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Foreland basin unconformity, Western Himalaya, Pakistan: timing gap, regional correlation and tectonic implications

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Abstract

This study estimates the timing of unconformity between marine–continental transitional sequence of the Kuldana Formation and continental sequence of the Murree Formation for the first time across the Hazara-Kashmir syntaxis, western Himalaya, Pakistan. The ages of the studied units are constrained using detrital zircon U–Pb geochronology. The maximum depositional ages constrained by weighted mean and youngest detrital zircon age are 37 ± 1.7 Ma and 22.5 ± 0.6 Ma for top of Kuldana and base of Murree formations, respectively. Based on this age, the duration of hiatus is estimated to be ~ 14.5 Ma. The comparison of this unconformity and sedimentation pattern along strike suggests that the initial collision occurred in the central segment causing its early uplift and erosion with development of the unconformity. The sedimentation in the central segment culminated at ~ 37 Ma and resumed at ~ 22.5 Ma. The wider gap in central segment becomes narrower at western and eastern margin suggesting discontinuous deposition due to gradually closure of western and eastern margin. This supports the diachronous collision of the Indian and Asian plates with initial contact at the central segment.

Keywords Depositional ages, Marine–continental sequence, Unconformity period, Western Himalaya, India–Asia collision

1 Introduction

The unconformities are important geological discontinuities representing sedimentation gap and the processes of uplift and erosion. The erosion, subsidence, uplift and flexural bulging of lithosphere associated with regional tectonics formed these unconformities. On the one hand, it keeps records of the sediments supply from the source, while on the other hand, it keeps records of the interval gap.

Many researchers have studied the unconformities to better understand the collision and tectonic uplift (Ding et al. 2016; Qasim et al. 2018). Moreover, in order to understand the history of the mountain system through sedimentary records, it is important to estimate the timing of the unconformities. This gap explains the uplift history of a basin and its sedimentation pattern. In case of the Himalayan Mountain system, an unconformity marks a boundary between the Eocene marine and overlying Miocene continental sedimentation. The Himalayan Mountain system is developed during the Cenozoic because of Indian and Asian plates collision (Ding et al. 2005; Qasim et al. 2018; Yin and Harrison 2000) (Fig. 1A).

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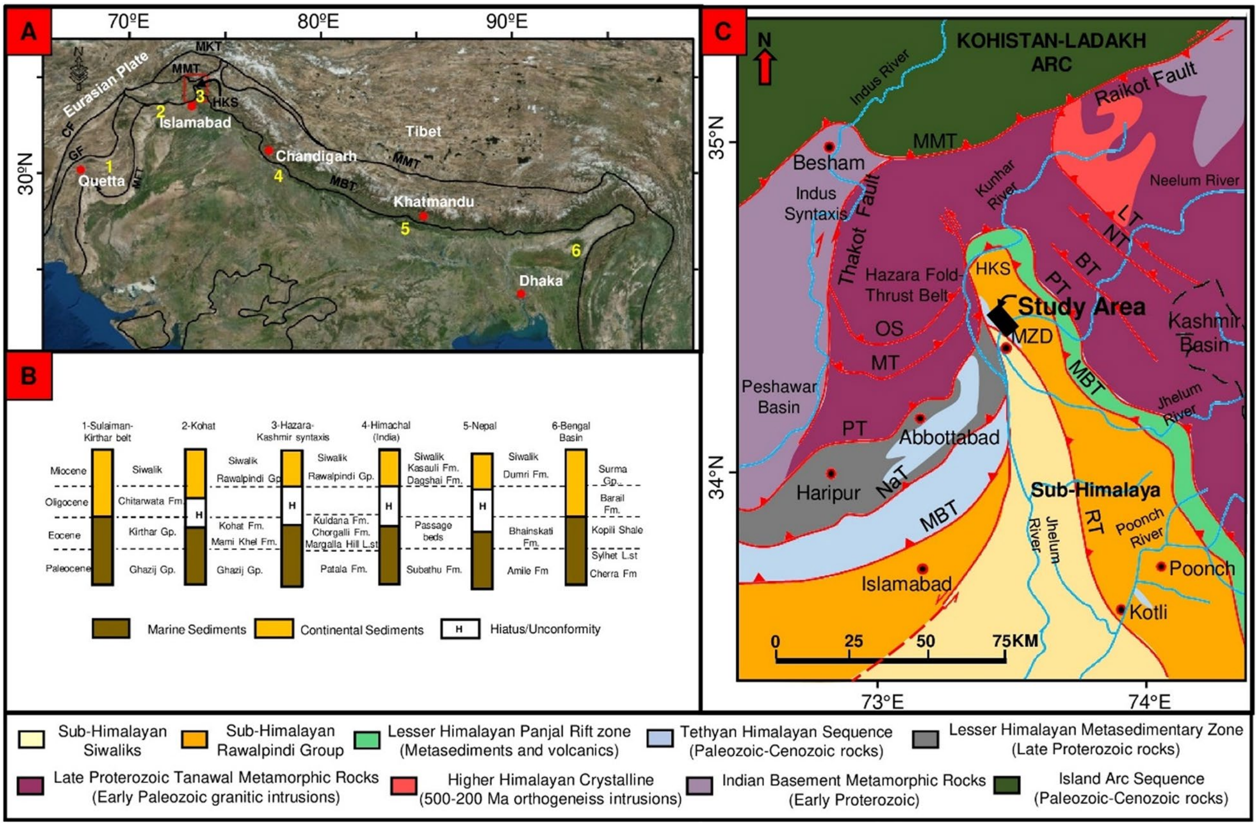

