

Article

The Early Paleocene Ranikot Formation, Sulaiman Fold-Thrust Belt, Pakistan: Detrital Zircon Provenance and Tectonic Implications

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Abstract: This study reports on the detrital zircon provenance of the sandstones of Early Paleocene Ranikot Formation exposed in the Fort Munro section, Sulaiman fold-thrust belt, Pakistan. This marks the Cretaceous-Tertiary boundary sequence. The detrital zircon U-Pb ages reported are mainly clustered around ~460–1100 Ma, ~1600–1900 Ma and ~2300–2600 Ma. The age cluster ~460–1100 Ma is mainly matched well with the Tethyan Himalaya. However, the age clusters ~1600–1900 Ma and ~2300–2600 Ma matched fairly with the lesser Himalayas and Higher Himalayas. In addition, the sandstone petrography suggests the craton interior provenance. The two younger Cretaceous zircon ages may be derived from the Tethyan Himalaya volcanic rocks as supported by a high (>0.3) Th/U ratio. Furthermore, the absence of the ophiolitic component ~115–178 Ma suggests that the western ophiolite may be emplaced at the same time as Ranikot Formation deposited or later. Moreover, the absence of the Eurasian (zircon with ages <100 Ma) in the Ranikot Formation excludes the possibility of the early collision along the western margin, as reported in earlier studies.

Keywords: western Indian margin; Sulaiman fold-thrust belt; Ranikot Formation; detrital zircon; U-Pb geochronology; provenance



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1. Introduction

The start of the Paleocene period is an important time in the geological history of the Indian plate. At this time, the three most pronounced geological events that occurred were associated with the movement of the Indian plate. These events are ophiolite emplacement, Deccan traps volcanism and the India–Asia collision [1,2]. The ophiolite emplacement occurred along the northern, eastern and western margins marking the initial stage of the Tethys Ocean closure [3]. The second geological event is the Deccan trap volcanism, which is associated with the movement of the Indian plate over the mantle hotspot [2]. The third one is the terminal India–Asia collision marked on the bases of stratigraphic records studied on the western margin [4]. The first two geological events are reported to have occurred during the Cretaceous–Paleocene time [2,3]. The India–Asia collision is reported to have occurred in the Paleocene–Eocene time in northwestern Himalaya [4–7]. Source rocks that were formed and exposed to erosion during these geological events played an important role in providing detritus to nearby sedimentary basins. Therefore, the location of this study can provide information on the role and contribution of these geological events in paleogeographic reconstruction. The information stored in the sedimentary basins can be obtained by studying the provenance of their siliciclastic rocks [8–10]. In the last two decades, advanced U-Pb geochronology has been widely applied to restore the geological

information from sedimentary basins [6,11–19]. Previously, sandstone petrography was used extensively to obtain such information [10,20–25]. However, the sandstone petrographic studies may have generic interpretations because sediment composition can be matched with source rocks from several adjacent blocks. Therefore, the advanced U-Pb age data may complement this information in its capacity to recognize more precisely which are the most probable source areas. In this study, we provided detrital zircon U-Pb age data for the sandstone of the Ranikot Formation from the Sulaiman fold-thrust belt supplemented with petrography (Figure 1A–C). This integrated approach provides insight on the provenance of the Paleocene Ranikot Formation and its tectonic implications.

