Cenozoic Deformation and the History of Sea-Land Interactions in Asia

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Of the existing continents, Asia has experienced the most significant deformation during the Cenozoic. From the Cretaceous to early Paleogene, Asia was smaller and "slimmer" compared with the present continent. After the India-Asia collision in the Eocene, Asia significantly enlarged its size and increased its altitude. The west-tilting topography of East Asia was reversed with uplift of the Tibetan Plateau and the opening of marginal seas, resulting in an Asian fluvial system radiating from the uplifted center of the continent. Plateau uplift may have promoted the establishment and growth of the Arctic ice-sheet not only by alteration of atmospheric circulation and enhancement of weathering, but also by formation of north-flowing Siberian rivers, which provide the Arctic Ocean with freshwater run-off. Cenozoic deformation of Asia was also responsible for the initiation of the Asian monsoon system during the early Miocene and its further strengthening at ~8 Ma and ~3 Ma. The formation of a series of seas fringing the East Asian margin has changed the material and energy flux between the Asian continent and Pacific Ocean. The Western Pacific boundary currents flowing through the marginal seas are highly sensitive to eustatic and tectonic changes. During low sea-level stands caused by glaciation, the boundary currents flowed outside the marginal seas and reduced the heat and humidity supply from the ocean to the continent. Today, the most active energy and material fluxes in the Earth System occur between Asia and the Pacific, yet the role of Asia in controlling global climatic and environmental history has been underestimated.

1. INTRODUCTION

Proposed links between the tectonic evolution of the solid Earth and climate represent an important, controversial, and yet poorly understood part of the global climate system. Testing and quantifying such links is crucial to our understanding of long-term environmental changes, and Asia offers the best opportunities for its study. For a long time Tibet has been the global focus for researchers exploring the climatic consequences of plateau uplift, while in recent years, the Western Pacific marginal seas have become increasingly attractive for paleoclimate studies. The thick sequences of hemipelagic sediments that have accumulated, for example, from the South China Sea, yield not only high-resolution stratigraphy, but also a unique record of land-sea interactions.

Compared with the huge size and primary importance of Asia in the global climate system, our knowledge of its geologic history is rather limited. Vast areas of the Asian continent and its associated marginal seas remain known only in outline. Because of the linguistic and political diversity, many of the results of geological survey and scientific researches are not readily accessible to the global community. A broad, comprehensive vision of the climatic and geologic evolution of the continent is missing.

This study reviews some major aspects of the Cenozoic deformation of Asia and their environmental consequences,

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with emphasis on land-sea interactions. Because of the broad scope, only general outlines are given, and detailed discussions with supporting data have been or will be published elsewhere.

Significant new contributions on these topics can be found within this monograph. *Ali and Aitcheson* provide new paleomagnetic constraints that suggest that India-Asia collision, and by implication Tibetan surface uplift did not occur until the Miocene, much later than the Eocene age more typically accepted. Conversely, *Clift et al*. show that clastic flux from the rivers of East Asia increased steadily after the middle Eocene and jumped sharply during the Oligocene (~33 Ma), supportive of surface uplift and monsoon strengthening at that time. *Clift et al*. also note that erosion accelerates again in the Pliocene, an observation that may support the contention of *Tada* that this is a time of stronger monsoon activity, possibly linked to renewed uplift of the plateau. Tada makes the case for a tectonically induced monsoon intensification that then varies in strength over orbital cycles in parallel with North Atlantic Dansgaard-Oeschger Cycles. *Murray and Dorobek* use the marine sedimentary record of the Mekong River to propose uplift, enhanced erosion and river capture in eastern Tibet during the late Miocene, which correlates with the well-documented paleoceanographic and climatic events around 8 Ma. The second major form of tectonically induced land-sea interaction profiled in this monograph is the link between Australia-Indonesian collision and the formation of the Western Pacific Warm Pool, together with the major boundary currents of the Western Pacific, most notably the Kuroshio Current. *Kuhnt et al*. note that closure of deep water flow between the Indian and Pacific Oceans through the Indonesian passageway began prior to 25 Ma, but they also identify the Pliocene as a time when changes in the throughflow caused major changes in both Indian and Pacific paleoceanography. *Holbourn et al*. provide a high-resolution benthic foraminifer isotope record from the South China Sea to show that deep-water connection between the Indian and Pacific was already restricted in the middle Miocene (11–17 Ma). These workers also demonstrate a shift from low latitude forcing linked to the eccentricity of the Earth's orbit to high latitude obliquity forcing at 14.9 Ma.

The subject of ocean-continent and especially climate-tectonic interactions remains a very active field, with additional studies now in progress, In particular, the final report of the Scientific Committee on Oceanic Research (SCOR)/International Marine Global Change Study (IMAGES) Working Group on the evolution of the Asian monsoon system represents important future advances to our understanding of land-sea interactions in East Asia, with special reference to the Asian monsoon.

2. INTERACTIONS BETWEEN ASIA AND PACIFIC

2.1. A Center of Material, Energy, and Genetic Flux

Asia is the only continent sandwiched between two convergent plate margins: the Pacific plate subducting from the east and the Indian Plate colliding from the southwest. As a result, Asia is not only the largest, but also the highest continent on the modern planet. Except for the western side bordered by the Ural Mountains, Asia is surrounded by three oceans: the Siberian Seas of the Arctic in the north, the Western Pacific marginal seas in the east, and the Northern Indian Ocean in the southwest. Of particular climatic importance is the Western Pacific Warm Pool located southeast of Asia. A number of large rivers empty into these seas, influencing the Western Pacific Warm Pool in the south and the Arctic Ocean in the north. It is a remarkable geomorphologic feature of the continent that almost all large rivers in Asia rise in its center, within the Tibetan and Mongolian plateaus (Figure 1).

Geographically, Asia is distinguished by its strong topographic gradient. There is nearly 20 km of vertical contrast in topography within a distance of 4000 km, between the highest peak in the World (Zhumolongma or Everest in the Himalayas, 8848 m elevation) and one of the deepest trenches in the ocean (Philippine Trench, 10,497 m water depth; Figure 1). Furthermore, as a result of the topography and monsoon rain, the eastern and southern parts of Asia with its islands contribute nearly 70% of the total terrigenous suspended load to the global ocean [*Milliman and Meade*, 1983]. Comparing modern rates of total denudation (mechanical and chemical) for all the major externally drained basins on Earth (> $5x10^5$ km^2 in area), almost all the largest fluxes are in South and East Asia (Figure 2 B) [*Summerfield and Hulton*, 1994]. A combination of topographic gradient, humid climate and young geological formations has led to high denudation rates and material flow from continent to ocean.

Climatically, the Western Pacific Warm Pool with a multi-annual average surface water temperature over 28°C, located to the southeast of Asia, is the centre of global heating at sea level (Figure 2A)[*Yan et al*., 1992], whereas the Tibetan Plateau is the centre of heating at an altitude of 5000 m [*Kutzbach et al.*, 1993]. Since these heat sources, as well as the coldest Siberian High Cell, are all in this region, the great contrast has led to extremely active atmospheric energy flow. The intensive tropical heating in the Western Pacific Warm Pool gives rise to active convection: warm and humid light air rises, resulting in deep penetrative circulations extending to the top of troposphere. This is the source of three major divergent wind cells: the cross-equatorial circulation of the monsoon ("lateral monsoon"), and two traverse circulations driven by longitudinal