Fig. 1 **A** Generalized tectonic map of the Himalaya showing major tectono-stratigraphic zones. Red rectangle represents the location of Hazara-Kashmir syntaxial region and the extent of (**C**). **B** Simplified log showing the marine-to-continental transitional sequences and the time gap. 1—Sulaiman-Kirther Range, 2—Kohat, 3—Hazara-Kashmir syntaxis (HKS), 4—Himachal (India), 5—Nepal, 6—Bengal Basin. **C** Modified geological map of the Hazara-Kashmir syntaxis and surrounding area (Adopted from Awais et al. 2021)

As a result of this collision, a foreland basin formed on the leading edge of the Indian plate, with influx of the detritus from the Asian plate. The sediments supply is affected due to the mountain building and development of an unconformity between the stratigraphic units. The younger strata were deposited in the foreland basin with resumption of sedimentation. This important unconformity is present between Eocene and Oligocene–Miocene sequences in the Himalayan foreland basin (Fig. 1B), which might be associated with the migration of the fore bulge (Bilham et al. 2003). From east to west, this unconformity is documented all along the entire northern boundary (Bera et al. 2008; DeCelles et al. 1998; DeCelles and Giles 1996) (Fig. 1B). The current study is focused on the unconformity between Eocene and the overlying Oligocene–Miocene sequence exposed in the Hazara-Kashmir syntaxial region. To estimate the unconformity gap time, two sections were selected located at Balakot and Muzaffarabad (Fig. 1C). The Eocene sequence is represented by the Kuldana Formation, whereas the overlying sequence is represented by the Murree Formation, which is Oligocene–Miocene in age. The estimated gap is compared all along the strike with the coeval sections in India, Nepal and Bengal basin to the east and Kohat and Sulaiman-Kirthar to the west (Fig. 1B). This comparison allows us to compare the estimated time gap to understand the collision process.

2 Geological setting and study area

The Himalayan mountain system is formed due to the collision of the Asian and Indian plates (Kazmi and Jan 1997). The Himalayas are made up of metamorphic, igneous and sedimentary rocks exposed in various tectono-stratigraphic zones. These tectono-stratigraphic zones of the Himalayas are broadly categorized as: the Sub-Himalayas, the Lesser Himalayas, the Higher Himalayas and the Tethyan Himalaya (Gansser 1964). These zones cover the deformed northern edge of the Indian plate in the footwall of Main Mantle Thrust. The hanging-wall block of the MMT consists of Kohistan-Ladakh arc, which is an Island arc collided with the Indian plate and caused the development of the mighty Himalayan Mountain system (Yin and Harrison 2000). The boundary of this arc to the north is marked by Main Karakoram Thrust, which separate it from the Karakoram block. The collision of these blocks is responsible for major tectonic deformation in the region (Ding et al. 2016).

The youngest event in the geological history of the Indian plate is the Cenozoic India–Asia collision, which developed the mighty Himalaya (Yin and Harrison 2000). The timing and location of initial collision is debated especially in the western Himalaya, where to the west it is proposed earlier at ~ 60 Ma considering the stratigraphic evidence (Beck et al. 1995). However, the recent investigations in the western sections placed this collision close to 50 Ma based on detrital zircon and whole rock Nd isotopic signatures (Zhuang et al. 2015). Similarly, recent studies placed the timing of collision in the central part between 70 and 59 Ma (Ding et al. 2005; Hu et al. 2016). This age difference in collision timing and location is a key scientific question in understanding the Himalayan tectonics.

In response to the collision, a foreland basin was developed in the footwall of MMT at ca. 55 Ma, which received detritus from the colliding blocks (Fig. 2) (DeCelles et al. 2014). This sedimentation continued until cessation of marine facies has occurred overlapping continental facies. Currently, this foreland basin occupies a position in the footwall of the Main Boundary Thrust with juxtaposition of Paleocene–Eocene marine sediments over the Oligocene–Miocene continental deposits of similar stratigraphy but different nomenclature along strike of the Himalayas (Singh 2012, 2013; Singh and Singh 1995).

