Unroofing the Ladakh Batholith: constraints from autochthonous molasse of the Indus Basin, NW Himalaya

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Abstract: The Indus Molasse records orogenic sedimentation associated with uplift and erosion of the southern margin of Asia in the course of ongoing India–Eurasia collision. Detailed field investigation clarifies the nature and extent of the depositional contact between this molasse and the underlying basement units. We report the first dataset on detrital zircon U–Pb ages, Hf isotopes and apatite U–Pb ages for the autochthonous molasse in the Indus Suture Zone. A latest Oligocene depositional age is proposed on the basis of the youngest detrital zircon U–Pb age peak and is consistent with published biostratigraphic data. Multiple provenance indicators suggest exclusively northerly derivation with no input from India in the lowermost parts of the section. The results provide constraints on the uplift and erosion history of the Ladakh Range following the initial India–Asia collision.

Supplementary material: Method description, Sample locations, Figures S1 and S2 and Tables S1 to S3 are available at: https://doi.org/10.6084/m9.figshare.c.4858848

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The uplift of the Earth’s highest mountain range, the Himalaya, has been a central topic in geology because of the critical role these mountains play in the evolution of regional and global climate and oceanography (e.g. Raymo and Ruddiman 1992; Richter et al. 1992). Many methods have been suggested for inferring topographic growth, including stable-isotope-based palaeoaltimetry (e.g. Huntington and Lechler 2015), fossil leaf morphology (e.g. Whipple and Tucker 1999), and low-temperature thermochronology (e.g. Reiners and Brandon 2006). Geological constraints including the exhumation of deep-seated lithological units and the deposition of intermontane sediments also serve to record the growth of high topography. In the Himalaya, continental deposits along the Indus–Yarlung–Tsangpo suture zone (IYTS) chronicle a history of collision between India and Eurasia and the attendant rise of the Himalaya–Tibetan Plateau (e.g. Searle 1983; Garzanti and Van Haver 1988; Jaeger et al. 1989; Aitchison et al. 2007; van Hinsbergen et al. 2012). Depositional ages and source-to-sink relationships constrain aspects of past ocean closure and provide information on the uplift of source terrains, yet there are challenges and complications in studying related rock units. First, these coarse-grained deposits do not always contain suitable fossils or volcanic ash layers that may provide true depositional ages. First, these coarse-grained deposits do not always contain suitable fossils or volcanic ash layers that may provide true depositional ages. One common approach is to employ detrital zircon U–Pb or mica \(^{40}\)Ar/\(^{39}\)Ar dating to constrain the maximum depositional age. However, the utility of results obtained using this methodology could be strongly influenced by the size of the dataset. The common practice of dating c. 100–200 mineral grains from a given lithological unit might not be sufficient. Second, commonly used provenance indicators, including detrital mineral ages and radiogenic isotopic compositions, geochemistry, analysis of clast compositions and sandstone petrography, do not always provide unique criteria with which to discriminate amongst potential sources, some of which may not have been adequately characterized.

This study focuses on the northern edge of the Indus Basin, where continental deposits (the Indus Molasse) lie in direct contact with the Ladakh Batholith. Because it provides important information with which to constrain uplift history, we investigate the nature of contact between the batholith and preserved basin sediments. We also provide the first U–Pb age constraints for these deposits. Using multiple lines of evidence, we further identify source regions for sediments within the basin and constrain the timing of uplift of the Ladakh Range (NW Himalaya).

Background

Ladakh Range and Ladakh Batholith

The Ladakh Range in the western Himalaya extends ∼NW–SE for over 250 km with peak elevations of c. 6100 m (Fig. 1). It is dominated by the Ladakh Batholith, which is part of the Trans-Himalayan magmatic belt that extends for over 2500 km along the southern margin of the Eurasian continent. The range lies between the predominantly intra-oceanic arc rocks of the Kohistan arc to the west and continental margin arc rocks of the Gangdese arc to the east. Thus it bridges an important transition along-trend from intra-oceanic to continental margin subduction systems (e.g. Hébert et al. 2012). The Ladakh Batholith incorporates Cretaceous to Early Cenozoic plutonic rocks intruded by dykes that are as young as c. 45 Ma (Weinberg and Dunlap 2000; White et al. 2011; Heri et al. 2015). The Khardung Volcanics are remnants of a volcanic carapace for parts of the batholith and crop out along the northern flanks of the range (e.g. Dunlap et al. 1998; Lakan et al. 2019). Their original extent is less well known.

