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The India–Asia collision in north Pakistan: Insight from the U–Pb detrital zircon provenance of Cenozoic foreland basin

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A B S T R A C T

The northernmost exposures of sub-Himalayan Cenozoic strata in the Hazara–Kashmir syntaxial region of north Pakistan comprises the Paleocene–Eocene marine strata in the lower part and Oligocene–Miocene nonmarine strata in the upper part. This study provides the detrital zircon U–Pb geochronology of the Cenozoic strata in this area. The strong resemblance of U–Pb age spectra of Paleocene Hangu, Lockhart and Patala formations with those of Himalayan strata indicate an Indian plate provenance. The first appearance of <100 Ma detrital zircon U–Pb ages within the lower most part of the Early Eocene Margalla Hill Limestone indicates a shift from an Indian to Asian provenance. Geologic mapping shows the existence of a disconformity between the lower and upper most part of the Patala Formation, which is interpreted to have been formed by the migration of a flexural forebulge through this region. We consider the upper most part of the Patala Formation to have been deposited within the distal foredeep of the foreland basin. The Indian to Asian provenance shift and the presence of a possible foreland basin forebulge provide strong evidence that India–Asia collision was underway in northern Pakistan at ca. 56–55 Ma.

1. Introduction

The Himalaya, a giant mountain system in South-Central Asia has resulted from the India–Asia collision in the Cenozoic (Coward et al., 1988), and is a natural laboratory to study continent–continent collisional tectonics. Knowledge of the exact timing of this event is necessary to understand its impact on geologic, climatic and biotic records. To determine the accurate timing of this tectonic event, a number of approaches have been undertaken. These are applied along and across the entire orogen from Myanmar in the east to Pakistan in the west and from Gangdese arc and suture zone in the north to the Himalayan foreland basin in the south. Studies have yielded a wide range of collision age estimates ranging from Late Cretaceous (∼65 Ma) (Cai et al., 2011; Ding et al., 2005) to as late as Oligocene (∼34 Ma) (Aitchison et al., 2007). This raises several questions regarding the location of initial contact between the Indian and Asian Plates. It is proposed that the collision occurred in the northwestern Himalaya first and then in the eastern Himalaya as a consequence of counter clockwise rotation (Beck et al., 1995). However, it has been proposed that the collision first occurred as early as ∼65 Ma in the Central Himalaya in Tibet (Cai et al., 2012, 2011; Ding et al., 2005). In addition, Van Hinsbergen et al. (2012) proposed Greater Indian Basin model and considers the collision at 50 Ma to be accretion of rifted Tethyan Himalaya with Asia and final collision at 25–20 Ma with Indian margin after consumption of intervening ocean basin between Tethyan Himalaya and Indian margin.

The collision age is also disputed in the northwestern Himalayas of Pakistan, ranging from 65 to 40 Ma (Beck et al., 1995; Khan et al., 2009; Najman et al., 2001). The earlier studies by Bossart and Ottiger (1989) proposed that the collision occurred at ca. 55 Ma near the western Himalayan syntaxis based on detailed biostratigraphy and petrography of the Murree Formation. The ∼55 Ma age of the Murree Formation has been revised to Oligocene–Miocene by excluding marl bands from the Murree Formation (Najman et al., 2002). Najman et al. (2001) assigned ca. 34 Ma age for the Balakot Formation (Fig. 1C) based on Ar–Ar detrital white mica dating and proposed that the collision occurred

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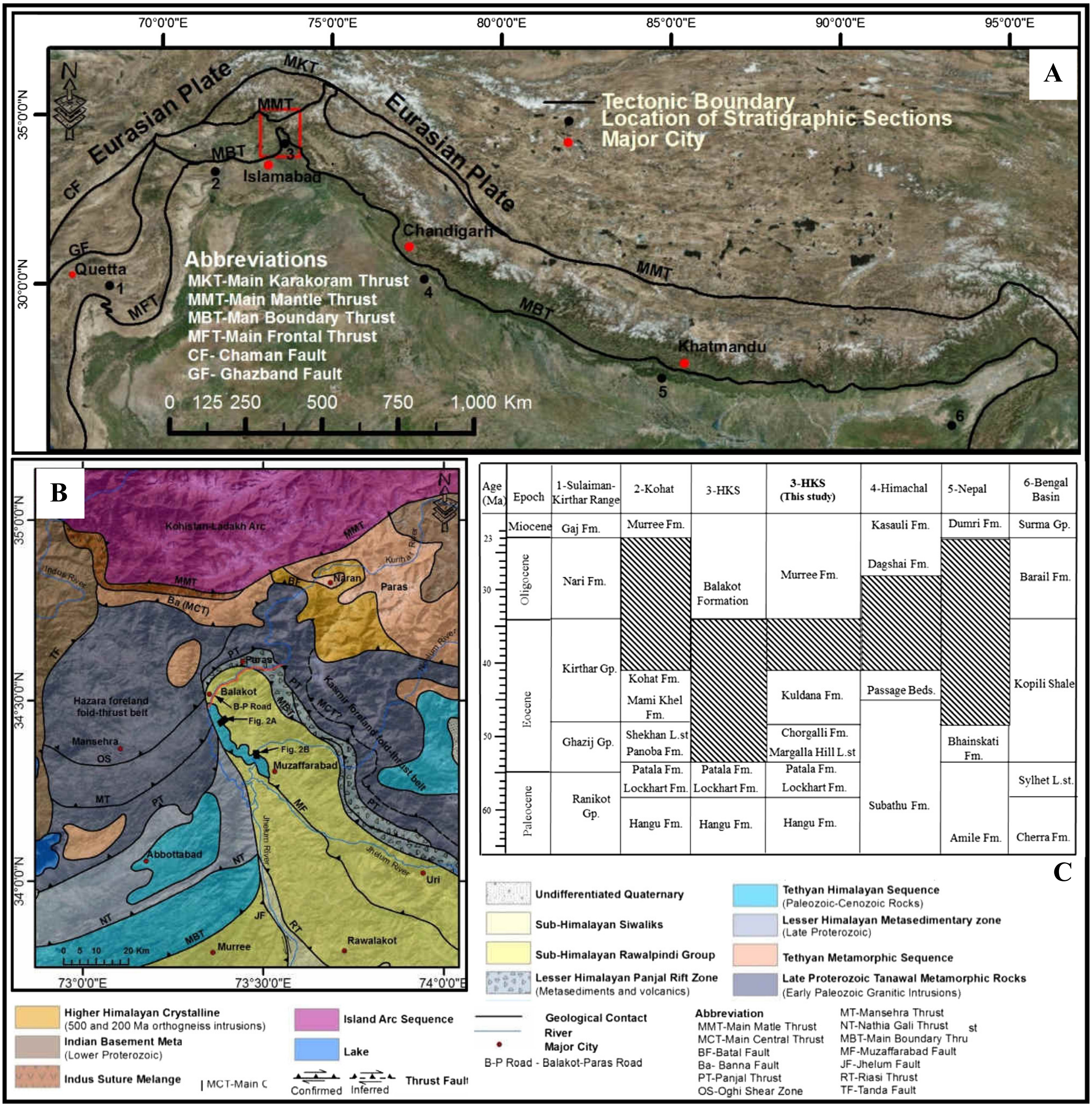


Fig. 1. A) Generalized tectonic map of the Himalaya showing major tectonostratigraphic zones. Red rectangle represents the extent of panel B. The black filled circle with number shows the location of stratigraphic sections given in panel C. 1 – Sulaiman–Kirther Range, 2 – Kohat, 3 – Hazara Kashmir Syntaxis (HKS), 4 – Himachal (India), 5 – Nepal, 6 – Bengal Basin. B) Modified geological map of the Hazara–Kashmir syntaxis and surrounding area, with references provided in supplementary data. The filled rectangle indicates the study area. C) The Stratigraphic Correlation chart of Tertiary sequence of Himalayan Foreland Basin (modified after Najman, 2006, Singh, 2013). Hatched area represents unconformity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at ∼40 Ma. West of the Balakot section, a detailed biostratigraphic study by Beck et al. (1995) in the Waziristan and Kurram areas, proposed a collision age between 66 and 55.5 Ma, as indicated by accretionary prism and trench strata thrusting onto the passive Indian margin, while final suturing occurred at 49 Ma.

The Hazara–Kashmir syntaxial region of northern Pakistan includes the northernmost exposures of Cenozoic foreland basin strata, contains the lithologies that straddle the transition between marine and continental deposition (Figs. 1B–C and 2). We applied detrital zircon U–Pb geochronology on the Cenozoic strata of the Balakot and Muzaffarabad sections to differentiate an Indian versus Asian provenance. We present a complete detrital zircon U–Pb record of the Cenozoic foreland basin strata in Pakistan, which gives insight on timing of collision between Indian and Asian plates.

