Asian Monsoon and Cenozoic Tectonic History:

Report of the Detailed Planning Group

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A. Introduction

The Earth's climate has varied through geological time as a result of both external, orbital processes and internal climatic feedbacks, as well as the positions of continents, growth of mountains and oceanic gateway openings/closures controlled by tectonic forces. Typically these processes act over time spans of less than 10^5 yrs and more than 10^6 yrs respectively. While significant progress has been made in linking climate change to solar insolation driven by perturbations in the Earth's orbit, links between tectonic processes and climate have remained more conjectural due to the more complex forcing as well as from a lack of long duration geological records. The archetypal example of climate-tectonic coupling is the proposed link between the intensity of the Asian monsoon and the uplift history of the Tibetan Plateau (Prell and Kutzbach, 1992; Molnar et al., 1993; An et al., 2001). Although atmospheric scientists have demonstrated the importance of a wide, high Tibetan Plateau in controlling the climate in South and East Asia (for example Hahn and Manabe, 1975; Webster et al., 1998) the detailed co-variation of monsoon intensity and Tibetan elevation over geological time has yet to be documented. This lack of a causative relationship reflects, in part the controversial uplift history of Tibet (Harris, 2006), and the poorly known Cenozoic evolution of the monsoon beyond the past few million years. A long-term reconstruction of mountain building and associated erosion, and monsoon activity is key to testing the proposed links between climate and Tibetan evolution, and to show that this uplift, rather than other possible triggers, is dominant. For example, alternative models propose that the retreat of shallow seas from Central Asia is a crucial boundary condition influence (Ramstein et al., 1997), while others have argued that strengthening of the monsoon is linked to opening of the South China Sea (Zhang et al., 2007a) and/or to formation of the Western Pacific Warm Pool (Li et al., 2006).

Understanding the controls on monsoon strength is important not only to science but also to society, given the large number of people - nearly half of Earth's population - who live within the influence of the modern monsoon and the economic importance of monsoonal regions to the global economy. Furthermore, the monsoon has been suggested to have a wider influence on global climate (Wang et al., 2003), and may even control the tectonic evolution of mountains in Asia, via its effect on continental erosion. Plate tectonic processes have long been recognized to affect climate but climate-driven erosion can also influence tectonism and the architecture of mountain belts (Hodges et al., 2004; Thiede et al., 2004; Wobus et al., 2005). Indeed, orogenesis and climate change may feed back on each other. In order to understand how these processes interact, detailed records of climate and continental erosion must be developed so that linkages can be tested and quantified.

Chemical weathering of the Himalaya, which is thought to have drawn down atmospheric CO_2, may have affected global climate since the Eocene (Raymo and Ruddiman, 1992). Initial Ocean Drilling Program (ODP) studies from the Indian Ocean in the late 1980s emphasized a climate change event at 8 Ma as being the time of initial monsoon intensification (Quade et al., 1989; Kroon et al., 1991; Prell et al., 1992). While this interval of climate change is well documented, the cored record in the Arabian Sea off Oman is only ~16 m.y. long (e.g., ODP Site 730). In contrast, India-Asia collision dates back to around 50 Ma (Garzanti et al., 1987; Beck et al., 1995; Rowley, 1996) and the Greater Himalaya themselves are at least 22 Ma old (Searle, 1986; Hodges, 2000; Godin et al., 2006). Very few records of monsoon intensity extend as far back as the major known tectonic events, making convincing testing of earlier climate-tectonic coupling impossible. Indeed, the coupling of the Indian with the East and South Asian monsoons over long periods of time is unclear, as might be anticipated by some numerical models (Prell and Kutzbach, 1992; Kitoh, 2004).

The India-Asia continental collision likely began some time during the Eocene (Windley, 1993), along with a several-fold increase in sediment flux to the East Asian basins (Clift, 2006), closure of the Paratethys (Ramstein, 1997) and a drastic decrease in pCO_2 and global cooling (DeConto and Pollard, 2003; Pagani, et al., 2005). GeoCarb type geochemical cycle modelling suggests that approximately 70% of the late Eocene/early Oligocene CO_2 decrease could be explained by increases in uplift-related chemical weathering rate and organic carbon burial rate (Tajika, 1998). At present, the rivers draining the Himalaya-Tibet region deliver ca. 28% of the global sediment flux to the ocean, and these high mountain rivers are characterized by higher sediment yield by one to two orders of magnitude compared to the low land rivers (Milliman and Syvitski, 1997). Hence, uplift of Himalaya-Tibetan Plateau and consequent enhancement of continental erosion may have increased global sediment yield by 20 to 30%. Scientific ocean drilling and the recovery of sediment as old as late Eocene from the Indian/East Asian seas is the only direct way to test the possible relations among mountain uplift, erosion, sea level change, sediment deposition, carbon burial, chemical weathering and CO_2 drawdown.

This Detailed Planning Group (DPG, Appendix 1) examined the existing proposals submitted to IODP and assessed how they might be used to make a significant advance in monsoon science before the end of the current program. In particular, we considered Proposal 552 for the Bengal Fan, Proposal 595 for the Indus Fan/Murray Ridge, Proposal 618 for the Vietnam margin/South China Sea and Proposal 683 for the East China Sea. Figure 1 shows the distribution of the proposed drill sites, together with those from previous cruises by ODP and the Deep Sea Drilling Project (DSDP) that have been used to constrain the temporal evolution of the monsoon. Together these proposals cover both South and East Asian systems and are designed to

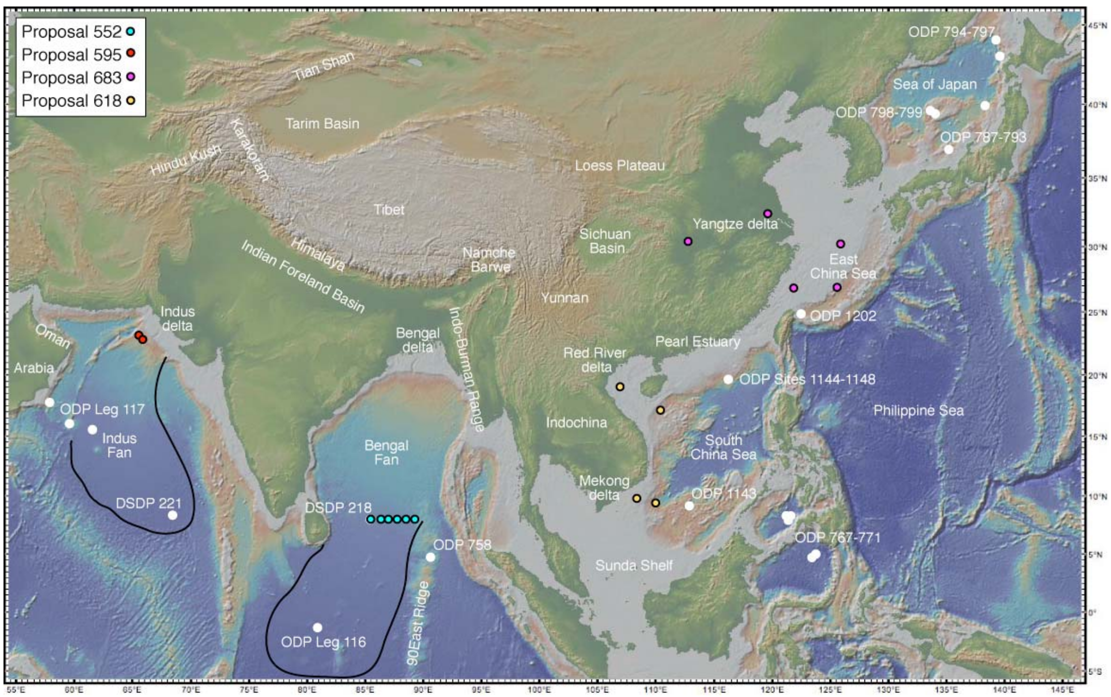

Figure 1. Shaded bathymetric and topographic map showing the location of the proposed drill sites considered here, together with existing drill sites and the major geographic features mentioned in this report.

reconstruct the long-term evolution of sedimentation and paleoceanography on the Asian margin and thus monsoon intensity. The DPG did not consider proposals 549 and 605, which target onset and evolution of the millennial scale variability of the monsoon in the Arabian Sea and Sea of Japan respectively.

Existing data

Many marine and terrestrial records now show that summer monsoon intensity has decreased since 3–4 Ma (An et al., 2001). This change is often linked to the onset of Northern Hemispheric Glaciation (NHG), yet this association has yet to be properly demonstrated. At ODP Site 885/886 in the North Pacific dust blown by westerlies accumulates at an increased rate after 4 Ma (Rea, 1994; Rea et al., 1998; Pettke et al., 2000), as does magnetic susceptibility in the Loess Plateau (Sun et al., 2006), somewhat predating the onset of NHG at around 2.6 Ma (Shackleton and Opdyke, 1977; Tiedemann et al., 1999). Similar poor fits are noted for the monsoon upwelling records in the Arabian Sea, suggesting that other controls, such as Pliocene uplift in northern Tibet (Zheng et al., 2000) or the Tian Shan have also played an important role in controlling climate.

