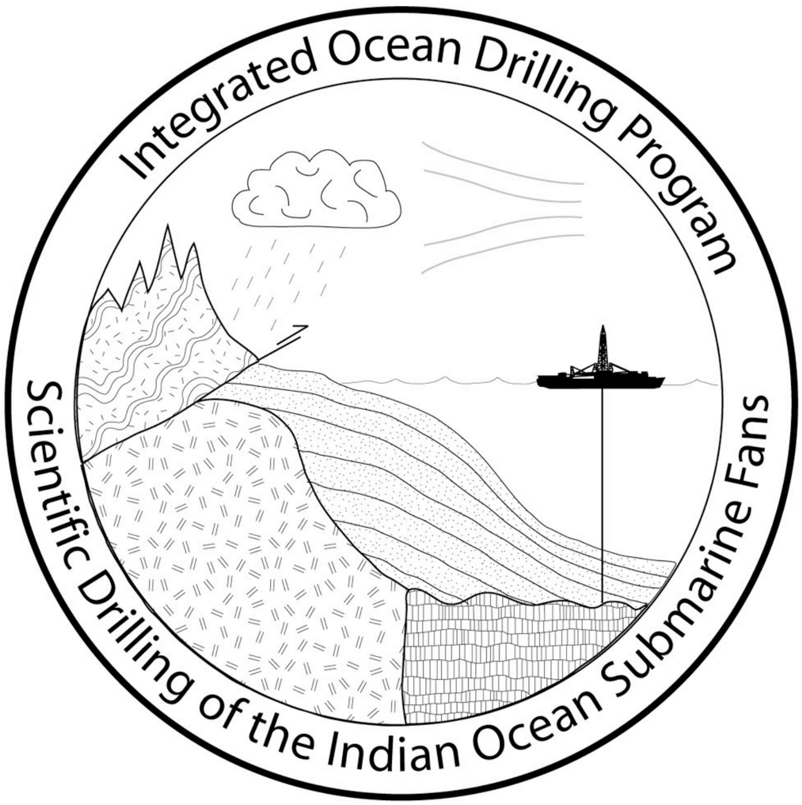
Scientific Drilling of the Indian Ocean Submarine Fans

A Report on the JOI/USSAC workshop for future IODP Drilling

23-25th July 2003, University of Colorado, Boulder, CO



Convened by
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Sponsored by
National Science Foundation
Joint Oceanographic Institutions
Cooperative Institute for Research in Environmental Science (CIRES)

Endorsed by
Indian Ocean Marine Affairs Co-operation

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A workshop to address scientific objectives for drilling of the Indus and Bengal submarine fans was hosted by the Cooperative Institute for Research in Environmental Science (CIRES) at the University of Colorado at Boulder, Colorado on 23–25 July 2003. The meeting was partially sponsored by the Joint Oceanographic Institutions and the National Science Foundation. A list of attendees (from nine countries) and the program of presentations are attached below. Drilling in the Indian Ocean submarine fans is intended to address the nature of climate-tectonic interactions, a topic that was highlighted in the Initial Science Plan for the Integrated Ocean Drilling Program (IODP). In particular, the Indian Ocean is ideally suited to explore the intensification of the Asian monsoon and the growth. of the Himalaya and Tibetan Plateau. We summarize the scientific issues in the spheres of both tectonic and paleoclimatic studies that require deep ocean drilling.

Background

The collision and penetration of India into mainland Asia has provided us with the world's outstanding laboratory for understanding not only continental collisions in general, but also their role in shaping both global and regional environments. The Tibetan Plateau, the most obvious manifestation of the collision, profoundly influences both regional climate, through its impact on the Indian and East Asian monsoons [e.g., Hahn and Manabe, 1975], and global climate, by forcing a standing wave pattern of global mid-latitude circulation [e.g., Held, 1983], if not also by altering atmospheric pCO_2 [e.g., Derry and France-Lanord, 1996b; France-Lanord and Derry, 1994, 1997; Raymo, 1991; Raymo and Ruddiman, 1992; Raymo et al., 1988]. In particular, simulations of climate suggest that without the Plateau the Asian monsoons would be much weaker [e.g., Hahn and Manabe, 1975; Kutzbach et al., 1989, 1993; Prell and Kutzbach, 1991], so that the climate in south and east Asia, which sustains approximately two-thirds of mankind, would be very different.

Erosion of the Himalaya and adjacent terrain, which currently is strongly affected by the monsoon, has formed the world's two largest submarine sediment masses, the Indus and Bengal submarine fans (Fig. 1). (For comparison, volumes of sediment in the Bengal, Indus, and Amazon fans are 12.5, 5, and 0.7 million km^3, respectively). Together, these fans contain records of both the tectonic development of the collision zone and environmental changes resulting from it. With its strong tectonic, climatic, and erosion signals, high Asia and its surrounding basins offer the world's best field laboratory to understand how the solid earth and climate interact. Thus, we urge a coordinated program of scientific drilling surrounding the southeast Asian landmass to investigate how climate, erosion, and continental tectonics have evolved over long and short periods of geological time since the India-Asia collision began some time between ~55 and 37 Ma.

Figure 1. Bathymetric and topographic map of the northern Indian Ocean and high Asia showing the location of the existing scientific drill sites in the area. Note that most of these do not drill the fans, and most of those that do penetrate only shallow depths and and distally located relative to the deltas.

Let us give two examples of problems that require drilling of the fans for their solutions. First, the abrupt change in the percentage of *Globigerina bulloides* in the Arabian sea at ~8 Ma (Fig. 2) suggests that the Indian summer monsoon strengthened at that time [e.g., Kroon et al., 1991; Prell et al., 1992], when loess deposition over North China also began (Fig. 3)

[Ding et al., 1999; Qiang et al., 2001; Sun et al., 1998a, 1998b]. Despite this pattern doubts remain as to whether 8 Ma is really the time of initial monsoon strengthening. Some records from land suggest little change since 11 Ma in the marked seasonality typical of monsoonal climate of Nepal [Dettman et al., 2001], while the weathering regime of southern China also suggests little change there since 15 Ma [Clift et al., 2002a]. Part of these disagreements may reflect difficulties in how to define the geological history of the monsoon. For most of us intense rain provides the defining characteristic of the monsoon. Thus, a record of environmental change over the Bay of Bengal and the low terrain to its north should provide a test of whether or not the monsoon as we know it today developed at 8 Ma. A demonstration of sharply defined, simultaneous climate changes all around Tibet would implicate the rise of the Tibetan Plateau and the tectonic processes that created it.

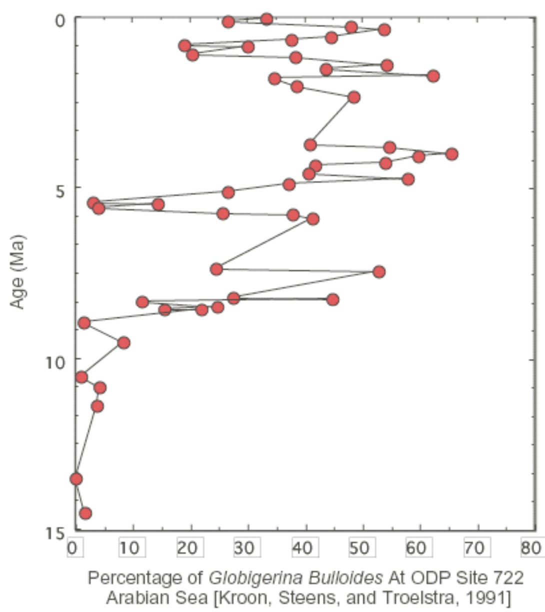

Figure 2. Diagram showing the rapid increase in the abundance of *Globigerina bulloides* on the Oman margin after 8 Ma, interpreted to indicate monsoon intensification at that time (data are from Kroon et al., 1991).