2. Geological setting

In Pakistan, three major terranes are juxtaposed with each other and which dominate the geology of the Himalaya (Searle et al., 1999). From north to south, these terrenes consists of the Karakoram Block to the north of the Main Karakoram Thrust (MKT)/Shyok suture zone, the Kohistan–Ladakh Arc (KLA), and the Indian Plate to the south of Main Mantle Thrust (MMT)/Indus Suture Zone. The Karakoram block (KB) consists of a Paleozoic–Mesozoic sedimentary belt in its northern part, Cretaceous–Miocene Karakoram batholiths rocks in its central part, and the

Karakoram metamorphic complex of late Paleozoic–Cenozoic age affected by pre- and post-collisional metamorphism and intruded by Eocene–Miocene granitic intrusions in its southern part (Fraser et al., 2001; Zanchi and Gaetani, 2011). The KLA is a typical island arc sequence consisting of Cretaceous–Paleocene volcanic and metasedimentary rocks in the northern part along MKT, Late Cretaceous Kohistan batholith with younger ∼34–29 Ma leucogranitic intrusions in the central part, and Early Cretaceous mafic–ultramafic complexes in its southern part north of MMT (Bouilhol et al., 2013; Jagoutz and Schmidt, 2012; Khan et al., 1993; Petterson, 2010).

The collision of the KLA with the KB is considered to have occurred in Late Cretaceous (∼75 Ma), which is based on the age of Jutal dykes, which crosscut the collision related fabric (Searle et al., 1999). The age of regional metamorphism (80–60 Ma) in the Eastern Karakoram is also consistent with late Cretaceous accretion of the KLA with the KB (Borneman et al., 2015; Heuberger, 2004). Similarly, Paleomagnetic studies in northern Pakistan also support Cretaceous accretion between the KLA and KB (Zaman and Bamousa, 2015; Zaman and Torii, 1999).

From north to south, the Indian Plate sequence south of MMT is classified into three tectono-stratigraphic zones: the Higher/Greater, Lesser and Sub Himalayan zones (Greco, 1991). Although, the exact position of the Main Central Thrust (MCT) is disputed in Pakistan, we consider it to be the Batal Fault in Kaghan valley, following Chaudhry and Ghazanfar (1990). Following this classification, the Higher/Greater Himalayan zone lies to the north of Batal Fault/MCT and consists of pelitic–psammatic schists and gneisses, meta-carbonates and amphibolites containing eclogite lenses (Kaneko et al., 2003). These rocks are Archean–Middle Proterozoic in age and locally intruded by the ∼1850 Ma, ∼500 Ma and ∼47 Ma plutonic rocks (Argles et al., 2003; DiPietro and Isachsen, 2001). The Lesser Himalayan zone is bounded by the Batal Fault in the north and the Main Boundary Thrust (MBT) in the south (Figs. 1 and 2). The Lesser Himalayan zone north of MBT, consists of Proterozoic basement and Pre-Himalayan cover strata of the Indian Plate, which is unconformably overlain by the Cambrian–Triassic carbonate, graphitic phyllite, argillite and metabasalt of Tethyan affinity (DiPietro and Pogue, 2004; DiPietro et al., 2008). The Proterozoic basement and cover sequence of the Lesser Himalaya are intruded by Cambrian–Ordovician granites (Le Fort et al., 1980). The Sub Himalayan zone mainly consists of the Miocene and younger rocks of the Cenozoic foreland basin with few exposures of the Cambrian and Paleocene–Eocene strata in the Balakot, Muzaffarabad and Kotli areas (Baig and Munir, 2007). The folding and doming structures are responsible for the exposure of the Cambrian and Paleocene–Eocene sequence.

The Balakot and Muzaffarabad sections lie in the footwall of MBT, and are part of the sub-Himalayan zone in north Pakistan (Figs. 1 and 2). The foreland deposits are mainly exposed south of MBT along the strike in the Himalayan orogen. Thus, in north Pakistan, these sections are the northernmost exposures and contain strata recording the oldest transition from marine to continental deposition.

3. Stratigraphy of the Tertiary foreland basin

The Cenozoic sequence exposed in the Balakot and Muzaffarabad areas, consists of lower Paleocene–lower Miocene marine to continental sedimentary deposits. The Cenozoic sequence unconformably overlies the Lower Cambrian Abbottabad Formation, which consists dominantly of dolomite with subordinate limestone, shale, and sandstone, in a major anticlinal structure (Fig. 2). The Cenozoic sequence is divided, from older to younger, into the Hangu Formation, Lockhart Formation, Patala Formation, Margalla Hill Limestone, Chorgalli Formation, Kuldana Formation and Murree Formation (Fig. 2, Fig. S1 and Fig. S2; see supplementary data).

3.1. Hangu Formation

The Hangu Formation consists of a laterite horizon, bauxite nodules, arenaceous limestone, quartzite, claystone, carbonaceous shale, and coal seams. The shales are gray and sandstone is light gray and reddish brown on fresh surfaces while rusty brown when weathered. The sandstone is fine to coarse grained, and in some places hematitic (Fig. S1A). In the Muzaffarabad section, Hangu Formation is comprised of clay, limonitic sandstone and carbonaceous shales (Fig. S1B). The limonitic sandstone is very hard and yellow to brownish in color, while the color of the shales varies from black to brown (Fig. S1B). The thickness of the formation also varies within the study area ranging from 2 m to 15 m. The lower contact is unconformable with the Lower Cambrian Abbottabad Formation, while the upper contact with the overlying Lockhart Formation is conformable (Figs. S1A and S1B). A rich fossil assemblage has been documented in the Hangu Formation at different exposures in the Kohat–Potwar Plateau and Salt Range, which suggests an Early Paleocene age (Shah, 2009 and the references therein).

3.2. Lockhart Formation

The Lockhart Formation is comprised of interbedded nodular limestone and shale. The limestone is thick bedded to massive and gray to dark gray in color (Fig. S1C). The thickness of the formation is ∼100 m. The massive portion of the limestone exhibits nodules that vary in length and width from 2–7 cm and 1–4 cm respectively. In the lower portion, the limestone contains algal lamellas, while in the upper part the nodules become more prominent in limestone and the proportion of shale increases. The upper and lower contact of the Lockhart Formation is conformable (Figs. S1B, S1C and S1D). The age assigned to the Lockhart Formation is Late Paleocene (∼60–57 Ma) based on detailed biostratigraphy of the Muzaffarabad section and other areas in Pakistan (Baig and Munir, 2007; Hanif et al., 2014; Shah, 2009 and the references therein).

3.3. Patala Formation

The Patala Formation consists of brown shale and minor sandstone, siltstone and dark gray limestone interbeds (Figs. S1D, S1E and S1F). The thickness of the formation varies between ∼80–130 m. The sandstone interbeds are quartz rich and 5–7 cm in thickness. Towards the top of the section the limestone and shale beds become more prominent. The lower contact is sharp and conformable with underlying Lockhart Formation (Fig. S1D). An erosional surface, indicated by a 30–50 cm laterite horizon, was observed ∼1.5 m below the upper contact with the Margalla Hill limestone in the Muzaffarabad section (Fig. S1D). A disconformity may also be indicated by a conglomeratic bed ∼2 m below the upper contact in the Balakot section (Fig. S1F). The laterite horizon and conglomeratic bed may represents the regional unconformity between the Paleocene and Eocene sequences as recognized along the strike in Himalayan foreland basin (Garzanti et al., 1987). The part of the Patala Formation above the erosional surface is considered as the uppermost part. The reported faunal assemblage from the Patala Formation is assigned to SB-5 to SB-6 of Late Paleocene age (∼57–55 Ma) (Baig and Munir, 2007).