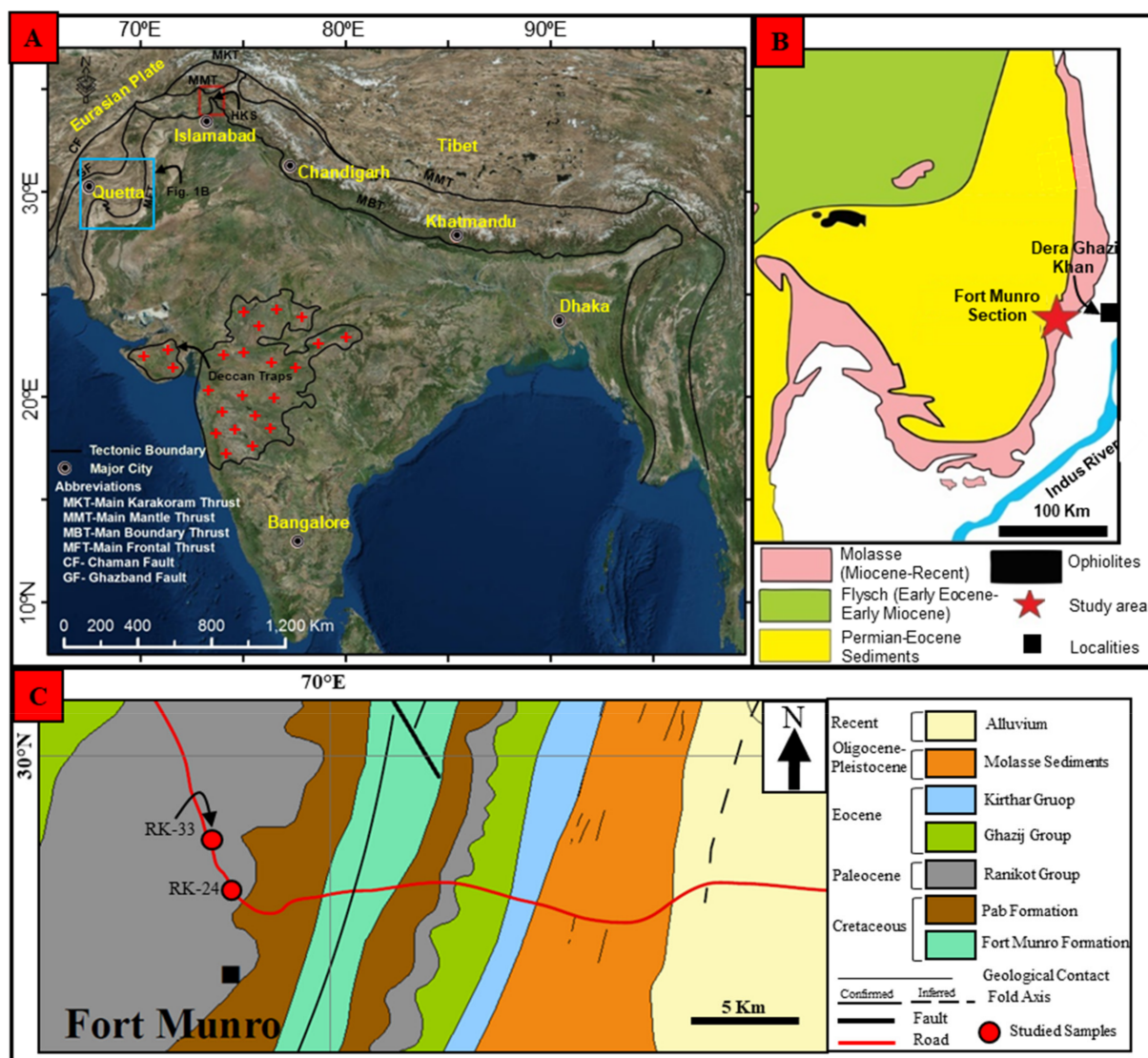


Figure 1. (A) Generalized map showing regional tectonic features. The location of Sulaiman fold-thrust belt (SFB) is marked by blue rectangle. The red rectangle shows the Hazara–Kashmir syntaxial bend (After [7]). (B) The simplified geological map of SFB showing the location of the studied section (After [26]). (C) Modified geological map of the Fort Munro area showing major stratigraphic units and locations of the studied samples (After [27]).

2. Geological Setting and Stratigraphy

The Sulaiman fold-thrust belt (SFB) was developed in response to the oblique collision of the Indian plate with the Afghan block (Asian Plate) [28,29]. The SFB is ~300 km wide and has a curved lobe-shaped asymmetrical structure (Figure 1A,B). Its eastern boundary is marked by the Sulaiman range, which is oriented N–S. The younger (Pleistocene–Oligocene)

rocks are exposed along the eastern edge of the SFB, while older (Eocene–Cretaceous) rocks are exposed towards the western edge of the SFB. The older strata in the SFB are exposed consistently in the core of the anticlines without the existence of emergent thrust in the foreland. This impression of the stratigraphy suggests monoclinical structure of the eastern SFB [30]. In the southern SFB, the monoclinical structure is less pronounced than the eastern SFB, with wide detachment folds over the basement [29]. At the western and northern boundary of the SFB, the ophiolitic sequence is emplaced over the Cretaceous–Eocene sedimentary rocks and marked by the Zhob valley thrust (Figure 1B). The stratigraphy of the SFB is generally subdivided into three groups: Permian–Eocene carbonate sedimentary rocks, Eocene–Oligocene Khojak flysch overlies the Muslimbagh ophiolite and Oligocene–Recent molasses [28]. The Ranikot Formation is exposed in the anticlinal structure at the eastern edge of SFB. It mainly consists of varied color sandstones with intercalations of shale and limestone (Figure 2A,B). The limestone is grey with thickness varying between 10 cm to 30 cm. The shales are calcareous and occur in the lower part of the formation. The contact relationship of the Ranikot Formation with the Cretaceous Pab Formation is unconformable and marked by the erosional surface, while the upper contact with the Dunghan Formation is conformable. The age assigned to the Ranikot Formation is Early Paleocene (Danian) [31].