Driven by India–Eurasia collision, the Ladakh Range is thought to have been uplifted as early as late Eocene time. Low-temperature thermochronologic data record differences between unroofing
histories along the northern and southern margins (Kirstein et al. 2006, 2009). In general, apatite fission-track ages are older (c. 35–25 Ma) towards the southern margin of the range and younger (c. 10–5 Ma) to the north, implying later exhumation or uplift for the Ladakh Range along its northern margin (Kirstein 2011).

**IYTS and Indus Basin**

The Indus-Yarlung-Tsango suture zone (IYTS) lies at the contact between two colliding continental landmasses: India and Eurasia (Fig. 1). In NW India, the suture follows the Indus River, immediately south of the Ladakh Range (Fig. 1). The term ‘Indus Basin’ collectively refers to sedimentary rocks preserved along this suture. Historically, this name has generally been applied to several lithological units, many of which are in faulted contact with one another (Searle 1983; Sinclair and Jaffrey 2001; Clift et al. 2002; Henderson et al. 2010, 2011) and are not necessarily genetically related. Eocene-age nummulitic limestones within the basin are regarded as the last products of marine deposition within the Tethyan Ocean (Green et al. 2008) (Fig. 1). Although most units have not been directly dated, limited biostratigraphic data are available (e.g. Bajpai et al. 2004; Green et al. 2008). The majority of age constraints are provided by detrital zircon U–Pb or mica 40Ar/39Ar dates, which only give maximum depositional ages (Clift et al. 2002; Tripathy-Lang et al. 2013; Wu et al. 2007; Henderson et al. 2010, 2011). Many studies have attempted to propose a stratigraphic scheme for the Indus Basin (e.g. Brookfield and Andrews-Speed 1984; Garzanti and Van Haver 1988; Searle et al. 1990; Sinclair and Jaffrey 2001; Clift et al. 2002; Henderson et al. 2010; Tripathy-Lang et al. 2013; Baxter et al. 2016).

The term ‘Indus Molasse’ was first applied to coarse-grained clastic deposits that crop out within and flanking the IYTS (e.g. Fuchs 1979). This early work acknowledges the existence of several different units to which the descriptive term molasse could apply and Fuchs (1979) suggested that two main types could be recognized on the basis of their structural relationships with the Ladakh Batholith. Fuchs (1979) referred to one type as an ‘autochthonous molasse’, which is deposited upon an exhumed Ladakh Batholith surface. This relationship has been recognized at several locations along the southern margin of the Ladakh Range (e.g. Fuchs 1979; Brookfield and Andrews-Speed 1984; Garzanti and Van Haver 1988). Here the molasse commonly involves bright purple, red or green, and beige banded rocks that were likely derived from, and deposited on, a sloping landscape eroded on the Ladakh Range (Fuchs 1979). Another type of molasse occurs in fault-bounded units and is regarded as ‘parautochthonous’. Several units of this nature are recognized (Hemis Conglomerate, Chokstok Conglomerate and Chogdo Formation, e.g. Fuchs 1979; Clift et al. 2002; Henderson et al. 2010). The unit on which this study focuses exhibits an unambiguously depositional relationship upon an eroded surface of Ladakh Batholith rocks.