3.4. Margalla Hill Limestone and Chorgalli Formation

The Eocene nodular limestone unit consists of the Margalla Hill Limestone and Chorgalli Formation. The Margalla Hill Limestone is distinguished by the dominant appearance of nodular limestone as compared to the Patala Formation. Thin interbeds of arenaceous

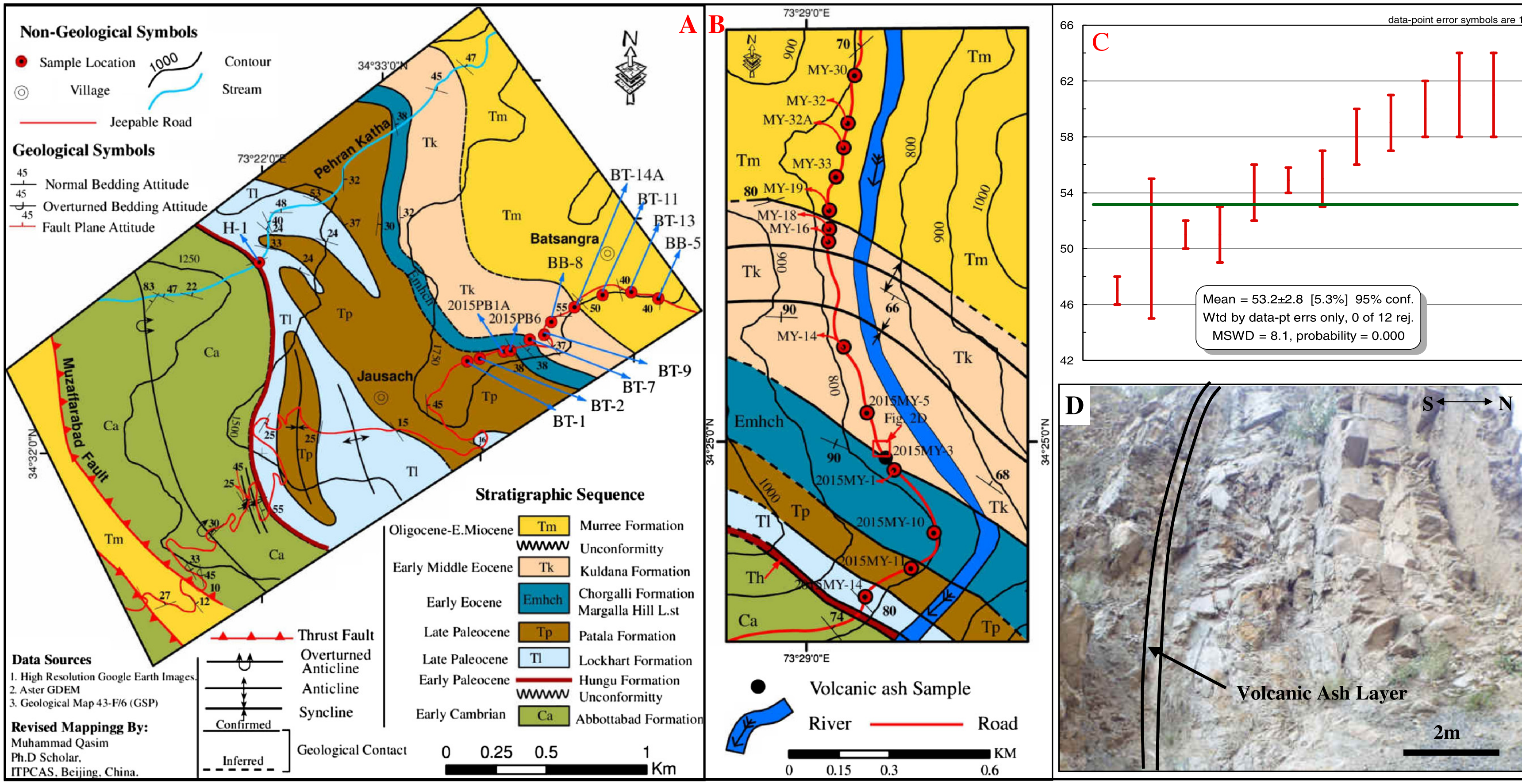


Fig. 2. A) Revised detailed geological map of the Balakot section, showing structural geology and stratigraphic units. The locations of rock samples for U–Pb geochronology are shown by red circles. B) Revised geological map of the Muzaffarabad section, showing major formations and their contact relationships. C) Weighted Mean age plot of Volcanic ash sample of Kuldana Formation. D) Field photograph of the Volcanic ash layer in Muzaffarabad Section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shale are present, which separate the bedding of the nodular limestone. The limestone is dark grayish in color (Fig. S2A). The size of the nodules varies between 10–20 cm in length and 15–25 cm in width. In the upper part, a relatively thick brownish shaly horizon is present. The thickness of the Margalla Hill Limestone and Chorgalli Formation is ∼50 m in Balakot section and Muzaffarabad section. The limestone is fossiliferous and contains large forams. The age of the Margalla Hill Limestone and Chorgalli Formation is constrained to Early Eocene age (∼55–53 Ma) by both foraminiferal assemblage (Baig and Munir, 2007) and an interbedded tuffite of the lower Kuldana Formation with weighted mean age of 53.2 ± 2.8 Ma (see below) in Muzaffarabad section (Table S1, Figs. 2C and 2D).

3.5. Kuldana Formation

The Kuldana Formation consists of shale, limestone, marl, sandstone and siltstone (Fig. S2C). The thickness of the formation ranges from 130–160 m. The shales are multicolored, with red, maroon, purple and olive green color. The shales are argillaceous to calcareous in nature. The sandstone and siltstone are red, green and gray in color. The thickness of the sandstone beds varies between 20–200 cm. The limestone and marl beds are grayish in color and contain abundant large foraminiferas. The top of the section consists of an oyster-bearing bed that includes broken shells of nummulite fossils. Sandstone is also present in the form of lenticular beds within shales. Pebbly sandstone beds are present near the upper contact and the sandstone contains reworked fossils at contact with the Murree Formation (Figs. S2E and S2F). The upper contact with Murree Formation is considered to be unconformable and is marked by the cyclic appearance of sandstone and shale. Biostratigraphic studies on the Kuldana Formation in various parts of the foreland basin in Pakistan and especially in the Balakot, Muzaffarabad and Murree areas, suggest an Early Middle Eocene age (53–43 Ma) corresponding to shallow benthic (SB) zones SB-12, SB-13 and SB-14 (Baig and Munir, 2007; Gingerich, 2003). A volcanic ash layer is identified in the lower part, which yielded weighted mean age of 53.2 ± 2.8 Ma (Table S1, Figs. 2C and 2D).

3.6. Murree Formation

In the Balakot section, Murree Formation represents the northernmost exposure of continental deposits exposed in the sub-Himalayan foreland basin. It consists of a cyclic sequence of red, maroon, green and purple shale and mudstone, red, gray to greenish gray siltstone and sandstone (Fig. S2G) with intraformational conglomerate at several stratigraphic levels. The sandstone is fine to medium grained and the presence of detrital muscovite gives it a shiny appearance. In the middle part of the sequence, the sandstone becomes thick bedded and commonly contains calcite and quartz veins.

Previous studies proposed an Eocene age for the Murree Formation (Bossart and Ottiger, 1989) based on marl band biostratigraphy, which is later revised considering that the marl band is a structural slice of the underlying formation (Najman et al., 2002). The Oligocene–Miocene age has been proposed to the Murree Formation relying on the detrital white mica ages reported from Balakot and Murree areas (Najman, 2006). ∼200 km south of the study area mammal fossils has been reported from the Fateh Jhang member (lower part of Murree Formation), which suggest an Early Miocene age (Shah, 2009 and the references therein).

4. U–Pb zircon geochronology

We collected a total of 29 sandstone and sandy shale samples from the Paleocene–Miocene foreland basin sequence exposed in Balakot and Muzaffarabad sections (Figs. 2, 3 and 4). These include one sample from the Hangu Formation, one from the Lockhart Formation, six from the Patala Formation, four from the Margalla Hill Limestone and Chorgalli Formation, nine from the Kuldana Formation and eight from the Murree Formation.

4.1. Methods

The U–Pb geochronology for detrital zircon grains was performed by using the Agilent 7500a Quadruple Inductively Coupled Plasma Mass Spectrometer (ICP-MS) attached with a New Wave UP 193 nm ArF excimer laser-ablation system at Institute of Tibetan Plateau Research, Chinese Academy of Sciences. The detailed analytical procedure (Cai et al., 2011) and the Cathode Luminescence (CL) images for selected samples were described in supplementary data. The U–Pb ages are presented by probability density plots using ISOPLOT (Ludwig, 2003) and Kernel density estimate (KDE) plots (Fig. S4) using DZstats software (Saylor and Sundell, 2016). The detailed zircon results are provided in Table S1 of supplementary data.

4.2. Zircon ages of tuffite from Kuldana Formation

The 12 concordant ages of the tuffite sample range between 47–61 Ma (Table S1). The weighted mean age is 53.2 ± 2.8 Ma, which constrain the lower age limit for the Kuldana Formation and upper age limit for the Chorgalli Formation. The presence of volcanic glass, albite, illite, chlorite and rutile indicates the volcanic origin. The results of EPMA analyses (Fig. S3) are given in supplementary Table S2.

4.3. Detrital zircon ages

4.3.1. Balakot section

Sample H-1 was collected from the Hangu Formation, which is the oldest Paleocene unit in Pakistan (Fig. 2A). The zircon crystals are euhedral. The 98 concordant ages were obtained from 100 analyses. The U–Pb zircon age spectrum shows age populations between ∼450–600 Ma with a major peak at 500 Ma, ∼720–950 Ma with peaks at 782 Ma and 875 Ma, ∼1600–1760 Ma with a peak at 1700 Ma, a minor peak at ∼2430 Ma, and scattered ages between ∼2550–3315 Ma (Fig. 3).

