

U–Pb monazite ages from the Pakistan Himalaya record pre-Himalayan Ordovician orogeny and Permian continental breakup

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ABSTRACT

The Greater Himalayan sequence in India and Nepal records crustal thickening processes during and following the onset of India–Asia collision (ca. 54–50 Ma), which resulted in Late

Eocene–Early Miocene kyanite- and sillimanite-grade regional metamorphism, and Oligocene–Miocene crustal anatexis forming migmatites and leucogranites. In the Pakistan Himalaya, these events are not recorded in the exposed rocks beneath the obducted Kohistan island arc. Instead, the kyanite-grade gneiss of the Besham Group and sillimanite-grade gneiss of the calcareous Alpurai schist record U–Pb monazite ages of 482.4 ± 7.9 Ma and 464.5 ± 4.0 Ma, respectively. These ages, together with along-strike equivalent rocks in the Lesser Himalaya of India and Nepal, record an Ordovician-age orogeny (the Bhimpedian orogeny) spanning at least from 490 to 460 Ma, following Neoproterozoic–Cambrian sedimentation, and preceding late Ordovician–Silurian post-orogenic molasse deposition and development of a stable shelf margin at 460–440 Ma. These new ages for peak metamorphism in the Pakistan Himalaya overlap with those of widespread S-type granites occurring along the Lesser Himalaya (e.g. Mansehra, Mandi, and Kathmandu granites), Greater Himalaya (e.g. Nanga Parbat, Kinnaur Kailas, and Ama Drime), and in the North Himalayan domes (e.g. the Tso Moriri, Kangmar, and Kampa domes). We suggest that in Pakistan, the unexposed Tethyan and Greater Himalayan sequences have been overthrust by the Kohistan arc, and the Besham–Alpurai gneisses are equivalent to Lesser Himalayan rocks to the east.

Keywords: Pakistan, Himalaya, Bhimpedian orogeny, high-grade metamorphism, monazite

INTRODUCTION

The collision of India with Asia and closure of the intervening Neotethys Ocean at ~54–50 Ma resulted in crustal shortening and thickening, regional-scale Barrovian kyanite- and sillimanite-grade metamorphism, and melting to form migmatites and leucogranites. The timing

of these events along the main Himalayan range in India, Nepal, Bhutan and South Tibet is well constrained by U–Pb monazite and zircon geochronology, and shows three main stages of metamorphism: (1) an ultrahigh-pressure (UHP) eclogite-facies event (~27.5–25.5 kbar, 630–650 °C) recorded at Kaghan, Pakistan, and Tso Moriri, India, at ~51–46 Ma (Kaneko et al., 2003; Parrish et al., 2006; Wilke et al., 2010; St-Onge et al., 2013), (2) a high-pressure kyanite event (9.5–10.5 kbar; 650–620 °C) at ~37–29 Ma (Searle et al., 1992, 1999; Walker et al., 1999, 2001), and (3) a sillimanite-grade event leading to migmatization and crustally-derived leucogranites from ~24–11 Ma (Noble and Searle, 1995; Searle et al., 1999, 2003, 2010; Godin et al., 2001, 2006; Cottle et al., 2009a). In the Nanga Parbat syntaxis, a fourth event (4) is recorded by Pliocene–Pleistocene sillimanite- and cordierite-bearing migmatites with leucogranites as young as 1.7 Ma, which formed at ~5 kbar (Crowley et al., 2009; Searle, 2015).

Although the geometry and timing of Cenozoic-aged deformation, metamorphism, and crustal anatexis in the Indian Plate of the Main Himalayan range in India and Nepal is well established, that in the Indian Plate of North Pakistan to the west of the Nanga Parbat syntaxis is more ambiguous (Fig. 1). There are significant differences between the Indian Plate rocks exposed in the Himalayan range east of the Nanga Parbat syntaxis and those exposed in North Pakistan. In the Pakistan sector, Indian Plate rocks were subducted beneath the Kohistan island arc along the footwall of the Main Mantle Thrust (MMT), a feature for which no analogue exists in the main Himalayan range. In Pakistan, no thick sedimentary sequence analogous to the Tethyan Himalayan Series crops out; there is no evidence for Miocene high-grade metamorphism, anatexis and leucogranite emplacement; the metamorphic peak appears to pre-date 40 Ma; and there is no obvious evidence of a Main Central Thrust (MCT) separating rocks of the Lesser Himalayan Sequence from rocks of the Greater Himalayan Sequence.

In North Pakistan, the Early Cenozoic metamorphic phase in the North Indian Plate was effectively over even before the Eo-Himalayan (Eocene–early Miocene) metamorphic peak in the main Himalayan range. Evidence for prograde regional metamorphism comes mainly from the coesite eclogites that crop out in Permo-Triassic rocks in the Upper Kaghan Valley on the footwall of the Main Mantle Thrust. Here, a number of chronometers date UHP peak metamorphism at ca. 47 Ma (Kaneko et al., 2003; Treloar et al., 2003; Parrish et al., 2006; Wilke et al., 2010; Rehman et al., 2013). In addition, Foster et al. (2002) used Sm–Nd garnet dating techniques to suggest that Barrovian metamorphism in the Upper Kaghan Valley, to the south of the coesite eclogites, reached a peak at 45 Ma. These data imply that Barrovian metamorphism in rocks of the northern Indian Plate in North Pakistan was synchronous with UHP metamorphism. No other peak metamorphic ages are recorded from the Pakistan Himalayan. However, hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ dating from across the region shows that cooling back through 500 °C occurred regionally at about 40 Ma (see references in Treloar, 1997). As initial India–Asia collision in the northwest Himalaya is conservatively dated at no older than 55 Ma (Wu et al., 2014; Hu et al., 2016; Ding et al., 2016), and the youngest Tethyan oceanic rocks along the Indus suture and North Indian plate margin are 50.5 Ma (Green et al., 2008), these data suggest that peak metamorphic conditions were achieved very soon after the onset of collision. Such rapid, and short-lived, regional metamorphism may not be unusual in collisional orogenic belts through time, worldwide. In a recent review article, Viete and Lister (2016) suggest that rapid, short-lived metamorphic pulses are common, and that the simple model of Barrovian metamorphism taking place over many tens of millions of years, as implied by thermal relaxation models (England and Thompson, 1984), is probably incorrect.

In this work, our initial intention was to confirm the timing of Cenozoic-aged Barrovian metamorphism indicated by Foster et al. (2002), to confirm that the UHP and Barrovian events were indeed synchronous, and to confirm the regional extent of that metamorphism. To do this, monazites from schistose and gneissose samples for which P – T data had previously been published (Treloar et al., 1989a; Treloar, 1997) were analyzed using U–Pb dating techniques. As will be shown, the data produced some unexpected results which have the effect of enabling us not just to answer some long-standing questions that pertain to the Pakistan Himalaya south of the suture zone, but also to comment critically on the pre-Himalayan thermal history of the North Indian Plate.

THE INDIAN PLATE IN NORTH PAKISTAN

During Himalayan collision, the Indian Plate was subducted beneath the Kohistan Island Arc along the MMT. Blueschists exposed along the suture zone yield muscovite Ar–Ar cooling ages of ca. 80 Ma (Anczkiewicz et al., 2000), which do not necessarily date India–Asia collision, but likely relate to the timing of accretion to the Kohistan Island Arc. UHP coesite-bearing eclogites with depths of metamorphism of ca 25 kbar (O’Brien et al., 2001) yielded peak metamorphic ages of ca ~47 Ma (Kaneko et al., 2003), which also do not date the timing of collision between Kohistan and the leading edge of the Indian Plate. Subduction of continental rocks beneath oceanic lithosphere is known to occur beneath obducted ophiolites prior to any continental collision, for example as seen in Oman (Searle et al., 2004).

The stratigraphy of the Indian Plate rocks of North Pakistan is now well established and has been summarized in detail by DiPietro et al. (1993, 1999) and Pogue et al. (1999). Fundamentally, it can be divided into a Paleo-Proterozoic basement, a Neo-Proterozoic sequence

of clastic sediments intruded by Ordovician granites, and a carbonate-rich shelf sequence unit that was deposited over a period ranging from the Carboniferous through to the Triassic.