Second, the land-based record of Himalayan erosion before ~20 Ma is so incomplete as to be of only limited value, but that record should be complete offshore. No Oligocene (24–34 Ma) sediment is preserved at all in the foreland basin. We know that the last marine sediment between India and Tibet vanished some time between ~55 and 37 Ma [e.g., Clift et al., 2002b; Garzanti and van Haver, 1988; Garzanti et al., 1987; Najman et al., 2002; Rowley, 1996, 1998], and therefore that collision began to occur sometime in that interval. Did the Himalaya rapidly grow into a high terrain, which in turn eroded as it grew, or is it possible that during the initial stages of collision, India merely flexed down and was underthrust beneath an Andean-type margin at the edge of Eurasia, as oceanic lithosphere does at island arcs? If the collision occurred as early as 55 Ma, then plate motion (Fig. 4) requires that as much as 1000 km (or more) of intact Indian lithosphere, including all of its continental crust, may have been subducted into the asthenosphere beneath Tibet. The demonstration of such a result should alter our images of how the Earth evolves chemically, to say nothing of how collisions occur. The early history of erosion of the Himalaya and southern Tibet provides a test of both when collision occurred and the date when Indian crust was first shaved off its northern margin to start building the Himalaya.

In this report, we concentrate on scientific objectives for drilling within the Indian Ocean, but we recognize that the fans there can constrain only part of the development of high terrain and its environmental impact. In particular, the east Asian marginal seas should contain a clearer erosional signal of the growth of the Tibetan Plateau than these two fans can. Thus, we do not mean to overlook the need to integrate results from the northern Indian Ocean with those from the Mekong, Red, Pearl, and Yangtze Rivers to understand the wider nature of climate-tectonic coupling in Asia. We do however emphasize the need to drill the Indian Ocean submarine fans as these massively dominate the erosional flux from Asia during the Neogene and also provide the best record of Himalayan exhumation.

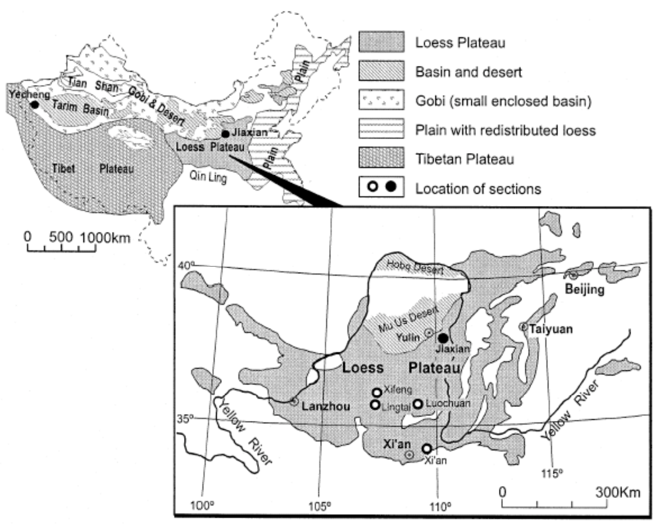

Figure 3A. Map of the Tibet and central China, showing the location of the loess plateau and in the insert the position of crucial sections, where the variability of the winter monsoon has been reconstructed.

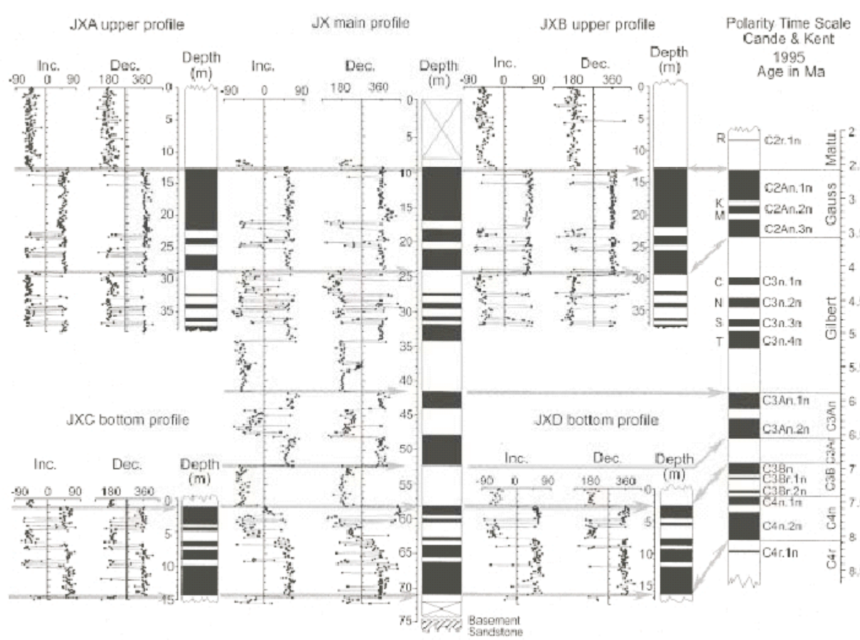

Figure 3b. Loess records from central China showing the onset of rapid wind blown dust accumulation after 8 Ma, interpreted as a strengthening of the winter monsoon at that time.

Linking and correlating climatic, tectonic, and erosional records is at the heart of the proposed drilling efforts on the fans. Yet, the migration of channels and levees across growing submarine fans makes obtaining a continuous record of sediment at any single drill site impossible. At present, virtually all sediment entering the Bengal Fan at its northern end is channeled along a meandering zone only tens of kilometers wide, with the vast majority of the fan receiving no terrigenous sediment at all (Fig. 5) [Curray et al., 2003]. Nonetheless, the absence of a significant depositional hiatus at ODP Sites 717–719 on the distal Bengal Fan does suggest that no region of the fan is non-depositional for long periods of geological time. To derive high-resolution climate records, however, will require additional drilling and sampling of nearby sites with more continuous pelagic or drift sedimentation. In the Arabian Sea we urge exploitation of both existing records from the Oman margin and proposed sites on the Murray Ridge (IODP Proposal 549) that contain detailed climate records extending back to early Miocene time (18 Ma). We recognize that longer records will be required both there and in the Bay of Bengal if the entire system is to be studied from the start of India-Asia collision. The submarine fan deposits principally record erosion, but their sampling should help constrain climate change once cores from them have been compared and calibrated using sites drilled largely to obtain paleoceanographic records. Hence, we urge using fan sediment not only as records of the evolving erosional response and as tracers of tectonic evolution, but also for paleoclimatic impacts.