Samples BT-1, BT-2, 2015PB1A, 2015PB06, and BTP-4 are siltstones collected from the lower to upper part of the Patala Formation (Fig. 3). The zircon crystals are rounded to sub-rounded. The 482 detrital zircon grains yielded 461 concordant ages. The detrital zircon ages in BT-1 and BT-2 are clustered between ∼900–1930 Ma. The largest age population is clustered between ∼1500–1800 Ma with peaks at ∼1550 Ma and ∼1750 Ma. A smaller age population is observed at ∼2360–2550 Ma with a mean age at 2500 Ma (Fig. 3). The samples from the uppermost part of the Patala Formation exhibit a very different age spectra compared to those of the lower and middle part. Samples 2015PB1A and 2015PB06 yielded age populations between ∼750–950 Ma with a peak age at ∼875 Ma, between ∼500–600 Ma with a peak age at ∼575 Ma, and ∼1800–1900 Ma (Fig. 3). There are also minor age populations between ∼2000–2250 Ma and ∼2400–2800 Ma (Fig. 3). The stratigraphically highest sample BTP-4 shows a dominant age population between ∼100–160 Ma with peak age at 135 Ma. A significant age group is also present between 1200–2100 Ma (Fig. 3).

Samples BTM-1 and BTM-3 are sandy shales from the bottom and middle part of the Eocene nodular limestone sequence, respectively (Fig. 3). The 134 out of 165 detrital zircons yielded concordant ages. Major age populations are <300 Ma, ∼470–700 Ma, and ∼800–1500 Ma. A minor age population is between 1600–1900 Ma

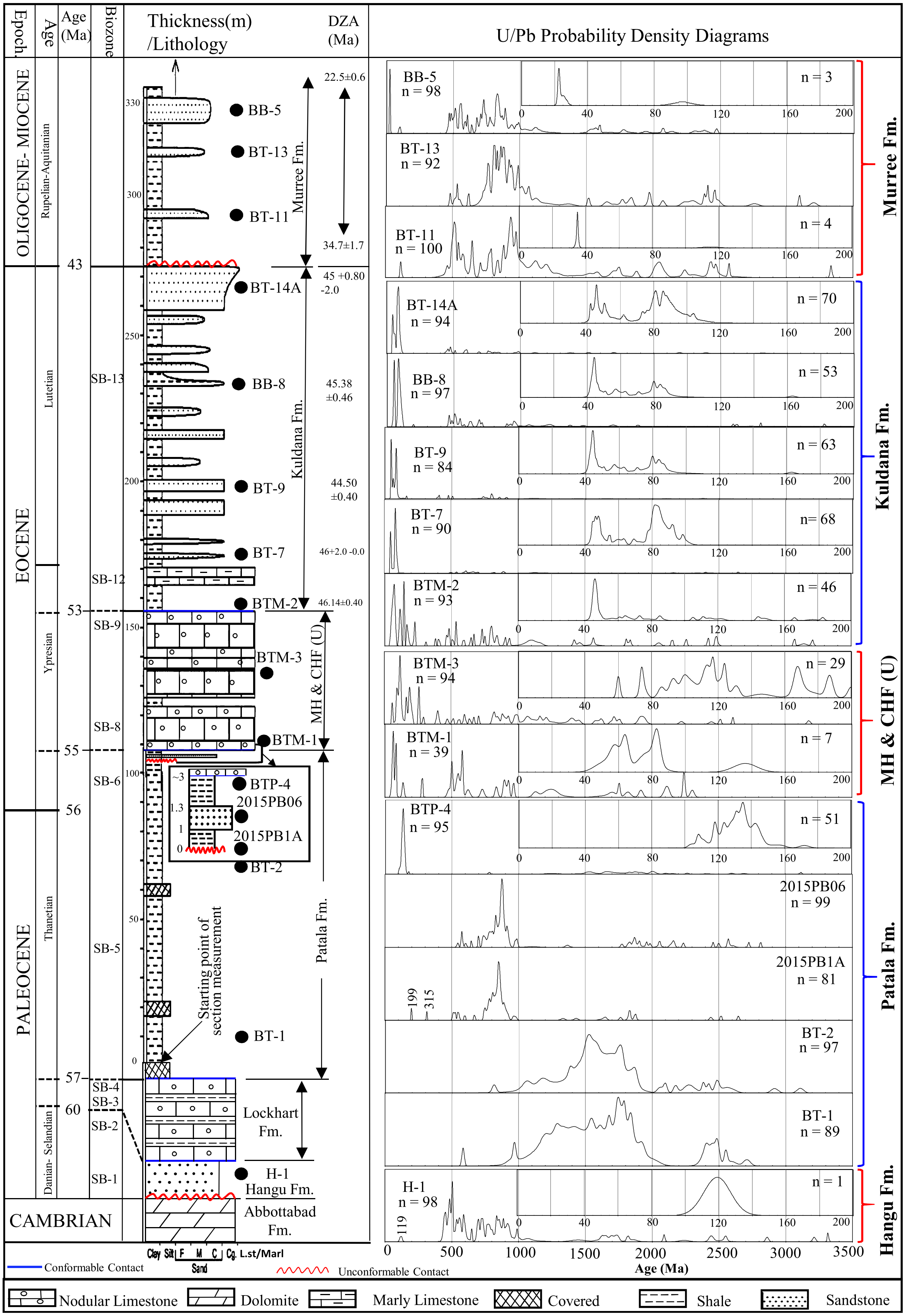


Fig. 3. Lithostratigraphic chart of the Balakot section showing sample locations and U–Pb probability plots for selected samples. The corresponding biozones are compiled from literature and references are given in supplementary data. MH and CHF (U) stands for Margalla Hill Limestone and Chorgalli Formation (undifferentiated).