A Paleo-Proterozoic metamorphic complex dominated by biotite gneisses forms the basement to later sediments. Termed the Besham Complex by Treloar et al. (1989a) this has been subsequently differentiated into a number of units by DiPietro et al. (1999). Of these, felsic intrusions into the Kishar Unit yield zircon ages of 2157 ± 7 Ma (DiPietro and Isachsen, 2001). The Karora complex, which broadly equates to the Besham Complex of Treloar et al. (1989b), is dated by two different mechanisms. The Shang granite yields a zircon U–Pb age of 1858 ± 17 Ma (DiPietro and Isachsen, 2001). This is consistent with hornblende Ar–Ar cooling ages from high grade metabasic rocks of about 1860 Ma reported by Treloar and Rex (1990a, b) which clearly date a major thermal event. It is notable that these amphibole Ar–Ar ages show no sign of a Cenozoic metamorphic imprint, despite being located only a few kilometers south of the Main Mantle Thrust (Fig. 1).

The basement complex is overlain by argillaceous to arenaceous sediments of the Tanawal Formation which have a probable turbiditic origin. Although there is no clear age for these sediments they are intruded by the Mansehra, Utlā, and Swat granites. These are all biotite-rich, K-feldspar phenocrystic, peraluminous S-type granites. The Mansehra granite has been dated using Rb–Sr whole rock techniques at 516 ± 16 Ma (Le Fort et al., 1980). DiPietro et al. (1999) cited an unpublished U–Pb zircon age for the Swat Granite of 468 ± 5 Ma. In the type area of the Indus Valley, rocks of the Tanawal Formation are metamorphosed to sillimanite grade along a typical Barrovian type sequence (Calkins et al., 1975; Treloar et al., 1989a; Treloar, 1995, 1997). This sequence is similar to that described more recently from the Kaghan Valley by Rehman et al. (2007). These workers have all assumed that this metamorphism was Cenozoic in age and

related to the Himalayan collision. Other than the garnet Sm–Nd age reported by Foster et al. (2002), there are no mineral age data that date peak metamorphism for these rocks. However, hornblende Ar–Ar age data (Treloar and Rex, 1990a, b) that date cooling though ~500 °C at ca. 40 Ma support this assumption.

The Alpurai Group is a dominantly calcareous sedimentary sequence which includes limestones, calc-arenites, arenites, argillites and, in places, mafic sills. Full details of the stratigraphy of the Alpurai Group are given by DiPietro et al. (1993, 1999). Faunal evidence is limited but conodont fossils date the lower part of the sequence (Marghazar Formation) as mid Carboniferous and middle parts of the sequence (Kashala Formation) as Late Triassic (Pogue et al., 1992). Intercalated mafic units in the Kashala Formation have been correlated with Permo–Triassic Panjal Trap units elsewhere in the Himalayan range (DiPietro et al., 1999). Rocks of the Alpurai Group can be correlated with interbedded calcareous, argillitic and meta-basic units in the Upper Kaghan Valley where they have been metamorphosed to UHP conditions (O’Brien et al., 2001; Parrish et al., 2006). In their type area in the Swat Valley, kyanite-bearing Alpurai Group rocks have been metamorphosed, along paths of increasing pressure and temperature, to pressures of 12 kbar at temperatures of ca 600 °C (Treloar et al., 1989b). Hornblende Ar–Ar age data (Treloar and Rex, 1990a, b) that date cooling though 500 °C at ca. 40 Ma imply an Early Cenozoic age for this metamorphism. This is consistent with peak metamorphic ages from stratigraphically equivalent UHP (Kaneko et al. 2003; Rehman et al., 2013) and medium-pressure (~8–10 kbar; Foster et al., 2002) rocks from the Upper Kaghan Valley, which also show hornblende cooling ages of ca. 40 Ma.

PETROGRAPHY AND MINERAL CHEMISTRY

Five metasedimentary samples from the Hazara Nappe were analyzed in this study in order to determine their individual thermobarometric and geochronologic histories: two from the staurolite zone (625 and 626), two from the kyanite zone (755D and 756), and one from the sillimanite zone (RB169). Mineral compositional data were obtained on a JEOL JXA-8200 electron microprobe housed at the Institute of Geosciences, Johannes-Gutenberg University of Mainz, Germany. Operating conditions included an acceleration voltage of 15 kV, a beam current of 12 nA, and a spot size of 2 μ m. A matrix correction for atomic number, absorption, and fluorescence was automatically applied to all analyses. For the data presented below, mineral compositions were recalculated to a standard number of oxygens per formula unit (pfu), with H₂O assumed to be present in stoichiometric amounts. Where relevant, the proportion of ferric iron was estimated using the software AX (Holland, 2009). Representative mineral compositions from each sample are given in Table S1

Staurolite zone

Samples 625 and 626 are pelitic schists with strongly foliated matrices comprised of muscovite, biotite, ilmenite, and quartz, with accessory apatite, monazite, tourmaline, and zircon. Both samples were collected from adjacent outcrops situated approximately 20 km due west of Balakot (Fig. 2). While plagioclase was observed in minor proportion in sample 626, it is absent from sample 625. Garnet and staurolite porphyroblasts up to 4 mm in diameter in both samples contain rare quartz inclusions, and are both wrapped by the matrix foliation (Fig. 3a–b). Chlorite occurs within garnet strain shadows in sample 625. Garnet porphyroblasts in each sample show prominent and similar compositional zoning, with Fe and Mg contents increasing from core to rim, and Ca contents decreasing. Spessartine showed typical bell-shaped profiles in all analyzed

grains, with almost-zero concentrations at outer rims, indicating the preservation of prograde growth zoning (Woodsworth, 1977) and a lack of post-peak resorption and/or diffusional re-equilibration (Kohn and Spear, 2000). Staurolite exhibits no compositional variation within or between grains in either sample, with XMg values of 0.14–0.15 for sample 625 and 0.14–0.16 in sample 626. Plagioclase in sample 626 had XCa [=Ca/(Ca+Na+K)] of 0.10–0.13. Biotite in both samples exhibited similar compositions, with XMg = 0.41–0.47 and Ti = 0.08–0.10 cations pfu (for 11 oxygens) in sample 625, and XMg = 0.41–0.46 and Ti = 0.07–0.10 cations pfu in sample 626 (Table S1).

Kyanite zone

Samples 755D and 756 were collected from separate outcrops approximately 30 km south-southeast of Besham (Fig. 2), and have broadly similar petrographic features. Sample 755D exhibits a crenulated matrix foliation composed of alternating muscovite- and biotite-rich bands, and quartz- and plagioclase-rich bands (Fig. 3c). Accessory tourmaline, monazite, zircon, and pyrite are present in the matrix. Kyanite occurs as abundant, small laths (~1 mm in length) aligned with and wrapped by the matrix foliation. Garnet porphyroblasts up to 3 mm in diameter have inclusion-rich cores and are also wrapped by the matrix foliation. Included phases comprise biotite, muscovite, staurolite, kyanite and ilmenite (Fig. 3d), although staurolite does not occur within the matrix. Porphyroblasts exhibit weak compositional zonation in Ca and Mn contents, whereas Fe and Mg show no variation from core to rim. The absence of Mn inflections at porphyroblast–matrix interfaces infers the lack of retrograde resorption (Kohn and Spear, 2000), indicating that outer rim compositions likely represent those attained at peak metamorphic conditions. Plagioclase is compositionally similar throughout the sample, with XCa = 0.27–0.29,

and staurolite inclusions have $XMg = 0.15\text{--}0.22$. Biotite shows slight compositional variation according to petrographic position, with garnet-core inclusions exhibiting $XMg = 0.52\text{--}0.55$ and $Ti = 0.14\text{--}0.17$ cations pfu, and matrix grains exhibiting $XMg = 0.49\text{--}0.54$ and $Ti = 0.16\text{--}0.23$ cations pfu (Table S1).