The study area is in the western Sub-Himalaya consisting of two sections, (1) Balakot and (2) Muzaffarabad (Figs. 1A–C and 3). These sections are located on the limbs of the Muzaffarabad anticlinal structure, where the Cambrian Abbottabad Formation is exposed in the core, comprising mainly of carbonate strata with chert intercalations. This Cambrian sequence is unconformably overlain by a complete Paleocene–Eocene marine sequence, including the Hangu, Lockhart, Patala, Margalla Hill Limestone and Chorgali formations. The marine carbonate strata change to marine–continental transitional strata of the Kuldana Formation (Fig. 3). The age assigned to the Kuldana Formation is Early-middle Eocene based on the biostratigraphy of the marly limestone preserved in the lower part (Baig and Munir 2007). However, recent studies in the Hazara-Kashmir syntaxis reported volcanic ashes in the lower part, constraining the age to be ~ 53–51 Ma for the lower part (Ding et al. 2016; Qasim et al. 2018). This marine–continental transitional sequence is overlain by continental deposits of the Murree Formation, which is believed to be Oligocene–Miocene in age (Najman et al. 2001). The age of the Murree Formation is designated as Eocene based on the marl biostratigraphy (Bossart and Ottiger 1989). The marl bands are later interpreted as structural slivers and excluded from the Murree Formation (Najman et al. 2002). The age of the Murree Formation is constrained to be 34 Ma based on detrital white mica thermochronology (Najman et al. 2001). Considering the older collisional age ~ 70–65 Ma (Beck et al. 1995; Ding et al. 2005; Hu et al. 2017), the Paleocene–Miocene deposits are considered as foreland basin deposits. In this study, the Kuldana and Murree formations are assessed to estimate the unconformity gap between them and comparison of the coeval units. The unconformity gap, thus, provides us an insight into the collision process generally all along the Himalayas and specifically in the western Himalaya.

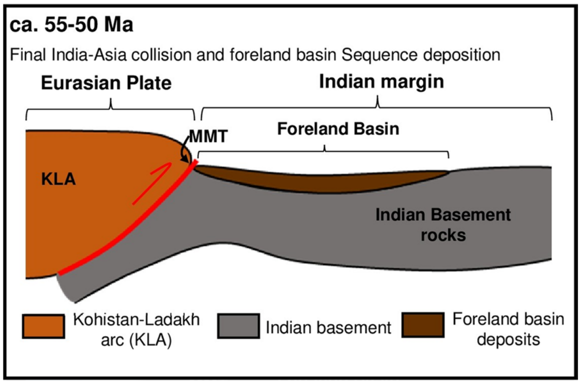

Fig. 2 Schematic diagram showing the location of the foreland basin in response to India–Asia collision (after Qasim et al. 2022)

3 Data and methods

In this study, we used detrital zircon U–Pb geochronology data of the Kuldana and Murree formations to estimate the maximum depositional ages of the formations. The detrital zircon U–Pb ages provided a broad age spectrum, which is broadly applied to assess the provenance. The younger detrital zircons may provide the maximum depositional age of the stratigraphic units. In this study, the group of the youngest detrital zircons were used to calculate the mean age that represents the maximum depositional age of the siliciclastic sequence. Relying on the maximum depositional age the uppermost part of the Kuldana Formation and the lowermost part of the Murree Formation was assigned an age. The difference in the age is considered as the estimated gap timing of the unconformity.

As a process, the representative samples were crushed and treated by heavy liquids and magnetic separation to collect the detrital zircon grains. The grains were mounted on the glue strip in epoxy resin. The samples were polished to make the surface of the grains smooth. To remove lead contamination, a solution of dilute nitric