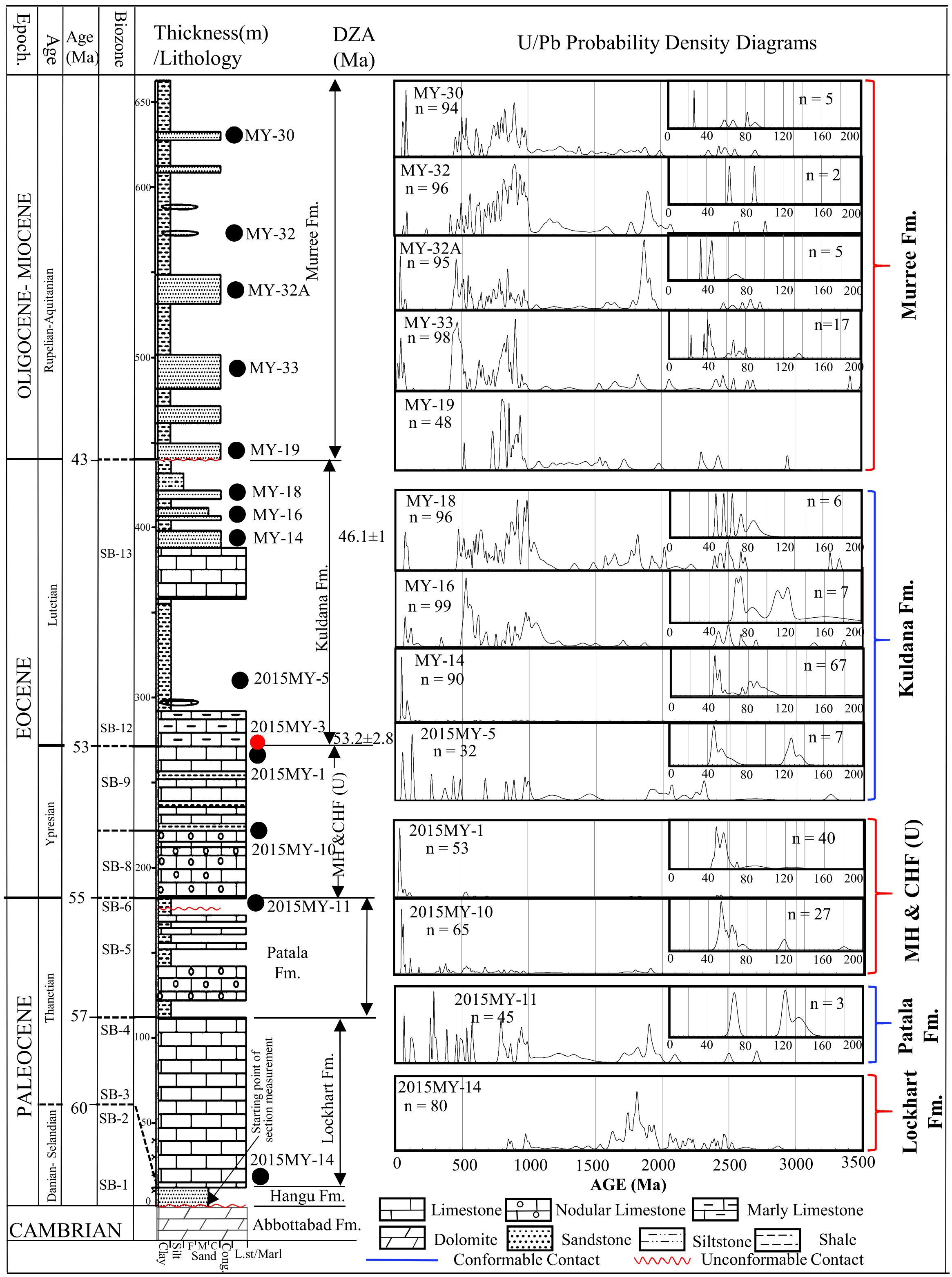


Fig. 4. The lithostratigraphic column of the Muzaffarabad section showing stratigraphic position of the samples selected for U–Pb analysis. The biozones and ages are assigned based on biostratigraphic studies (Baig and Munir, 2007; Gingerich, 2003; Serra-Kiel et al., 1998). The U–Pb probability density diagrams represent the sample analyzed. MH and CHF (U) stands for Margalla Hill Limestone and Chorgalli Formation (undifferentiated). The red filled circle represent the position of volcanic ash found in the Kuldana Formation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and there are some scattered ages between ∼2200–2700 Ma. The youngest suite of ages includes peaks at ∼60 Ma, ∼75 Ma, 100 Ma, 115 Ma and 170 Ma (Fig. 3).

Samples BTM-2, BT-7, BT-9, BT-14A and BB-8 were collected from the lower, middle, and upper part of the Kuldana Formation (Fig. 3). Most of the zircon crystals were rounded and sub rounded. Collectively, the five samples yielded 477 detrital zircons with concordant ages. The vast majority (∼68%) of the detrital zircon ages are between ∼43–113 Ma (Fig. 3). The two most significant age populations are between ∼43–60 Ma with a peak at ∼45 Ma, and between ~70–113 Ma with a peak at ~82 Ma. Subordinate age populations are around ~500 Ma and ~1000 Ma, and few scattered ages between ~2400–3200 Ma (Fig. 3).

Three samples (BT-11, BT-13 and BB-5) of fluvial sandstones were collected from the Murree Formation. Of the 300 detrital zircon grains analyzed, 290 yielded concordant ages. The most significant age populations are between ~400–600 Ma with a major peak at 500 Ma, ~700–1200 Ma, ~1500–1800 Ma, and ~2300–2500 Ma. The scattered ages are between ~2700–3400 Ma (Fig. 3). Only 7 detrital zircon grains out of 290 yielded <100 Ma ages.

4.3.2. Muzaffarabad section

Sample 2015MY-14 from the bottom of Lockhart Formation yielded 80 concordant ages out of 100 analyses (Fig. 4). The ages are mainly clustered around ~1600–2000 Ma, with a peak age at ~1800 Ma. Minor age populations are present between ~900–1100 Ma and 2100–2500 Ma (Fig. 4).

Sample 2015MY-11 was collected from the upper part of Patala Formation near the contact with Margalla Hill Limestone. The 50 detrital grains yielded 46 concordant ages. The dominant age populations are between ~785–1400 Ma and ~1700–2000 Ma (Fig. 4). There is a minor age population between ~450–580 Ma. Three grains yielded ages in the 100–200 Ma range.

Samples 2015MY-10 and 2015MY-1 were collected from the middle and upper part of the composite Margalla Hill Limstone and Chorgalli Formation, respectively. Collectively, of the 144 detrital zircons analyzed, 118 yielded concordant ages (Fig. 4). Almost half (~54%) of the grains yielded ages of <200 Ma. The other ages are clustered between ~350–900 Ma and ~1700–1950 Ma. The <200 Ma ages are clustered between ~48–100 Ma with a peak at 55 Ma and 110–130 Ma with a peak at 120 Ma (Fig. 4).

The lowermost sample (2015MY-5) was collected ~40 m above the lower contact with Chorgalli Formation. The 40 detrital zircons analyzed yielded 33 concordant ages. The main age groups are between ~46–135 Ma, ~800–100 Ma, and ~1900–2300 Ma (Fig. 4). Sample MY-14 was collected from the first sandy unit above the marly limestone of the Kuldana Formation. The 97 out of 100 analyses yielded concordant ages (Fig. 4). The majority (~65%) of the grains yielded ages <100 Ma with populations between ~45–55 Ma and ~75–100 Ma. The remaining grains yielded ages scattered between ~500–2400 Ma. Samples MY-16 and MY-18 collectively yielded 195 concordant ages. The age spectra depict prominent age populations around ~500–1100 Ma and ~2400–2500 Ma, with distinct peaks at ~500 Ma, ~650 Ma, ~875 Ma, ~915 Ma, ~990 Ma and ~1040 Ma (Fig. 4).

A total of 450 zircon grains were analyzed from five samples (MY-19, MY-33, MY-32A, MY-32 and MY-30) of Murree Formation, of which 431 yielded concordant ages (Fig. 4). The age spectra show major age populations at 90–22.7 Ma, ~420–550 Ma, ~700–900 Ma and ~1800–1900 Ma with peaks at ~47 Ma, ~70 Ma, ~450 Ma, ~500 Ma, ~740 Ma, ~825 Ma, ~900 Ma, and ~1870 Ma (Fig. 4). Minor age populations are also present between ~1000–1700 Ma and ~2300–2750 Ma.

4.4. Quantitative analyses

We performed different statistical analyses to compare our data with source terranes, i.e., Himalayan source (Indian Affinity) and/or Asian source (Kohistan–Ladakh arc, Karakoram Block and Lhasa Block). These analyses include cross correlation, likeness, similarity, Kolmogorov–Smirnov test (K–S test) and Kuiper's statistic test using DZstats software (Saylor and Sundell, 2016). The statistical values range between 0–1, which shows weak to perfect relation respectively. While the "k" value for Kolmogorov–Smirnov test and Kuiper's statistic test shows inverse relation from 0–1 (i.e., strong to weak relation from 0 to 1). The Paleocene Hangu, Lockhart and Patala formations from both sections show good relation with Indian affinity detritus (Figs. 5B and S5–S8). The Margalla Hill Limestone and Chorgalli Formation from Balakot section shows a good relation to both Indian and Asian sources, while in the Muzaffarabad section, these show a comparatively strong relation to Asian sources (Figs. 5B and S5–S8). The statistical results of Kuldana Formation from both sections show a strong relation to Asian sources. The quantitative analyses show that the Murree Formation has a comparatively strong relation to Indian affinity source (Figs. 5B and S5–S8).

