1-1-2020

Climate-tectonic interactions in the eastern Arabian Sea

Peter D. Clift
Louisiana State University

Dhananjai K. Pandey
National Centre for Polar and Ocean Research

Denise K. Kulhanek
Texas A&M University

Recommended Citation

Clift, P., Pandey, D., & Kulhanek, D. (2020). Climate-tectonic interactions in the eastern Arabian Sea. *Geological Magazine*, 829-833. https://doi.org/10.1017/S0016756820000461

Geological Magazine

www.cambridge.org/geo

Climate–tectonic interactions in the eastern Arabian Sea

Peter D. Clift[1], Dhananjai K. Pandey[2] and Denise K. Kulhanek[3]

[1]Department of Geology and Geophysics, E235 Howe-Russell-Kniffen Geoscience Complex, Louisiana State University, Baton Rouge, LA 70803, USA; [2]ESSO–National Centre for Polar and Ocean Research, Ministry of Earth Sciences, Goa 403804, India and [3]International Ocean Discovery Program, Texas A&M University, 1000 Discovery Drive, College Station, TX 77845, USA

Preface

Cite this article: Clift PD, Pandey DK, and Kulhanek DK (2020) Climate–tectonic interactions in the eastern Arabian Sea. *Geological Magazine* **157**: 829–833. https://doi.org/10.1017/S0016756820000461

Potential interactions between the solid Earth and the climate system have long been recognized by geoscientists. Such links have been the subject of both modelling and observational studies that have attempted to assess the degree and nature of any coupling. The uplift of high mountains and the closure of ocean gateways disrupt circulation patterns in the atmosphere and oceans, and thereby affect the transfer of heat from low latitudes to the poles (Borrelli *et al.* 2014; Korte *et al.* 2015; Tada *et al.* 2016). It has been suggested that uplift of mountains also causes long-term cooling as a result of increased chemical weathering of silicate minerals that draws down concentrations of CO_2, a greenhouse gas, in the atmosphere (Raymo & Ruddiman 1992). Rapid sedimentation may further sequester organic carbon in major depocentres where it remains, at least until it is subducted or uplifted in a new phase of orogeny (Galy *et al.* 2007). In turn, the atmosphere and hydrosphere influence the solid Earth, largely through the action of surface processes that cause erosion and exhumation and consequentially help to define the structure of mountain belts (Koons *et al.* 2003; Sinclair *et al.* 2005; Whipple 2009). No system is believed to typify these interactions better than the Asian monsoon and the building of the Himalaya, Tibetan Plateau and associated ranges (Prell & Kutzbach 1992; Molnar *et al.* 1993; Clift & Webb 2019).

This special issue of *Geological Magazine* is designed to showcase results of research undertaken after International Ocean Discovery Program (IODP) Expedition 355 in the spring of 2015 (Pandey *et al.* 2016*c*). This research effort involved deep coring of the sediments deposited in the Laxmi Basin of the eastern Arabian Sea by the research vessel *JOIDES Resolution*. The objective was to recover a record of evolving erosion, weathering and continental climate linked to the Indus Basin, as well as the oceanography of the Arabian Sea, which has long been recognized to be closely linked to the intensity of the South Asian monsoon (Kroon *et al.* 1991; Prell *et al.* 1992). A secondary objective was to better understand the tectonics of the Laxmi Basin itself and assess its role in the opening of the Indian Ocean. While some results have been published elsewhere, this special issue represents the biggest single collection of work completed by the science party, exploiting the unprecedented long-duration sedimentary records that are required to examine how climate and tectonics may have co-varied in the western Himalayas since the start of the India–Asia collision, likely at *c.* 60–50 Ma (Najman *et al.* 2010; DeCelles *et al.* 2014; Wu *et al.* 2014). The emplacement of a large mass-transport complex (MTC) into the Laxmi Basin during late Miocene time (Calvès *et al.* 2015; Dailey *et al.* 2020) means that much of the earlier history remains unknown either because of erosion by the MTC, or because of drilling difficulties caused by the rocks within the MTC (Pandey *et al.* 2016*a*, *b*). Nonetheless, a record of evolving climate and erosion dating from *c.* 10.8 Ma to the present represents a major improvement in our understanding of evolving climate, erosion and tectonics in SW Asia. Coring was undertaken at two sites. Site U1456 is located in the middle of the Laxmi Basin, whereas Site U1457 is located on the western side of the basin adjacent to Laxmi Ridge; the latter was specifically positioned to recover samples from the igneous basement, which was successful (Pandey *et al.* 2016*c*).