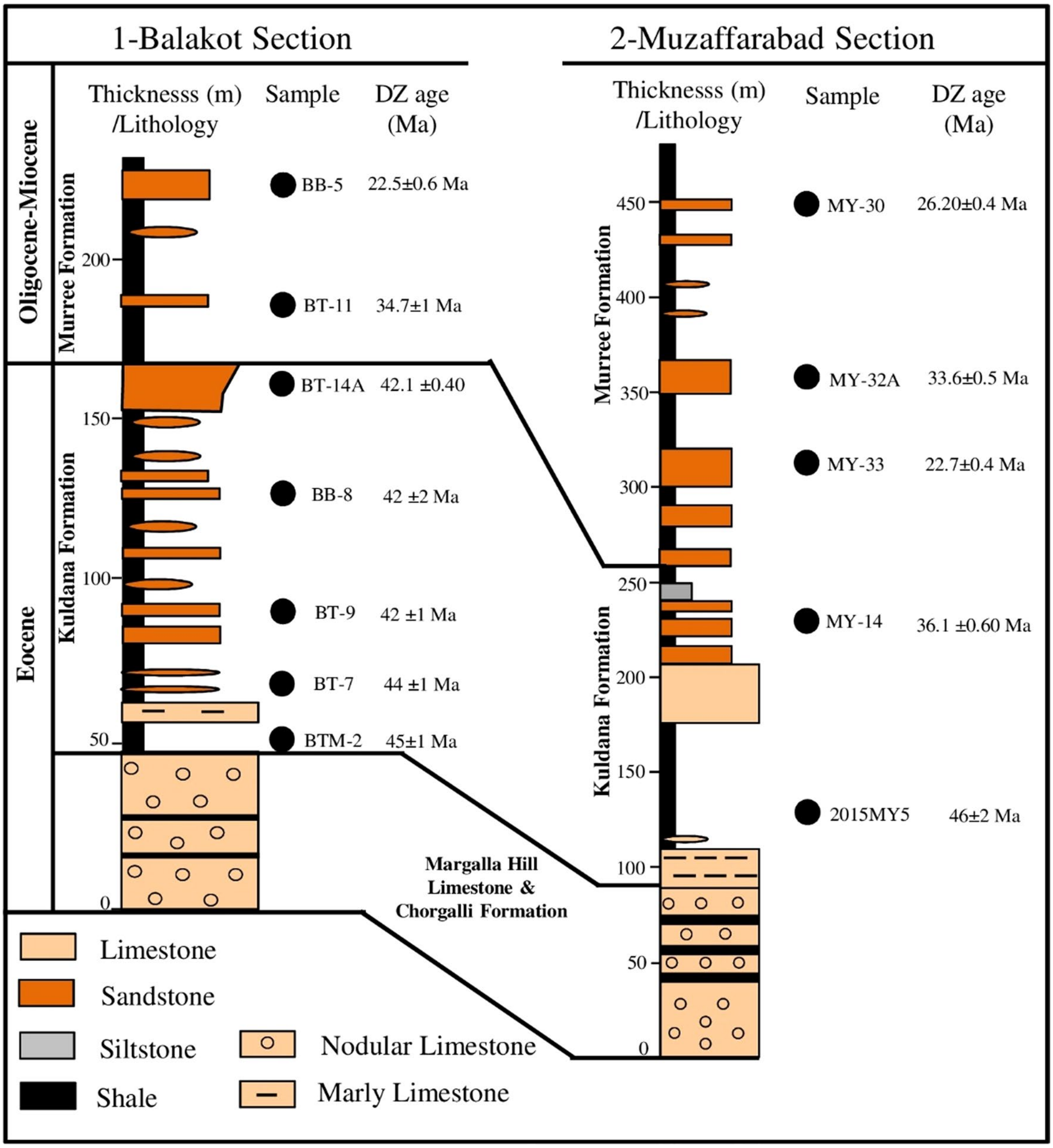

Fig. 3 Measured stratigraphic log of the Balakot and Muzaffarabad sections showing lithological variations and location of the studied samples

acid and pure alcohol was used to wash the surface of the prepared samples before in situ laser U–Pb analysis. The analyses were carried out using Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LAICPMS) installed at Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China. The raw data were processed at the Department of Earth Sciences, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, Pakistan. In each sample, 100 detrital zircon grains were analyzed. The youngest population from each sample is selected to calculate the mean age of the sample, which represents the maximum depositional age of the representative horizon. The age plots were prepared using Isoplot software (Ludwig 2003).

4 Results-U–Pb geochronology

4.1 Kuldana Formation

The Kuldana Formation overlies the Eocene Chorgali Formation and consists of marly limestone, sandstone and shales. The thickness of the Kuldana

Formation in Balakot and Muzaffarabad sections is ~ 130 m and ~ 170 m, respectively (Fig. 3). The samples were collected from lower, middle and upper parts of the Kuldana Formation (Fig. 3). To estimate the maximum depositional age of the Kuldana Formation, total seven samples were selected from Balakot and Muzaffarabad sections (Figs. 1C and 3). The five samples represent the Balakot section, whereas the two samples represent the Muzaffarabad section. The sample BTM-2 is representative of the lower part and consisted of the younger age group between 43 and 49 Ma (Fig. 3). The total thirteen detrital zircons yielded younger age cluster out of 100 analyses (Additional file 1: Table A1 and Additional file 2: Table A2). The mean age for this sample is calculated as 46 ± 1 Ma (Fig. 4A). The middle part of the Kuldana Formation in the Balakot section is represented by the samples BT-7, BT-9 and BB-8. The youngest ages are yielded by six, twenty and eight grains, respectively, which range between 44 and 47 Ma, 43 and 45 Ma and 42–47 Ma (Additional file 1: Table A1). The mean ages calculated from the younger clusters are 45.85 + 1.25 and − 1.85 Ma (Fig. 4B), 43.80 with an error of + 0.70 − 0.80 Ma (Fig. 4C) and 45.20 with the error of + 1.80 − 3.20 Ma (Fig. 4D) for the samples BT-7, BT-9 and BB-8, respectively (Fig. 3).

The uppermost part of the Kuldana Formation is represented by BT-14A. The younger ages exhibited by nine detrital zircons. The younger ages are present between 44 and 46 Ma. For this sample, the maximum depositional age is interpreted to be 45.70 with an error of + 0.30 − 0.70 Ma (Fig. 4E).

Similarly, the sample MY-14 represents the upper part, and 2015MY5 represents the lower part of the Kuldana Formation in Muzaffarabad section. The only two detrital zircons from the sample 2015MY5 yielded the younger ages of 46 Ma and 47 Ma. Based on the youngest detrital zircon ages, the age assigned is 46.5 ± 2.8 Ma (Fig. 4F). The zircons from the upper part of the formation yielded twenty-one younger ages ranging between 37 and 49 Ma. Relying on the youngest population the age is 36.1 ± 0.6 Ma.

