Downloaded from geology.gsapubs.org on September 16, 2010

Geology

Locating earliest records of orogenesis in western Himalaya: Evidence from Paleogene sediments in the Iranian Makran region and Pakistan Katawaz basin

Andrew Carter, Yani Najman, Abbas Bahroudi, Paul Bown, Eduardo Garzanti and Robert D. Lawrence

Geology 2010;38;807-810
doi: 10.1130/G31087.1

Email alerting services	click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article
Subscribe	click www.gsapubs.org/subscriptions/ to subscribe to Geology
Permission request	click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2010 Geological Society of America

THE
GEOLOGICAL
SOCIETY
OF AMERICA

Locating earliest records of orogenesis in western Himalaya: Evidence from Paleogene sediments in the Iranian Makran region and Pakistan Katawaz basin

Andrew Carter[1], Yani Najman[2], Abbas Bahroudi[3], Paul Bown[1], Eduardo Garzanti[4], and Robert D. Lawrence[5]
[1]Joint Research School of Earth Sciences, University College London and Birkbeck, University of London, London WC1E 7HX, UK
[2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[3]Mining Engineering Faculty, University of Tehran, Northern Kargar Avenue, P.O. Box 11365-4563, Tehran, Iran
[4]Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, 20126 Milan, Italy
[5]Department of Geosciences, Oregon State University, Corvallis, Oregon 97331-5506, USA

ABSTRACT

A combination of sediment petrography, detrital zircon U-Pb, and fission-track dating is used to show that provenance of the Paleogene sedimentary rocks exposed in the Makran region of southern Iran and the Katawaz basin of Pakistan is consistent with a source from the nascent western Himalaya and associated magmatic arc. Results from this important archive show that Paleogene erosion was focused mainly on the arc and northern Indian margin, and, in contrast to the east-central Himalaya, we have not detected widespread rapid exhumation indicative of strong forcing by climate-driven erosion at that time.

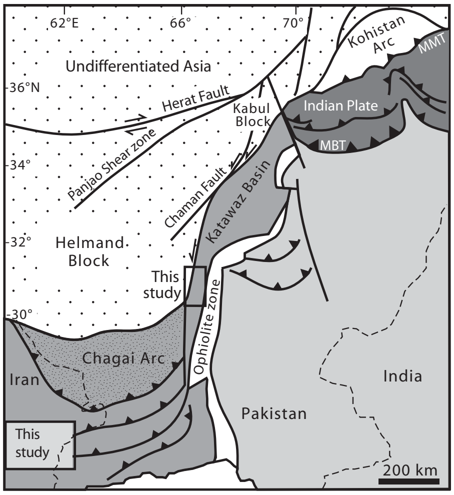

Figure 2. Location map showing study areas (boxes). MMT—Main Mantle thrust; MBT—Main Boundary thrust.

INTRODUCTION

Early stages of India-Asia collision and crustal thickening generated significant growth in topography, but when these took place remains controversial (e.g., Aitchison et al., 2007). Although metamorphic studies of Himalayan bedrock record peak Barrovian-type metamorphism dated to between ca. 35 and 30 Ma (Vance and Harris, 1999) followed by sillimanite-grade metamorphism, partial melting, and leucogranite formation between 23 and 16 Ma (e.g., Harris et al., 2004), the preceding (Paleogene) stages of orogenic growth history are not well understood due to removal of bedrock records by extensive erosion or overprinting by later metamorphism. To address this shortfall research efforts are increasingly being directed at Paleogene sedimentary rock located around the collision zone (e.g., Najman et al., 2008).

One of the largest and most complete Paleogene erosion records in the western Himalaya is considered to be related to the paleo–Indus River and its associated delta and submarine fan. Qayyum et al. (1996) first proposed that the deltaic and turbiditic sedimentary rocks in the Katawaz basin in Pakistan represent a large Paleogene delta-fan system similar to the modern Indus delta, and that sedimentary rocks exposed in the Makran region of southern Pakistan and Iran (McCall and Kidd, 1982) represent the submarine fan part of this routing system. Miocene uplift of the Murray Ridge–Kirthar fold belt (Clift et al., 2001) is considered to have changed the location of the submarine fan, shifting it eastward toward its present-day location (Fig. 1). Paleogene–Neogene sedimentary rocks in the Sulaiman fold belt and Bugti Hills of central Pakistan, a small branch of the Katawaz basin, likely record this transition (Waheed and Wells, 1990). This study examines provenance to test whether the Paleogene sedimentary rocks exposed in the Makran area were once part of an early submarine fan connected to the Katawaz basin sourced from the nascent Himalaya.