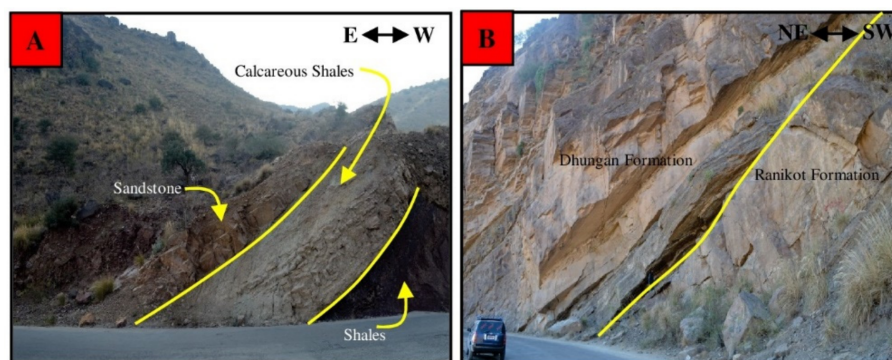


Figure 2. Field photographs showing various lithological units and geological contacts. (A) sandstone of the Ranikot Formation at lower contact with calcareous shales of the Pab Formation. (B) Upper contact with Dunghan Formation.

3. Analytical Methods

3.1. Petrography

For petrographic observations, two representative Ranikot sandstone samples from the Fort Munro section were chosen. In the Rock Cutting and Thin Section Lab at the Department of Earth Sciences, COMSATS University Islamabad, Abbottabad Campus, Pakistan; these samples were cut and thin sections were made. Under a polarizing petrographic microscope, the thin sections were examined. Using the point counting approach, 400 individual framework grains were counted from various angles of the thin section [32].

3.2. U-Pb Geochronology

U-Pb geochronology of detrital zircon grains is used extensively in provenance studies. In this method, detrital zircon grains are separated from the representative samples of siliciclastic rocks and analyzed through Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) to measure the isotopic ratios and estimate their ages of crystallization. In this study, two representative samples of the Ranikot Formation were collected from the base and top. The detrital zircon grains were separated from the samples using classical methods (heavy liquids and magnetic separation). Approximately 200–300 zircon grains from each sample were mounted on the glue strip and finally, epoxy resin was poured on the glue strip. In the next stage, the zircon grains were polished to make the surface of the grain plane. Before the in situ laser ablation, the samples were

cleaned with alcohol and dilute nitric acid to remove the lead contamination. The analyses were performed at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China. One hundred analyses spots of 35 μm were placed on 100 individual grains of each sample. The age of detrital zircon was calibrated using the GJ-1 standard, which has a mean age of 609 Ma [33]. The raw data obtained after analyses by Agilent 7500 LA-ICPMS were processed using Glitter 4.0 software. After the lead correction, the data with >10% uncertainty were removed from the final interpretation. The final age data were displayed by probability density plots (PDPs) using Isoplot [34]. The U-Pb geochronology data are provided in the supplementary data (Supplementary Material Table S1).

To prevent the mixing of the core and rim ages, the cathode luminescence (CL) images were taken before the in situ U-Pb investigations.

4. Results

4.1. Sandstone Petrography

Two thin sections of sandstones from the Ranikot Formation were examined. The sample RK-24 comprised 96% quartz, 3.75% feldspar and 0.25% lithics (Figure 3A), whereas the sample RK-24 comprised 95% quartz, 4% feldspar and 1% lithics. The quartz grains were mostly monocrystalline. Polycrystalline quartz grains were also observed (Figure 3B,C). The feldspar was entirely alkali feldspar. The lithics observed were sedimentary. Hematite occurred as an accessory mineral. The framework grains observed were sub-angular to sub-rounded with moderate sorting (Table 1). Ranikot sandstone is plotted in a craton interior field on ternary diagrams (Figure 3D,E).