Considering these ages documented for the samples of the Kuldana Formation, the maximum depositional age assigned is to be 46–37 Ma.

4.2 Murree Formation

The Murree Formation is mainly composed of cyclic sequence of sandstone, siltstone and shale (Fig. 3). The average thickness of the Murree Formation is over ~ 1000 m. The samples were mainly collected immediately above the lower contact, being representative of the lower portion (Fig. 3). A total of five samples of the Murree Formation were studied for calculation of the younger ages. Two samples are from the Balakot section, whereas three are from Muzaffarabad section. The sample BB-5 yielded only two younger detrital ages which are 22 Ma and 27 Ma. Based on the youngest detrital zircon age, the unit is assigned 22.5 ± 0.6 Ma (Fig. 4G). The second sample BT-11 yielded three younger ages (Additional file 1: Table A1). These ages range between 34.7 and 35 Ma. Based on the youngest detrital zircon age, the unit is designated 34.7 ± 1 Ma (Fig. 4H).

Similarly, three samples MY-33, MY-32A and MY-30 represent the Murree Formation exposed in the Muzaffarabad section. These three samples represent the lower portion of the Murree Formation. The lowermost sample of the Murree Formation is represented by MY-33. The younger cluster yielded from a total 7 detrital zircons, which ranges from 22.7 to 42 Ma. The maximum depositional age for this sample based on the youngest detrital zircon method is 22.7 ± 0.4 Ma (Table 1). The second sample of the Murree Formation is represented by MY-32A. The younger age cluster exhibited from 4 detrital zircons, which ranges from 33.6 to 45.7 Ma. The youngest detrital zircon age for this sample is 33.6 ± 0.5 Ma (Table 1). The uppermost sample of the Murree Formation is represented by MY-30. The only youngest detrital zircon yielded 26.20 Ma age. Based on the YDZ, the age assigned is 26.20 ± 0.4 Ma (Table 1). Based on the YDZ ages from all the samples of the Murree Formation, the estimated maximum depositional age for the formation is 34–22.7 Ma.

5 Discussion

5.1 Maximum depositional ages and unconformity period

To estimate the depositional gap between the Kuldana and Murree Formation, it is important to discuss the maximum depositional ages. The Kuldana Formation is important marine to continental transitional sequence which consists of the multicolor shales with subordinate sandstone, siltstone and marly limestone. The marly limestone is richly fossiliferous and consisted of various nummulitic species (Baig and Munir 2007). The Kuldana Formation has been assigned the Early to Middle Eocene age (55–43 Ma) based on the fossil assemblage, which corresponds to the shallow benthic zones (SBZ) SBZ-12, SBZ-13 and SBZ-14 zones (Gingerich 2003). The volcanic ashes from the lower most part of the Kuldana Formation have been dated at ~ 53.2 ± 2.8 Ma (Ding et al. 2016) and ~ 51 ± 2 Ma (Qasim et al. 2018) from the Muzaffarabad section and Murree section (located ~ 50 km southwest of the studied sections). The detrital zircon ages of the analyzed samples are range between < 100 Ma and as old as ~ 3500 Ma (Additional file 2: Table A2). The samples of the Kuldana and Murree formations are plotted to show the age distribution of the total analyzed detrital zircons (Additional file 3: Fig. S1). The age distribution

Table 1 The summary of the ages of the studied samples from Kuldana and Murree formations and estimated unconformity period, northwestern Himalayas, Pakistan

Formation name	Sample Nos.	Section name	Age estimation method	Sample age (Ma)	Formation age (Ma)	Unconformity period	References
Murree Formation	BB-5	Balakot section	Weighted mean age	22.5 ± 0.6	22.5 ± 0.6	~ 14.5 Ma	This study and Ding et al. (2016), Qasim et al. (2018)
	BT-11		Weighted mean age	34.7 ± 1			
	MY-33	Muzaffarabad section	Youngest detrital zircon age	22.7 ± 0.4			
	MY-32A		Youngest detrital zircon age	33.6 ± 0.5			
	MY-30		Youngest detrital zircon age	26.20 ± 0.4			
Kuldana Formation	BTM-2	Balakot section	Weighted mean age	46 ± 1	37 ± 1.7		
	BT-7		Weighted mean age	45.85 + 1.25 − 1.85			
	BT-9		Weighted mean age	43.80 + 0.70 − 0.80			
	BB-8		Weighted mean age	45.20 + 1.80 − 3.20			
	BT-14A		Weighted mean age	45.70 + 0.30 − 0.70			
	MY-14	Muzaffarabad section	Weighted mean age	46.5 ± 2.8			
	2015MY5		Weighted mean age	37 ± 1.7			