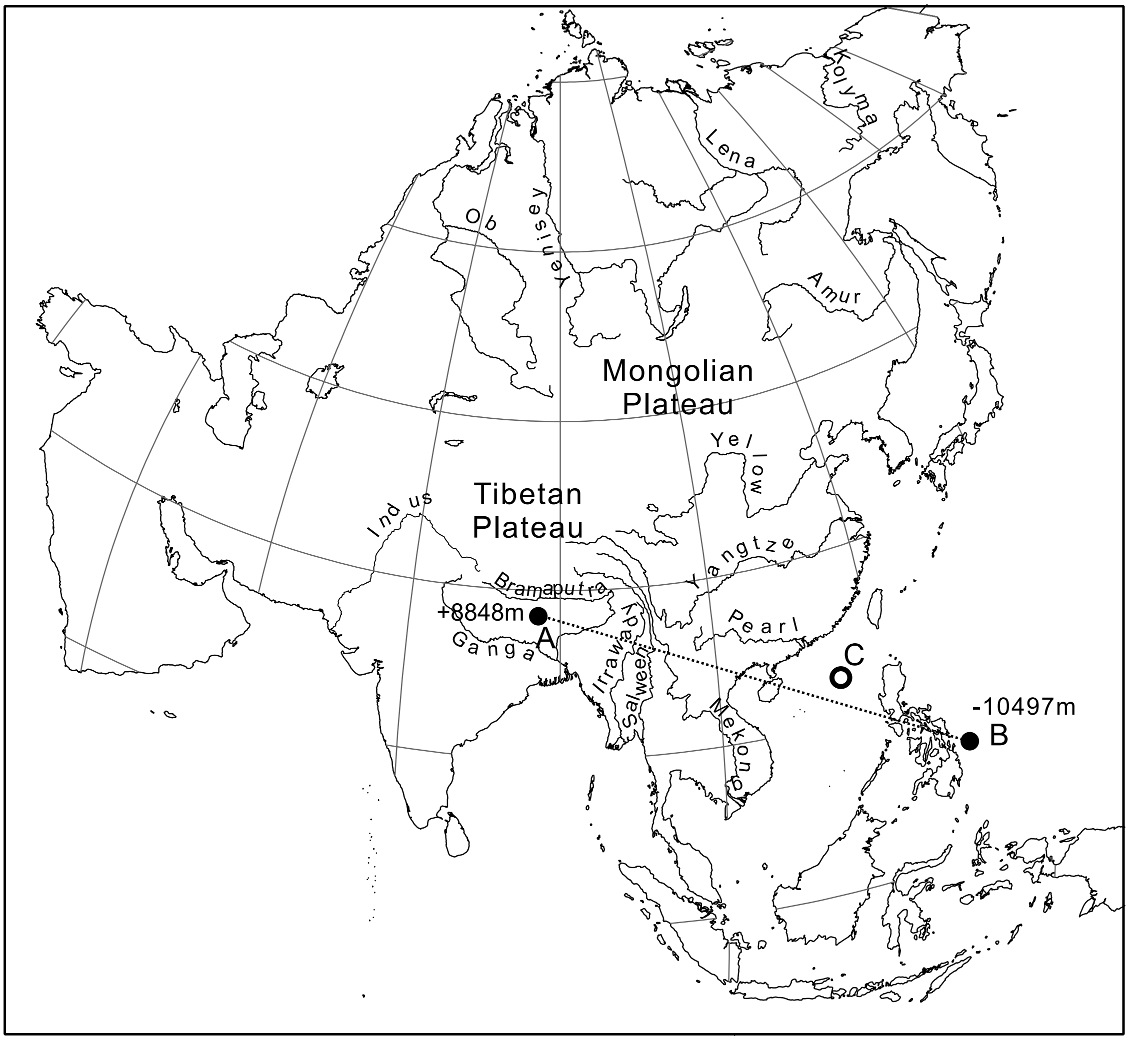

Figure 1. Map of Asia and its surrounding seas. Note that all large rivers originate in the Central Asian plateaus. Solid circles mark the highest peak in the World (A, Zhumolongma or Everest in the Himalayas, 8848 m altitude) and one of the deepest trenches in ocean (B, Philippine Trench, water depth 10,497 m), with nearly 20 km of vertical contrast in topography within a distance of 4000 km between the two sites. Open circle (C) shows location of ODP Site 1148.

heating gradients, including the "traverse monsoon" circulation between South Asia and the arid regions of north Africa and the Middle East; and the "Walker Circulation" between the cool eastern and warm western Pacific Ocean responsible for El Niño (Figure 2A) [*Webster et al.*, 1998].

Land-sea interactions, through their material and energy flux linkage, are of primary importance to global climate change. The supply of terrigenous material to the ocean changes water chemistry and productivity in the ocean and, hence, the CO_2 concentration in the atmosphere. Conversely, the heat and humidity transfer from the ocean to land is a major control for terrestrial climate. It is not a coincidence that the most active energy and material fluxes on the modern Earth occur between the largest continent and the largest ocean.

In addition, the Western Pacific Warm Pool region approximately coincides with the so-called "East Indies Triangle" where modern marine and terrestrial biodiversity is a global maximum (Figure 2C). Most tropical marine families have their greatest species diversity within the "Triangle", and the average generic age is youngest, suggesting that the region has operating as a center of evolutionary radiation [*Briggs*, 1999]. The richness in species is probably related to the convergence of two plates, Eurasian and Australian, and of two oceans, Pacific and Indian [*Benzie*, 1998], as traced by the famous "Wallace's Line" in terrestrial biogeography [*David et al.*, 2002] and even a "Marine Wallace's Line" in genetic distribution [*Barber et al.*, 2000]. Although it remains a matter of debate about the origin of the high diversity, the "Maritime

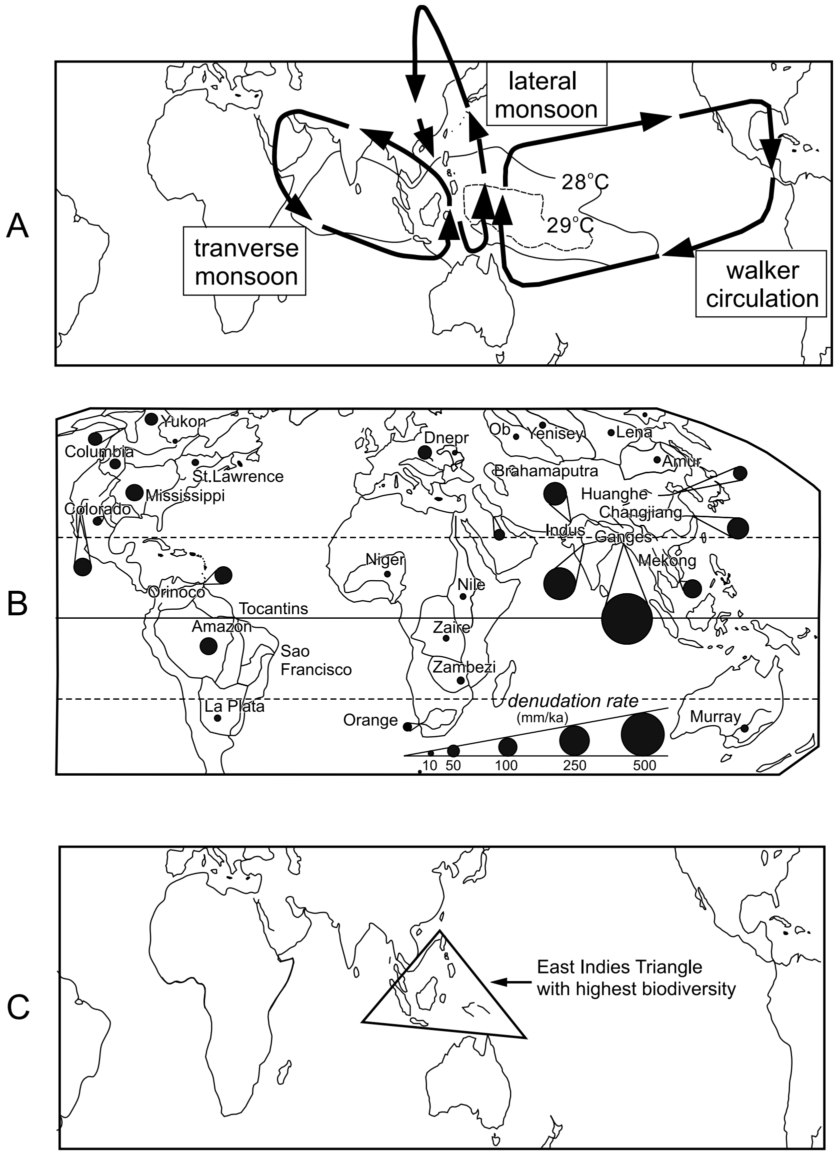

Figure 2. The global significance of the contrast between Asia and the Pacific Ocean. (A) The Western Pacific Warm Pool as a center of major divergent atmospheric circulations: the lateral and traverse monsoons, and the Walker Circulation responsible for El Niño. A synthesis of modern winter wind circulation is shown (modified from *Webster et al.* [1998]). Isolines denote multi-annual sea surface temperature, and the 28ºC isotherm that outlines the Western Pacific Warm Pool. (B) Southeast Asia as a region of maximal continent weathering and sediment supply to the modern ocean. Estimated denudation rates of major externally drained basins are shown (modified from *Summerfield and Hulton* [1994]). (C) Location of the "East Indies Triangle" of highest biodiversity (based on *Briggs* [1999]).

Continent" of SE Asia and its neighboring areas undoubtedly represent a maximum in gene flow.