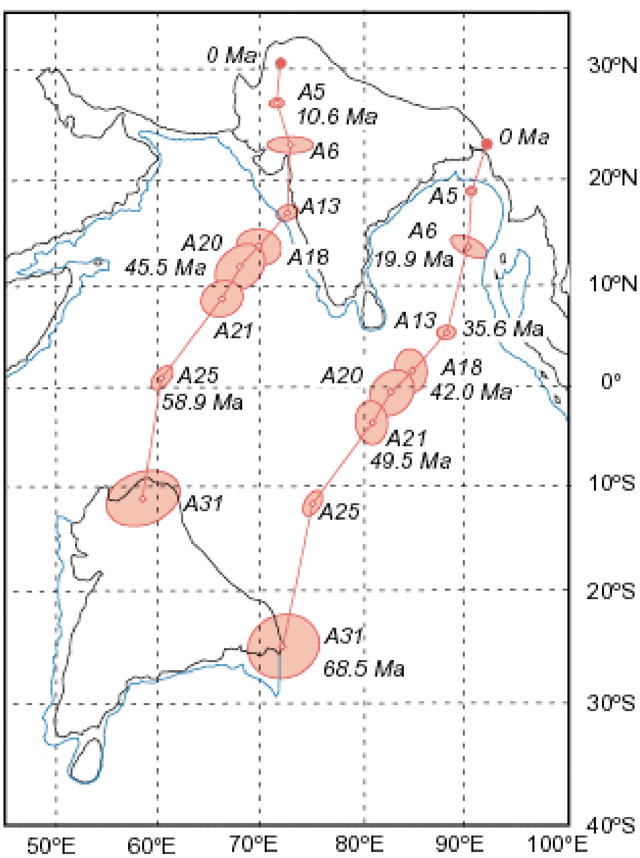

Figure 4. Reconstructed positions of India with respect to Eurasia since ~68 Ma, based on magnetic anomalies and fracture zones in the Atlantic and Indian Oceans. A precise inference of the timing of collision will allow determination of how much Indian continental lithosphere has been subducted below the paleo-Asian margin. (Redrawn from Molnar *et al.*, 1993)

Although Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) drilled only a few holes into the two fan systems (Fig. 1), they provide a background of knowledge that gives us confidence that we can pose and test specific scientific hypotheses. The two fan systems record different sediment sources and different manifestations of the monsoon. The

Arabian Sea region experiences stronger monsoon winds and coastal upwelling but receives less precipitation than the Bay of Bengal. Because of these differences, drilling both fan systems is vital for addressing both tectonic and climatic questions as well as their interactions.

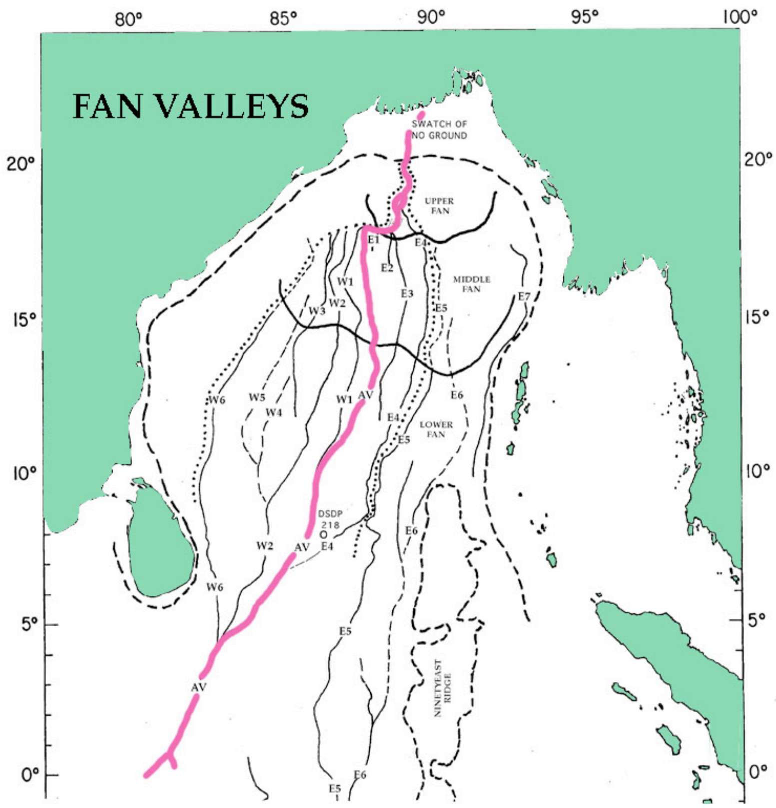

Figure 5. Map showing the large number of mapped channels on the surface of the Bengal Fan. Note that only the darker channel marked AV is currently active. Dashed line represents shelf break. Figure from Curray et al. [2003].

Scientific Objectives

Drilling on the Indian Ocean submarine fans can address scientific questions at a variety of time scales, ranging from Paleocene to Holocene. As a result the scientific return on drilling will begin from the recovery of material at the modern seafloor to the base of each fan sequence, with each proposed stage of exploration yielding advances worthy of coring such material. Here we outline scientific problems for different time periods identified by the workshop that can be best tackled through scientific ocean drilling.

The Indian Ocean submarine fans basically represent repositories of information on the erosion of the Himalaya that can be compared with tectonic and climatic records, largely derived from other sources. Nonetheless we foresee drilling of the fans as answering many tectonic questions not easily addressed with material on land. As geochemical techniques for fingerprinting advance, including dating through different closure temperatures, the potential for addressing tectonic questions will also grow. As always, with new data not previously available, new questions will be posed, and answered. The most important result from drilling the fans probably cannot yet be anticipated.

Objectives at the 0–4 Ma Timescale

Due to proposed and existing drilling within the Indian Ocean, but not on the fans themselves, the variability of the monsoon since 1 Ma is being documented in detail. We urge that the fan records be used to reconstruct the erosional response of the Himalaya to this forcing. In addition, we urge drilling in the Bay of Bengal to collect evidence for the hydrological response to monsoon variability seen as changes in freshwater run-off and evaporation in this region. Specifically, changes plankton assemblages and oxygen isotopes will reflect major changes in surface water salinity in the Bay of Bengal, which receives the major share of freshwater runoff in the region [Cullen, 1982; Duplessy, 1981]. Furthermore, We aim to document how the volume and source of the erosional flux from both fans has varied with changing monsoon strength. Mass balances, stratal architecture, and accumulation histories will be used to constrain variation in sediment fluxes, particularly when combined with ongoing land-based research on this same issue. Using isotopic and thermochronologic fingerprints we can define the temporal history of provenance for the bulk of sediment. If the sources of sediment changed substantially over the short-term cycles in monsoon strength, we should be able to correlate them. Such analysis addresses both erosional process in the mountains and their downstream impacts on the marine realm. We have tantalizing evidence from the late Quaternary that changes in erosion have been large over short time scales and need to be considered if the long-term flux to the ocean is to be understood [e.g,, Goodbred, 2003; Goodbred and Kuehl, 2000].

Controversy surrounds the role of glacial and fluvial erosion of high terrain [e.g., Hallet et al., 1996; Harbor and Warburton, 1992; Hicks et al., 1990; Summerfield and Kirkbride, 1992], and the Indus and Bengal Fans may provide evidence to discriminate between them. In this respect, the Indus and Bengal Fans may have recorded different responses to glaciation, because the Karakorum Ranges within the Indus drainage are much more heavily glaciated than areas in the central and eastern High Himalaya. Thus, quantification of sedimentation rates on the fans during the Quaternary, with attention to provenance and grain sizes, might allow us to address whether glaciation has been the principal agent of erosion since ~3 Ma.