**Methods and results**

**Field mapping and sedimentary logging**

Field mapping was undertaken from the Basgo to Tia areas (Fig. 2), with a focus on determining the nature of the contact between the Ladakh Batholith and sediments of the Indus Molasse. We were able to trace a nonconformable contact along strike for c. 25 km. Granitic clasts ranging from pebble to boulder sizes crop out immediately above an eroded Ladakh Batholith surface with localized palaeosol development (Supplementary material). Our observations are consistent with earlier reports by Fuchs (1979), Brookfield and Andrews-Speed (1984) and Garzanti and Van Haver (1988) suggesting that any faulted contacts (Tripathy-Lang et al. 2013) are of restricted local extent. Higher stratigraphic levels in the section (up to several hundreds of metres thick) are truncated at a regionally extensive north-directed thrust fault.

Six sections were measured along the strike of the autochthonous molasse basin, from the depositional contact (nonconformity) upon the Ladakh Batholith to the footwall of the thrust fault at which the section terminates (Fig. 1d). Four semi-continuous members could be discriminated within the preserved Indus Molasse sections.
M1 is a crudely stratified, poorly sorted, clast-supported conglomerate with clasts ranging from boulder (c. 1 m) to pebble (several centimetres) sizes (Fig. 4). Clasts are dominantly felsic and andesitic with subordinate granitic clasts. M2 is dominated by red to grey mudstone. M3 and M4 are laterally continuous conglomeratic units. M3 is a poorly sorted, clast-supported monomictic conglomerate dominated by angular to subangular andesitic clasts ranging in size from c. 3–4 cm to 10 cm. M4 is polymictic, horizontally stratified and cross-bedded and incorporates trough cross-bedded sandstone together with well-sorted pebble layers. Field counts indicate 87% felsic and andesitic volcanic clasts in M1 (total \( n = 384 \)) and 80% in M4 (total \( n = 181 \)) with the remainder comprising granitic lithologies. Clasts in unit M3 are entirely of volcanic origin.

**U–Pb geochronology**

Detrital zircon from medium- to coarse-grained sandstones of units M1, M3 and M4 were dated by laser ablation inductively coupled plasma mass spectrometry (ICP-MS) at the School of Earth and Environmental Sciences, The University of Queensland. Zircon grains were extracted by heavy-liquid and magnetic separation, before being hand-picked under a binocular microscope for mounting in epoxy resin. Zircon grains range from c. 50 to 100 µm in width. Most grains are euhedral and few are rounded, implying a short transportation distance. Analyses of a total of 1885 detrital zircon grains with -5 to 10% discordance are reported (Fig. 5). Detailed methods are provided in the Supplementary material. All units yield ages that are dominantly <90 Ma, with peaks around 23–24, 50, 57, 62 and 78 Ma (Fig. 5). The youngest peak from a single grain in M3 and 12 grains in M4 cluster around a latest Oligocene (late Chattian), with a mean age of 23.58 ± 0.11 Ma.

Detrital apatite from M1 were also dated by laser ablation ICP-MS. Grains define an isochron on the Tera–Wasserburg plot that provides a value for \( 207\text{Pb}\/206\text{Pb} \) of 0.8501 ± 0.0030. This initial common lead value was used to correct all ages (Fig. 6) with the IsoplotR program (Vermesch 2018). Detrital apatite U–Pb ages range from c. 100 to 30 Ma, consistent with major peaks observed in detrital zircon U–Pb ages.

**Zircon Hf isotopic analysis**

Hafnium isotopic data for 329 zircons (231 from M1, 41 from M3 and 57 from M4) were obtained using a Nu Plasma II multi-collector-inductively coupled plasma mass spectrometry (MC-ICP-MS) with laser ablation (Fig. 5) at the School of Earth and Environmental Sciences, The University of Queensland. (Analytical details are provided in the data repository). \( \varepsilon_{\text{Hf}}(t) \) values were calculated with \( ^{206}\text{Pb}\/^{238}\text{U} \) ages and range from −10 to 17. Grains older than 45 Ma are characterized by dominantly positive \( \varepsilon_{\text{Hf}}(t) \).
values, clustering around 5–15. All $\epsilon_{147}(t)$ values for grains within the youngest peak of c. 24–23 Ma are negative: $-2.4$ to $-9.4$ (Fig. 5c).