2.2. A Changing System of Land-Sea Interactions

A distinguishing feature of Asia-Pacific interactions is the presence of marginal seas between the open ocean and the continent. Over 75% of the marginal basins in the modern ocean are concentrated along the Western Pacific continental margin [*Tamaki and Honza,* 1991]. Four large marginal seas lie between the East Asian continent and the Pacific, i.e., the Okhotsk Sea, Sea of Japan, and the East and South China Seas. These seas cover approximately 7×10^6 km^2 in area and 7.6×10^6 km^3 in volume, accounting for 2% and 0.5% of the

Table 1. Morphological features of four Western Pacific marginal seas*
[Modified from Wang, 1999]

Marginal sea	Sea of Okhotsk	Sea of Japan	East China Sea	South China Sea
Shallow sea area (<200m; %)	41.2	26.3	75.6	52.4
Average depth (m)	777	1,361	370	1,212
Basin depth B (m)	3,374	4,049	2,719	5,377
Sill depth S (m)	~2000	130	>2000	2,600
S/B	0.59	0.03	0.74	0.48
Passage width P (km)	455	136	981	950
Surface area A (10^3km^2)	1590	978	1228	3500
P/A	0.29	0.14	0.80	0.27
Connecting section C (km^2)	184	8	321	493
Basin volume V (10^5km^3)	1,365	1,713	303	4,242
C/V (10^{-5})	13.48	0.48	105.96	11.61

* Including all shelf seas and bays. For example, the East China Sea includes the Yellow Sea and the Bohai Gulf.

global ocean, respectively. However, their role in controlling the global climate changes goes far beyond their size, because the marginal seas are the sites of the most active material and energy exchanges between continent and ocean. Table 1 compares the morphological features of the four major seas, including their size and the extent of isolation from the open ocean. Apart from the atmospheric transmission of vapor and dust, both river and oceanic currents enter the marginal seas where they are able to mix. The hydrological system in the marginal seas is thus highly sensitive to changes in both the continent and ocean, and in particular to sea-level fluctuations during glacial-interglacial cycles. Even a minor drop of the sea level can cause major changes in water circulation and, hence, the nature of regional land-sea interactions [*Wang,* 1999].

In this paper I argue that the geographic features of Asia, including the marginal seas, have been formed only since the start of the Miocene (~24 Ma), and that the gradual development of the present geography of Asia has been accompanied by changes in the climate system, most notably the monsoons. The Late Cenozoic history of Asia provides an example of how tectonic and eustatic changes can cause regional responses in paleoceanography, but which have global climatic impacts.

3. DEFORMATION OF ASIA AND HYDROLOGICAL NETWORK

All the features of Asia described above are geologically young, mostly forming as a consequence of the collision of Eurasian with the Indian and Australian Plates. The Central Asian plateaus and the hydrological net radiating from there, as well as the series of marginal seas in the Western Pacific, did not exist until the Neogene (after 24 Ma). The most conspicuous expression of the India-Asia collision in East Asia is the topographic reversal of China.

3.1. Topographic Reversal in China

During the Mesozoic China displayed a general west-titling topography, contrasting with the present east-titling relief that is the result of India-Asia collision [*Wang, 1998*]. A sequence of Triassic flysch deposits up to 7000–8000 m thick is present over a vast area of the Songpan-Garze (or Ganzi) region of SW China. The flysch represents erosion of a collisional belt exposed in East China, lying between the North China and the South China Blocks. The depositional setting of the Songpan-Garze flysch was comparable to that of the Bengal and Indus Fans, suggesting the presence of high mountain ranges in eastern China from the Triassic to the Early Jurassic (~240–200 Ma) [*Yin and Ni*, 1993]. From Middle Jurassic to Middle Cretaceous times, a mountainous belt formed in the present coastal zone of SE China, as a result of subduction-related magnetism [e.g., *Chen,* 1995]. Following uplift and rapid erosion, massive sandstones and conglomerates ranging from several hundreds to 2000 m in thickness accumulated in the intermontane basins in that region. The Zhejiang-Fujian area of SE China is still marked by ranges up to 2158 m high today, with an average elevation of 1500 m. Given the modern elevation and the eroded mass, these ranges are estimated as having reached 3500 m to 4000 m altitude across a width of 500 km during the Cretaceous. They provided the source to terrigenous deltaic sediments in Hubai and Hunan Provinces of central China [*Chen*, 1995]. Thus, from early to late Mesozoic the large rivers in China rose in the east and flowed towards the west.

The west-tilting character of China was maintained during the Paleogene (Figure 3A). Paleogene sediments in China mostly accumulated in large lacustrine basins ponded in rift grabens (Figures 3D–E), providing, together with the Cretaceous basins, the main source of non-marine hydrocarbon production in China today. During the Paleogene (65–24 Ma), large lacustrine basins were developed in the location of the present Yangtze (Changjiang) and Yellow (Huanghe) River deltas [*Wang et al.*, 1985]. Provenance studies show a predominantly eastern source in the case of the Paleogene Ji-Yang Basin, occupying the present Yellow River delta area [*X.-R. Cheng*, pers. comm.]. Unlike other large rivers in the world, the Yangtze and Yellow Rivers are geologically young. No delta older than Pleistocene (1.8 Ma) has been identified in either region, recording discharge into the East China Sea [*Li et al.*, 1996; *Wang,* 1998].

The Neogene depositional system of China differs significantly from the Paleogene, though non-marine deposits predominated in both cases. In contrast with the large Paleogene lacustrine basins focused in rift structures, the Neogene fluvial-lacustrine deposits covered large areas as a result of general subsidence in eastern China at this time (Figure 3D–E)

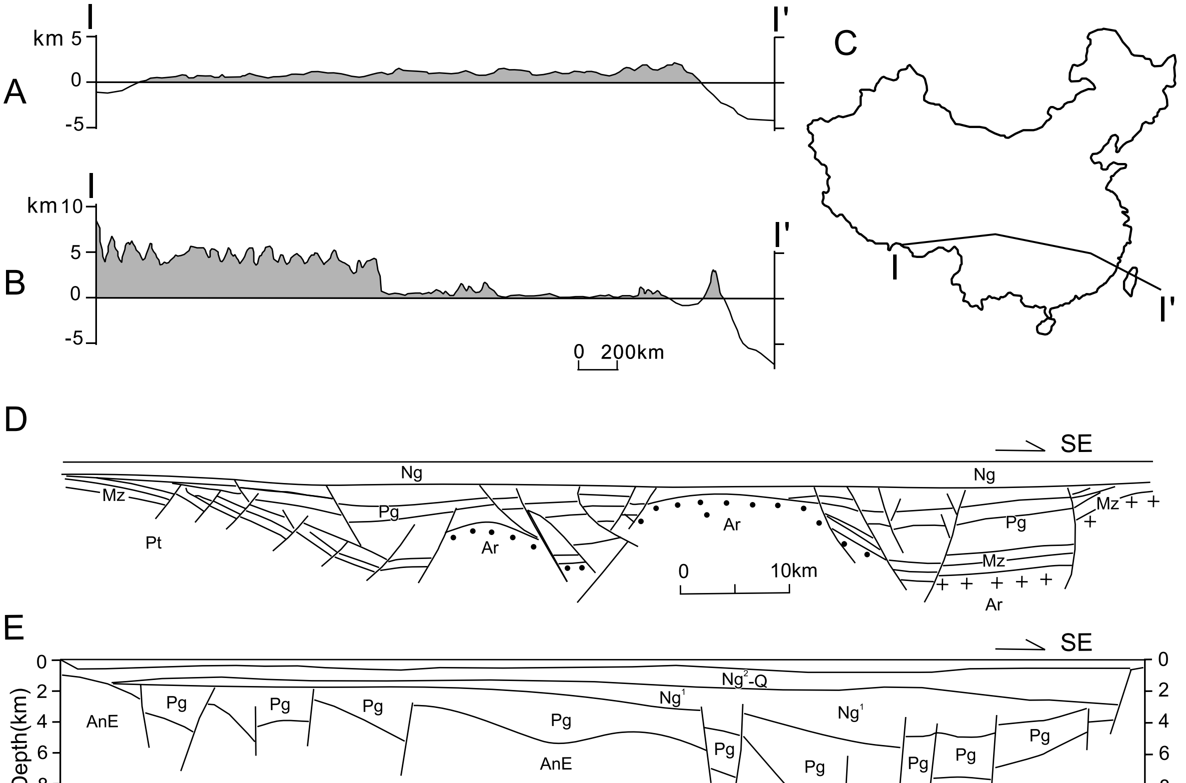

Figure 3. Mid-Cenozoic tectonic changes in China. Upper panels show a comparison of Paleogene and Neogene topographic transects of China, with grey areas indicating land above sea level. (A) A hypothetical transect of Southern China (I-I') during the Eocene about 50 Ma. (B) Modern transect (I-I') showing east-tilting topography. (C) Location of the transect I-I' (modified from *Wang* [1998]). Lower panels display two typical transects of Cenozoic basins in eastern China showing Paleogene sediments deposited during active extension and Neogene sediments formed during regional thermal subsidence: (D) the Liao River Mouth Basin, Northeast China [*Wang,* 1997]; (E) the East China Sea Shelf Basin [*Liu,* 1993]. Stratigraphic units used in transects: Q — Quaternary; Ng — Neogene; Ng^1 — Miocene; Ng^2 — Pliocene; Pg — Paleogene; Mz — Mesozoic; AnE — Pre-Paleogene; Pt — Proterozoic; Ar — Achaean.