Sample 756 similarly contains a biotite–muscovite–plagioclase–quartz matrix, but lacks staurolite, has notably smaller garnet grains (~1–2 mm in length) than sample 755D (Fig. 3e), and small (<0.1 mm), rare kyanite exhibits anhedral morphologies. Tourmaline, apatite, and monazite are additionally present as accessory phases. Matrix plagioclase clasts exhibit weak sigma-shaped strain shadows, indicating that the sample may have experienced shearing during or after metamorphism. Garnet lacks significant compositional zoning in Fe and Mg, but outer rim domains are relatively Ca-enriched and Mn-depleted compared to cores. Plagioclase exhibits $XCa = 0.18\text{--}0.23$, and biotite has $XMg = 0.49\text{--}0.51$ and $Ti = 0.17\text{--}0.24$ cations pfu (Table S1).

Sillimanite zone

Sample RB169 is a semi-pelitic schist characterized by millimeter-scale quartz–plagioclase–K-feldspar bands and thin biotite–sillimanite–ilmenite bands that together define a weakly crenulated schistosity. Anhedral garnet porphyroblasts up to ~2 mm in length are elongate and aligned with the matrix foliation, which wraps around them. Small (<0.2 mm) subhedral kyanite grains occur in close association with prismatic sillimanite (Fig. 3f). Accessory monazite, zircon, and apatite also occur. Chlorite occurs solely within garnet fractures, and thus is interpreted as retrograde. Garnet porphyroblasts exhibit no notable compositional variation within or between grains, with typical compositions of $Alm_{82}Prp_5Grs_3Sps_{10}$. Plagioclase exhibits $XCa = 0.23\text{--}0.34$, and biotite has $XMg = 0.48\text{--}0.55$ and $Ti = 0.20\text{--}0.26$ cations pfu (Table S1).

THERMOBAROMETRY

The pressure–temperature (P – T) conditions of peak metamorphism for each sample were determined via two independent methods: the Ti-in-biotite thermometer of Henry et al. (2005) and the average P – T ‘optimal thermobarometry’ method of Powell and Holland (1994) using THERMOCALC (Powell et al., 1998) and the internally-consistent thermodynamic dataset of Holland and Powell (2011). While individual conventional thermobarometers are known to carry significant uncertainties on the order of at least ± 50 °C and ± 1 kbar at 1 S.D. (Powell and Holland, 2008), the Ti-content of biotite that equilibrated in the presence of Al- and Ti-saturating phases is accurate to ± 12 – 24 °C at the same confidence interval for rocks that equilibrated at medium pressure crustal conditions (4–6 kbar), and so provides a more suitable indication of peak metamorphic conditions.

The analyzed Ti contents and XMg ratios of fabric-forming biotite in all samples are shown on Fig. 4a, and indicate that staurolite-zone samples 625 and 626 reached maximum temperatures of ~ 610 – 620 °C, kyanite-zone samples 755D and 756 reached ~ 725 °C, and sillimanite-zone sample RB169 reached peak metamorphic temperatures of ~ 720 °C. These results are consistent with the average P – T results using THERMOCALC (Table 1), which additionally gives pressures of ~ 7.1 – 7.2 kbar (staurolite zone), 7.4–7.9 kbar (kyanite zone), and 6.3 kbar (sillimanite zone), equivalent to crustal depths of 20–25 km (Fig. 4b).

These P – T data for Hazara Nappe units are notably different from those documented along strike in the main Himalayan Range east of the western syntaxis (Nanga Parbat; Fig. 1). Predicted P – T paths for THS, LHS, and GHS lithologies based on lithospheric-scale modeling of India–Asia collision (Jamieson et al., 2004) are shown on Fig. 4b by dotted lines, and match

thermobarometric data reported by numerous workers showing a high-pressure kyanite-grade event in the GHS (9.5–10.5 kbar; 650–620 °C) at ~37–29 Ma (Searle et al., 1992, 1999; Walker et al., 1999, 2001), followed by a sillimanite-grade event with associated migmatization at ~24–11 Ma (Noble and Searle, 1995; Searle et al., 1999, 2003, 2010; Godin et al., 2001, 2006; Cottle et al., 2009a). The Hazara Nappe samples documented herein show notably lower-grade conditions than those from the central Himalayan GHS, and more closely resemble the evolution of LHS units (Fig. 4b). Moreover, the P – T conditions predicted here suggest that partial melting would have been relatively minor, with only the peak metamorphic conditions for the highest-grade samples (756 and RB159) being sufficiently high for muscovite breakdown melting (Fig. 4b).

U–PB MONAZITE GEOCHRONOLOGY

All geochronological analyses utilized *in-situ* laser ablation from thin section in order to provide a robust petrographic context to the age data obtained. All geochronological analyses were performed at the Institute for Geosciences, Johannes Gutenberg University of Mainz, Germany, on an Agilent 7500ce quadrupole inductively coupled plasma mass spectrometer (ICP-MS) coupled with a ESI NWR193 laser ablation system equipped with the TwoVol² ablation cell. Laser ablation was performed using a 30 µm spot size, 10 Hz frequency, and 2.8 J/cm² fluence. Twenty-second-long background measurements were followed by a 30-s ablation time and 20-s washout. All isotopic data were normalized to the primary monazite reference material 44069 (Aleinikoff et al., 2006), with secondary reference materials Moacir (Palin et al., 2013), Madel (Payne et al., 2008), and TMM (Williams et al., 1996) used as quality controls. Data

processing and uncertainty propagation was performed by an in-house Excel spreadsheet (Richter, 2013).

All U–Pb sample data were interpreted using Tera-Wasserburg plots and all calculations were performed using the Isoplot MS Excel add-in (Ludwig, 2003). Where distinct populations were not apparent, regressions were used to delimit durations of crystallization and a generalized age range is given. Absolute errors are provided only for regressed populations with a calculated MSWD value. Regressions assumed a $^{207}\text{Pb}/^{206}\text{Pb}$ ratio of 0.83 ± 0.02 ; a composition representing that acquired during Phanerozoic mineral growth (Stacey and Kramers, 1975). Calculated ^{238}U – ^{206}Pb ages are accurate to ~3% according to contemporaneous measurement of primary and secondary standards, which produced ^{238}U – ^{206}Pb ages of 425.2 ± 4.6 Ma for 44069 (424.0 ± 3.0 Ma (2 S.D.); SHRIMP; Aleinikoff et al., 2006), 512 ± 12 Ma for Moacir (515.6 ± 1.4 Ma (2 S.D.), ID-TIMS; Palin et al., 2013), 515.3 ± 8.2 Ma for Madel (513.9 ± 1.6 Ma (2 S.D.), ID-TIMS; Payne et al., 2008), and 1762 ± 14 Ma for TMM (1766.0 ± 0.3 Ma (2 S.D.), ID-TIMS; Williams et al., 1996). All ellipses on Tera-Wasserburg plots and uncertainties are given at the 2σ level. All U–Pb geochronological data are given in Table S2.

Staurolite zone

Monazite in sample 625 occurred within the matrix and as inclusions in garnet porphyroblast cores, although many of the latter grains were too small to be analyzed by LA-ICP-MS ($<10\text{ }\mu\text{m}$). Larger matrix grains were generally anhedral, 30–60 μm in diameter, and exhibited no internal zonation in BSE images. Sixteen spot analyses were obtained from nine different grains throughout the sample, although four were discarded due to having poor ablation profiles. All other data lie close to concordia on a Tera-Wasserburg plot (Fig. 5a). All spot

analyses considered together ($n = 12$) produced a U–Pb lower-intercept age of 268.1 ± 4.3 Ma (2σ , MSWD = 2.9), whereas lower-intercept age of 267 ± 4.7 Ma (2σ , MSWD = 3.0) was obtained when considering only monazite grains in the matrix ($n = 10$; Fig. 5a), which we interpret to date peak metamorphism.

Sample 626 contained abundant and large monazite grains (up to 100 μm in diameter) situated both as inclusions in garnet porphyroblasts and in the matrix. Many grains showed a degree of chaotic internal zoning in their cores in BSE images, but generally homogenous rim domains. Thirty-five spot analyses were obtained from 14 grains, of which two were rejected due to poor ablation profiles. The remaining thirty-three analyses form a tight cluster on the Tera-Wasserburg plot (Fig. 5b) and are interpreted as a single population with a U–Pb lower-intercept age of 272.9 ± 2.2 Ma (2σ , MSWD = 2.3). Grains included within garnet showed no systematic age difference from those grains situated in the matrix. Thus, this age is interpreted to date peak metamorphism in sample 626, and is very similar (and within error) of that produced from monazite in sample 625.

