5	2.5	3.4	2.5	4.0	2.5	2.5	17.7	2.5	2.5	16.8
Zn	55.9	12.1	68.0	17.3	38.5	72.4	2.30	47.6	56.6	89.2	46.2	17.0	45.1
Ga	18.5	21.0	21.7	24.5	19.9	21.3	18.6	18.9	21.2	17.8	19.7	22.4	28.3
As	2.30	1.5	1.5	1.5	1.5	1.5	2.9	1.5	1.5	0.9	1.5	1.5	0.5
Se	5.0	22.3	5.0	44.4	13.8	5.00	26.5	5.0	5.0	5.0	18.7	22.7	28.0
Br	4.0	14.9	10.5	23.4	13.3	8.1	17.6	11.1	5.0	5.0	14.6	15.0	17.5
Rb	127	285	295	221	229	288	279	68.4	103	73.5	209	274	329
Sr	131	60.8	104	15.7	84.0	144	62.0	826	809	619	395	128	161
Zr	268	81.3	126	7.8	104	175	87	197	226	165	147	66.7	36.1
Mo	2.0	1.0	2.0	5.0	1.7	3.0	2.1	1.0	2.0	2.3	11.0	6.0	6.0
Sn	2.20	6.5	1.5	23.2	7.5	1.5	10.6	1.5	1.5	1.8	1.5	6.6	9.5
Sb	1.00	9.7	3.8	5.8	1.0	8.0	6.9	1.0	1.0	1.0	1.0	2.9	4.0
Cs	2.2	7.2	11.9	2.5	7.7	5.7	3.8	2.5	5.1	0.7	5.3	11.6	2.5
Ba	619	138	226	2.5	212	298	358	1147	717	631	773	103	158
Hf	7.5	15.4	13.2	17.8	3.1	12.3	2.6	12.0	11.6	3.6	13.9	14.1	13.8
W	5.0	32.8	17.4	43.5	20.4	5.0	35.6	18.9	10.6	5.0	32.0	33.1	26.9
Pb	28.0	27.0	50.0	32.9	53.1	49.7	44.6	22.2	24.9	7.60	58.9	74.6	89.8
Bi	2.5	18.5	13.6	50.4	23.7	2.5	31.6	16.8	6.7	2.5	22.5	27.9	35.4
Ce	128	36.0	39.0		41.0		32.0		46.0	54.0	42.0		
Dy	5.16	9.67	2.57		2.55		1.64		1.92	3.69	0.89		
Er	2.88	6.06	1.08		1.53		0.82		0.89	2.05	0.34		
Eu	1.32	0.31	0.58		0.59		0.44		1.10	1.51	0.64		
Gd	6.87	6.20	3.30		2.87		2.18		2.64	4.50	1.53		
Ho	1.23	2.54	0.52		0.63		0.36		0.45	0.92	0.18		
La	63.0	19.0	21.0	2.50	19.0	19.0	17.0	21.0	24.0	26.0	27.0	13.0	10.0
Lu	0.40	1.20	0.17		0.20		0.10		0.16	0.30	0.05		
Nb	14.0	22.2	16.0	22.0	10.0	17.6	9.00	8.10	18.0	8.00	7.0	11.0	9.7
Nd	46.3	18.1	18.3		15.6		11.9		21.1	25.2	15.5		
Pr	14.00	5.19	5.38		4.55		3.54		6.10	6.46	5.03		
Sm	8.40	5.09	3.80		3.36		2.48		3.52	5.24	2.26		
Ta	1.37	5.80	2.96	4.72	2.36	2.76	1.96	2.16	1.56	0.72	0.98	1.50	9.10

Table 2

Sample Name	Concentration (ppm)			Measured Isotopic Ratios						Measured Isotopic Ages						
	U	Th	Pb	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb		2s %	²⁰⁷ Pb/ ²³⁵ U		2s %	²⁰⁶ Pb/ ²³⁸ U		2s %	Rho	²⁰⁷ Pb	
					2s %	2s %		2s %	2s %		2s %	2s %			2s %	2s %
date																
S80_01	450	246	55	0.55	0.05719	0.332	0.62650	0.670	0.07933	0.630	0.87	492.1	3.0	492.0	3.2	
S80_02	904	260	59	0.29	0.05712	0.298	0.63670	0.770	0.08100	0.741	0.91	502.1	3.6	502.2	3.8	
S80_03	3191	360	106	0.11	0.05807	0.654	0.64100	1.872	0.08020	1.621	0.97	497.3	7.6	496.8	8.3	
S80_04	190	34	9	0.18	0.05580	2.151	0.51100	6.654	0.06770	3.840	0.96	422.0	16.0	422.0	16.6	
S80_05	2215	409	95	0.19	0.05749	0.191	0.64250	0.763	0.08135	0.676	0.97	504.2	3.3	504.1	3.5	
S80_06	1427	442	101	0.31	0.05785	0.225	0.64070	0.812	0.08042	0.771	0.96	498.6	3.7	498.2	3.9	
S80_07	2025	381	88	0.19	0.05785	0.190	0.65390	0.811	0.08218	0.779	0.97	509.1	3.8	508.9	4.1	