of the Kuldana Formation is mainly clustered between 36 and 120 Ma (Additional file 3: Fig. S1), which is more pronounced. The second group of ages clustered between ~ 400 and ~ 1200 Ma. The scattered ages exist between ~ 1600 and 3500 Ma (Additional file 3: Fig. S1), whereas the age plots of the Murree Formation exhibit major age clusters between ~ 22 and ~ 120 Ma, ~ 400 and ~ 1200 Ma, ~ 1500 and ~ 2100 Ma and ~ 2300 and ~ 2700 Ma (Additional file 3: Fig. S1). The samples of the Murree Formation shows more pronounced increase in the ~ 400–1200 Ma and ~ 1500–2100 Ma ages as compared to the Kuldana Formation. This age distribution reflects the various sources, which indicates particular provenance. These sediments are mainly derived from the Kohistan arc and the uplifting of the Higher Himalayan block (Ding et al. 2016; Qasim et al. 2018). In this study, we interpreted the youngest cluster to estimate the maximum depositional ages of the Kuldana and Murree formations. The weighted mean ages and youngest detrital zircon ages obtained from the studied samples from both Balakot and Muzaffarabad sections suggest 37 ± 1.7 Ma maximum depositional age for the Kuldana Formation (Table 1). This age marks the upper limit of the Kuldana Formation. Similarly, the Murree Formation marks the continental deposits, which consists of cyclic deposition of sandstone, siltstone and shale. The age proposed earlier for the Murree Formation was Eocene, based on the biostratigraphy of the marly bands reported from the Hazara-Kashmir syntaxial region (Bossart and Ottiger 1989), that are later interpreted to represent the lower part of the Kuldana Formation, which are structurally emplaced within the Murree Formation (Najman et al. 2002). Thus, ages were revised to Oligocene–Miocene based on detrital white mica ages documented for the sequence exposed in the Hazara-Kashmir syntaxial region (Najman et al. 2001). Another study documented the Early Eocene age for the Murree Formation based on the mammal fossil reported from the Fateh Jhang area located ~ 200 km south of the Hazara-Kashmir syntaxial region (Shah 2009). This study also suggests the 22.5 ± 0.6 Ma maximum depositional age for the Murree Formation relying on youngest detrital zircon ages (Table 1). The Early Miocene age is also supported by the previous studies carried out in the Hazara-Kashmir syntaxial region (Awais et al. 2021; Ding et al. 2016; Najman 2006; Qasim et al. 2018).

Relying on the ages of the Kuldana and Murree based on previous and present study, we can confidently