5. Discussion

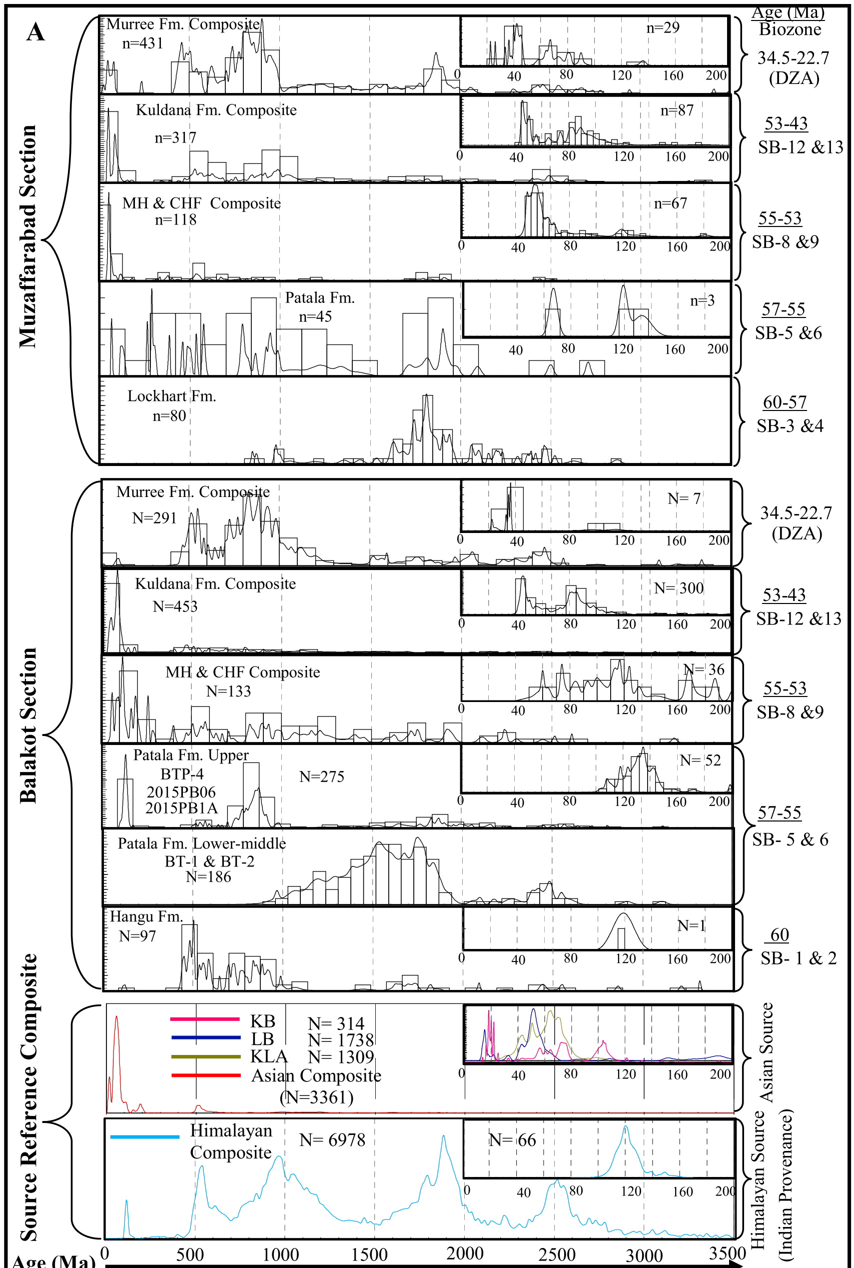
5.1. Detrital zircon provenance of Cenozoic sequences

In order to mark the India–Asia provenance transition, the U–Pb detrital zircon age data of various terranes were compiled (Fig. 5A; Supplementary text 2). Of which the Higher Himalaya (HH), Lesser Himalaya (LH) and Tethyan Himalaya (TH) represents the Indian affinity and considered collectively as Himalayan source, while Kohistan–Ladakh arc (KLA), Karakoram Block (KB) and Lhasa Block (LB) represents the Asian affinity. We considered the KLA as a southern margin of Asian Plate accreted to KB during the latest Cretaceous (Searle et al., 1999). In the following section the detrital provenance is explained with reference to these terranes.

One sample of the Hangu Formation matches with the Himalayan spectrum, which suggests derivation from the Indian Plate provenance (Fig. 5A). A single Cretaceous detrital zircon with age 119 ± 8 Ma in the Hangu Formation probably represents the derivation from volcanic rocks of the Indian craton (DeCelles et al., 2000).

The one sample of the Lockhart Formation from Muzaffarabad section shows a dominant age population between ~1600–1900 Ma with a peak at ~1800 Ma (Fig. 5A). This age spectrum also matches with that of Himalayan spectrum indicating Indian Plate provenance.

The detrital zircons from the lower and middle Patala Formation exhibit age cluster between ~900–1930 Ma with a major population around ~1500–1800 Ma (Fig. 5A). In the upper part, sample 2015PB1A is from the conglomeratic bed, while samples 2015PB06 and BTP-4 were collected from the sandy unit above the conglomeratic bed and from arenaceous shale at the upper contact respectively. The detrital zircon ages from these samples are clustered around ~675–975 Ma with a peak at ~875 Ma (Fig. 5A). A minor age population present between ~1600–2200 Ma with a peak at ~1800 Ma (Fig. 5A). Sample BTP-4 also shows ages between ~100–160 Ma with peaks at 120 Ma, 135 Ma and 143 Ma (Fig. 5A). Similarly, sample 2015MY-11 represents the same stratigraphic level of the Patala Formation in the Muzaffarabad section, as the samples 2015PB06, 2015PB1A, and BTP-4 in the Balakot section. The age spectrum of the 2015MY-11 is broadly similar to the age spectra of samples collected from the upper part of Patala Formation. However, the younger grains in this sample is less as compared to BTP-4. The possible reason might be the number of zircon analyzed or the drainage direction in the basin. The single 67 Ma detrital zircon might be derived from the Deccan Trap as suggested by the Garzanti and Hu (2014). This contrasting age pattern from lower–middle–upper part of Patala Formation points to different provenance, but from the same source i.e., Indian Plate. However the younger age spectrum (100–160 Ma) is similar to the younger age spectrum of Indian Plate provenance. The ophiolitic remnants preserved within Indus Suture zone also portray an age spectra within ~126–170 Ma (Bouilhol et al., 2013). This suggests that the younger detritus in the upper part of Patala Formation may possibly derived from these ophiolitic remnants and



B

	Statistical tests	Cross correlation Coefficient	Likeness	Similarity	Kolmogorov -Smirnov test k statistic	Kuiper Statistic test k statistic	Cross correlation Coefficient	Likeness	Similarity	Kolmogorov -Smirnov test k statistic	Kuiper Statistic test k statistic
Balakot Section Dataset											
	Formation	**Statistical Comparison with Asian source dataset**					**Statistical Comparison with Indian source dataset**				
Complete Detrital Zircon Dataset	Murree Fm	0	0.219	0.465	0.399	0.76	0.282	0.623	0.882	0.507	0.507
	Kuldana Fm	0.367	0.47	0.732	0.317	0.318	0.01	0.245	0.389	0.693	0.693
	MH&CHF Fms	0.172	0.374	0.659	0.581	0.581	0.023	0.601	0.804	0.369	0.375
	Patala Fm	0.004	0.199	0.385	0.714	0.718	0.129	0.579	0.863	0.218	0.218
	Hangu Fm	0.001	0.2	0.407	0.785	0.786	0.112	0.502	0.811	0.804	0.804
Younger (<200Ma) Detrital Zircon Dataset	Murree Fm	0.003	0.011	0.16	0.399	0.76	0	0.006	0.107	0.507	0.507
	Kuldana Fm	0.159	0.488	0.768	0.317	0.318	0.022	0.022	0.146	0.693	0.693
	MH&CHF Fms	0.001	0.286	0.481	0.581	0.581	0.016	0.241	0.369	0.369	0.375
	Patala Fm	0.052	0.057	0.11	0.714	0.718	0.086	0.354	0.585	0.218	0.218
Muzaffarabad Section Dataset											
Complete Detrital Zircon Dataset	Murree Fm	0	0.219	0.465	0.399	0.76	0.276	0.646	0.888	0.362	0.362
	Kuldana Fm	0.502	0.431	0.727	0.48	0.48	0.039	0.567	0.776	0.395	0.403
	MH&CHF Fms	0.79	0.558	0.745	0.208	0.223	0.002	0.264	0.39	0.673	0.673
	Patala Fm	0.037	0.281	0.545	0.703	0.712	0.085	0.679	0.888	0.262	0.262
	Lockhart Fm	0.007	0.113	0.232	0.869	0.874	0.284	0.54	0.834	0.379	0.49
Younger (<200Ma)	Murree Fm	0.003	0.011	0.16	0.399	0.76	0.016	-0.021	0.011	0.362	0.362
	Kuldana Fm	0.185	0.464	0.735	0.48	0.48	0.013	0.069	0.183	0.395	0.403
	MH&CHF Fms	0.7	0.663	0.845	0.208	0.223	0.002	0.074	0.269	0.673	0.673
	Patala Fm	0.007	0.113	0.232	0.869	0.874	0.027	0.082	0.288	0.262	0.262

Fig. 5. A) Comparison of probability density diagrams for detrital zircon ages from the Paleocene–Early Miocene foreland sequence of Balakot and Muzaffarabad areas (this study), Reference age populations from source terranes including Himalayas, Kohistan–Ladakh Island arc, Karakoram Block and Lhasa Block (see supplementary data). B) Results of the quantitative analyses for the detrital zircons U–Pb dataset of Balakot and Muzaffarabad Sections to the source terranes (Indian and Asian source dataset). Fm – Formation and MH&CHF-Margalla Hill Limestone and Chorgalli Formation.

the Indian Plate. This provenance change might be related with the migration of forebulge due to loading of KLA on the northern Indian margin and/or obduction of Ophiolitic remnants, which caused increased input to the upper part of Patala Formation from younger Himalayan sources and ophiolitic remnants. The age limit of the Patala Formation is ca. 57–55 Ma, based on biostratigraphic studies in Hazara and Kohat–Potwar region (Shah, 2009). This age constraint of the Patala Formation is consistent with being at stratigraphic position between Thanetian Lockhart Formation and Ypresian Margalla Hill Limestone (Baig and Munir, 2007; Hanif et al., 2014). Despite the contrasting provenance between lower and upper parts of Patala Formation, there is no evidence of unambiguous Asian detritus (<100 Ma) until sample BTP-4 in Patala Formation. This age cluster of Patala Formation points to the derivation from the Indian Plate source with contribution from ophiolitic remnants.