A number of lines of evidence have focused on 8 Ma as being a crucial period of intensification. Kroon et al. (1991) and Prell et al. (1992) used various paleoceanographic proxies from the Oman margin to show that upwelling strengthened there around 8 Ma (Figure 2) and inferred that because upwelling here is presently linked to the summer monsoon winds that these also intensified at that time. The notion of major Asian climate change at this time was supported by changes in carbon isotopes onshore in the Himalayan foreland basin (Quade et al., 1989) that were driven by changes in flora from C3 to C4 type. In addition, dust transported by winds is seen to accelerate in its accumulation both in the Chinese Loess Plateau (An et al., 2001) and in the North Pacific (Rea et al., 1998), an event associated with monsoon enhancement by Sun and Wang (2005) (Figure 2). Further evidence from the South China Sea is also consistent with increased upwelling under monsoon influence at around 8 Ma (Li et al., 2005).

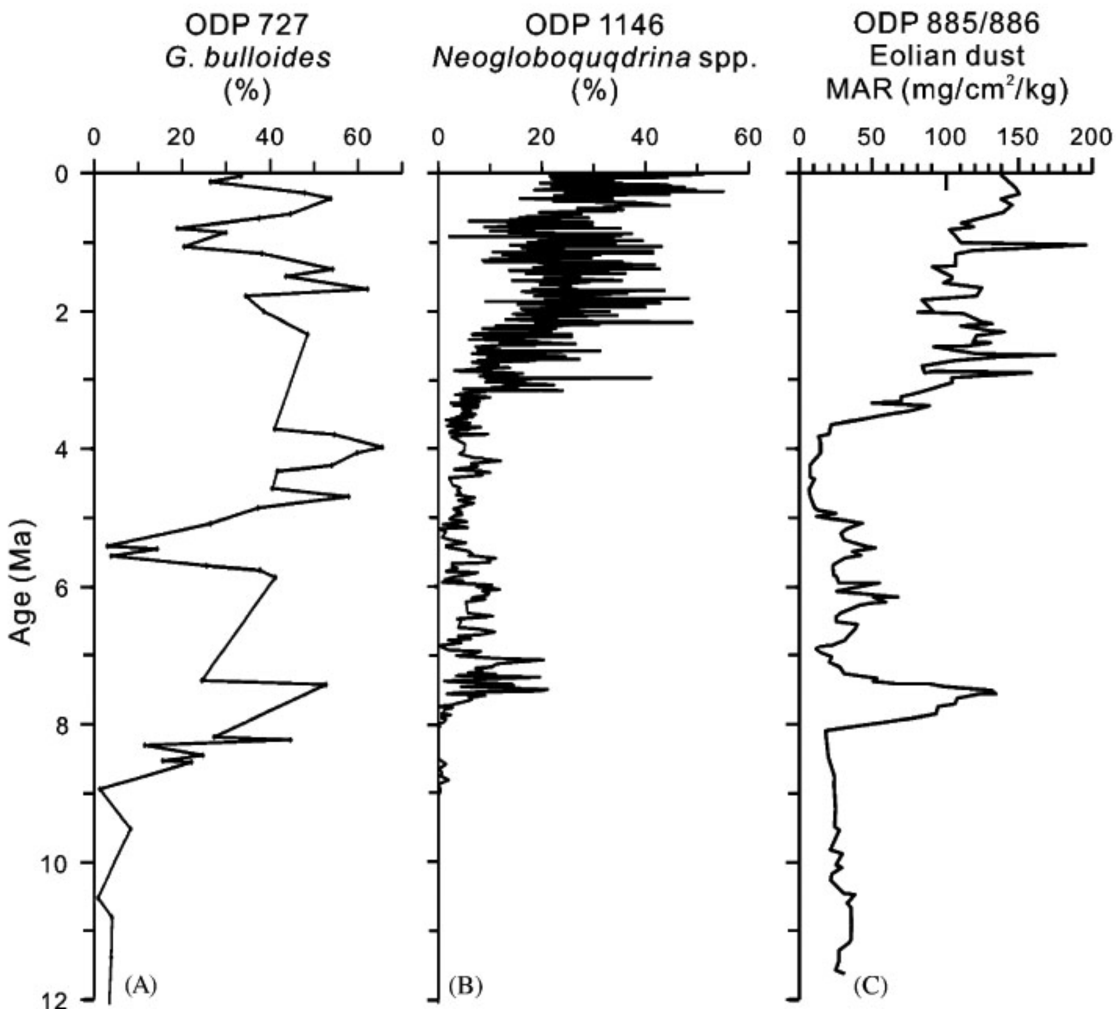

Figure 2. Summary figure from Sun and Wang (2005) showing variability in three separate monsoon proxies across Asia: (A) the upwelling G. Bulloides record from Oman (Kroon et al., 1991), (B) another upwelling-related foraminifer (Neogloboquadrina) from the South China Sea (Li et al., 2005) and (C) dust flux to the North Pacific (Rea et al., 1998). Note that none of these records extends beyond 12 Ma here.

While the late Miocene-Recent record is relatively comprehensive, older reconstructions are more patchy. In the Bay of Bengal changes in clay mineralogy and Sr isotope character at ODP Sites 717/718 were used to identify an 8 Ma change in continental weathering (Derry and France-Lanord, 1996), but provide only a sketchy, albeit apparently unchanging image of monsoon strength between 17 Ma (base of the drilled section) and ca. 10 Ma. Further east drilling by ODP Leg 184 penetrated to the Oligocene in the South China Sea and attempts have been made to use the evolving clay mineral suites to identify earlier phases of monsoon strengthening, most notably at ~15 Ma (Clift et al., 2002) and evidence also is pointing to a change at around 23 Ma (Clift, 2006; Jia et al., 2003). Unfortunately, the monsoon records from the Arabian Sea are much shorter and it is not possible with existing record to correlate the East and South monsoon prior to around 17 Ma.

Proposed expeditions

Unlike earlier monsoon-oriented cruises (ODP Legs 117 and 184) the new proposals considered here are mostly designed to look at the varying compositions and volumes of clastic sediment on the Asian margins rather than at oceanic paleoproductivity and upwelling. In many cases the objectives are three-fold: (1) to use the varying chemistry and mineralogy of the sediments to reconstruct changing continental provenance and weathering intensities, which are largely governed by the monsoon strength, glacial activity, and sea level changes; (2) to use the organic carbon and other biogenic components of the sediments to reconstruct past oceanic conditions (e.g. temperature, salinity) and productivity linked to the monsoon; and (3) to assess the erosional impact of the changing monsoon precipitation on the mountains. This latter task is achieved by constraining the sources and volumes of sediment estimated from regional seismic stratigraphy and dated by drilling, combined with thermochronology work on the detrital minerals that allows source exhumation rates to be estimated.

Proposal 595 targets the Indus Fan and the erosional/weathering history of the western Himalaya. Drilling is designed to penetrate to the fan base (presumed Eocene) at around 3.6 km depth using the sequences uplifted along the Murray Ridge and which are not buried under the Neogene as in the central Arabian Sea. Proposal 552 addresses the clastic sedimentation history in the Bay of Bengal as a way to reconstruct erosion in the eastern and central Himalaya where the South Asian monsoon is strongest. Again the drilling targets the base of the fan section where it is uplifted along the NinetyEast Ridge. A major goal is to understand when the Greater Himalaya began to form and how that relates to monsoon intensification. Proposal 618 is designed to core the sediments delivered by the Mekong and Red Rivers along the margin of Vietnam. This proposal aims to examine changing continental weathering in Indochina and SE Tibet, but also to test models for drainage evolution in East Asia. Brookfield (1998) has suggested that progressive uplift of Tibet has forced the re-organization of these rivers, by transferring headwater drainage from one to another. In particular, the Red River appears to have lost drainage to the Yangtze (Clark et al., 2004; Figure 3). Thus reconstructing the history of river evolution can help to understand the timing and patterns of Tibetan uplift and is also essential to using sediment budgets in any one delta as a measure of monsoon driven erosion intensity. Because this drainage evolution impacts the Yarlung Tsangpo (the headwaters of the Brahamaputra), this influence extends also to the Bengal Fan. Finally, Proposal 683 aims to understand the sediment flux from Tibet into the East China Sea. This project involves linked onshore drilling in eastern China (Subei Basin) as well as offshore. Proposal 683 will date the onset of flow from the Yangtze River (captured away from the Red River) and provide information on the climate history of eastern China and the incision of gorges in Sichuan and Yunnan on the flanks for the Tibetan Plateau. Although some workers have suggested a relatively young (Pleistocene) age to the river initiation (Wang, 2004) this remains controversial.

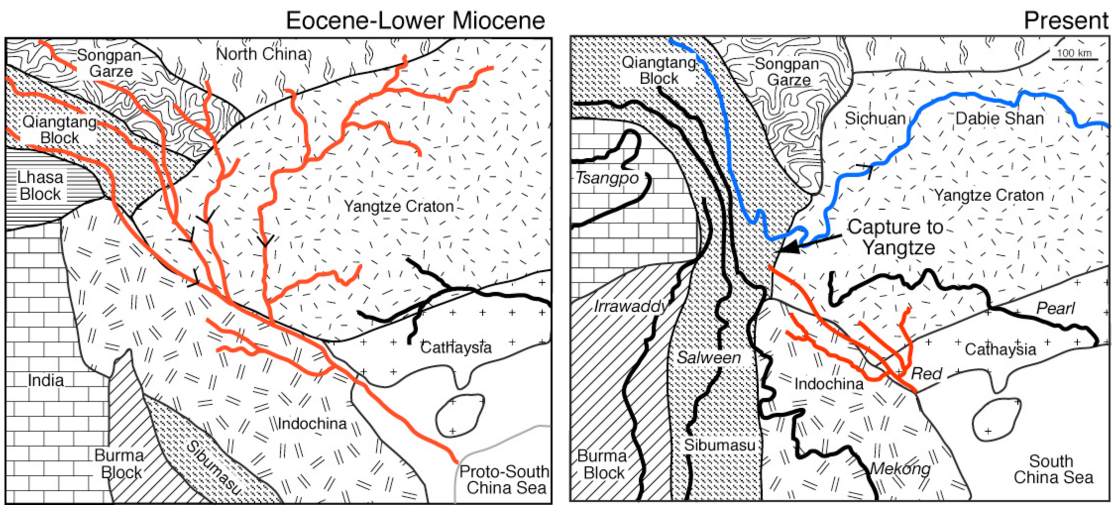

Figure 3. Proposed river evolution in SE Tibet during the Cenozoic, modified from Clark et al. (2004). The fact that the river headwaters start in different tectonic blocks of Tibet provides a method of identifying capture events in the delta/fan sediment by provenance methods.