**Discussion**

Our study indicates a latest Oligocene age for initial sedimentation along the northern margin of the Indus Molasse. Detrital zircon U–Pb ages reveal a younger c. 24–23 Ma peak for M4 and provide a maximum depositional age for this unit. This radiometric age is consistent with palaeontological (ostracod) data reported by Bajpai et al. (2004) from correlative sediments near Basgo (Fig. 2). Sediments in the studied area were entirely sourced from the north with no evidence for any southerly provenance, from the Indian Plate, for example, which contains older zircon with ages >500 Ma (e.g. Gehrels et al. 2011). Granitic clasts and sandstone with detrital zircon ages of c. 85–45 Ma are consistent with uplift and erosion of the Ladakh Batholith, which served as an important source (Brookfield and Andrews-Speed 1984; Searle 1986; Garzanti and Van Haver 1988). Abundant andesitic and felsic volcanic clasts (comprising 100% of clasts in M3 and c. 85% of clasts in M1 and M4) strongly suggest a volcanic source, which we consider most likely to be a local equivalent of the Khardung Volcanics. Such rocks must first have been eroded to expose the Ladakh Batholith above and upon which they were erupted. Documented ages for these volcanics include 51.95 ± 0.4 and 56.4 ± 0.4 Ma (whole-rock

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**Fig. 3.** Stratigraphic logs of measured sections. Section locations are labelled in Figure 2 and located at the following coordinates. Section 1: 34° 16′ 54.60″ N, 77° 10′ 25.36″ E; Section 2: 34° 16′ 57.50″ N, 77° 10′ 12.60″ E; Section 3: 34° 17′ 20.95″ N, 77° 9′ 22.78″ E; Section 4: 34° 17′ 54.50″ N, 77° 7′ 27.83″ E; Section 5: 34° 18′ 50.66″ N, 77° 4′ 44.88″ E; Section 6: 34° 20′ 9.69″ N, 77° 1′ 35.48″ E.
source of the youngest age peak (c. 24–23 Ma) remains less definitive. The Karakorum Batholith potentially represents a source of younger zircon grains c. 40–20 Ma (e.g. White et al. 2012; Borneman et al. 2015) and is characterized by negative zircon $\epsilon_{Hf}(t)$

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**Fig. 4.** Field photographs. (a and b) Depositional contact between the exhumed Ladakh Batholith and M1 unit. Locations: 34° 18′ 1.72″ N, 77° 8′ 20.67″ E (a) and 34° 18′ 56.80″ N, 77° 5′ 33.78″ E (b). (c) Photograph of M1 unit. Large boulders (c. 1 m) are made of granite and granodiorite, material eroded off the Ladakh Batholith. The photo was taken at 34° 16′ 56.09″ N, 77° 10′ 20.61″ E with the camera facing approximately south. (d) Contact between M1 (conglomerate) and M2 (mudstone). M2 unit is the same unit documented near Basgo (e.g. Bajpai et al. 2004). The photo was taken at 34° 18′ 43.59″ N, 77° 6′ 7.33″ E with the camera facing approximately east. (e) Field photograph of M3, a conglomerate that is entirely made of felsic to intermediate volcanic clasts. The photo was taken at 34° 18′ 49.10″ N, 77° 5′ 24.33″ E. (f) Field photograph of M4. Conglomerate layers contain felsic to intermediate volcanic and granitic clasts. The photo was taken at 34° 18′ 53.36″ N, 77° 4′ 50.44″ E.
values as low as \(-10.5\) \cite{Ravikant2009}, consistent with our results. Dykes that intrude the Oligocene Saltoro Molasse have been reported from the Shyok suture to the north \cite{Rai1983}. Oligocene–Miocene dykes have also been reported from within the Ladakh Batholith with a Rb–Sr isochron age of \(c.24\text{ Ma}\) obtained by Ravikant \cite{2006}. However, we note that no existing studies from the Ladakh Batholith report zircon U–Pb ages younger than \(c.45\text{ Ma}\) \cite{Weinberg2000, White2011, Heri2015}.