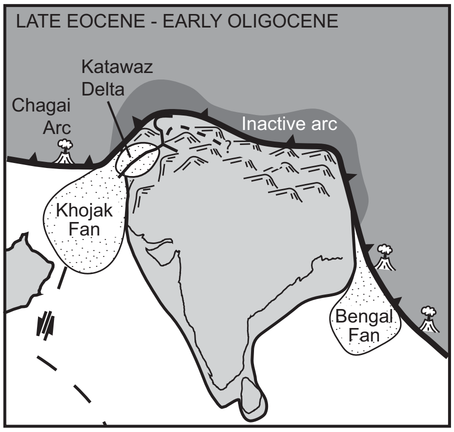

Figure 1. Reconstruction of Paleogene drainage of northwest Himalaya based on model of Qayyum et al. (1996). Miocene uplift along Murray Ridge–Kirthar fold belt is considered to have diverted this drainage east.

REGIONAL SETTING

The 700-km-long Katawaz basin contains as much as 8 km of sedimentary rock (Fig. 1). It formed along the margin of the remnant Neo-Tethys Ocean, bound to the east by the Indian plate, and has been incorporated into the thrust belt and transform system along the left-lateral Chaman fault (Fig. 2), which marks the western transform boundary with the Afghan block (Treloar and Izatt, 1993). The basin developed as an elongate trough along which axial submarine turbidites once flowed, supplied by a southward-prograding delta. Studies of Katawaz basin sedimentary rocks (Qayyum et al., 1996, 2001) recognize a submarine fan (rhythmically bedded turbidities of the Margha Faqirzai Member) and wave-modified fluvial-dominated delta (Shaigalu Member) with a high sediment flux. Qayyum et al. (1996) considered the India-Asia collision zone to be the main source region, based on observed south- and southwest-directed paleoflow indicators and sandstone petrography, which showed that the lithic arenites had recycled orogenic compositions (Dickinson, 1985).

Paleogene sedimentary rocks now exposed in the Makran accretionary complex of southern Pakistan and Iran (Fig. 2) formed by northwest subduction of the Indian and Arabian plates (Auden 1974) are considered the submarine fan extension of the Katawaz system (Qayyum et al., 2001). Individual stratigraphic units are typically kilometers thick dominated by Bouma-type turbidite sandstones and shales (McCall, 1985). Most of the Makran sandstones are classed as sublithic, lithic, volcanic, quartzose, and feldspathic arenites and contain dateable assemblages of benthic and planktonic

---

Geology, September 2010; v. 38; no. 9; p. 807–810; doi: 10.1130/G31087.1; 6 figures; Data Repository item 2010227.

foraminifera. Paleocurrents varied, but most units are recorded as being sourced from the north or northeast (McCall, 1985), consistent with sources from the India-Asia collision zone. A petrographic study of Makran sedimentary rocks (Critelli et al., 1990) recognized a strong recycled orogenic source in addition to volcanic detritus interpreted as from either the Kohistan-Ladakh region and/or more local sources connected to the Raskoh-Chagai arc, north of the Makran. For the purposes of this study representative sandstone samples from the Makran were collected from each of the principal Paleogene units, where possible from type areas described by the Geological Survey of Iran (McCall, 1985). Comparison of provenance is made with the Katawaz basin using samples from the original study of Qayyum et al. (1996).