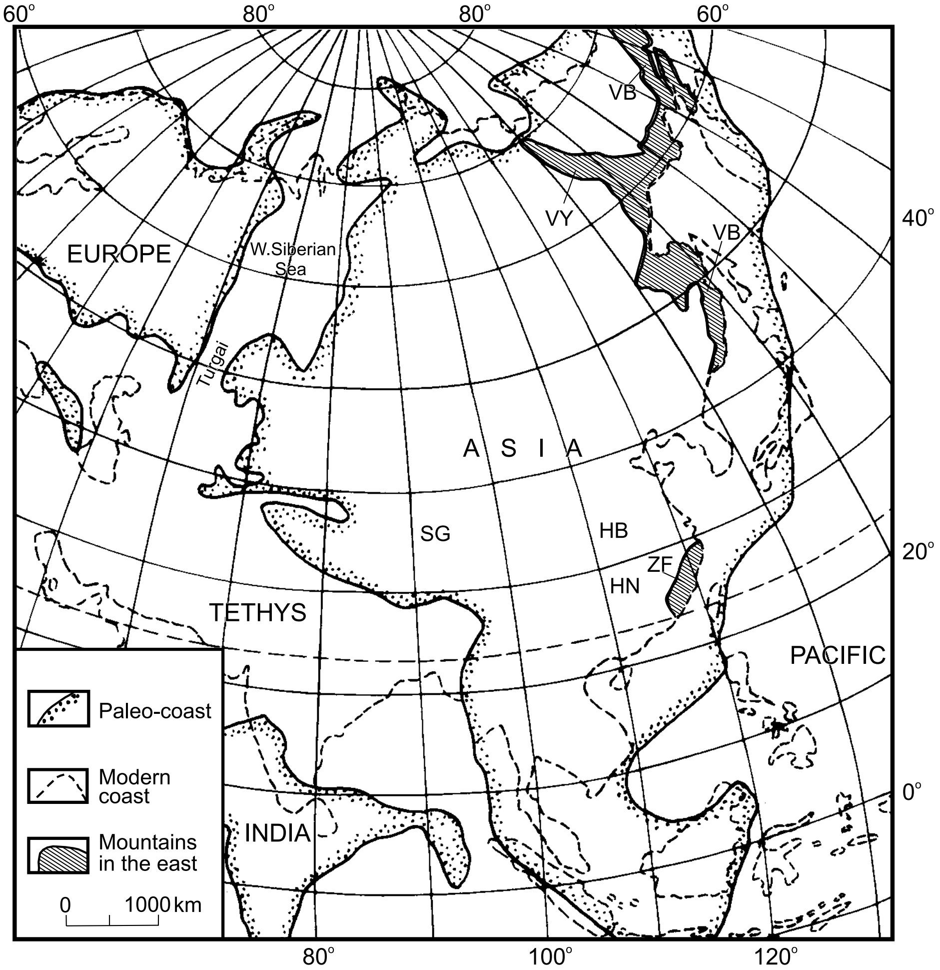

Figure 4. A sketch map of Pre-Neogene Asia exemplified by the middle Eocene based on *Hall* [1998, 2001], *Tsekhovsky et al.* [2003b] and *Chen* [1995]. VB – "East Asian Volcanic Belt"; VY – Verkhoyansk Fold Belt; ZF–Zhejiang-Fujian mountainous area. The mountain belts were formed during the late Mesozoic and remained high into the Paleogene. Mesozoic basins filled with flysch and deltaic sediments eroded from the mountainous areas: SG – Songpan-Ganzi (Garze); HB – Hubei; HN – Hunan.

[*Wang,* 1990]. This pattern suggests an east-tilting topography had developed (Figure 3B) [*Wang,* 1998]. The Paleogene topography in China was in sharp contrast to the modern, which is marked by the Tibetan Plateau in the west and marginal seas in the east. To understand the process of the topographic change in China, the tectonic evolution of Central Asia must first be considered.

3.2. Pre-Neogene Asia

The modern Eurasian Continent crosses more than 180° of longitude, occupying the entire Eastern Hemisphere. By contrast, Asia was much smaller and "slimmer" during the late Mesozoic and Paleogene. Without Europe, India, the Middle East and Western Siberia, the paleo-Asian continent was only slightly larger than half its present width, although latitudinally it occupied almost the entire North Hemisphere, extending from the Northern Polar area to the Southern tropics. This "slim" Asia existed from the Late Jurassic to the Oligocene. A paleogeographic map of Asia during the middle Eocene (~45 Ma) is shown as an example (Figure 4).

Between the Urals and the Siberian Platform stretches the vast lowland of Western Siberia, which was covered by a shallow sea since the Late Jurassic [*Milanovsky*, 1989]. Over a hundred boreholes covering the entire area have been analyzed for various groups of microfossils, and recent correlation has led to a unified Paleogene biostratigraphy for the Western Siberian Sea [*Akhmetiev et al.*, 2001]. The Western Siberian Sea was a huge sedimentary basin with a maximum area exceeding 2 x 10^6 km^2. From the Late Jurassic to early Oligocene the basin accumulated clastic marine sediments eroded from the Urals and the Siberian Platform [*Milanovsky,* 1989; *Tsekhovsky and Akhmetiev*, 2003b]. Paleogeographic reconstructions show that during the Paleocene and Eocene, the Western Siberian Sea was covered by shallow water, connecting the Arctic Ocean in the north and the Tethys Ocean in the south through the Turgay Passage (Figure 4). The connection was subject to short interruptions due to partial emergence in response to eustatic or tectonic changes. Evidence from subsurface sampling of deposits in the Turgay Passage shows that the connection with the Tethys was established by the end of Paleocene (~55 Ma), but its northern linkage with the Arctic Ocean was cut in the late Eocene (~40 Ma) [*Radionova et al*., 2001], at which point the Siberian Sea became a gulf within the Tethys [*Tsekhovsky and Akhmetiev,* 2003a,b]. In the southern part of Western Siberia and Turgay, brackish-water deposits accumulated during the late Oligocene (~28–24 Ma), recording marine incursions from the Tethys [*Shatsky,* 1978; 1984].

Mountain ranges began to form along the Eastern margin of paleo-Asia during the Oligocene. Lying within the Circum-Pacific subduction system, the coastal zone of what is now Far East Russia experienced major volcanic and tectonic activity, resulting in the formation of the "giant East Asian volcanic belt", a feature that is still geomorphologically expressed as a mountain chain locally exceeding 3000 m in altitude (Figure 4). In some intermontane basins, Cretaceous volcanic-terrigenous deposits, including turbidite sandstones associated with the belt, formed deposits up to 13,000 m thick [*Kirillova*, 2003], similar in origin to the Zhejiang-Fujian ranges in SE China [*Chen,* 1995]. Along the eastern margin of the Siberian Platform deformation in the Verkhoyansk Fold Belt (Figure 4) involved Upper Jurassic to Upper Cretaceous strata, and resulted in about 2000 m of erosion [*Parfenov et al.*, 1995]. All these geomorphological features were maintained into the Paleogene, and caused a west-tilting topography in East Asia.

3.3. Uplift of Tibet and Deformation of Asia

The western tilt of Asian topography began to change around the end of the Paleogene, driven by Tibetan Plateau uplift and most clearly recorded in China. The west-tilting paleogeography survived until the late Eocene when marine conditions in western China ended following India-Asia collision. The uplift of the Tibetan Plateau continues to be controversial, but several authors have argued that this started about 21–20 Ma [*Copeland et al.*, 1987; *Harrison et al.,* 1992] and was accompanied by a general subsidence of East China. Other studies indicate that at least parts of the Tibetan Plateau were uplifted earlier, prior or shortly after collision [e.g., *England and Searle*, 1986; *Murphy et al*., 1997; *Tapponnier et al*., 2001], or even much later [e.g., *Li,* 1991]. However, there is no doubt that these tectonic changes led to a reversal of the topographic trend in China from west-tilting to east-tilting, with the west-east gradient in altitude increasing continuously since then. In addition, the early Miocene was also the time of formation for many of the western Pacific marginal seas [e.g., *Tamaki & Honza,* 1991; *Briais et al.*, 1993; *Jolivet et al.*, 1994]. The radical changes that occurred in the topography of Asia during the Cenozoic must have had a profound impact on climate, including the onset or strengthening of monsoon circulation in East Asia. Extensive coastal plains and continental shelves have been constructed around the edge of East Asia, driven by development of the east-sloping topography, as well as by deposition of sediments eroded by the strengthening monsoon and delivered by large rivers to the newly formed marginal seas [*Wang,* 1998].

