# Continent-Ocean Interactions within the East Asian Marginal Seas

An American Geophysical Union Chapman Meeting

AGU

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## Executive Summary

Understanding interactions between the continents and oceans represents a frontier area for the ocean and earth sciences in the 21st century. At an AGU Chapman meeting, held in November 2002 and sponsored by JOI/USSSP, the nature of these interactions in east Asia were discussed with presentations examining climate-tectonic interactions, continental-oceanic climate variability, material flux from the great rivers of Asia into the global ocean, as well as how the tectonic development of Asia following India-Asia collision has influenced the oceanic tectonics of the western Pacific. Apart from scientific interest, understanding the climatic systems of East Asia (monsoon and Western Pacific Warm Pool) is of high societal relevance to the countries of that region and worldwide, given the influence these systems appear to have on the global climate.

The sedimentary sequences preserved in the marginal seas that surround the Asian continent were identified as detailed recorders of how continent-ocean interactions have evolved through time in this region, making them appropriate targets for future marine geological and geophysical surveying. Drilling of the Asian marginal seas during the tenure of the Ocean Drilling Program has already lead to important developments in our understanding of how and when these basins formed, and how the paleoceanography of these regions has evolved in response. Significant advances have been made in showing that basin opening was roughly synchronous in the Sea of Japan and South China Sea, suggesting a linked origin, possibly related to continental extrusion tectonics. In climate studies major changes in continental erosion are now recognized starting at 16 Ma, possibly caused by early Miocene monsoonal strengthening, while on shorter orbital and millennial time-scales variations in the oceanic carbon reservoir, which is driven by monsoonal strength, were seen to be modulating high latitude glacial cycles. The paleontological record from the South China Sea also showed that the present West Pacific Warm Pool was formed probably 3–4 Ma, an important part of the El Nino cycle that affects much of the circum-Pacific climate.

The great thicknesses of sediment on many of the passive margins and the common development of hydrocarbons has previously hampered research in the region. However, IODP marks an important change in its ability to drill these previously difficult targets. The meeting made a series of recommendations for possible future drilling goals, including investigation of (1) the rift tectonics in the Asian marginal seas, especially the South China Sea, as a contrast to both the volcanic and non-volcanic margins of the Atlantic, (2) the arc-continent collision zone of Taiwan and the formation of the Okinawa Trough with significance for the origin of the continental crust and the formation of active continental margins, (3) the delta and deep-sea fan complexes associated with the great rivers of East Asia, as records of Tibetan topographic uplift, climate change and the erosional response, (4) the carbonate reefs of the South China Sea, as recorders of high resolution climate and sea-level change, and (5) the Sunda Shelf to establish the long-term history of climate and sea-level changes and its relationship to atmospheric processes where the greatest ocean-atmosphere transfer of heat and moisture occurs. Success in these areas will require long-term commitment and planning by scientists from many sub-disciplines working together with colleagues through the East Asian region.

## Introduction

The marginal seas of the East Asian continent represent natural laboratories for the study of a wide variety of geologic and climatic processes that have been highlighted as being of strong interest to the global IODP community. These basins form the transition between the world's largest continent and its largest ocean and are major repositories of information on the interaction between the two within the tectonic, sedimentary and climatic spheres. In addition, approximately one third of mankind lives in the countries adjacent to the East Asian marginal seas, making the comprehension of their geologic and climatic character important on a societal level. Because of this an AGU Chapman meeting was convened to explore the nature of the relations between ocean and continents, summarizing achievements to date, especially those derived from Ocean Drilling Program exploration in this area, and also highlighting topics for future work. This meeting was directed at bringing together an international and multi-disciplinary group of ocean and earth sciences to examine the origin and development of the East Asian Marginal Seas and to coordinate future research efforts in the region. It was the particular hope of the conveners to foster interaction between normally separate communities such as tectonic and oceanographic workers.

The meeting split into three major thematic sections

(1) Regional tectonics and the forces that drive the opening of the basins,

(2) Sediment transport in the East Asian marginal seas and the sediment fill of the basins.

(3) The paleoceanographic record preserved in the basins.

In order to constrain the possible scope of the meeting we limited the contributions to those on the seas marginal to east and Southeast Asia, but excluded the main Indian Ocean basin. Likewise, we choose to include the Kurile-Sea of Okhotsk region, but not the Aleutians. The Mariana-Izu-Bonin and Indonesian Arc systems were not included since they are not adjacent to the Asian continent, although the interaction of the Philippine Sea Plate with Asia was included. The meeting presented material from the Andaman Sea, the South China Sea, the Gulf of Thailand and Malaysian basins, the East China Sea, the Okinawa Trough, the Yellow Sea, the Sea of Japan (East Sea) and the Sea of Okhotsk. Together these form a series of major basins whose origins may be related and whose development is linked directly to the tectonic evolution of continental Asia. The possibility of direct onshore-offshore correlation is what makes this region especially attractive for study, and uniquely different from the oceanic marginal basins of the SW Pacific.

Understanding how the evolution of Asia and the Pacific Ocean affects the marginal seas was a key goal of the meeting. In addition, we aimed to examine solid earth-climatic coupling in this region.

## SCIENTIFIC THEMES OF THE MEETING

### Regional Dynamics

The origin of the East Asian Marginal Seas is a controversial topic that revolves around the relative importance of continental versus oceanic influences. Resolving this problem is important for understanding the modern geology of the region, but is also of significance to the general problem of why marginal seas open, and indeed how and when they close. This cycle is of interest to orogenic geologists, most notably those studying the Appalachian-Caledonian and Tethyan systems, who use the region as a template for understanding the complex series of rifts and collisions, they see in their ancient records. The significance of understanding the processes that formed the basins of eastern Asia thus extends beyond the immediate vicinity and the regional community.

In one type of model for basin development lateral extrusion of southeast Asia, followed by southern and central China, towards the east may cause basins to open due to lateral shear between major continental blocks (e.g., Tapponnier *et al.*, 1986). Alternatively, some have argued that it is the regional extensional stresses induced by subduction that cause continental arc crust to rift and form marginal seas (e.g., Hall, 1996, 2002). Although radiometric dating of rocks within the major strike-slip fault zones is broadly coincident with the age of spreading, most notably in the South China Sea (Harrison *et al.*, 1996), these ages postdate the start of extensional deformation, at least in the South China Sea (Pearl River Mouth basin), making a convincing correlation difficult. Indeed although the age of spreading is well known from marine magnetic anomaly patterns, the age of onset of extension is not tightly constrained because the syn-rift continental facies of many of the basins have only limited biostratigraphic data. Where marine units are found extension can be seen to have dated from the Maastrichtian (>65 Ma), somewhat before the start of India-Asia collision (55–50 Ma). Some workers (e.g., Wang *et al.*, 1998) have even argued that radiometric ages do not support extrusion-driven rifting. Arguments continue as to whether the timing and degree of offset on the major faults is consistent with a purely continental explanation for basin opening. On the other hand regional basin analysis work (e.g., Wheeler and White, 2000) indicates that the amount of modern dynamic topography or subsidence induced by subduction is small. If induced stresses from the subduction zones bordering the eastern side of the basins are low then these may not be effective in driving the extension during the Cenozoic. In summary it can be stated that the driving mechanisms for marginal sea formation in East Asia are poorly understood.

#### *Rift Tectonics*

The East Asian marginal seas are ideal places to examine the nature of continental rifting, break-up and the onset of seafloor spreading. Although they are mostly inactive today, the young age of the basins means that the basement and syn-rift sediments are not deeply buried by post-rift strata, as seen in Atlantic margins. The oldest oceanic crust has not yet had time to subside to great water depths. The thin cover is important for both seismic imaging and for drilling and sampling of the sediments and basement.

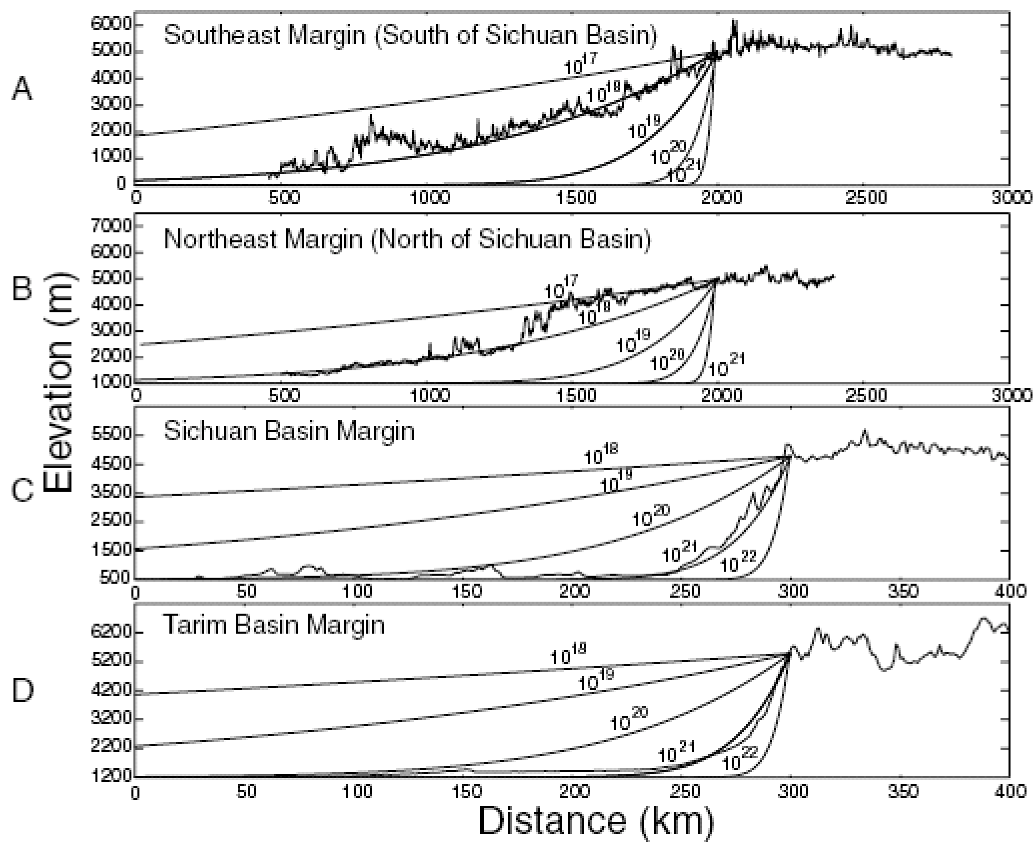
Accessibility to the syn-rift sediments and structures makes these basins ideal for studying extension and the rift-to-drift transition. This latter process is generally poorly documented in major ocean basins, and those that have been well studied typically fall into two very different groups, the non-volcanic (Iberia-type) and volcanic (Greenland-type) margins. Existing studies of the East Asian Marginal Seas suggest that these may not fit neatly into either of these categories. Impressive submarine volcanic centers have been recognized along the southern Chinese margin, as well as from offshore Vietnam and the Dangerous Grounds area. Seismic images show volcanic edifices whose form is suggestive of magmas of intermediate compositions. Although the volcanism might suggest a more Greenland-type rifting event sediments deposited in the rift axis during break-up show deep marine facies, unlike the subaerial exposure that characterize the North Atlantic. The marine conditions preclude very large thermal anomalies under the rift axis during break-up.

The Miocene is a period of rapid magnetic reversals and consequently good marine magnetic anomalies in the oceanic crust, allowing detailed correlation from oceanic spreading history to rifting in the continental crust. The biostratigraphic framework for this period allows a high-resolution record to be derived from the sedimentary fill of the rift basins, which in turn allows rates and timing of extension to be accurately determined. Understanding extension patterns is also easier than normal because the basins typically stopped extending when their width was modest, matching conjugate margins is not difficult, even when flow lines are hard to trace because of poorly defined fracture zones. In South China Sea the propagating spreading center is frozen at the SW end, which allows the two conjugate margins to be pinned there, and aids the correlation of conjugate margins farther east.

All of these factors make the East Asian marginal seas good places to examine rifting in arc crust, if not in cratonic crust, such as seen in the Baikal Rift and the Red Sea. This style of extension represents a large fraction of global rifted margins. A good deal of drilling and seismic data has already been collected by both industrial and academic groups in many of these basins, allowing their evolution to be reconstructed in some detail. As well as shallow crustal reflection seismic images, some basins also have deep penetrating seismic refraction data (e.g., South China, Nissen *et al*., 1995; Sea of Japan, Kurashimo *et al*., 1996). The additional control on the degree of crustal extension provides confidence in the rifting models derived by traditional subsidence modeling techniques, or from shallow structural data. Seismic refraction data also provides the possibility of identifying underplated magmatic bodies that accreted during break-up, similar to those seen in the North Atlantic (Nissen *et al*., 1995). Their recognition and quantification is essential to understanding melting processes during the rift-to-drift transition.

The East Asian marginal seas may be used to address issues such as the nature of strain partitioning along rifted continental margins. Since the recognition of the importance of low-angle detachment faults in governing continental extension in the Basin and Range Province, marine geologists have attempted to apply the same model to passive margins, albeit with greater amounts of extension. Unfortunately, as noted by Driscoll and Karner (1998), workers have tended to interpret all margins as upper plates within simple shear systems, even when the conjugate has already been interpreted as an upper plate.

The most common reason for this apparent problem is that total observed subsidence normally exceeds that expected from the degree of normal faulting imaged seismically. Clift *et al*. (2001) have suggested from data in the South China Sea that this apparent anomaly reflects not simple shear, but instead the preferential loss of the ductile lower continental crust adjacent to the continent-ocean boundary for a distance of up to 100 km. The same loss and subsidence mis-match is not seen basins within the same arc crust but far from the continent-ocean boundary (e.g., Beibu Gulf Basin). The style of rifting may be a function of the thermally juvenile nature of many East Asian Marginal Seas caused by their recent association to active subduction systems. However, the recognition of low crustal viscosity under Tibet and much of southern China (Clark and Royden, 2000) may instead place the East Asian Marginal Seas in a regional context of lower crustal flow.




Topographic profiles from the eastern flank of the Tibetan Plateau used by Clark and Royden (2000) to demonstrate the low viscosity of the Tibetan lower crust. This observation is important because it de-emphasizes the significance of large scale strike slip faulting in accommodating strain in the India-Asia collision and in the formation of the South China Sea. Clift *et al*. (2003) showed that this zone of weak crust extends offshore, controlling the nature of extensional deformation during continental break-up.

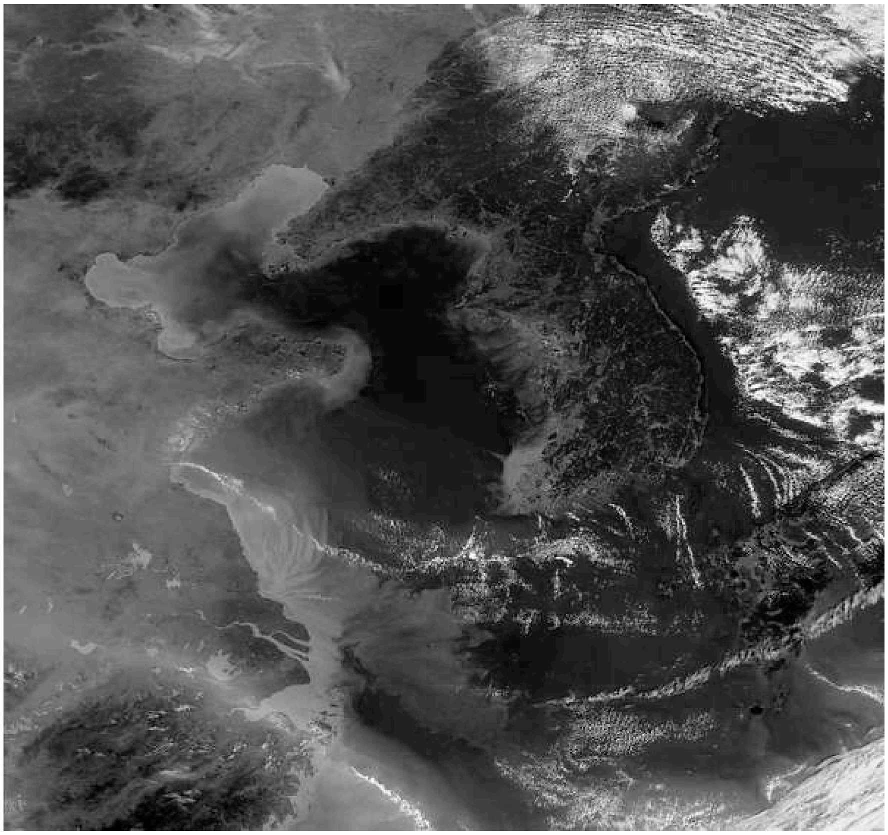
The East Asian Marginal Seas allow models of strain accommodation to be assessed because both sides of a margin can be analyzed and directly compared. Allowing a full mass balance of both margins prevents the generation of inconsistent models for conjugate margins.

*The Sedimentary Fill*

The sedimentary fill of the basins of east and Southeast Asia represents an important repository of information on the tectonic and climatic evolution of the region. Southern Asia accounts for ~75% of the fluvial sediment to the global ocean; the six high-standing islands of Indonesia alone accounting for 20–25%, despite only representing about 2% of the land area draining into the ocean. The large rivers that drain East Asia feed many of the basins and consequently the sediments may record the uplift and erosion of the orogenic belts and plateaus that largely formed as a result of the India-Asia collision. An uncertain amount of sediment, especially in the East and South China Seas is derived from the volcanic island arcs of the region. Other sediment is derived from plate margin collisions, especially from the collision of the Luzon Arc with the passive margin of southern China in Taiwan. The sedimentary fill of the marginal seas thus provides information on the nature of arc-continent collision, the most likely method by which the continental crust has been constructed, at least since the late Precambrian. In addition, records of the evolving arc magmatism are found in the form of tephra. Serious attempts to mass balance the flux of material through active margins on geologic time-scales requires the use of these deposits to assess arc output beyond that exposed in modern arc volcanic islands.

Uplift patterns onshore in Asia largely reflect the nature of strain accommodation during the India-Asia collision. Continental geologists continue to debate the competing roles of lateral extrusion (e.g., Molnar and Tapponnier, 1975), continental crustal subduction and horizontal compression in accounting for continental crust involved in the India-Asia collision. Understanding which of these processes was dominant and during which specific stages in the collision history is important to regional orogenic models. Resolution of this also has significance to the ongoing debate concerning the interaction between climate and orogenic uplift because the nature of strain accommodation influences the generation of high topography, the apparent trigger for much climatic change, most notably the Asian monsoon. The timing of Tibetan uplift in particular has proven to be a difficult issue because of lack of a Tibetan erosional signal in the Indian foreland basin and because of the general lack of a well-dated complete sedimentary record on the plateau itself. Uplift may be traced in part through the marine erosional record, because although the central plateau is flat, the eastern flank is heavily incised by large rivers that carry material into the Asian marginal seas.

The apparent lateral growth of elevated topography due to the flow of low viscosity lower crust out from under Tibet towards the east (Clark and Royden, 2000) might be expected to have had an influence in diverting river courses, while compression of the large east Asian rivers around the Namche Barwe syntaxis of the Himalaya has allowed the progressive capture of drainage basins from one river to another. The end result is documented in the offshore region, where large sedimentary basins are now fed by rivers with very modest drainage basins, most notably the Irrawaddy and the Red Rivers. In these areas offshore sediment thicknesses reach ~9 km (e.g., Yinggehai Basin), but drainage areas are small and marked by low elevations compared to the modern Brahmaputra. The Brahmaputra appears to have captured the drainage basins of the Red and Irrawaddy as it migrates NE with the Namche Barwe orogenic syntaxis. The marine record thus provides a way in which the evolving continental tectonics can be dated and quantified. Changes in the rates of sediment accumulation and the provenance of the sediments will be governed by continental evolution.