Reconstructions of the palaeoceanography in the western Indian Ocean represented some of the first and most important constraints on the varying intensity of the South Asian monsoon (Kroon *et al.* 1991; Prell *et al.* 1992). In the west, summer monsoon winds cause coastal upwelling of nutrient-rich deep water offshore Oman, resulting in blooms of plankton (Curry *et al.* 1992). A number of proxies have now been applied to the newly recovered sediment in order to understand how the palaeoceanography in the eastern Arabian Sea also varied. Satpathy *et al.* (2019) examined upper water column dynamics using an assemblage of records based on oxygen and carbon isotopic variations in foraminifers, as well as a Mg/Ca-based sea-surface temperature reconstruction. Their work indicates two discrete intervals of monsoon-related change in the upper water column at 2.7–1.85 Ma and 1.65–1.55 Ma. They suggest that the upper water column was more stratified between 2.7 and 1.85 Ma as a result of weak Asian monsoon circulation. The 1.65–1.55 Ma interval was instead related to strong winter monsoon winds.

The study identified long-term changes in monsoon intensity not related to glacial cycles and in particular to a strengthening of the winter monsoon between 1.85 and 1.65 Ma.

Saraswat *et al.* (2019) looked at stable oxygen isotope and assemblage data of foraminifers spanning the last 350 ka. An increasing abundance of the foraminifer *Globigerina bulloides* is used to infer greater upwelling during Marine Isotope Stage (MIS) 7 (243–191 ka) and the beginning of MIS 6 (191–130 Ma) in the eastern Arabian Sea caused by a stronger South Asian monsoon. This is important because there was a significant decrease in upwelling at the same time in the western Arabian Sea, identified by the same *G. bulloides* proxy. Decreased upwelling and increased winter convection occurred during the remainder of MIS 6, as well as in the subsequent glacial interval (MIS 4–2), whereas conditions during interglacial MIS 5 were similar to today. The coherent response on the western and eastern sides of the Arabian Sea indicates that the northern part of the Arabian Sea at least responds as a single unit to glacial–interglacial changes. Contrast between the oxygen isotope (δ^{18}O) values seen in the glacial versus interglacial times shows that there was a maximum salinity contrast at glacial Termination II (*c.* 130 ka) and III (*c.* 240 ka), implying a major change in monsoon strength, but a very small difference at Termination IV (*c.* 330 ka), suggesting little change in the monsoon strength at that time.

All of the proxy records in the Laxmi Basin are reliant on good age control and, in their study, Routledge *et al.* (2019) revised the age framework of the cored sediments using a combination of biostratigraphy, magnetostratigraphy and strontium isotopes. In doing so they confirmed the presence of four unconformities at both sites that disrupt the continuous record desired. Their new age model also better constrained the age of emplacement of the MTC to between 9.83 and 9.69 Ma, significantly younger than previously understood. The oldest unconformity is at the base of the MTC and is of very different duration at each site. At Site U1456 in the middle of Laxmi Basin, sediment underlying the MTC is of early–middle Miocene age, whereas at Site U1457 the sediment below the MTC is dated of early Paleocene age. The unit overlying the MTC is dominated by hemipelagic sediment and thin sandstones, and is separated by a second unconformity from the overlying unit with *c.* 0.5–0.9 Ma of missing section. The upper Miocene interval deposited between *c.* 8.5 and 5.5 Ma is dominated by mudstone with frequent thin sand beds in the lower part and a hemipelagic interval of chalk deposited between *c.* 8 and 6 Ma. A third longer unconformity of 1.4–1.6 Ma duration spans the Miocene–Pliocene boundary. Siliciclastic sedimentation resumed during the Pliocene – early Pleistocene period, interrupted by a short hiatus of *c.* 0.45 Ma duration. Above that unconformity the succession consists of a rapidly deposited series of Pleistocene sand and mud, deposited in the Laxmi Basin between *c.* 1.8 and 1.2 Ma. Since 1.2 Ma, hemipelagic sedimentation has dominated Laxmi Basin.