The U–Pb age spectra for the arenaceous shale samples of Margalla Hill Limestone and Chorgalli Formation from both Balakot and Muzaffarabad sections indicate an appearance of Cretaceous–Eocene detritus (Fig. 5A). Age populations are present at <200 Ma and between ∼300–700 Ma, 800–1500 Ma and 1600–1900 Ma. The younger ages are mainly clustered between ∼48–120 Ma with peaks at ∼55 Ma, ∼60 Ma, ∼75 Ma and ∼110 Ma (Fig. 5A). These younger ages are similar to the KLA, KB and LB age spectra. The prominent peaks around ∼100–110 Ma are characteristic of the KB (Ravikant et al., 2009), while the LB zircons depict a more pronounced peak at 52 Ma (Fig. 5A). Therefore, in our interpretation, the detritus of the composite Margalla Hill Limestone and Chorgalli Formation were most likely derived dominantly from the KLA with contribution from the KB and LB, which represents the Asian terranes (Fig. 5A). This appearance of Asian affinity detritus, recorded in the bottom most part of Margalla Hill Limestone, indicates the India–Asia provenance transition. The depositional age of the Margalla Hill Limestone is Early Eocene (∼55–53 Ma) based on foraminiferal biostratigraphy of Balakot and Muzaffarabad areas (Baig and Munir, 2007). The volcanic ash in the lower part of Chorgalli Formation constrain the upper age limit of 53.2 ± 2.8 Ma. Which indicates that the India–Asia provenance transition occurred after ca. 55 Ma. The statistical analyses of the detrital zircon age data also supports the mixed source. However, the relation to the Asian source is higher than Indian source (Figs. 5B and S5–S8).

The detrital zircons of Kuldana Formation show age clusters at ∼40–60 Ma and ∼70–113 Ma with major peaks at ∼45 Ma and ∼82 Ma, respectively. These ages overlap dominantly with those exhibited by the KLA with contribution from KB and LB indicating increased input from the Asian terranes in the north. There is also an increase in the number of <50 Ma grains going up-section in the Kuldana Formation. This is interpreted to indicate continued exhumation of the KLA in the hanging wall of the MMT. The statistical analyses also portray strong relation to the Asian source (Figs. 5B and S5–S8).

The detrital zircon ages of Murree Formation from both the Balakot and Muzaffarabad sections are similar, showing major populations between 700–1000 Ma and at ∼500 Ma (Figs. 3, 4 and 5A). However, a substantial number of detrital zircon ages are present between 1500–1800 Ma and 2300–2500 Ma. A fair number (∼7%) of younger zircons ages between 22–120 Ma are also present in the Murree Formation (Fig. 5). These age clusters and peaks can be explained by a contribution from various litho-tectonic terranes including the Asian and Himalayan. The statistical analyses shows the strong relation to the Himalayan source, while the Asian source has comparatively weak relation with the Murree Formation (Figs. 5B and S5–S8). Detrital contributions from all of these various litho-tectonic terranes is consistent with progressive southward propagation of Himalayan fold-thrust belt. Which suggests the large scale exhumation of Himalaya during Oligocene–Miocene period.

Although the Paleocene Hangu, Lockhart and Patala formations in Pakistan, and the Paleocene Charchare and Amile formations in Nepal lesser Himalaya lay atop the Paleozoic sequence of Indian continental lithosphere, which in turn were sourced from the Indian plate, many (∼30%) <100 Ma detrital zircons of Asian affinity are present within the Eocene Margalla Hill Limestone, Chorgalli Formation, Kuldana Formation and Oligocene–Miocene continental Murree Formation in northern Pakistan, but grains <100 Ma are very rare in the Eocene Bhainskati Formation, and Miocene Dumri Formation and even younger Siwalik formations, which are dominated by late Proterozoic and early Paleozoic grains in Nepal (DeCelles et al., 2004; Najman, 2006).

5.2. Implications for timing of India–Asia collision

In present study, India–Asia collision is considered as the first contact of continental blocks after disappearance of oceanic lithosphere. Following this collision the rocks from one block may be exhumed and provide detritus to the sedimentary basins formed on other block. The U–Pb age results from the Cenozoic strata allow distinction between Asian and Indian provenance. This dataset provides minimum age for the India–Asia collision in the northwestern Himalayas of Pakistan.

The Lower Paleocene Hangu Formation consists of laterite, bauxite, clays, arenaceous limestone and sandstones. The laterite/bauxite of the Hangu Formation is indicative of a marine regression and has been attributed to pre-Paleocene uplift at northern passive margin of the Indian Plate (Garzanti and Hu, 2014). The similarity of U–Pb age spectrum to the Himalayan source supports the derivation from the Indian affinity source. It is overlain by the Upper Paleocene Lockhart Formation, which is dominantly composed of nodular limestone indicating a shallow marine lagoonal environment (Hanif et al., 2014). The U–Pb age spectrum of the Lockhart Formation is also similar to the Himalayan spectrum, which also indicates an Indian provenance. The Lockhart Formation is overlain by the Upper Paleocene Patala Formation. The detrital zircon age cluster of the Patala Formation has a similarity with the Himalayan source. While younger age spectrum (104–172 Ma) of the upper part of Patala Formation shows the similarity with younger Himalayan spectrum and to the ophiolitic remnants preserved within Indus suture zone (Bouilhol et al., 2013). This absence of Asian affinity detritus strongly suggests an Indian affinity provenance for the Patala Formation. Based on the stratigraphic evidence, it is suggested that an erosional surface present in the upper part of Patala Formation, formed during ca. ∼56–55 Ma. We suggest that the contrasting provenance change below and above of this erosional surface might record the migration of flexural forebulge through this region, and the upper part of the Patala Formation sat within the distal foredeep which is of Indian affinity. However, forebulge depozone interpreted in other regions such as Zanskar in the northwestern Indian Himalaya (57 Ma) and the central Tethyan Himalaya at Zhepure Mountain (60–58 Ma), are older than that of this region (Hu et al., 2015b). The coeval foredeep depozone of the Zhepure Mountain forebulge lay at Sangdanlin and began to receive the Asian affinity deposits at 59 ± 1 Ma or as early as ∼65 Ma (Ding et al., 2005; DeCelles et al., 2014; Hu et al., 2015a). Considering the minimum distance (∼20 km) from the MMT to the MBT (compares with that of ∼300–200 km in northwestern India and Nepal Himalaya), the forebulge should quickly pass through this region when the Asian plate initially loaded onto the Indian plate, although flexural wavelength is controlled by various factors including rigidity of subducting lithosphere, fold-thrust belt load and density of the mantle (DeCelles et al., 2014). So the initi-