S80_08	612	145	35	0.24	0.05740	0.331	0.64910	0.739	0.08215	0.743	0.88	508.9	3.6	509.0	3.9	
S80_09	3199	435	101	0.14	0.05821	0.158	0.65120	0.691	0.08141	0.737	0.97	504.5	3.6	504.0	3.8	
S80_10	3123	512	119	0.17	0.05849	0.171	0.65750	0.745	0.08164	0.698	0.97	505.9	3.4	505.2	3.6	
S80_11	894	250	57	0.28	0.05772	0.295	0.64350	0.808	0.08084	0.656	0.92	501.1	3.2	500.8	3.4	
S80_12	1028	341	81	0.34	0.05772	0.243	0.66740	0.674	0.08409	0.595	0.94	520.5	3.0	520.5	3.2	
S80_13	2578	620	146	0.24	0.05815	0.189	0.66520	0.676	0.08312	0.626	0.97	514.7	3.1	514.4	3.3	
S80_14	1430	302	68	0.21	0.05790	0.225	0.64450	0.652	0.08091	0.692	0.93	501.6	3.3	501.2	3.6	
S80_15	278	147	33	0.53	0.05793	0.552	0.64290	0.855	0.08043	0.758	0.80	498.7	3.6	498.2	3.9	
S80_16	1866	407	93	0.22	0.05778	0.242	0.65710	0.730	0.08257	0.630	0.94	511.4	3.1	511.3	3.3	
S80_17	368	186	42	0.50	0.05731	0.523	0.63650	0.943	0.08059	0.769	0.81	499.6	3.7	499.6	3.9	
S80_18	1955	477	106	0.24	0.05767	0.208	0.63290	0.695	0.07942	0.579	0.74	492.7	2.7	492.3	2.9	
S80_19	460	267	64	0.58	0.05753	0.348	0.66700	0.885	0.08430	0.830	0.91	521.7	4.1	521.9	4.5	
S80_20	1055	376	85	0.36	0.05749	0.296	0.65200	0.936	0.08238	0.862	0.94	510.3	4.2	510.3	4.5	
S80_21	1147	285	67	0.25	0.05746	0.313	0.66830	0.793	0.08432	0.818	0.92	521.8	4.1	522.1	4.4	
S80_22	3880	463	105	0.12	0.05862	0.157	0.64280	0.747	0.07977	0.715	0.98	494.8	3.4	493.8	3.6	
S80_23	4493	572	124	0.13	0.05839	0.127	0.63730	0.643	0.07936	0.643	0.98	492.3	3.1	491.5	3.2	
S80_24	4110	982	215	0.24	0.05836	0.137	0.66050	0.742	0.08223	0.742	0.98	509.4	3.6	508.9	3.9	
S80_25	1589	372	85	0.24	0.05794	0.242	0.65730	0.898	0.08239	0.898	0.97	510.3	4.4	510.1	4.7	
S80_26	451	254	57	0.56	0.05762	0.469	0.65900	0.865	0.08297	0.795	0.85	513.8	3.9	513.8	4.2	
S80_27	1295	333	73	0.26	0.05761	0.260	0.63670	0.754	0.08022	0.686	0.83	497.4	3.3	497.2	3.5	
S80_28	1779	543	119	0.31	0.05772	0.208	0.64240	0.825	0.08077	0.755	0.96	500.7	3.6	500.4	3.9	
S80_29	1236	255	56	0.21	0.05768	0.260	0.63130	0.998	0.07947	0.881	0.97	492.9	4.2	492.6	4.5	
S80_30	2875	715	164	0.25	0.05829	0.165	0.66440	0.707	0.08282	0.712	0.97	512.9	3.5	512.5	3.7	
S80_31	108	57	16	0.53	0.08033	1.145	0.84300	1.423	0.07608	0.802	0.51	472.6	3.7	459.1	3.8	
S80_32	2454	545	124	0.22	0.05780	0.190	0.65340	0.689	0.08226	0.620	0.96	509.6	3.0	509.4	3.2	
S80_33	400	200	45	0.50	0.05734	0.331	0.63860	0.861	0.08095	0.741	0.90	501.8	3.6	501.7	3.8	
S80_34	1605	427	99	0.27	0.05765	0.225	0.67660	0.813	0.08503	0.764	0.92	526.1	3.9	526.2	4.1	
S80_35	4620	826	0	0.18	-7.08000	-5.508	-0.00053	-28.302	0.00000	22.248	-0.72	0.0	0.0	0.0	0.0	
S80_36	2530	374	81	0.15	0.05771	0.225	0.66600	0.465	0.08372	0.442	0.88	518.3	2.2	518.3	2.4	
S80_37	1289	351	84	0.28	0.05746	0.244	0.67080	0.537	0.08471	0.425	0.90	524.2	2.1	524.4	2.3	