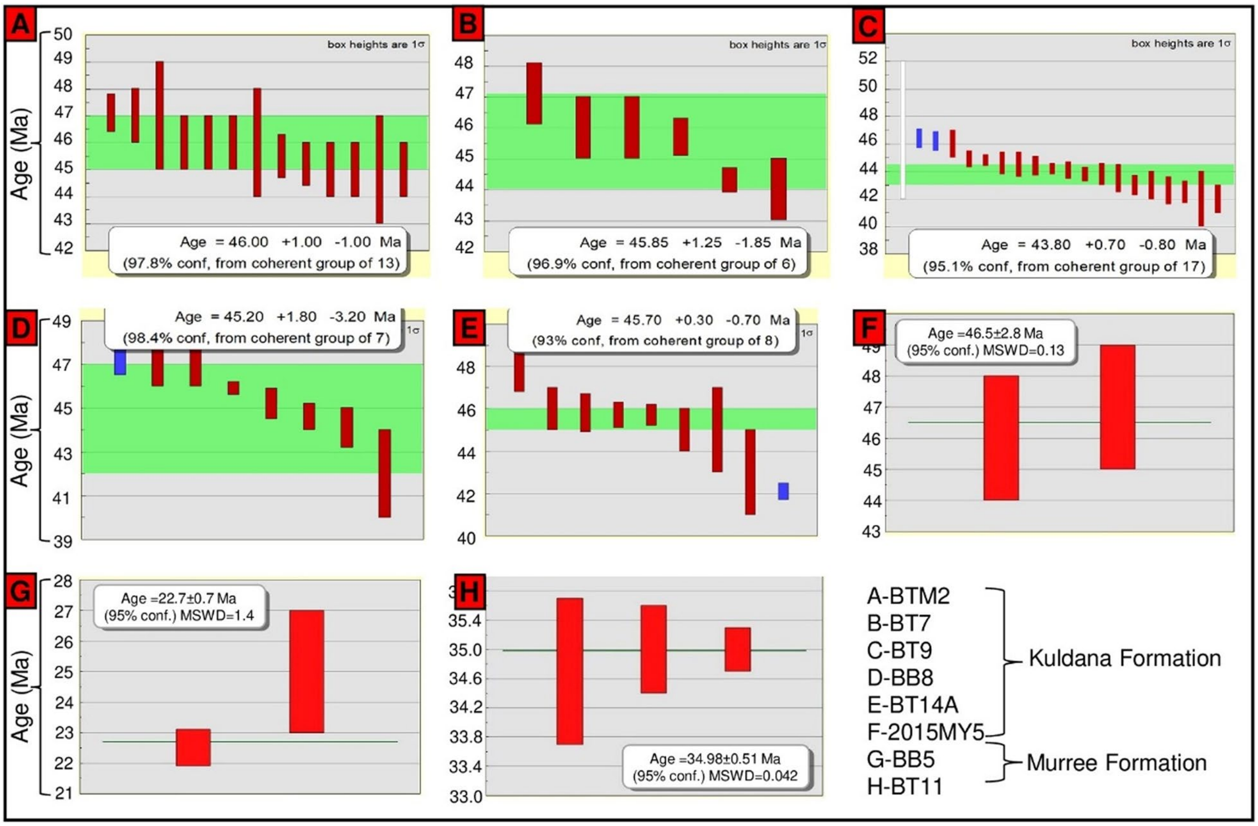

Fig. 4 The weighted mean age plots of the zircon age data obtained from the representative studied samples of the Kuldana and Murree formations. The green box in the figures shows the extent of the error in age (± Ma). The red columns show the age of individual grain age and height of the column represent the error in age (± Ma). The blue column in the figure also represents age of the individual age grain, but excluded by the software in estimation of average age

constrain the timing of the unconformity between them. Considering the maximum depositional age of the Kuldana Formation and Murree Formation, the sedimentation stopped after ~ 37 Ma and resumed again after ~ 22.5 Ma. Thus, the period of the unconformity was ~ 14.5 Myr in the western Himalaya (Table 1). Along strike, this gap is almost consistent with sections from India (Singh 2013) and Nepal (Baral et al. 2019; Najman 2006; Najman et al. 2005). The age of the sediments below unconformity in the Indian section (Passage Beds) is ~ 40 Ma (Singh 2013), whereas in Nepal, it is ~ 48 Ma (DeCelles et al. 2014). However, the gap toward west becomes shorter to ~ 5–10 Myr in the Kohat Section (Table 1). The age of the sediments below the unconformity in the Kohat section is ~ 40 Ma, but the continental sedimentation resumed earlier at ~ 34 Ma, causing a shorter gap for the unconformity period. Furthermore, in the easternmost (Bengal Basin) and westernmost (Sulaiman-Kirthar) sections the sedimentation is more continuous (Khan and Clyde 2013).

5.2 Tectonic implications

The timing and location of India–Asia collision in the Western Himalaya is disputed. Considering the stratigraphic evidence of the Ophiolite emplacement over the Paleocene sequence along the western margin dated the collision timing as early as ~ 65 Ma (Beck et al. 1995). However, detailed studies along the westernmost margin placed this collision timing at ~ 50 Ma based on advanced detrital zircon and Sm–Nd isotopic studies (Roddaz et al. 2011; Zhuang et al. 2015). Furthermore, the collision ages were reported at ~ 56 Ma in the Hazara-Kashmir syntaxial region located east to the Beck's section. These recent studies negate the early collision in the western Himalaya as compared to the central Himalaya. The collision ages reported from the Central Himalaya are older than the western Himalaya (Ding et al. 2005; Hu et al. 2015, 2017). In the current study, the unconformity periods explain the uplift history of the mountain system and closure of the ocean basin. The India–Asia collision occurred, when intervening

Tethys Ocean closed and a foreland basin developed. In the early stage of the foreland basin, a shallow ocean exists, where marine sedimentation occurred. This is evident from the present day example of Australia and Papua New Guinea, where Arafura Epicontinental Sea existed in a foreland basin setting (Ding et al. 2017). The marine sedimentation gradually closed as the collision progressed. Following this idea, it can be assumed that the area which collided earlier will possibly uplift earlier and the unconformity gap in the foreland basin sequence will be larger at the site of earlier collision, whereas the sites where the epicontinental sea closed at the end will have more continuous sedimentation. After the complete expulsion of shallow epicontinental sea, the river system developed which started to deposit continental sequences. This concept suggest that the area which collided earlier will have larger age gap in the sedimentation. In case of the Himalayan Mountain system, a foreland basin is formed in response to India–Asia collision (DeCelles et al. 2014, 2000; Ding et al. 2005; Hu et al. 2015; Najman et al. 2005; Qasim et al. 2018). In response to the India–Asia collision, the Tethys Ocean started to close, and the marine sedimentation gradually ceased. This cessation of the marine sedimentation is associated with the uplift. As the collision margin closed gradually, the Tethys Ocean also gradually closed with the expulsion of the seawaters to the western and eastern pathways (Fig. 5A). In this study, the comparison of the marine and continental sedimentation record with the coeval sections all along the entire margin suggest a particular pattern of sedimentation. This particular pattern is supported by the timing of unconformity in the central segment. The unconformity gap in the Central Himalaya (Nepal and India) is about 15–20 Myrs (Najman 2006; Singh 2013), while it is ~14.5 Myrs in western Himalaya at HKS region (north Pakistan) and ~5–10 Myrs further west in Kohat section (Khan and Clyde 2013) (Fig. 1B). However, this marine-to-continental sedimentation is continuous in westernmost section at Sulaiman-Kirthar ranges (Khan and Clyde 2013) and easternmost section at Bengal Basin (Fig. 1B). The timing of unconformity and sedimentation pattern calls on the collision pattern, suggesting that the Indian plate collided initially in the central segment resulting in its early uplifting and comparatively wider unconformity period (Figs. 1B and 5A). Thus, early collision and uplift in the central part caused the remnant Tethys Ocean to flow east and westward, obstructing the sedimentation in the central part with formation of the unconformity, and persistent sedimentation toward west and east until the margin was completely closed (Figs. 1B and 5B). Our interpretation is also supported by various earlier studies with suggestion of an early collision in the central segment (Cai et al. 2011; Ding et al. 2005; Hu et al. 2015, 2012, 2017; Zhu et al. 2005). Our interpretation strongly supports the diachronous collision of the Indian plate with initial collision in the central segment, while the western and eastern margin closed gradually afterward. However, it is probable if Indian subcontinent has made