B. Proxies

Uplift and monsoon proxies

The interpretation of past tectonic uplift, erosion, and monsoon activity using geologic proxies is both complex and multi-faceted. Simply stated, no single or even small set of proxies uniquely identifies and quantifies past tectonic and/or monsoon activity. The reason for this nonuniqueness is that both tectonic activity and monsoon circulation have a wide variety of impacts and signatures on the erosional, depositional and environmental systems. For example, monsoon strengthening might be characterized by increased erosion and lowered salinities in one area and stronger upwelling and increased dust flux in another. In the marine realm, monsoon circulation has the capability of changing near surface environments (temperature, mixed layer depth, salinity, productivity, etc.) whereas terrestrial manifestations of monsoonal climate might be observed as changes in weathering products, vegetation and organic biomarkers.

Proxies relevant to the Asian Monsoon and Cenozoic Tectonic History DPG can be broadly divided into three major areas: (1) Proxies that reflect tectonics through indicators of source rock areas, exhumation rates, and age structure; (2) Proxies that reflect changes in the terrestrial environment that could be attributed to monsoon activity; and (3) Proxies that reflect changes in the marine environment that can be attributed to changes in monsoon circulation. Understanding the potential coupling between tectonics and monsoon climate will require the detailed intercomparison of time series of tectonic, terrestrial, and marine proxies. Identifying the internally consistent responses between tectonic, terrestrial, and marine processes, guided by a framework of coupled climate model sensitivity simulations, is the most likely solution to assessing the tectonic-climate connections. The question of causation will remain hypothesis driven. Does uplift cause stronger monsoons or does monsoon-related erosion result in tectonic uplift? If tectonic and monsoon changes/responses are tightly coupled, as might be expected, the lead-lag between the causes and responses are unlikely to be resolved well enough to distinguish causation. Hence, the lack of co-variation between tectonic, terrestrial, and marine indicators of change would also provide insight into the nature of coupling among these systems.

The strategy to sorting out the tectonic-climate question is therefore to recover continuous sections of marine sediments over key intervals of known or hypothesized boundary conditions and to compare the tectonic proxies with those of the terrestrial and marine monsoon proxies. The sites proposed in the Bay Bengal and the East Asian seas are in the appropriate locations and cover the critical time intervals to provide the materials for generation of the tectonic and monsoon proxies that will contribute to our understanding on how these two complex systems are related.

Below, we summarize many, but not all, of the proxies that could be used in marine sediments to document the tectonic, terrestrial, and marine changes that are related to the connections between tectonics and monsoon climates.

Proxies for the Sources of Clastic Sediment

Petrologic and geochemical data can be used to constrain the continental sources of clastic sediments, the intensity of chemical alteration, and the rate that source areas were being exhumed. Although no single measurement can address all these factors, a combination of geochemical measurements can simultaneously constrain these various processes.

<u>Bulk Nd isotope analysis</u> allows the calculation of the average age of crustal genesis and is an integrated signal that is relatively insensitive to sedimentary processes. Thus it is a relatively simple and reliable measure of average provenance.

<u>Zircon U-Pb ages</u>. Zircon is extremely robust during weathering as well as metamorphism and even melting. Because the closure temperatures are in excess of 750°C, U-Pb ages in zircon can be taken to approximate the crystallization age. The age of crustal genesis differs across the Indus Suture Zone and between the Lesser and Greater Himalaya. It also allows the flux from Indochina, Yangtze Craton, Tibet and the Tsangpo Suture Zone to be distinguished.

<u>Hf isotopes in dated zircon grains.</u> Hf isotopes in zircon grains provide information on the pre-history of the zircon's host that is a measure of the average time of residence in the continental crust prior to formation of the zircon. The methods for measuring Hf in zircon are improving such that it is practical to measure Hf isotopes on all the dated

zircons. The potential source regions are known to be heterogeneous with respect to Hf over large-scale tectonic units.

Pb isotopes in K-feldspar grains. Because feldspars are susceptible to weathering as well as metamorphism, they tend to be derived from the crystalline basement. Pb isotopes in K-feldspars approximate the initial Pb isotope compositions of its source host because the parents, U and Th are excluded from its structure. Pb isotope values in single grain K-feldspars are especially good for separating input from young arc units from ancient cratonic crust.

Petrology and chemistry of mineral grains. Basic petrographic analysis constrains the mineralogy of the source and can identify specific heavy mineral suites that have specific origins, such as ophiolitic, high-pressure terrains, volcanic, cratonic, and recycled sediments. Probe analysis of certain minerals with a range of natural compositions (e.g., amphiboles) also allows identification of populations unique to a given source. Both the petrology and chemistry of potential source areas are well enough known to allow the geochemical fingerprint of specific source areas to be identified in the cored sediments

Proxies for estimation of exhumation rates

The comparison of radiometric cooling ages with depositional ages allows the rates of exhumation of the source terrains to be determined. Comparison of cooling ages of detrital grains with the known ages from different source terrains also allows the provenance of the grains to be constrained. A variety of minerals and radionuclide systems can be used in clastic sediments to estimate the closure ages. The mass accumulation rate of terrigenous sediment is a direct function of the amount of erosion on land.

U-Pb in zircon (and Ti thermometry) provides the crystallization age, and will generally estimate the timing of major tectonothermal events within a drainage basin. Ti thermometry gives an estimate of the crystallization temperature (depth in the crust)

Ar-Ar dating in hornblende, muscovite, biotite, and K-feldspar provides records of crystallization or cooling rates from temperatures of 450°C to 200°C

Fission track dating in zircon and apatite constrains the timing of cooling from temperatures of 220°C to 100°C.

(U-Th)/He dating in zircon and apatite provides crystallization or cooling temperatures from 180°C through 60°C. Given the different indicators of crystallization temperature, composition, and age, the combination of several mineral systems and geochemical measurements is sufficient to identify specific source areas and exhumation rates in the clastic sediments to be recovered by the proposed drilling.

Proxies for the Terrestrial Response to Monsoon Strength

In the terrestrial environment, monsoon proxies have focused on weathering, soil formation, vegetative cover, and the sedimentary character of the land surface that are thought to be related to the temperature, seasonality and moisture changes associated with monsoons.

Clay mineralogy can reflect changes in climate (temperature and moisture) and the direction of wind transport but also support other evidence for provenance, with greater chlorite and illite contributions from rapidly exhuming metamorphic blocks. In addition the δD, $\delta^{18}O$ of pedogenic clays can potentially quantify the changes in rainfall and temperature. Magnetic characteristics, such as the ARM/SIRM ratio, in sediments can also be used as a sensitive measure of soil formation and weathering.

Bulk geochemistry reflects the loss or gain of chemically distinctive sources, such as ophiolite belts; carbonate platforms, granite plutons, etc. from a drainage. A careful assessment of elemental ratios that are sensitive to sedimentary processes will help to identify chemical alteration in the weathering environment.

Specific pollen assemblages, charcoal, and compound-specific organic geochemical biomarkers reflect the vegetation types in equilibrium with the terrestrial climate, the precipitation and temperature regimes, and patterns of terrestrial transport. New organic geochemical proxies may also provide information on the changes in vegetation, as well as the hydrology of the terrestrial environment.

Sedimentology; basic sedimentology can provide insight to loess sediments where modal grain size reflect the strength/capacity of wind transport, source regions, and land surface state.

Proxies for the Marine Response to Monsoon Strength

The near-surface marine environment responds to the solar heating, winds, precipitation, and convergence/divergence of water masses. All of these atmospheric and oceanic variables are affected by the strength of the monsoon circulation. Hence, a variety of biotic, isotopic, and geochemical proxies can be used to reconstruct environmental changes that might be attributed to changes in the monsoon system.

Biotic assemblages (planktonic and benthic foraminifera, radiolaria, diatoms, nannofossils) reflect changes in the near surface environment forced by monsoon winds, temperature, and precipitation. Marine responses include changes in temperature, salinity, depth of mixed layer and thermocline, productivity and floral/faunal assemblages.

$\delta^{18}O$ and $\delta^{13}C$ of planktonic and benthic foraminifera reflect ice volume variations, which are needed for detailed stratigraphy, and near surface temperature, salinity, and productivity gradients along with the vertical structure of the water column.

Organic geochemical proxies (organic carbon % and flux, opal % and flux, ^{15}N, ^{13}C in near-surface dwelling planktonic foraminifera, Alkenone SST, TEX86, and compound specific biomarkers) reflect the temperature, productivity, nutrient utilization, and water column structure that can be forced by changes in winds, mixing, and precipitation.

