

Workshop for Climate-Tectonic Drilling Studies in Southeast Asia

*An Integrated Ocean Drilling Program-InterMARGINS
Workshop*



Funded by JAMSTEC, JOI, J-DESC and InterMARGINS

5–7th June 2006

Kochi Core Center (KU/JAMSTEC), Kochi, Japan

Executive Summary

Interactions between the tectonic evolution of the solid Earth and the planet's climate system have been recognized, yet are presently only understood in outline. The Asian monsoon – Himalaya-Tibetan Plateau system appears to be one of the most dramatic examples of such interactions and is ideally suited for deconvolving and unraveling the coupling that can occur between high topography and the climate system. Climate models suggest a strong linkage between Tibetan altitude and the strength of the monsoon. However, these models are largely untested. A meeting was held 5–7th June 2006 in Kochi, Japan, to discuss marine and terrestrial geoscience research on the subject of climate-tectonic studies focused in SE Asia. The meeting summarized recent research advances in the field and recommended the coordination of research activities across the region, particularly in the context of the Integrated Ocean Drilling Program (IODP). SE Asia is particularly well suited to this type of work because the Asian monsoon is strong and the rivers of the region incise the edge of the Tibetan Plateau. Recent advances in the science of climate-tectonic coupling include new evidence for the monsoon experiencing a series of steps in intensification, possibly dating back to the Early Miocene ~25 Ma. Furthermore, while central Tibet appears to have been relatively high possibly back to >30 Ma, the NE and SE edges appear to have been elevated only since 10 Ma. Phases of plateau uplift or climate change must generate erosional pulses that are delivered to the deltas of the marginal seas, where they can be sampled and quantified. The importance of drilling in the Song Hong-Yinggehai Basin was recognized as an important step to testing models for climate change in East Asia. However, the erosional pulses observed can only be interpreted if the uplift and exhumation histories of the sources in SE Tibet can be reconstructed in detail and if variations in monsoonal climate can also be dated. Because of variations in the nature of the monsoon across Asia, and because the source rivers have interacted with each other in the past, drilling in the Red River fan-delta alone will be insufficient to address the science goals of the community. The meeting called for coordinated drilling in the Sea of Japan, in the East China Sea and in the Mekong delta, which in turn must be linked to related programs on the Indus and Bengal Fans in the Indian Ocean. Ocean drilling will need to be supplemented in key regions by continental coring operations, with the Hanoi Basin, the Jiangnan and Subei Basins of the Yangtze River, and smaller sedimentary basins in SE Tibet particularly highlighted.

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Introduction

Interactions between the solid Earth and the global climate system are a frontier area for ocean and Earth science research and have been highlighted as a focus area for the Integrated Ocean Drilling Program (IODP). Of all the possible links between these earth systems the proposed associations between the elevation of the Tibetan Plateau and the strength of the Asian monsoon is one of the most dramatic and controversial. Testing and quantifying these proposed links requires independent records of the evolving climatic, tectonic and erosional histories that can be correlated, or not, in order to determine how these systems are linked over long periods of geologic time. The most complete sedimentary records necessarily lie offshore on the continental margins where sediments preserve the evolving erosional flux since the start of India-Asia collision, likely around 50 million years ago. The continental margins of SE Asia are fed by some of the largest rivers on Earth, and the rivers of Asia account for ~70% of the total sediment flux to the global ocean. As a result the Asian deltas are ideal laboratories for the study of sediment “source-to-sink” processes that forms a focus topic for the US MARGINS initiative. The geology of the SE Asian continental margins and their source regions in Eastern Tibet and Indochina are pivotal to current studies of both margin tectonics, stratigraphy and climate evolution.

A meeting was held 5–7th June 2006 at Kochi Core Center (KU/JAMSTEC) at Kochi, Japan. The meeting was attended by 38 geoscientists from 29 institutions and 10 countries. The goal of the meeting was to present recent research findings on the solid Earth tectonic, erosional and climatic evolution of SE Asia and synthesize these to assess what is known about the factors that control climate-tectonic interactions in this region. The meeting then discussed what the most urgent research goals for the next 5–10 years should be, and how these could be addressed through application of the drilling technologies of IODP and the International Continental Drilling Program (ICDP).