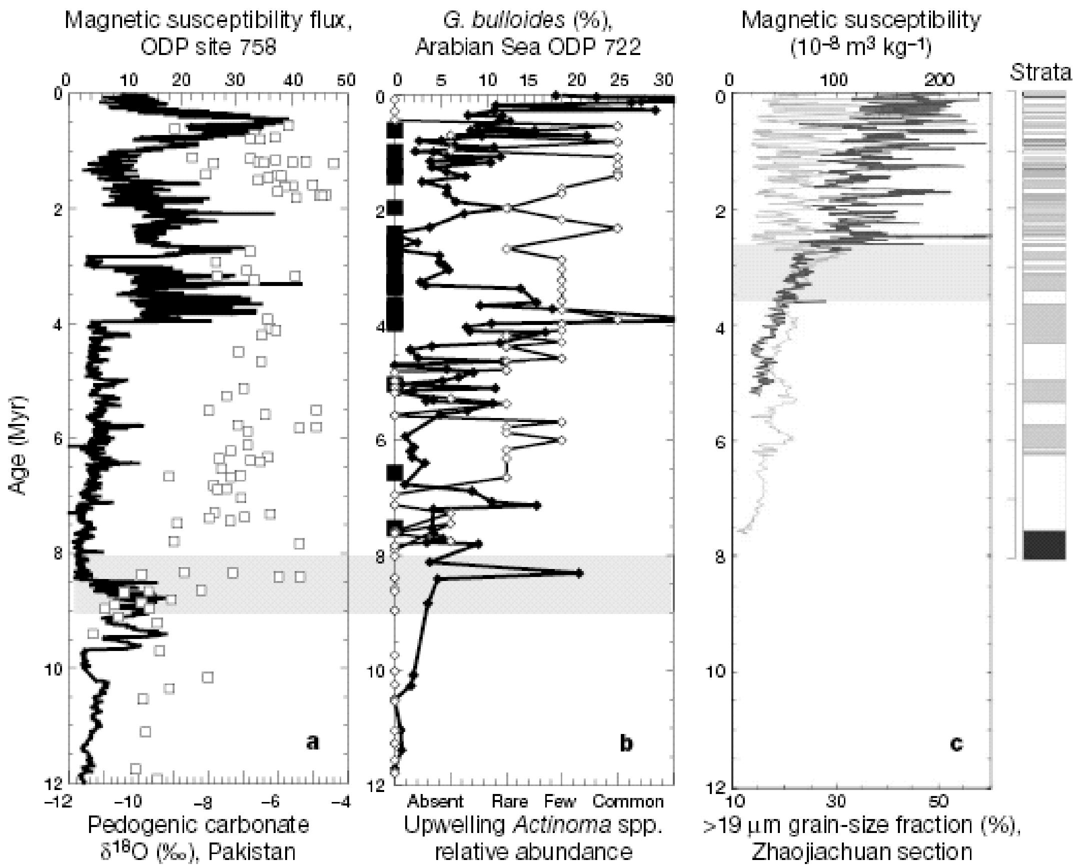


Sediment plumes from the Yellow and Yangtze Rivers are seen in this MODIS satellite image of East Asia. The sediment flux from continent to ocean delivered by the giant rivers draining the Tibetan Plateau represents one of the most dramatic forms of continent-ocean interaction. Sediment flux in East Asia dominates the global fluvial budget.

*Paleoceanographic Record*

The sedimentary fill of the East Asian marginal seas is also a valuable record of the climatic evolution of the region. Changes in the paleoceanography, including circulation patterns, upwelling, and biological productivity may be reconstructed from the foraminiferal assemblages within the sediments. The western boundary currents of East Asia, the Kuroshio and Oyashio, flow through several of the marginal seas and exert an important influence on the climatic evolution of the neighboring Asian continent, as well as productivity in the basins themselves. Because the passageways between the seas are often narrow and shallow the boundary currents are extremely sensitive to tectonic uplift and subsidence as well as rises and falls in eustatic sea level. Circulation is aided by the opening of marginal basins and inhibited by the closure of deep-water gateways. While the rifting of the Sea of Japan (East Sea) allowed flow through that region, the collision of the Luzon Arc with the Chinese passive margin has closed a major deep-water passage, restricting flow to the deepest sill along the Luzon Arc ridge. This sensitivity by the East Asian currents has the effect of amplifying the response of the Asian Marginal Seas to glacial cycles.

Global climatic changes, most notably the northern hemispheric glaciation must have had a profound effect in isolating basins from the open oceans. This is especially true where those basins are rimmed by relatively shallow ridges and continental platforms, as in the Sea of Japan and the South China Sea. In these cases, the basins would have become stagnant or enclosed during glaciations. In some case (e.g., the Yellow Sea) the entire basin would have drained or desiccated during major sealevel fall.




Onshore and offshore proxies for climate change in Asia related to the strengthening of the monsoon (An *et al.*, 2001). Note changes in both marine and terrestrial data at ~8 Ma and 3 Ma indicating strengthening of the summer and winter monsoon.

Beyond global climate changes, the Asian monsoon is generally considered the greatest influence on the paleoceanography of the East Asian marginal seas. The monsoon is one of the major components of the global climate system and its evolution plays a significant role in our understanding of global climates (Webster *et al.*, 1998). The Asian summer and winter monsoons dominate the seasonal winds, precipitation and run-off patterns, and the character of land vegetation over southern and eastern Asia. The monsoon controls the volume and mineralogy of the continental run-off into the seas, as well as the flux of wind-blown dust. In practice the sedimentary fill of the marginal seas provides a record of the continental Asian climate, as well as the paleoceanography, both of which are influenced by the monsoon. The winter monsoon is characterized by high pressure over northern Asia, northeast winds across the South China Sea, and enhanced precipitation in the Austral-Asian equatorial zone. The summer monsoon circulation is characterized by low pressure over Tibet, strong southwesterly winds, upwelling in the Arabian Sea, and high precipitation over southern and eastern Asia. The Asian marginal seas are ideally located to record the paleoceanographic responses to both winter and summer monsoons. Recent drilling by the Ocean Drilling Program of the South China Sea (Leg 184; Wang *et al.*, 2000) now provides the opportunity to study the evolution in this region to compare with the existing Arabian Sea record of Leg 117 (Prell *et al.*, 1989).

Evolution of the Asian monsoon system is thought to reflect at least four types of large-scale climate forcing or boundary conditions: (1) tectonic uplift of the Himalayan-Tibetan orogen, (2) changes in the atmospheric $CO_2$ concentration, (3) changes in the Earth's orbital parameters and the resulting variations in seasonal solar radiation, and (4) changes in the extent of glacial climates. These factors act to amplify or dampen the seasonal development of land-sea heating and pressure gradients, latent heat transport, and moisture convergence over the Asian continent.

Another potentially important influence on global climate in the East Asian region is Pacific circulation and the western Pacific warm pool. These are linked to the East and SE Asian basins and the Indian Ocean by the narrow gateways of eastern Indonesia and the Philippines. Relatively little is known about the impact of these gateways and the warm pool on local or global climate, although there are increasing indications of their importance. Even less well understood is the role of the tropical oceans in the past, the age of the ENSO system, the influence of summer monsoons on high latitude climate, and the sensitivity of global climate to land and sea topography in the tropics. If the warm pool and current systems connecting the Pacific and Indian Oceans are globally important today perhaps there are links between this seaway closure and climatic change in the past, for example as proposed by Cane and Molnar (2001) for Pliocene African aridification. It is probable that the warm pool would not have existed before the Australia-Asia gap was closed or severely restricted but it is uncertain exactly when this closure took place. It is certain to have occurred since 20 Ma and the timing of tectonic events along the Pacific margin at the boundaries of the Philippine Sea plate suggest that critical changes may have occurred at the times often identified with the rise of Asia and the development of the Asian monsoon. At present, the relative importance of these two systems is unclear.

## KEY RECENT ADVANCES

### Tectonics

*Dating of Basin Formation*

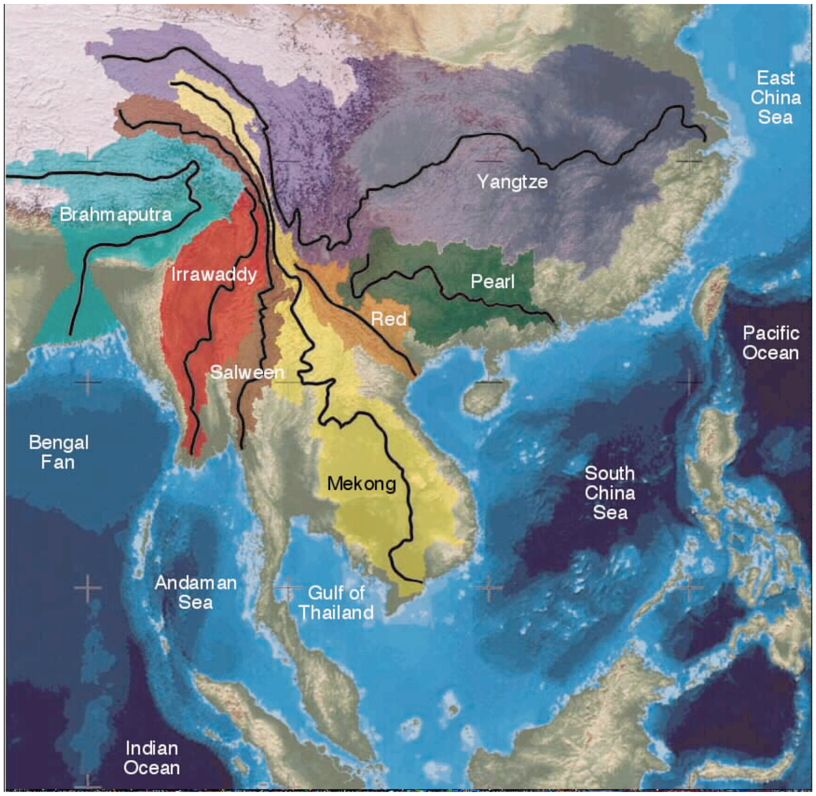
In assessing the progress achieved since the start of the Ocean Drilling Program (ODP), a series of important achievements in our understanding of the East Asian Marginal Seas were high-lighted at the Chapman meeting. Much of the work followed from scientific drilling of the Sea of Japan and the South China Sea. Not least of these research achievements is a first order dating of the major basins and some basic constraints on the age of rifting. When this data is considered along with the recent radiometric dating of the major strike-slip faults that dissect East Asia this has resulted in a strengthening of the apparent link between the tectonic evolution of the Asian continental interior, and especially the eastward extrusion of crustal blocks and the formation of the East Asian marginal seas. At the same time, while a first order correlation exists, the current age constraints on the start of extension in the East Asian Marginal Seas are insufficient to make a detailed comparison convincing. Indeed, continental work in Tibet is beginning to reveal recent rates of strike-slip motion that fall far below the levels initially predicted by the Molnar and Tapponnier (1975) model for strain accommodation, and consequently casting doubt on the ability of the extrusion hypothesis to account for the formation of the East Asian marginal seas. Resolution of the tectonic trigger to rifting must remain as a first order objective for tectonic work in East Asia.

*Deformation of Sundaland*

Further problems with a simple application of the extrusion hypothesis to the East Asian marginal seas has come in the recognition that Sundaland has suffered strong deformation and extension during the Cenozoic, quite at odds with the expected behavior as a rigid block during this time. Nonetheless, our understanding of the regional tectonic development is now enhanced by improved recent paleomagnetic constraints on the motion of mainland China, as well as the crustal blocks of Indochina. The rotation of many of these does not agree easily with a simple extrusion model for Cenozoic Indochina, suggesting a more complex origin for the marginal seas.

*Deformation of Asia and River Capture*

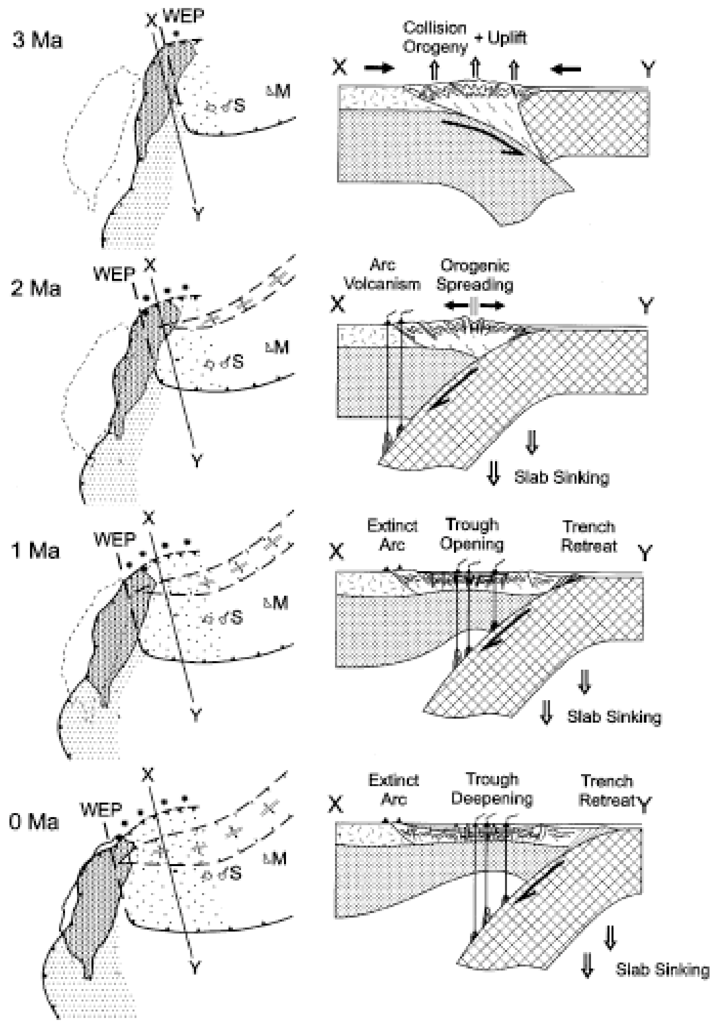
Recent suggestions that lower crustal flow accounts for much of the elevation of the Tibetan plateau and surrounding regions without significant upper crustal shortening (Clark and Royden, 2000) have very important implications for understanding deformation within East Asia and sedimentation in the marginal basins. It is suggested that an erosional land surface of at least 50 Ma age can be traced from China and Indochina onto the Tibetan plateau and this surface is essentially undeformed except for large scale regional tilting. Interpretation of drainage patterns suggests the surface was deeply incised by rivers flowing east and that river capture at about 8 Ma may have led to the present pattern of drainage. If correct, these hypotheses are inconsistent with large-scale strike-slip extrusion deformation of East Asia and Indochina, and imply significant changes in sediment provenance in the last 10 my. Most Asian sediment would have been carried down the Red River or other Chinese rivers to the north. All the basins between the Gulf of Thailand and southern South China Sea margins from Vietnam, Malaysia and Indonesia would have been filled from local sources.




Map of East Asia showing the major drainage basins and the river systems that funnel sediment from Tibetan Plateau to the continental margins in the East Asian marginal seas. Note the narrow separation of rivers in eastern Tibet, allowing ready capture of headwaters from one river to another as the plateau grew and the eastern syntaxis of the Himalaya migrated to the northeast.

*Seismic Tomography and Rifting*

Regional seismic tomography has represented a major important new dataset to the understanding of the East Asian Marginal Seas. The seismically slow, upper mantle that has been recognized under much of SE Asia, and especially the South China Sea, forms a continuum with that under Eastern Tibet. Mantle seismic velocities may reflect increased temperatures but could also be due to small compositional differences, such as increased $H_2O$ or $CO_2$ contents, and it is noteworthy that many of the offshore hydrocarbon-rich basins are characterized by unusually high $CO_2$ contents. The weakened state is important to models for continental extension and magmatism during break-up of the East Asian marginal seas. Work using ODP data from South China Sea now shows that the East Asian marginal seas do not fit into either the Iberia-type amagmatic or Greenland-type volcanic models for continental break-up, but rather form a separate grouping of warm, arc crustal rifts. In this style of deformation the lower crust is mobile and flows into the rift axis from under each conjugate margin resulting in strong subsidence with little upper crustal faulting. Large scale detachment faulting is not recognized, although a wide "Basin and Range" style extensional regime precedes final continental rupturing. The mantle is warm enough to promote break-up magmatism but without the subaerial flood basalt provinces seen in the presence of mantle hotspots.




Tectonic model of Teng (1996) showing the model of progressive arc collision between the Luzon arc and South China, showing that the Okinawa Trough is a product of continued orogenic extension driven by gravity once the reversal of subduction polarity removes the buttressing effect of the Philippine Sea plate.

*Taiwan Tectonics*

The importance of Taiwan as a site of tectonic research has become stronger over the past decade, as it is uniquely well developed to shed light on the process by which oceanic island arc units become accreted to passive continental margins. This is likely the most effective method by which new material is added to the continental margins and through which active continental margins are initiated. New seismic refraction and reflection data collected around Taiwan, added to detailed seafloor mapping, now complement the onshore surveys, allowing the evolution of the collision zone to be assessed. A key advance was the recognition that the northern Taiwan orogen is suffering rapid extension and collapse along major detachment structures, culminating in the total collapse and formation of the Okinawa Trough (Teng, 1996). As such the Okinawa

Trough may represent a whole new class of backarc basin, driven by collapse tectonics, not trench roll-back (Clift *et al.*, 2003). This basin is now one of the major depocenters for the vast amounts of sediment eroded from the orogen. Recent ODP drilling has demonstrated extremely fast accumulation rates in the southern Okinawa Trough reworked by the Kuroshio Current.

Analysis of the sedimentary records recovered by ODP around Asia form the single largest source of information of the evolving paleoceanography of the East Asian Marginal Seas. Key advances in the documentation of the Asian monsoon came from drilling of the Arabian Sea and Bengal Fan, complemented by more recent work in the South China Sea. Drilling suggests that the South Asian monsoon strengthened at 8 Ma, but that this may have occurred at 16 Ma in East Asia. Subsequently the strength of the monsoon has been closely linked, together with glacial intensity to the solar insolation, controlled by the orbital characteristics of the planet. Work has yet to address how the terrestrial evolution of the Asian continental climate, preserved in records such as the loess plateau, is linked to the paleoceanography of the East Asian Marginal Seas.

## Paleoceanography

Because of low sedimentation rates and poor carbonate preservation in the open Western Pacific, the deep-sea sediments in the marginal seas are much better for paleoceanography studies. Up to now, five DSDP/ODP legs plus one site were devoted to the West Pacific marginal seas (Legs 31, 127, 128 in the Japan (East) Sea, 124 to the Celebes and Sulu Seas, 184 to the South China Sea, and ODP Site 1202 in the Okinawa Trough), and the recovered cores, together with numerous piston/gravity cores, have provided unique paleoenvironmental records from the region. Particular attention has been paid to the Sea of Japan and the South China Sea.

### *Sea of Japan*

Increasing number of high-resolution paleoceanographic studies have been conducted especially for the late Quaternary part of the sedimentary record in the Japan Sea (e.g., Oba *et al.*, 1991; Tada *et al.*, 1999). Through these studies it has been demonstrated that the paleoceanography of the Japan (East) Sea, especially the surface water salinity, productivity and the bottom water oxygenation conditions have changed drastically in response to the eustatic sea level changes and intrusion of the East China Sea Coastal Water [ECSCW], the latter having been strongly influenced by the intensity of the East Asian Summer Monsoon and consequent variation in river discharge from Yangtze River. It is now clear that the Japan (East) Sea became semi-isolated, low salinity surface water developed, and deep water became sulfidic anoxic, repeatedly, when eustatic sea level dropped by more than 90 m below the present level. It is also evident that dark sapropelic layers were deposited, repeatedly, during interstadials of the Dansgaard-Oeschger Cycles [DOC]. This phenomenon is explained by variability of East Asian Summer Monsoon synchronized with DOC with stronger summer monsoon during DOC interstadials, and consequent expansion of the low salinity and nutrient enriched ECSCW which lead to the increase in influx of the ECSCW to the Japan Sea during interstadials (Tada *et al.*, 1999). The sediments of the Japan (East) Sea have been recognized as detailed recorders of the monsoon wind strength in East Asia in the form of a high-resolution, well-preserved eolian dust record in the Japan Sea sediments (e.g., Irino and Tada, 2000). These dust record seems to reflect variation in westerly intensity or its position, which seems to have been modulated by DOC.