METHODS AND RESULTS

Figure 3 summarizes the stratigraphic age ranges for the sampled sedimentary rocks in the two study areas (Fig. 2). Depositional ages exposed in the Makran are based on foraminifera assemblages described in McCall (1985). Examination for nannofossils failed to find dateable samples. Age controls for Katawaz samples are based on the age range outlined in Qayyum et al. (2001), and new age constraints obtained from nannofossils that place the Nisai Formation (Fig. 3) between biozones NP13 and NP 20; this requires the overlying Khojak Formation to be slightly younger (Oligocene) than reported in Qayyum et al. (1996). The youngest detrital zircon U-Pb ages measured on samples and the positions within the sampled stratigraphic sections provide additional age control. Full details are provided in the GSA Data Repository.[1]

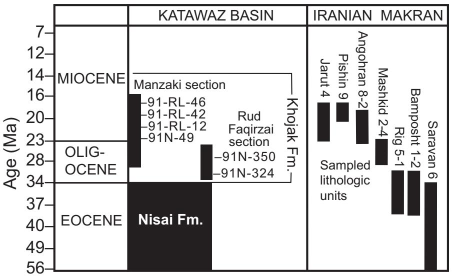

Figure 3. Stratigraphic age ranges for rock units from which zircon dated samples were collected. For Katawaz basin, black boxes represent age range for sections reported by Qayyum et al. (2001) and sample position within section. Sample age is less constrained for Makran, where black boxes represent possible age range for each sample based on foraminifera assemblages (Data Repository [see footnote 1]).

Petrography and Heavy Minerals

Petrographic study of the Katawaz basin sedimentary rocks by Qayyum et al. (2001) found quartz-rich sandstones with low-grade metamorphic lithic fragments with subordinate amounts of detrital feldspars and volcanic lithic fragments. On this basis Qayyum et al. (2001) concluded that the main source was a collisional orogen with minor inputs from a magmatic arc. Our petrographic study of the fine- to medium-grained sandstones of the Makran also show fold-thrust belt sources as dominant, but there is also a higher contribution from a volcano-plutonic arc seen in plagioclase-rich Eocene–Early Oligocene samples that contain abundant andesite- to rhyodacite-derived volcanic lithics. Late Oligocene–Miocene samples show a sharp decrease in volcanic lithics and an increase in low-grade metamorphic grains and detrital micas, indicating a greater contribution from metamorphic rocks (fold-thrust belt). Low heavy-mineral concentration and lack of unstable species (pyroxene, amphibole) indicates extensive diagenetic dissolution (Garzanti and Andò, 2007). The coexistence of common Cr-spinel and garnet shows a mixed provenance from arc or suture-zone rocks (ophiolites, or recycled from forearc or remnant-ocean turbidites) and orogenic metamorphic rocks. The quartz-feldspar-lithic (QFL) plot in Figure 4 shows these main differences (Dickinson, 1985; Garzanti et al., 2007).

Zircon Chronology

To constrain further the provenance of the sedimentary rocks zircon U-Pb age spectra were produced. A useful strategy successfully employed in Himalayan studies (e.g., De Celles et al., 2004) is to compare sample detrital zircon U-Pb age spectra with plots that summarize published U-Pb ages from the principal rock units within the probable source areas, in this case the Kohistan-Ladakh island arc intruding through the Trans-Himalayan Andean margin of Asia, contributing predominantly Cretaceous–Paleogene ages, and the Indian plate, contributing predominantly Precambrian ages (Fig. 5). The distribution of age peaks can then be compared between basins and potential sources aided by statistically modeled age components (Jasra et al., 2006), as summarized by the plots in Figure 5. Both basins show very similar age spectra, the bulk of zircon ages between 500 and 1000 Ma, and a distinct age mode ca. 93 Ma. Zircons older than 1000 Ma compose <20% of all dated grains.

Since zircon U-Pb data alone cannot be used to determine source erosion rates, important for understanding orogenic growth history, samples were also dated by the zircon fission-track (ZFT) method, as it is sensitive to erosion-driven cooling from metamorphic temperatures. To verify whether a ZFT age documents postmetamorphic cooling rather than an age that relates more directly to rock formation, U-Pb ages were measured on the same grains used for ZFT dating (Carter and Moss, 1999) (Fig. 6). Young ZFT ages that have similar (within error) U-Pb ages indicate magmatic ages. Double dating reveals that within each sample some of the ZFT ages record grain formation while others record cooling in response to exhumation; hence sample ZFT central ages cannot be used to plot lag times to constrain source exhumation rates.