Inorganic Geochemical proxies (i.e.: Mg/Ca, Ba/Al, Cd/Ca) reflect a variety of temperature and productivity responses related to monsoon circulation.

C. Modeling

Overview

General circulation models (GCMs) and coupled climate system models (CSMs) enable hypotheses based on paleoenvironmental inference to be evaluated in a physically plausible and self-consistent framework. GCM modeling has historically played an important role in the uplift-monsoon hypothesis and CSMs continue to give insights into the impact of orography on monsoon processes. At this time, largely driven by improvements in computational power and climate modeling associated with the Intergovernmental Panel on Climate Change (IPCC) reports, a powerful modeling toolbox is available for understanding monsoon dynamics and for improved, multiparameter comparison with proxy records. Here we summarize lessons learned from prior work, show a feasibility study for how current state-of-the-art models might help the DPG objectives, and finally make a series of recommendations of how to move ahead.

Modeling of the effect of orographic forcing on climate has a long and impressive history, both from the point of view of climate dynamics theory (Charney and Eliassen, 1949; Manabe and Terpstra, 1974) and from the applied paleoclimate perspective (Kutzbach, 1981; Kutzbach and Guetter, 1986; Kutzbach et al., 1989; Rind and Chandler, 1991). This pioneering showed that emplacement of a significant orogen at the margins of the subtropics would have large local and globally teleconnected climate responses. For the Indian-Asian monsoon region, the large local responses include a strong cross-equatorial flow of water vapor, intensive upwelling along the eastern coasts of Africa and Arabia that is associated with the monsoonal southwesterlies, a massive increase in summer precipitation maxima, and a distinct seasonal alteration of these phenomena between hemispheres. The teleconnected impacts of orographic forcing are communicated by planetary wave perturbations that potentially affect the major quasi-stationary high and low pressure systems in the Pacific and Atlantic Oceans, altering temperatures, winds, storm tracks, throughout the Northern Hemisphere.

The Indian-Asian monsoon is a complex and multifaceted phenomenon that can be lumped together and attributed to a large-scale dynamical, balanced flow or split into regional monsoons with more local causes and sensitivities. From a theoretical point of view monsoons arise when there is a strong violation of a balance criterion, e.g. a critical meridional entropy gradient, which engenders a large scale flow to return the system to balance (Plumb and Hou, 1992; Emanuel, 1995). Anomalous sensible heating, for example of the Tibetan Plateau, drives a strong meridional circulation, which in turn transports latent heat, greatly enhancing the overturning circulation (Webster et al., 1998; Rodwell and Hoskins, 2001). Within this conceptual model, regional scale and local scale forcings and response become important. For our purposes distinguishing between the Indian and the East Asian monsoon (See Figure 4) may be helpful because they may reflect conditions in the Indian versus Pacific oceans (Wang et al., 2003), despite having gross dynamical similarities and sensitivities in common. Hence, proxy records from both the Indian Ocean and South China and east Asian Seas will be needed in order to deconvolve the forcing and response relationships in these two areas.

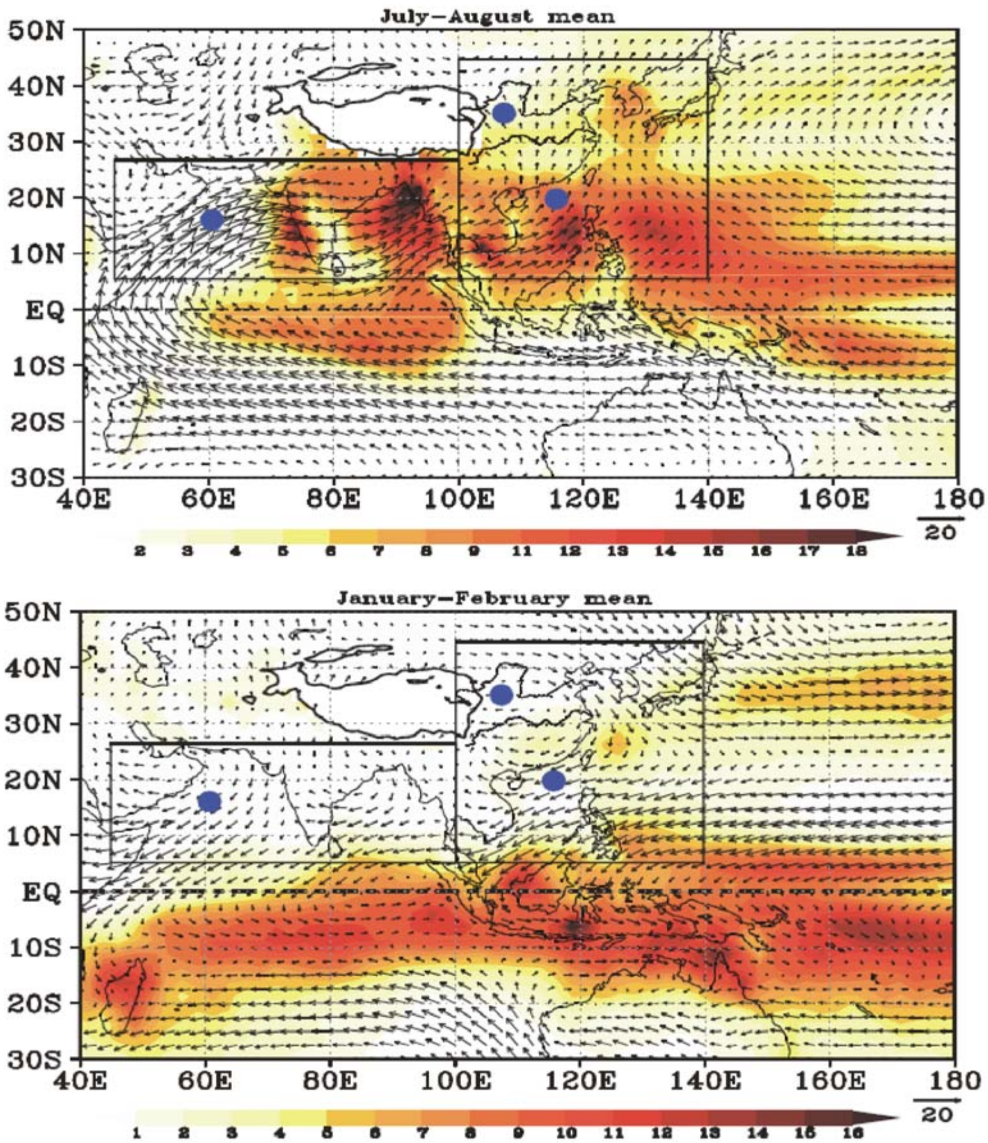

Figure 4. Monsoon winds (arrows; ms-1), precipitation (shading; mmd-1), and site locations (dots). ODP Site 722 in the Arabian Sea, ODP Site 1146 in the South China Sea, and stacked records from Lingtai and Zhaojiachuan in the south central Chinese Loess Plateau. Boxes delineate Indian and East Asian monsoon sectors. Climatological summer and winter mean precipitation (CMAP, 1979-2000) and wind patterns (NCEP/NCAR reanalysis, 1951-2000) are reproduced from Wang et al., (Wang et al., 2003) with permission from Elsevier.

As collected in *Tectonic Uplift and Climate Change* (ed. Ruddiman, 1997) paleoclimate simulations have yielded a variety of important insights into the possible affects of orographic changes. Broccoli and Manabe (1997) used a GCM to conclude that a world with no mountains was significantly moister in midlatitudes than a world with modern mountains. Rind et al. (1997) using a low-resolution coupled model found that lower topography in Southern Asia (300 meters) produced a strong anticyclonic flow in winter and stronger cyclonic flow in summer over the Tibetan Plateau in agreement with previous work. The world was found to be slightly cooler without the plateau, and midlatitude northern interiors were somewhat moister. Interestingly, ocean heat transport was somewhat decreased from the modern state without the plateau. Kutzbach et al. (1997) used NCAR's CCM1 model coupled to a 50-m thick mixed layer "slab" ocean and a bucket hydrology scheme to explore the importance of changing elevation globally and also changing pCO_2. In general, their study indicated cooling with uplift, and rainout and surface moistening on the upstream side of uplifted mountains and drying on the downstream side.

All of these previous studies should be considered as sensitivity studies because none of them used high-resolution topography of the Tibetan/Himalayan orogen or other realistic boundary conditions such as changed ocean gateways or interactive vegetation. Subsequent work has built upon those results to incorporate more realistic elements of the likely evolution of paleogeographic boundary conditions through the mid-to-late Cenozoic.