S80_38	3756	593	138	0.16	0.05824	0.170	0.65880	0.410	0.08212	0.329	0.94	508.8	1.6	508.3	1.7	
S80_39	2414	557	126	0.23	0.05807	0.207	0.64740	0.355	0.08100	0.284	0.70	502.1	1.4	501.6	1.5	
S80_40	1691	368	82	0.22	0.05766	0.208	0.63920	0.375	0.08044	0.286	0.89	498.8	1.4	498.5	1.5	
S60_001	555	201	47	0.36	0.05762	1.305	0.62790	1.420	0.07858	0.560	0.80	487.7	3.6	487.2	2.8	
S60_002	861	252	61	0.30	0.05719	1.222	0.63980	1.565	0.08134	0.977	0.78	504.1	3.1	504.2	5.1	
S60_003	1553	421	100	0.28	0.05607	1.125	0.63010	1.272	0.08126	0.594	0.91	503.6	4.2	504.4	3.1	
S60_004	963	311	74	0.33	0.05614	1.160	0.62060	1.288	0.08069	0.560	0.84	500.2	3.9	500.9	2.9	
S60_005	280	127	30	0.46	0.05566	0.826	0.61290	1.239	0.08046	0.923	0.65	498.9	2.8	499.8	4.7	
S60_006	191	80	19	0.42	0.05687	0.897	0.63320	1.046	0.08094	0.538	0.64	501.7	3.7	502.0	2.8	
S60_007	462	127	32	0.28	0.05673	1.490	0.64150	1.807	0.08222	1.021	0.63	509.4	3.6	509.8	5.4	
S60_008	969	282	66	0.29	0.05696	1.189	0.62490	1.312	0.08035	0.556	0.90	498.2	3.8	498.3	2.9	
S60_009	316	128	31	0.41	0.05780	0.779	0.64700	0.947	0.08149	0.540	0.67	505.0	3.7	504.7	2.8	
S60_010	547	198	48	0.36	0.05828	1.333	0.63270	1.671	0.07967	1.008	0.74	494.1	3.0	493.4	5.1	
S60_011	386	121	30	0.31	0.05834	0.754	0.64700	1.292	0.08133	1.050	0.68	504.1	3.4	503.4	5.4	
S60_012	274	124	31	0.46	0.05827	0.875	0.64800	1.304	0.08143	0.967	0.61	504.6	2.9	504.1	5.0	
S60_013	245	93	23	0.38	0.05840	0.890	0.64730	1.355	0.08102	1.021	0.56	502.2	3.2	501.5	5.3	

Table 3

Sample Name	Concentrations (ppm)				Measured Isotopic Ratios									measured Isotopic Age	
	Pb	U	Th	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	2s %	²⁰⁷ Pb/ ²³⁵ U	2s %	²⁰⁶ Pb/ ²³⁸ U	2s %	Rho	²⁰⁸ Pb/ ²³² Th	2s %	²⁰⁸ Pb/ ²³² Th	2s abs
C-65_001	67	11820	51900	4.39	0.0523	1.86	0.0256	2.347	0.00355	1.717	0.68	0.001147	2.131	23.2	0.5
C-65_002	72	11140	54000	4.85	0.0507	1.84	0.0260	2.075	0.00372	1.424	0.50	0.001158	1.854	23.4	0.4
C-65_003	85	9800	63500	6.48	0.0530	2.08	0.0265	2.298	0.00362	1.272	0.43	0.001170	1.668	23.6	0.4
C-65_004	69	11920	53100	4.45	0.0487	1.68	0.0254	2.202	0.00376	1.277	0.57	0.001149	1.605	23.2	0.4
C-65_005	67	10430	49200	4.72	0.0500	2.20	0.0258	2.833	0.00369	1.381	0.51	0.001173	1.664	23.7	0.4
C-65_006	65	17090	50500	2.95	0.0490	1.39	0.0245	1.963	0.00361	1.496	0.68	0.001127	1.808	22.8	0.4
C-65_007	75	8560	56300	6.58	0.0517	2.32	0.0274	2.812	0.00383	1.514	0.55	0.001174	1.918	23.7	0.5
C-65_008	73	6840	53800	7.87	0.0528	2.46	0.0290	2.763	0.00396	1.414	0.53	0.001163	1.848	23.5	0.4
C-65_009	98	6280	64200	10.22	0.0561	2.14	0.0344	2.353	0.00447	1.455	0.47	0.001331	1.878	26.9	0.5
C-65_010	67	16390	50900	3.11	0.0495	1.80	0.0241	1.989	0.00359	1.423	0.55	0.001160	1.938	23.4	0.5