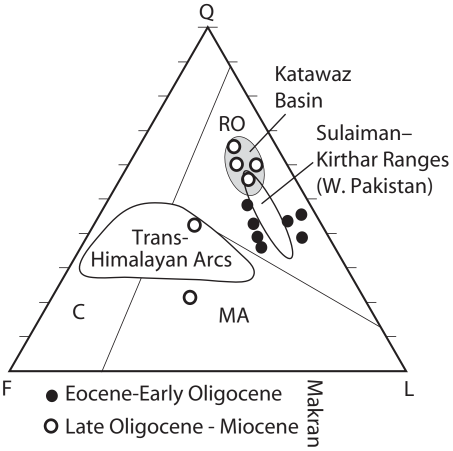

Figure 4. Comparison of sandstone petrography shows predominant fold-thrust belt (RO—recycled orogen field of Dickinson, 1985) source for both Makran and Katawaz samples. Eocene–Early Oligocene samples from Makran show closer affinity to Sulaiman ranges, located adjacent to Katawaz basin (Garzanti et al., 2007). By Late Oligocene time, Makran sandstone petrography is identical to that of Katawaz basin. Two samples (MAK 5–1, MAK 5–2) are much richer in feldspars, suggesting major plutonic contribution (granodiorites to tonalites possibly batholithic roots of arc massif). When plotted these samples match rocks from Trans-Himalayan arc (Garzanti et al., 2005). For each sample, 400 points were counted by Gazzi-Dickinson method (Ingersoll et al., 1984). Q—quartz, F—feldspar, L—lithic fragments, C—continent derived, MA—magmatic arc derived.

DISCUSSION

Provenance

Comparison between detrital zircon U-Pb and ZFT ages for individual samples from both the Makran region and the Katawaz basin reveals a

---

[1] GSA Data Repository item 2010227, details of biostratigraphic constraints and data sources for the plots used in Figure 5, Figure DR1 (zircon U-Pb concordia), Figure DR2 (probability plots of sample U-Pb ages), Figure DR3 (zircon fission-track radial plots), Table DR1 (sample locations), Table DR2 (raw zircon fission-track data), Table DR3 (raw U-Pb data), and Table DR4 (raw heavy mineral data), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

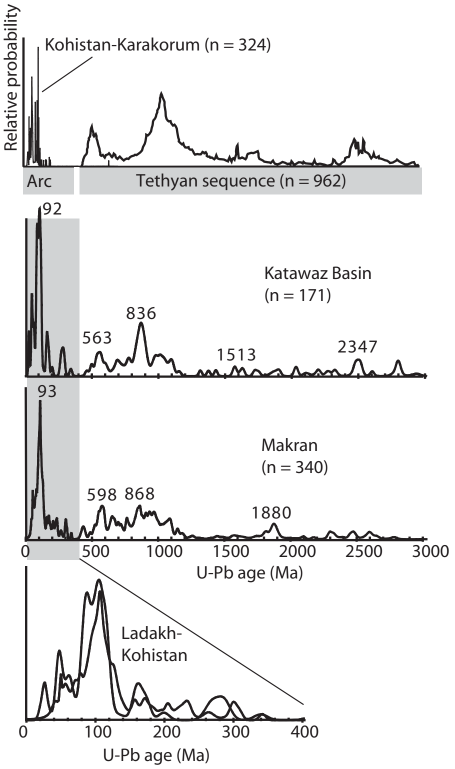

Figure 5. Summary plots of zircon U-Pb age spectra comparing results from Makran and Katawaz samples with Tethyan Himalaya and arc rocks (for sources, see the Data Repository [see footnote 1]). Peak values derived using Bayesian mixture models aided by Markov chain Monte Carlo methods (Jasra et al., 2006).