Kyanite zone

Sample 755D was relatively monazite-poor in comparison to the other samples investigated in this study, although contained few, small (10–40 μm in diameter) grains within the matrix and as inclusions within garnet cores. Seventeen spot analyses were obtained from seven grains, with two analyses rejected due to poor ablation profiles. These data displayed a large spread along concordia on a Tera-Wasserburg plot, and exhibited no systematic trends between age and petrographic position (Fig. 5c). Although the interpretation of such data is difficult, four analyses obtained from two grains were interpreted to form a small population

with a U–Pb lower-intercept age of c. 461 Ma, and all-but-one of the remaining analyses exhibited lower-intercept ages in the range c. 793–608 Ma (Fig. 5c). In addition, a single analysis obtained from a small monazite grain situated in the matrix produced a U–Pb lower-intercept outlier age of c. 353 Ma.

Sample 756 contained abundant monazite within the matrix and as inclusions within garnet rims, although all grains were relatively small (10–40 μm in diameter). Twenty-four spot analyses were obtained from 11 grains within garnet and the matrix, although one was discarded due to its poor ablation profile. In contrast to sample 755D, age data obtained from monazite in sample 756 showed a clear correlation with petrographic position: inclusions in garnet rims ($n = 7$) were systematically older than those within the matrix (Fig. 5d), with U–Pb lower-intercept ages spread along concordia between c. 621 Ma and c. 507 Ma. The remaining 17 spot analyses obtained from six matrix grains were more clustered and treated as a single population, and produced a U–Pb lower-intercept age of 482.4 ± 7.9 Ma (2σ , MSWD = 4.4) (Fig. 5d). This age is taken to be representative of the timing of peak metamorphism in the kyanite zone of the Hazara Nappe region.

Sillimanite zone

Owing to the lack of garnet and other porphyroblasts, monazite in sample RB169 occurred exclusively in the matrix. Grains exhibited no systematic internal compositional or textural zoning. Thirty spot analyses were obtained from nine grains, of which four spot analyses on two grains were rejected due to poor ablation profiles. The remaining 26 analyses contained negligible common lead, and produced a concordant U–Pb age of 464.5 ± 4.0 Ma (2σ , MSWD =

0.2) (Fig. 5e), which is taken to represent the timing of sillimanite-grade metamorphism in the region.

DISCUSSION

None of the three samples dated here produced Cenozoic Himalayan ages of metamorphism as expected from existing interpretations of the area. Instead, the kyanite- and sillimanite-grade gneisses have robust Ordovician ages, in common with several well-dated granites from the Lesser Himalaya, and the staurolite-grade schist gave a Permian age, similar to a few S-type granites in the Greater Himalayan Sequence in Suru valley of Zaskar, in the Indian Himalaya (Noble et al., 2001). We now discuss these two pre-Himalayan events in the context of the dated samples from the Pakistan Himalaya.

Ordovician Bhimpedian orogeny

Figure 6 shows a Neoproterozoic–Silurian time chart for the Himalaya showing the known stratigraphic ages together with U–Pb zircon and monazite age data on granites and metamorphic rocks. A comprehensive review of the Cambrian–Ordovician stratigraphy along the Himalaya in India and Nepal (Myrow et al., 2006, 2009, 2016) shows that the Cambrian was a time of relatively stable sedimentation along the Indian plate. The youngest pre-orogenic biostratigraphic ages from sedimentary rocks are Late Cambrian from Kashmir through India to Nepal and Bhutan. These rocks include the Karsha Formation in Zaskar (Gaetani and Garzanti, 1991), the Sanctuary and Annapurna Yellow Formations in Annapurna (Searle and Godin, 2003) and the Yellow Band below the summit of Everest (Searle et al., 2003; Myrow et al., 2009). Following the Upper Cambrian, a biostratigraphic gap in the sedimentary record lasting between ~36 Ma

(maximum) to 22 million years (minimum) from ~490 Ma to ~460 Ma is evident before post-orogenic Late Ordovician molasse-type sediments were deposited above a regional Cambrian unconformity (Myrow et al., 2016).

A number of U–Pb zircon ages of granites occur in this upper Cambrian–Ordovician gap. These include many peraluminous S-type granites along the Lesser Himalaya, such as the Mandi granite in India (Miller et al., 2001), and the Palung and Simchar granites from the Kathmandu area in Nepal (Schärer and Allègre, 1983; Gehrels et al., 2003, 2006). Similar U–Pb zircon ages of granites that have been preserved from the overprinted Cenozoic Himalayan thermal events have been published from along the Greater Himalayan Sequence structurally above the Main Central Thrust. These include the Kinnaur Kailash (Marquer et al., 2000) and Temasa (Pognante et al., 1990) granites, and protoliths of the Leo Pargil and Ama Drime (Cottle et al., 2009b) granitic orthogneisses. Similar ages have also been published from the North Himalayan domes, including the Tso Moriri and Rupshu granites in India (Girard and Bussy, 1999), the Kangmar dome (Lee et al., 2000) and the Kampa dome (Quigley et al., 2008) in southern Tibet. These data all imply a major and widespread crustal melting event along (Pakistan to Bhutan) and the across (Lesser, Greater, and Tethyan Himalaya) the Himalayan range between ~490–460 Ma, possibly extending back to the Early Cambrian ~530 Ma (Fig. 6). Cawood et al. (2007) termed this the Bhimpedian orogeny. Our Early to Middle Ordovician U–Pb monazite ages from the Besham and Alpurai regions support this contention. The most surprising aspect of our new ages is that these samples show no evidence of the Cenozoic Himalayan thermal effects. The ages support the correlation of these rocks in Besham and Alpurai as lateral equivalents of the Lesser Himalaya to the east, rocks that also have not seen any Cenozoic metamorphic overprint.

Permian continental break-up

The rifting and break-up of the Gondwana continents during the Late Carboniferous–Permian led to the opening of the NeoTethys Ocean. Along the western Himalaya, this event is documented by the outpourings of up to 3 km thickness of high-Ti flood basalts exposed around the Kashmir valley called the Panjal Traps, typical of Large Igneous Provinces. The thickness of the lavas decreases both westward into Pakistan and eastward to Zaskar (Chauvet et al., 2008). The Panjal Traps are dominantly mildly alkaline basalts with minor components of basaltic andesites, rhyolites, and dacites (Shellnutt et al., 2014, 2015). A U–Pb zircon age from the silicic part yielded an Early Permian age of 289 ± 3 Ma (Shellnutt et al., 2011).

Our samples of monazite inclusions in garnet from staurolite schists from the Pakistan Himalaya records U–Pb monazite ages of 267 ± 4.7 Ma and 272.9 ± 2.2 Ma. These ages coincide very closely with Permian Himalayan granites within the Greater Himalayan complex at Parkatchic (~ 270 Ma) and Sankoo (268 ± 5 Ma) in the Zaskar region of the Indian Himalaya (Noble et al., 2001). Although they are ~ 20 Ma later than the age of the Panjal Trap basalts, it is speculated that heat for crustal melting may have been provided by basaltic intrusions into the lower crust. The coeval timing of the crustally-derived S-type granites in Zaskar with the staurolite-grade metamorphism recorded here implies a genetic link.

Model for the Pakistan Himalaya

Our proposed model for the evolution of the Pakistan Himalaya based on our new U–Pb monazite ages from staurolite-, kyanite-, and sillimanite-grade gneisses is shown in Figure 7. The uplift of the Nanga Parbat massif separating the Pakistan Himalaya in the west from the main Himalaya in India and Nepal to the east occurred during the middle to late Cenozoic (Crowley et

al., 2009). Prior to this, the Pakistan and Ladakh sectors were contiguous, sharing a common tectonic and metamorphic evolution. Both Pakistan and Ladakh show evidence of Late Cretaceous–Palaeogene south-vergent ophiolite obduction (Corfield et al., 2001), pre-Palaeogene deformation involving isoclinal folding and crustal thickening (Searle and Treloar, 2010), and early Eocene northward-directed subduction of continental crust to ultrahigh-pressure coesite-eclogite facies at Kaghan and Tso Moriri (e.g. Parrish et al., 2006; St-Onge et al., 2013; Palin et al., 2017). In the Pakistan Himalaya the large Cretaceous–Palaeogene intra-oceanic Kohistan island arc (Pettersen and Treloar, 2004; Jagoutz and Schmidt, 2012) was obducted southwards onto the Indian continental margin along the Main Mantle Thrust and intruded by numerous calc-alkaline granites belonging to the Asian continental margin in the north (Kohistan–Ladakh–Gangdese batholith), prior to the main Himalayan regional metamorphism (~38–20 Ma).