Geochemical logs have become a critical part of environmental reconstructions based on piston core material, and in particular X-ray fluorescence (XRF) core scanning data are now routinely used to illuminate variations in chemical weathering and/or provenance. These data are often calibrated with the major- and trace-element compositions of discrete samples obtained using conventional XRF or inductively coupled plasma mass spectrometry techniques. In their study, Hahn *et al.* (2019) compared the performance of data collected by a handheld XRF to those measured using a conventional (benchtop) XRF. They demonstrated highly significant correlations between the handheld and conventional XRF measurements of discrete samples ($R^2 \geq 0.98$) for all elements examined, including ratios typically used for environmental interpretations such as Al/Ca, Ti/Ca, Mn/Ca and Fe/Ca, indicating that the handheld device yielded high-quality and easily generated results appropriate for the calibration of core scanning data. The study concluded that the handheld device can play a critical role in future high-resolution geochemical studies.

The flux of eroded material from mountain sources in the Himalaya to the bottom of the Arabian Sea is controlled over long timescales by sea level as well as tectonics and climatically modulated sediment supply. In their study, Kumar *et al.* (2019) looked at the effect of sea level and climate on clastic sediment grain size, a proxy that is potentially affected by a number of possible processes. Data were collected from 203 samples spanning the last 200 ka, and an end-member modelling technique was used to look for coherent patterns. The work identified a period between 200 and 130 ka when there was an increase in the amount of coarse silt deposited. The study concluded that this increase was the result of reworking on the Indus Fan during the development of deep-sea canyons linked to a drop in sea level that affected sediment supply from both the Indus and Narmada rivers, which drain peninsular India. In general, lower sea level caused more incision and coarser sediment sizes. Since 130 ka, sedimentation has been more clay-dominated as a result of higher sea levels and warmer climate.

It has long been believed that there was an important climatic transition in SW Asia after 8 Ma, as initially identified from oxygen and carbon isotope studies of the foreland basin (Quade *et al.* 1989; Singh *et al.* 2011), as well as upwelling along the Oman margin (Kroon *et al.* 1991; Gupta *et al.* 2015). In their study, Clift *et al.* (2019*a*) used a combination of core scanning XRF data and colour spectral records to examine evidence for changing chemical weathering and humidity during the late Miocene Epoch. They identified increasing amounts of hematite relative to goethite, which suggests long-term drying after 7.7 Ma. Times of dry climate were associated with weaker chemical alteration as measured by K/Rb records, as well as reduced coarse clastic flux. The study also identified an interval of increased humidity between 6.3 and 5.95 Ma when there was stronger weathering and erosion. The trends in relative aridity do not coincide with those identified in palaeoceanographic records, and cannot be correlated with changes in the elevation of the mountains in the hinterland. A better correlation is seen with trends in global cooling (Zachos *et al.* 2001). In this respect, trends in humidity in the Indus Basin are opposed to those seen in southern China, a feature that is attributed to the contrasting topography and generally wetter climate seen in SE Asia.

Andò *et al.* (2019) conducted a multidisciplinary study of sediments in the Indus Fan dating from late Pliocene to early Pleistocene time. They examined the heavy mineral assemblages and showed that Indus Fan sediments are relatively rich in heavy minerals. The concentration of these phases was higher in sediments associated with channel fill rather than in overbank deposits, reflecting the fast settling rate of very dense minerals such as zircon. In contrast, the overbank deposits are richer in phyllosilicates, which have a platy morphology. This work was coupled with biomarker analysis that explored the provenance of the clay-sized fraction. This method showed that organic material at Site U1456 was largely derived from terrestrial sources, whereas at Site U1457 it was more dominated by open-marine organic material. Biomarker results also indicate low thermal maturity at both sites, with Site U1456 showing slightly higher values, although these results also indicate a somewhat higher geothermal gradient than expected based on *in situ* formation temperature measurements made during the expedition.