Recent studies show that the rise and growth of Tibet was not a simple one stage process [*Copeland,* 1997]; rather, some authors now argued that it was a step-wise process, propagating from south to the northeast [*Tapponnier et al.*, 2001], while other propose a more gradual growth towards the southeast [*Clark and Royden*, 2000]. The topographic reversal may have also occurred gradually or in several phases. Although reconstruction of plateau uplift remains a topic for further studies, the transition from sedimentation in rift-grabens to the more general subsidence in East China may have occurred more rapidly. On the basis of the sediment sequences in Cenozoic basins both onshore and offshore China, this event appears to have occurred sometime between the Paleogene and Neogene (~24 Ma; Figure 3D–E). Fortunately, Ocean Drilling Program (ODP) Site 1148, near the foot of the northern continental slope of the South China Sea (Figure 1), has penetrated a series of depositional unconformities between 28.5–23.4 Ma in the late Oligocene, with a sediment record representing ~3 m.y. missing [*Wang et al.*, 2000; *Li et al.*, in press]. ODP Site 1148 documents a series of events that coincided with a drastic change in sedimentary provenance from southwest to north, suggestive of a major tectonic reorganization of the region [*Li et al.*, 2003] (Figure 5). Judging from the 32 m.y. history recorded at ODP Site 1148, this is the most significant tectonic event in the late Cenozoic in the South China Sea, which is also recognized from the different diagenetic imprint below and above the unconformity [*Wang et al.*, 2003]. Although *Clift et al*. [2001a] argue that this surface represents a break-up unconformity I instead consider this latest Oligocene event to probably reflect the transition from rifting to the large-scale subsidence in East China, synchronous with a reversal in relief.

3.4. Reorganization of the Hydrological Network

The modern river system in Asia (Figure 1) has developed in response to the topographic and climatic changes that have

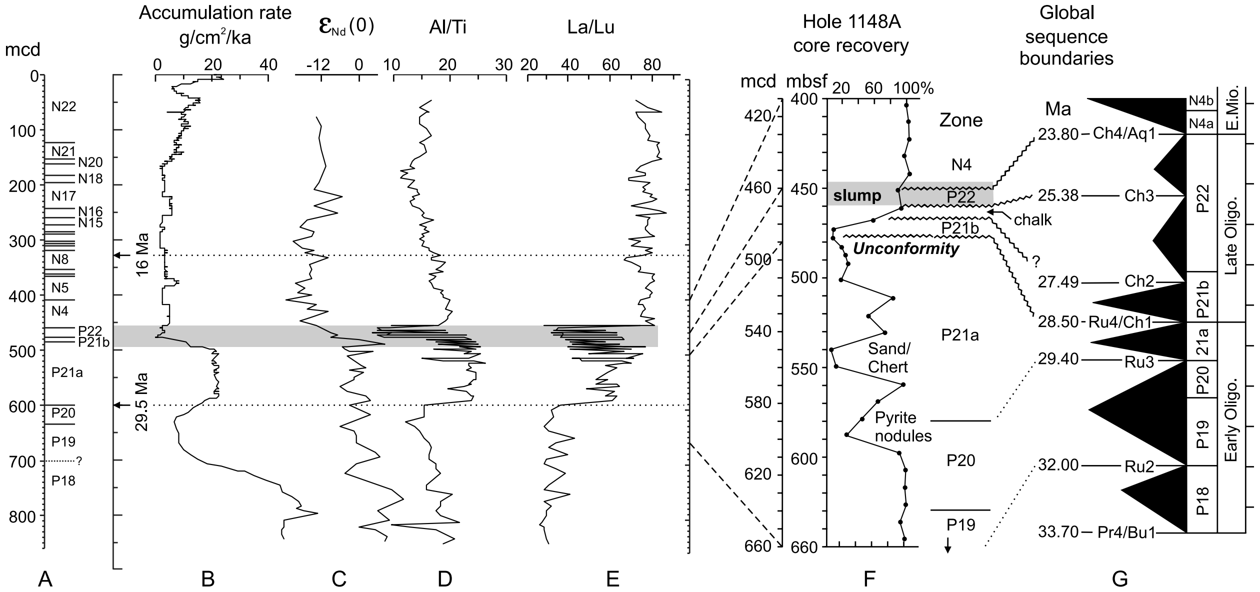

Figure 5. Tectonic events in the late Oligocene recorded at ODP 1148, northern South China Sea (18º50'N, 116º34'E, water depth 3294 m). (A) Planktonic foraminiferal zone; (B) accumulation rate (g/cm^2/k.y.); (C) ε_{Nd}; (D) Al/Ti ratio; (E) La/Lu ratio; (F) ODP Hole 1148 core recovery (%); (G) correlation to the global stratigraphic scale [after *Li et al.*, 2003, and *Li et al.*, in press].

influenced East Asia since India-Asia collision. The oldest documented river is the Indus, which has been traced back to the Eocene, as shown by evidence from the suture zone, as well as the Indus submarine fan [*Clift et al.,* 2001b]. The Indus was followed by the formation of the Ganges-Brahmaputra Rivers that formed the Bengal Fan after the late Eocene [*Derry and France-Lanord,* 1997; *Curray et al.*, 2003]. The increased sedimentation during the middle Miocene in both deep-sea fans may have been a response to the strengthened topographic contrast or/and monsoon moisture supply.

In contrast, the large rivers discharging into the Western Pacific marginal seas are much younger in age. Numerous studies have been devoted to the Huanghe (Yellow River) history, from its source [e.g., *Li et al.*, 1996; *Fothergill and Ma*, 1999] to its delta [e.g., *Xue*, 1993; *Saito et al.*, 2000]. Although the results diverge in detail, all show a Pleistocene age of flow. This is consistent with the fact that the marine basins of Huanghai (Yellow Sea) and Bohai Gulf into which the rivers discharge are themselves of Pleistocene age, although lacustrine rift basins existed there since the early Paleogene [*Wang, 1985*; *Wang, 1990*]. Recent studies show that a paleolake occupied the middle reach of the modern Huanghe at its outlet from the Loess Plateau at 5 Ma. It was in the late Pleistocene that the Huanghe cut its valley through the Sanmen Gorge and connected eastwards to the sea [*Wang et al.*, 2002]. The same applies to the Changjiang or Yangtze River, which has its present source very close to that of Huanghe in Tibet (Figure 1). A synthesis of stratigraphic data from all available deep drill holes in the onshore Changjiang Delta shows that its history can be traced back only to the Pleistocene [*Wu and Li,* 1987]. The deltaic sediments are mostly of the Late Pleistocene and Holocene age [*Li et al.*, 2000; *Hori et al.*, 2002], and no older submarine delta has yet been found. Offshore sedimentation in eastern China shows a rapid increase in the Plio-Pleistocene, consistent with a recent origin to these rivers [*Métivier et al.*, 1999].

Along the northern margin of the Asian continent, most of the modern rivers flow northward, emptying into the Arctic Ocean. The three largest of these are the Ob, Yenisey and Lena (Figure 1), all winding through the vast Western Siberian plain between the Ural and Verkhoyansk Ranges. Today these rivers play a critical role in the hydrological balance of the Arctic Ocean, together providing more than a half of the freshwater contribution to the Arctic and making up one tenth of the global fluvial input to the ocean [*Stein,* 2000]. Again, these are geologically young features, post-dating the late Pliocene [*Shatsky,* 1984], although some authors have argued for an earlier age of the Lena River, which drains the Siberian Platform [*Galabala*, 1979]. As discussed above, that part of Siberia, located between the Circum-Pacific Volcanic Belt and West Siberian Sea (Figure 4), was also west tilting during late Mesozoic and Paleogene, and the rivers must have then been directed to the west. When the Western Siberian Sea emerged during the late Oligocene and Neogene, the northern part of Siberia was uplifted, and fluvial-lacustrine deposits accumulated only in the south [*Milanovsky,* 1989]. The river system running to the North developed only since the late Pliocene [*Shatsky,* 1984], whereas the paleo-river valleys and marine transgression deposits found in the lower reaches of the Ob and Yenisey Rivers are all of Pleistocene age [*Milanovsky,* 1989]. Although precise dating is still lacking, the available sedimentological and geomorphological data suggest that the Yenisey River most probably formed in the late Pliocene, the Lena River in the early Pleistocene, and Ob in middle to late Pleistocene [*S. Laukhin*, pers. comm., 2004].