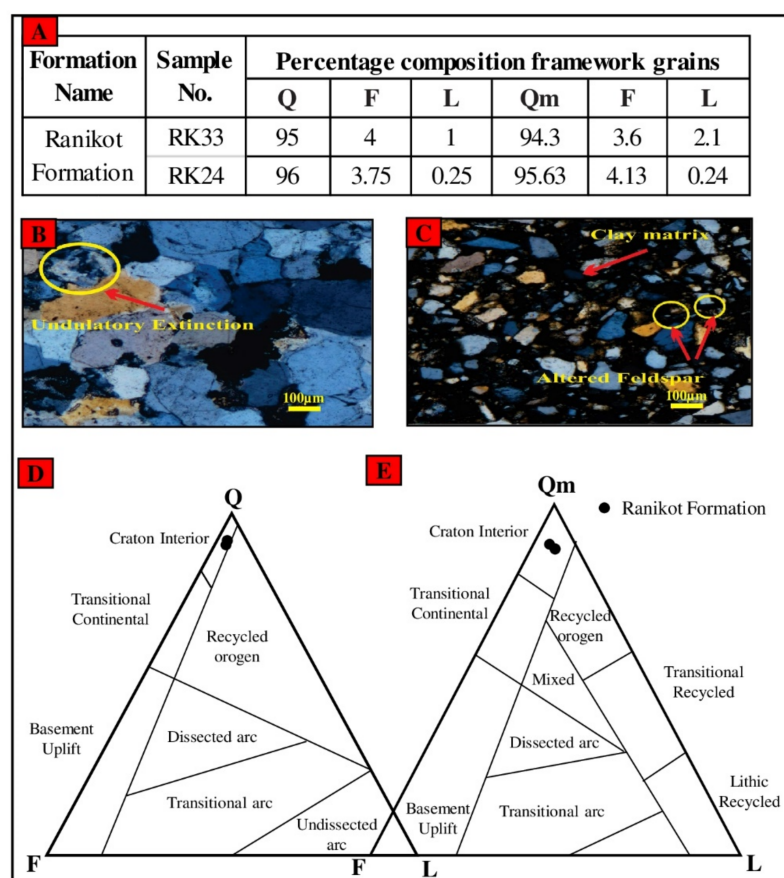


Figure 3. (A) Percentage composition of the Ranikot sandstone. (B,C) Photomicrographs of the studied thin sections of the Ranikot Formation. (D,E) The ternary diagrams [32] showing tectonic discrimination of the studied samples. Q—quartz, Qm—monocrystalline quartz, F—feldspar and L—lithics.

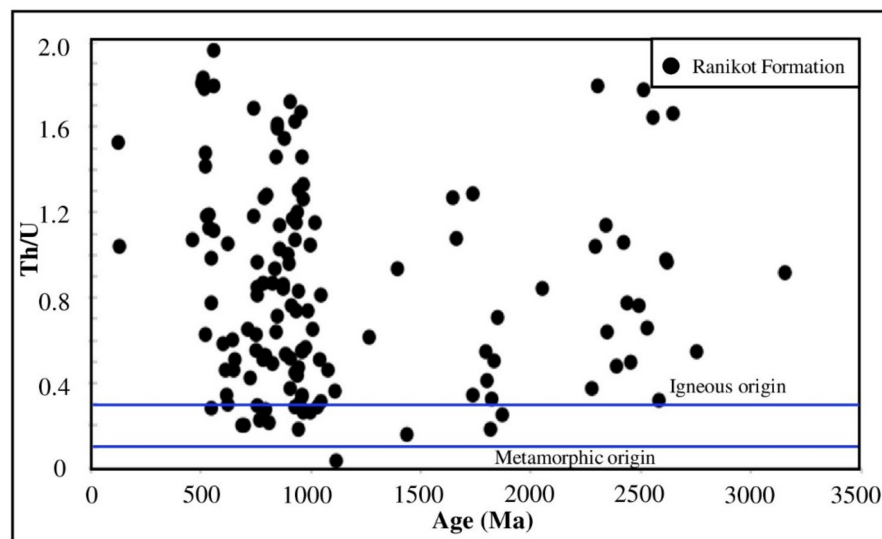
Table 1. The petrographic properties of the grains observed in thin sections.

Formation Name	Sample No.	Grain Shape		Fabric Support/ Contacts	Sorting	Maturity	
		Roundness	Sphericity			Textural	Mineralogical
Ranikot Formation	RK-33	Sub angular-Sub rounded	Low	Grain supported, Pointed contacts	Moderately sorted	Mature	Mature
	RK-24	Sub rounded-rounded	Low-Medium	Grain supported, Pointed contacts	Moderately sorted	Mature	Mature

4.2. U-Pb Geochronology of Detrital Zircon

Based on their internal structure, it is crucial to distinguish between zircon grains with a volcanic, metamorphic and sedimentary origin [35]. The oscillatory zoning pattern that is observable in the few imaged samples evidences an igneous origin [36], as well as a core and rim structure, which suggests a metamorphic origin. Many of the zircon grains have rim and core structures. The internal structure of zircon grains shows sectoral and xenocrystic core structures. Morphologically, euhedral zircon crystals are present. Most zircon crystals present stubby and stalky appearances with a rounded to sub-rounded shape. While needle-like crystals are extremely uncommon, a small percentage of the crystals have a prismatic look.

Zircon grains' elemental ratios of Th and U are utilized to distinguish between igneous and metamorphic zircons in addition to zoning patterns [37]. In general, volcanic zircons have an elemental Th/U ratio of >0.3 , while metamorphic zircons have a ratio of <0.3 [36]. To distinguish between volcanic and metamorphic zircon, the Th/U ratio is plotted against their U-Pb ages. Most of the zircon grains have a high Th/U ratio (>0.3), which suggests derivation from the igneous rocks (Figure 4). Very few detrital zircon grains have a Th/U ratio <0.3 , which suggests derivation from the metamorphic origin. The two younger grains with ages 122 Ma and 128 Ma show Th/U ratio >0.3 (Figure 4).