Objectives at the 4–8 Ma Timescale

As noted above, the date when the Indian monsoon strengthened remains an open but widely debated question. Evidence continues to grow in support of abrupt environmental change in South Asia at ~8 Ma, close to the time of blooming of C4 plants on the Indian subcontinent [e.g., Cerling et al., 1993, 1997; Quade and Cerling, 1995; Quade et al., 1989, 1995], but by no means do all observations bearing on environmental change concur with this date [e.g., Dettman et al., 2001]; nor do they even require that the change be monsoon strengthening instead of some more global effect [e.g., Peterson et al., 1992]. Documenting the effect of monsoon strengthening on both the oceanography of the Indian Ocean and the erosion of the Himalaya must be a primary scientific goal of IODP drilling in the Indian Ocean. Specifically, we seek evidence for increased rainfall and run-off from south Asia, which should be recorded by lower salinity in the waters of the Bay of Bengal [e.g., Cullen, 1981;

Duplessy, 1982] after ~8 Ma, if the monsoon did strengthen at that time. Erosion and/or chemical weathering may have concurrently increased, for which evidence should be detectable in the sediment of the submarine fans. Rates of sediment accumulation determined by dating sedimentary depositional packages might have increased, if physical erosion accelerated in higher rainfall [e.g., France-Lanord et al., 1993], as it does in the modern Himalaya [Galy and France-Lanord, 2001]. Clay mineralogy might also be expected to change to reflect increased mechanical weathering during higher precipitation, resulting in an illite/chlorite dominated assemblage rather than a smectite/kaolinite dominance. Conversely, the clay mineralogy might record increased chemical erosion due to greater saturation of lowland sediment [e.g., Derry and France-Lanord, 1996a, 1997; France-Lanord et al., 1993; West et al., 2002]. In this respect the two fans, one draining the relatively arid Indus watershed, and the other the moist Brahmaputra and Ganges Basins, may record very different signatures of a change in rainfall, if such a change occurred.

Harrison et al. [1998] suggested that the Main Central Thrust was rejuvenated at ~8 Ma, and that before that time erosion within the Himalaya was slow. Eight million years ago is a special date, for it marks the approximate initiation of slip of the largest dated normal fault within Tibet, that along the Nyainqentanglha [Harrison et al., 1992, 1995b; Pan and Kidd, 1992]. Although recent dating of more minor normal faulting within Tibet at 13.5 Ma [Blisniuk et al., 2001] denies the 8-Ma date for the Nyainqentanglha its uniqueness, the onset of widespread normal faulting within Tibet (not just on its margins) implies a marked change from processes that built the Plateau, to those of its ongoing collapse. An increase of as little as 1000 m in the mean elevation of the Plateau could have triggered that change [e.g., Harrison et al., 1992; Molnar et al., 1993]. The rejuvenation of thrust faulting within the Himalaya is a predictable result of such surface uplift within Tibet, which in turn may have led to other environmental and geodynamic changes in the surrounding regions, e.g., folding of the Indian Ocean lithosphere south of Sri Lanka [e.g., Cochran, 1990; Eittreim and Ewing, 1972; Krishna et al., 2001]. The chemical and isotopic composition of sediment in the fans should allow detection of such a change in erosion of the crystalline rock of the Himalaya at that time, and hence a test a sustained period of slow erosion suggested by Harrison et al. [1998].

Objectives at the 8–15 Ma Timescale

Geomorphologists debate the relative effects of tectonics and climate on erosion. For the Himalaya, both local and global climates affect erosion. As well as documenting the erosional response of the Himalaya to monsoon strengthening, we urge quantification of the relationship between clastic sediment accumulation rates and global Cenozoic cooling events. We recognize the need to examine the shorter term changes in Quaternary glaciation marked by the cyclicity of the benthic oxygen isotope record, but also on longer time scales, such as the increase in Antarctic glaciation near 14 Ma [e.g., Flower and Kennett, 1993], the onset of Antarctic glaciation near 35 Ma [e.g., Zachos et al., 2001], and the gradual cooling of the planet since ~55 Ma [e.g., Lear et al., 2000; Zachos et al., 2001], which may, in fact, be linked to the generation of high topography in central and eastern Asia or to the closure of the equatorial Tethyan deep water passage at that time. A few high-resolution studies have called attention to the period near 14 Ma as being characterized by rapid sedimentation (Fig.

7) [e.g., John et al., 2003; Lavier et al., 2001; Steckler et al., 1999; Steckler, unpublished data, 2003], and hence rapid erosion, though what aspect of climate change led to this rapid erosion remains open. A documentation of the same phenomenon from the Himalaya could hold the key to understanding this link, if it exists globally.

Drilling into strata older than 8 Ma will allow competing proposed ages for monsoon strengthening to be assessed. Special attention should be paid to the period between 10 and 20 Ma, during which some have argued that the monsoon strengthened [e.g., Fluteau et al., 1999; Ramstein et al., 1997], and which others tentatively have identified as a period of faster sedimentation after relatively low Paleogene rates [e.g., Clift and Gaedicke, 2002; Clift et al., 2002a, 2002c]. Only drilling of these sediment bodies can assess the changing erosion history at this time.

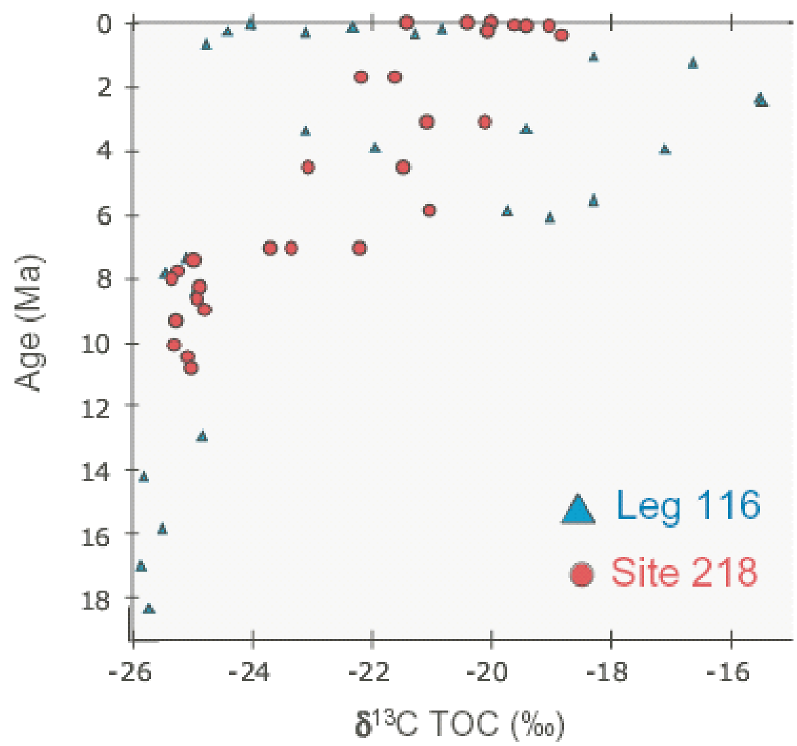

Figure 6. Diagram showing the rapid change in carbon isotopic character of organic matter in sediment deposited on the Bengal Fan. This shift reflects the switch from C3 to C4 plants in India, driven not by the monsoon but by falling atmospheric CO_2 levels. [Unpublished work of C. France-Lanord, P. Huyghe, and V. Galy]

Objectives at the 15–25 Ma Timescale

Thermochronometers from widely spaced parts of Asia suggest rapid cooling and exhumation of rock between 25 and 17 Ma. Such observations apply not only to sites within the Himalaya and southern Tibet [e.g., Copeland et al., 1987; Harrison et al., 1992; Richter et al., 1992], but also to Yunnan, southwest China [Schärer et al. 1990; 1994], the Pamir [e.g., Arnaud et al., 1993], and even the Tien Shan [Dumitru et al., 2001; Sobel and Dumitru, 1997; Sobel et al., 2001]. Most authors have interpreted these dates as evidence of the erosional response to tectonically induced vertical movement, though some such cooling may reflect exhumation by normal faulting [e.g., Hodges et al. 1992, 1993, 1998]. Harrison et al. [1992], in particular, cited this period as one in which the Tibetan Plateau grew higher. Moreover, others have used the apparent cessation of left-lateral slip on the Red River fault in southwest China as evidence that a change from large-scale extrusion of material out of India's northward path occurred at this time, and hence that the Tibetan Plateau began to grow in response to India's inexorable northward penetration of Eurasia [e.g., Lacassin et al., 1997, Leloup et al., 1993; Schärer et al., 1990. 1994; Tapponnier et al., 1990]. Obviously, if cooling at 25–17 Ma was really as widespread as the examples cited above suggest, it implies that some profound tectonic event occurred. The marine stratigraphic record necessarily samples wide areas of crust, contrasting with the localized nature of field studies, and therefore can be used to test widespread, simultaneous exhumation of different terrains near 25–17 Ma. In addition, Guo et al., [2002] suggested that loess deposition began in western China at 22 Ma, significantly earlier than its onset farther east where deposits are especially thick. Obviously, a pulse of sediment deposited on the fans during this interval would lend credibility to the occurrence of a widespread change in erosion, presumably due to a tectonic event. Such a pulse has tentatively been identified on the Indus Fan [Clift and Gaedicke, 2002], though the poor age control and low resolution needs to be improved through continuous coring. The absence of such a pulse might be taken as evidence that the thermochronometers recorded cooling due to normal faulting, and not erosion, at least in some regions.