C-65_011	66	13050	50600	3.88	0.0507	1.70	0.0270	2.594	0.00384	1.640	0.71	0.001143	2.137	23.1	0.5
C-65_012	60	6260	38700	6.18	0.0535	2.24	0.0322	2.767	0.00434	1.497	0.54	0.001351	1.928	27.3	0.5
C-65_013	62	16270	46500	2.86	0.0499	1.74	0.0247	2.106	0.00355	1.154	0.51	0.001164	1.503	23.5	0.4
C-65_014	74	7410	55300	7.46	0.0528	2.08	0.0290	2.931	0.00395	1.316	0.60	0.001157	1.769	23.4	0.4
C-65_015	87	9290	65000	7.00	0.0532	2.07	0.0269	2.643	0.00364	1.319	0.63	0.001161	1.764	23.5	0.4
C-65_016	76	11570	56100	4.85	0.0498	1.73	0.0256	2.113	0.00376	1.488	0.67	0.001181	1.993	23.9	0.5
C-65_017	78	8720	58700	6.73	0.0508	1.97	0.0272	2.461	0.00388	1.496	0.52	0.001163	1.762	23.5	0.4
C-65_018	70	13740	52800	3.84	0.0507	1.40	0.0252	2.107	0.00364	1.677	0.66	0.001175	1.917	23.7	0.5
C-65_019	68	15350	51600	3.36	0.0500	1.44	0.0245	2.166	0.00358	1.958	0.71	0.001153	2.121	23.3	0.5
C-65_020	64	9580	47700	4.98	0.0499	2.20	0.0258	2.250	0.00379	1.372	0.50	0.001170	1.838	23.6	0.4
C-65_021	77	17120	57500	3.36	0.0501	1.70	0.0244	2.414	0.00356	1.545	0.70	0.001155	1.772	23.3	0.4
C-65_022	67	8700	49500	5.69	0.0514	2.33	0.0271	3.026	0.00375	1.815	0.59	0.001161	2.195	23.5	0.5
C-65_023	64	15630	48300	3.09	0.0483	1.47	0.0244	2.299	0.00368	1.551	0.71	0.001169	2.096	23.6	0.5
C-65_024	69	8740	50600	5.79	0.0516	2.33	0.0266	2.972	0.00371	1.781	0.64	0.001179	2.336	23.8	0.6
C-65_025	64	7540	46080	6.11	0.0511	2.54	0.0266	2.783	0.00381	1.705	0.53	0.001210	2.283	24.4	0.6
C-65_026	71	10850	52300	4.82	0.0503	2.19	0.0265	3.014	0.00383	1.595	0.65	0.001188	2.236	24.0	0.5
C-65_027	72	8310	52700	6.34	0.0523	1.91	0.0286	2.410	0.00394	1.421	0.47	0.001180	1.741	23.8	0.4
C-65_028	64	14030	47500	3.39	0.0492	1.56	0.0247	2.230	0.00362	1.739	0.69	0.001167	2.271	23.6	0.5
C-65_029	77	8730	57600	6.60	0.0502	2.19	0.0257	2.721	0.00374	1.497	0.59	0.001183	2.244	23.9	0.5
C-65_030	60	14030	44270	3.16	0.0498	1.79	0.0272	2.425	0.00397	1.536	0.65	0.001167	1.928	23.6	0.5
C-65_032	64	10060	47800	4.75	0.0497	2.21	0.0257	2.806	0.00374	1.525	0.59	0.001175	1.917	23.7	0.5
C-65_033	71	11870	53100	4.47	0.0492	1.69	0.0256	2.269	0.00373	1.581	0.66	0.001170	1.924	23.6	0.5
C-65_034	76	12010	57200	4.76	0.0475	1.81	0.0247	2.634	0.00380	1.606	0.79	0.001151	2.125	23.2	0.5
C-65_035	67	13660	50200	3.67	0.0509	1.67	0.0253	2.213	0.00359	1.391	0.64	0.001165	1.845	23.5	0.4
C-65_036	66	15700	48900	3.11	0.0499	1.42	0.0250	2.201	0.00363	1.542	0.79	0.001178	1.828	23.8	0.4
C-65_037	67	7930	49600	6.25	0.0492	2.24	0.0258	2.825	0.00384	1.799	0.54	0.001181	2.078	23.9	0.5
C-65_038	65	14510	49700	3.43	0.0487	1.50	0.0240	2.039	0.00353	1.388	0.63	0.001144	1.961	23.1	0.5
C-65_039	75	13340	54700	4.10	0.0510	1.88	0.0253	2.137	0.00364	1.539	0.50	0.001181	1.824	23.9	0.4