**Figure 4.** Binary plot of U-Pb ages and Th/U ratios showing the igneous and metamorphic origin zircons.

One hundred spots were analyzed on 100 individual detrital zircon grains of the sample RK-24, which yielded 99 concordant ages. The majority of the detrital zircon ages are in the range ca. 460–1100 Ma, which is ~70% of the total age population. The main age peaks are at ca. 526 Ma, 546 Ma, 607 Ma, 751 Ma, 875 Ma and 957 Ma. The second group (~9%) of detrital zircon ages correspond to Paleoproterozoic zircon in the range ca. 1600–1900 Ma. The third age cluster (~16%) includes Late Paleoproterozoic to Neoproterozoic

zircon, between ca. 2300 and ca. 2650 Ma (Figure 5). The youngest zircon grains yielded lower Cretaceous age of 122 ± 3 Ma and 128 ± 10 Ma.

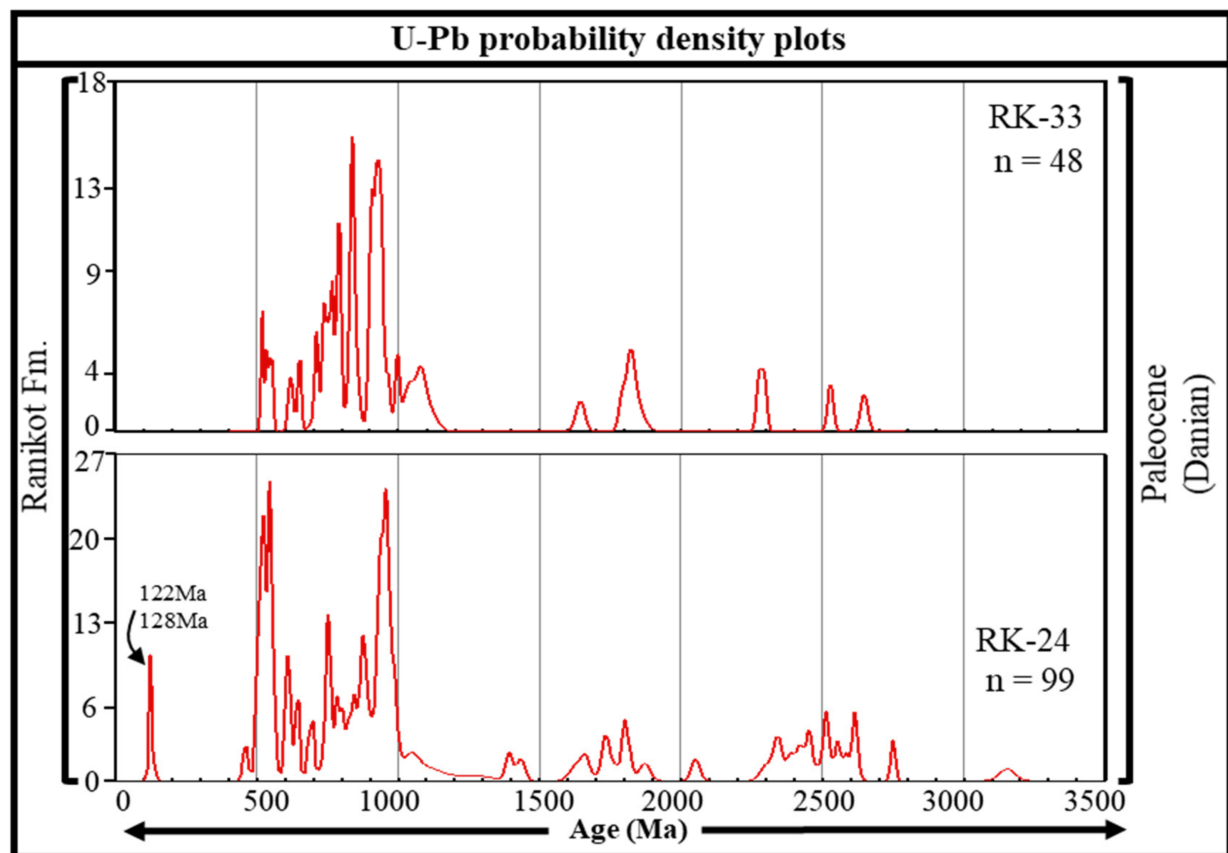


Figure 5. The probability density plots (PDPs) of the detrital zircon U-Pb ages from the Ranikot sandstone.

The detrital zircon grains of sample RK-33 yielded 48 concordant ages from a total of 100 analyses. The major age cluster includes zircon grains ranging between ca. 519 and ca. 1109 Ma, which is ~80% of the total population. In this spectrum of Cambrian to Mesoproterozoic zircon ages, the major peaks are at ca. 520 Ma, 650 Ma, 788 Ma and 929 Ma. The remaining older grains show scattered ages between ca. 1600 and ca. 2600 Ma (Figure 5).

5. Discussion

5.1. Source Terranes Detrital Ages

The age record of the potential source terranes is crucial for determining the most probable origin of the Paleocene Ranikot sandstone. Tethyan Himalaya (TH), Higher Himalaya (HH) and Lesser Himalaya (LH) were the main contributing blocks. The detritus was fed from these geologic areas, which are part of the Indian Plate. Additional significant terranes include those in the north, known as Eurasian Provenance, such as the Kohistan–Ladakh arc (KLA), Karakoram Block (KB) and Lhasa Block (LB). To predict when the Neotethyan ocean will close and when the final India–Eurasia collision will occur, it is crucial to consider the mixing of sediments from Indian and Eurasian provenances. These sources also shed light on the suturing procedure, particularly the positioning of the ophiolite and the final collision.