Although IODP operations have been proposed for the Bengal Fan and are already approved for the Indus Fan, these bodies are dominated by erosion from the Himalaya and are not appropriate for examining the erosional flux from Tibet, which lies at the heart of the monsoon climate-tectonic coupling debate. Instead the erosion of eastern Tibet is stored in the sedimentary archives preserved in the East Asian marginal seas. Deep drilling of margin stratigraphy in these basins was identified as a priority for climate research in Asia by a JOI-sponsored workshop/AGU Chapman meeting held in 2003. At this meeting plans for drilling in the South China Sea, East China Sea and Sea of Japan were presented and the need for additional drill sites was debated.

Principle Conclusions

Scientific results were presented in 23 lectures and in 14 posters, with an additional five presentations of existing drilling proposals for monsoon-tectonic studies in SE Asia. The full abstracts of these studies can be downloaded from the meeting web site at <http://www.abdn.ac.uk/~wpg008/RedRiverWorkshop.html>. Here we summarize the major results in six sub-sections:

Cenozoic Climate Evolution

Although a sharp change in the paleoceanography and continental climate of Asia has been recognized for many years in the Late Miocene (~8 Ma) it has recently been observed that enhanced biogenic production linked to monsoon wind-driven oceanic upwelling documented in the Arabian Sea is also observed in other parts of the Indian and Pacific

Oceans. At the same time evidence for mountain building in the Himalaya or Tibet at this time is questionable, either suggesting little link between mountain building and the monsoon intensification, or implying that the climate event at 8 Ma is global and not triggered by Asian tectonics. While the NW Arabian Sea is suitable for summer monsoon studies, the marine records offshore Sri Lanka may be better for winter monsoon studies in the Arabian Sea. On shorter time scales new data from the Laccadive Ridge of the Indian Ocean show clear monsoon intensification after 20–25 ka, following a period of weak summer monsoon intensity since 180 ka. This is consistent with the general pattern of weaker summer monsoon during glacial periods.

Further constraints on the long term evolution of the monsoon comes from East Asia, where botanical and sedimentary facies data now indicate an initial strengthening of the monsoon since the start of the Early Miocene (~25 Ma) when the present climatic belts developed in China. Wind-blown loess accumulated more rapidly after 8.0, 3.5 and 2.5 Ma, together with increased productivity in the ocean basins. Monsoon intensification at 3.5 Ma is also mirrored by faster erosion of the flanks of the Tibetan Plateau. In the Tarim Basin, along the northern edge of plateau, a major influx of sand was noted around 4.6 Ma, followed by conglomerates starting at 3.5 Ma. This quickening erosion is linked to a more intense wetter summer monsoon at that time and possibly to uplift of the northern edge of Tibet.

The possibility of a Middle Miocene monsoon requires improved knowledge of the paleogeography and global climate system at that time. Plate tectonic reconstructions indicate a more open Indonesian through-flow and an open, albeit largely shallow-water gateway to the western Tethys north of Arabia. Climate in SE Asia during the Middle Miocene can be put into context by Ocean Drilling Program (ODP) cores from the eastern Pacific Ocean. A complete record was generated by splicing records together from parallel holes based on detailed XRF geochemical scanning. Carbon isotope data show a clear record of ice sheet expansion at ~13.9 Ma over a short time span of only around two obliquity cycles (~80 k.y.). Cooling drove ice sheet expansion after 14.7 Ma, a process that had stabilized by 13.8 Ma, coincident with a transition from climate variation on a 41 k.y. obliquity cyclicity to variation on an eccentricity-based 100 k.y. variability. The change is associated with a re-organization in Pacific circulation at that time. The South China Sea paleoceanographic record shows moderate differences with the Eastern Pacific that may be linked to unique Asian events. At 15 Ma there is a transition in color to a more oxidized condition in South China Sea, possibly linked to a drier climate in southern China.

Monsoon intensity in South China Sea has been reconstructed to vary not only on tectonic timescales that may be linked to uplift of Tibet, but also on orbitally modulated glacial-interglacial cycles during the Plio-Pleistocene. As in the Arabian Sea monsoon winds drive regional upwelling of deep, cold, nutrient-rich waters that enhance biogenic production offshore southern China and Taiwan, as well as offshore central Vietnam. Studies of ODP cores in southern South China Sea showed there is more detrital mineral influx to the basin during glacial periods, due to a stronger winter monsoon bringing eolian dust. In the northern South China Sea chlorine and organic carbon data indicate greater marine productivity in glacial times compared to interglacial times. Interpreting the changing paleoceanography of the South China Sea in terms of monsoon strength can however be complicated by the fact that water exchange into the basin from the Pacific Ocean was largely cut during glacial times, as the narrow gateways in the Philippines and in the Sunda Strait constricted or closed. The same is also true of the Sea of Japan where Dansgaard-Oeschger cycles are preserved as laminated dark and light layers in core. Dark, organic-rich layers are formed during glacial

times, when circulation stagnated but the sea was fed by nutrients from the Yangtze River, which in turn is fed by the summer monsoon rains. In both South China and Japan seas eolian dust flux is largely transported there by winter monsoon winds that were stronger in glacial periods.