*South China Sea*

Since the 1990es, the South China Sea has become one of the global foci in paleoceanographic studies. Successive thematic cruises to this sea culminated in ODP Leg 184 which recovered carbonate-bearing deposits over the last 32 my (Wang *et al.*, 2000). Drilling sites along the Chinese passive margin found that carbonate dissolution strengthened and the thermocline depth shallowed around 11 Ma, which might be related to the closure of the Indonesian Seaway, whereas rises in biogenic productivity recorded at about 7.8 Ma and 3.2 Ma were linked to the strengthening of the Asian monsoon at those times. In the southern South China Sea (Dangerous Grounds), an astronomically tuned timescale over the last 5 my was established (Tian *et al.*, 2002), and the high resolution (2–3 kyr) isotopic sequence has revealed a long-term periodicity in the oceanic carbon reservoir responding to 400-kyr eccentricity cycles, and the carbon-reservoir changes preceded major ice-sheets expansion in the Pleistocene. Because the long-term variations of oceanic carbon reservoir are related to low-latitude climate such as monsoons, the low-latitude processes are supposedly modulating the glacial cycles though carbon reservoirs (Wang *et al.*, 2003). The paleontological record from the southern South China Sea also showed that the present West Pacific Warm Pool was formed probably 3–4 Ma.

Much more has been learned from the South China Sea for the late Quaternary paleoceanography, revealing orbital and millennial-scale variations of the East Asian monsoons of the Pleistocene, and centennial-scale variations in the Holocene (e.g., L. Wang *et al.*, 1999). The deep-sea pollen records have shown a striking N-S contrast in vegetation types at the Last Glacial Maximum (LGM): The exposed shelf was covered by grassland in the northern South China Sea, but by forest in the south, indicating the strengthening of winter monsoon (Sun *et al.*, 2000). The monsoon variations based on a variety of proxies in the South China Sea display a major role of precession forcing both in the Pleistocene, and in Pliocene (Wehausen and Brumsack, 2002), again indicating to the significance of low-latitude processes in driving climate changes.

Another aspect in recently developed high-resolution records in the South China Sea is the sea-level history. An example is the abrupt sea surface temperature warming over 1ºC at 14.6 kyr in the southern tropical South China Sea (Kienast *et al.*, 2001), accompanied by the rapid flooding of the Sunda shelf, with a rise of sea level of 16 m within 300 years (14.6–14.3 ky; Hanebuth *et al.*, 2000).

*The West Pacific Warm Pool*

The West Pacific Warm Water Pool (WPWP) represents the largest equatorial heat reservoir of the earth, and plays a key role in regulating the global heat budget (Bjerknes, 1969; Wyrtki, 1981; Bastacov, 1996; Webb *et al.*, 1997; Patrick and Thunell, 1997). The warm pool expands and contracts in response to the strength of both the Hadley (meridional) and Walker (zonal) convective cells (Wyrtki, 1981) and thus exerts a major influence on the equator-to-pole temperature gradient, atmospheric circulation, the location of the convergence zones, and subsequently the relative strength of the southeast trade winds and equatorial upwelling.

The temporal and spatial variability of the WPWP is closely linked to the development of the El Nino – Southern Oscillation (Yan *et al.*, 1992), i.e. easterly migration of the warm pool associated with a shoaling of the thermocline to the west are typical for El Nino years. For the development of predictive climate models it is critical to identify how sensitive the tropics are to changes in climate forcing related to glacial-interglacial cycles (temperature, evaporation, precipitation, heat transfer, oceanic $pCO_2$). The WPWP is a key region to understand these climate forcing mechanisms and the ocean's role in long-term climate change. To better constrain the variability of the WPWP, particularly with regard to temporal and geographical extension, on time scales ranging from decadal variations to Milankovitch type forcing was one of the main objectives of the West Pacific Margin cruise (MD122/MAGES VII, Bassinot and Baltzer, 2001).

*Kuroshio Current*

One of the more significant findings in the paleoceanography of the marginal seas is the glacial shift of the Kuroshio Current. The evidence shows that the Kuroshio Current was running northward mainly outside the marginal seas at the LGM, whereas the modern Kuroshio Current flows through the marginal seas. A switch between the two patterns has resulted in different climates in East Asia and in different water mass structure of the northern Pacific. This glacial decline or even disappearance of Kuroshio Current influence was first discovered in the Okinawa Trough, together with a late Holocene event of the Kuroshio weakening at about 4–2 kyr (Li *et al.*, 1997; Ujiie & Ujiie, 1999); later it becomes clear that the intensity of the Kuroshio Current in the East China Sea displays a periodicity of ~1500 years in the Holocene (Jian *et al.*, 2000). The shift of the Kuroshio Current in glacial cycles has been found also in other marginal seas, but systematic studies are needed to understand its variability at the orbital and millennial time scales, and its relation with other factors in the regional climate system.

*The Indonesian Throughflow*

The modern Indonesian Throughflow represents a narrow band of warm, low salinity water that transports excess freshwater from the Pacific to the Indian Ocean through the Indonesian Gateway (Yan *et al.*, 1992; You and Tomczak, 1993; Gordon and Fine, 1996). Sealevel-controlled fluctuations of the Indonesian Throughflow strongly influenced the paleoceanography of the Eastern Indian Ocean and Western Pacific Ocean during the Quaternary. During the last glacial cycle, changes in the intensity of the South Asian monsoon and productivity fluctuations in the easternmost Indian Ocean have been closely related to the strength of the Indonesian Throughflow (Wells and Wells, 1994; Wang *et al.*, 2000; Müller and Opdyke, 2000). However, neither higher frequency glacial fluctuations on a Dansgaard-Oeschger timescale, nor changes related to ENSO-cycles (Meyers, 1996) are documented. The long-term history of the Throughflow and its influence on the temporal and spatial variability of the West Pacific Warm Pool and consequent climatic and paleoceanographic changes are extremely poorly understood. Today, the West Pacific Warm Pool plays a key role in regulating the heat budget of the Earth (Bjerknes, 1969; Wyrtki, 1981; Bastacov, 1996; Webb *et al.*, 1997; Patrick and

Thunell, 1997). Kennett et al (1985) proposed that closure of the Indonesian Gateway in the Middle Miocene had dramatic repercussion on circulation patterns in the Pacific Ocean and was a critical trigger for global climate change. Latest plate tectonic reconstructions of SE Asia for selected time slices of the Cenozoic by Hall (1996, 2002) show that the Indonesian Gateway was an area subjected to intense tectonic activity from the Middle to Late Miocene. Significantly, Hall's reconstructions indicate that the Molucca Sea, a very wide area forming part of the Philippine Sea plate until about 15 Ma, was eliminated by subduction beneath Halmahera by about 12 Ma. Thus, the scenario of a rapidly closing deepwater gateway between the Indian and Pacific Oceans during the Middle Miocene is increasingly supported by geological, paleomagnetic and tectonic evidence in SE Asia.

A late Pliocene closure of the Indonesian seaway as a major passage of warm surface water flow from the Pacific to the Indian Ocean at 3-4 Ma was suggested by Cane and Molnar (2001). These authors used simple theory and results from an ocean circulation model to show that the northward displacement of New Guinea since approx. 5 Ma may have switched the source of the Indonesian throughflow waters from warm South Pacific to relatively cold North Pacific waters. This would not only have decreased sea surface temperatures in the Indian Ocean leading to the aridification of East Africa around 3-4 Ma, but also may have reduced atmospheric heat transport from the tropics to high latitudes (end of the Pliocene “permanent El Niño”), stimulating global cooling and the growth of ice sheets.

*Sealevel rise since the last glacial maximum: critical boundary conditions for reconstructing the history of the Indonesian Throughflow*

Intensity and pathways of the Indonesian throughflow are significantly influenced by sealevel fluctuations. Especially a precise reconstruction of the sealevel position during the last glacial maximum (LGM, 22 000 to 20 000 years B.P.) is of major importance for the understanding of the glacial circulation pattern within the Indonesian passages, (i.e. since the broad and shallow NW Australian shelf, which today is a major passage for the shallow water throughflow would have been completely exposed at a LGM sealevel below -130 m). High resolution reconstructions of the late post-Pleistocene sea-level rise along transects on the Sunda Shelf (Hanebuth *et al*., 2000) and the North-Australian Bonaparte Gulf (Yokoyama *et al*., 2000) have recently fueled the ongoing controversy on the sea-level position during the LGM (see discussions of the EPILOG (Environmental Processes of the Ice Age: Land, Ocean Glaciers) working group, Clark and Mix, 2002; Peltier, 2002; Lambeck 2002). Evidence for a marginal marine to brackish facies at 121 m below the present day sealevel was provided from the Bonaparte Gulf offshore NW-Australia (Yokoyama *et al*. 2000). A sealevel lowstand of approx. –135m was initially proposed, based on calculations of the geoid and estimates of the glacial global ice volume (Yokoyama *et al*., 2000), however, these calculations were partly based on unrealistic model assumptions (Peltier, 2002, Lambeck *et al*., 2002). Recently, the broadly accepted lowstand of –116 m to –120 m (Hanebuth *et al*., 2000; Peltier, 2002) below present has again been cast into doubt, and a lowstand of as much as -135 m is once more favored (Peltier, 2002).

# AREAS OF FUTURE RESEARCH

## Tectonic

In order to better comprehend the relationship between the tectonic evolution of East Asia and the East Asian Marginal Seas the first requirement is better age control on the development of the marginal basins. The current poor dating both on land and offshore makes correlation between processes easy but unconvincing, most noteworthy being the approximate match between motion on the Red River Fault and the rifting of the South China Sea. Drilling and dating of continental margin sediments and basement would greatly aid this effort, but must be accompanied by continued onshore work on the strike slip faults. Controversy continues as to the significance of strike slip faulting in the overall development of East Asia and its marginal seas. Only by further work, exploring new data sets, such as stratigraphic and provenance work from the sedimentary fill of the pull-apart basins along the faults, can the true amount of offset along the faults and their timing be defined. Without such definition then no meaningful comparison of the terrestrial and marine evolution can be made.

A regional compilation of tectonic, climatic and erosional events all across the East Asia area is a priority needed to define existing patterns of deformation and to highlight where the most crucial advances are needed. The age controls bear directly on one of the most outstanding tectonic issues yet to be addressed and that is determining the trigger for basin formation in the first place. The similar ages of the Asian marginal seas does suggest a possible common origin, a hypothesis that is largely unconstrained at the present time.

Any serious attempt to tackle this wider question of basin origin must necessarily tackle the history of the Philippine Sea Plate. While this is not one of the East Asian marginal seas itself it shares plate boundaries with parts of South China Sea, East China Sea and the southern Sea of Japan. The rotation history and rates of subduction of the Philippine Sea Plate need to be understood if its possible influence on the rifting of the marginal seas is to be quantified. Of special interest is an improved dating of the oceanic lithosphere within the western Philippine Sea, representing the oldest crust predating the start of subduction along the Mariana-Izu Trench. Current dating of this crust is only loosely defined using magnetic anomaly data and needs to be ground truthed by drilling of the oceanic crust in a number of key locations.

The tectonic evolution of Taiwan was highlighted as a region for future study. Significant work in the region over the last ten years has now defined the basic framework of an arc-continent collision zone between the Luzon Arc and the South China margin. What is not clear is when this collision began and to what extent the collision point has been migrating westwards along the margin since that time. Apart from the tectonic significance the timing of collision is important to paleoceanographers trying to understand the significance of the Taiwan Strait as an oceanic gateway, controlling the flow of the western boundary currents. Of special interest to the collision story is the reversal of subduction polarity. There is a need to better define the plate boundaries in this region both at depth in the upper mantle and at the surface. In particular, we wish to define where the lithospheric slabs are underthrusting, what is the role of slip partitioning between the Luzon Arc and the Philippine Sea Plate and how does the Taiwan Orogen pass north from compression into extension of the Okinawa Trough?

A major missing data set that represents a priority for future work is a high-resolution structural and stratigraphic model of the East China Shelf. Unique in the East Asian marginal seas the East China Sea has no published deep penetrating seismic profiles that define the regional character of the sea. This is essential for a number of goals including (1) models of regional extension throughout east Asia, (2) the role of the Okinawa Trough and Taiwan-Shinxi Fold Belt in the arc-continent collision process, (3) quantifying the sediment flux from the Yangtze through time, with implications for the uplift history of the Tibetan Plateau and the strengthening of the East Asian monsoon. Defining the older extension history of the East China Sea is one aspect of a greater regional need to better define the pre-Cenozoic structure of East Asia, as this forms the template on which all later deformations are superimposed. Although the Cretaceous subduction history of southern China is relatively well understood and dated this is anomalous in a region where the nature of the older basement is often obscure and the timing of tectonic events unknown. Sundaland represents a classic example of this issue, due to lack of deep penetrating seismic and well data.

Another stated goal for future research is to improve the regional coverage of dated seismic reflection profiles in order to better constrain the flux of sediment to the oceans during the Cenozoic. Only by covering both shelf and slope areas can the true flux of eroded materials to the oceans be constrained. Because of the limited accommodation space for sediment onshore in East Asia much of the eroded sediment carried by the rivers must be directly delivered to the marginal seas. Understanding this flux is important for constraining the influence of East Asian rivers on the chemistry of the global ocean and also to assess the erosional impact of Tibetan uplift and monsoon strengthening. In order to do this it will be essential to have a good estimate of clastic fluxes from the volcanic arcs bordering all the marginal basins on their east sides. Prevailing winds should carry significant amounts of sediment into the basins for most of the year, and for the Cenozoic as a whole, the almost continuous subduction at the East Asian margins means that a large proportion of material should have been derived from this source.

Going along with this effort the modern discharge character of each of the large river systems also needs to be better characterized. Existing data indicates that the erosion of East Asia and Indonesia dominates the global sedimentary flux from continents to the oceans, emphasizing the need to document the rivers of the region if their influence on the global ocean is to be constrained. Data on the relative volumes of dissolved versus bedload flux are needed, as are seasonal records of how each river responds to the cycle of winter and summer monsoon. If offshore clastic sediment records are to be used to identify and date river capture events within the continental interior, potentially driven by Tibetan uplift, then the chemical and mineralogical character of the modern river bedloads need to be characterized. Only after a provenance fingerprint for each modern river and its drainage basin has been defined can we begin to look for changes in this flux offshore.

## Paleoceanography and Climate

A number of the paleoceanographic objectives in East Asia overlap with the tectonic goals, reflecting the strong emphasis on understanding how the tectonic development has controlled the climatic evolution. Documentation of the sediment and chemical flux budgets from the large rivers of east Asia are needed to understand how these affect the regional and global ocean chemistry. It is now understood that the region is easily the largest fluvial influence on the global ocean and better quantification of that flux is needed. This is true not only on the seasonal and yearly time scale but also over geologic time scales that will require high resolution regional seismic profiles and associated shallow coring, as well as deep drilling. The flux to the ocean cannot be properly understood without the better documentation of the deltas themselves, the simplest form of land-sea interaction. Seismic mapping and coring has begun to reconstruct some of these areas (e.g., Mekong), but many of the other river mouths are poorly understood. These efforts are not unrelated to the important issue of how human activity has affected the land-sea interaction because the river flood plains and their deltas are the location of much of the agriculture and settlement in this region. How has the sedimentary history of the river flood plains affected the human colonization of the region, especially in the Yangtze and Mekong regions? How did this change during the rapid sea-level rises that followed the last glacial maximum? Conversely, if modern river flux data is to be used to interpret the geological record then the influence that human activities have played needs to be understood, since widespread cultivation in the river valleys has increased the sediment flux to the oceans in the recent past.

Another aspect of climatic tectonic interactions that needs to be explored is the relationship between the opening of the East Asian marginal seas and the strengthening of the western boundary currents, especially the Kuroshio Current. If better tectonic histories are available these models may be testable, but only if the history of the currents is known over long periods of geologic time. At the moment their origin and history of strengthening is poorly defined. Understanding how the strength of the currents is related to tectonic triggers, as opposed to global climatic factors, such as glaciation is important, not least because of the role these currents play in driving the biological productivity in the marginal seas.

Understanding climatic variations on small time scales and in high resolution is a key goal for understanding land-sea interactions in East Asia. Naturally these cycles operate on orbital and suborbital scales and will not be linked to tectonic evolution. Nonetheless, their relationship with the continental climate needs to be improved. This involves new work on and offshore. The recent revelation that the continental loess record may extend back to 22 Ma in central China opens up the possibility of a detailed, well dated continental climate record that needs to be reconstructed and correlated with marine sequences. How does strengthening of the monsoon affect the oceanic circulation compared to the continental climate? Detailed climate records exist for parts of the South China Sea and the Sea of Japan, but regional coverage of the expanded high sedimentation rate sequences is otherwise poor, beyond one recent section in the southern Okinawa Trough.

Interpretation of the ancient record must require a good knowledge of how the climate systems of the region interact with one another on ultra-short time scale, documented either through modern instrumentation, as well as high resolution coring. Climatic and oceanographic variability during the rapid oscillations in stage 3 was identified as a key time period for future work. In addition, the relationship between monsoon strength and ENSO was highlighted as a objective for high-resolution study at millennial and sub-millennial time scales. Lastly, the role of the tropics in the global climate system needs to be defined and quantified, with specific reference to the behavior of the Western Pacific warm pool. This goal has strong societal relevance for future climate change work, as well as for the reconstruction of past climate change events. The Western Pacific warm pool is itself linked to the efficiency of Indonesia to act as a gateway between the Indian and Pacific Oceans, a gateway whose long-term history has been tectonically controlled. However, short-term variability of Indonesian through-flow is known and may be related to climatic factors, as well as sealevel changing the depths of the sills through the Indonesian archipelago, in turn controlling the volumes of water that can pass. Studies to quantify such flow must require interchange with physical oceanographers, whose detailed measurements can define the present nature and variability of the through flow.

Understanding the influence of eustatic sea-level variations in controlling the paleoceanography of the East Asian marginal seas was identified as a key target for future work. All the seas are heavily influenced by sea level. The East China Sea is exposed during sea level low stands, while the deeper basins of the South China Sea, Sea of Japan and Sea of Okhotsk are largely isolated from interchange with the Pacific Ocean. Thus variations in sealevel may be quantified by the stratigraphic record of the marginal seas, work already started for the last deglaciation in the East China Sea, but work that remains to be addressed in detail in other basins and on longer time scales. Any reconstruction of regional paleoceanography for any of these seas that did not appropriately account for such a large driving control cannot be correlated meaningfully with the continental climate or with tectonic events. However, because sea level must affect all the marginal seas, albeit in different fashions, basin-to-basin correlation can be used to deconvolve regional from supra-regional signals such as sea level. Clearly, well-dated complete stratigraphic records will be required from each of the marginal seas if that exercise is to be performed.

**Areas for Future Ocean Drilling**

Given the list of future key objectives a number of possible areas were discussed with a view to future scientific drilling. The Gulf of Tonkin was highlighted as being a sedimentary basin that may contain an especially complete record of Tibet uplift preserved in the changing sedimentation rates and provenance of the basin fill. Moreover, lying along the line of one of major strike-slip zones implicated in the extrusion tectonic hypothesis drilling of this region may provide important constraints on a number of outstanding continental tectonic and climatic issues

Drilling of the Taiwan collision zone and especially Okinawa Trough was identified as area that would address tectonic geologic objective not covered during ODP but for which extensive complementary geophysical data sets now exist. The sedimentary fill of the Okinawa Trough may preserve not only the exhumation history of the Taiwan

Orogen but also the evolving strength of the western boundary currents of the western Pacific, most notably the Kuroshio Current. Tectonic drilling of the Ryukyu Ridge is required to test controversial models for continuous arc accretion that would predict the presence of deformed Luzon Arc crust rather than Chinese continental basement.