These blocks' detrital zircon age spectra exhibit a distinctive pattern with some shared and unique characteristics. The TH, HH and LH are characteristics of the Indian Plate origin. There are three discrete age clusters in the detrital zircons from the TH sequence: ca. 480–570, 700–1200 and 2430–2560 Ma (Figure 6) [38–40]. The TH sequence also included younger zircons with ages between 110 and 140 Ma, which are typical for volcanic rocks

from the Indian Plate [9,11,14]. Detrital age clusters are shown in the HH sequence and located around 540–750 Ma, 800–1200 Ma, 1600–1900 Ma and 2400–2600 Ma. However, the HH sequence's separate cluster is located between 900 and 1100 Ma [14]. With a clear peak at 485 Ma, the higher Himalayan granitic rocks display an age group between 470 and 550 Ma [41]. Similar to the LH sequence, minor zircon ages in the LH sequence range from 2400 to 2600 Ma, while dominant zircon ages are between 1700 and 1900 Ma [14]. Most of the younger ages (100 Ma), which dominate the entire spectrum, are what most widely characterize the Eurasian provenance (Figure 6). The KLA's zircon ages range from 40 to 110 Ma, with maxima at 50 Ma, 65 Ma and 70 Ma. Zircon ages in the KB vary from 11 to 22 Ma, 53 to 80 Ma and 93 to 110 Ma (Figure 6) [42–46]. Similar to this, the LB's zircon ages show age clusters between 40 and 60 Ma and a small population at 18 Ma (Figure 6) [47]. Ages between 115 and 178 Ma can be seen in the age spectrum of ophiolitic rocks exposed inside the Indus suture zone [48].

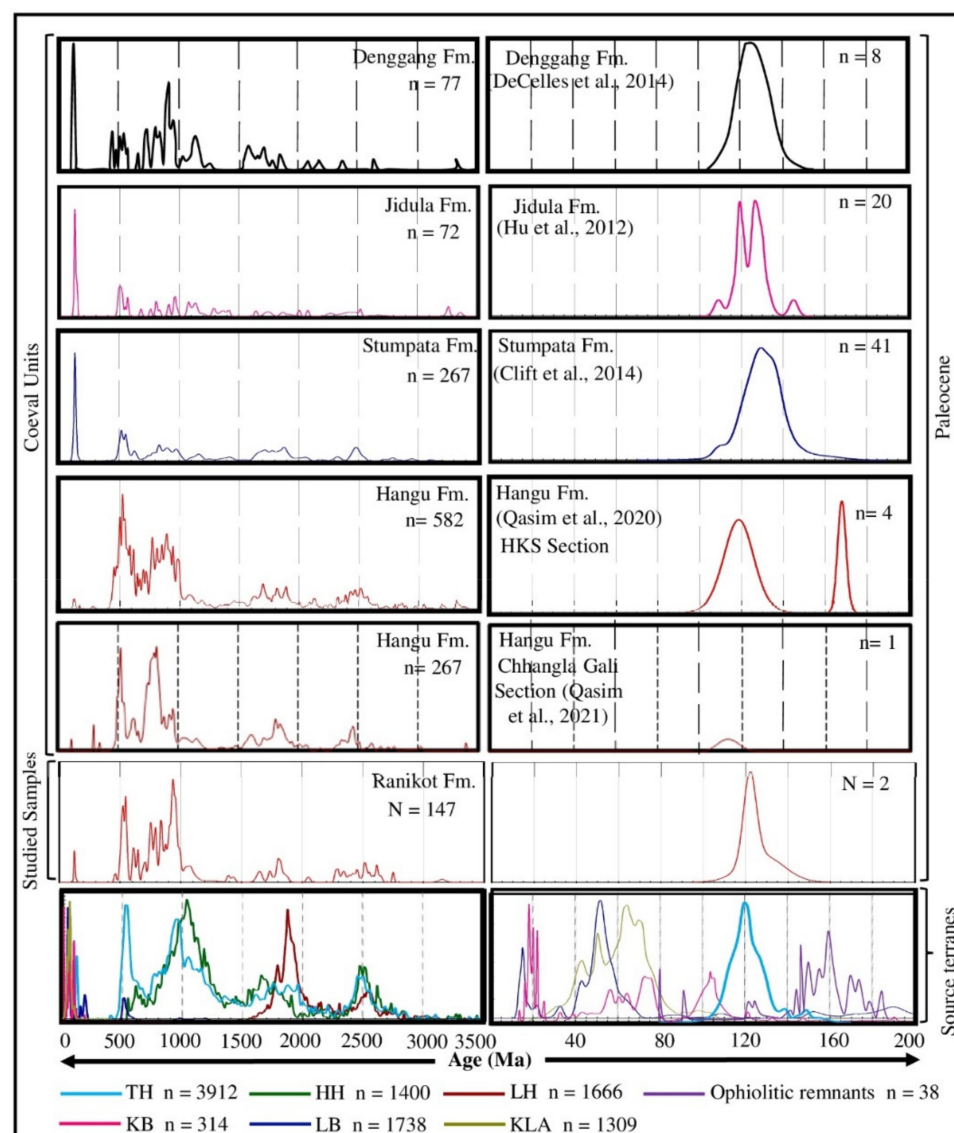


Figure 6. Comparison of the U-Pb ages with the source terranes and coeval units exposed along strike on the northern margin.