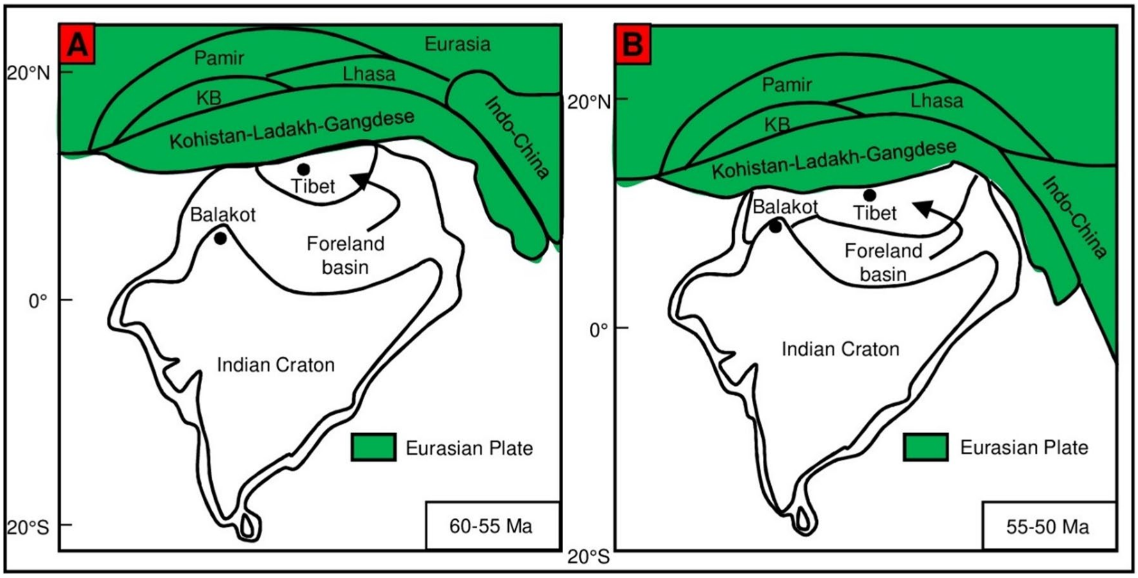

Fig. 5 Tectonic model explaining the collision process and location. **A** The model shows the initial collision in the central segment of the Indian margin in Tibet and development of the foreland basin. **B** Gradual closure of the ocean basin toward west and east during 55–50 Ma and expansion of the foreland basin sedimentation

an initial contact with the Eurasian plate in northwest Himalayas (Powell 1979), with significant rotation prior to collision and uplift in the central Himalayas.

6 Conclusion

This study concludes the following.

(1) Based on weighted mean and youngest detrital zircon ages, the maximum depositional ages attributed to the upper part of Kuldana and lower part of Murree formations are 37 ± 1.7 Ma and 22.5 ± 0.6 Ma, respectively.
(2) Relying on the maximum depositional ages of the Kuldana and Murree formations, the duration of the unconformity period is ~ 14.5 Myrs.
(3) The comparison of the along strike unconformity time gap and sedimentation pattern calls on significant initial India–Asia collision, indentation, and uplift to be in the central segment as compared to the western and eastern margins. This supports the diachronous collision of the Indian and Asian plate with unconformity in the central segment.

Abbreviations

MMT	Main Mantle Thrust
Myrs	Million years
Ma	Million years ago
LAICPMS	Laser Ablation Inductively Coupled Plasma Mass Spectrometer
YDZ	Youngest detrital zircon

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40645-023-00584-w.

Additional file 1. **Table A1**. U–Pb isotopic data of youngest age cluster of the studied samples.

Additional file 2. **Table A2**. Complete U–Pb isotopic data of detrital zircons of the studied samples.

Additional file 3. Fig. S1. Probability density plots of the composite detrital ages of the samples of the Kuldana and Murree formations.

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Author contributions

MQ contributed to conceptualization, investigation, writing—review and editing, project administration and funding acquisition; ZUR was involved in field data collection, and MS contributed to thesis writing; LD was involved in conceptualization, investigation, funding acquisition, and writing—review and editing; JIT contributed to writing, review and editing; and WA, MJ, ZIB and MU were involved in writing—review and editing. All authors analyzed the data and contributed to final editing of the manuscript.

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Availability of data and materials

The data that support the findings of the study are available in the article as Additional file 1, Additional file 2, and Additional file 3.

Declarations

Competing interests

The authors declare that they have no competing interest.

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