Further investigation of the thermal history of the basin was conducted using apatite fission track (AFT) data from both drilling sites (Zhou *et al.* 2019). Because the AFT ages are older than the depositional ages, it is clear that they were not reset after sedimentation and so reflect cooling of the source terrains as a result of erosion. Comparing the minimum cooling age of each sample with its depositional age showed that there was an acceleration in exhumation of the source bedrocks between 7.8 and 7.0 Ma. Lag times, which were *c.* 6.0 Ma between 8.5 and 7.8 Ma, were reduced to close to zero between 7.0 and 5.7 Ma. This period of rapid exhumation most likely reflects faster erosion in the Karakoram and to a lesser extent the Himalayas, a conclusion based on comparison with detrital zircon data (Clift *et al.* 2019*b*). The increased erosion rate in the source areas correlates with a period of climatic drying and not a stronger summer monsoon as might be expected. Following the transition, there was a resumption of slower exhumation with lag times of *c.* 4.5 Ma after 5.7 Ma.

The nature of vegetation in the Indus Basin is closely linked to the intensity of the summer monsoon precipitation. In their study, Suzuki *et al.* (2019) analysed the carbon isotope composition of fatty acids in sediments from Site U1457. They showed a shift in the δ^{13}C signature of C_{32} fatty acids towards less negative values between 10 and 6.3 Ma. In contrast, C_{24} fatty acids did not show this change, and these shorter molecules are interpreted to represent the contribution from freshwater aquatic C3 plants. After 5.8 Ma, the δ^{13}C remained relatively constant but the average chain length varied. The authors interpreted that, prior to 6.3 Ma, the fatty acid signal represents variations in the abundance of terrestrial C3 plants to aquatic (freshwater) C3 and (terrestrial) C4 plants, whereas after 5.8 Ma, the signal is dominated by C4 and aquatic C3 plants. Suzuki *et al.* (2019) proposed that terrestrial C3 plants were replaced by C4 plants in the drainage basin between 8.2 and 6.3 Ma, a change they infer to be driven by drying of the source area during late Miocene time.

Khim *et al.* (2019) reconstructed long-term variations in carbon isotopes of sedimentary organic matter at Site U1457, assuming that the sedimentary organic matter represents a mixture of marine and terrestrial materials. The δ^{13}C values measured from upper Miocene to upper Pleistocene sediments were generally low and show little variation, reflecting a consistent supply of terrestrial organic matter dominated by C3 plants from the Indus basin. However, from *c.* 8 to 7 Ma, δ^{13}C values were somewhat more depleted, suggesting increased input of C3 plant organic matter at that time. After 7 Ma, higher δ^{13}C values support an increase in the contribution from C4 plants, consistent with the Suzuki *et al.* (2019) study. Khim *et al.* (2019) interpreted the change in terrestrial vegetation to reflect a shift towards enhanced aridity in the Indus catchment.

Change in the source of siliciclastic material to the submarine fan was reconstructed since 3.4 Ma by Lu *et al.* (2020) using a combination of neodymium and strontium isotopes, together with single-grain zircon U–Pb age data. These authors show that the sediments represent a combination of erosion from the Himalayas, Karakoram and Kohistan–Ladakh, as well as some sediment flux from the peninsula of India, including the Deccan Traps and Indian Craton. They interpreted changes in the sediment source to be associated with sea-level changes, which vary along with Asian monsoon rainfall. They also examined grain size and hematite content spanning the same time period, and found a three-stage evolution since late Pliocene time. Between 3.4 and 2.4 Ma there was strong chemical weathering despite weak monsoon precipitation. The record implies an increasing but quite variable summer monsoon between 1.8 and 1.1 Ma, followed by weaker summer rainfall and moderate chemical weathering after 1.1 Ma. Spectral analysis indicates orbital cyclicities of 100 ka (eccentricity) and 41 ka (obliquity), but not 21 ka (precession) apparent in the grain size and hematite content records. This spectral record mirrors the precipitation record of Clemens *et al.* (2018) from the discharge of the Yangtze River, which is tied to the East Asian monsoon. These observations suggest that the monsoon, as well as sea level and global temperatures, controlled weathering and erosion in SW Asia since late Pliocene time.