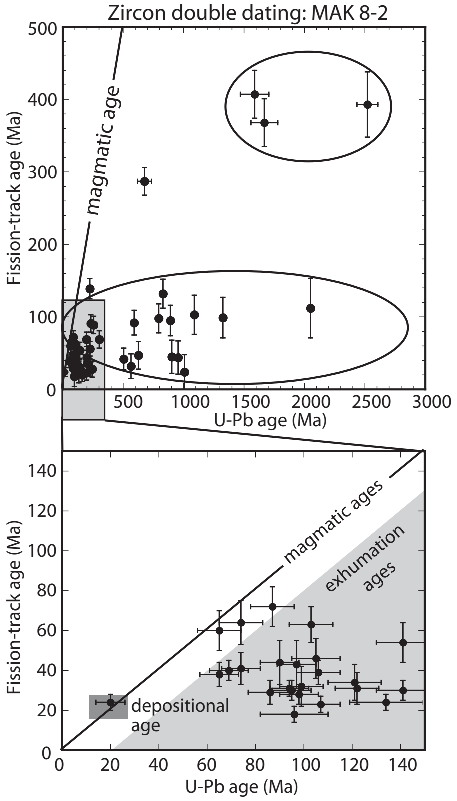

Figure 6. Double dating plots comparing zircon U-Pb and fission-track (FT) ages measured on same grains. Zircon FT ages that plot on 1:1 line date zircon formation, otherwise ages record postmetamorphic cooling and exhumation. MAK8-2 is taken from Angohran Unit (Fig. 3).

close similarity consistent with a shared source and common drainage. If the source were the nascent Himalaya, extending back to the suture zone, as suggested by Qayyum et al. (1996), the sandstone provenance should be represented by Asian plate material (including the magmatic arc) with contributions from the metamorphic rocks of the evolving Indian plate thrust belt. Sandstone petrography indicates recycled orogenic detritus with contributions from a magmatic arc (Fig. 4), supported by the U-Pb data, which identify Cretaceous–Paleocene zircon grains derived from the magmatic arc and older grains derived from basement rocks, either Indian plate or the Asian plate Karakoram (Fraser et al., 2001). The Indian plate is more likely to be the source for these old grains, considering that Paleogene products of erosion from the Asian plate, deposited in the suture zone, show that detritus was predominantly arc derived (Wu et al., 2007).

While our data confirm that provenance characteristics of the Makran and Katawaz sedimentary rocks are consistent with derivation from the Himalaya, we cannot rule out contributions from sources within the Afghan terrane, which, as defined by Treloar and Izatt (1993), includes the Helmand and Kabul blocks. These consist of Precambrian–Paleozoic basement overlain by Mesozoic cover (Shareq, 1981), possibly part of the same Cimmerian Gondawana unit as the Asian Lhasa block and Karakoram of the Himalaya (Le Fort et al., 1995). Jurassic–Cretaceous subduction-related granitoids and the Kandahar arc volcanics (Treloar and Izatt, 1993) were emplaced into this substrate in the northeast of the Helmand block, and the Jurassic to Paleogene Chagai-Roskoh arc volcanics were emplaced on the southern margin (Arthurton et al., 1982; Perello et al., 2008). It is also likely that the Chagai-Roskoh arc and the Makran accretionary complex were once located closer to the Katawaz basin than at present, on the basis of the initial geometry and evolution of the Chaman fault and how India-Asia convergence was partitioned on this fault.

We consider the Himalayan arc, rather than the andesitic Raskoh-Chagai arc, as the main source for the arc-derived zircons of the Makran, since zircon grains from the Himalayan arc are of comparable age to those of the Makran while those of the Chagai arc are largely younger. Jurassic zircons, characteristic of the Raskoh arc (Siddiqui, 2004), are absent from the Makran.

A western source would also be at variance with paleocurrents from the northeast reported by Qayyum et al. (1996, 2001). Further, double dating shows most Precambrian zircons have Tertiary pre-Pliocene ZFT exhumation ages (Fig. 6); the grains are more likely to have been sourced from the Himalayan orogen than the Afghan block since Tertiary tectonism did not occur in the Afghan block until the Pliocene, when it collided with India (Treloar and Izatt 1993). An Indian plate source from the east may be ruled out on the basis that it would be dominated by populations of Paleoproterozoic and Archean grains. By contrast, the Himalayan Indian plate thrust belt of the Tethyan Himalaya (passive margin India) and low-grade Higher Himalayan cover are characterized by all components that are found in the data reported herein (including the Paleozoic ages). Lesser Himalayan sources are unlikely as Haimanta cover is considered to have overlain this unit until unroofing ca. 9 Ma (Najman et al., 2009).