Our work refines and builds upon earlier investigations. Garzanti and van Haver \cite{1998} reported a Maastrichtian age for the Basgo Formation based on identifications of an ostracod fauna. However, we note that no existing studies from the Ladakh Batholith report zircon U–Pb ages younger than \(c.45\text{ Ma}\) \cite{Weinberg2000, White2011, Heri2015}.

As sediments documented here overlie a surface eroded into the Ladakh Batholith, they place a minimum constraint on the time needed to erode the former southern margin of Eurasia. The removal of a thick crustal section (several kilometres or more) must have preceded deposition of the molasse, earlier than \(c.24–23\text{ Ma}\). This is consistent with thermochronological modelling from nearby

\begin{figure}
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\includegraphics[width=\textwidth]{Fig_5.png}
\caption{Results of detrital zircon U–Pb dating and Hf isotopic analysis. (a) Kernel density estimates of all detrital samples, plotted by unit. (b) Weighted mean age of the youngest age cluster (top) and Concordia plot of M4 (bottom). (c) Zircon \(\epsilon_{\text{Hf}}(t)\) values (red circles) of analysed grains based on \(^{206}\text{Pb}/^\text{238}\text{U}\) ages. The black line is the kernel density estimate of ages that have accompanying Hf isotope measurements. (d) Comparison of detrital zircon U–Pb ages reported by Tripathy-Lang \emph{et al.} \cite{2013} and this study. Note that the sample location of Tripathy-Lang \emph{et al.} \cite{2013} is located in the hanging wall of a north-directed thrust fault and is structurally separated from the units in this study.}
\end{figure}
that sedimentation began in the latest Oligocene and investigation that infer Late Oligocene regional uplift of the Gangdese Batholith around the same time (including the Kailas, Qiuwu, Dazhuqu and Luobusa formations) are consistent with those from elsewhere along the length of the IYTS (Gangrinboche facies in southern Tibet) and Karakoram terrane being the most likely sources. The deposition of the autochthonous molasse of the Indus Basin is analogous to the formation of the Gangrinboche facies in southern Tibet (Aitchison et al. 2002, 2009).

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Author contributions RZ: conceptualization (equal), formal analysis (lead), investigation (lead), methodology (lead), project administration (supporting), writing - original draft (leading), writing - review & editing (equal); JCA: conceptualization (leading), funding acquisition (lead), investigation (equal), project administration (leading), supervision (lead), writing - original draft (equal), writing - review & editing (equal); KL: conceptualization (supporting), project administration (supporting), writing - original draft (supporting), writing - review & editing (supporting); ER: formal analysis (supporting), methodology (supporting), writing - original draft (supporting), writing - review & editing (supporting); YF: formal analysis (equal), methodology (equal), writing - original draft (supporting), writing - review & editing (supporting); JZ: formal analysis (supporting), methodology (supporting), writing - original draft (supporting), writing - review & editing (supporting)

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Correction notice: Figure 1 has been updated.

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Conclusions
Initial continental sediments deposited directly upon an uplifted and eroded surface that developed on the Ladakh Batholith on the southern margin of the Eurasian continent are no older than latest Oligocene, with a possible depositional age of c. 24–23 Ma. Deposits were derived entirely from the north, with the Ladakh arc and Karakoram terrane being the most likely sources. The deposition of the autochthonous molasse of the Indus Basin is analogous to the formation of the Gangrinboche facies in southern Tibet (Aitchison et al. 2002, 2009).

Fig. 6. Results of detrital apatite U-Pb dating. (a and b) Plots and calculation were completed using IsoplotR (Vermesch 2018) assuming all apatite grains have a similar common lead composition. The calculated common lead composition (0.8501 ± 0.0030) was then applied to correct all analyses to generate common-Pb-corrected ages (b). All errors are shown at the 2σ level.