Drilling of the continent-ocean transition within the South China Sea was pin-pointed for its use in dating the enigmatic magnetic anomalies that mark the transition and provide better ages that can be compared to the dated continental extension on the shelf, thus allowing the nature of strain accommodation during break-up to be assessed. Furthermore, samples of the break-up related volcanism will allow the thermal and chemical state of the mantle underlying the rift axis to be determined. Finally samples of the oldest oceanic crust allows the proposed flow of continental material oceanward during break-up to be tested.

Climate-related drilling in the East Asian Marginal Seas may be directed at the carbonate platforms in South China Sea. As indicators of changing climate, sealevel and continental run-off they offer a rich source of information. Although the reef complexes on the Dangerous Grounds may be located in regions too politically sensitive for ready drilling at the present time there are other suitable sequences on the Vietnam and Chinese margins for which seismic reflection exist and which can be used to address similar questions, probably via a mission specific platform. Additional climate related drilling is recommended for the Sunda Shelf region, in the shallow epeiric seas of Southeast Asia and northern Australia. This drilling target will likely require deployment of a mission specific shallow-water platform in order to core a stratigraphy that is anticipated to allow the establishment of a long-term history of climate and sea level changes, which may then be related to atmospheric processes in a region where the greatest ocean-atmosphere transfer of heat and moisture occurs. In addition, drilling of the Sunda Shelf permits a unique comparison of modern tropical epeiric seas with the widespread cratonic seas of the pre-Neogene.

The meeting noted that paleoceanographic drilling in East Asia will need to address the Sea of Okhotsk because this is a possible source area for North-Pacific deep or intermediate water formation during glaciation, and thus potentially an important control on the regional climate. At the present time there is insufficient marine geophysical survey information to allow competitive proposals to be submitted from this area.

Although lying outside the specific area of concern for this meeting the participants recognized the potential importance of drilling in the Banda, Celebes and Sulu Seas, as this arcs and associated backarc basins form a essential link between the East Asian Marginal Seas and the Australian margin. Understanding how these basins have evolved is important to constraining the development of the Philippine Sea Plate, which influences so many of the other major basins along its westerly subduction boundary. In addition, the Indonesian basins form the crucial gateway whose closure allows the western Pacific warm pool to develop and also strengthen the western boundary currents of the region. If the relationship between tectonic evolution and these paleoceanographic phenomena is to be quantified then an improved documentation of the Banda, Celebes and Sulu Seas will be needed.

## Summary

The Chapman Meeting on "Continent-Ocean Interactions in the East Asian Marginal Seas" highlighted important advances in our understanding of how the tectonic evolution of East Asia and especially the Tibetan Plateau has influenced the regional climate and paleoceanography since the Oligocene. Despite important advances in documenting variability in the Asian monsoon and western Pacific warm pool, as well as in nature of continent-arc collision in Taiwan and in the nature of strain accommodation in the rifting of the South China Sea, much work remains to be done in quantifying the nature of continent-ocean interactions in East Asia. Still no clear link between Tibetan uplift, monsoon strength and erosion can be demonstrated. Indeed the tectonic trigger to the formation of the East Asian Marginal Seas is still debated between the influence of continental extrusion tectonics versus trench forces, along the Pacific rim. We conclude that a number of first order scientific questions to the ocean and earth sciences community can be addressed through work in the East Asian Marginal Seas and that new international programs such as IODP now offer new opportunities to examine the deep structure and stratigraphy of these margins, making the solution to some of these problems tractable for the first time.

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## Appendix A: Abstracts of Presentations

**Problematic Palaeomagnetics and the Position of Palaeogene Eurasia: a Review; Implications for the Tectonic Modeling of East Asia; Efforts to Resolve the Issue**

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Palaeomagnetic data provide key quantitative information for the positioning of crustal blocks, and have proved particularly valuable in modeling the Cenozoic tectonic evolution of continental eastern Eurasia and its adjacent marginal basins. In essence "arriving" blocks and arcs and opening basins are positioned relative to a "fixed" (in reality slowly moving) Eurasia. However, the palaeomagnetism community is currently debating the mechanism and effects of what is termed the "stable Asia shallow inclination problem". That is, assuming a coherent Eurasia, palaeomagnetic data obtained from Upper Cretaceous-Miocene red-beds from "stable" central Asia are too shallow with respect to Palaeogene Eurasia's apparent pole, which is based almost entirely on data from the British sector of the North Atlantic Igneous Province (NAIP). Several explanations have been proposed, the most radical being an incoherent Eurasia with tectonic boundaries along the Tornquist-Tesserye Line and/or Ural Mountain belt (Cogne et al., JGR, 1999). With a possible positioning error of ~1600 km for southern and eastern Eurasia, the implications for modeling for the India Collision are critical and for marginal basin formation in E-SE Asia, extrusion model and arc-arc collision in central Japan etc are quite considerable. The "shallow inclination" issue will be reviewed, followed by a discussion of the various efforts palaeomagnetic workers are currently carrying out to resolve the problem. These include a reinvestigation of NAIP rocks (Rissager et al., EPSL, in press: old NAIP pole too high), and the first datasets from (i) mid-late Palaeogene basalts from central Asia (Bazhenov & Mikolaichuk, EPSL, 2002: old NAIP pole about right) and (ii) Lower Eocene sedimentary rocks from southern England (Ali et al., GJI, in review: old NAIP pole too high).

**Response of Southeast Asian marginal basins to the India-Asia collision**

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The formation and demise of Southeast Asian marginal basins such as the South China Sea Basin and the Sulu Sea Basin have, on the one hand, been directly related to the India-Asia collision as in the extrusion tectonics model, and on the other hand have been attributed to processes that are unrelated to the collision. New age and geochemical data from the Palawan ophiolite in the western Philippines, place new geodynamic constraints on the formation of these marginal basins. The data seem to require that initial opening of the South China Sea was a response to extrusion tectonics, but then subsequent stages of opening may have been aided by slab pull from the south dipping subduction zone associated with the Cagayan Ridge-Sulu Sea Basin arc-backarc system.

The island of Palawan is located between the South China Sea and the Sulu Sea. Central and southwest Palawan consists of two ophiolite slabs and continent-derived turbidites deposited on the proto-South China Sea basin floor. The ophiolites and turbidites form thrust slices that are part of the Palawan accretionary complex associated with the Cagayan arc-Sulu Sea Basin backarc subduction system. The Cretaceous ophiolite represents a sliver of proto-South China Sea basin seafloor trapped between the North Palawan Continental Terrane and the Cagayan arc. The Cretaceous-Eocene turbidites represent the sedimentary carapace of the Cretaceous ophiolite. Thrust on top of these two units is a separate ophiolite sheet recently dated as latest Eocene-earliest Oligocene (~34 Ma). This latter ophiolite is the main ophiolite body exposed in central Palawan. Trace element data from available samples from five separate areas of the ophiolite all have N-MORB characteristics with a hint of IAT characteristics in a few sample in terms of some trace element ratios (e.g., Hf/Ta and Th/Hf). Differentiation trends using major and minor oxides are like those of “mature” backarc basins such as the Mariana and Lau backarc basin. The main Palawan ophiolite is therefore interpreted to be a fragment of a mature backarc basin similar to the Lau and Mariana backarc basins. I tentatively suggest that the arc associated with this backarc basin is now found in the Zamboanga Peninsula. The onset of this arc-backarc system is not known.

The age of formation of the high temperature and pressure metamorphic sole of the ophiolite, which formed during the initiation of south-directed subduction, is indistinguishable from the crystallization age of the ophiolite. This strongly suggests that detachment of the Palawan ophiolite occurred at a spreading ridge. This in turn requires that an external force initiated thrusting and subduction initiation because of the buoyancy of young zero age lithosphere as well as the "ridge push force". The ages cited above, available ages from the Red River Shear zone, including U-Pb crystallization ages from high grade gneisses at 32-33 Ma, and the age for the oldest magnetic anomalies in the South China Sea basin at ~30 Ma, all strongly suggest that extrusion of the Indochina block provided the external force to initiate thrusting/subduction along the Palawan ophiolite backarc spreading center and opening of the South China Sea.

During the early stages of thrusting in the backarc, young hot oceanic lithosphere was underthrusted beneath what is now the Palawan ophiolite. However, the young lithosphere was followed by underthrusting of older, denser, early Cretaceous oceanic lithosphere (fragments of which are preserved beneath the main Palawan ophiolite). Once the Cretaceous lithosphere began subducting, a significant slab pull force could have come into play in the opening of the South China Sea. This suggested shift in geodynamic forces in the opening of the South China Sea basin may explain the two-stage strain pattern observed along the eastern edge of Indochina: an earlier stage consistent with extrusion tectonics and a second stage consistent with slab pull-induced opening of the South China Sea basin. Development of the Cagayan arc and opening of the Sulu Sea Basin south of Palawan followed the initiation of subduction.

The collision of India with Asia therefore forced the closure of some existing oceanic basins (preserved as the Palawan ophiolite) as well as forced the opening of others (South China Sea basin). It also initiated at least one new subduction zone (Palawan trough-Cagayan arc system) that in turn spawned another marginal basin (Sulu Sea basin)

**Extracting Dynamic Topography from Sedimentary Basins in SE Asia**

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The demonstrable existence of dynamic subsidence and uplift has important implications for understanding sedimentary basin formation, relative sea-level changes, as well as the Earth's viscosity and density structure. In SE Asia, dynamical predictions are thought to be well constrained since the history of subduction is reasonably well known and thus it is an important region to analyse. Here, I present the results of a combined analysis of 417 age-depth intercepts from oceanic marginal basins and 353 boreholes from the fringing continental shelves. This joint analysis constrains the maximum amplitude of dynamic subsidence to be ~300 m with a range of 0-500 m, significantly less than predicted. There is also disagreement between the predicted and observed distribution of anomalous subsidence as well as inconsistencies in initiation and duration. These results suggest that mass excess within the SE Asian mantle, represented by subducted slabs, has little discernible effect on surface topography. Instead, subsidence and marine inundations throughout the region are predominantly controlled by lithospheric extension and/or by foreland loading. The lack of dynamic topography suggests that mass excess generated by mantle convection is generally decoupled from the surface. In contrast, mass deficiency appears to generate significant topography.

**A New Geodynamic Model for the Evolution of Australia's Northwest Shelf and Southern Southeast Asia**

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The Argo and Gascoyne Abyssal Plains off northwest Australia are the only preserved patches of Tethyan ocean floor, containing vital information about the plate tectonic evolution of northeastern Gondwanaland, the eastern Tethys and Southeast Asia. Subduction of the oceanic crust north of Australia has destroyed evidence of the exact configuration of seafloor spreading around northeastern Gondwanaland.In this study magnetic and gravity data from the Argo and Gascoyne Abyssal Plains have been interpreted jointly with compiled geological information from the Northwest Shelf and Southeast Asia to reconstruct Tethyan oceanic lithosphere based on the assumption of symmetrical seafloor spreading. The interpretation of magnetic data has been constrained by modelling synthetic magnetic profiles, sequence stratigraphic analysis, industry well data and ODP/DSDP results. On the basis of lithological affinities of sequences exposed in the Indo-Burman Ranges, Timor and surveyed by seismic profiles and drilling on the Exmouth /Wombat Plateaus the West Burma Block has been identified as the continental fragment breaking up from the Northwest Shelf in the Late Jurassic. Seafloor spreading off northern Australia separated this block first in northward motion before the drift path became fixed relative to the motions of the Middle Greater India Block. According to our model the West Burma continental fragment was accreted to the Southeast Asian mainland in Santonian / Coniacian times (85- 80Ma) in the vicinity of present day western Thailand. We used mantle tomography(S20RTS model) to further constrain the subduction history of our model. Positive P-wave velocities beneath Sumatra and the Malay Peninsula in a depth of 1000 - 1200km could indicate the piece of subducted Meso-Tethyan oceanic lithosphere that was originally situated north of the West Burma Block and broke off after West Burma was amalgamated to Southeast Asia. A new subduction zone was initiated west of the accreted block, consuming Neo- Tethyan and Indian ocean lithosphere, which could be represented now by shallow (100-400km) P-wave anomalies beneath Sumatra the Malay Peninsula. Our plate model and paleo-age grids for the Neo-Tethyan Ocean are useful for constraining the history of sedimentary basins in Southeast Asia, and will be used as input for regional mantle convection models.

**Plate Boundary Configurations in SE Asia: Results From Geodynamic Modelling**

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The configuration of plate boundaries in SE Asia, the region between continental Eurasia and the Pacific plate, is a tectonically complex region with abundant constraints allowing us to address outstanding questions. The region is characterised by numerous micro-plates, which are separated by a complex system of subduction zones, marginal and back-arc basins, strike-slip boundaries and accreted terranes. This level of complexity is observed in the present day and likely existed here in the past. However much of the evidence for this earlier tectonic complexity has subsequently been destroyed.

In an attempt to decipher the configuration of plate boundaries in SE Asia during the Cenozoic as well as to understand the forces driving the complex motions and deformations, we are formulating 3D time-dependent geodynamic models of the region with a particular focus on the Philippine, Caroline and South China Seas. Our geodynamic modelling is a combination of three separate but inter-related techniques:
(1) Plate tectonic reconstructions of the region through time determined from the spreading histories of several oceanic basins in the region (using all available gravity, magnetic and bathymetric data) and linking their history to known aspects of the surrounding areas, based on onshore geology.
(2) Mantle convection modelling in which our plate tectonic reconstructions are integrated into a regional spherical formulation of flow (CitComS) as velocity boundary conditions. CitComS is a finite element code designed to handle the rapid changes in temperature and viscosity which exist in subduction zones.
(3) Comparing the predicted images of the mantle temperature from RegCitcoms to observed mantle seismic velocity anomalies from global tomography.

Our results suggest that throughout its history, the tectonics of SE Asia have been dominated by the effects of global plate events (the most significant of which is the collision of India with Eurasia) and changes in global plate motions (particularly of the Pacific and Australian plates). These events have caused the initiation and cessation of subduction, back-arc basin opening and continental rifting. The largest plate in the region, the Philippine Plate, has undergone major episodes of clockwise rotation (Hall 1995). However, we have found that this rotation cannot be correlated with global plate events, leading us to speculate that the dynamics of regional plate boundaries triggered the major rotation of this plate. Evidence for the age and degree of rotation of the Philippine Plate and hence an idea of regional plate boundaries, can be found in the spreading histories of the West Philippine, Parece Vela and Shikoku Basins and the South China Sea.

In the earliest Cenozoic (~61 Ma), the West Philippine Basin initiated opening as a consequence of roll-back of a subduction zone along the north and western margin of the Philippine Plate. A strike-slip margin existed between the Philippine and Pacific plates and subduction was active along the Eurasian and Sunderland margin. At ~50 Ma, both the seafloor spreading record and palaeomagnetic data of Hall (1995) suggest that the Philippine Plate underwent significant clockwise rotation which led to an increase in subduction rate between the western margin of the Philippine Plate and the Eurasian margin. At 40 Ma, the rotation of the Philippine plate ceased as indicated through a change in spreading rate and direction in the West Philippine Basin. As a consequence of the changing kinematics of the plate boundaries, the Philippine Plate was entirely surrounded by subduction. As the spreading in the West Philippine Basin stopped at 35 Ma, the spreading in the Caroline Basin was underway through the roll-back of a north-dipping subduction system. Between 32-20 Ma, South China Sea spreading occurred (possibly as a consequence of India-Eurasia collision). The Parece Vela Basin was opening on the eastern margin of the Philippine Plate through trench roll-back of the proto-Mariana Trench. Spreading in the Shikoku Basin was established at ~26 Ma. At ~21 Ma, we observe significant changes in the spreading rates and directions in the Parece Vela and Shikoku Basins and the South China Sea. We correlate this with a further episode of clockwise rotation of the Philippine Plate, with these basins marking the boundaries of the rotating plate. A major event at 15 Ma, corresponding to a global change in plate motions led to the cessation of spreading in the Parece Vela and Shikoku Basins and the South China Sea. At ~7 Ma, back-arc opening initiated in the Mariana Trough and presently back-arc rifting is occurring along the Izu-Bonin Arc.

Our results are an important contribution to the understanding of the tectonics of the region throughout the Cenozoic. Our geodynamic models may help to explain the driving forces behind the anomalously complex arrangement of plate boundaries in SE Asia. It is particularly important to observe the interactions of plates at the surface but also understanding the resulting convection in the mantle, especially how that convection will influence back-arc opening, continental rifting, major plate rotations and the initiation and cessation of subduction. The geodynamic models also assist in quantitatively linking mantle heterogeneity to the sedimentary record through changes in subsidence, uplift and sedimentation driven by dynamic topography.

**Sundaland Basins**

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Sundaland includes the large area of shallow seas (Sunda Shelf) between Indochina, Borneo, Java and Sumatra. This continental region has been in a similar position with respect to Asia from the early Mesozoic and since then has been largely emergent or submerged to very shallow depths. It is now surrounded on three sides by subduction and collision zones. There are numerous Cenozoic sedimentary basins and many are very deep (up to 14 km). The basins are extensional, and some indicate oblique extension; there is no evidence of major through-going strike-slip faults. They are not foredeeps, nor are they backarc basins. The influence of older basement structures is very important. Causes of basin formation, subsidence and later inversion are not clear, partly because dating of events is uncertain. Possible contributory mechanisms are India-Asia collision, Australia-SE Asia collision, backarc extension, subduction hinge rollback, regional strike-slip faulting, mantle plume activity, and differential crust-lithosphere stretching.

Subsidence began between the Paleocene and Oligocene. It is not clear if basin initiation was synchronous or if there was a systematic diachroneity. The older parts of most basins are terrestrial, commonly unfossiliferous, and the deeper parts are unsampled. Some of the basins may contain sediment supplied from Asia following India collision but most was probably locally derived. For example, deep circum-Borneo basins are filled by sediment derived from Borneo which supplied sediment at a similar rate to the Himalayas during the Neogene. Such estimates of long-term sediment yields are consistent with estimates of current rates which suggest that SE Asian islands provide about 20-25% of the sediment to the global ocean, although they represent only about 2% of global land area and are topographically rather low. Despite long-term fall of global sea level since the early Miocene there was a change to marine conditions in about late Miocene. There was Miocene inversion in the southern part of the Sunda Shelf and also Mio-Pliocene mountain-building at the subduction margins of Sundaland. These events are difficult to explain in terms of plate motions, which suggest relatively continuous subduction at the Sunda-Java trenches.

The region is one of relatively high heat-flow, and gravity data and subsidence histories suggest a thin elastic thickness for the lithosphere. Although arc magmatism may be responsible for elevated heat-flow at the subduction margins, it is also high in the interior Sundaland basins far from volcanic arcs. Seismic tomography indicates unusually low velocities for a continental region for the Sundaland lithosphere and underlying mantle and suggest a thin, warm and weak lithosphere. The distribution and differences in nature and timing of subsidence and inversion suggest a complex and shifting pattern of extension and contraction with time.

What caused basin formation and can a single mechanism account for most of the basins? What caused inversion and how were high long-term sediment yields maintained? Why are these so high today? The deformation which led to subsidence and uplift is suggested to be a response to long-term subduction beneath this region during the late Mesozoic and Cenozoic, resulting in a weak lithosphere highly sensitive to changes in the balance of forces acting at the plate margins. The changes in tectonics and magmatic activity in this region caused changes in land-sea distribution, topography and climate, which have in turn influenced distribution of natural resources, and evolution of biota.