Thus, the large rivers draining the eastern and northern margins of Asia are much younger than major rivers in other parts of the world. This is the result of the late Neogene uplift of central Asia, where all these rivers originate (Figure 1). Not only has the northern part of Tibet uplifted in the late Pliocene [e.g., *Zheng et al.,* 2000], but other Central Asian mountains north and northeast of Tibet also experienced geologically recent uplift. Major uplift of the Tian Shan took place about 5–6 Ma [*Métivier and Gaudemer,* 1997], while the Gobi-Altai region experienced mountain building in the late Cenozoic, continuing to the present time [*Cunningham et al.*, 1996; *Owen et al.*, 1998].

4. CLIMATE IMPACT OF ASIAN DEFORMATION

The uplift of the Tibetan Plateau has been proposed as the trigger to the most significant global climate changes in the Cenozoic [*Ruddiman et al.*, 1997]. Taken in a broader scope, the uplift of the Asian continent affects climate as a result of three processes: generation of a high plateau, changes in land-sea patterns, and the reorganization of river networks. All these affect the climate system to various degrees, although their relative roles are still a matter of debate. Here I review their impact on the formation of the polar ice-sheets and the Asian monsoon, two of the biggest changes in Cenozoic climate.

4.1. Development of the Arctic Ice-Sheet

The initiation of the Northern Hemisphere glaciation was a step-wise process, with the earliest ice-rafting records extending back to the late Miocene [*Thiede and Myhre,* 1996]. However, the δ^{18}O enrichment in benthic foraminifera shows its onset between 3.15 to 2.50 Ma [*Tiedemann et al.*, 1994], and the appearance of large-scale ice-rafted debris in the Subarctic Pacific indicates further intensification at ~2.67 Ma [*Prueher and Rea*, 1998]. Numerous hypotheses have been put forward to explain its initiation, many invoking the uplift of Tibet and/or the closure of the Panama Gateway.

If Tibetan uplift caused the onset of Northern Hemisphere glaciation, this would represent a direct impact of Asian deformation on global climate. However, the original hypothesis that uplift led to glaciation though alteration of the atmospheric circulation [*Ruddiman and Raymo,* 1988] was rejected because of the timing of uplift was too early. Instead these same authors suggested that Himalayan uplift induced an increase in chemical weathering, so depleting greenhouse CO_2 in the atmosphere and leading to global cooling [*Raymo and Ruddiman,* 1992]. However, the evidence for fast global, late Cenozoic chemical erosion was challenged [*Kump and Arthur,* 1997]. In any case slow weathering process cannot account for the rapid onset and strengthening of the Northern Hemisphere glaciation [*Prueher and Rea,* 1998]. As a result other mechanisms have been proposed as a trigger, including widespread explosive volcanism, or the variations in the Earth's orbital parameters. In these models other processes precipitate glaciation after tectonically induced changes have already brought global climate to a critical threshold [*Maslin et al.*, 1998].

An alternative explanation for Northern Hemisphere glaciation is one linked to the emergence of the Panama Isthmus. The closure of the Middle American oceanic gateway strengthened the Gulf Stream and so provided additional moisture to the polar region, where it could contribute to ice sheet growth. However, the closure of the gateway also increased heat transport to the high latitudes, which would work against glaciation [*Berger and Wefer*, 1996]. The significance of Panama gateway closure to the intensification of Northern Hemisphere glaciation remains controversial [*Maslin et al.,* 1998]. A possible solution to this problem may lie in the role of the Siberian rivers. The Yenisey, Lena and Ob Rivers provide more than half the freshwater flux to the Arctic and thus exert a marked effect on the hydrology of the Arctic Ocean. Today the Arctic Ocean is covered by a surface layer of cold and relatively fresh water several tens of meters deep [*Aagaard and Carmack,* 1994]. Increased fresh-water input from the Siberian rivers would facilitate the formation of sea ice, which in turn would increase albedo and insulate the atmosphere from the high heat capacity of the ocean. Because the Gulf Stream was intensified by the closure of the Panama Gateway, the greater moisture delivered to high latitudes would provide additional vapor to the Siberian river drainage, which in turn could have triggered a rapid intensification of Northern Hemisphere glaciation [*Driscoll and Haug,* 1998]. Because gateway closure could have had a major impact on deeper water circulation at 4.6 Ma, much earlier than the observed intensification of glaciation, the increased obliquity amplitude of the Earth's orbit between 3.1 to 2.5 Ma was invoked by *Driscoll and Haug* [1998] to explain the time delay between cause and effect.

The Siberian river model for Arctic glaciation proposed by *Driscoll and Haug* [1998] was based only on the climate history recorded in Lake Baikal, and did not account for the history of the Siberian rivers themselves. However, the major Siberian rivers only began to discharge into the Arctic Ocean in the Pleistocene or Late Pliocene. Until these rivers formed, the increased moisture supply that started at 4.6 Ma could not have contributed to the water in the Arctic Ocean. The reorganization of rivers in Siberia, driven by surface uplift in Asia, may be the primary mechanism for the increased fluvial input to the Arctic Ocean and in turn the intensification of the North Hemisphere glaciation.

In summary, it may be seen that deformation of Asia has had a profound impact on the onset and intensification of the North Hemisphere glaciation driven by the uplift of the Tibetan and Mongolian plateaus, either directly by the formation of north-flowing Siberian rivers, or indirectly by the enhanced chemical weathering of the Himalayas and Tibet. At the present stage, however, these models are speculative because of the lack of sufficient supporting data, especially quantitative data based on a reliable chronology.

4.2. Development of the Asian Monsoon System

A fundamental question in Cenozoic paleoclimatology is when the modern monsoon system was established and how it has evolved. Three tectonic triggers have been proposed to control the evolution of Asian monsoon circulation: plateau uplift, sea-land distribution, and the opening and closure of oceanic gateways, which are all related to the deformation of Asia.

Studies of Asian monsoon strength have been closely tied to the history of the Tibetan Plateau. General Circulation Model (GCM) experiments indicate that strong monsoons can be induced by solar forcing only when the elevation of Tibet and the Himalaya is at least half that of today [*Prell and Kutzbach*, 1992]. Based on the long-term records from ODP Leg 117 in the Arabian Sea, it has become the prevalent hypothesis that the Asian monsoon system first strengthened at about 8 Ma, when some evidence indicates uplift of the Tibetan Plateau [*Harrison et al.*, 1992; *Prell and Kutzbach*, 1992, 1997; *Molnar et al.*, 1993]. This model was supported by land-based studies, in particular from the Loess Plateau of China. As a wind blown sediment, loess is strongly linked to the intensity of the winter monsoon, and the intercalated paleosols are indicative of summer monsoon. Originally, the base of the loess-paleosol sequences, which is dated to about 2.6 Ma, was interpreted to reflect the initiation of the East Asian monsoon [*Liu and Ding*, 1993]. Later it was found that the Red Clay underlying the loess sequence was also of wind-blown origin, and the history of aeolian deposition and thus monsoon transport on the Loess Plateau was extended to 7–8 Ma [*An et al.*, 2001] (Table 2). Because of the altitude of the Tibetan Plateau causes enhanced aridity in the Asian interior and intensification of the Asian monsoon system [*Kutzbach et al.*, 1993], the nearly coincident beginning of upwelling in the Indian Ocean and dust accumulation in central China about 8 Ma was explained by the onset of the Indian and East Asian monsoons [*An et al.*, 2001].

Table 2. Development of the dust history in the Loess Plateau, China

Deposits	Age	Reference
Loess-paleosol sequence	0-2.6 Ma	Liu & Ding, 1993
Red clay	2.6-8 Ma	An et al., 2001
Qin'an loess sequence	6-22 Ma	Guo et al., 2002

Given the links between Tibetan altitude and monsoon strength inferred from climate modeling it might be expected that Tibet would have experienced an increase in altitude at 8 Ma [*An et al.*, 2001]. However, Tibetan uplift is now known to have started much earlier. The recent discovery of a early-middle Miocene loess sequence from Qin'an, western Loess Plateau (Figure 6), has further extended the Chinese dust history to before 22 Ma [*Guo et al.*, 2002]. A total of 231 interbedded loess-paleosol layers represent a nearly continuous history of aeolian dust accumulation from 22 to 6.2 Ma (Table 2). Like its Pleistocene equivalent, the Miocene loess testifies to enhanced aridity in the dust source areas and energetic winter monsoon winds required for dust transport. Associated paleosols indicate increased moisture supply by summer monsoon winds.