Cai *et al.* (2018) examined sediment deposited at Site U1456 since 3.7 Ma. They analysed the clay mineral content, and found that the samples were dominated by smectite and illite, with lower proportions of chlorite and kaolinite. Using these data they were able to define four phases of deposition that they attributed to changes in provenance. From 3.7 to 3.2 Ma the Indus River dominated, whereas from 3.2 to 2.6 Ma the Indus was supplemented by additional flux from the Deccan Traps. The Indus River again dominated between 2.6 and 1.2 Ma, with a resumption of flux from the Deccan Traps after 1.2 Ma. This study proposes that these variations were driven by changes in the intensity of the summer monsoon. When the monsoon was relatively weak the Indus River dominated, whereas strengthening of the summer rains increased sediment supply from the Deccan Traps. They concluded that clay minerals may be a useful method for tracing provenance at least since 3.7 Ma, despite the fact that these are also influenced by chemical weathering driven by climate (Thiry 2000).

A similar approach was used by Khim *et al.* (2018) covering the last 800 ka at Site U1456. They compared the values of strontium and neodymium isotopes of the sediment in the Indus Fan to possible river sources and interpreted the data to represent mixtures of sediment supplied from the Tapti, Narmada and Indus rivers. They propose that the Indus River was more important during glacial times, but that isotopic variations do not correspond precisely to glacial–interglacial cycles. They noted that sandy turbidite deposits tended to be associated with high ^{87}Sr/^{86}Sr ratios and low ε_{Nd} values, likely linked to erosion from the Himalayas and delivered by the Indus River. As in the Kumar *et al.* (2019) and Lu *et al.* (2020) studies, they propose that sea level plays a critical role in controlling sediment flux into the basin.

The tectonics of the Laxmi Basin was investigated by Pandey *et al.* (2018) using two-dimensional post-rift flexural backstripping methods (Kusznir *et al.* 1995). They estimated the degree of extension across the basin, assuming a low flexural rigidity and thermal subsidence following a pure shear extensional model (McKenzie 1978). They further restored the flat-topped Raman Seamount located within the basin, considered to have been emplaced shortly after the late Cretaceous extension, to sea level. Their backstripping analysis demonstrates that the Laxmi Basin has undergone an extreme stretching of pre-existing crust since Late Cretaceous time. At the same time they calculated de-compacted sedimentation rates and estimated that sedimentation rates would have peaked during early–middle Miocene time, coeval with uplift of the Himalaya and with a phase of strong activity by the South Asian summer monsoon, similar to values derived from the upper fan, adjacent to the modern delta (Clift 2006).

References

Andò S, Aharonovich S, Hahn A, George SC, Clift PD and Garzanti E (2019) Integrating heavy-mineral, geochemical and biomarker analyses of Plio-Pleistocene sandy and silty turbidites: a novel approach for provenance studies (Indus Fan, IODP Expedition 355). *Geological Magazine*, published online 14 August 2019, doi: 10.1017/S0016756819000773.

Borrelli C, Cramer BS and Katz ME (2014) Bipolar Atlantic deepwater circulation in the middle-late Eocene: Effects of Southern Ocean gateway openings. *Paleoceanography* **29**, 308–27, doi: 10.1002/2012PA002444.

Cai M, Xu Z, Clift PD, Khim B-K, Lim D, Yu Z, Kulhanek DK and Li T (2018) Long-term history of sediment inputs to the eastern Arabian Sea and its implications for the evolution of the Indian summer monsoon since 3.7 Ma. *Geological Magazine*, published online 27 December 2018, doi: 10.1017/S0016756818000857.

Calvès G, Huuse M, Clift PD and Brusset S (2015) Giant fossil mass wasting off the coast of West India: The Nataraja submarine slide. *Earth and Planetary Science Letters* **432**, 265–72, doi: 10.1016/j.epsl.2015.10.022.

Clemens SC, Holbourn A, Kubota Y, Lee K E, Liu Z, Chen G, Nelson A and Fox-Kemper B (2018) Precession-band variance missing from East Asian monsoon runoff. *Nature Communications* **9**, 3364, doi: 10.1038/s41467-018-05814-0.

Clift PD (2006) Controls on the erosion of Cenozoic Asia and the flux of clastic sediment to the ocean. *Earth and Planetary Science Letters* **241**, 571–80.