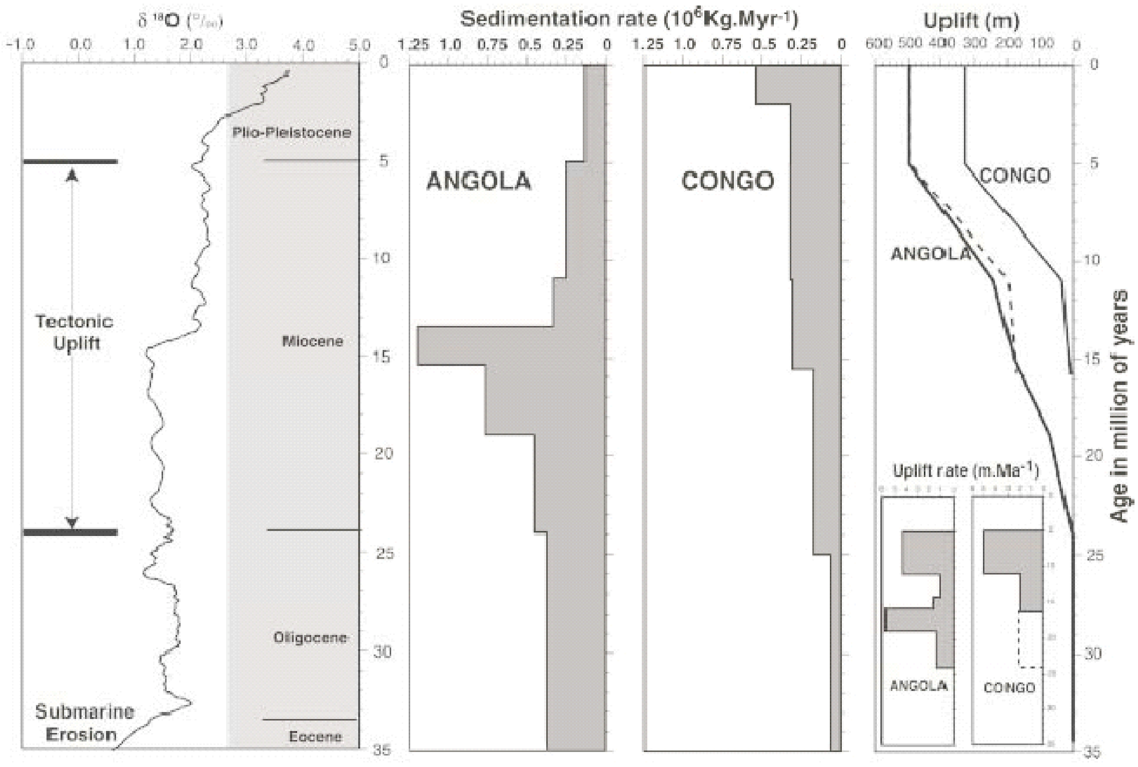

Figure 7. Enhanced clastic sedimentation on the Angola margin at ~14 Ma implies faster erosion at that time [from Lavier *et al.*, 2001], synchronous with similar pulses in New Jersey and the Mediterranean. The role of climate in stimulating faster erosion and whether similar pulses exist in the Indian Ocean have yet to be tested by drilling in the submarine fans.

Objectives at the 25–55 Ma Timescale

Erosion of the Himalaya has figured importantly in attempts to understand the nearly monotonic cooling of the Earth's climate since ~55 Ma. Increased surface area of mass-wasted rock in high terrain and the subsequent chemical weathering of it provide a mechanism by which the greenhouse gas CO_2 can be removed from the atmosphere [e.g., Raymo, 1991; Raymo and Ruddiman, 1992; Raymo et al., 1988], and the resulting global cooling. In addition, burial of organic carbon within the sediment of the fan may also affect the global carbon budget [Derry and France-Lanord, 1996b; France-Lanord and Derry, 1994, 1997]. Tests of these processes require analyses of both the organic carbon content of the fan sediment and the degree of chemical weathering of the detrital minerals, both of which require drilling of the fans and cannot be addressed by study of sediment in the Himalayan foredeep.

Although collision between India and Eurasia seems to have occurred between 55 and 37 Ma, the record of the Himalayan development before approximately 20 Ma is poor, particularly on land. Magnetostratigraphic dating of the Siwalik sequence in the Ganges Basin has yielded largely Mio-Pliocene ages that reach as old as 18 Ma [e.g., Burbank and Tahirkheli, 1985; Burbank et al., 1986, 1996; G. D. Johnson et al., 1982, 1983, 1986; N. M. Johnson, et al., 1982; Ojha et al., 2000; Tauxe et al., 1982]. The apparently slightly older sequences (Dumri in Nepal [DeCelles et al., 1998; Sakai, 1983, 1989], Dagshai in western India [e.g., Najman et al., 1997], and Murree in Pakistan [Najman et al., 2001, 2002]), which crop out in the adjacent Lesser Himalaya, extend to as young as ~20 Ma in the east to perhaps 37 Ma in the west. Sediment deposited in the two fans, however, should fill that gap (Oligocene sediment was cored on the Owen Ridge at Site 731), and accordingly it should allow tests for how the orogenic belt developed. We noted above the possibility that a large fraction of what was once the Indian subcontinent was subducted to great depth under Tibet. Underlying this possibility is ignorance of the date for when the Main Central Thrust became active.

For more than 40 years [e.g., Gansser, 1964, 1966; Heim and Gansser, 1939; Le Fort, 1975], the simple view of the Himalaya's development included (1) suturing of India to the rest of Eurasia and presumably some underthrusting of India's ancient northern margin beneath southern Tibet; then (2) slip on the Main Central Thrust, on which crystalline rock of India's lower crust and its overlying sedimentary cover were thrust atop sedimentary and mildly metamorphosed rock now cropping out in the Lesser Himalaya; and finally (3) activation of thrust faults that now crop out in the foothills but merge at depth to form a gently northward dipping fault beneath the Himalaya. In such a simplistic view, the birth of the Main Central Thrust would mark the birth of the Himalaya, which in turn would be recorded by sediment derived from rock that had been part of India, not part of Eurasia's southern margin. Several studies of chemical and isotopic compositions suggest that discriminating between these different provenances will not be difficult [e.g., Clift et al., 2002d, 2003; France-Lanord et al., 1993; Galy et al., 1996, 1999; Quade et al., 1997; Robinson et al., 2001]. What we know is that the Main Central Thrust was active near 20 Ma [e.g., Hubbard and Harrison, 1989; White et al., 2002], but as to when it formed there are few hard constraints. Imagine two possibilities. The fault became active shortly after collision, say 45 Ma, and the Himalaya began to grow then. This would allow for as much as 500–1000 km of underthrusting (25 Myr at 20-40 km/Myr), which would permit, if not support, Argand's [1924; Argand and Carozzi, 1977] suggestion of underthrusting of India beneath the whole of Tibet, or recent revisions such as that by DeCelles et al. [2002]. Alternatively, suppose the Main Central Thrust became active at 25 Ma, which would imply that intact Indian continental lithosphere underthrust southern Eurasia for at least 20 Myr (~1000 km) before the Himalaya formed; the subducted crust might now lie deep in the mantle. Of course, other implications or interpretations of such results can be imagined, but we emphasize here that deciding when the Himalaya emerged and began shedding sediment offers the solution to a basic question of continental collision.