Figure 7b shows the classic section across the main Himalayan ranges in Zaskar and Ladakh (Indian Himalaya) where Cenozoic metamorphic rocks (GHS) have been thrust over Lesser Himalayan rocks unaffected by Cenozoic metamorphism (Stephenson et al., 2000; Searle et al., 2008). The Lesser Himalayan rocks include Proterozoic–Cambrian sedimentary rocks, Ordovician S-type granites, and late Ordovician–Early Mesozoic sediments showing no effects of the Himalayan Cenozoic metamorphism. All rocks affected by Cenozoic Himalayan-age metamorphism occur above the Main Central Thrust in the Greater Himalayan Sequence (Searle, et al., 2008).

In the Pakistan profile (Fig. 7a) the metamorphic rocks beneath the Main Mantle Thrust are Ordovician in age and correlate with Lesser Himalayan rocks in the main Himalayan range in India and Nepal. We suggest that the Kohistan arc overthrust both the Tethyan Himalayan sequence and the Greater Himalaya Sequence (Fig. 7a). The metamorphic rocks around Besham

and Alpurai show no Cenozoic ages, no Cenozoic migmatites or leucogranites, and they cannot be correlated with late Eocene–Miocene kyanite or sillimanite grade rocks in Zaskar and along the Greater Himalayan Sequence. Our new U–Pb ages record evidence of an orogenic event that resulted in medium-grade, amphibolite-facies metamorphism, deformation and intrusion of S-type granites during the Ordovician Bhimpedian orogeny; an event recorded along the length of the Lesser Himalaya in Pakistan, India, Nepal and Bhutan. Our new age on the staurolite-grade sample records crustal heating following intrusion of voluminous alkaline flood basalts (Permian Panjal Trap) during Gondwana break-up, ultimately leading to opening of Neo-Tethys.

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REFERENCES CITED

- Aleinikoff, J.N., Schenck, W.S., Plank, M.O., Srogi, L.A., Fanning, C.M., Sandra L. Kamo, S.L. and Bosbyshell, H. 2006. Deciphering igneous and metamorphic events in high-grade rocks of the Wilmington Complex, Delaware: Morphology, cathode-luminescence and backscattered electron zoning, and SHRIMP U–Pb geochronology of zircon and monazite. *Geological Society of America Bulletin*, v. 118, p. 39–64.
- Anczkiewicz, R., Burg, J.P., Villa, I.M. and Meier, M. 2000. Late Cretaceous blueschist metamorphism in the Indus Suture Zone, Shangla region, Pakistan Himalaya, *Tectonophysics*, v. 324, p. 111–134.

457 Calkins, J.A., Offield, T.W., Abdullah, S.K. and Ali, S.T. 1975. Geology of the southern
 458 Himalaya in Hazara, Pakistan, and adjacent areas. USGS Professional Paper No. 716-C.
 459 US Government Printing Office 29.

460 Cawood P.A., Johnson M.R., and Nemchin A.A. 2007. Early Palaeozoic orogenesis along the
 461 Indian margin of Gondwana: Tectonic response to Gondwana assembly. *Earth and*
 462 *Planetary Science Letters*, v. 255, p. 70–84.

463 Chauvet, F., Lapierre, H., Bosch, D., Guillot, S., Mascle, G., Vannay, J.C., Cotten, J., Brunet, P.
 464 and Keller, F. 2008. Geochemistry of the Panjal Traps basalts (NW Himalaya): records of
 465 the Pangea Permian break-up. *Bulletin de la Société géologique de France*, v. 179, p. 383–
 466 395.

467 Corfield, R.I., Searle, M.P. and Pederson, R B. 2001. Tectonic setting, origin and obduction
 468 history of the Spontang Ophiolite, Ladakh Himalaya, NW India. *Journal of Geology*, v.
 469 109, p. 715–736.

470 Cottle, J.M., Searle, M.P., Horstwood, M.S.A. and Waters, D.J. 2009a. Timing of midcrustal
 471 metamorphism, melting, and deformation in the Mount Everest region of southern Tibet
 472 revealed by U(–Th)–Pb geochronology. *The Journal of Geology*, v. 117, p. 643–664.

473 Cottle, J.M., Jessup, M.J., Newell, D.L., Horstwood, M.S.A., Noble, S.R., Parrish, R.R., Waters,
 474 D.J. and Searle, M.P. 2009. Geochronology of granulitised eclogite from the Ama Drime
 475 massif: implications for the tectonic evolution of the South Tibetan Himalaya. *Tectonics* v.
 476 28, TC1002, doi:10.1029/2008TC002256.

477 Crowley, J.L., Waters, D.J., Searle, M.P. and Bowring, S.A. 2009. Pleistocene melting and rapid
 478 exhumation of the Nanga Parbat massif, Pakistan: Age and *P–T* conditions of accessory

479 mineral growth in migmatite and leucogranite. *Earth and Planetary Science Letters*, v. 288,
480 p. 408–420.

481 Ding, L., Qasim, M., Jadoon, I.A.K., Khan, M.A., Xu, Q., Cai, F., Wang, H., Baral, U. and Yue,
482 Y. 2016. The India–Asia collision in north Pakistan: Insight from the U–Pb detrital zircon
483 provenance of Cenozoic foreland basin. *Earth and Planetary Science Letters*, v. 455, p. 49–
484 61.

485 DiPietro, J.A. and Isachsen, C.E. 2001. U–Pb zircon ages from the Indian plate in northwest
486 Pakistan and their significance to Himalayan and pre-Himalayan geologic history.
487 *Tectonics*, v. 20, p. 510–525.

488 DiPietro, J.A., Pogue, K.R., Hussain, A. and Ahmad, I. 1999. Geologic map of the Indus
489 Syntaxis and surrounding area, northwest Himalaya, Pakistan, Himalaya and Tibet. In:
490 Macfarlane, A., Sorkhabi, R.B. and Quade, J. (eds). “Mountain Roots to Mountain Tops”,
491 Special Paper of the Geological Society of America, v. 328A, p. 159–178.

492 DiPietro, J.A., Pogue, K.R., Lawrence, R.D., Baig, M.S., Hussain, A. and Ahmed, I. 1993.
493 Stratigraphy south of the Main Mantle Thrust, Lower Swat, Pakistan. In: P.J. Treloar and
494 M.P. Searle (eds) “Himalayan Tectonics”. Geological Society of London Special
495 Publication, v. 74, p. 207–220.

496 England, P.C. and Thompson, A.B. 1984. Pressure–temperature–time paths of regional
497 metamorphism I. Heat transfer during the evolution of regions of thickened continental
498 crust. *Journal of Petrology*, v. 25, p. 894–928.

499 Foster, G.L., Vance, D., Argles, T.W. and Harris, N.B.W. 2002. The Tertiary collision-related
500 thermal history of the NW Himalaya. *Journal of Metamorphic Geology*, v. 20, p. 827–844.

501 Gaetani, M. and Garzanti, E. 1991. Multicyclic history of the Northern India continental margin
 502 (Northwestern Himalaya). AAPG Bulletin, v. 75, p. 1427–1446.

503 Gehrels, G.E., DeCelles, P.G., Martin, A., Ojha, T.P., Pinhassi, G. and Upreti, B.N. 2003.
 504 Initiation of the Himalayan Orogen as an Early Palaeozoic thin-skinned thrust belt. GSA
 505 Today, September 2003.

506 Gehrels, G.E., DeCelles, P.G., Ojha, T.P. and Upreti, B.N. 2006. Geologic and U–Th–Pb
 507 geochronologic evidence for early Paleozoic tectonism in the Kathmandu thrust sheet,
 508 central Nepal Himalaya. Geological Society of America Bulletin, v. 118, p. 185–198.