The meeting recognized the importance of mathematical climate models in understanding the relationships between plateau growth and monsoon intensification, as they are powerful tools for identifying regions that should experience the most dramatic changes in climatic conditions during intensification. Current models suggest that 60–80% of the present mountain topography is required before a major climate response is noted. Because it is a product of the temperature differences between land and sea the monsoon would exist without the presence of Tibet, yet it is mountain growth that makes this system as strong as it is today. Changes in precipitation predicted by models are most strongly shown in Burma, SE Asia and SW China. In addition, salinity decreases, driven by monsoon-enhanced runoff are predicted in the Bay of Bengal, South China Sea, East China Sea and Sea of Japan. Models indicate that sea surface temperatures should increase in the eastern coastal equatorial Indian Ocean, as the monsoon strengthens, but they correspondingly decrease in western coastal regions.

Elevation History of the Tibetan Plateau

In order to assess the relationship between monsoon development and Tibetan Plateau elevation it is necessary to have independent records of how each of these factors have evolved during the Cenozoic. There has been significant advance in the understanding of Tibetan altitude over the past few years as a result of analysis of oxygen isotopes from lacustrine sediments and soil carbonates from different parts of the plateau. This method is based on the observation that rainfall changes its isotopic character ($\delta^{18}\text{O}$) by about 2.8‰ for every kilometer of elevation. Although there are a number of potential pitfalls related to evaporation and diagenetic change this technique has provided important new constraints on elevation through time. Nonetheless, an accuracy of ± 500 m is difficult to improve on and reflects isotopic changes driven by evaporation. Fluvial and lacustrine sediments dated at ~ 25 Ma are exposed at Nyima in Central Tibet. After correcting for global temperature changes the isotopes at Nyima are interpreted to indicate similar conditions at 25 Ma as seen today, i.e. elevation ~ 5 km and a dry climate. This implies that the Asian monsoon was already operational at ~ 25 Ma, as the strong negative $\delta^{18}\text{O}$ values require altitude and strong rainfall.

Further constraints on altitude and climate evolution can be derived from the sedimentary basins in NE Tibet. The Linxia Basin is a flexural basin that lies on the northeastern edge of Tibet, just north of the major reverse West Qinling Fault. Age control from magnetostratigraphy indicates a sedimentary sequence spanning 4–29 Ma, and comprised of a series of fining-upwards fluvial and lacustrine clastic cycles. Oxygen and carbon isotope data show a major baseline shift around 13 Ma suggestive of increasing elevation at this time. The West Qinling Fault became active after 13–14 Ma, driving surface uplift in this part of Tibet. The record also suggests a sharp increase in aridity at ~ 8 Ma, and again at ~ 4 Ma. After 7 Ma the Qinling Shan foreland started to fragment and the climate seems to have dried, as lacustrine sedimentation ceased and instead paleosols formed as the lake disappeared.

Because of the stronger precipitation in SE Tibet plateau uplift in that region can be measured by the incision of the major river gorges that characterize that area. Erosion pulses need not imply increased relief but may also be driven by climate. However, slow erosion

rates are impossible to sustain in high relief environments unless climate is very arid. (U-Th)/He thermochronology can be used to record the residence time of rocks between 40 and 80°C and is effective at measuring the incision of gorges. While (U-Th)/He ages in NE Tibet span Mesozoic to Cenozoic dates, Late Cenozoic ages are only seen in the core of deeply incised structures because the Yellow River has not yet incised sufficiently to generate widespread young (U-Th)/He ages. In the West Qinling Shan cooling was slow at 150–45 Ma, but quickened after 45 Ma reflecting thrusting shortly after the onset of India-Asia collision. There is additional acceleration of exhumation after 5–15 Ma. Low surface strains and the arid climate limit the feedback between plateau growth and erosion. In contrast, gorge incision in the wetter summer monsoon conditions in SE Tibet is more dramatic. (U-Th)/He ages indicate gorge incision after ~10 Ma. 3.0–4.5 km of increased elevation is inferred over ~1000 km of plateau width in SE Tibet since that time.