Initial Drilling Priorities

The scientific objectives for each phase of ocean drilling will be determined by the individual proposals that build on what has been done so far. For instance, accurate dating of sediment within the fan may require extensive drilling of nearby material not overwhelmed by terrigenous flux, where a clear paleoceanographic-paleoclimate record can be reconstructed (e.g., von Rad et al. *IODP Proposal # 549*). Nonetheless, we recognize a number of objectives that can be achieved relatively early in a long-term program of drilling in the Indian Ocean that not only could address several of the goals outlined above, but also lay the foundation for future drilling studies. In the end, we recognize the need for longer term drilling focused on sampling the deeper levels of the fans through riser drilling, though we hesitate to define specific targets, besides the onset of Himalayan erosion, at this time.

Dating of fan sediment poses a challenge not commonly encountered in studies addressing climate change. The best approach almost surely will be to match the high-resolution climate records obtained in regions of high pelagic sedimentation to those within the fans that record erosion using seismic stratigraphy to correlate units. In the Arabian Sea, existing records generated following ODP Leg 117 on the Oman margin provide a context for drilling of the adjacent fan. Existing seismic data from the upper fan indicates that this may be achieved within the shallowest 2 km of the fan near Pakistan coast without the need for riser drilling (IODP Proposal #595; Fig. 8). In addition, IODP Proposal 549 by von Rad et al., to drill the Murray Ridge and Pakistani slope to study the oxygen minimum zone, should allow the generation of high-resolution Quaternary and late Tertiary paleoclimate records. As these records will penetrate terrigenous sediment, they should allow an assessment of the erosional response to short-term climate forcing within the Indus drainage, as well as a detailed record of sedimentation since ~7 Ma (if not longer). Earlier drilling at DSDP Site 222 and the shallow water depth indicate that dating of such sequences should be readily achieved. In the Bay of Bengal and in the Arabian Sea, seismically sharply defined channel-levee complexes [e.g., Clift et al., 2002c; Droz et al., 1991; Michels et al., 1998; Weber et al., 1997] also provide the chance to examine sedimentation processes at high resolution in the late Pleistocene. Although piston coring has yielded a basic understanding of how and when channels have been abandoned in one region and initiated in another, the 100–200-meter thicknesses of channel fills requires that they be drilled, if their entire sequences are to be sampled [Spiess et al., 1998]. This will be necessary if sand comprises much of the sediment.

Additional drilling may be necessary in the Bay of Bengal (though likely not on the fan itself) to define a purely pelagic paleoceanographic record, which may then be compared to the erosional record from that fan.

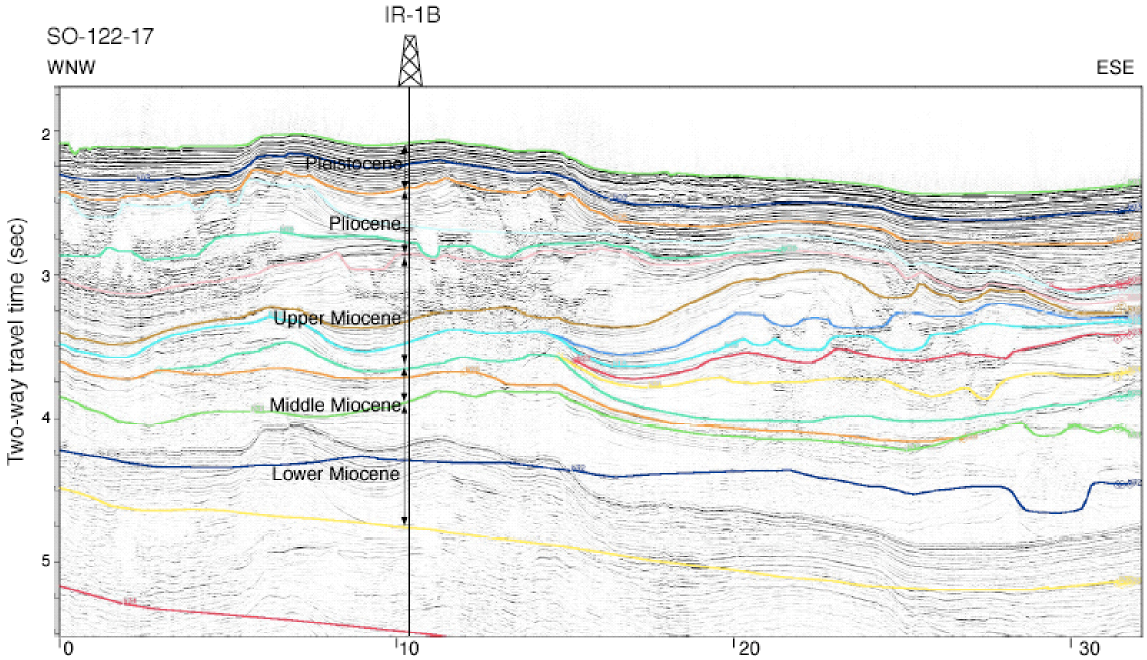

Figure 8. Seismic section through proposed site IR-1B on the Indus Fan where the base of the Late Miocene lies within the capabilities of a non-riser drill ship. This allows the erosional response to climate change at 8 Ma to be assessed early in any drilling program. Deeper drilling in this location would likely require a riser-capable vessel.

Drilling of the Bay of Bengal to assess the possible role of climate change at 8 Ma should be given high priority. Despite the likely difficulties of dating material, the demonstration of an abrupt shift of ^{13}C in terrestrial organic material at DSDP Sites 218 and 758 assures that the horizon at ~8 Ma can be identified (Fig. 6) [Derry and France-Lanord; 1996b; France-Lanord and Derry, 1994, 1996; unpublished work of C. France-Lanord, P. Huyghe, and A. Galy]. The combination of oxygen isotopes in planktonic microorganisms and inferences of sea-surface temperature either from Mg/Ca ratios or from alkenones should allow inferences of changes in salinity. We urge that more than one hole be drilled, in part because both north-south and east-west gradients in salinity should vary as run-off from the Brahmaputra and Ganges varies over time [e.g., Cullen, 1981; Duplessy, 1982].

The progradation of deep-sea fans makes drilling the oldest sediment of the fan difficult; where sediment is thin, fan sedimentation will be young, and where older, it will be very thick. Clearly, drilling to the base of thick accumulations eventually will be targets for riser drilling, but suggesting precise localities requires further site survey. One possibility for early drilling in the Arabian Sea, however, is on the Murray Ridge. Because the ridge rose and tilted during the Early Miocene (~20 Ma), it has never been buried by later Neogene sediment. Consequently, drilling on the Murray Ridge allows Oligocene sedimentary rock to be sampled close to the seafloor using non-riser technology [Clift et al. 2001]. Such a record is expected to span the onset of rapid Himalayan sediment flux into the sea, which is presently known only to predate 20 Ma. Dating the start of that flux helps address the age of rapid movement on the Main Central Thrust and the question of how continental weathering may have influenced the global draw-down of CO_2 at that time. Further deepening of a Murray Ridge hole, possibly by riser drilling, would allow the base of the Indus Fan to be sampled relatively close to the seafloor.