More recent sophisticated modeling studies over the past decade have generally confirmed the apparent relationship between enhanced topography and the monsoon circulation

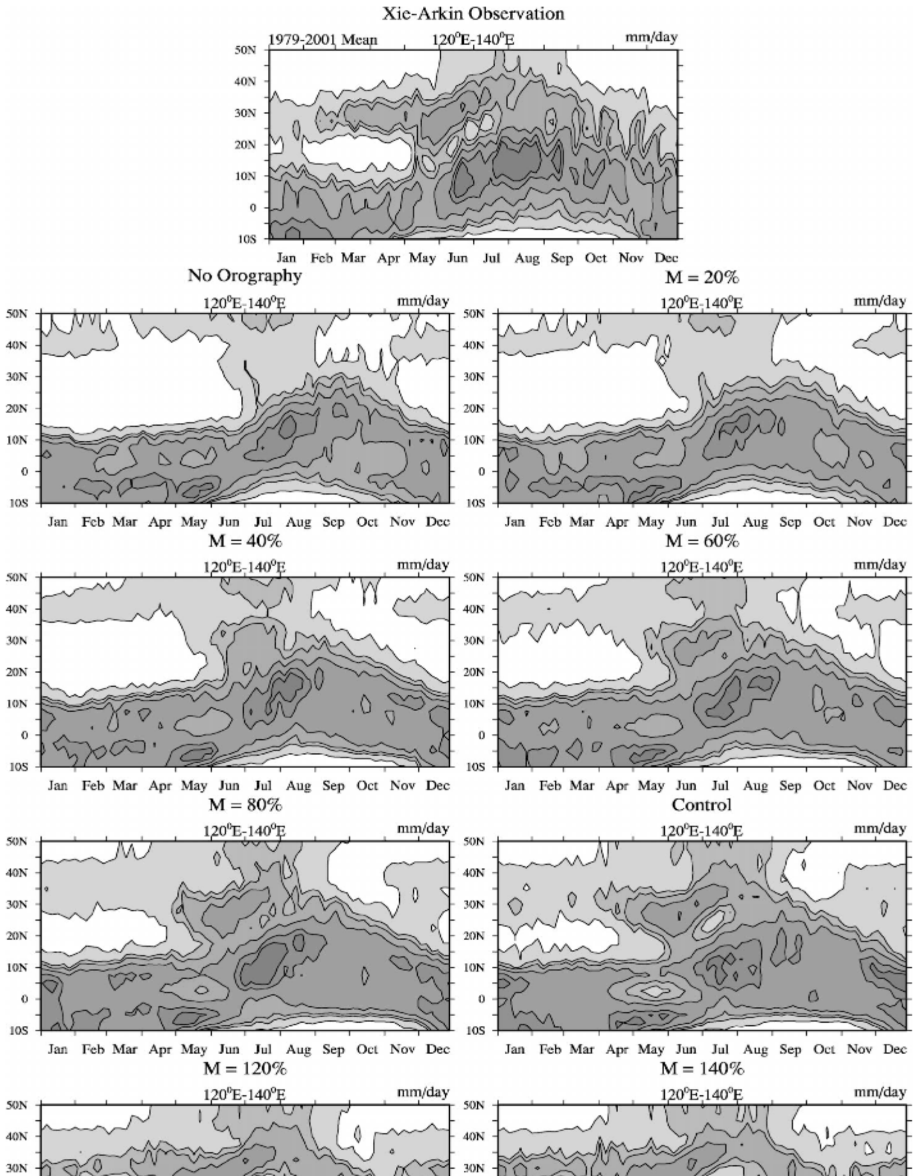

Figure 5. Time-latitude sections of the climatological pentad mean precipitation averaged for 120°E-140°E for the observations and the M0 (no topography run), M2 (20%), M4 (40%), M6 (60%), M8 (80%), and M10 (control run), M12 (120%), and M14 (140%) runs. The observations are the 23-year averages for 1979-2001 from Xie and Arkin (1997). Figure from Kitoh (2004).

(Figure 5). For instance the retreat of the Paratethyan epicontinental sea and the expansion of the East and South China seas may have played a role in the nature of the Indian and Asian monsoons respectively (Ramstein et al., 1997; Vavrus and Kutzbach, 2002; Kitoh, 2004; Zhang et al., 2007a, 2007b).

While these studies have explored explicitly the role of changing orography on the monsoonal climate, other paleoclimate modeling has addressed the more distant geological past and has routinely changed global boundary conditions. These include fully coupled simulations for the Jurassic (Kiehl and Shields, 2005), Cretaceous (Markwick and Valdes, 2004; Otto-Bliesner, et al., 2002; Sewall et al., 2007), and Eocene (Huber and Nof, 2006). In Eocene simulations, even without a Tibetan Plateau a monsoon-like circulation exists but does not have the strong onshore and cross-equatorial flows associated with the modern monsoon. As preparation for this DPG report, Huber used a fully coupled GCM to perform a simple sensitivity study by doubling the height of the low Asian Eocene paleotopography in his simulations. Peak elevations doubled from 2000 m to 4000 m whereas mean elevations increased from 500 to 1000m. With Eocene boundary conditions aspects of the canonical response remain the same: cooling over the uplifted region (Figure 6, top left), a large stationary wave response emanating from the plateau and extending into North America (Figure 6, top right), and a large increase in precipitation in summer in the regions with strongest relief, with a rain shadow behind it (Figure 6, lower left). Some important local responses are different from similar studies with modern boundary conditions, such as a warming behind the uplifted mountains, which would increase local evaporation (this is associated with increase advection off of the northern extension of

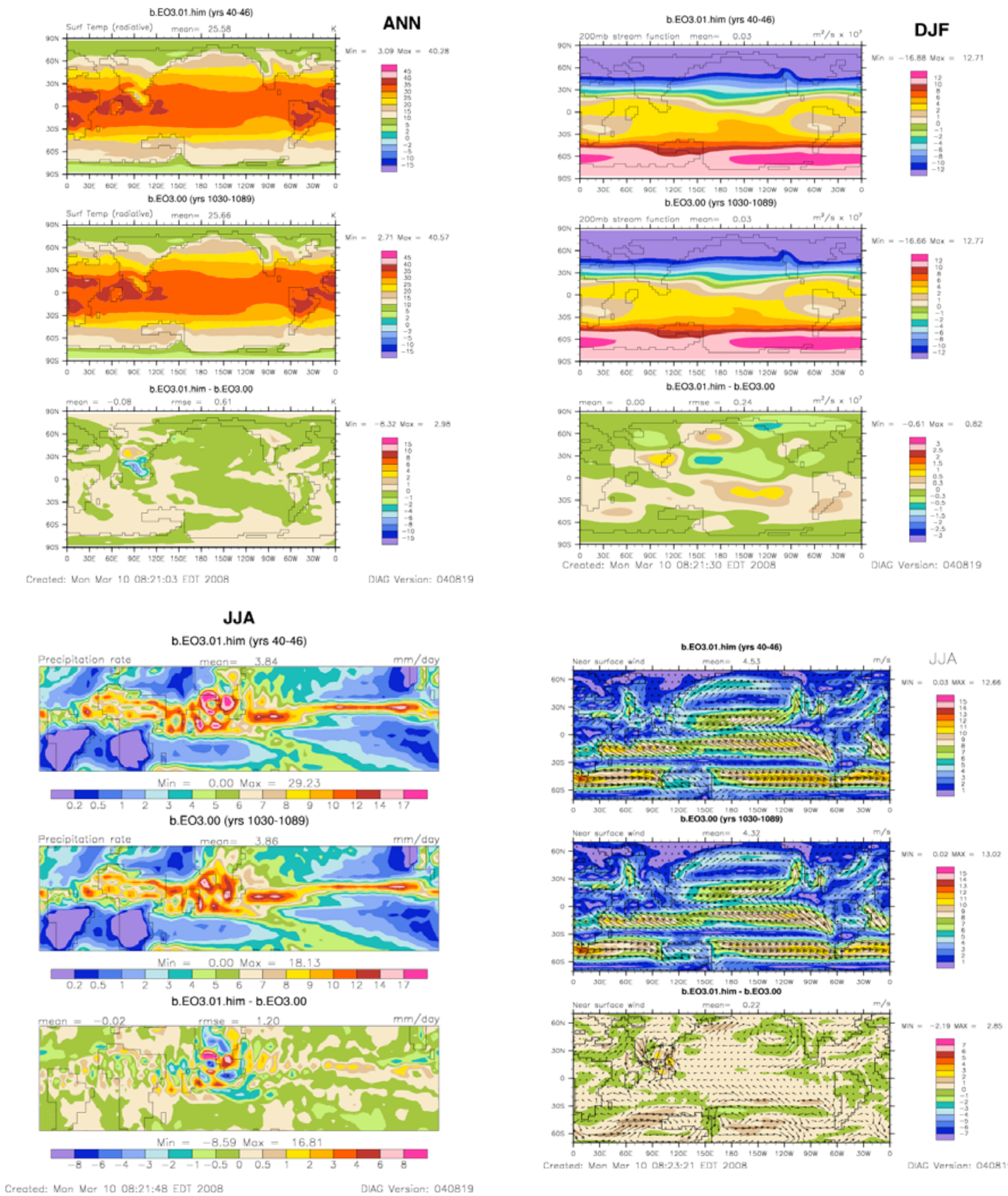

Figure 6. Results of a GCM sensitivity study that increased the mean and maximum topography of southern Asia by x2. Top row shows temperature, left panel, and the 200 mb stream function, right panel. Bottom row shows precipitation, left panel, and near surface wind. See text for details.

Tethys). These results demonstrate that simulations with fully interactive ocean-atmosphere coupled models with a realistic history of paleogeographic boundary conditions will increase the realism of the resulting climatic simulations and increase the body of available proxy evidence for comparison.

Specific recommendations and value-added components that could grow out of this report:

Potential modeling partners should be contacted as soon as possible. There is great opportunity for synergies here because monsoon evolution remains a key area of interest to modelers internationally, including in the Japan, China, the U.K., U.S., and Germany. While it is outside our purview to suggest how such interaction might be funded, one concrete step would be to include modelers as shore-based members of the proposed cruises. This would provide an IODP-centered and concrete means to encourage interactions between dynamicists and paleoclimate/tectonics experts.