Tectonics of the Red River Fault Zone

In the model of Tapponnier *et al.* (1984) the Ailao Shan-Red River Fault Zone (ASRRFZ) is the primary left-lateral lithospheric structure related to extrusion of Indochina from mainland Asia, as well as opening of the South China Sea. This model is disputed by a series of alternative lithospheric strain accommodation hypotheses that emphasize lower crustal flow, horizontal compression, or book-shelf type rotations. The ASRRFZ is active from at least 32 Ma (probably 35 Ma) to 16 Ma, roughly coincident with the timing of seafloor spreading in the South China Sea measured by magnetic anomalies. Alternative tectonic models separate Borneo and Indochina and imply that the ASRRFZ finishes in the Hanoi Basin. However, if the ASRRFZ does not reach the main South China Sea then a minimum of 500 km of offset has to be absorbed within Indochina for which there is little evidence.

Structural trends in the rocks within the ASRRFZ are steep in the Ailao Shan of China but flatten towards the south into the Day Nui Con Voi in Vietnam. Th-Pb dating of monazite inclusions within garnet crystals allows the timing of growth to be determined at 34–24 Ma for the Ailao Shan and northern ranges. Modeling of the cooling data, which youngs to the North, indicates rapid cooling of the Ailao Shan at 19–21 Ma. Motion along the ASRRFZ is predicted to be compressive in the northern part of the fault, perfectly strike-slip in the “Midu Gap” and then transtensional in the region of the Ailao Shan and Day Nui Con Voi. Samples north of the Midu Gap do not show extension or cooling until after 5 Ma when the sense of motion is inferred to have flipped from being sinistral to dextral. The modern Red River Fault is active in a dextral sense, but also involves an extensional component, with a “down to the NE” sense of motion. Volcanism linked to the motion is quite continental in terms of its isotope chemistry during the sinistral activity, but became more primitive after the sense of motion reverses. Shear heating alone is insufficient to heat the fault zone rocks rapidly to the degree needed to account for high metamorphic grades and the formation of garnet soon after the start of ASRRFZ motion. Additional heating from below, linked to magmatism is inferred, although it is also possible that motion on ASRRFZ started earlier than 35 Ma, and culminated in high temperatures at that time.

Lying at the southern end of the ASRRFZ the Song Hong-Yinggehai Basin is generally interpreted to be a pull-apart basin formed after ~35 Ma during left-lateral motion along that structure. Analogue modeling of the basin shows that its general form is compatible with a strike-slip mechanism linked to the ASRRFZ. The Song Hong-Yinggehai Basin can be explained by partial clockwise rotation of Indochina away from Hainan Island

during this phase of motion, not necessarily involving large degrees of strike-slip motion. An initial stage of tectonic activity of the Yinggehai Basin may involve simple extension and dextral pull-apart, reflected by rifting across the Beibu Basin, possibly as early as the Late Cretaceous (~65 Ma). This deformation was then followed by clockwise rotation of Indochina and the Dangerous Grounds relative to a stable China. Basins in the southern South China Sea also seem to be related to motion on the ASRRFZ, whose western strand follows the line of the East Vietnam and Lupar Faults. Basin stratigraphic analysis suggests basin formation to have started ~45 Ma, somewhat earlier than the 35 Ma start of motion inferred from radiometric dating of metamorphic rocks along the ASRRFZ. Sinistral motion and progressive basin inversion continued until 15.5 Ma, and was in turn succeeded by right-lateral faulting, believed to have started around 10.4 Ma.

Sedimentary Geology

The deep structure of the Song Hong-Yinggehai Basin is illuminated by gravity and magnetic data, as well as dense industrial seismic reflection data. Faulting in the basement is mostly limited to the Oligocene and Lower Miocene section. However, minor amounts of faulting cut high into the section and correlate with a phase of intensified subsidence after ~5 Ma. Active faulting on splays of the ASRRFZ moves from SW towards the NE during the Cenozoic. Inversion progressively affected different parts of the basin during the Middle Miocene to Early Pliocene, migrating from NW to SE. Most of the basin fill is provided by the Red River itself, with little sediment coming from other sources on the basin margins.