Additional support for an early Miocene monsoon comes from a recent study of deep-sea sediments from the South China Sea. *Jia et al.* [2003] reconstructed a carbon stable isotope record of black carbon over 30 m.y. from the northern South China Sea. The record indicates that C4 plants have appeared gradually as a component of the flora in East Asia since the early Miocene (~20 Ma), suggesting an early initiation of the East Asian monsoon. This observation is consistent with clay mineralogy evidence from the same sediment indicating wettening of the southern Chinese climate before 15 Ma [*Clift et al.*, 2002]. An early Miocene change in vegetation and climate zones in eastern China has been long recognized. Synthesizing the data from oil exploration and stratigraphic studies, it was found that a broad belt of aridity stretched across China from West to East in the Paleogene (Figure 6A), particularly during the Paleocene. In the Neogene the arid zone retreated to NW China (Figure 6B), suggesting a transition to a monsoonal system of atmospheric circulation [*Wang*, 1990; *Liu*, 1997]. This transition is now confirmed by paleobotanical/palynological and lithological data, implying that the East Asian summer monsoon brought moisture to eastern China. The reorganization of the climate system around the Oligocene/Miocene boundary would have been caused by strengthening, if not establishment of the East Asian summer monsoon [Sun and Wang, personal communication]. The transition to monsoonal climate broadly corresponds with the radical tectonic change and topographic reversal sometime in the late Oligocene (Figure 3).

The Asian monsoon system now appears to have a longer history than previously thought. Nonetheless, the monsoon system also displays great variability both in space and in time. In the Miocene loess sequence of Qin'an, two intervals are distinguished by higher dust accumulation: 15–13 Ma and 8–7 Ma [*Guo et al.*, 2002]. These times might represent periods of enhanced aridity in the source areas, an interpretation supported by pollen data from Yumen, NE of Tibet [*Ma et al.*, 2004]. The increased aridity around 8–7 Ma was recorded also in the North Pacific as a peak in dust accumulation rate [*Rea et al.*, 1998]. All this is consistent with, though not unique to a stepwise uplift model of the Tibetan Plateau initiated in the late Paleogene [*Tapponnier et al*., 2001].

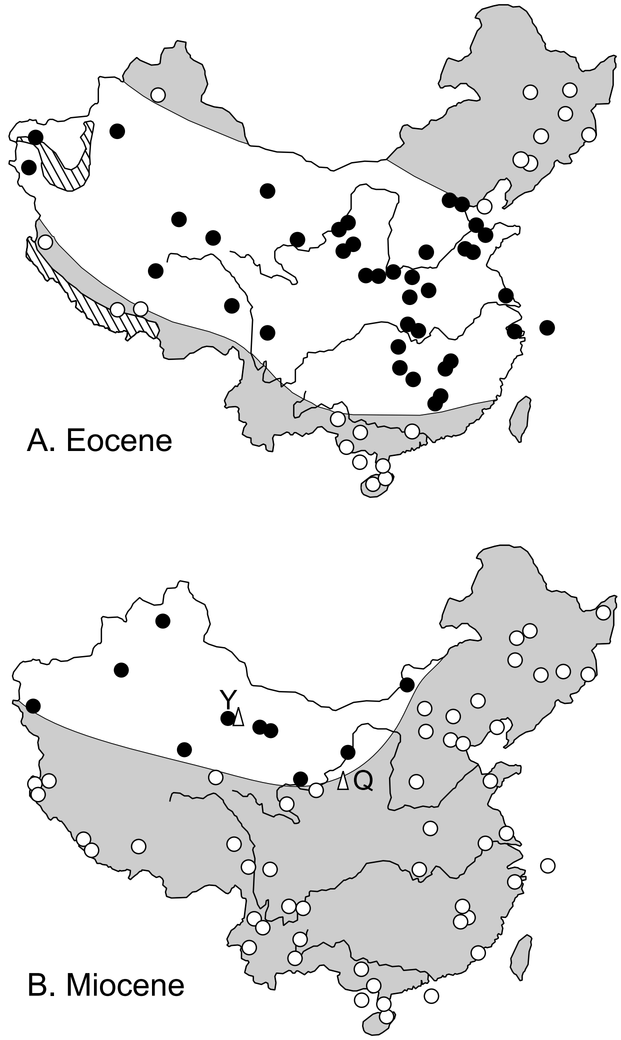

Figure 6. Arid zone (white) in China (A) during the Eocene, when a zonal atmospheric circulation system was prevailing, (B) during the Miocene, with a monsoon circulation system prevailing (based on a manuscript by X. Sun and P. Wang "How old is the Asian monsoon system? Palynological constraints from China"). Filled and open circles denote paleovegetation sites indicating arid and humid climate, respectively; triangles denote locations of Miocene loess and pollen sections: Q – Qin'an, Y – Yumen; hatched areas mark sea and brackish-water bay.

Another factor influencing monsoon strength is sea-land distribution, especially the Paratethys, an epicontinental sea that extended over much of central Eurasia prior to 30 Ma, but which receded during the early Miocene. Numerical simulation shows that the retreat of the Paratethys resulted in continentalization of the Asian interior and an enhancement of monsoon circulation. *Ramstein et al.* [1997] showed that the role played by this change in sea-land pattern was as important as Tibetan uplift in controlling monsoon strength. As the Paratethys reduced from the Oligocene to the middle-to-late Miocene, its effect on the monsoon might be expected to occur between 30 and 10 Ma. This is in agreement with the new discovery of Miocene loess and the recession of arid zone in China at that time.

A more significant change in sea-land pattern occurred in the late Paleogene. As mentioned above, Pre-Neogene Asia was smaller and "slimmer", compared to the present continent (Figure 4). Until the late Eocene, the Western Siberian Sea and Turgay Strait separated Asia from Europe, while northeastern Asia was connected with North America (Figure 7). GCM simulation shows a zonal distribution of high precipitation in the tropics and more arid conditions in eastern China at that time (Figure 8) [*Chen et al.,* 2000]. This pre-monsoonal climate pattern corresponds well with the paleoenvironmental reconstructions (Figure 6A). All these findings underscore the role of sea-land patterns in the evolution of a monsoon climate.

Along with the geographic changes, continental deformation also had an effect on the marginal seas, through oceanic gateway closure. Modeling of the oceanic circulation has revealed that 'closure' of the Indonesian seaway 3–4 Ma could be responsible for east African aridification [*Cane and Molnar*, 2001]. These authors found that the northward drift of the Australian plate may have switched the source of the Indonesian Throughflow from the warm South Pacific to relatively cold North Pacific waters. This would have decreased sea surface temperatures in the Indian Ocean, leading to reduced precipitation in East Africa and to declined strength of the Indian summer monsoon, similar to that recorded in marine deposits [*Prell and Kutzbach,* 1992].

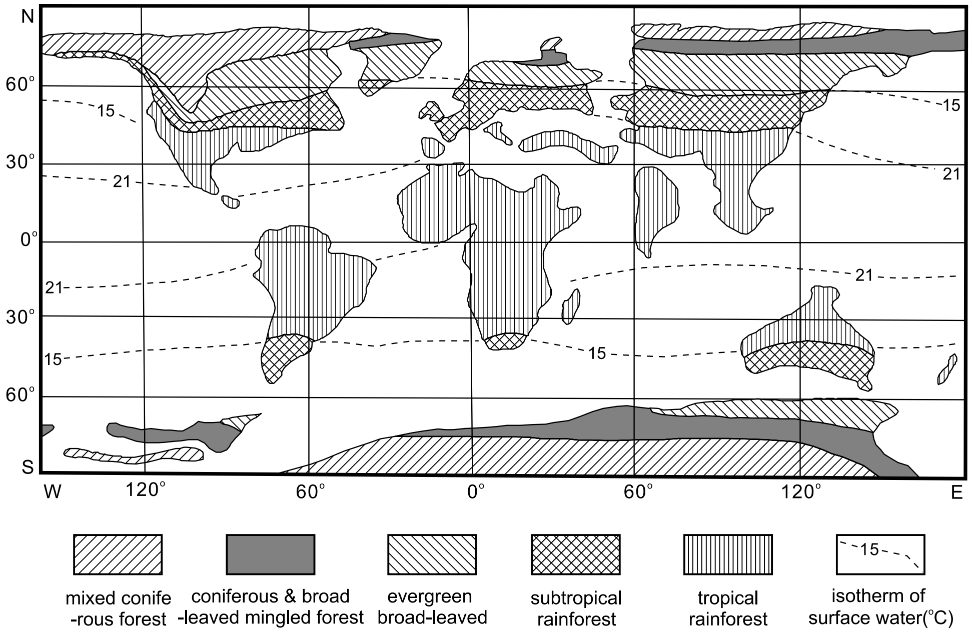

Figure 7. Early Eocene paleogeography: Sea-land distribution and environment at about 50 Ma [data from *Barron*, 1985; *Haq*, 1981; *Crowley and North*, 1991; *Wang,* 1990]

Despite the fragmentary record it can be seen that Asian continental deformation plays a key role both in Late Cenozoic global cooling and intensification of the Asian monsoon system. Tectonic deformation, global cooling and monsoon development, have all been coupled as step-wise processes. Further efforts are required to obtain long-term high-resolution records with better time constrains if the existing hypotheses are to be tested.