To enable the testing of the hypotheses that have been proposed requires a more refined and explicit characterization of the paleogeographic and orographic boundary conditions through a wide swath of time. Because recent work (summarized in Rowley and Garzione, 2007) suggest that some fraction of the Tibetan Plateau topographic uplift (in addition to Andean-type orogenesis in the Himalayas) may have occurred as early as the Eocene, a paleotopographic and paleogeographic reconstruction of the region from the late Eocene to present is crucial as input to climate models. Since the true paleotopographic history is unknown, several possible scenarios are needed to establish different climatic responses that might be expressed in the paleoclimatic and geochemical record.

Thus specifically, we recommend that modeling groups work with geologists to create and disseminate a small suite of potential boundary condition scenarios from the late Eocene to modern covering this region. From the modeling prospective, a gridded, 0.5x0.5° dataset with a temporal resolution of ~10 m.y. would be ideal. The modeling should include coupled oceans and known ocean gateways which may play a significant role in determining monsoon response (Ramstein, et al., 1997), and many of the proxy records will be marine in origin.

In addition, modern monsoon modeling studies, such as those that are focused on predicting the impacts of anthropogenic CO_2 on climate, have found that fine atmospheric resolution (>T42) is a great benefit. Consequently we recommend that as far as possible, some studies should employ resolutions equivalent to T85 or greater, if only in fixed sea-surface temperature (SST) mode, to evaluate the sensitivity to resolution. We also recommend that some simulations use a dynamic vegetation component, for two reasons. First, vegetation radiation and hydrological interactions are well established as means by which plants can modulate monsoon onset and intensity. Secondly, paleobotanical and related proxy records exist in China and nearby regions and predictive vegetation can provide a key means for model-data comparison.

A link with geochemical and sediment modeling would also be important. Spatially resolved geochemical weathering models (Sloan et al., 1997) produce fundamentally different weathering rates than do global mean models, and if a suite of GCM simulations were carried out a geochemical model could be driven with output from the model to produce weathering fluxes. Climate models with explicit river routing (several exist and have been applied in paleoclimate) can be combined with the spatially resolved weathering model output to generate specific predictions about relative changes in river discharge of dissolved constituents. Similarly, ocean biogeochemical models that explicitly include sediment could be utilized to explore the important issues of climate change and geochemical fluxes.

In summary, climate model experiments can simulate many of the climate conditions and processes that are related to the proxies measured in drill cores. Comparison of model results with time series of monsoon-related proxies offers the best approach to interpreting the functional relations between uplifted orography and the monsoon response.

D. Drilling Plan

Stage 1 Operations

The first stage of an IODP program to address monsoon evolution should target both Indian and Asian monsoons. We consider this important in order to establish the degree of linkage between the regional monsoon systems, which has significant implications for the possible processes that could trigger monsoon intensification. In addition, sediment budgets in either the Bengal Fan or southeast Asia are hard to interpret in terms of changing continental erosion unless both regions are taken into account. Our first phase of drilling can all be accomplished using the *D/V JOIDES Resolution* (SODV), while leaving open the option to use *D/V Chikyu* in non-riser mode.

Due to political, security, and technical uncertainties related to drilling in the Arabian Sea close to Pakistan using the *D/V Chikyu*, we have not included Proposal 595 drilling on the Indus Fan and Murray Ridge in our discussion. We select the Bengal Fan (Proposal 552) as our highest priority location for examining the Indian-South Asian monsoon. This location targets a region where monsoon intensity is great and thus the erosional response is strong (Galy and France-Lanord, 2001). Furthermore, the provenance of the river-borne sediment appears to be relatively simple, at least back to 17 Ma (France-Lanord et al., 1993). Although the major objective of Bengal Fan drilling is to address the Neogene monsoon history, a major advantage to drilling the Bengal Fan is that one site (MBF-3A) may penetrate to the Eocene, dating a major regional reflector that could indicate the start of fan sedimentation. As such, Site MBF-3A may provide a critically important record that is needed to extend the monsoon/erosion record back into the Eocene or at least far beyond the 17 Ma record now available for the Bengal Fan. We also prioritize Sites MBF-1 and MBF-2A as important because they will provide additional details regarding the late Miocene-Recent accretion of the fan. Because the sites form a transect across the fan width, together they will provide a comprehensive history of Neogene sediment flux into the Bay of Bengal. Sites MBF-1 and MBF-2A are projected to reach sediments dating to 10 Ma at ~800 and 1150 mbsf respectively. The other sites within Proposal 552 (MBF-4A, -5A and -6A) are recommended for drilling as part of Stage 1, even though their emphasis is on shorter timescales. This is because understanding of how the channel-levee complexes are constructed is central to interpreting the overall sediment budget and they will provide an expanded section allowing millennial scale erosion response to monsoon variability to be constrained. While a drilling ship is in the area this provides a significant scientific bonus with modest additional operations time.

In South and East Asia we target three drill sites, one each in the deep-water slopes of the Mekong, Red and Yangtze River systems, in order to recover a late Miocene to Recent outflow record from the three river systems. Drilling to 1000 mbsf is recommended, with additional non-riser deepening of the hole desired depending on hole stability and time availability. Site ECS-3A (Proposal 683) is located on the eastern edge of the East China Shelf, in the transition to the deep water Okinawa Trough. The major source of clastic material is presumed to be the Yangtze River and correlation to industrial boreholes indicates that a late Miocene horizon will be reached at 1000 mbsf. The sediments are expected to yield a record of provenance evolution, allowing any major changes in Yangtze River drainage configuration to be constrained. Comparison with known compositions in the upper Yangtze allows the hypothesis of a continuous river feeding material to the ocean to be tested. Clay mineral and geochemical analysis of the clastic sediments fraction allows long-term changes in continental weathering intensity to be reconstructed and compared with other targeted regions, including the South China Sea.

Site VN-3 (Proposal 618-Add 3) is located in 1506 m of water offshore the Mekong River. The top of the middle Miocene is estimated at 1120 mbsf so that we anticipate around 10 Ma of record from a 1000 m hole. The Mekong River provides a record of weathering in Indochina, a region of especially strong modern summer monsoon rains, similar to the Bay of Bengal. We shall be able to test the hypothesis of monsoon changes around 8 Ma and assess recent capture into the system from the Red River. In particular, drilling will examine the nature of a major clinoform sequence apparently dating from the Pliocene and which could represent the effects of a number of possible processes, including monsoon strengthening, tectonic uplift in the Vietnamese Central Highlands (Carter et al., 2000) or drainage capture from the Red River. Accurate dating and provenance analysis is expected to resolve these competing hypotheses.

Site PA-1B (Proposal 618-Add 3) lies south of Hainan Island with the Paracel Basin in the NW South China Sea. Phase one operations will again penetrate to the upper Miocene, dating a major Pliocene-Recent foreset sequence. This region is chosen because it is located in deep water offshore the Red River delta. As explained above the history of the Red River is especially important to the drainage evolution of southeastern Asia, and because there are no major onshore basins erosional pulses in southeast Tibet should be rapidly communicated to the marine record. Of all the East Asian areas Site PA-1B should provide the clearest image of tectonically induced erosion on the flanks of Tibet. Studies of the modern river confirm that the sediment load is derived from regions of active rock uplift (Clift et al., 2006a) meaning that the sediments should reveal periods of accelerated gorge incision driven by tectonism. Clay mineral studies confirm that the sediments show less chemical weathering compared to the neighboring basins (Liu et al., 2007), making the site an important complement to VN-3 and to the existing ODP sites offshore the Pearl River. Changes in weathering seen in these basins should result in changes at Site PA-1B if monsoon intensity is the dominant control on continental erosion, a hypothesis that can be tested by this program.

Stage 2 Operations

Having generated a late Miocene-Recent monsoon and erosion record in East Asia we recommend following up the initial two expeditions of Stage 1 drilling with a program of deeper sampling based on riser methods and the *D/V Chikyu*. The primary objective of Stage 2 is to extend the East Asian record into the Paleogene in order to match the record derived from the Bengal Fan Stage 1 recovery. This will allow us to determine the degree to which the two monsoon systems are coupled and to what extent environmental conditions in the Mekong basin are controlled by either the Indian or the East Asian monsoons. Comparison of the Mekong record with those of the Bengal Fan and the Yangtze is important because Indochina lies between the two main focus regions. By reaching the Eocene we also have the opportunity to characterize the climate across Asia prior to the onset of major mountain building outside the initial collision zones in the Indus-Yarlung Suture Zone. Establishing the baseline is key to demonstrating phases of subsequent intensification.

The Paleogene is also likely a crucial time of drainage capture, because pilot work on the Red River suggests the greatest reorganizations there to be Oligocene in age (Clift et al., 2006b). This would be consistent with recent advances in our understanding of the paleo-altitude of central Tibet which points to significant uplift soon after India-Asia collision (Rowley and Currie, 2006), even if major topographic uplift in southeastern Tibet is known to be significantly later e.g. 8 Ma (Clark et al., 2005; Schoenbohm et al., 2006).