Implications

This study details a provenance consistent with erosion of mainly Tethyan and/or low-grade Higher Himalaya and Cretaceous magmatic arc material. How fast this region was undergoing erosion in the Paleogene can be judged from FT and U-Pb double dating. Results show that most of the U-Pb ages are within two distinct ranges of ZFT ages. For the example shown in Figure 6 the oldest ZFT ages range from ca. 370 to 400 Ma, and have Paleoproterozoic and Archean U-Pb formation ages indicative of Indian plate sources unaffected by Cenozoic metamorphism. The low number of grains present shows this was not an important source. The second cluster is dominated by much younger than ca. 100 Ma ZFT ages, most of which were derived from arc sources, although Precambrian U-Pb ages are also present, diagnostic of contemporaneous exhumation of country rocks. Comparison of ages with sample depositional age range (ca. 23–18 Ma for the example shown in Fig. 6) shows that within this grouping exhumation rates were varied; some magmatic sources underwent fast exhumation, and other sources, which cluster around 40 Ma, underwent slower exhumation at the time of deposition. Such provenance is consistent with bedrock studies, which indicate that in the northwest Himalaya, early major exhumation of the orogen occurred in the arc and northern Tethyan region (Kirstein et al., 2009; Schlup et al., 2003; van der Beek et al., 2009).

Until discovery of Paleogene rocks in the Bengal Basin, Bangladesh, that record exhumation of the east-central Himalaya (Najman et al., 2008), there was little sedimentary evidence to support significant rates of erosion in the Paleogene, due mainly to a general absence of Oligocene detritus in the foreland basins across Pakistan, India, and Nepal. Are the Makran and

Katawaz basin archives the western equivalent of the Bengal Basin detritus? Similar to the Bengal Basin rocks, those of the Katawaz and Makran record mixed arc and Indian plate Himalayan sources. However, unlike the Bengal Basin, we have not detected evidence for widespread rapid exhumation of the hinterland during the Paleogene. This may be significant and reflect differences in accommodation of convergence, an early short initial orogenic phase of crust thickening (e.g., van der Beek et al., 2009), and/or low relief and an arid climate; however, more detailed investigations will be required on these important archives to test this further.

CONCLUSIONS

The results of this study are consistent with the model of Qayyum et al. (1996), whereby a river sourced from the nascent western Himalaya and associated magmatic arc supplied sediment to the Katawaz delta and its associated submarine fan in the remnant Neo-Tethys Ocean. Thus, Paleogene sedimentary rocks exposed in the Makran region of southern Iran and Katawaz basin provide an important archive for study of the early history of the western Himalaya, potentially equivalent to the archive that the Bengal Basin provides for the central-eastern Himalaya.

ACKNOWLEDGMENTS

We thank the Geological Survey of Iran for their help collecting the Makran samples and Giovanni Vezzoli and Sergio Andò for bulk petrography and heavy mineral analyses. We are grateful for the constructive reviews provided by Peter deCelles, Linda Kirstein, and three other reviewers. This work was funded by the Natural Environment Research Council (grant NE/B503192/1).

REFERENCES CITED

Aitchison, J.C., Ali, J.R., and Davis, A.M., 2007, When and where did India and Asia collide?: Journal of Geophysical Research, v. 112, B05423, doi: 10.1029/2006JB004706.

Arthurton, R.S., Farah, A., and Ahmed, W., 1982, The Late Cretaceous–Cenozoic history of western Baluchistan, Pakistan—The northern edge of the Makran subduction complex, *in* Legett, J.K., ed., Trench-forearc geology: Sedimentation and tectonics on modern and ancient active plate margins: Geological Society of London Special Publication 10, p. 373–385.

Auden, J.B., 1974, Afghanistan–west Pakistan, *in* Spencer, A.M., ed., Mesozoic-Cenozoic orogenic orogenic belts: Geological Society of London Special Publication 4, p. 235–253.

Carter, A., and Moss, S.J., 1999, Combined detrital-zircon fission-track and U-Pb dating: A new approach to understanding hinterland evolution: Geology, v. 27, p. 235–238, doi: 10.1130/0091-7613(1999)027<0235:CDZFTA>2.3.CO;2.