Seismic stratigraphy has been used to reconstruct changing rates of sediment flux and this methodology indicates a gradual increase in rates from Eocene to the Middle Miocene, followed by a sharp decrease in the Late Miocene. This variability is believed to mirror progressive uplift in the Tibetan source regions of the Red River, but also intensification of the monsoon rains, followed by drying of the climate after ~15 Ma. Renewed rapid sedimentation is seen in the Pliocene when the monsoon strengthened again. Sediment was derived both from the Red River and also from erosion of Hainan Island that was experiencing volcanism and uplift at that time. Apatite fission track (AFTA) ages in Hainan span 20–30 Ma, but indicate subsequent Pliocene exhumation of 1.5–2.0 km. Nd isotope compositions of the sediments suggests a rapid evolution of the source regions during the Oligocene (33–24 Ma) that may be interpreted to reflect the loss of drainage from the Red River due to headwater capture driven by region surface uplift and eastward tilting of Asia.

In order to better understand the marine erosional record in the Song Hong-Yinggehai Basin a more detailed understanding of the sediment flow and mixing processes in the modern rivers and of the Red River delta is required. A series of geochemical and thermochronologic analyses indicates that the source of modern delta sediment was mixed sedimentary and intermediate igneous rock terrains, with some chemical evidence to suggest input from Chinese loess. U-Pb dating of detrital zircons and Ar-Ar dating of mica grains shows that the ASRRFZ itself accounts for a little over 25% of the total sediment load.

The most effective sediment budgets are those that try to balance volumes of sediment in the offshore with eroded rock on the onshore. Fission track methods are ideal for quantifying the degree of erosion and sediment flux in the landmasses around the South China Sea because exhumation is relatively modest over much of the region. AFTA ages over much of the southern Chinese province of Guangdong range 40–60 Ma, and indicate 1–2 km of exhumation since opening of the South China Sea, broadly consistent with the volume of material in the Pearl River mouth basin. Fission track ages from the Mesozoic sedimentary

rocks of the Khorat Basin in Indochina indicate cooling from 2–4 km around 55–50 Ma, driven by basin inversion. Similar values of erosion have been measured in Laos, but data from Peninsular Thailand indicates faster erosion prior to 20 Ma, likely linked to the rift tectonics of the Malay Basin, followed by slower rates since that time. AFTA ages from the ASRRFZ span 25–33 Ma in the Day Nui Con Voi, with ages ~20 Ma in the Song Chay Massif. Further south in central southern Vietnam the Kontum Massif showed accelerated cooling at 15–7 Ma.

Holocene-Recent Sedimentology

Asia accounts for 70% of the modern sediment flux to the ocean, i.e. around 12,500 million ton/yr, but it is not clear how much of that sediment is delivered to the deep ocean basins. New shallow, high-resolution seismic data now show a well defined sediment lobe, up to 40 m thick, developed offshore eastern China along the Shandong Peninsula up to 300 km from its source in the Yellow River delta. This body has formed since the mid Holocene, after 8000 yr BP. No Yellow River sediment has reached the Okinawa Trough since that time. Similarly, offshore the Yangtze delta the Holocene lobe extends only ~100 km offshore, although sediment is moved south along the margin >800 km. Indeed, isopach maps show that sediment from the Yangtze River now reaches the Taiwan Straits. In addition, 50% of the sediment delivered by the Yangtze is captured in its subaerial delta and 20% in the subaqueous delta, limiting flux to the deep basins. Sediment from the Pearl River appears to be transported to the SW of the delta, a pattern that is also seen around the mouth of the Mekong and the Red River. In this latter case studies suggest that foraminifers have great potential for monsoon intensity studies, as their proloculus size appears to be linked to river discharge and could be a powerful proxy in older sediments. Benthic foraminifers in the modern delta show strong deformation of test morphology under the influence of coal and coal-derived arsenic contamination.

In the Sea of Japan a Holocene sediment body called the Korea Strait Shelf Mud has been interpreted as a high stand system tract body, similar to those developed further to the south. Coring and dating indicates that mud sedimentation occurred between 8000 and 2000 yr. BP. The mud is deposited over an unconformity formed during the last glacial maximum, ~20 ka, and is constructed in three stages, two marked by aggradation and landward onlap (transgressive systems tract) and a middle progradational unit (regressive systems tract). A gradual fall of around 25–30 m in sea level is inferred between 6500 and 3000 yr BP. Rapid rises in sea level are dated at 8000–6500 yr. BP and since 2500 yr. BP. This sea level reconstruction is quite different from many published globally, as it predicts much deeper water for much of the Holocene. This discrepancy may be due to tectonic motions inducing subsidence, or ocean processes, such as intensified flow of the Tsushima Current through the straits (which straits?) during the LGM.