509 Girard, M. and Bussy, F. 1999. Late Pan-African magmatism in the Himalaya: new
 510 geochronological and geochemical data from the Ordovician Tso Moriri metagranites
 511 (Ladakh, NW India). Schweizerische Mineralogische und Petrographische Mitteilungen, v.
 512 79, p. 399–418.

513 Godin, L., Parrish, R.R., Brown, R.L. and Hodges, K.V. 2001. Crustal thickening leading to
 514 exhumation of the Himalayan metamorphic core of central Nepal: Insights from U–Pb
 515 geochronology and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. Tectonics, v. 20, p. 729–747.

516 Godin, L., Grujic, D., Law, R.D., and Searle, M.P. 2006. Channel flow, ductile extrusion and
 517 exhumation in continental collision zones: an introduction. In: Law, R.D., Searle, M.P. and
 518 Godin, L. (eds) Channel Flow, Ductile Extrusion and Exhumation in Continental Collision
 519 Zones. Geological Society, London, Special Publications, v. 268, p. 1–23

520 Green, O.R., Searle, M.P., Corfield, R.I. and Corfield, R.M. 2008. Cretaceous–Tertiary carbonate
 521 platform evolution and the age of the India–Asia collision along the Ladakh Himalaya
 522 (northwest India). The Journal of Geology, v. 116, p. 331–353.

523 Henry, D.J., Guidotti, C.V. and Thomson, J.A. 2005. The Ti-saturation surface for low-to-
 524 medium pressure metapelitic biotite: Implications for Geothermometry and Ti-substitution
 525 Mechanisms. *American Mineralogist*, v. 90, p. 316–328.

526 Holland, T.J.B. 2009. A program to calculate activities of mineral endmembers from chemical
 527 analyses (usually determined by electron microprobe). [http://www.metamorph.geo.uni-](http://www.metamorph.geo.uni-mainz.de/thermocalc/software/ax)
 528 [mainz.de/thermocalc/software/ax](http://www.metamorph.geo.uni-mainz.de/thermocalc/software/ax).

529 Holland, T.J.B. and Powell, R. 2011. An improved and extended internally consistent
 530 thermodynamic dataset for phases of petrological interest, involving a new equation of
 531 state for solids. *Journal of Metamorphic Geology*, v. 29, p. 333–383.

532 Hu, X., Garzanti, E., Wang, J., Huang, W., An, W. and Webb, A. 2016. The timing of India–Asia
 533 collision onset – Facts, theories, controversies. *Earth-Science Reviews*, v. 160, p. 264–299.

534 Jagoutz, O. and Schmidt, M.W. 2012. The formation and bulk composition of modern juvenile
 535 continental crust: the Kohistan arc. *Chemical Geology*, v. 298–299, p. 78–96.

536 Jamieson, R.A., Beaumont, C., Medvedev, S. and Nguyen, M.H. 2004. Crustal channel flows: 2.
 537 Numerical models with implications for metamorphism in the Himalayan-Tibetan orogen.
 538 *Journal of Geophysical Research*, v. 109, B06407.

539 Kaneko, Y., Katayama, I., Yamamoto, H., Misawa, K., Ishikawa, M., Rehman, H.U., Kausar,
 540 A.B. and Shiraishi, K. 2003. Timing of Himalayan, ultrahigh-pressure metamorphism:
 541 sinking rate and subduction angle of the Indian continental crust beneath Asia. *Journal of*
 542 *Metamorphic Geology*, v. 21, p. 589–599.

543 Kohn, M.J. and Spear, F.S. 2000. Retrograde net transfer reaction insurance for pressure–
 544 temperature estimates. *Geology*, v. 28, p. 1127–1130.

545 Le Fort, P., Debon, F. and Sonet, J. 1980. The “Lesser Himalayan” cordierite granite belt,
546 typology and age of the pluton of Manserah, Pakistan. *Geological Bulletin of the*
547 *University of Peshawar*, v. 13, p. 51–62.

548 Lee, J., Hacker, B.R., Dinklage, W.S., Wang, Y., Gans, P., Calvert, A., Wan, J., Chen, W.,
549 Blythe, A.E. and McClelland, W. 2000. Evolution of the Kangmar Dome, southern Tibet:
550 Structural, petrologic, and thermochronologic constraints. *Tectonics*, v. 19, p. 872–895

551 Ludwig, K.R., 2003. User’s Manual for Isoplot 3.00: A Geochronological Toolkit for Microsoft
552 Excel; Berkeley Geochronological Centre, Berkeley, California.

553 Marquer, D., Chawla, H.S. and Challandes, N. 2000. Pre-alpine high-grade metamorphism in
554 High Himalaya crystalline sequences: Evidence from Lower palaeozoic Kinnauer Kailas
555 granite and surrounding rocks in the Sutlej Valley (Himachal Pradesh, India. *Eclogae*
556 *Geologicae Helveticae*, v. 93, p. 207–220.

557 Miller, C., Thöni, M., Frank, W., Grasemann, B., Klötzli, U., Guntli, P. and Draganits, E., 2001.
558 The early Palaeozoic magmatic event in the Northwest Himalaya, India: source, tectonic
559 setting and age of emplacement. *Geological Magazine*, v. 138, p. 237–251.

560 Myrow, P.M., Thompson, K.R., Hughes, N.C., Paulsen, T.S., Sell, B.K., and Parcha, S.K., 2006.
561 Cambrian stratigraphy and depositional history of the northern Indian Himalaya, Spiti
562 Valley, north-central India. *Geological Society of America Bulletin*, v. 118, p. 491–510.

563 Myrow, P.M., Hughes, N.C., Searle, M.P., Fanning, C.M., Peng, S.-C., and Parcha, S.K. 2009.
564 Stratigraphic correlation of Cambrian–Ordovician deposits along the Himalaya:
565 Implications for the age and nature of rocks in the Mt. Everest region. *Geological Society*
566 *of America Bulletin*, v. 121, p. 323–332.

567 Myrow, P.M., Hughes, N.C., McKenzie, N.R., Pelgay, P., Thomson, T.J., Haddad, E.E. and
 568 Fanning, C.M. 2016. Cambrian–Ordovician orogenesis in Himalayan equatorial
 569 Gondwana. *Geological Society of America Bulletin*, v. 128, p. 1679–1695.

570 Noble, S.R. and Searle, M.P. 1995. Age of crustal melting and leucogranite formation from U–
 571 Pb zircon and monazite dating in the western Himalaya, Zaskar, India. *Geology*, v. 12, p.
 572 1135–1138.

573 Noble, S.R., Searle, M.P. and Walker, C.B. 2001. Age and tectonic significance of Permian
 574 granites in western Zaskar, High Himalaya. *The Journal of Geology*, v. 109, p. 127–135.

575 O’Brien, P.J., Zotov, N. Law, R.D., Khan, M.A. and Jan, M.Q. 2001. Coesite in Himalayan
 576 eclogite and implications for models of India–Asia collision. *Geology*, v. 29, p. 435–438.

577 Palin, R.M., Searle, M.P., Waters, D.J., Parrish, R.R., Roberts, N.M.W., Horstwood, M.S.A.,
 578 Yeh, M.W., Chung, S.L. and Anh, T.T. 2013. A geochronological and petrological study of
 579 anatectic paragneiss and associated granite dykes from the Day Nui Con Voi metamorphic
 580 core complex, North Vietnam; constraints upon the timing of metamorphism within the
 581 Red River shear zone. *Journal of Metamorphic Geology*, v. 31, p. 359–387.

582 Palin, R.M., Reuber, G.S., White, R.W., Kaus, B.J. and Weller, O.M. 2017. Subduction
 583 metamorphism in the Himalayan ultrahigh-pressure Tso Moriri massif: An integrated
 584 geodynamic and petrological modelling approach. *Earth and Planetary Science Letters*, v.
 585 467, p. 108–119.

586 Pognante, U., Castelli, D. Benna, P. Genovese, G. Oberli, F. Meier, M. and Tonarini. S. 1990.
 587 The crystalline units of the High Himalayas in the Lahul–Zaskar region (northwest India):
 588 metamorphic–tectonic history and geochronology of the collided and imbricated Indian
 589 plate. *Geological Magazine*, v. 127, p. 101–116.