Clift, P.D., Shimizu, N., Layne, G., Gaedicke, C., Schlüter, H.U., Clark, M., and Amjad, S., 2001, Development of the Indus Fan and its significance for the erosional history of the western Himalaya and Karakoram: Geological Society of America Bulletin, v. 113, p. 1039–1051, doi: 10.1130/0016-7606(2001)113<1039:DOTIFA>2.0.CO;2.

Critelli, S., Rosa, R.D., and Platt, J.P., 1990, Sandstone detrital modes in the Makran accretionary wedge, southwest Pakistan: Implications for tectonic setting and long-distance turbidite transportation: Sedimentary Geology, v. 68, p. 241–260, doi: 10.1016/0037-0738(90)90013-J.

DeCelles, P.G., Gehrels, G.E., Najman, Y., Martin, A.J., Carter, A., and Garzanti, E., 2004, Detrital geochronology and geochemistry of Cretaceous–Early Miocene strata of Nepal: Implications for timing and diachroneity of initial Himalayan orogenesis: Earth and Planetary Science Letters, v. 227, p. 313–330, doi: 10.1016/j.epsl.2004.08.019.

Dickinson, W.R., 1985, Interpreting provenance relations from detrital modes of sandstones, *in* Zuffa, G.G., ed., Provenance of arenites: NATO Advanced Study Institute Series 148: Dordrecht, Netherlands, D. Reidel, p. 3–61.

Fraser, J.E., Searle, M.P., Parrish, R.R., and Noble, S.R., 2001, Chronology of deformation, metamorphism and magmatism in the southern Karakoram: Geological Society of America Bulletin, v. 113, p. 1443–1455, doi: 10.1130/0016 7606(2001)113<1443:CODMAM>2.0.CO;2.

Garzanti, E., and Andò, S., 2007, Heavy-mineral concentration in modern sands: Implications for provenance interpretation, *in* Mange, M., and Wright, D., eds., Heavy minerals in use: Developments in Sedimentology 58: Amsterdam, Elsevier, p. 517–545.

Garzanti, E., Vezzoli, G., Andò, S., Paparella, P., and Clift, P.D., 2005, Petrology of Indus River sands: A key to interpret erosion history of the Western Himalayan Syntaxis: Earth and Planetary Science Letters, v. 229, p. 287–302.

Garzanti, E., Doglioni, C., Vezzoli, G., and Andò, S., 2007, Orogenic belts and orogenic sediment provenances: Journal of Geology, v. 115, p. 315–334, doi: 10.1086/512755.

Harris, N.B.W., Caddick, M., Kosler, J., and Goswami, S., 2004, The pressure-temperature-time path of migmatites: Journal of Metamorphic Geology, v. 22, p. 249–264, doi: 10.1111/j.1525-1314.2004.00511.x.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., and Sares, S.W., 1984, The effect of grain size on detrital point-counting: A test of the Gazzi-Dickinson point-counting method: Journal of Sedimentary Petrology, v. 54, p. 103–116.

Jasra, A., Stephens, D.A., Gallagher, K., and Holmes, C.C., 2006, Bayesian mixture modelling in geochronology via Markov chain Monte Carlo: Mathematical Geology, v. 38, p. 269–300, doi: 10.1007/s11004-005-9019-3.

Kirstein, L.A., Foeken, J.T.P., van der Beek, P., Stuart, F.M., and Phillips, R.J., 2009, Cenozoic unroofing history of the Ladakh Batholith, western Himalaya, constrained by thermochronology and numerical modeling: Geological Society of London Journal, v. 166, p. 667–678, doi: 10.1144/0016-76492008-107.

Le Fort, P., Lemennicier, Y., Lombardo, B., Pêcher, A., Pertusati, P., Pognante, U., and Rolfo, F., 1995, Geological map of the Himalaya-Karakorum junction in Chogo Lungma to Turmik area (Baltistan, northern Pakistan), *in* Upreti, B.N., and Dhital, M.R., eds., Proceedings of the 9th Himalaya-Karakoram-Tibet Workshop: Nepal Geological Society Journal, v. 11, p. 81–83.

McCall, G.J.H., 1985, Area report, east Iran, area no. 1. Geological Survey of Iran Report 57, 643 p.