Understanding of the modern sediment flux to the sea is important when interpreting ancient marine climate and erosion records. The relative contribution of the Pearl River, Taiwan and the Yangtze River as sources of sediments to the northern South China Sea is unclear, yet because rainfall and temperatures change radically across the Pearl, Red and Mekong basins there should be differences in weathering products that must be transferred to the deep sea. Greater physical weathering is seen in the Red River basin, while the Mekong basin favors more chemical weathering. The Pearl River carries little smectite in its load, but is abundant in kaolinite. In contrast, kaolinite is much less abundant in the Red and Mekong Rivers. Illite, which is typically the product of physical erosion is most abundant in the Red

River. A linear relationship between Sr isotope composition of the river clastic loads and the degree of chemical weathering implies control by both climate and tectonism on the intensity of the weathering processes in any given catchment.

Further west the sediment in the Brahmaputra River is now being derived from various sources that have distinctive isotopic fingerprints that can be traced into the river sediments. Analysis of these tracers allows the relative contributions of different ranges to be assessed. Boreholes have been used to reconstruct the contrasting and evolving fluxes from the Ganges and Brahmaputra rivers. Sr isotope analysis shows clear temporal evolution, with the Pleistocene values appearing to be much more radiogenic than in the Holocene. In general Brahmaputra sediment shows low degrees of chemical weathering, and there is no temporal variability in the clay mineralogy during the Holocene. Sr and Nd isotope data from the Bengal Fan indicate dominance of flux from the Brahmaputra during the Holocene, while the Ganges shows more influence during the Pleistocene, probably reflecting changes in weathering and erosion during periods of stronger and weaker summer monsoon rains, linked to the glacial cycles.

Tectonics and Erosion in the Eastern Himalaya Region

Located just to the east of the Red River basin the mountains and rivers around the eastern Himalayan syntaxis are important to understanding climate-tectonic interactions in SE Asia because they may have been linked to the Red and other Indochinese rivers in the geologic past. In this scenario drainage capture triggered by surface uplift removed these areas from the Red River system during the early stages of topographic growth. Radiometric dating of the ranges and associated foreland sedimentary rocks indicate that the High Himalaya are formed by at least 15–14 Ma, probably around 21 Ma. In contrast, the modern Lesser Himalaya were formed at 14.5–10.5 Ma. At 10 Ma there is a rapid increase in metamorphic debris into the Indian (Siwalik) foreland basin, suggestive of a major exhumation event in the Himalaya at that time. The Lesser Himalayan crystalline nappe is dated by zircon fission track analysis (ZFTA) at ~8–9 Ma and by apatite fission track (AFTA) at ~7 Ma, implying rapid cooling of the nappe during emplacement at 9–7 Ma.

Apart from direct measurement of orogenic crystalline rocks exhumation may also be reconstructed using a battery of geochemical and radiometric isotope techniques applied to eroded sediments. The differences between a mineral cooling age and its depositional age, known as the lag time, can be used to measure changes in exhumation rates. This approach is especially useful when the original ranges have been completely eroded away, as is the case for the Paleogene Himalaya. Zircon dates from Eocene detrital grains indicates Himalaya erosion had started by that time. Large changes in mineral lag times have been identified at 17 Ma and 11 Ma. At the same time more low-grade metamorphic rock detritus was seen to reach the foreland basin after 17 Ma. Later at 11 Ma major changes are documented in Sr and Nd isotope compositions of sediments indicating Lesser Himalaya exhumation. New work on the Indo-Burman Ranges is now aimed at understanding the evolution of the paleo-Bengal Fan and its related rivers in the Ganges, Brahmaputra and Irrawaddy.