### The signficance of deformation in Thailand for understanding the regional Tertiary tectonics of Indochina

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The extrusion model, and finite element models of the Himalayan collision zone generally envisage the main Tibet-India collision as being the dominant driver of deformation in Indochina. Much of the focus of structural work in Indochina has focused on the kinematics, timing and displacement of major strike-slip faults, in particular the Red River Fault zone. The Tertiary rift basins of Thailand provide a detailed record of the stress history for the late Tertiary of one of the key crustal blocks involved in extrusion tectonics (which lies between the Sagaing Fault zone to the west and the Red River Fault zone to the east). Far from being a passive rigid block extruded between strike slip faults Thailand shows a very dynamic Tertiary deformation history involving 1) Eocene (?)- Oligocene left lateral motion on major NW-SE trending strike-slip faults, 2) Hints of an early Tertiary contractional, crustal thickening event, 3) Oligocene-Miocene extension, including metamorphic core complex development, 4) Significant, episodic episodes of inversion during rift basin development, ending in an important episode in the Pliocene, and 5) Diachronous timing of thermal subsidence (Middle Miocene in Gulf of Thailand, Late Miocene-Pliocene in northern Thailand). There is also the problem of how to explain the rapid, massive thermal subsidence (4 km in 10 Ma) over low-extension (beta factor < 1.3) rift basins. A review of the geology of Thailand and Myanmar suggests the following: 1) The early Tertiary collision of India with the West Burma Block, rather than the main Himalayan collision drove the early extrusion tectonics, in particular on the Mae Ping and Three Pagodas fault systems. It also caused folding and thrusting. Some areas of thickened continental crust later collapsed to produce metamorphic core complexes. The Sagaing Fault or an adjacent fault strand underwent sinistral motion at this time. 2) Oligocene-Miocene extension occurred largely independently of major strike-slip faults. The driving mechanism for extension is uncertain, but may partly involve buoyancy forces, and possibly very limited subduction rollback. 3) The episodic inversion events that interrupted extension generally require N-S to NW-SE maximum horizontal principal stress directions, suggesting inversion could be driven by stresses associated with the Himalayan collision zone. These stresses probably resulted in episodic, minor, right-lateral reactivation of the NW-SE striking strike-slip faults from the late Oligocene-Pliocene.

### The Dangerous Grounds Area: Extended Continental Crust in the Southeastern South China Sea

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Seafloor spreading in the South China Sea occurred from about 30 Ma to 18 Ma. This process separated the Dangerous Grounds area, which now lies northwest of Palawan and Borneo from the China mainland. Prior to the onset of seafloor spreading, continental crust of the China margin rifted due to Late Cretaceous back-arc extension. This crust was formed primarily through Mesozoic accretionary processes related to the subduction of oceanic crust under China. Asymmetric rift grabens were filled with clastics and the Early Oligocene Nido carbonate platform developed on top of the extended continent and overlying sediments. Once seafloor spreading was initiated, rapid thermal subsidence occurred in the Dangerous Grounds area. Carbonate buildups continued to grow only on the high sides of rotated fault blocks and on the Reed Bank where crustal thickness was sufficient to maintain the proper water depth for reef development. Southeastward subduction of Mesozoic oceanic crust beneath Palawan and Borneo occurred as the South China Sea opened. This subduction ceased and significant structural deformation occurred as the Dangerous Grounds crustal thick entered the subduction zone.

Reflection seismic, gravity, magnetic and bathymetry data were collected in the Dangerous Grounds area during six cruises between 1982 and 2001. An integrated study of this dataset provides an improved understanding of the processes involved in the drift of a continental fragment in an oceanic environment. Five long magnetic profiles crossing the oceanic basin of the South China Sea allow a refinement of the interpreted seafloor spreading history. A close correlation of bathymetry and free-air gravity is observed in the Dangerous Grounds area. This morphology reflects the extended character of the continental crust with its half-graben structures. Density models which are based on seismic interpretations support the interpreted basement structure. The extensional structures, which have a characteristic wavelength of 30 - 40 km, are similar to those found in the Basin and Range province of the western United States. We do not find indications for major strike-slip faults

although zones of wrenching do exist. They are more similar to the accommodation zones of the Basin and Range province. Magnetic anomalies in the area are poorly correlated to the recent tectonics except in a small area offshore Sabah (NW Borneo). The magnetic anomalies in the Dangerous Grounds mainly reflect magnetization variations within the continental crust and not basement structure. The lack of magnetic anomalies related to extensional structures indicates that the extension process was not associated with considerable igneous activity.

**Lateral Variation of the Crustal Structure in the Northern Margin of the South China Sea**

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The crustal structure of the northern margin of the South China Sea and the adjacent South China is revealed by inversion of deep seismic data and gravity data. The approximately S-N extension in the South China Sea has resulted in high variation of crustal structure not only cross the margin but also very different sedimentary features along it. In the westernmost of the margin, the crust thins even to 5 km over the central Yinggehai Basin. In the southwest of the margin, the Xisha Trough extends westward as a narrow intra-continental rift from the central basin of the South China Sea. Over the Xisha Trough the crust thickness varies from 25 km plus over the two flanks to 10 km minus over the trough valley. Over the Pearl River Mouth Basin, which occupies the middle section of the margin, the crust thickness decreased generally southward, from ca. 30 km onshore South China to 7-8 km in the central basin of the South China Sea. Over the lower slope nearby, a high P wave velocity (7.2-7.5 km/s) layer with a thickness of 3-4 km was found under the crust. Further eastward, the crust thickens locally over the continental shelf where the high P wave velocity layer is also found. Over Taiwan area, where the margin changes its strike from ENE to NNE direction, the Moho discontinuity under the Taiwan-Luzon arc becomes deeper than 30 km, whereas the continental crust (excluding the accretive wedge) still preserves features of crustal attenuation.
In the westernmost section, the Yinggehai Basin, formed by the strike-slip transtension by relative displacement of Indochina block along the Red River, represents a transform continental margin. Located in the middle of the northern margin of the South China Sea, the Pearl River Mouth Basin area and Xisha Trough area, typical of rift structure, constitute

the main part of the northern passive continental margin. In the northeast, the Taiwan area, the crust was deepened and complicated by the arc-continental collision resulted from the convergence of West Philippine Sea Plate.

**Study on the Crust Structures of the Northern Margin of the South China Sea**

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Explosion seismic data and two-ship Expanding Spread Profiles (ESPs) reveal the crust structures on the northern margin of the South China Sea. The crust thickness decreases from the continent of 30km to the ocean of less than 10km. Contrasting variation occurs in the upper crust (Vp<6.4km/s) with the thickness more than 10km on the continent to several kilometer in the sea area, but reverse change in the lower crust (Vp<6.4km/s) for the existence of high velocity layer. The xenoliths from the basaltic rock on the continent and sea area all include gabbro-granulite which is thought to come from the bottom of the lower crust constructing the high velocity layer and widely distributed in the study area. Furthermore, it can be inferred from the isotope age that the high velocity layer may form during late Mesozoic extension because of the upper mantle underplating at the lower crust. Otherwise, low velocity layer beneath the upper crust is only found along the shoreline which demonstrates a boundary exists between the continent and the sea.

**The Basin Formation Dynamics and Experimental Evidence of Ying-Qiong basin, NW South China Sea**

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Yinggehai basin and Qiongdongnan basin(abbreviated to¡¯Ying-Qiong basin) are Tertiary basins developed on the NW shelf of South China Sea. Yinggehai basin lies on the suture of Indochina peninsula and the northern shelf of South China Sea. It¡¯s the seaward elongation of the Red River Fault Zone. The longest axis of Yinggehai basin is NW trending. Qiongdongnan basin is NE-trending, whose east part connects with the NW sub-sea basin of South China Sea through Xisha trough. The west part of Qiongdongnan basin connects with Yinggehai basin. The Ying-Qiong basin experienced three main stages of subsiding: (1)From Eocene to early Oligocene, both basins are characterized by rapid subsidence, the interface between early and middle Oligocene appear angular unconformity. (2)From late Oligocene to middle Miocene, subsidence is obviously different between Yinggehai and Qiongdongnan basin. Sequence analysis revealed that in Yinggehai basin unconformity developed between early and middle Oligocene, while in Qiongdongnan basin between late Oligocene and early Miocene. (3) From late Oligocene to present, the sedimentary sequences are basically not controlled by early boundary faults of Ying-Qiong basin. Ying-qiong basin united as one. Yinggehai basin is maily controlled by NW, NNW and nealy NS-trending fault systems. While Qiongdongnan basin is mainly controlled by NE and nealy EW-trending fault systems. From Eocene to early Oligocene, the Ying-Qiong basin is in rifting stage. According to analogue modeling experiment of Ying-Qiong composite area, we proposed that, Yinggehai basin experienced oblique rifting related to sinistral slip caused by Indochina extrusion, while Qiongdongnan basin developed into two blocks from west to east. In the west block of Qiongdongnan basin, faults are mainly EW-trending affected by sinistral slip of NW-trending boundary faults when under extension caused by subduction of Pacific plate toward Eurasia. In the east block, faults are mainly NE-trending controlled by extensional stress.

**Cenozoic Stratigraphy and Subsidence History of the South China Sea Margin in the Taiwan Region**

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Seismic reflection profiles and well data are used to determine the Cenozoic stratigraphic and tectonic development of the northern margin of the South China Sea. In the Taiwan region, this margin evolved from a Palaeogene rift to a latest Miocene-Recent foreland basin. This evolution is related to the opening of the South China Sea and its subsequent partial closure by the Taiwan orogeny.

Seismic data, together with the subsidence analysis of deep wells, show that during rifting (~58-37 Ma), lithospheric extension occurred simultaneously in discrete rift belts. These belts form a > 200 km wide rift zone and are associated with a stretching factor in the range ~1.4-1.6. By ~37 Ma, the focus of rifting shifted to the present-day ocean-continent boundary off southern Taiwan which led to continental rupture and initial seafloor spreading of the South China Sea at ~30 Ma. Intense rifting during the rift-drift transition (~37-30 Ma) may have induced a transient, small-scale mantle convection beneath the rift. The coeval crustal uplift (Oligocene uplift) of the previously rifted margin, which led to erosion and development of the break-up unconformity, was most likely caused by the induced convection.

Oligocene uplift was followed by rapid, early post-break-up subsidence (~30-18 Ma) possibly as the inferred induced convection abated following initial seafloor spreading. Rapid subsidence of the inner margin is interpreted as thermally-controlled subsidence, whereas rapid subsidence in the outer shelf of the outer margin was accompanied by fault activity during the interval ~30-21 Ma. This extension in the outer margin (beta ~1.5) is manifested in the Tainan Basin which formed on top of the deeply eroded Mesozoic basement. During the interval ~21-12.5 Ma, the entire margin experienced broad thermal subsidence. It was not until ~12.5 Ma that rifting resumed, being especially active in the Tainan Basin (beta ~1.1). Rifting ceased at ~6.5 Ma due to the orogeny caused by the overthrusting of the Luzon volcanic arc.

The Taiwan orogeny created a foreland basin by loading and flexing the underlying rifted margin. The foreland flexure inherited the mechanical and thermal properties of the underlying rifted margin, thereby dividing the basin into north and south segments. The north segment developed on a lithosphere where the major rift/thermal event occurred ~58-30 Ma and this segment shows minor normal faulting related to lithospheric flexure. In contrast, the south segment developed on a lithosphere which experienced two more recent rift/thermal events during ~30-21 Ma and ~12.5-6.5 Ma. The basal foreland surface of the south segment is highly faulted especially along the previous northern rifted-flank, thereby creating a deeper foreland flexure that trends obliquely to the strike of the orogen.

**New Insights on the Tectonics of the Northern South China Sea**

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Recently we have conducted marine geophysical surveys in the northernmost portion of the South China Sea. Magnetic and multi-beam bathymetric data were collected in order to understand the tectonics of the northern South China Sea. The South China Sea was generally developed in a N-S trending sea floor spreading and was considered to be the age between 15 and 32 Ma (magnetic polarity chrons 5c-11). Based on our new magnetic anomaly data, to the north of the magnetic polarity chron 11 several almost E-W magnetic reversal pattern can be clearly recognized. At least two N-S trending fracture zones are associated. It suggests that the initial age of the oceanic crust of the South China Sea could be much earlier than 32Ma. The oceanic crust can extend northwards till a NW-SE trending escarpment, located in the southwest of Taiwan. The vertical offset of the escarpment can reach 300 meters and the northern end of the escarpment terminates near the continent-ocean boundary. Formosa canyon is developing along this topographic feature. The magnetic anomalies also show different patterns on each side of the escarpment. It indicates that the NW-SE trending structure could be an extinct transform fault. On the basis of gravity anomalies, Hsu and Sibuet (1995) have suggested that the former Ryukyu trench system could extend southwestwards to the southwest of Taiwan. Based on our findings, the discovered extinct transform fault could be the southwesternmost truncation of the former Ryukyu Trench and link the former Ryukyu trench and the former Manila trench

**The Tectonics of Arc-Continent Collision and Subduction Polarity Reversal in Taiwan**

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The collision of the Luzon Arc with southern China represents a classic example of arc-continent collision in the modern oceans. This is an important process because it is likely the most effective mechanism by which the continental crust has been built up at least during the Phanerozoic, as well as being the mechanically easiest method to initiate subduction at continental margins. We propose a general model for steady-state arc-continent collision in which oceanic arc crust is progressively added to a passive continental margin during a process of compression, orogeny, metamorphism, magmatism and orogenic collapse lasting only 3-10 million years at any one location on the margin. Depending on the obliquity of the angle of collision, the timing of active collision may be diachronous and long-lived along the margin. One of the major problems encountered in constructing the continents from island arc units is that oceanic arc are typically too mafic and light rare earth element depleted to match the average composition of the continents. However, magmatism accompanying arc collision is more enriched in incompatible trace elements than average continental crust, contrasting with more depleted magmatism prior to collision. Accretion of a mixture of depleted and enriched arc lithologies to the continental margin allows the continental crust to grow through time by arc-passive margin collision events. During the collision the upper and middle arc crust are detached from the depleted ultramafic lower crust, which is subducted along with the mantle lithosphere on which the arc was founded. Such detachment is proposed to occur because of the hot, ductile quartzose lithologies in the mid crust. Rapid (2-3 million years) exhumation and gravitational collapse of the collisional orogen forms the Okinawa Trough, which is then filled by detritus eroded from the adjacent collision zone.

During subsequent subduction polarity reversal, continuous tearing and retreat of the oceanic lithosphere along the former continent-ocean transition provides space for the new subducting oceanic plate to descend without need for breaking of the original slab. The Okinawa Trough thus represents a unique style of Asian marginal sea, in that it is generated by orogenic collapse, not trench roll-back forces, as is assumed for the other major basins of the region, e.g., South China Sea, Sea of Japan.

**Foreland Sedimentation, Longitudinal Sediment Transport and Shifting Submarine Canyon in a Remnant Margin Sea off SW Taiwan**

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Flexural subsidence of the Chinese margin crust formed a foreland basin west of the Taiwan orogen. With the collisional thrust belt of Taiwan propagating toward the basin, the subsidence of the foreland basin continued into the Pliocene to the Recent. The southern Taiwan orogen was marked by the incipient collision of the northern Luzon Arc with the Chinese margin and accompanied by an early-stage foreland basin off its southwest coast. Much sediment shed from the Central Range of southern Taiwan pours longitudinally through submarine canyons into the northernmost part of the South China Sea north of latitude 21 degrees, forming a remnant ocean basin by filling with synorogenic sediment. South of latitude 21 degrees, the South China Sea is characterized by an oceanic subduction system that is still actively consuming the South China Sea oceanic crust beneath the Luzon Arc.

The remnant ocean basin off southwestern Taiwan consists of two parts: the western flank Chinese passive margin with a northeast trend and the eastern active Taiwan margin with a northwest regional trend. These two margins converge in the north and enclose two deep-water (>3,000 m) submarine slopes facing each other, forming a triangle shape tapering to the north and opening to the south. The major Penghu Submarine Canyon developed along the axis of the deep-water foreland basin following the regional dip toward south and paralleling to the strike of the Taiwan orogen, showing a characteristic longitudinal sediment transport route.

Progressive uplift of the Taiwan orogen and progradational filling of the foreland basin switch the transverse dip of drainage base level in central Taiwan to the longitudinal direction along the strike of the orogen in southern Taiwan. Longitudinal paleo-submarine canyons developed for each progressive stage of foreland basins.

Shifting of axes of Pliocene-Pleistocene canyons from southwest Taiwan on land to the present-day of the Penghu Submarine Canyon in the northernmost South China Sea reflects the evolving foreland basins with a longitudinal sediment transport system progressively migrating from Late Pliocene to the present.

**Hydrothermal Vent / Submarine Volcano / Earthquake in the Southernmost Part of Okinawa Trough**

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The Okinawa Trough is a backarc basin resulting from the subduction of Philippine Sea plate underneath the Eurasian plate. The tectonic forces come from the Philippine Sea plate subducting northwest is the main geodynamic source for the formation of Okinawa Trough. The southernmost part of Okinawa Trough propagated onto Ilan Plain, northeastern Taiwan; therefore, it closely associated with the arc-continent collision system. Under this complex environment, the Okinawa Trough is characterized with the frequent earthquakes, numenous submarine volcanoes, high heatflow and active hydrothermal vents. We believe if we can understand well between earthquake and plate tectonic, it may be an initial tool to set up an earthquake pre-warning system. We are now planning to monitor the earthquake and hydrothermal circulation system in this area. In the first stage, we will continuously measure the temperature of hydrothermal vents in shallow water (20-30 m) and relate them to the seismological information on the Turtle Island, an active volcanic island at the southern end of the Okinawa Trough. In the second stage, we will propose an international co-operation to measure the temperature of deep hydrothermal vents (1500-2000 m) and obtain the ocean bottom seismometer data. In the long-term, we hope to build up a deep-sea monitoring station. Transmitting the information include earthquake, hydrothermal temperature, current, earth tide and other relevant information through an underwater cable to the labortory on land. It is aiming to monitor in a real time mode.

**Formation of the Japan and the Kuril Basins in the Late Tertiary**

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Using a late Tertiary reconstruction of the NW Pacific Margin, we suggest the following stages for the formation of the Japan and the Kuril basins. 1) collision of Sakhalin with the Amurian Plate in the Eocene, 2) clockwise rotation of central Hokkaido in the latest Eocene, 3) opening of the Japan and the Kuril basins in the Oligocene and in the Miocene, and 4) opening of the Yamato Basin by clockwise rotation of SW Japan in the middle Miocene. Both basins were formed under the same fundamental tectonic regime, compression due to westward motion of the North American Plate coupled with eastward motion of the Amurian Plate. Northern Japan and western Kuril in the earlier stage and eastern Kuril in the later stage were extruded to southward. Then, both genesis and subsequent modification and translation of these basins are related to the North American Plate and Amurian Plate collision.