Developing a long-term erosion history for the Red River is an important goal for the work proposed by this DPG. As a result, for Stage 2 we propose to deepen Site PA-1B (Proposal 618-Add 3) to the middle Oligocene (~28 Ma), predicted to lie at 2874 mbsf. Basement lies at around 5 km, but the additional scientific benefit of recovering the earliest syn-rift is insufficient to warrant the major extra logistical effort at this time. Instead we prefer to examine the Eocene climatic history in South China Sea via deepening of Site VN-3A. Both these operations require use of the riser and thus *D/V Chikyu*. The acoustic basement at VN-3A (Proposal 618-Add 3) lies at 2790 mbsf. Although much of the Paleogene section below 1815 mbsf is expected to be Oligocene, because this is the time of active extension and rapid sedimentation (Lee et al., 2001), industrial drilling in the neighboring Nam Con Son Basin indicates that an Eocene section can be expected, allowing comparison with the Bay of Bengal. In any case VN-3A can be expected to yield an especially complete monsoon record for the mid and early Miocene.

We also propose to extend the Yangtze/East China weathering record by drilling at proposed site ECS-2B (Proposal 683), located in 102 m of water on the East China Shelf within the Xihu sub-basin. In this location the top of the Oligocene is predicted to lie at 3155 mbsf. Drilling would attempt to recover a section through that interval and test the hypothesis that the Middle Yangtze was lost from the Red River and diverted into the East China Sea before that time. The same section can be used to chart the changing degrees of chemical weathering in eastern China and help test the notion of a wetter monsoon climate across the region starting at the Oligocene-Miocene boundary (Sun and Wang, 2005).

In proposing these operations we do not ignore the drilling opportunities at Site MU-1 (Proposal 595) on the Murray Ridge (Arabian Sea). The Indus Fan has an especially well developed Paleogene section and should be a key part of any comprehensive monsoon reconstruction, not least because of the links to the established monsoon records on the Oman margin. There are suggestions that India-Asia collision is older in the western Himalaya than in the east and that early Himalayan drainage is dominated by a paleo-Indus system (Qayyum et al., 1997). In this case the onset of fan sedimentation in the Bay of Bengal would significantly postdate that in the Arabian Sea. Drilling at MU-1B also offers a good chance to image oceanographic state of a pre-monsoonal/pre-collisional Tethys.

In the event that the security situation changes in this region then operations at this site would be considered of high priority. If that does not occur then seismic profiles held by the proponents, lying outside the Pakistan EEZ and already submitted to the IODP Site Survey Data Bank, should be used to identify a new drill site over thinner parts of the fan that could be sampled using the SODV. Results from DSDP Site 221 showed that fan sedimentation started in this distal location in the late Oligocene (Whitmarsh et al., 1974). The base of the fan was recovered at only around 170 mbsf in a partially recovered, spot-cored borehole. Even a fully recovered succession from such a section would be of great use in understanding the temporal and spatial variability in the monsoon. Deriving a similar but extended and more proximal record should be a priority for Stage 2.

E. Technical issues

Drilling

Stage I of the drilling proposed will utilize the *D/V JOIDES Resolution* in normal operations mode, including APC, XCB and rotary drilling. Recovery of sediments is expected to be good in silty clays of the offshore China and Vietnam sites, and less good in the Bengal Fan sites. Low recovery will not jeopardize the primary results, as questions posed are on the longer tectonic timescales. Even in the lowest recovery zones of ODP Sites 717 and 718 in the distal Bengal Fan the temporal sample spacing is 50 to 100ky because of the very high sedimentation rates. Drilling and logging times for all sites are given in Tables 1 and 2 and sum to about 2.5 legs of drilling and logging.

Phase II drilling will require the riser capabilities of the *D/V Chikyu* for deep penetration of, and sediment recovery from, sites in the western Pacific. The new sea-floor mud recovery system being designed and built by AGR, Norway, is being considered by IODP-MI may allow the use of the SODV for drilling into/through the Indus Fan.

Analyses

The DPG senses an urgency to have exciting, high-visibility results by the 2012 time frame, in time to publicize any new understanding of linkages between mountain uplift and monsoons before project renewal decisions in 2013. This requires that the drilling be scheduled in 2010 or 2011. To analyze thousands of samples for the many proxies described above will require multiple laboratories and several years, so thought should be given to what science can be done on board the *JOIDES Resolution* to provide first-order results. The standard measurements include the MST data of bulk density, P-wave velocity, natural gamma logs, and magnetic susceptibility, color scanning of the cores, and X-Ray mineralogy, rock magnetic properties, major element and minor element geochemistry, TOC and $CaCO_3$ abundance. Other scans, like those by XRF or CAT, can be done immediately upon the arrival of the cores at the repository. These measurements, along with the mass fluxes of the sediments and their components will shed light on the timing and nature of the first order changes in the sedimentary systems being considered and can form the basis for high-visibility publications that can be largely prepared on board ship.

Within two or three years post cruise, the many investigators from both the East China/Vietnam drilling and the Bengal Fan project should convene to compare and integrate results. Only in such a manner can the histories of, and differences between the South Asian and East Asian monsoon systems be determined. Such a meeting, attended also by climate modelers, should result in a number of manuscripts, including a summary/overview paper that can be submitted to a journal for ultimate presentation of results.

Other issues

None of the sites proposed for the Stage 1 or Stage 2 drilling lie in contested waters. The Bengal Fan sites are in international waters, Site VN-3 is in Vietnamese waters, and Sites PA1-B and ECS-3B are in Chinese territorial waters. The estimated time for Stage 1, for the science proposed, is about 2.5 legs worth of drilling, logging and transit (Tables 1 and 2).

Sites proposed for the Indus Fan project lie in the EEZ of Pakistan, and the Foreign Office of Japan will not permit the *D/V Chikyu* to enter Pakistani waters. The Indus project, which was well regarded by the DPG, could be slightly redesigned by moving the sites south of the EEZ where the fan sediments would be thinner and where it might be possible to use the *D/V JOIDES Resolution* in conjunction with the sea-floor mud recovery system to penetrate the 1500+ meters of sediment that would be needed to fulfill the science objectives there.

F. Outreach and Education

Importance

Asian monsoon evolution and its potential linkage with the uplift of Himalaya and Tibet has high social relevance because: (1) Nearly half of the world's population lives in the area under the influence of the Asian monsoon, and changes in its intensity and spatial pattern has a strong impact on the life of the people living there. Thus to know the variability of Asian monsoon and its controlling factor(s) are crucial for the society. (2) Understanding the mechanism underlying the linkage between the monsoon and tectonics will provide a chance to find new feedback mechanisms that either enhance or reduce the variability of Asian monsoon and specify factors that control its spatial pattern. (3) The enhanced sediment discharge to the marginal seas due to the erosion of the uplifted Himalaya and Tibet and increased monsoon intensity buried large amount of organic material that removes CO_2 from the atmosphere and eventually becomes the source of oil and natural gas.

Public outreach and education, once the step-child of large projects, has become an integral part of the management programs for scientific ocean drilling. JOI-Ocean Leadership, CDEX, and ECORD all have outreach and education programs that are aimed at teachers at all levels, students of elementary through college age, and the general public. For instance, the JOI – Ocean Leadership office in Washington runs the Deep Earth Academy and the School of Rock that takes science teachers to sea, sets up real-time interactions between shipboard scientists and classrooms on land, and provides curricular materials based on ocean drilling results to educators at all levels. ECORD supports an annual teachers workshop and summer schools for students, held last year in Urbino and Bremen. CDEX is supporting a round of lectures by distinguished scientists to be given at the National Museum of Emerging Science and Innovation in Tokyo, and also exhibits at the National Museum of Nature and Science, also in Tokyo. All organizations fund distinguished lecture programs, mount sophisticated exhibits at national and international meetings, and provide hands-on experiences for students. Full information on these activities may be found at the respective web sites (www.ecord.org/edu/education, www.jamstec.go.jp/chikyu/eng/index.html, and http://oceanleadership.org/learning).

Outreach and education suggestions

IODP drilling for this objective will provide us a good opportunity to display our scientific activity to the Asian community and demonstrate the potential relevance to their daily lives. Invitations of scientists and possibly teachers from Asian countries to join a shipboard party, selection of ports in nearby countries, open houses at the ports, and giving outreach lectures in these countries will be good opportunities to broaden public recognition of our project.

Given the abilities of the several organizations with regard to highlighting IODP accomplishments with educational exercises and materials, the DPG suggests that a number of the scientific questions being addressed in this work are eminently suitable for such an education/outreach effort.

A topic as simple to Earth Scientists as telling the story of where India came from, migrated north, and how it came to collide with Asia with the resulting building of mountains would be something that a non-specialist audience would appreciate. There already are materials developed in this context such as the following website which is a good start, or maybe even enough in this regard http://www.scotese.com/indianim.htm. In addition, there are 3-dimensional, dynamical models of Asian deformation (e.g., Ghosh et al., 2006) that could be incorporated into curricular material.

Another simple concept – to Earth Scientists – is the idea that we can tell with some certainty where sediment grains come from. Describing the several geochemical clues to provenance and how they are utilized will permit students in particular and the public in general to understand this basic geologic concept. Much of the anticipated success of the Mountains and Monsoons program hinges on our provenance studies.

The potential impact of mountain building on climate has multiple aspects that seem like they would lead to good interactive lessons for students and the curious non-specialist. These include using something like the Educational General Circulation Model (EdGCM), which runs on a desktop machine and allows students to test their own ideas about how certain changes in the solid Earth system might result in climate changes. Such basic modeling exercises could be readily incorporated into curricula for high school and college students.