Similarly, in the Bay of Bengal early Himalayan Paleogene sediment can be traced by seismic profiles onto aseismic ridges like the 85-East and 90-East Ridges [e.g., Curray and Moore, 1971, 1974; Curray et al., 2003], where that sediment may be sampled. We urge that such possible sites be considered for drilling long before riser drilling is seen as a last resort, as IODP Proposal 552 seeks.

Difficulties in Drilling Submarine Fans

Dating of sediment within submarine fans, which historically has proven to be harder than where pelagic sediment dominates, needs to be considered in any strategy for the Indian Ocean submarine fans. Dating will be more problematic on the distal end of the submarine fans, because of the dissolution of calcareous microfauna in depths >4 km. In contrast, the muddy tops of turbidite beds on the proximal Indus Fan at DSDP Site 222 suggest that drilling in shallower water should yield cores that are well constrained by nannofossil biostratigraphy. Locating drill sites in shallow water may be an effective strategy in the Arabian Sea, where the total sediment thickness is much less than in the Bay of Bengal. In the latter case deep penetration may require drilling in waters depths below the CCD. Fortunately, terrestrially derived organic material deposited in the fans records clearly the change in the ^{13}C isotopic composition that occurred when C4 plants became widespread on the Indian subcontinent at ~8 Ma (Fig. 6) [Derry and France-Lanord; 1996b; France-Lanord and Derry, 1994, 1996; unpublished work of C. France-Lanord, P. Huyghe, and V. Galy]. Thus, this change provides a crucial date for testing whether changes of a variety of kinds occurred at that time.

To decode the erosional record preserved in the submarine fans requires understanding the role played by sea-level changes and the consequent erosion of continental shelves during this period [e.g., Weber et al., 1997]. Here we should be able to use what has been learned from the effect of sea-level variation on fan sedimentation in other settings (e.g. Amazon) [e.g., Flood and Piper, 1997, Maslin and Mikkelsen, 1998]. Deep-sea sedimentation is known to continue through the Holocene sea-level rise on the Bengal Fan [e.g., Weber et al., 1997], while globally most such systems became drowned and inactive. Fan sedimentation appears to have been vigorous during the Pleistocene. The Quaternary section of the upper Bengal Fan can be subdivided by seismic stratigraphy into four sub-fans, which show lateral shifting as a function of the location of the submarine canyon supplying the turbidity currents and sediments [Curray et al., 2003]. Probably more than one canyon, with its associated sub-fan, was active during the Quaternary. (Even on the Indus Fan, sedimentation has been active in the submarine canyon, if not on the mid fan during the Holocene sea-level rise. A Holocene hiatus in shelf sedimentation offshore Pakistan [von Rad and Tahir, 1997] implies bypassing of sediment past the shelf at that time. Clearly, estimating the flux of sediment to the oceans is not totally straightforward in either Indus or Bengal systems, but the processes by which sediment moves to the deep fan must be understood in the recent geologic past if the older record is to be exploited. In a similar mode, understanding of the continental sediment dispersal patterns will be needed, if we are to use the marine sediment to test hypotheses for the evolution of the eroded terrain. Pilot work in the present-day Indus drainage indicates that the vast majority of sediment entering the ocean is derived from the modern high topography rather than being recycled from earlier sedimentary rocks in the foreland [Clift et al., 2003]. Over geological time this may result in a much simpler record than if recycling was dominant.

Detailed sediment provenance techniques will need to be employed if the erosion history preserved in the fans is to be documented. The wide variety of both isotopic and rare-earth signatures of rock exposed in the Himalaya allows them to be fingerprinted [e.g., Clift et al., 2002d, 2003; Lee et al., 2003; France-Lanord et al., 1993; Galy et al., 1996, 1999; Quade et al., 1997; Robinson et al., 2001]. Thus, we can decide not only if sediment was derived from rock that was part of India (Himalaya) or Eurasia (southern Tibet), but also to some extent from where both across and along the Himalaya (or elsewhere in Asia) the rock was eroded. If single grain thermochronology can be coupled with the determination of provenance, then the exhumation rates as well as the patterns of erosion can be reconstructed. Currently the two syntaxes of Tibet erode more rapidly than the 2000-km long region between them [e.g., Burg et al., 1997; 1998; Sorkhabi et al., 1996; Zeitler, 1985; Zeitler et al., 2001]. Such a pattern fits well with hypotheses calling for flow within the crust [e.g., Clark, 2003; Royden, 1996; Royden et al., 1997] or within a viscous uppermost mantle [England and Houseman, 1986; Houseman and England, 1986, 1996], but need that pattern have always existed? Can we identify when plate tectonics ceased to describe adequately subduction and collision at the collision zone, and when flow within the Eurasian lithosphere began? Fingerprinting of sediment in the Indus and Bengal fans offers one, and perhaps the only, hope for answering these questions.

Drilling sands has historically posed a problem for scientific drilling because sands are not penetrated by piston cores and are unstable in open boreholes, resulting in collapse and loss of the hole. In addition rotary coring has resulted in low or zero core recovery. In older fan sections consolidated sandstones can be readily recovered by drilling, but at shallow levels care will be necessary in planning drilling sites. DSDP drilling on the upper Indus Fan at DSDP Site 222 did penetrate to 1300 mbsf with no loss of core, demonstrating that in the right places deep drilling is possible. In any case drilling with the riser will result in more borehole stability than has been typical in DSDP or ODP. In order to minimize risks during the initial phases of drilling high resolution 2D or even 3D seismic surveys will be needed to map channel-levees complexes. Sands are typically concentrated in the channel itself, while the levees are dominated by muddy facies, making them the more appropriate target. Industrial 3D seismic data now show that, like their modern equivalents, subsurface channel complexes meander across the fan in a fashion that is potentially problematic for drilling. Good site survey is needed to understand the geometries of the fan stratigraphy and the precise location of the sand bodies. Detailed pre-drilling geophysical investigation is needed if the expense of the drilling, whether riser or non-riser is to be justified. Nonetheless, in some areas good 2D data already exist, such as where channel-levee complexes have been mapped. Such data is being collected in other areas, so that practical drill sites can be selected for both shallow and deeper scientific drilling.

Collaboration with South Asian Scientists

Participants of the workshop recognized the importance of active scientific collaboration between the scientists of the IODP member countries and consortia, and the communities of ocean and earth scientists in South Asia. Participants strongly supported exploring possibilities of countries in the region becoming members of IODP. Not only does the local geological expertise play a key part in planning drilling, but also access to data sets and even territorial waters would be greatly enhanced by such a development.

Coordination with land-based activities

Much of what we know of climate change, both globally and regionally in South Asia, derives from records obtained from existing DSDP and ODP drill sites. Recently excellent work by Chinese scientists studying loess sequences has broadened our knowledge of the East Asian monsoon and Cenozoic climate change east of Tibet [e.g., An et al., 2001; Liu et al., 1985], but the virtually continuous records obtained at sea almost surely will continue to make the marine record of climate change the reference to which these and other records are compared.