**The Crustal Structure of the NW Sabah/Borneo Continental Margin from Seismic Data**

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The NW Sabah/ Borneo continental margin is located at the southeastern boundary of the South China Sea basin and occupies a central position in the area of the junction between the Eurasian, Indo-Australian, Pacific and Philippines plates. The accretionary margin off NW Sabah has the peculiarity that subduction of the (hypothetical) proto-South China Sea ended due to collision with a continental fragment which presumably was subducted in part. Alternatively the margin may be interpreted as the result of back thrusting of the Sulu volcanic arc resulting from the northward subduction of the Celebes Sea. The NW Sabah continental margin still looks like a typical accretionary margin: SE of the NW Sabah Platform that comprises the Dangerous Grounds, the Reed Bank, and Northern Palawan the NW Sabah Trough (also referred as NW Borneo Trench or Borneo-Palawan Trough) is situated. Landwards a fold-thrust belt of parallel and partly overlapping faults, all dipping in the same general direction, developed. The thrust belt is bounded to the shelf by a wide area of particularly pronounced structural complexity. In addition to intensified thrust faulting and duplexing, a multitude of additional features developed, ranging from piercement structures to growth faulting in local depressions which are filled with thick Neogene sediments. However, according to the nearly total absence of natural seismicity and the undisturbed layering of the uppermost sediments, presently there are no horizontal movements between the involved plates. In 2001 the Federal Institute for Geosciences and Natural Resources (BGR) has carried out a marine geophysical survey off NW Sabah with the focus on the deep water areas. A total of 2900 km of multichannel reflection seismic lines were acquired during the cruise with a 6 km long streamer. In addition a refraction seismic profile with 4 ocean-bottom hydrophone stations was surveyed. The oldest event which is clearly visible in the reflection seismic data of the Dangerous Grounds area is an extension of the crust that is proved by a system of horsts, tilted blocks, and syn-rift half-grabens. From the rift-fill we infer that the event lasted from the Late Cretaceous to the Late Eocene. Near the end of Eocene time, the clastic sediment supply dissipated and a wide-spread Early Oligocene to Early Miocene carbonate platform developed. We interpret the Dangerous Grounds area as a piece of extended and subsided continental crust which to the south was limited by a proto-South China Sea. West Palawan and NE Borneo formed the southern margin of this ocean. The origin of the NW Sabah Trough is still under debate. One possible interpretation is the development as a subduction related trench. But according to our data the trough is presumably floored by subsided continental crust, similar to the type known from the Dangerous Grounds. Extensional features as normal faults and tilted blocks are clearly visible in the seismic data. The fold-thrust belt, which increases in thickness and thrusting intensity in landward direction, is made up of sets of subsidiary faults cutting through post-Early Miocene sediments. Beneath the individual, fold-related ridges we observe widely extended Bottom Simulating Reflectors (BSRs) that indicate the presence of gas hydrates. Apparently the thrust belt's sediments are thrusted onto the progressively subsiding continental crust of the gradually overridden NW Borneo-Palawan Trough. The top of the subsiding continental crust, the Oligocene to Early Miocene carbonate platform, forms the major detachment surface. This interpretation is in contrast to the assumption of gravitational delta tectonics as origin for the thrust belt. With the new acquired data we suppose the following scenario for the development of the NW Sabah continental margin. Seafloor spreading in the present South China Sea started at about 30 Ma in the Late Oligocene, it ceased in late Early Miocene. The spreading process separated East Palawan and the Dangerous Grounds area from the SE Asian continent. When subsidence of the Dangerous Grounds accelerated, the carbonate buildups became restricted to isolated reefs on the up-lifted sides of rotated fault blocks and to some places of presumably slower subsidence. During Lower and/or Middle Miocene Borneo rotated counterclockwise and in front of the rifted continental block of the Dangerous Grounds oceanic crust of a proto-South China Sea subducted below the eastern part of Sabah, instead of along the present NW Sabah Trough.

**Comparison of Structural Styles and Regional Subsidence Patterns Across the Nam Con Son and Cuu Long Basins, Offshore Southeast Vietnam**

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The Cuu Long and Nam Con Son (NCSB) basins are Tertiary rift basins located offshore southeast Vietnam. Observations from regional 2D seismic data indicate both basins consist of smaller sub-basins with similar E-W to ENE-WSW basin axes and rift onset histories (late Eocene(?)-Oligocene time). Structural styles, subsidence histories, stratigraphic fills, and the end of tectonic deformation, however, are markedly different for each basin. The Cuu Long Basin is characterized by extensional fault systems that are probably shallower (involving only the upper crust) and more closely spaced than extensional faults in the NCSB. Additionally, almost no deformation affected the Cuu Long Basin once rifting ceased in Oligocene time. Post-rift stratigraphic patterns in the Cuu Long Basin also show little variation in thickness across the basin, suggesting that extension did not generate a significant post-rift thermal anomaly in the lithosphere beneath the basin.

Farther to the south, the NCSB underwent pulsed regional subsidence related to three phases of rifting from late Eocene(?) to Miocene time. Unlike the Cuu Long Basin, the NCSB is characterized by major extensional faults, with apparently greater strike length and vertical offset, and was subjected to varying magnitudes of structural inversion during middle Miocene time. Stratigraphic thickness patterns within the NCSB indicate that tectonic subsidence has continued through the Pleistocene at varying rates across the basin, although there is an increase in post-rift subsidence toward the southeast. As post-rift subsidence occurred in the NCSB, sediment bypassed the Con Son High to the north and formed highly progradational Neogene shelf-edge deltaic complexes, the paleo-Mekong Delta, that prograded toward the central and southern regions of the NCSB. Major southeastward progradation of the paleo-Mekong Delta began in latest Miocene-early Pliocene time, which may reflect when the Mekong River linked to its present-day headwaters in the eastern Tibetan Plateau.

**Tectonics and History of the Andaman Sea Region**

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The Andaman Sea is an active backarc basin lying above and behind the Sunda subduction zone where convergence between the overriding southeast Asian plate and the subducting Australian plate is highly oblique. The effect of the oblique convergence has been formation of a sliver plate between the subduction zone and a right lateral fault system, which has evolved since the Oligocene into the Sumatra Fault System, the Sagaing Fault in Myanmar, and the obliquely-opening Andaman Sea at the bend in the once-continuous strike slip fault.

The middle Eocene hard continent-continent collision of India and Asia started clockwise rotation and bending of the northern and western Sunda Arc. Sliver faulting started in the Oligocene on the West Andaman Fault extending through the outer arc ridge offshore from Sumatra, through the present region of the Andaman Sea into the Sagaing fault. In late Oligocene, ca 32 Ma, the Mergui Basin started opening at the intersection with the Klong Marui and Ranong faults by extension of continental and/or volcanic arc crust. In early Miocene, ca 23 Ma, backarc spreading started forming the sea floor which later became Alcock and Sewell Rises. From middle Miocene, ca 16 Ma, these contiguous features were separated from the foot of the continental slope by NW-SE spreading, and the motion of the southern part of the West Andaman Fault was taken up by the Mentawai Fault in the forearc basin off Sumatra. At about 3-4 Ma, the present plate edge was formed, Alcock and Sewell were separated by formation of the central Andaman Basin, and the faulting started moving from the Mentawai Fault to the Sumatra Fault System bisecting Sumatra

**High-Resolution Miocene Sequence Stratigraphy of South China Sea Continental Margins: an Outcrop/Subsurface Example of Taiwan**

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High-resolution sequence stratigraphy has been proven essential for demonstrating interplay of eustasy, sediment supply and local tectonics in continental marginal basins around the South China Sea. It requires detailed sedimentologic and stratigraphic databases that are however scarce in most of the subsurface SCS basin fills due to exploration concerns and limitation of geophysical survey. A complete Miocene basin fill of the NE SCS margin exposes and has been drilled in western Taiwan, providing complementary facies and stratigraphic details for conducting a high-resolution outcrop-subsurface sequence analysis. A study based on five outcrop sections and seven well logs outlines the Miocene sedimentation of this particular SCS basin along depositional strike and dip, and is believed to contribute to the adjacent SCS basins. The eleven-sequence scheme shows distinct similarities to isotope records and many tectonic-independent marginal records, demonstrating manipulation of the Miocene eustatic fluctuations. The sequence geometries and compositions characterize significant variations in basin geometry and sediment accumulation, indicating the influences of long-term changes in tectonic subsidence and sediment supply from rifting-drifting transition, early and late drifting. It is also noteworthy that these Taiwan sequences are commonly observed in the other northern SCS basins, suggesting valuable applicability of this new-established sequence stratigraphy

**Crustal Composition of the Northern Margin of South China Sea: Implication for Rheological Heterogeneity and Basin Evolution**

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Based on the velocity structure of northern margin of South China Sea (SCS) from the seismic refraction profiles, we infer crustal composition as a function of depth by comparing these velocities with the results from high-pressure laboratory measurements of seismic velocity for rocks in the crust. The velocities of profiles were corrected to the standard P-T condition (25 degree C and 600 MPa) according to the geotherms constructed along each profile by 1-D and 2-D modeling. Both of the downward continuation calculation of heat flux data under steady state conductive assumption and the cooling plate non-steady heat transfer model are used and compared in our modeling. The average velocities are calculated for each position at 5-km depth intervals to Moho depth. Then, the model for crustal composition of northern margin of SCS was developed. Beneath the sediment layer, the relative uniform velocity of around 6.0 km/s in upper crust are observed in northern margin of SCS, and i! t is matched by granite-granodiorite or felsic gneiss in lithology. However, the lateral variation of velocity in lower crust is significant in the northern margin of SCS. The thick high velocity (>=7.0 km/s) lower crust exists in the eastern and middle portions of the margin. Meanwhile, the velocity of lower crust in western portion is in range of 6.5-6.8 km/s. After the P-T correction, we infer the lithology of lower crust in eastern and middle portions as mafic garnet granulite, or the mixture of mafic granulite and upper mantle rocks. The composition of lower crust in western portion is the mixture of felsic lithologies and mafic granulite, with a tendency of increasingly mafic component with depth. The thermo-mechanical profiles in northern margin of SCS were calculated from the thermal modeling and crustal composition estimation. The results show the lateral strength variation of lower crust exists between eastern and western portions of the margin mainly due to the comp! osition heterogeneity. Since the variation of crustal properties are believed to result primarily from contrasting, pre-rift crustal structure across the margin (Nissen et al, 1995, JGR, v100, 22407), we proposed that the composition-related rheological heterogeneity of lower crust had influenced the basin evolution in northern margin of SCS. The ability of crustal rock to flow affects the style and kinematics of rifted regions (Bertotti et al, Tectonophysics, 2000, v320,195). Therefore, no flow occurred in the relative rigid east portion of the margin, and subsidence affected the extending areas to form the Pearl River Mouth basin. However, Xisha Trough, in where the felsic lower crust exists, could not prevent the flow to take place. The lower crustal rocks move towards the rifted zone causing isostatically driven upward movements. These may explain why Xisha Trough has thin post-rifting sediment, and failed to develop into the stage of sea-floor spreading.

**Development of South China Sea and Philippines Arc**

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The tectonic history related to the opening of South Chine Sea and the formation of Palawan Island has been carried out. Palawan Island is located along the southern margin of South China Sea and composed of Cretaceous to Eocene turbidites and Cretaceous ophiolite. Folded structures, metamorphism and sandstone composition of the turbidites were analyzed. Attitudes of folds indicate directions of plate movements. Type of metamorphism provides an information on the tectonic setting where the turbidite was metamorphosed. Sandstone composition suggests the provenance of the clasts of the turbidites.

Sandstone composition; The Palawan sandstones are rich in quarts, ranging from 46 to 50 modal percentage, and also contain 6.5 to 11 modal percentage feldspar (P/F fanges from 0.73 to 0.81). The acidic volcanic variety is by far the most abundant in lithic fragments. Whole rock chemical analysis show that the sandstones are characterized by moderate to high $SiO_2$ contents (73-81 wt%) and low FeO plus MgO contents (1.4-2.7 wt%). So far little pre-Cretaceous acidic igneous rocks have been described in Philippines, the sandstone compositions suggests that the source area of the Palawan sandstones is thought to be the Southern China continent. The Basin of the Cretaceous to Eocene turbidites of Palawan was situated near Southern China continent.

Folded structures; Three phases of deformation D1, D2 and D3 have been identified. The D1 occurred first and is the most important deformation which penetrates the entire sequence. The deformation formed F1 fold which associates slaty cleavages lie subparallel to the axial plane. The plane trends ENE-WSW and dips to the south. The attitude supports that the Basin of turbidites was drifted to southward from a margin of the Southern China continent and subducted in almost recent position.

Metamorphism; Illites which define the slaty cleavages are recrystallized under D1 drformation. Crystallinity (IC) and b0 cell parameters of the illites have been determined by X-ray diffraction. IC values were converted to CIS values (Warr & Rice, 1994) using calibration curves based on standards provided by Dr L. Warr. 0.22 to 0.60 IC values indicate anchizonal (prehnite-pumpellyite facies) to epizonal (greenschist facies) conditions. The b0 values vary from 9.008 to 9.050 and have an average value of 9.033. When compared with the results obtained by Sassi and Scolari (1974), moderate high P condition are indicated. These IC and b0 values are similar to the values from slates of the Shimanto Belt, Outer Side of Japan which we are analyzing. It suggests that the turbidites were subducted in a trench of a paleo-Palawan arc.

**Evolution of the Southwestern Margin of the East Sea (Sea of Japan): Sequence Stratigraphy and Geologic Structures**

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This study presents an evolutionary history of the southwestern Ulleung Basin margin. Sequence stratigraphic and structural analyses of multi-channel seismic reflection data suggest that the prograding shelf-slope system comprises ten seismic sequence units which can be divided into 3 stages of basin development in the early Miocene to Pliocene. In the early Miocene, the basin experienced extensional force bordered on the west by a steep basement fault with normal sense of offset, forming a deep marine depositional setting. The basin-bordering fault movement ceased at the end of the early Miocene, and subsidence progressively slowed, which, coupled with increased terrigenous sediment input, resulted in the development of prograding shelf margin. In the middle to late Miocene time (12.5-5.5 Ma), the basin was characterized by compressional readjustment by thrusting and folding. The sequential effects of the tectonic event include local and regional angular unconformities, progradation-dominant shelf-margin depositional system and frequent triggering of large-scale mass-failures in front of the thrust belt. Since the end of the late Miocene, the basin has progressively subsided, forming aggradation-dominant shelf-slope system.

**Mesozoic-Cenozoic Rifting and Origins of the North Yellow Sea Basin**

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Yellow Sea is a semi-closed continental shelf basin which is bounded by Tanlu fault to the west and by Korea peninsula to the east. The Yellow Sea basin can be tectonically divided by two subbasins by Qianliyan rise, named north Yellow Sea basin (NYSB) and south Yellow Sea basin based on the acoustic basement and tectonic evolution. Here we discuss the tectonic evolution and regional kinematics of the NYSB by using seismic data and field survey.

NYSB was developed on the Proterozoic metamorphic basement and Paleozoic basement of the North China Block in the west and eat respectively. Two rifting stage can be revealed from the seismic data and well data at central depression. The first rifting happened from Late Jurassic to Early and Middle Cretaceous and thickness of 1000 to 4000m terrigenous deposits and volcanic rocks were deposited in half-graben basins. The deposit sequences were revealed in onshore Jiaolai Basin of Shandong Peninsula, During early Cretaceous probably between 140-120Ma, the Tanlu fault zone was activated as a dextral fault. Transitional tectonics cased pull-apart opening of the early Cretaceous Jiaolai Basin. The period of middle Cretaceous possibly between 120-100Ma was marked by widespread occurrence of volcanic eruption in the Jiaolai Basin. This stage was dominated by extensional tectonics and normal faulting. During late Cretaceous, the direction of compression changed from NW-SE to NE-SW. The Tanlu fault zone was a dextral strike-slip fault. Second rifting was from early Paleocene to Oligocene and was not well-developed rifting basin because it accepted very thin early Tertiary deposits and distributed in isolated local depressions. The evolution of early Tertiary rifting and crust extension of the NYSB was originated from back-roll mantle convection induced by northwestward subduction of the Pacific plate beneath Asian plate. During Pliocene to Quaternary NYSB became thermal subsidence with 300-600m marine sediments developed on the anticlines and controlled by some NEE striking faults.

Tectonic evolution of the continental shelf basin has three features as follow: (1) it has two levels of structures. Upper structure of the basin was developed a break unconformity; (2) thermal subsidence rate must be correspond to the rifting rate, which is <50m/Ma; and (3) Gentle detachment faults were formed along the margin of the depression and disappeared at plasticity layer. NYSB could be interpreted by Flexural-Cantilevers simple-shear model (Kusznir, 1992). At the early stage occurred thinning of the lithosphere, of which the upper crust decrease by simple shear and lower crust and lithosphere are pure shear.

**Seismic Observation in the Southern Okinawa Trough Based on Combined OBS and Land Network Data**

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A network of four ocean bottom seismographs (OBSs) was deployed offshore of northeastern Taiwan and acquired earthquake signals for four weeks in 1994. We picked arrival time of P- and S-wave to relocate hypocenters with different models and found one of the routinely used models in locating procedure by the Central Weather Bureau of Taiwan can best fit the velocity structure beneath the combined OBS-land network. We compared the locations determined with and without OBS data and found that incorporating OBS data improved the quality of relocation; hypocenters are shifted toward OBS while their foci are deepened. It implies that offshore seismicity based on land network data alone may be mislocated with too shallow depths.

Spectral analysis of the events shows variations of frequency content related to azimuth, hypocentral distance and OBS site. Events registered at OBS2, situated on the axis of the Okinawa Trough, show low frequencies. Distance generally affects the frequency content of P waves but not so prominently as does azimuth. We hypothesize that some of the remarkable low frequency signals observed are caused by the effect of a magma chamber beneath the trough; indeed, shear waves even disappeared in most seismograms observed at OBS2. In addition to volcanism, steep faulted walls and fractured crust associated with the rifted trough might induce a shadow zone which prevents signals of events south of the trough axis from arriving at OBS1. The microearthquakes exhibit two types of focal mechanisms: the rifting and the subducting types. Focal mechanisms of deeper events from the subducting slab are thrusts with maximum principal axes orientated NW-SE, consistent with the direction of convergent plate motion along the Ryukyu Trench. Shallow events of the rifting zone possess normal faulting mechanism related to the back arc spreading.

**The Sea of Okhotsk Paleotectonics and Zoning**

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The Sea of Okhotsk region is a part of the West Pacific Transition Zone - the youngest and tectonically the most active structure generation of the Pacific Tectonic Belt. On the north the region is bounded by the Udsko- Murgalskaya island arc system, on the south - by the Kuril one. Problems concerning the origin of bottom positive and negative morphostructures and those related with the tectonic systems bordering on Sakhalin and Kamchatka ones remain debatable. So this is the problem that is studied in the present paper based on generalization of the results of geological and geophysical investigations carried out in this region during the last decades.

The analysis of magmatic and metamorphic complexes dredged from the Sea of Okhotsk bottom enabled to close the question about the ancient granite- metamorphic basement of the "Okhotia" massif being hypothetically a morphostructural base of the Sea of Okhotsk shelves. Seismic data reveal here three ridges, which are regarded as remnant island arcs by M.L. Krasny (1979) and A.V. Zhuravlev (1982). The said ridges show relation with Sakhalin and Kamchatka structures where a number of island arc fragments has been found. Three generations of Cretaceous transregional island arc systems have been reconstructed based on complex interpretation of geophysical fields allowing for dradging data. The mentioned systems consist of the following formations:

i) the basement complex: the Paleopacific oceanic crust (possibly with locally spread relics of the pre-Rephean continental crust); ii) the intermediate complex: dynamothermal polycyclically metamorphised oceanic and island arc formations; iii) island arc complex: a) early stage: effusive and intrusive formations of tholeiitic series including as well boninite-marianite series and their analogues and b) mature stage: volcano-plutonic formations of gabbro- plagiogranite complexes belonging to tholeiite and calc-alkali series; iv) the post-island arc complex: gabbro-granite volcano-plutonic associations of andesite series.

So positive morphostructures of the region are the inheritedly developing island arc system fragments within which granite-metamorphic layer grows. Negative morphostructures are represented by troughs oriented in accordance with the orthogonal system of island arc faults. The troughs extending along the paleoarcs develop inheritedly from their back-arc and interarc basins. The troughs oriented normally to the arcs extension are evidently inherited from transverse depressions. In early stages of development 'eugeosyncline' sedimentation followed by formation of acoustically rigid mass took place within the troughs of both types. Due to decrease of the crust permeability, within early generation basins 'miogeosyncline' sedimentation accompanied by formation of acoustically permeable part of the sedimentary cover takes place. Lateral growth of the crust is compensated by its absorption within the remnant Benioff zones and by its obduction within Sakhalin and Kamchatka tectonic heaping border structures.

The developed model of the Sea of Okhotsk region as of a combination of island arc systems, epioceanic basins and border zones of tectonic heaping allows a new approach to the structural zoning of the Sea of Okhotsk oil-and-gas bearing province, one of which is proposed by the authors.