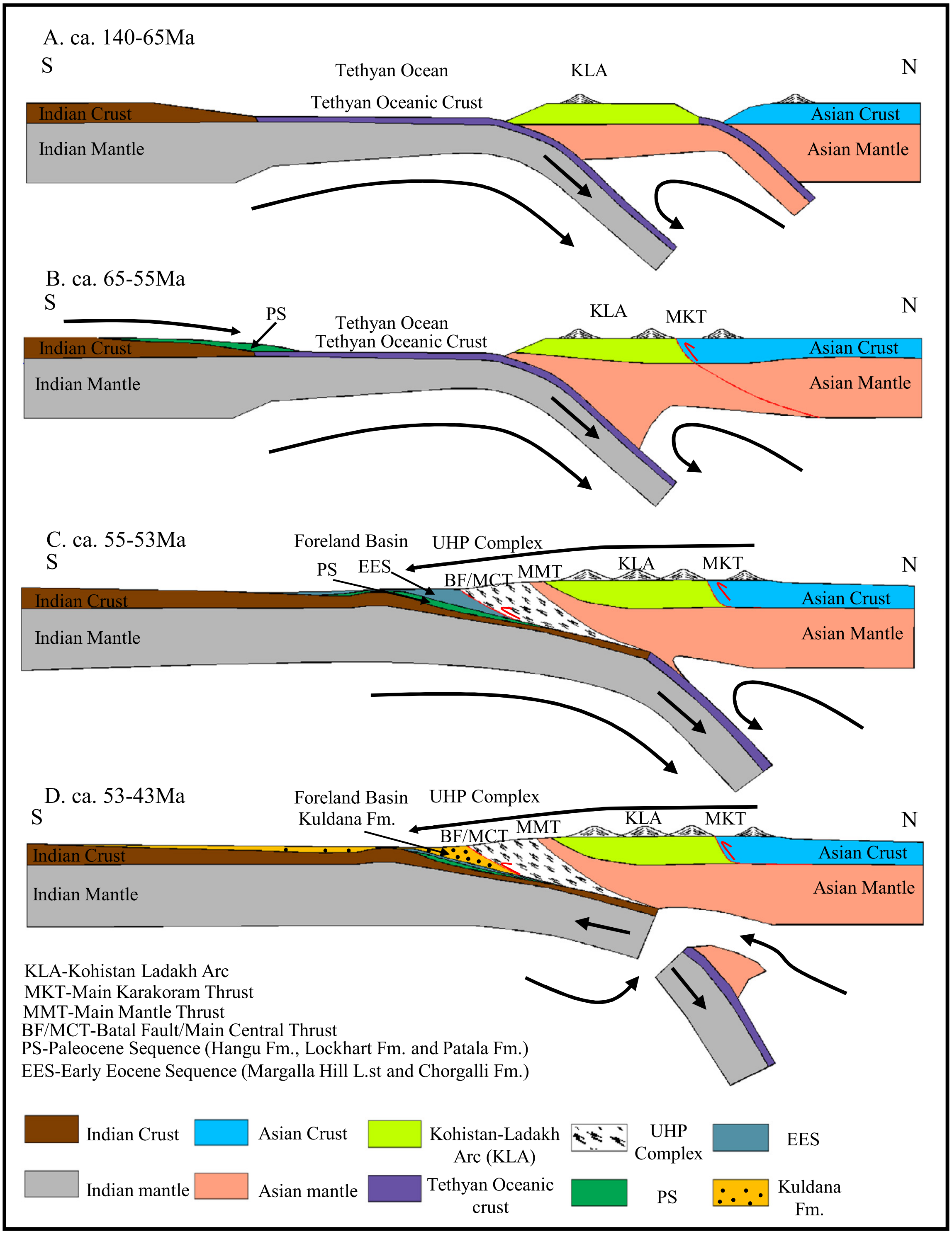


Fig. 6. Tectonic evolution model of India–Asia collision. A) The formation of Kohistan Island arc and subsequent collision with the Asian Plate along MKT during Cretaceous. B) Continued subduction of Tethyan oceanic crust and deposition of Paleocene sequence, which is sourced from south. C) Sediment source shifted from south to north after ca. 55 Ma and deposition of Early Eocene sequence started, which shows signature of Asian affinity detritus. D) Subsequent uplift with MMT and increased contribution of detritus from KLA during deposition of Kuldana Formation.

ation of the foreland basin system along the northernmost Indian plate may be the same age of forebulge development at ca. ∼56–55 Ma in this region. The Patala Formation is overlain by shallow marine carbonate of the Early Eocene Margalla Hill Limestone and Chorgalli Formation. The detrital zircon age spectra show the first appearance of Cretaceous–Eocene detritus at the contact with Patala Formation. This first appearance of the Asian detritus provides minimum age constraint on timing of India–Asia collision. These age spectra clearly indicate the provenance transition from India to Asia occurred prior to deposition of Margalla Hill Limestone. The biostratigraphic age of this Limestone unit is Early Eocene (∼55–53 Ma) based on studies in the Balakot, Muzaffarabad and Kohat–Potwar Plateau (Baig and Munir, 2007; Sameeni et al., 2013). These shallow marine carbonate sequences are overlain by Lower–Middle Eocene Kuldana Formation, which is dominantly composed of variegated color shale, silt- and sandstones with subordinate marly limestone and calcareous shales. The U–Pb age spectra of the Kuldana Formation indicate the derivation of detritus from the Asian terranes including KLA, KB and LB. Both the Early Eocene Margalla Hill Limestone and Chorgalli Formation may have been deposited in a foredeep depozone (∼55–48 Ma). So, this stratigraphic record and the U–Pb age spectra provide minimum age constraint on collision timing of India and Asia, which occurred before the deposition of Margalla Hill Limestone at ca. 56–55 Ma.

Along strike in the Zanskar region, stratigraphic studies indicate collision onset at ca. 57 Ma (Garzanti et al., 1987). In the Zanskar–Hazara region, the stratigraphic evidence suggests onset of collision around ca. 52 Ma (Rowley, 1996) and ca. 50 Ma (Zhu et al., 2005). To the southwest of study area, Khan and Clyde (2013) proposed initiation of collision at ca. 55 Ma. Moreover, the Ultra high pressure (UHP) eclogite metamorphic age at Tso Morari complex shows the onset of India–Asia continental collision at ca. 53 Ma (Leech et al., 2005). Our results, in combination with previous work, from the northernmost exposures of Paleocene–Miocene sequence suggest that initial India–Asia collision occurred at ca. 56–55 Ma in northwestern Himalaya of Pakistan.

Van Hinsbergen et al. (2012) suggested that the Tethyan Himalaya (TH) rifted from the Indian Plate between 120–70 Ma, and resulted in the opening of a >1900 km wide Greater India Basin (GIB). Subsequently, the TH collided with Asia at ∼50 Ma and then the GIB itself closed along the MCT at ∼25–20 Ma. The opening of the GIB is supported by paleomagnetic data and the eruption of lower Cretaceous alkali-basalt within the TH. However, geologically, there is no evidence, such as a volcanic arc or Cenozoic deep marine strata, which confirm the subduction of GIB along MCT. Furthermore, if the GIB exist, DeCelles et al. (2014) suggested modification to the GIB model by placing suture placed to north of STDS and closure time at 45 Ma to fit the deformation history of the HH and the TH. However, as previous discussion of our data of the north Pakistan Sub-Himalayan foreland basin, the younger (<100 Ma) Asian affinity record since Early Eocene still challenge this modified GIB model, this would require both GIB and Indus Suture Zone completely closed before ∼55 ± 1 Ma, alternatively, there is no existence of GIB in north Pakistan.

5.3. Tectonic implications for Himalayan orogenesis

The India–Asia collision resulted in the development of a fold-thrust belt with variable shortening estimates from west to east. The minimum shortening at western Himalaya in Pakistan is ∼470 km, which increased in to the central Himalaya upto ∼817 km and decreased further in the east upto ∼579 km (DeCelles et al., 2002). This shortening is related with the raising of the Himalayan lithotectonic terranes with several south verging faults. The detrital record of the Tertiary sequence in the Balakot–Muzaffarabad areas provide significant information about uplifting and source terranes feeding the Tertiary foreland basin as a result of India–Asia collision. The detrital zircon provenance of the lower Paleogene sequence indicates the Indian sources (Figs. 6A and 6B). The Indian–Asian provenance change occurred after 55 Ma and recorded in the lowermost part of Margalla Hill Limestone (Figs. 6C and 6D). This provenance shift is a clear evidence of India–Asia collision, and the collision zone was marked by the MMT.

The increased input from the Himalayan source in the Murree Formation indicates large scale exhumation of Himalayan terranes in response to southward propagation of fold-thrust belt.

6. Conclusion

The Cenozoic foreland basin strata in the Hazara–Kashmir syntaxial region of northern Pakistan unconformably overlies various stratigraphic units ranging in age from Cambrian to Cretaceous. The Cenozoic sequence is composed of Paleocene–Eocene marine deposits in the lower part and Oligocene–Miocene continental deposits in the upper part. The Paleocene Hangu, Lockhart and Patala formations were deposited on the northern Indian passive margin, and their U–Pb age spectra resemble with the Himalayan spectrum, which points derivation from the source of Indian affinity. A ∼56–55 Ma erosional surface, between the lower and upper most part of the Patala Formation is interpreted to mark the migration of flexural forebulge through this region. Despite of contrasting provenance of the lower and upper part of Patala Formation, all detrital zircon samples are strong indicative of an Indian affinity. We consider the upper part of the Patala Formation to have been deposited within the distal foredeep of the foreland basin. The provenance shift from Indian affinity to Asian affinity occurred between the uppermost part of Patala Formation and the lowermost part of Margalla Hill Limestone after ca. 55 Ma. A large percentage (∼45%) of <100 Ma detrital zircons are present within Eocene Margalla Hill Limestone, Chorgalli Formation, and Kuldana Formation, and indicate the derivation from the Asian terranes including KLA, KB and LB, and deposition within foredeep depozone (∼55–48 Ma). Detrital zircon geochronology in combination with previous biostratigraphic work clearly indicates the initial India–Asia collision occurred at ca. 56–55 Ma in the northwestern Himalaya of Pakistan. The increased appearance of Himalayan detritus in the Oligocene–Miocene (35–23 Ma) Murree Formation suggests the exhumation of Himalaya as a result of southward propagation of fold-thrust belt.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.09.003.

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