5.2. Provenance of the Ranikot Formation

The samples of the Ranikot Formation yielded major ages between ~400 Ma to ~1200 Ma, which is strongly matched with the TH age spectrum (Figure 6). In addition, the

minor age groups existed around ~1600–1900 Ma and ~2250–2700 Ma, which is matched with the age pattern of LH and HH (Figure 6). The two younger grains with age 122 Ma and 128 Ma might be derived from the TH igneous rocks. The TH, HH and LH sources suggest the sediments of the Ranikot Formation are derived from the Indian provenance (Figure 7). The ternary diagrams QFL and QmFL show the tectonic provenance as craton interior for the samples of the Ranikot Formation (Figure 5D,E). This craton interior provenance and detrital zircon provenance strongly suggest derivation mainly from the Indian provenance.

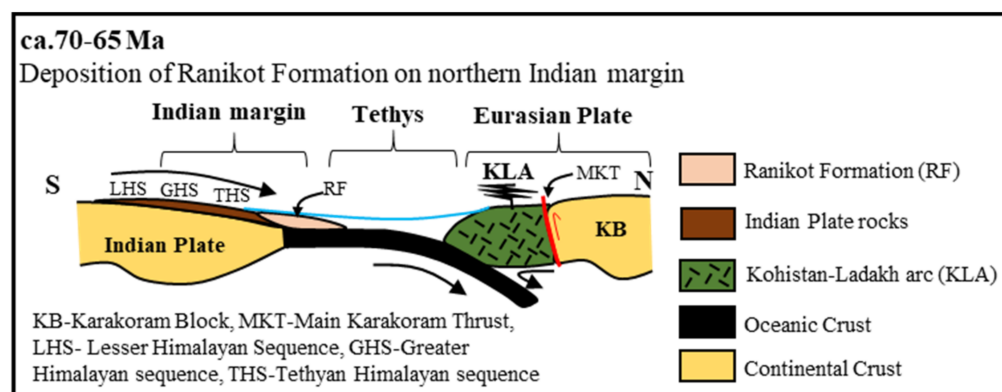


Figure 7. A schematic tectonic model showing the provenance of the Early Paleocene Ranikot Formation.

The ophiolites along the western margin are believed to be emplaced after the Paleocene as reflected by the stratigraphic relationship [4]. This possibility excludes the contribution of the ophiolitic source to the Paleocene Ranikot Formation. Similarly, the absence of the Eurasian detritus in the Ranikot Formation also excludes the contribution from northern provenance. This suggests that the Tethys Ocean was opened during the Paleocene in the northern segment as well, which acts as the sink to the northern sources. Therefore, the early collision as reported in the western segment [4] might be due to the timing of the emplacement of ophiolite rather than the India–Eurasia collision [49].

5.3. Tectonic Implications

A significant geological unit, the Early Paleocene Ranikot Formation, delineates a local and worldwide unconformity with the underlying Cretaceous period. After the Mesozoic era, there was a significant mass extinction that was linked to a variety of significant occurrences, such as asteroid impact [50], volcanic eruptions [51] and climatic change [52]. As a result of the Deccan Volcanic eruption, which was estimated to have occurred 65–70 Ma ago, the Mesozoic mass extinction was hastened [53]. In the context of this setup, the Early Paleocene is crucial for reconstructing the Indian margin's paleogeography. Detrital zircon U–Pb dating allows us to assess the possible provenance and tectonic setting of the western margin of the Indian plate during the Early Paleocene. The Ranikot Formation's detrital zircon age pattern shows a striking similarity to the zircon age pattern of the TH rocks that were predominately sourced by Indian cratonic region during Paleocene. It is hypothesized that the northwestern ophiolites were obducted during Cretaceous over the northern margin of the Indian Plate, causing a widespread Cretaceous–Tertiary unconformity. Numerous investigations [3,54] have shown that the ophiolitic sequence was obducted around Late Cretaceous. However, towards the west, the ophiolites (Bela, Muslimbagh and Zhob valley) were obducted comparatively later around Cretaceous–Paleocene, which is supported by stratigraphic record [4,55]. The obduction and ultimate erosion of the ophiolitic sequence, however, may be indicated by the detrital fingerprints for the ophiolitic component found in the Patala Formation, which is Late Paleocene in age, cropped-out in northern sections [5,7]. One theory is the same as the one previously put out, according to which the ophiolite obducted around the Late Cretaceous and was unearthed around the terminal India–Eurasia collision at Eocene. Alternatively, it is also conceivable that the ultimate collision and the placement of the ophiolitic leftovers