The array of sedimentary analytical tools available for understanding mountain exhumation and sediment routing is now being extended thanks to a new method of bulk sediment Ar-Ar analysis developed for rivers in the western USA, but applicable to SE Asia. The approach shows particular promise in dealing with fine-grained (< 63 microns) terrigenous sediments commonly delivered to marine deltas and fans. Step heating results in progressive degassing of all K-bearing minerals, with plagioclase and K-feldspar grains

likely dominating the age spectra. Intriguingly plateau ages are quite commonly measured in the river sediments, despite the fact that different minerals are contributing to form such a feature. Different rivers along the western USA margin show coherent variations in Ar-Ar ages that relate to the contrasting geology onshore. Comparing basement source ages and the bulk sediment mineral ages has shown a good fit in river examples, and indicates that erosion patterns can be revealed by the bulk sediment Ar-Ar method applied to delta or fan sediments offshore. Application of these methods to sediments from SE Asia promise to reveal much about monsoon-driven erosion in the region.

Future Drilling Plans

The meeting discussed a series of drilling proposals for monsoon-related studies already submitted to IODP and that span a wide range of geography and time-scales. Operations are now proposed on the Sunda Shelf in the southern South China Sea, with the aim of investigating Pliocene-Pleistocene sea level and climate change over glacial-interglacial cycles. The Sunda Shelf is very wide and generally exposed in glacial periods, while it is an important gateway area at times when sea level was higher. Coring in these waters would be relatively shallow sub-seafloor and would require use of a Mission Specific Platform (MSP) due to the shallow water depths.

Drilling is also planned for the Sea of Japan where Dansgaard-Oeschger climatic cycles are known to be preserved since 1.5 Ma as laminated dark and light layers following earlier drilling. The dark layers are formed during interstadial times. Productivity in the Sea of Japan is controlled in part by the flux of nutrients from the Yangtze River, which in turn is fed by the summer monsoon rains. Furthermore, eolian dust in the Sea of Japan is largely blown to this region by winter monsoon winds. This drilling proposal hypothesizes that the Westerly Jet has two semi-stable meandering modes, reflected in the Dansgaard-Oeschger cycles. Eolian dust studies can also be used to look at winter monsoon strength and determine the Westerly Jet axis position. In contrast, summer monsoon intensity can be tracked by organic carbon contents. Drilling is designed to test possible monsoonal controls on Northern Hemisphere glaciation.

On the western side of the same basin monsoon-related drilling is also proposed in the Ulleung Basin offshore Korea. This is a multidisciplinary proposal whose goals span monsoon intensity reconstructions, and assessing changes in oceanic circulation patterns with special regard to the Tsushima Current. Ulleung Basin is located close to the southern gateway into the Sea of Japan, providing a good record of flow through the Tsushima Straits. Monsoon intensity could be tracked by upwelling proxies including biosiliceous sedimentation and eolian dust accumulation rates. In addition the proposal includes tectonic objectives that focus on the nature of strain accommodation during back-arc extension and the emplacement of volcanic sill/flow complexes.

Further south plans now exist for drilling in the East China Sea, where operations are proposed for both on and offshore basins in order to trace monsoon evolution and determine the age of the Yangtze River. The formation of the modern Yangtze River can be used to reconstruct the timing of when the modern east-tilting topography in East Asia was established. Enhanced sediment flux may also constrain gorge incision along the edge of the Tibetan Plateau. A prime objective is to reconstruct the history of the East Asian monsoon and intensification. Large-scale trapping of sediment onshore means that drilling onshore is required in the Jiangnan and Subei Basins. Three sites are targeted for the offshore, including

one in the Okinawa Trough. Models for the existence of a paleo-Yangtze River, pre-dating the capture of the middle and upper Yangtze reaches from the Red River can be assessed.

In the South China Sea drilling of the fans and deltas of the Red and Mekong rivers has been proposed in order to quantify erosion from the eastern flanks of the Tibetan Plateau since the onset of India-Asia collision around 50 Ma. Each fan-delta is targeted by a shallow and deep-water well in order to account for sediment flux whether deposited during sea level high or low stands and to account for the progressive oceanward progradation of deltas through time. The proposal aims to test hypotheses for drainage capture in East Asia and to identify times of gorge incision in Eastern Tibet linked to topographic uplift. A variety of proxies will be used to assess the changing state of continental weathering intensity, which can in turn be used to chart monsoon precipitation intensity and seasonality. The proposal will generate erosion records that can then be correlated with changing monsoon intensity and tectonic events onshore.