590 Parrish, R.R., Gough, S.J., Searle, M.P. and Waters, D.J. 2006. Plate-velocity exhumation of
 591 ultrahigh-pressure eclogites in the Pakistan Himalaya. *Geology*, v. 34, p. 989–992.
 592 Payne, J.L., Hand, M., Barovich, K.M. and Wade, B.P., 2008. Temporal constraints on the
 593 timing of high-grade metamorphism in the northern Gawler Craton: implications for
 594 assembly of the Australian Proterozoic. *Australian Journal of Earth Sciences*, v. 55, p.
 595 623–640.
 596 Pettersen, M.G. and Treloar, P.J. 2004. Volcanostratigraphy of arc volcanic sequences in the
 597 Kohistan arc, north Pakistan: Volcanism within island arc, backarc-basin, and
 598 intracontinental tectonic settings. *Journal of Volcanology and Geothermal Research*, v.
 599 130, p. 147–178.
 600 Pogue, K.R., Qardlaw, B.R., Harris, A.G. and Hussain A. 1992. Paleozoic and Mesozoic
 601 stratigraphy of the Peshawar basin, Pakistan: Correlations and implications. *Bulletin of the*
 602 *Geological Society of America*, v. 104, p. 915–927.
 603 Pogue, K.R., Hylland, M.D., Yeats, R.S., Khattak, W.U. and Hussain, A. 1999. Stratigraphic and
 604 structural framework of Himalayan foothills, northern Pakistan, Himalaya and Tibet: In:
 605 Macfarlane, A., Sorkhabi, R.B. and Quade. J. (eds). “Mountain Roots to Mountain Tops”.
 606 Special Paper of the Geological Society of America, v. 328A, p. 257–274.
 607 Powell, R. and Holland, T.J.B. 1994. Optimal geothermometry and geobarometry. *American*
 608 *Mineralogist*, v. 79, p. 120–133.
 609 Powell, R. and Holland, T.J.B. 1988. An internally consistent dataset with uncertainties and
 610 correlations; 3, Applications to geobarometry, worked examples and a computer program.
 611 *Journal of Metamorphic Geology*, v. 6, p. 173–204.

612 Powell, R. and Holland, T.J.B., 2008. On thermobarometry. *Journal of Metamorphic Geology*, v.
613 26, p. 155–179.

614 Quigley, M.C., Liangjun, Y., Gregory, C., Corvino, A., Sandiford, M., Wilson, C.J.L. and
615 Xiaohan, L. 2008. U–Pb SHRIMP zircon geochronology and T – t – d history of the Kampa
616 Dome, southern Tibet. *Tectonophysics*, v. 446, p. 97–113.

617 Rehman, H.U., Yamamoto, H., Kaneko, Y., Kausar, A.B., Murata, M. and Ozawa, O. 2007.
618 Thermobaric structure of the Himalayan Metamorphic Belt in Kaghan Valley, Pakistan.
619 *Journal of Asian Earth Sciences*, v. 29, p. 390–406.

620 Rehman, H.U., Kobayashi, K., Tsujimori, T., Ota, T., Yamamoto, H., Nakamura, E., Kaneko, Y.,
621 Khan, T., Terabayashi, M. and Yoshida, K. 2013. Ion microprobe U–Th–Pb geochronology
622 and study of micro-inclusions in zircon from the Himalayan high- and ultrahigh-pressure
623 eclogites, Kaghan Valley of Pakistan. *Journal of Asian Earth Sciences*, v. 63, p. 179–196.

624 Richter, M., 2013. Evaluation of U–Th–Pb dating of monazite by LA–ICP–MS. Unpublished
625 PhD thesis, Johannes Gutenberg University of Mainz, pp. 1–191.

626 Schärer, U. and Allègre, C.J. 1983. The Palung granite (Himalaya); high-resolution U–Pb
627 systematics in zircon and monazite. *Earth and Planetary Science Letters*, v. 63, p. 423–432.

628 Searle, M.P., 2015. Mountain Building, Tectonic Evolution, Rheology, and Crustal Flow in the
629 Himalaya, Karakoram, and Tibet. *Treatise on Geophysics*, 2nd edition, v. 6, p. 469–511.

630 Searle, M.P. and Godin, L., 2003. The South Tibetan Detachment and the Manaslu Leucogranite:
631 A structural reinterpretation and restoration of the Annapurna Manaslu Himalaya, Nepal.
632 *The Journal of Geology*, v. 111, p. 505–523.

633 Searle, M.P. and Treloar, P.J. 2010. Was Late Cretaceous–Paleocene obduction of ophiolite
634 complexes the primary cause of crustal thickening and regional metamorphism in the

635 Pakistan Himalaya? In: Kusky, T.M., Zhai, M.G., and Xiao, W (eds) The Evolving
 636 Continents: Understanding Processes of Continental Growth: Geological Society of
 637 London, Special Publications, v. 338, p. 345–359.

638 Searle, M.P., Waters, D.J., Rex, D.C. and Wilson, R.N. 1992. Pressure, temperature, and time
 639 constraints on Himalayan metamorphism from eastern Kashmir and western Zaskar.
 640 Journal of the Geological Society of London, v. 149, p. 753–773.

641 Searle, M.P., Waters, D.J., Dransfield, M.W., Stephenson, B.J., Walker, C.B., Walker, J.D. and
 642 Rex, D.C. 1999. Thermal and mechanical models for the structural and metamorphic
 643 evolution of the Zaskar High Himalaya. Geological Society of London, v. 164, p. 139–
 644 156.

645 Searle, M.P., Simpson, R.L., Law, R.D., Parrish, R.R. and Waters, D.J. 2003. The structural
 646 geometry, metamorphic and magmatic evolution of the Everest massif, High Himalaya of
 647 Nepal–south Tibet. Journal of the Geological Society, London, v. 160, p. 345–366.

648 Searle, M.P., Warren, C.J., Waters, D.J. and Parrish, R.R. 2004. Structural evolution,
 649 metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman
 650 Mountains. Journal of Structural Geology, v. 26, p. 451–473.

651 Searle, M.P., Law, R.D., Godin, L., Larson, K.P., Streule, M.J., Cottle, J.M. and Jessup, M.J.
 652 2008. Defining the Himalayan Main Central Thrust in Nepal. Journal of the Geological
 653 Society, London, v. 165, p. 523–534.

654 Searle, M.P., Cottle, J.M., Streule, M.J. and Waters, D.J. 2010. Crustal melt granites and
 655 migmatites along the Himalaya: melt source, segregation, transport and granite
 656 emplacement mechanisms. Transactions of the Royal Society of Edinburgh, v. 100, p. 219–
 657 233.

658 Shellnutt, J.G., Bhat, G.M., Brookfield, M.E. and Jahn, B.M. 2011. No link between the Panjal
 659 Traps (Kashmir) and the Late Permian mass extinctions. *Geophysical Research Letters*, v.
 660 38, L19308.

661 Shellnutt, J.G., Bhat, G.M., Wang, K.L., Brookfield, M.E., Jahn, B.M. and Dostal, J. 2014.
 662 Petrogenesis of the flood basalts from the Early Permian Panjal Traps, Kashmir, India:
 663 Geochemical evidence for shallow melting of the mantle. *Lithos*, v. 204, p. 159–171.

664 Shellnutt, J.G., Bhat, G.M., Wang, K.L., Yeh, M.W., Brookfield, M.E. and Jahn, B.M. 2015.
 665 Multiple mantle sources of the Early Permian Panjal Traps, Kashmir, India. *American*
 666 *Journal of Science*, v. 315, p. 589–619.

667 Stacey, J.S. and Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a 2-
 668 stage model. *Earth and Planetary Science Letters*, v. 26, p. 207–221.

669 Stephenson, B.J., Waters, D.J. and Searle, M.P. 2000. Inverted metamorphism and the Main
 670 Central Thrust: field relations and thermobarometric constraints from the Kishtwar
 671 Window, NW Indian Himalaya. *Journal of Metamorphic Geology*, v. 18, p. 571–590.

672 St-Onge, M.R., Rayner, N., Palin, R.M., Searle, M.P. and Waters, D.J. 2013. Integrated
 673 pressure–temperature–time constraints for the Tso Moriri dome (Northwest India):
 674 implications for the burial and exhumation path of UHP units in the western Himalaya.
 675 *Journal of Metamorphic Geology*, v. 31, p. 469–504.