occurred simultaneously [13]. Given that other studies have documented evidence for the ophiolite's obduction during the Late Cretaceous in the central and western segment of the Himalayan mountain system [1,4,56], we prefer the first scenario. However, the absence of the KLA's usual traces in the Ranikot Formation and its coeval Hangu Formation rules out an initial collision of the arc with the Indian plate at Early Paleocene. According to the U-Pb geochronology dataset in adjacent basins, arc and ophiolite debris arrived in the early part of the Paleocene Patala Formation [5,6]. This suggests that KLA emplacement has finally exhumed the ophiolitic sources. Our data from the Ranikot Formation and the coeval Hangu Formation [7,49] suggest that the TH had a significant role in providing detritus. The Indian affinity of the detritus is also supported by the sandstone petrography, which reveals craton interior region. In the examined samples, there isn't any observable proof of ophiolitic debris. In the neighborhood of the research area, the coeval Early Paleocene Hangu Formation marks an angular relationship with the Cretaceous sequence, indicating regional compression [7]. The theory of ophiolite obduction may also be supported by this compression. However, as described from the Cretaceous sequences in Tibet, Nepal, India and western Pakistan, the Deccan volcanism that took place around the Late Cretaceous may also have contributed debris to the Indian edge in the north [18,25]. In addition, the Indian Plate's velocity has increased, which may be related to hotspot migration that finally led to Deccan volcanism [57]. As the Tethys closure began, the increased movement speed of the Indian Plate may have caused compression to occur along the northern Indian margin. As a result, we propose that the compressional tectonics that may be related to the ophiolite emplacement at the beginning of the Paleocene may have had an impact on the northern boundary of the Indian Plate. However, this angular relationship is not reported along the western margin, which supports the closure of the Tethys Ocean later along the western margin. The combined evidence from detrital U-Pb age dating and petrography may indicate that the Tethyan Himalayan source is the primary source of detritus in the Ranikot Formation with a possible minor contribution from the LH and HH (Figure 7).

Along the strike, the Ranikot Formation can be comparable in terms of stratigraphy to the various formations, which are the Hangu Formation of the Hazara–Kashmir syntaxis, Sangdanlin Formation, Denggang Formation and Jidula Formation of the Tibet and Stumpata Formation of northwest India. These contemporaneous formations have some similar detritus, but there are also differences. Comparing the detrital age record, it is clear that the younger ages (Mesozoic) are more prevalent in contemporaneous strata than in the Ranikot Formation and the coeval Hangu Formation, where the wider age spectrum is virtually constant and shares 450–1000 Ma detritus (Figure 6). This may be because the contemporaneous siliciclastic rocks were deposited in the main depocenter of the basin while the Ranikot and Hangu formations were deposited in the distal part. This also supports the existence of a large basin spread over the entire margin.

6. Conclusions

The Ranikot Formation exposed in the Fort Munro section is an important geological unit due to its stratigraphic age that marks the Cretaceous–Tertiary boundary and has never been studied from the point of view of its provenance. The detrital zircon ages of the Ranikot sandstone shows a striking resemblance to the age pattern of the Tethyan Himalayas (~480–1200 Ma) with a possible minor contribution from the lesser Himalayas (~1700–1900 Ma) and Higher Himalayas (~900–1100 Ma). The younger Cretaceous zircon grains may be derived from the Tethyan Himalayan volcanic rocks (~110–140 Ma), as the ophiolitic sequence emplaced along the western margin at the same time or later. Furthermore, the absence of the Eurasian detritus (~40–110 Ma) in the Ranikot Formation also excludes the early collision of India and the Eurasian plate along the western margin. Finally, combining the petrography and detrital zircon U-Pb geochronology of the sandstone of the Ranikot Formation (~400–1200 Ma, ~1600–1900 Ma and ~2250–2700 Ma), the provenance of the Ranikot Formation is the Indian plate with a dominant source from the Tethyan Himalayan rocks.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min13030413/s1>, Table S1: U-Pb isotopic analyses of detrital zircons of the Ranikot sandstones.

Author Contributions: Conceptualization, M.Q. and L.D.; methodology, software, validation and formal analysis, J.A. (Junaid Ashraf); investigation, M.Q.; resources, L.D.; data curation, O.T.; Writing—original draft preparation, M.Q. and O.T.; Writing—review & editing, J.I.T., I.K., M.U.R., M.A., J.A. (Jalil Ahmad) and I.A.K.J.; visualization, M.Q.; supervision, M.Q. and L.D.; project administration, M.Q. and L.D.; Funding acquisition, L.D. All authors have read and agreed to the published version of the manuscript.

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