Related drilling proposals for the submarine fans of the Indian Ocean were also presented. Plans for the Indus Fan of the Arabian Sea have now been accepted by IODP and aim to penetrate a complete stratigraphic record of sedimentation on the flanks of the Murray Ridge, critically recovering an Oligocene section that should span the initial onset of Himalayan exhumation and which does not exist onshore in the Indian subcontinent. An erosional record for the western Himalaya and Karakoram can be directly correlated with the existing monsoon records from the Oman margin in order to determine interrelationships. On the eastern side of India a mature proposal for the Bengal Fan aims to date the onset of fan sedimentation by coring through the base of the section where it is uplifted, and in so doing provide age control over the vast sediment volumes in the central fan region. As well as looking at erosion over tectonic timescales this proposal has a number of shallower penetration objectives designed to quantify and date at high resolution and time scales of <1 m.y. the construction of the channel-levee complexes that form the bulk of the mid-fan.

Future Research Areas

The meeting agreed that documentation of the evolving climate and erosional history preserved in the ocean basins and on the continental margins of East Asia should be a priority for research on climate-tectonic issues over the next 5–10 years. Recent advances provide the community with optimism that progress is being made in relating climate-tectonic processes in Asia. There is now a general consensus that high topography in central and southern Tibet is likely quite old, probably Oligocene or older, while SE and NE Tibet probably experienced major topographic growth in the last 10 Ma. At the same time monsoon reconstructions are now suggestive of an initial intensification in the Early Miocene, with a series of climatic events since that time resulting in variations of the relative summer and winter monsoon strength. IODP plays a crucial and central role in furthering these efforts, but must be supplemented by related ICDP drilling onshore and by linked fieldwork in Tibet and Indochina. The meeting recognized the importance not only of different disciplinary groups working together to address monsoon-related research, but also geoscientists from different countries throughout the area, especially those in non-IODP member nations, as well as between academic and industrial organizations. International collaboration related to proposed IODP drilling in the Red River offshore was seen as a key first step in this effort.

A priority for future research is the generation of climate records that span tectonic timescales. Without these the relationships between monsoon climate and the solid Earth cannot be understood. While recognizing the importance of earlier work, it was agreed that

monsoon records in the Arabian Sea needed to be extended beyond the 18 Ma presently studied, and that these must be matched by similar records of >25 Ma from the South China Sea and the Sea of Japan. Concern was voiced regarding the fact that the best East Asian monsoon records are now based on winter monsoon proxies, while in South Asia the monsoon is mostly reconstructed with summer monsoon proxies. Questions about whether the South and East Asian monsoon really evolve in step with one another are hard to address without matching records from each area. Outside the generally simple setting of the Oman margin it seems likely that robust monsoon records will likely require use of a series of proxies, as a single measurement is rarely uniquely attributable to the monsoon system alone.

The use of ICDP in furthering our research goals was highlighted. In particular, the meeting identified drilling in sedimentary basins in SE Tibet and Yunnan as probable important targets in providing information on the long-term climate and evolving altitude of the area. Many tools for tracing paleo-altitude and climate changes now exist but the dated sections to apply them on are not always available. Exhumed sedimentary basins exist in Tibet and these need to be studied in order to extend the altitude control that already exists, yet drilling is needed in other areas where appropriate exposures are not exposed. Further ICDP opportunities may exist in the Hanoi Basin, the onshore extension of the Song Hong-Yinggehai Basin. A continental drill site here would be a good location to examine the evolving flux in the Red River itself, generally isolated from other potential sources in coastal Vietnam or Hainan. Similarly, ICDP is needed to sample Yangtze sediment flux in the Jiangnan and Subei Basins.

While recognizing the importance of studying regions of presently strong monsoon activity (e.g., Bay of Bengal, South China Sea) the meeting noted that a complete understanding of the system will require consideration of far-field sites, such as the Sea of Japan, which can act as powerful proxy sites for documenting eolian transport and biogenic productivity. It was concluded that Asia monsoon-tectonic studies should be framed in the context of a wider “mission” integrating IODP, ICDP and related field programs. Individual programs can then be understood in the context of a coordinated, wider research program. Far-field sites are an integral part of the program and need to be supported, as well drilling in the proximal monsoon regions of Indochina and the Bay of Bengal.

The importance of climate modeling in directing observational work was emphasized and the need to develop improved, coupled ocean-atmosphere models that could assess the impact of increasing Tibetan elevations, the formation of the Western Pacific Warm Pool and the retreat of the Paratethys from Central Asia was noted. Although not perfect these models do form an important role in identifying crucial regions for research that can then be targeted for coring or field work. Models with improved spatial resolution are particularly urgently needed, as is the ability to quantify whether there are threshold values in plateau growth that would trigger monsoon intensification.