**Impact of Climate Change, Eustasy, and Margin Physiography on the Geologic Record of Continental Margins**

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Late Quaternary Stratigraphy of the East China Sea margin is characterized by highstand deposits that are thick, extensive offlapping silty-clays and clay-silts in outer shelf locales, to almost flat-lying, parallel stratified, silty-clays and clayey-silts in mid shelf locales and similar but thinner and not as continuous deposits on the inner shelf. Transgressive deposits range from fields of tidal ridges, to extensive, but thin veneers of silty-sand. Lowstand architecture is characterized by isolated incised valley formation and amazingly laterally extensive (100's of km along strike continuity) lowstand fluvial successions.

A shelf/slope break depth of between 150-190 meters, during intervals when maximum eustatic fall was on the order of 120-130 meters, limited incision and bypassing of sediment across to the slope. Over wide areas the gradient of the shelf is less than or the same as the major rivers draining into it. When combined with extremely high sediment supply, this produces the lowstand architecture with limited incision and laterally extensive fluvial successions. Topographic relief associated with down-dip and lateral transitions from paleo- delta plain to paleo- delta front produced localized gradient increases that generated isolated incision. Climate modulated discharge of the rivers systems produced drier conditions during portions of the lowstands minimizing incision. Increasingly wetter conditions during portions of transgressions resulted in rapid fluvial aggradation within unflooded sections of the incised areas and laterally extensive stacked fluvial deposits. Thus the stratigraphy of the East China Sea margin reveals that eustatic and climatic change, and shelf physiography all played equally important roles in the development the stratigraphic architecture of the margin.

**Deposition of the Orogenic Sediment in the Huatung Basin East of Taiwan**

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Situated at the western corner of the Philippine Sea plate, the Huatung is a major sink for the orogenic sediment from the Taiwan mountain belt. A prominent north-south trending Gagua ridge that runs along 123›XE traps most sediment derived from central and southeastern Taiwan in this basin. Swath bathymetry mapping and seismic reflection surveys conducted in this basin provide insights on the sediment transport paths and the distribution of sediment in the basin. The seafloor of the Huatung Basin is covered by thick sediment of 1.5 to 2.0 sec twt. Three morphological zones have been observed: the steep east-dipping arc slope, the submarine fan belt, and the deep basin. In the western half of the Huatung Basin, numerous submarine canyons have been developed across the arc slope and submarine fans. These submarine canyons act as major conduits that transport organic sediment from the Taiwan mountain belt into the deep Huatung Basin. Three of the major submarine canyons connect to three major rivers on land in eastern Taiwan. The Hualien Canyon connects to the Hualien Hsi river in the northern part of the Longitudinal Valley. The Chimei Canyon connects to the Hsiu-Ku-Luan Hsi river, which is the only river cuts across the Coastal Range in central Taiwan. The Taitung Canyon connects to the Pai-Nan-Tai Hsi river in the southern portion of the Longitudinal Valley, and is responsible for carrying sediment derived from the southern Central Range to the Ryukyu Trench. The volume of sediment carried by the submarine canyons and the energy of the turbidity currents in some of the submarine canyons are very high. For example, the large amount of orogenic sediment provided by the Hsiu-Ku-Luan Hsi has blanketed the hills and gullies of the Luzon Arc slope and formed a smooth east-dipping canyon floor that is 8 to 9 km wide. A huge submarine fan was developed at the foot of the arc slope. Topographic and seismic reflection data reveal that the northern half of this fan has been washed away by turbidity currents, so that the Chimei Canyon now runs directly eastward into the Hualien Canyon. Sliding sediment has also caused changing paths of a major submarine canyon.

Sediment isopach maps are constructed in the Huatung Basin. Two major unconformities have been identified, which suggests that the deposition of the Huatung Basin sediment consist of at least three phases. The bottom sedimentary layer that fills the lows of the Huatung Basin basement might be deposited before the Taiwan orogen. The middle sedimentary layer that is more evenly distributed across the Basin should be deposited after the initiation of the Taiwan mountain building. The distribution of the top sedimentary layer reflects the paths of the submarine canyons. Though we lack the age constraints to establish a deposition history of the Huatung Basin sediment, this study provides the first picture of the sediment distribution in a major sink for orogenic sediment from the eastern Taiwan mountain belt.

**Late Holocene Delta Evolution of the Mekong River, Southern Vietnam**

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The Mekong River Delta, southern Vietnam, is a typical mixed-tide and wave energy delta with a wide delta plain formed during the last 6 ky and is one of the largest deltas in the world. Evolutionary changes, delta progradation, and sediment discharge of the Mekong River Delta, southern Vietnam, during the late Holocene are presented based on detailed analyses of samples from 6 boreholes on the lower delta plain. Sedimentological and chronostratigraphic analyses indicate clearly that the changes from tide-dominated to tide-wave dominated delta of the Mekong River Delta during the late Holocene. The last 3 ky were characterized by delta progradation under increasing wave influence, southeastward sediment dispersal, decreasing progradation rates, beach-ridge formation, and steepening of the face of the delta front. Estimated sediment discharge of the Mekong River for the last 3 ky, based on sediment-volume analysis, was 144 +- 36 million t/y on average, or almost the same as the present level.

**Controls on the Terrigeneous Sediment Supply to the Okinawa Trough During the Late Quaternary**

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Okinawa Trough is a back-arc basin located behind the Ryukyu arc-trench system, and is covered with very thick sediments.The sediments are composed mainly of terrigenous material (>60-70% of total sedimentation quantity),and the sediments are of fine- grained (silt-clay,clay fractions) in grain-size.The main terrigenous material source is considered to be the continental shelf of East China Sea,but whether mainly from Yangtze or Yellow River in origin,i.e.,the quantified contributions of them,has been unknown yet.The input of terrigenous sediments along the East China Sea maring is studied on the basis of 3 sediment cores recovered from the basin. Spatial and temporal variations in terrigenous sediment grain-size composition, sedimentation rates,turbidite frequency and composition,volcanic activity etc.,in late Pleistocene-Holocence times will be discussed and related to the sea-level changes, changing Kuroshio Current,and climate (mainly Chinese continent) and Tectonic activies. And in this way,we can study in detail the sea (ocean)/continent interaction in the East China Sea.

**Provenance Study of the Yellow Sea Sediment: Geochemical Evidence From Chinese and Korean Rivers**

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The Yellow Sea is a world-famous epicontinental sea, semi-enclosed by landmass of China and Korea. It has held great fascination for marine geologists by offering itself as a world-class laboratory in which to study the interplay among sea-level change, terrigeneous sediment input, and hydrology for the typical epicontinental sea. Although the Yellow Sea sediment has been extensively characterized for the understanding of dispersal patterns and limits of terrestrial sediments from two gigantic rivers from China, Changjiang and Huanghe, and from several small Korean rivers (Han, Keum and

Yeongsan), the intractable source problem remains unsolved so far because of poor knowledge on compositions of the Chinese and Korean river sediments and instability of source indicators for discrimination.

Compositions of major, trace and rare earth elements in bulk and acid-leached sediments of Chinese and Korean rivers were measured by ICP-MS and compared, in order to characterize different source sediments. Source rock composition and chemical weathering intensity are two most important factors constraining distinct elemental compositions of river sediments, whereas grain size effect and human impact are minor. On the basis of element mobility and difference in compositions, chemical parameters, including Ti content, (La/Yb)N, GdN, ratios of Ti/Nb and Cr/Th, are suggested as source indicators to discriminate Changjiang and Huanghe sediments from Korean river matters. These source indicators, therefore, create the opportunity to decipher the provenance of the Yellow Sea sediment. Surface sediment samples from the Yellow Sea were determined for elemental compositions, and the provenance was identified by a discrimination model on the basis of the above geochemical indicators. The Huanghe river matter governs major part of the Yellow Sea, while the Changjiang and Korean river sediments contribute considerably to the southern and eastern parts of the Yellow Sea, respectively. The present study will shape our further understanding of the depositional system and paleoenvironmental changes during the later Quaternary in the Yellow Sea.

**Post-Glacial Sea Level and Sedimentation in a River-Dominated Epicontinental Shelf: The Yellow Sea**

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Shallow-marine, sub- and inter-tidal, and terrestrial (peat samples) data from the East China Sea (ECS) and Yellow Sea (YS), augmented by data from the Sunda shelf of South China Sea, show a series of rapid flooding events (as faster as 90-100 mm/y), separated by a series of slow rises (2-6 mm/y). By about 15 ka cal BP, sea level had reached -100 m, and seawater just entered the South Yellow Sea (SYS). A rapid rise during MWP-1A occurred between 14.3 -14.1 ka, sea level jumped from -95 m to -75 m (100 mm/yr). At the end, the sea water had reached the southern edge of the North Yellow Sea (NYS), after which sea level rose again slowly (6 mm/yr) from -72 m to -60 m. Beginning about 11.6 ka, it again jumped, from -60 m to -42 m at 11.4 ka (MWP-1B), resulting in a rapid westward flooding of the NYS. Sea level then again stagnated (between -42m to -36 m) for about 1.6 ky. Starting about 9.8 ka, the sea-level advanced again from -36m to -16 m at 9.0 ka (MWP-1C), after which most of Bohai Sea (BS), YS, and ECS had been submerged. Then another slowdown occurred between 9.0-8.0 ka when sea-level rose from -16m to -10m. The last major transgression happened between 8.1 and 7.0 ka (MWP-D), and resulted in Holocene highstand of at least +2 to 4 m along most of Chinese and Korean coastlines.

Deltaic depositional sequences on this epicontinental shelf show strong landward horizontal changes, instead of the vertical changes. The first major deltaic system was developed in the NYS, together with the decelerated sea-level rise after MWP-1B, the re-intensified Asian summer monsoon and subsequent increased river discharge at about 11 ka cal BP. The second subaqueous delta was built in the SYS between 9-7 ka which during another slackened sea-level after MWP-C. The modern subaqueous and subaerial deltas in the west Bahai Gulf have been formed during the sea-level highstand after the last jump of MWP-1D.

**Interaction and Correlation Between Ocean Bottom Currents and the Formation of Deep-sea Erosional and Depositional Features in the Western Sea of Japan**

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The Sea of Japan is a complicated environment, with respect to both oceanography and geology. Results from the two separate research programs, one oceanographic and one geophysical/geological were reviewed in an attempt to understand the complete ocean environment. From the oceanographic perspective, bathymetric features can significantly impact the oceanographic environment (bottom currents, meanders, eddies, etc.). Oceanographers from the Naval Research Laboratory

(NRL, Codes 7320 and 7330) have been defining the oceanography of the Japan Sea through ONR's Japan East Sea (JES) DRI (1998-2001), collecting oceanographic data and developing state of the art oceanographic predictive models. From the geophysical perspective, oceanographic features can significantly impact the ocean bottom environment by inducing furrows, scours, sandwaves, etc. Geologists and geophysicists from NRL (Code 7422) have been defining the ocean bottom geology and geophysics along the eastern coast of South Korea in the Ullueng Basin, utilizing data collected as part of joint NRL/NAVOCEANO/Republic of Korea Navy (ROKN) surveys. One joint survey was conducted in 1995, which generated MR-1 side scan sonar and multibeam bathymetric data. A preliminary analysis of the correlation between modeled ocean currents and the formation of erosional and depositional bottom features is presented.

**High-resolution Acoustic Characteristics of Epicontinental Shelf Deposits, Central-Eastern Yellow Sea**

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Large amounts (45,390 line km) of closely spaced (2.2-4.4 km) high-resolution subbottom profiles (Chirp, 2-7 kHz) made it possible to identify detailed echo types and their distribution in an epicontinental shelf environment. On the basis of seafloor morphology, surface bedforms and subbottom acoustic characters, eleven echo types are identified in the uppermost sedimentary sequence. Flat seafloor with sharp bottom echoes (echo types 1-1, 1-2 and 1-3a; transgressive sediment sheets or relict sands) is widespread in the offshore area and underlain to the west by an acoustically transparent wedge (echo type 1-3b; highstand muds). Mounded seafloor with either smooth surface or superposed bedforms (echo types 2-1, 2-2 and 2-3; tidal ridges) and flat seafloor with regularly spaced, wavy bedforms (echo type 1-4; large-scale dunes) are dominant in the eastern nearshore area. Large-scale mounds with continuous, inclined internal reflectors (echo type 2-4; giant mud bank) occur in the southeastern nearshore area. Broad mounds with shingled internal reflectors, truncated by seafloor, are present in the southwestern part of the Yellow sea (echo type 2-5; ?tidal ridge). Various-scale eroded seafloor (echo types 3-1 and 3-2; channels) and flat seafloor with regularly spaced, wavy bedforms (echo type 1-4; large-scale dunes) are present in the northern part. The distributional pattern of echo types in the central-eastern Yellow Sea reflects depositional processes and sediment dispersal systems during the Holocene transgression and highstand: 1) development of tidal ridges and large-scale dunes in response to strong tidal currents and waves in the eastern nearshore area; 2) construction of transgressive to highstand mud bank (Huksan mud belt) by deposition of muds derived from the Keum river in the southeastern nearshore area; 3) active erosion due to intensified currents in the northern part; and 4) highstand deposition of mud derived from the Huanghe river on the transgressive sediment sheets in the offshore area.

**Sedimentary Processes of Quaternary Sediments in the Southwestern Part of the East Sea (Sea of Japan)**

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The southwestern part of the East Sea consists of complex topographic setting (Ulleung Basin, Korea Plateau, Ulleung Interplain Gap and Oki Bank). A detailed analysis of 20,349 line-km of dense- and regular-spaced (5.5 km intervals), high-resolution (Chirp, 2-7 kHz) subbottom profiles and 38 long (8-12 m) piston cores reveals a distinctive zonal distribution of sedimentary processes. Pelagites/hemipelagites prevail on the uppermost slope of the Ulleung Basin and Oki Bank and the summits of ridges/seamount chains of the Korea Plateau. Slides/slumps and creeps occur extensively on the upper to lower slope of the Ulleung Basin and Oki Bank and the entire slopes of the ridges/seamount chains of the Korea Plateau. The mass-movement deposits change downslope to debrites and turbidites in the basin plain, the intervening troughs of the Korea Plateau, and the margins of the Ulleung Interplain Gap (UIG). In the UIG, a deep-water passageway between Ulleung and

Japan basins, a large-scale channel system is present along the axis, formed by deep-water circulation. The voluminous creeps, slides and slumps over the entire slope areas of the Ulleung Basin, Oki Bank and Korea Plateau, deeper than 300 m in water depth, were most likely generated by frequent seismic shakings.

**Tectonics, Dynamics and Geomorphology of the Eastern Tibetan Plateau**

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Eastern Tibet is a major source of the sediments deposited along the East and South China Sea margins. Thus its uplift history is closely linked to the spatial and temporal patterns of Cenozoic sedimentation along the adjacent continental margins, both because uplift drives surface erosion and because the increasing elevation of the plateau is thought to have triggered the onset of the Indian monsoon in Miocene time.

The eastern Tibetan plateau stands approximately 5 km above sea level with a crustal thickness approaching 70 km, nearly double the thickness of normal continental crust. Large-scale crustal shortening features are absent at the surface and the crust appears to have thickened by eastward flow of weak material within a deep crustal channel, without significant disruption of the surface rocks and sediments. This has producing wide (~2000 km) gently sloping topographic margins where the adjacent crust is weak, and narrow (~50 km) steep topographic margins where the adjacent crust is strong. This deep crustal flow has resulted in non-lithostatic pressure gradients in the deep crust and is expressed at the surface by excess topography and high-standing mountains where flow impinges on areas of strong crust that indent the plateau margin.

The eastern plateau is mantled by an erosion surface that appears to predate uplift of the plateau. Surface uplift created by crustal flow has resulted in the rapid incision of major rivers into this erosion surface, as well as river capture events and major geographical reorganization of the rivers that drain the plateau. Because of the lack of geological surface structures associated with plateau uplift, understanding and dating the geomorphic evolution of eastern Tibet, and the associated sedimentation in the East and South China Seas, remains one of the best avenues for constraining its lithospheric dynamics.

**Surface Uplift, Tectonics and Erosion of Eastern Tibet as Inferred From Major River Incision and Large-Scale Drainage Patterns**

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An understanding of river incision and drainage pattern evolution in eastern Tibet is an important step in being able to link onshore tectonic history with the erosional history recorded by sedimentary budgets and isotopic provenance in the continental margin basins that surround southern Asia. We present compiled geomorphic, stratigraphic, and structural data that outline a history of major river incision and drainage pattern reorganization in eastern Tibet that reflect the uplift and development of the eastern Tibetan Plateau margin. We propose that river capture and reversal of drainage directions are due to both long wavelength uplift of the southeastern plateau margin and more local tectonic deformation associated with that uplift. The Upper Yangtze, Upper Mekong, and Upper Salween Rivers reconstruct into to an original river course through the Red River into the South China Sea. This original drainage geometry significantly reduces estimates of shear strain calculated from modern length to drainage area ratios for these rivers. Major reversal of the Middle Yangtze River (culminating with the capture of the Upper Yangtze river to the East China Sea) indicates: 1) river capture occurred prior to or coeval with uplift and bedrock incision of major rivers, and 2) > 2km of surface uplift of the southeastern plateau margin has occurred since the capture/reversal event. We relate more recent captures of the Tsangpo/Brahmaputra and the Dadu/Anning Rivers to local/ sub-regional tectonic deformation associated with the geometry of the plateau margin.

Summary compilation of regional river captures and reversals provides a means by which the past history of the drainage organization can be used to establish a lower bound on the timing and amount of surface uplift. In the modern landscape, we observe continental scale rivers that have incised major canyons into an uplifted, relict, low-relief landscape. The initiation of major bedrock incision of these rivers into the relict landscape serves as a proxy for uplift of the eastern plateau margin. New low-temperature thermochronologic data suggest that rocks beneath the modern rivers occurred cooled very slowly through the early Tertiary until mid-late Miocene time, but that major river incision was well under way by late-Miocene time.

**An Erosional Response to Tibetan Plateau Uplift in the East Asian Marginal Seas?**

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Although the Tibetan Plateau is typically thought of as contrasting with the Himalaya in not being strongly eroded, but instead being dominated by internal drainage patterns, the fact remains that its eastern flank is strongly dissected by deep river valleys. Uplift of the plateau might be expected to generate an increase in sedimentation offshore as these river valleys were incised. Indeed, because the strength of the monsoon is also linked to Tibetan elevation, it might be expected that surface uplift would increase precipitation, run-off and thus further increase erosion along the plateau margins. A new regional compilation of seismic and well data from a series of the East Asian marginal seas now reveals a coherent pattern of increasing sedimentation during the Early to Middle Miocene, 15-20 Ma. The basins were selected to record the outflow of sediment from several of the major river systems draining East Asia, specifically the Irrawaddy, Mekong, Red, Pearl and Yangtze Rivers. This new sediment budget is quite different from earlier published reconstructions, probably because, for the first time, sediment deposited across the entire margin from the coast to the abyssal plain has been accounted for. This is important because accumulation rates in basins close to the coast will tend to reflect the rates of tectonic, thermal subsidence when the basin is close to being full. Conversely, accumulation rates at the foot of the continental rise are strongly linked to periods of lower sealevel. Only by accounting for the sediment wherever it is deposited in any given system can a robust budget be derived. The influx of sediment during the Early to Middle Miocene correlates with several other erosional events that also suggest a major realignment of the regional climate at this time. Sedimentation rapidly increases and peaks in the Indus Fan during the Middle Miocene, while rates also increase in the Tarim Basin, demonstrating that increased erosion affected most of south and central Asia, not just the eastern river systems. Changing clay mineralogy on the South China margin (ODP Site 1148) indicates a change from a dry (smectite-dominated) to a wetter (illite-dominated) climate starting at ~16-20 Ma. New data from the Loess Plateau in central northern China now indicates that wind blown sediments associated with the winter monsoon have been accumulating there since at least 22 Ma. Recent attempts to date the age of E-W extension in Tibet, a process commonly linked to increased plateau elevation and gravitational collapse, now indicate that this started at ~15-20 Ma, not the ~8 Ma previously accepted, supporting the idea of an early elevation of Tibet. When viewed together these data indicate that the Early-Middle Miocene is a period of strong tectonic activity in the Tibetan Plateau, coincident with changing erosional regimes. The sedimentary record of the East Asian marginal seas now provides evidence to support major Early-Middle Miocene uplift of the Tibetan Plateau and associated strengthening of the Asian monsoon. This model implies a simple positive relationship between tectonic activity, precipitation and the flux of material to the oceans during the Cenozoic.