Clift PD, Kulhanek DK, Zhou P, Bowen MG, Vincent SM, Lyle M and Hahn A (2019a) Chemical weathering and erosion responses to changing monsoon climate in the Late Miocene of Southwest Asia. *Geological Magazine*, published online 13 June 2019, doi: 10.1017/S0016756819000608.

Clift PD & Webb AG (2019) A history of the Asian monsoon and its interactions with solid Earth tectonics in Cenozoic South Asia. In *Himalayan Tectonics: A Modern Synthesis* (eds MP Searle and PJ Treloar), pp. 631–52. Geological Society of London, Special Publication no. 483, doi: 10.1144/SP483.1.

Clift PD, Zhou P, Stockli DF and Blusztajn J (2019b) Regional Pliocene exhumation of the Lesser Himalaya in the Indus drainage. *Solid Earth* **10**, 647–61, doi: 10.5194/se-10-647-2019.

Curry WB, Ostermann DR, Guptha MVS and Itekkot V (1992) Foraminiferal production and monsoonal upwelling in the Arabian Sea; evidence from sediment traps. In *Upwelling Systems: Evolution since the Early Miocene* (eds CP Summerhayes, WL Prell and KC Emeis), pp. 93–106. Geological Society of London, Special Publication no. 64.

Dailey SK, Clift PD, Kulhanek DK, Blusztajn J, Routledge CM, Calvès G, O'Sullivan P, Jonell TN, Pandey DK, Andò S, Coletti G, Zhou P, Li Y, Neubeck NE, Bendle JAP, Bratenkov S, Griffith EM, Gurumurthy GP, Hahn A, Iwai M, Khim B-K, Kumar A, Kumar AG, Liddy HM, Lu H, Lyle MW, Mishra R, Radhakrishna T, Saraswat R, Saxena R, Scardia G, Sharma GK, Singh AD, Steinke S, Suzuki K, Tauxe L, Tiwari M, Xu Z and Yu Z (2020) Large-scale mass wasting on the Miocene continental margin of western India. *Geological Society of America Bulletin* **132**(1–2), 85–112, doi: 10.1130/B35158.1.

DeCelles PG, Kapp P, Gehrels GE and Ding L (2014) Paleocene-Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: Implications for the age of initial India-Asia collision. *Tectonics* **33**, 824–49, doi: 10.1002/2014TC003522.

Galy V, France-Lanord C, Beyssac O, Faure P, Kudrass H-R and Palhol F (2007) Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. *Nature* **450**, 407–11, doi: 10.1038/nature06273.

Gupta AK, Yuvaraja A, Prakasam M, Clemens SC and Velu A (2015) Evolution of the South Asian monsoon wind system since the late Middle Miocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **438**, 160–67, doi: 10.1016/j.palaeo.2015.08.006.

Hahn A, Bowen MG, Clift PD, Kulhanek DK and Lyle MW (2019) Testing the analytical performance of handheld XRF using marine sediments of IODP Expedition 355. *Geological Magazine*, published online 4 April 2019, doi: 10.1017/S0016756819000189.

Khim B-K, Horikawa K, Asahara Y, Kim J-E and Ikehara M (2018) Detrital Sr-Nd isotopes, sediment provenances, and depositional processes in the Laxmi Basin of the Arabian Sea during the last 800 kyrs. *Geological Magazine*, published online 23 November 2018, doi: 10.1017/S0016756818000596.

Khim B-K, Lee J, Ha S, Park J, Pandey DK, Clift PD, Kulhanek DK, Steinke S, Griffith EM, Suzuki K and Xu Z (2019) Variations in δ13C values of sedimentary organic matter since late Miocene time in the Indus Fan (IODP Site 1457) of the eastern Arabian Sea. *Geological Magazine*, published online 7 January 2019, doi: 10.1017/S0016756818000870.

Koons PO, Norris RJ, Craw D and Cooper AF (2003) Influence of exhumation on the structural evolution of transpressional plate boundaries: An example from the Southern Alps, New Zealand. *Geology* **31**, 3–6, doi: 10.1130/0091-7613(2003)031<0003:Ioeots>2.0.Co;2.