The opposite applies to the growth of the Himalaya and Tibet; virtually everything known about them derives from studies made on land. Moreover, although drilling of the Indus, Bengal, and other fans will surely refine our understanding of how this region developed, the foundation on which this new information will be built will come from the land. In particular, the extreme topography of Asia seems to be the aspect of its geography that influences most both regional and global climate, but to date all quantitative constraints on paleo-altimetry of high terrain anywhere have derived from study of material on land. Sampling of material from the fans may allow hypotheses for topographic changes to be tested, but such data cannot, with current techniques at least, address quantitative changes in paleo-elevations. Thus, any attempt to relate environmental changes to the growth of the Tibetan Plateau will require study on land.

At present, the effect of Tibet's growth, upward and outward, on its surrounding environment looms as a challenge at the forefront of the earth sciences, not just IODP. Among four independent approaches to estimating paleo-altimetry - variations in oxygen isotopes precipitated from different heights [e.g., Garzione et al., 2000a; 2000b; Rowley et al., 2001], paleobotanical differences of leaf physiognomy [e.g., Forest et al., 1999; Gregory and Chase, 1992; Wolfe, 1993], pressure-dependent sizes of vesicles in lava flows [Sahagian and Maus, 1994; Sahagian et al., 2002], and variations in cosmogenic nuclide production with altitude [e.g., Brown et al., 1991] - the first two have been applied to Tibet [e.g., Garzione et al., 2000a, 2000b; Rowley et al., 2001; Spicer et al., 2003]. Although the localities sampled were a few hundred kilometers apart within southern Tibet, they yield similar results of

<1000 m change in elevation since 12–15 Ma; their agreement lends credence to both approaches. A thrust to extend the area covered by these techniques is in progress.

The outward growth of the plateau records itself by other means, including patterns of erosion and sedimentation on its flanks [e.g., Clift et al., 2002e; Fang et al., 2003; Métivier et al., 1998]. Major projects are underway to examine how the plateau has grown laterally, and the impact of such growth on evolving atmospheric circulation has not escaped the notice of climatologists [e.g., An et al., 2001] and land-based geologists, to say nothing of seismologists.

Twenty-five years ago, most of what was known of Tibet came from analyses of active faulting seen on satellite imagery and seismological studies of its earthquakes, both of which revealed pervasive normal and strike-slip faulting with overall east-west extension [e.g., Molnar and Tapponnier, 1975, 1978; Ni and York, 1978]. Although much of the Tibetan Plateau still has not been visited by geologists, few regions have seen such a surge of activity and interest [e.g., Yin and Harrison, 2000]. We now know that much of the plateau has undergone north-south shortening by thrust faulting and folding before the normal faulting began [e.g., Chang et al., 1986; Coward et al., 1988; Dewey et al., 1988]. Geophysically, the crust and upper mantle have received as much attention as any region; the enormous flat plateau camouflages lateral variation in upper mantle structure as large as anywhere on Earth [e.g., Molnar, 1988; Owens and Zandt, 1997; Tilman et al., 2003].

Similarly, geological and geophysical studies of the Himalaya have accelerated for 20 years. Modern equipment and techniques have in many cases found their best testing grounds to be in the Himalaya. For instance, the ion probe has revealed varying crystallization ages on micron scales [Harrison et al., 1995a]. The Himalaya arguably offer the best laboratory for the study of anatectic melting, and the tricks that remelting of ancient rock can play. The demonstration of a continuous reflector marking the top surface of Indian crust as it slides beneath the Himalaya [Zhao et al., 1993] is arguably deep seismic reflection profiling's most important result. Applications of thermochronology to rapidly exhumed Himalayan rock and geochemical tracers to modern sediment have revealed some of the world's highest erosion rates [Burg et al., 1997, 1998; Clift et al., submitted; Galy and France-Lanord, 2001; Vance et al., 2003; Zeitler, 1985], and it seems safe to say that what is known, to say nothing of understood, about erosion of the Himalaya is just the tip of the iceberg.

Finally, active programs to drill both ice [Thompson et al., 1989, 1997] and sedimentary records [Fujii and Sakai, 2002; Sakai, 2001 and accompanying papers; Sakai et al., 2002] to study late Quaternary climate change are rapidly growing and will surely play a crucial role in understanding how global and local processes are linked.

Thus, it is imperative that any drilling program of the fans not only be cognizant of ongoing studies on land, but also reach out to scientists working there. IODP should use the growing understanding of both the tectonic and climatic development of southern and eastern Asia to expand its role in linking multi-disciplinary earth sciences.

Summary

Drilling on the Indian Ocean submarine fans has for a long time been considered difficult or impossible because of limitations in drilling technology, despite important advances based on earlier shallow-penetration drilling. The advent of IODP with the new enhanced riser drilling capability now opens new opportunities for deep penetration at a time when the science of climate-tectonic interactions has reached the point where workable hypotheses can be tested. Addressing how the solid earth and the enveloping atmospheres and oceans are coupled has been highlighted as a scientific goal for IODP. The Indian Ocean remains the classic area to study such interactions because of the proposed coupling between the growth of the Himalaya and Tibet and the strengthening of the Asian monsoon. Land-based studies have now largely exhausted the terrestrial sedimentary record, requiring offshore drilling of the more complete marine stratigraphy if the long-term erosion history of the Himalaya is to be reconstructed.

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Scientific Drilling of the Indian Ocean Submarine Fans

Program

23rd July 2003

Day 1,

Summary of Current Knowledge of the Submarine Fans

8:30 am, Introduction, statement of objectives – Clift / Molnar

8:45 am, The Bengal Fan: morphology, geometry, stratigraphy, history and processes. Curray

9:30 am, The marine sedimentary record in the Bay of Bengal and its potential for future drilling - seismic data, drilling concepts and proposals Spiess

10:15 Break

10:45 am, Ganges-Brahmaputra since the last interstade: Records of the deltaic gateway and a source-to-sink view of the dispersal system Goodbred

11.30 am, The Erosional Record of Himalaya-Karakoram Erosion Preserved in the Indus Fan, Arabian Sea Clift

12:15 pm Discussion

12:30–1:45 Lunch

Summary of Current Knowledge of Climate and Paleoceanographic Evolution

1:45 pm, The Physical Basis for a Coupled Ocean-Atmosphere Monsoon System. Webster

2:45 pm, Orbital-scale monsoon variability over the past 3 million years Clemens

3:30 pm, Break

3:45 pm, The Geologic Record of the Indian Southwest Monsoon. Quade

4:30–5:00 pm Discussion

5:00–7:00 pm Reception

24th July 2003

Day 2

Summary of Current Knowledge of the Tectonic Evolution of Asia

8:30 pm, Ten untenable ways to make the Himalaya — Harrison

9:15 am, Modern and ancient chemical fluxes from the Himalaya - what might they tell about tectonic history and processes — Derry

10:00 am am, Tectonic Evolution of Tibet — Royden

10:45 am, break

Integrated Ocean Drilling Program Overview

11:15 am, IODP Planning - Where do we stand? — Austin

11:45 am, Drilling capabilities within the IODP — Fox

12:15 pm, Operation of the new drilling vessel CHIKYU towards the attainment of the scientific goal — Aoike

12:30 pm Paleo-Kathmandu Lake Drilling Project — Sakai

12:50 pm Lunch

2:15 pm

Definition of Scientific Objectives for IODP Operations

Group discussion of scientific objectives for scientific drilling. Three thematic groups met separately

A) Fan stratigraphy (Discussion chair - Speiss)

B) Paleo-climate and the Monsoon (Discussion chair - Anderson)

C) Continent tectonics (Discussion chair - Zeitler)

25th July 2003

Day 3

Joint meeting to present findings and recommendations of the previous afternoon discussion. Full group discussion of the key objective, limitations and requisites for fan drilling in the Indian Ocean.

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