**Land-Sea Linkages of Depositional Systems at the Western Margin of the South China Sea During the Past 130 Kyr**

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This study presents a transect which spans from the modern coastal lowlands of eastern Malaysia, over the Sunda Shelf downslope into the deep-sea basin (profile length ca. one thousand km). The three environments coastal zone (incl. deltas), shelf and continental slope are characterized by high sediment storage capacity, varying depositional and erosional patterns, (non-unidirectional) sediment transport, sediment bypassing, a high local facies variety, specific hydraulic conditions, and a high sensitivity to sea-level changes. They are framed by the hinterland acting as sediment source and the ocean basin sink. Variations of the fundamental conditions, such as sea-level changes over the past 130 kyr, therefore result in complex depositional patterns.

Synchronously deposited strata are linked together elucidating their causal relation. The 'end-member' conditions in terms of sea-level changes can be divided into two: 1) low sea-level: proximal valley incision, central bypassing, a thick distal shelf wedge and high accumulation rates in the open ocean; 2) high sea level: formation of sediment wedges in the coastal zone and nearshore and starvation of terrigenous sediments in the outer part of the transect. The depositional linkage in-between the 'end-member' conditions, i.e. during phases of (non-continuous) sea-level fall or rise, respectively, reflects the dynamics and rapidity of environmental changes. These changes are accompanied by rapid shoreline migration and facies shifts, relocation of accumulation space, channel incision, extended sediment drapes and detached sediment bodies.

**Bathymetry and Topography of the Northern Asian Pacific Margin**

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A combined bathymetric and topographic chart of the northern Asian Pacific margin was developed to gain insight on the influence of adjacent landmasses on the oceanography and geology of the marginal seas. Bathymetric information from the U. S. Naval Oceanographic Office's Digital Bathymetric Database 5 (DBDB5) was merged with topographic data from the U. S. Geological Survey's GTOPO30. Generic Mapping Tools (GMT, version 3.3.3) and software and techniques internal to NRL were used to produce the chart. With the combined data it is possible to visualize likely relationships between ground relief and submarine relief. The identification of drainage pathways can help to pinpoint major fresh water influxes to the seas. Knowledge of the river courses can also help to address the origins and types of terrigenous sediments. Major cities and farming regions are likely sources for pollutants in the marginal seas. In addition, the dispersal of fresh water, sediments and pollutants can be influenced by the interaction between the oceanography (currents, meanders, upwellings, etc.) and the bathymetry (submarine canyons, ridges, etc.) of the marginal seas. The combination of bathymetric and topographic data in chart form can be useful for understanding the physical environment as well as a planning tool for surveys and experiments in the northern Asian Pacific margin region.

**Environmental Magnetic Record of ODP Site 1148 (South China Sea): Direct Correlation of Marine and Terrestrial Paleoclimate Records?**

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We are studying the paleomagnetism and environmental magnetism of 110 u-channel samples from Site 1148 from ODP Leg 184 to the South China Sea. The NRM record from Site 1148 reveals a moderately strong and relatively stable magnetization that can be used to develop a magnetic polarity zonation for the site. More importantly, the ARM-normalized NRM record for the Brunhes Chron shows excellent agreement with the SINT-800 record of relative paleointensity. This correlation allows us to obtain a geomagnetic intensity time scale for the Brunhes Chron of Site 1148 that is independent of any correlation to the marine oxygen isotope record.

Initial environmental magnetic results from the Site 1148 u-channels show marked variations in the concentration of magnetic material incorporated in the sediments. Studies of the lithology and sedimentology of various sites from Leg 184 suggest that the primary input of sediment into this part of the South China Sea is fluvial detrital material from Taiwan, to the northeast. Given the nature of the bedrock on Taiwan, it is difficult to understand how this source could be responsible for the variations in concentration of magnetic material at Site 1148. An alternate explanation is that the magnetic material represents aeolian input from the loess plateau and that variations in magnetic concentration correlate with variations in the loess/paleosol sequence.

We have compared the environmental magnetic record of Site 1148 with the magnetic susceptibility record from the Jiaodao loess/paleosol section, Shaanxi Province, China. The time scale for the Jiaodao section is based on astronomical tuning of loess records from several sites. In general, intervals when paleosols were forming on the Chinese loess plateau correspond to intervals with a high concentration of magnetic material at Site 1148. These intervals do not correspond to features in the oxygen isotope record from the site. We conclude that the environmental magnetic record from Site 1148 was being influenced by terrestrial paleoclimate and that this site has the potential of providing a direct correlation between marine and terrestrial paleoclimate records.

**Middle to Late Miocene Paleoceanography of the South China Sea and Western Tropical Pacific: Testing Linkages Between Indonesian Seaway Closure and Sea Level Change**

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The South China Sea lies at the confluence of two, tectonically induced climate-ocean features, the East Asia monsoon and the Western Pacific Warm Pool (WPWP). The WPWP broadly influences tropical Pacific climate and ocean circulation and here we present preliminary results of an investigation into its early development as the Indonesian Seaway (IS) narrowed during late Miocene time. Planktic foraminiferal stable isotope paleoecology and population analyses were conducted on sediment samples from three locations [ODP Sites 1146 and 1143, South China Sea (SCS); ODP Site 806, Ontong Java Plateau, (OJP)] and at five time slices (0, 7, 9, 11 and 13 Ma). In addition, a continuous record of planktic foraminiferal population analyses and multi-species isotopic gradients, spanning 13.7 to 5.5 Ma, was completed at OJP and is on-going at the SCS. Both the time slice data and the continuous records document profound changes in the WPWP through this time interval, from its core at OJP to its nor thwestern limit in the

A population analysis of the modern planktic foraminiferal assemblage at Site 1146, which is influenced by the East Asian monsoon, reveals more thermocline species than surface species (56% to 42%, respectively). However, at OJP the surface species comprise 81% of the assemblage (17% thermocline species) which reflects the thicker mixed layer and deeper thermocline that is characteristic of the WPWP. The time slice data at 7Ma shows a reversal of population assemblages between the two sites, implying the lack of the WPWP at OJP. At 11Ma, the OJP assemblage is again dominated by surface species (74%; thermocline, 23%) while the 1146 assemblage resembles the modern OJP. These changes at 11 Ma suggest that a proto-WPWP may have existed at OJP and that warm pool-like conditions may also have characterized parts of the South China Sea prior to the intensification of the East Asian Monsoon.

The continuous record of population analyses and multi-species stable isotope gradients at OJP support the findings of the time slice data for that site. Noteworthy is a decrease in the d13C gradient (surface to benthic gradient) and dominance of surface species (with a corresponding rise in thermocline species) from 11.3 Ma to 7.5 Ma. This interval implies a transition from a possible proto-WPWP (having a thick mixed layer and a deep thermocline) to a time of no WPWP.

These data and similar data we have collected from the Marion Plateau (ODP Site 1195) support the idea that constriction of the Indonesian Seaway may have greatly modulated the tropical climate-ocean system during the late Miocene. This constriction and the development of the WPWP (~11-9 Ma) coincides with a marked decrease in tropical carbonate mass accumulation rates (e.g., Farrell et al., 1995; Droxler et al., 1998). We suggest that the early development of the WPWP was related to the major sea level fall at the middle to late Miocene transition. For example, Billups and Schrag (2002) showed that the Mi5 event at this transition indicates a major ice volume increase (correlative to the 10.5=Ser4/Tor 1 sea level fall of

Haq et al., 1987). Further, the subsequent late Miocene sea level rise increased IS Throughflow, reduced the WPWP and stimulated increased carbonate mass accumulation rates across the tropical Indo-Pacific (~8-5 Ma; e.g., Farrell et al., 1995; Lyle et al., 1995; Fil lippelli, 1997).

**Teleconnection and its Speed Between the Equatorial Pacific and the Western Pacific Margins: Evidence From the Sedimentation Record of Plutonium Isotopes in the Southern Okinawa Trough**

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Owing to its location, topography and hydrodynamic conditions, the southernmost part of the Okinawa Trough (SPOT) acts like an efficient receptacle for sediments from Taiwan and the East China Sea shelf. The high sediment flux in conjunction with the passage, upwelling, diversion and swirling of Kuroshio in the SPOT area leads to extremely intense boundary scavenging, with sedimentary inventories of $^{210}Pb$ and $^{239,240}Pu$ that are 1-2 orders of magnitude higher than their expected values. Such high Pu inventories are rather unusual considering the introduction of Pu only during the past five decades and that the water column in the study area is fairly deep (> 1000 m). It must be explained by advective transport of Pu westward from the Marshall Islands (the largest source for Pu in the Pacific) by the North Equatorial Current (NEC) followed by northward transport by Kuroshio to the SPOT area.

While sedimentation rates (S) in the SPOT area are high (~3 orders of magnitude higher than in pelagic sediments), mixing rates (D) deduced from $^{210}Pb$ and $^{239,240}Pu$ profiles are on the same order as those typical of pelagic sediments. Such high S/D ratios enabled us to differentiate the subsurface peak of $^{239,240}Pu$ marking the global fallout maximum in 1963 and the subsurface peak of $^{240}Pu/^{239}Pu$ resulting from neutron-rich thermonuclear tests conducted by the U.S. in the early 1950s at the Enewetak and Bikini Atolls of the Marshall Islands. Based on the sedimentation rates and the vertical offset between the subsurface peaks of $^{239,240}Pu$ and $^{240}Pu/^{239}Pu$, the transit time of Pu from the source (at ~12°N, 162°E) to the sink in the SPOT area is estimated to be 3-5 years. The mean velocity of NEC thus calculated, at ~0.03-0.05 m/s, is fairly consistent with the geostrophic transport of NEC above 400 m calculated from XBT data and the T-S relationship.
The present is the key to the past. This study suggests that the 410-m long ODP core recently collected from the SPOT area holds great promise in providing high-resolution records of paleooceanography in the Equatorial Pacific, along the Kuroshio and through the western Pacific margins in the past ~100,000 years.

**TOC and d13Corg Records of Monsoon-Driven Paleoproductivity Variations in the Southeastern South China Sea (IMAGES core MD972142) over the past 900 ka**

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High-resolution TOC and d13Corg records of IMAGES-core MD972142 (12º41.133'N, 119º27.90'E, water depth 1,557 m) generally show enhanced levels of organic carbon combined with significantly heavier d13Corg values during glacial compared to interglacial periods over the past 900 ka. These data indicate an increased primary productivity in the South China Sea during glacial times, potentially caused by a strengthened East Asian Winter Monsoon intensity. However, the organic carbon peak formed during the glacial maximum of MIS 12 stands out among the other peaks. The TOC content in MIS 12 reaches almost twice as high values as during the other glacial periods. Heavy d13Corg values and the lack of increased n-alkane concentrations, which would have indicated enhanced terrigenous input, indicate that increased primary productivity and not enhanced terrestrial input is responsible for the sharp peak in organic carbon. In contrast, opal and alkenone concentrations, that would be expected to peak under high productivity conditions, display no significant increase during the glacial maximum of MIS 12. Opal concentrations actually display a minimum during the glacial maximum of MIS 12. The exact cause of the strong TOC peak and the contradictory proxy records still remains unclear but the data point to exceptional East Asian Winter Monsoon conditions during MIS 12

**Early Evolution of the South China Sea: Sediments and Biofacies of Oligocene-Miocene Deep-Water Environments**

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We studied Oligocene-Miocene benthic foraminiferal assemblages, trace fossils, sediment color data, stable isotopes and sedimentological data at Site 1148 (ODP Leg 184), at the northern margin of the South China Sea. Our results have the following implications for understanding the early evolution of deep-water environments in the South China Sea: Deep water agglutinated foraminifers, including turbidite recolonizers, tubular suspension feeding forms and other "flysch-type" agglutinated foraminifers characterize Oligocene assemblages and indicate that turbidites and bottom currents exerted a strong influence in deep-water depositional environments. A significant change from Early Oligocene Nothia - dominated assemblages to Late Oligocene Rhabdammina dominated - assemblages probably reflects the transition from turbidity currents to contour currents. A major change from agglutinated deep water foraminiferal assemblages to predominantly calcareous deep-water assemblages occurs at the Oligocene-Miocene boundary,and coincides with a hiatus and a major gravity flow deposit. This redeposition event pre-dates the global early Miocene carbon isotope excursion and may be related to a major regional tectonic event. Oligocene and Miocene benthic foraminifers are cosmopolitan, and consistently indicate deep-water conditions (lower bathyal) at Site 1148 since the Early Oligocene. However, Oligocene assemblages exhibit a strong affinity to "Tethyan" assemblages, whereas Miocene assemblages are closer in composition to "Pacific" assemblages. This change in assemblage composition probably may reflect accelerated closure of the deep-water pathway between Australia and SE Asia since the Early Miocene and consequent development of faunal migration barriers between the Pacific and Indian Oceans.

**Middle Miocene Paleoceanographic Events in the South China Sea and Eastern Indian Ocean: The Role of the Indonesian Deepwater Pathway**

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The Middle Miocene represents a time slice of exceptional interest for deciphering the impact of global climatic and paleoceanographic change. It is the last period in the Earth's history that experienced a long-term positive carbon isotope excursion coincident with a period of extreme warm climate when major changes in the deep ocean benthic foraminiferal fauna occurred. One of the geographic key areas to understand this extraordinary paleoceanographic event is the Indonesian Gateway, where plate tectonic movements ultimately led to the closure of the deep-water gateway between the Pacific and Indian Oceans. We use sediment color reflectance data, organic carbon content and benthic foraminiferal d13C values as proxies of deep-water ventilation to reconstruct Middle Miocene changes in deep water ventilation at critical locations within the Indonesian Gateway (South China Sea, depth transect of ODP Sites 1146 and 1148), at the western end of the gateway (NW Australian margin, ODP Site 761). We use quantitative analyses of deep-water benthic foraminifers in combination with high resolution stratigraphy to constrain the timing of changes in carbon flux and oxygenation at the seafloor, and to reconstruct biogeographic patterns and potential migration events through the gateway. Preliminary results indicate that carbon flux to the seafloor became initially enhanced at all three locations during the Middle Miocene climate maximum before an improvement in deep-water ventilation during the subsequent global cooling that coincided with the expansion of the Antarctic ice cap. A maximum in organic flux at 15.8 Ma (between CM4 and CM5) is indicated at all sites by: (1) high total numbers of benthic foraminifers, (2) a distinct maximum of infaunal carbon flux indicators such as

Stilostomella and (3) at the two shallower sites by distinct maxima of buliminids. Immediately above this productivity maximum, a significant change in bottom water oxygenation occurs, as shown by the color reflectance record in both South China Sea cores. A rapid increase in d18O values at Site 761 suggests cooling of the deep water in the eastern Indian Ocean prior to the main expansion of the East Antarctic Ice Sheet. This event, which lasts from approx. 15.8 Ma to the Langhian-Serravallian boundary (14.8 Ma), coincides with a faunal change towards an oligotrophic Planulina-Cibicidoides biofacies. Late Middle Miocene d18O values (after the expansion of the East Antarctic Ice Sheet) at the Indian Ocean Site 761 are approx. 0.4 per mille higher than at the (deeper!) South China Sea Site 1148, indicating significantly different deep water masses on both sides of the Indonesian gateway after the Langhian Ventilation Event.

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**Oceanographic and Sedimentological Response of East Asian Marginal Seas to Tectonic and Eustatic Changes**

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Since their formation in the late Cenozoic, the East Asian marginal seas have become a unique tectonic and geographic feature separating Asia from the Pacific and modifying the material and energy flows between the largest continent and the largest ocean in the modern world. DSDP/ODP legs, oil-prospecting drillings, and numerous sediment cores from the Bering Sea in the north to the Banda Sea in the south, have provided deep-sea records to review the late Neogene paleoceanographic and sedimentolgical history of the marginal seas, with emphasis on the western boundary currents and carbonate content in deep sea sediments.

The western boundary currents of the oceans are the principle conduits for communication between the equatorial regions and the polar regions. In the modern Western Pacific, the boundary currents, Kuroshio and Oyashio, flow through the marginal seas and function as vehicles not only of energy exchanges between high and low latitudes, but also of sea-land exchanges between Asia and the Pacific. The tectonic closure of the Indonesian passageway has strengthened if not initiated the Kuroshio which in turn caused remarkable climatic changes in the region. Within the late Quaternary, the western boundary currents were mainly flowing outside the marginal seas during the glacial low sea-level stand, and the role of marginal seas in sea-land exchanges significantly diminished. Glacial reduction of the Kuroshio warm water in the marginal seas decreased the heat and humidity supply to East Asia; the glacial cut-off of Kuroshio from entering the South China Sea together with intensification of winter monsoon led to the increased N-S climate contrast inside the sea. On the other hand, the glacial model of boundary currents running outside the marginal seas and the enhanced influence of sea-ice and melt-water on the Oyashio is favorable to the intensified production of the North Pacific Intermediate Water (NPIW) which is formed by mixing of the two boundary currents. The glacial expansion and intensification of the NPIW might explain the oxygenated intermediate water during the glacial as recorded in the Santa Barbara Basin. The same mechanism could also be applied to explain the millennial cycles in the same basin.

Southern and Eastern Asia with their islands provide a majority of the terrigenous suspended material supplied to the global ocean, but the marginal seas intercept sediments and prevent the accumulation of deep-sea fans in the Western Pacific. The deep-sea sedimentation rates in the marginal seas, thus, can be one to two orders of magnitude higher than in the open ocean. As to biogenic sediments, the general pattern of CaCO3 distribution in the modern marginal seas displays a clear increasing trend toward low latitudes, but carbonate content has been changing significantly with tectonic evolution of marginal basins and glacial cycles, responding to deep-water sources and surface water productivity. Together with coral reef building and destruction, the variations in carbonate production and preservation in the marginal seas must have contributed to the global carbon cycle.

In sum, the recent progress in the Asian marginal seas raised a question: What has been their role in the Earth surface system: only a passive responder to high-latitude ice-cape changes, or one of active contributors to the global changes?

**The Japan Sea as a Sensitive System Responding to Regional and Global Environmental Changes**

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The Japan Sea is a semi-enclosed marginal sea with present sill depth of ca. 130m located on the mid-latitude East Asian margin. The sea is connected with other oceans with 4 shallow and narrow straits. The Tsushima Warm Current (TWC), a branch of the Kuroshio Current, is the only current flowing into the sea with the average flux rate of ca. 2 Sv. The warm, saline, and nutrients-poor TWC is cooled in the northern part of the sea during winter to form its own deep water called Japan Sea Proper Water that ventilates the deeper part of the sea with residence time of several hundred years. Due to this high ventilation rate the present Japan Sea is one of the most oxic basins in the world. However, the situation was completely different during glacial periods. The Japan Sea sediment cores recovered from the deeper part of the basin show distinct cm- to decimeter-scale alternations of the dark, org-C rich, laminated layers and light, org-C lean bioturbated layers with thick dark layers corresponding to glacial maxima. These dark and light layers reflect drastic oscillations in bottom-water oxygenation level as well as variations in surface productivity. Such factors are modulated by eustatic sea level changes and contribution of less saline and nutrient-rich East China Sea Coastal Water relative to the TWC, the latter having been influenced by variations in terrestrial climate and consequent variations in river discharges from East Asia.