Korte C, Hesselbo SP, Ullmann CV, Dietl G, Ruhl M, Schweigert G and Thibault N (2015) Jurassic climate mode governed by ocean gateway. *Nature Communications* **6**, 10015, doi: 10.1038/ncomms10015.

Kroon D, Steens T and Troelstra SR (1991) Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers. In *Proceedings of the Ocean Drilling Program* (eds W Prell and N Niitsuma), pp. 257–63. College Station, TX: Ocean Drilling Program, Scientific Results 117.

Kumar A, Dutt S, Saraswat R, Gupta AK, Clift PD, Pandey DK, Yu Z and Kulhanek DK (2019) A late Pleistocene sedimentation in the Indus Fan, Arabian Sea, IODP Site U1457. *Geological Magazine*, published online 17 May 2019, doi: 10.1017/S0016756819000396.

Kusznir NJ, Roberts AM and Morley CK (1995) Forward and reverse modelling of rift basin formation. In *Hydrocarbon Habitat in Rift Basins* (ed. JJ Lambiase), pp. 33–56. London: Geological Society of London, Special Publication no. 80.

Lu H, Liu R, Cheng L, Feng H, Zhang H, Wang Y, Hu R, Zhao W, Ji J, Xu Z, Yu Z, Kulhanek DK, Pandey DK and Clift PD (2020) Phased evolution and variation of South Asian monsoon, and resulting weathering and surface erosion in the Himalaya–Karakoram Mountains, since late Pliocene time using data from Arabian Sea core. *Geological Magazine*, published online 27 April 2020, doi: 10.1017/S0016756820000291.

McKenzie DP (1978) Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters* **40**, 25–32.

Molnar P, England P and Martinod J (1993) Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Monsoon. *Reviews of Geophysics* **31**, 357–96.

Najman Y, Appel E, Boudagher-Fadel M, Bown P, Carter A, Garzanti E, Godin L, Han J, Liebke U, Oliver G, Parrish R and Vezzoli G (2010) Timing of India–Asia collision: Geological, biostratigraphic, and palaeomagnetic constraints. *Journal of Geophysical Research* **115**, doi: 10.1029/2010JB007673.

Pandey DK, Clift PD, Kulhanek DK, Andò S, Bendle JAP, Bratenkov S, Griffith EM, Gurumurthy GP, Hahn A, Iwai M, Khim B-K, Kumar A, Kumar AG, Liddy HM, Lu H, Lyle MW, Mishra R, Radhakrishna T, Routledge CM, Saraswat R, Saxena R, Scardia G, Sharma GK, Singh AD, Steinke S, Suzuki K, Tauxe L, Tiwari M, Xu Z and Yu Z (2016a) Site U1456. In *Arabian Sea Monsoon. Proceedings of the International Ocean Discovery Program* (eds DK Pandey, PD Clift and DK Kulhanek). College Station, TX: International Ocean Discovery Program, vol. 355, doi: 10.14379/iodp.proc.355.103.2016.

Pandey DK, Clift PD, Kulhanek DK, Andò S, Bendle JAP, Bratenkov S, Griffith EM, Gurumurthy GP, Hahn A, Iwai M, Khim B-K, Kumar A, Kumar AG, Liddy HM, Lu H, Lyle MW, Mishra R, Radhakrishna T, Routledge CM, Saraswat R, Saxena R, Scardia G, Sharma GK, Singh AD, Steinke S, Suzuki K, Tauxe L, Tiwari M, Xu Z and Yu Z (2016b) Site U1457. In *Arabian Sea Monsoon. Proceedings of the International Ocean Discovery Program* (eds DK Pandey, PD Clift and DK Kulhanek). College Station, TX: International Ocean Discovery Program, vol. 355, doi: 10.14379/iodp.proc.355.104.2016.

Pandey DK, Clift PD, Kulhanek DK and Expedition 355 Scientists (2016c) Expedition 355 Summary. In *Proceedings of the International Ocean Discovery Program* (DK Pandey, PD Clift and DK Kulhanek), pp. 1–32. College Station, TX: International Ocean Discovery Program, doi: 10.14379/iodp.proc.355.101.2016.