Two other things about how the uplift and erosion process might have a global impact on the Earth are related to atmospheric CO_2. The suite of extant simple geochemical models should be able to simulate the drawdown of atmospheric CO_2 caused by chemical weathering. At the same time erosion-related chemical weathering is occurring on land, at the depositional end of the same system organic carbon is being buried in the deep-sea deposits. For instance, the burial of organic carbon in the Bengal Fan may be of a sufficient magnitude to have played an important role in the late Cenozoic CO_2 drawdown and resultant global cooling.

G. Summary and recommendations:

The Asian Monsoon – Cenozoic Tectonic History Detailed Planning Group (Appendix 1) met at IODP-MI headquarters in Washington, D.C., on March 10-12, 2008. The DPG followed its mandate to extract the best possible drilling plan from information and sites presented in IODP Proposals 552, 595, 618 and 683. The resulting plan, which has an earlier Stage-1 and a later Stage-2, is given below in our recommendations.

The objectives of the drilling program are to: (1) Determine the uplift-erosional history of both the Himalaya and Tibetan region as based on the records recovered from deep-sea sediments; (2) Use the sediment record to determine the long-term evolution and variability of the East Asian and Indian monsoons based upon multi-proxy reconstructions of the changing environment; (3) Test hypotheses of monsoon-uplift relations using modern coupled (atmospheric and oceanic) models of the climate system; and (4) Quantify to the extent possible any cause-effect relations between mountain uplift and intensity of the Indian and East Asian monsoons.

No single sedimentary proxy gives a uniquely clear picture of uplift, erosion, or marine or terrestrial environments. As a result we strongly encourage a multi-proxy approach to construction of records of past conditions. Every advantage should be taken from the use of computer models to create testable scenarios and, in turn, to test scenarios constructed by geologists and oceanographers. This type of data-model interaction, which should include linking modelers with the shipboard or shore-based scientific parties, has the possibility of leading this science to its ultimate goals.

Issues of outreach and education have become important aspects of IODP in the past several years. Japan, ECORD and the US all have offices and staff devoted to a variety of sophisticated and wide-ranging activities for students, teachers and the general public. There are no technical or clearance issues that should impede the drilling plan for Stage 1.

We recommend two stages of drilling, for Stage 1:

- Drill the Bengal Fan essentially in the manner recommended in Proposal 552. Among the sites, the highest priority should be assigned to the deep penetration

Site MBF-3A, which likely will provide a record back through the Eocene/Oligocene boundary, followed by the intermediate penetration Sites MBF-1A and -2A, then the three shallower sites. The Bengal fan drilling can be done with the SODV.

- Drill the top approximately1000 meters of the more distal sites offshore from the major Asian rivers: ECS-3B (Proposal 683) for the record of the Yangtze, PA-1B (Proposal 618 Add-3) for the Red, and VN-3 (Proposal 618 Add-3) for the Mekong River. The East Asian drilling can be done with the *D/V JOIDES Resolution*, however depending on its schedule the *D/V Chikyu*, in riserless mode, could be easily deployed to drill Site ECS-3B.

Stage 2:

- Deepen the holes at VN-3 and PA-1B (Proposal 618 Add-3), and drill a new hole at ECS-2B (Proposal 683) to depths of 2300 to 3500 mbsf, in order to reach Oligocene/Eocene targets. This is critical to determine pre-monsoon and pre-uplift conditions, and to understand when the whole process began. Drilling these sites to their full-recommended depth will require the *D/V Chikyu* in riser mode with current technology.
- Adjust the sites on the Indus Fan to lie outside the EEZ of Pakistan at existing seismic line crossings and drill them with the SODV using the expected advanced capabilities of the sea-floor mud recovery system.

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Table 1. Estimates of operation times for Stage 1 Bengal Fan drilling

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	Log (days)
Starting Port						
			Transit ~ nmi to Site (number) @ 10.5 kt			
MBF-1A	8° 0.42'N	3747 mbsl	Hole A: APC to ref. ~200m, XCB to ref. ~500m, Heat Flow		4.1	
	86° 16.97'E	3758 mbrf	Hole B: APC to ref. ~200m, XCB to ref. ~500m		4.3	
			Hole C: Drill to ~490 m, RCB 490-900m sedmt.		5.0	
	900 m sedmt		Log w/ Triple-Combo, FMS-Sonic			1.9
			Sub-Total Days On-Site: 15.3			
			Transit 80 nmi MBF-1A to MBF-2A @ 10.5 kt	0.3		
MBF-2A	8° 0.4'N	3678 mbsl	Hole A: APC to ref. ~200m, XCB to ref. ~500m, Heat Flow		4.0	
	87° 38'E	3689 mbrf	Hole B: APC to ref. ~200m, XCB to ref. ~500m		4.2	
			Hole C: Drill to ~490 m, RCB 490-900m sedmt.		5.0	
	900 m sedmt		Log w/ Triple-Combo, FMS-Sonic			1.9
			Sub-Total Days On-Site: 15.1			
			Transit 62 nmi MBF-2A to MBF-3A @ 10.5 kt	0.3		
MBF-3A	8° 0.4'N	3620 mbsl	Hole A: APC to ref. ~200m, XCB to ref. ~500m, Heat Flow		4.0	
	88° 41'E	3631 mbrf	Hole B: APC to ref. ~200m, XCB to ref. ~500m		4.2	
			Hole C: Drill to ~490 m, RCB 490-1100m sedmt.		8.0	
	1500 m sedmt		Drop FFF, Trip for bit, RCB 1100-1500m sedmt.		5.9	
			Log w/ Triple-Combo, FMS-Sonic			2.3
			Sub-Total Days On-Site: 24.4			
			Transit 159 nmi MBF-3A to MBF-4A @ 10.5 kt	0.6		
MBF-4A	8° 0.4'N	3694 mbsl	Hole A: APC to ref. ~200m, XCB to 300m, Heat Flow		2.4	
	86° 47.9'E	3705 mbrf	Hole B: APC to ref. ~200m, XCB to 300m		2.7	
	300 m sedmt		Log w/ Triple-Combo, FMS-Sonic			1.1
			Sub-Total Days On-Site: 6.2			
			Transit 70 nmi MBF-4A to MBF-5A @ 10.5 kt	0.3		
MBF-5A	8° 0.4'N	3687 mbsl	Hole A: APC to ref. ~200m, XCB to 300m, Heat Flow		2.4	
	87° 10.9'E	3698 mbrf	Hole B: APC to ref. ~200m, XCB to 300m		2.7	
	300 m sedmt		Log w/ Triple-Combo, FMS-Sonic			1.1
			Sub-Total Days On-Site: 6.2			
			Transit 55 nmi MBF-5A to MBF-6A @ 10.5 kt	0.2		
MBF-6A	8° 0.4'N	3672 mbsl	Hole A: APC to ref. ~200m, XCB to 300m, Heat Flow		2.4	
	86° 06.6'E	3683 mbrf	Hole B: APC to ref. ~200m, XCB to 300m		2.7	
	300 m sedmt		Log w/ Triple-Combo, FMS-Sonic			1.1
			Sub-Total Days On-Site: 6.2			
			Transit (~distance) nmi to (ending port) @ (speed) kt			
Ending Port				**1.7**	**64.0**	**9.4**

Subtotal On-Site Time:		**73.4**
Total Operating Days:		**75.1**
Total Expedition Including Port Call Days=	5	**80.1**

Note-1: Sea floor depth is prospectus water depth plus 11.0 m adjustment from water line to rig floor (i.e. drillers depth).

Table 2. Estimates of operation times for Stage 1 East Asian seas drilling.

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbsf)	Operations Description	Transit (days)	Drilling Coring (days)	Log (days)
PA-1B	17° 12' N	1460	Hole A: APC to ref. ~200 mbsf, XCB to 500 mbsf		3.2	
	110° 30' E		Wiper Trip, Hole Prep, Triple combo, FMS-Sonic, and VSP.			1.0
			Hole B: Drill to ~500 mbsf, RCB to 1000 mbsf		5.4	
			Drop bit w/ MBR, Hole Prep, Triple combo, FMS-Sonic, VSP and secure.			1.8
			Sub-Total Days On-Site: 11.4			
VN-3	08° 38' N	1506	Hole A: APC to ref. ~200 mbsf, XCB to 500 mbsf		3.2	
	109° 43' E		Wiper Trip, Hole Prep, Triple combo, FMS-Sonic, and VSP.			1.0
			Hole B: Drill to ~500 mbsf, RCB to 1000 mbsf		5.4	
			Drop bit w/ MBR, Hole Prep, Triple combo, FMS-Sonic, VSP and secure.			1.8
			Sub-Total Days On-Site: 11.4			
ECS-3B	28° 45' N	1000	Hole A: APC to ref. ~200 mbsf, XCB to 500 mbsf		2.9	
	127° 20' E		Wiper Trip, Hole Prep, Triple combo, FMS-Sonic, and VSP.			1.0
			Hole B: Drill to ~500 mbsf, RCB to 1000 mbsf		5.0	
			Drop bit w/ MBR, Hole Prep, Triple combo, FMS-Sonic, VSP and secure.			1.8
			Sub-Total Days On-Site: 10.7			

Appendix 1. Asian Monsoon and Cenozoic Tectonic History Detailed Planning Group and guests at the DPG meeting, March 10-12, 2008, Washington, D.C.

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Higgins, Sean		JOI		
Janecek, Tom		IMI		
Kawamura, Yoshi		CEDEX		
Kubo, Yusuke		CEDEX		