McCall, G.J.H., and Kidd, R.G.W., 1982, The Makran, south-eastern Iran: The anatomy of a convergent plate margin active from the Cretaceous to the present, *in* Leggett, J.K., ed., Trench-forearc geology: Sedimentation and tectonics on modern and ancient active plate margins: Geological Society of London Special Publication 10, p. 387–397.

Najman, Y., and 15 others, 2008, The Paleogene record of Himalayan erosion: Bengal Basin, Bangladesh: Earth and Planetary Science Letters, v. 273, p. 1–14, doi: 10.1016/j.epsl.2008.04.028.

Najman, Y., Bickle, M., Garzanti, E., Pringle, M., Barfod, D., Brozovic, N., Burbank, D., and Ando, S., 2009, Reconstructing the exhumation history of the Lesser Himalaya, NW India, from a multitechnique provenance study of the foreland basin Siwalik Group: Tectonics, v. 28, TC5018, doi: 10.1029/2009TC002506.

Perello, J., Razique, A., Schloderer, J., and Rehman, A., 2008, The Chagai Porphyry copper belt, Baluchistan Province, Pakistan: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 103, p. 1583–1612, doi: 10.2113/gsecongeo.103.8.1583.

Qayyum, M., Niem, A.R., and Lawrence, R.D., 1996, Newly discovered Paleogene deltaic sequence in the Katawaz basin, Pakistan and its tectonic implications: Geology, v. 24, p. 835–838, doi: 10.1130/0091-7613(1996)024<0835:NDPDSI>2.3.CO;2.

Qayyum, M., Niem, A.R., and Lawrence, R.D., 2001, Detrital modes and provenance of the Paleogene Khojak Formation in Pakistan: Implications for early Himalayan orogeny and unroofing: Geological Society of America Bulletin, v. 113, p. 320–332, doi: 10.1130/0016-7606(2001)113<0320:DMAPOT>2.0.CO;2.

Schlup, M., Carter, A., Cosca, M., and Steck, A., 2003, Exhumation history of eastern Ladakh revealed by ^{40}Ar/^{39}Ar and fission-track ages: the Indus River–Tso Morari transect, NW Himalaya: Geological Society of London Journal, v. 160, p. 385–399, doi: 10.1144/0016-764902-084.

Shareq, A., 1981, Geological observations and geophysical investigations carried out in Afghanistan over the period of 1972–1979, *in* Gupta, A.H., and Delany, F., eds., Zagros-Hindu Kush-Himalaya geodynamic evolution: American Geophysical Union Geodynamics Series, v. 3, p. 75–86.

Siddiqui, M.R.H., 2004, Crustal evolution of Chagai-Raskoh arc terrane, Balochistan, Pakistan [Ph.D. thesis]: Peshawar, Pakistan, University of Peshawar, 384 p.

Treloar, P.J., and Izatt, C.N., 1993, Tectonics of the Himalayan collision between the Indian Plate and the Afghan Block: A synthesis, *in* Treloar, P.J., and Searle, M.P., eds., Himalayan tectonics: Geological Society of London Special Publication 74, p. 69–87.

Vance, D., and Harris, N., 1999, Timing of prograde metamorphism in the Zanskar Himalaya: Geology, v. 27, p. 395–398, doi: 10.1130/0091-7613(1999)027<0395:TOPMIT>2.3.CO;2.

van der Beek, P.A., Van Melle, J., Guillot, S., Pilcher, A., Reiners, P.W., Nicolescu, S., and Latif, M., 2009, Eocene Tibetan Plateau remnants preserved in the Northwest Himalaya: Nature Geoscience, v. 2, p. 364–368, doi: 10.1038/ngeo503.

Waheed, A., and Wells, N.A., 1990, Changes in paleocurrents during the development of an obliquely convergent plate boundary (Sulaiman fold-belt, southwestern Himalayas, west-central Pakistan): Sedimentary Geology, v. 67, p. 237–261.

Wu, F.-Y., Clift, P.D., and Yang, J.-H., 2007, Zircon Hf isotopic constraints on the sources of the Indus Molasse, Ladakh Himalaya, India: Tectonics, v. 26, TC2014, doi: 10.1029/2006TC002051.

Manuscript received 2 February 2010
Revised manuscript received 9 April 2010
Manuscript accepted 13 April 2010

Printed in USA