676 Treloar, P.J., 1995. Pressure–temperature–time paths and the relationship between collision,
 677 deformation and metamorphism in the north-west Himalaya. *Geological Journal*, v. 30, p.
 678 333–348.

679 Treloar, P.J., 1997. Thermal controls on early-Tertiary, short-lived, rapid regional metamorphism
 680 in the NW Himalaya, Pakistan, *Tectonophysics*, v. 273, p. 77–104.

681 Treloar, P.J. and Rex, D.C. 1990a. Cooling, uplift and exhumation rates in the crystalline thrust
682 stack of the North Indian Plate, west of the Nanga Parbat syntaxis. *Tectonophysics*, v. 180,
683 p. 323–349.

684 Treloar, P.J. and Rex, D.C. 1990b. Post-metamorphic cooling history of the Indian Plate
685 crystalline thrust stack, Pakistan Himalaya. *Journal of the Geological Society of London*, v.
686 147, p. 735–738.

687 Treloar, P.J. Broughton, R.D., Williams, M.P., Coward, M.P. and Windley, B.F. 1989a.
688 Deformation, metamorphism and imbrication of the Indian Plate, south of the Main Mantle
689 Thrust, North Pakistan. *Journal of Metamorphic Geology*, v. 7, p. 111–125.

690 Treloar, P.J., Coward, M.P., Williams, M.P. and Khan, M.A. 1989b. Basement-cover imbrication
691 south of the Main Mantle Thrust, North Pakistan. *Geological Society of America, Special*
692 *Paper*, v. 232, p. 137–152.

693 Treloar, P.J., O'Brien, P.J., Parrish, R.R. and Khan, M.A. 2003. Exhumation of early Tertiary,
694 coesite-bearing eclogites from the Pakistan Himalaya. *Journal of the Geological Society of*
695 *London*, v. 160, p. 367–376.

696 Viete, D.R. and Lister, G.S. 2016. On the significance of short-duration regional metamorphism.
697 *Geological Society of London Special Publication*, v. 174, p. 377–392.

698 Walker, J.D., Martin, M.W., Bowring, S.A., Searle, M.P., Waters, D.J. and Hodges, K.V. 1999.
699 Metamorphism, melting, and extension: age constraints from the High Himalayan slab of
700 southeast Zaskar and northwest Lahaul. *The Journal of Geology*, v. 107, p. 473–495.

701 White, R.W., Powell, R., Holland, T.J.B., Johnson, T.E. and Green, E.C.R. 2014. New mineral
702 activity–composition relations for thermodynamic calculations in metapelitic systems.
703 *Journal of Metamorphic Geology*, v. 32, p. 261–286.

- Wilke, F.D.H., O'Brien, P.J., Gerdes, A., Timmerman, M.J., Sudo, M. and Khan, M.A. 2010. The multistage exhumation history of the Kaghan Valley UHP series, NW Himalaya, Pakistan from U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages. *European Journal of Mineralogy*, v. 22, p. 703–719.
- Williams, I.S., Buick, I.S. and Cartwright, I. 1996. An extended episode of early Mesoproterozoic metamorphic fluid flow in the Reynolds Range. *Journal of Metamorphic Geology*, v. 14, p. 29–47.
- Woodsworth, G.J. 1977. Homogenization of zoned garnets from pelitic schists. *The Canadian Mineralogist*, v. 15, p. 230–242.
- Wu, F., Ji, W., Wang, J., Liu, C., Chung, S. and Clift, P.D., 2014. Zircon U–Pb and Hf isotopic constraints on the onset time of India–Asia collision. *American Journal of Science*, v. 314, p. 548–579.

FIGURE CAPTIONS

Figure 1. Geological map of the Western Himalayan region in Pakistan and India (after Searle and Treloar, 2010). The Hazara Nappe is situated in the region marked by a red box, and its geological map is given in Fig. 2.

Figure 2. Isograd and sample locality map of the Hazara Nappe and environs. Zones of different Barrovian-type metamorphic grade are demarcated by the highest-temperature index mineral that occurs in the stable assemblage. Samples 625 and 626 were collected from within the staurolite zone, 755D and 756 from the kyanite zone, and RB169 from the sillimanite zone.

Figure 3. Photomicrographs of petrological associations and microstructures in Hazara Nappe samples. (a) Garnet and staurolite porphyroblasts in sample 625. Biotite commonly occurs in strain shadows. (b) Garnet porphyroblast in sample 626. By contrast with sample 625, staurolite mostly occurs within garnet strain shadows as opposed to forming separate crystals within the matrix. Fine-grained biotite and muscovite commonly occurs at the periphery of such staurolite grains. (c) Garnet porphyroblasts in sample 755 wrapped by the biotite-rich matrix foliation. Kyanite occurs as very small (<0.1 mm) crystals in the matrix and also within garnet rims (see (d)). (d) Back-scattered electron image of garnet rim inclusion associations. Both staurolite and kyanite occur as inclusions in rim domains, implying their stability during rim growth that is interpreted to have occurred at peak metamorphism. (e) Garnet porphyroblast–matrix relations in kyanite-zone sample 756. Kyanite is relatively rare in this sample, and occurs as small (<0.5 mm) grains in the matrix, which typically exhibit undulose extinction (inset). (f) Both kyanite and sillimanite occur in sample RB169, with the former occurring as clots around which the quartz- and biotite-rich foliation wraps. Prismatic sillimanite is elongate parallel to the foliation planes and partially defines them.

Figure 4. Results of geothermobarometry performed on all Hazara Nappe samples, provided by (a) the titanium-in-biotite thermometer of Henry et al. (2005), and (b) the average P – T (avPT) method of Powell and Holland (1994). On part (a), point data from 625 are given as orange triangles, 626 as grey hexagons, 755D as yellow circles, 756 as green diamonds, and RB169 as brown squares. Error ellipses for sample data in part (b) are given at 1 S.D. (solid grey ellipses) and 2 S.D. (faint grey ellipses), and are superimposed by the wet pelite solidus of White et al. (2014). The thick white arrow represents a schematic P – T path common to five samples, which

is noticeably different to those predicted to characterize the main Himalayan GHS, LHS, and THS during channel flow (from Jamieson et al., 2004).

Figure 5. Tera-Wasserburg diagrams plots showing the results of U–Pb monazite geochronology for all samples. Dashed lines, where present, represent regressions from a $^{207}\text{Pb}/^{206}\text{Pb}$ ratio of 0.83 ± 0.02 . All ages represent calculated intersections with Concordia: (a) 625, (b) 626, (c) 755D, (d) 756, and (e) RB169.

Figure 6. Paleozoic time chart for the Himalayan regions in Pakistan, India and Nepal showing stratigraphic ages of sedimentary rocks and U–Pb and Sm–Nd geochronological ages of granitic and metamorphic rocks. See text for sources of data.

Figure 7. Two structural profiles across (a) the Pakistan Himalaya, west of the Nanga Parbat uplift, and (b) the Indian Himalaya in Kishtwar–Zaskar–Ladakh, east of the Nanga Parbat uplift. The Tethyan Himalaya (TH) and Greater Himalayan Sequence (GHS) above the Main Central thrust (MCT) exposed in India are buried at depth beneath the overthrust Kohistan island arc in Pakistan. The Besham and Alpurai regions of Pakistan are parts of the Lesser Himalaya (LH) in green above the Main Boundary Thrust (MBT).

TABLE CAPTIONS

Table 1. Results of average P – T (avPT) calculations using the method of Powell and Holland (1994), the software THERMOCALC (Powell *et al.*, 1998) and the internally consistent

773 thermodynamic dataset of Holland and Powell (2011). Uncertainties are given at 1 standard
774 deviation (S.D.). N represents the number of independent reactions between end-members
775 utilized in each calculation. Cor is a correlation coefficient between P and T , where a value of 0
776 represents a complete non-correlation and a value of 1 represents a complete correlation.

777

778 ¹GSA Data Repository item 201Xxxx, containing mineral compositional data (Table S1) and
779 geochronological analyses (Table S2), is available online at
780 www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or
781 Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.