Pandey DK, Pandey A, Clift PD, Nair N, Ramesh P, Kulhanek DK and Yadav R (2018) Flexural subsidence analysis of the Laxmi Basin, Arabian Sea and its tectonic implications. *Geological Magazine*, published online 18 December 2018, doi: 10.1017/S0016756818000833.

Prell WL and Kutzbach JE (1992) Sensitivity of the Indian Monsoon to forcing parameters and implications for its evolution. *Nature* **360**, 647–52.

Prell WL, Murray DW, Clemens SC and Anderson DM (1992) Evolution and variability of the Indian Ocean Summer Monsoon: evidence from the western Arabian Sea drilling program. In *Synthesis of Results from Scientific Drilling in the Indian Ocean* (eds RA Duncan, DK Rea, RB Kidd, U von Rad and JK Weissel), pp. 447–69. Washington, DC: American Geophysical Union. Geophysical Monograph no. 70.

Quade J, Cerling TE and Bowman JR (1989) Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan. *Nature* **342**, 163–66.

Raymo ME and Ruddiman WF (1992) Tectonic forcing of Late Cenozoic climate. *Nature* **359**, 117–22.

Routledge CM, Kulhanek DK, Tauxe L, Scardia G, Singh AD, Steinke S, Griffith EM and Saraswat R (2019) Revised geological timescale for IODP Sites U1456 and U1457. *Geological Magazine*, published online 10 April 2019, doi: 10.1017/S0016756819000104.

Saraswat R, Kurtarkar SR, Yadav R, Mackensen A, Singh DP, Bhadra S, Singh AD, Tiwari M, Prabhukeluskar SP, Bandodkar SR, Pandey DK, Clift PD, Kulhanek DK, Bhishekar K and Nair S (2019) Inconsistent change in surface hydrography of the eastern Arabian Sea during the last four glacial–interglacial intervals. *Geological Magazine*, published online 15 November 2019, doi: 10.1017/S0016756819001122.

Satpathy RK, Steinke S and Singh AD (2019) Monsoon-induced changes in surface hydrography of the eastern Arabian Sea during the early Pleistocene. *Geological Magazine*, published online 8 March 2019, doi: 10.1017/S0016756819000098.

Sinclair H, Gibson M, Naylor M and Morris R (2005) Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes. *American Journal of Science* **305**, 369–406, doi: 10.2475/ajs.305.5.369.

Singh S, Parkash B, Awasthi AK and Kumar S (2011) Late Miocene record of palaeovegetation from Siwalik palaeosols of the Ramnagar sub-basin, India. *Current Science* **100**, 213–22.

Suzuki K, Yamamoto M and Seki O (2019) Late Miocene changes in C3, C4 and aquatic plant vegetation in the Indus River basin: evidence from leaf wax δ13C from Indus Fan sediments. *Geological Magazine*, published online 28 October 2019, doi: 10.1017/S0016756819001109.

Tada R, Zheng H and Clift PD (2016) Evolution and variability of the Asian monsoon and its potential linkage with uplift of the Himalaya and Tibetan Plateau. *Progress in Earth and Planetary Science* **3**, 1–26, doi: 10.1186/s40645-016-0080-y.

Thiry M (2000) Palaeoclimatic interpretation of clay minerals in marine deposits; an outlook from the continental origin. *Earth-Science Reviews* **49**, 201–21.

Whipple KX (2009) The influence of climate on the tectonic evolution of mountain belts. *Nature Geoscience* **2**, 1–8, doi: 10.1038/ngeo413.

Wu FY, Ji WQ, Wang JG, Liu CZ, Chung SL and Clift PD (2014) Zircon U-Pb and Hf isotopic constraints on the onset time of India-Asia collision. *American Journal of Science* **314**, 548–79, doi: 10.2475/02.2014.04.

Zachos J, Pagani M, Sloan L, Thomas E and Billups K (2001) Trends, rythms and abberations in global climate 65 Ma to Present. *Science* **292**, 686–93.

Zhou P, Carter A, Li Y and Clift PD (2019) Slowing rates of regional exhumation in the western Himalaya: fission track evidence from the Indus Fan. *Geological Magazine*, published online 3 October 2019, doi: 10.1017/S001675681900092X.