5. MARGINAL SEAS AND LAND-SEA INTERACTIONS

5.1. Formation of the Marginal Seas

The opening of a series of marginal seas in the NW Pacific represents another important, tectonic form of continent-ocean interaction and one that may have had a large influence on climate. Although opinions diverge on the cause rifting of the Western Pacific Marginal Seas [e.g., *Briais et al.*, 1993; *Clift et al.*, 2003; *Sun et al.*, this volume], the opening of the South China Sea [*Taylor and Hayes*, 1983], the Japan Sea [*Jolivet et al.*, 1994] and probably the Okhotsk Sea [*Ginibidenko and Khvedchuk*, 1982; *Worrall et al.*, 1996] are all dated as Oligocene-middle Miocene (30–15 Ma), broadly corresponding to the start of major deformation of Tibet. A causal relationship was proposed between the opening of marginal basins and the India-Asia collision [e.g., *Jolivet et al.*, 1989, 1994], yet the mechanism remains unclear and the role of Pacific oceanic tectonics is not well constrained. The most recent extension in the East China Sea is much later, with the Okinawa Trough formed only in the Pliocene [i.e., *Jin and Yu*, 1982; *Letouzey and Kimura*, 1985; *Sibuet and Hsu*, this volume], but may also be linked to the apparent enhanced Pliocene uplift in Asia. Together uplift of Tibet and the opening of the marginal seas have changed the Asian topography and allowed the reorganization of hydrological systems in Asia.

The formation of the marginal basins has changed the material and energy flux between the Asian continent and Pacific Ocean. Marginal seas intercept the flux of terrigenous sediment supplied from the continent. Although South and East Asia with their islands provide over 70% of the terrigenous suspended material to the global ocean [*Milliman and Meade,* 1983], there is no large submarine deep-sea fan developed in the Western Pacific comparable to Indian Ocean fans. Nonetheless, deep-sea accumulation rates in the marginal seas can be one or two orders of magnitude higher than in the open ocean [*Wang,* 1999; *Métivier et al*., 1999].

The formation of the Western Pacific Warm Pool and the Kuroshio Current both depend on the presence of island arcs together with their associated marginal seas. Before the formation of the marginal seas, the North Pacific Equatorial Current flowed westwards to the Indian Ocean and was not interrupted until the closure of the Indonesian Seaway in middle-late Miocene [*Kennett et al.,* 1985]. Similarly, until the rotation of the Philippine Sea Plate there was no Luzon Island to split the west-flowing Equatorial Warm Current into the

Kuroshio and the Mindanao Warm Currents, which is so essential to the existence of the Western Pacific Warm Pool.

The formation of marginal seas is also responsible for the appearance of broad continental shelves. The East China Sea shelf, including the Yellow Sea and Bohai Gulf, and the South China Sea shelf, including the Sunda Shelf or Great Asian Bank, cover a total area about 2,650,000 km^2, exceeding the Mediterranean in area. Falls in eustatic sea level during the last glacial maximum caused exposure of this immense area. Because the South China Sea is a major source of moisture for the summer monsoon rain in China [*Chen et al.*, 1991], the reduction of sea area at the last glacial maximum would have decreased the vapor supply from the sea, and, hence, enhanced aridity in the China hinterland. It remains, however, uncertain when the large-scale emergence of shelf seas started, because sediment records indicate that broad continental shelves off China appeared only around marine isotope stage 6 about 150 ka [*Sun et al.*, 2003].

A significant climatic influence of the marginal seas is the amplification of climate variability during glacial cycles. Because of the isolation of the semi-enclosed marginal basins, further strengthened by an enhanced winter monsoon, the winter sea surface temperature at the last glacial maximum was much cooler in the Western Pacific marginal seas than in the open ocean [*Wang,* 1999]. Moreover, because the Sunda Shelf is located within the Western Pacific Warm Pool, this would have decreased precipitation and suppressed deep atmospheric convection, leading to a lowering of tree and snow lines in the region [*De Deckker et al.*, 2003].

5.2. Western Boundary Currents in the Marginal Seas

The western boundary currents are the principle conduits for heat transfer between the lower and higher latitudes regions. Today, the western boundary currents, Kuroshio and Oyashio, flow through the marginal seas and function as vehicles of sea-land exchanges between Asia and the Pacific. This unique feature of the Western Pacific is a direct result of the chain of marginal seas arranged along the Asian margin. By comparison, North Atlantic boundary currents flow through marginal seas for a much smaller part of their route.

As shown in Table 1, the four marginal seas in the NW Pacific are connected with each other and comprise a hydrographic system (Figure 9). At the present time large rivers such as the Amur, Huanghe (Yellow River), Changjiang (Yangtze River), Zhujiang (Pearl River), Red and Mekong Rivers discharge into the four seas. The connection of a marginal sea with the ocean depends largely on sill depth of the gateway. The Sea of Japan is most isolated because of the shallow sill depths of all its gateways (Table 1), whereas the deep and broad gateways of the Okhotsk Sea and the East China Sea allow more efficient water exchange with the ocean (Figure 9A; Table 3). The routes of the boundary currents through the marginal seas are largely determined by the gateways and are thus strongly affected by eustatic sea level.

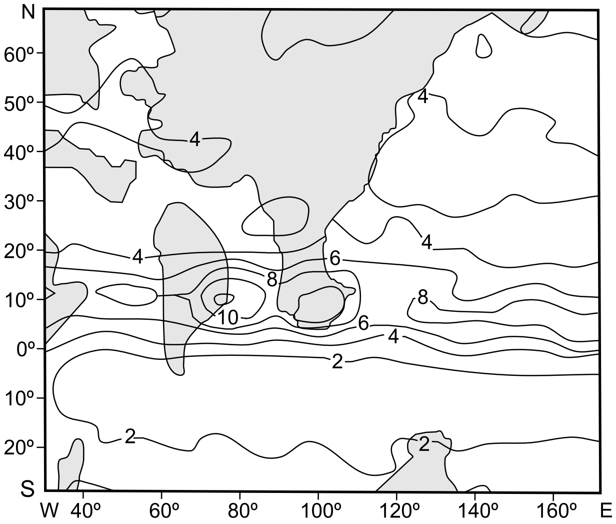

Figure 8. Simulated precipitation distribution in early Eocene Asia based on the surface conditions shown in Figure 7 [after *Chen et al.*, 2000].

The Kuroshio Current takes its source from the North Pacific Equatorial Current and runs northward offshore the Philippines. On its way north, the Kuroshio water partly enters the South China Sea through the Bashi Strait and then enters the East China Sea east of Taiwan. Within the East China Sea, the Kuroshio runs northeastward along the continental break to 30°N where exchange with shelf water brings about intense water mass modifications and large horizontal fluxes of heat and salt [*Su*, 1998; *Su and Lobanov*, 1998]. West of Kyushu, the Kuroshio Current gives rise to a northward current, the Tsushima Current, which passes through the Tsushima/Korea Strait, bringing high temperature and salinity to the Sea of Japan. When the Tsushima Current enters the Okhotsk Sea through the Soya Strait, it flows along the northern coast of Hokkaido and provides a relatively saline input to the Okhotsk Sea. In doing so subtropical Kuroshio water mixes with continental shelf waters diluted by fluvial runoff (Figure 9B). Finally, as it exits the marginal seas, the Kuroshio Current mixes with the Oyashio Cold Water east of Japan, forming the North Pacific Intermediate Water that then turns back towards the low latitudes (Figure 10). As a result Kuroshio warm water has a large effect on terrestrial climate in eastern Asia. Modification of this water during passage through the marginal seas is an important factor for water mass formation at high latitudes in the Northern Pacific [*Tally*, 1996; *Hsueh et al.*, 1997].

Table 3. Straits of the four NW Pacific marginal seas

Marginal sea	Total river discharge km^3/yr	Strait	Connected sea	Sill depth	Minimal width at surface
Okhotsk* Sea	586	Bussol	Pacific	2318 m	
		Kruzenshtern	Pacific	1920 m	
Sea of Japan	212	Tartar	Okhotsk	8 m	7 km
		Soya	Okhotsk	44 m	42 km
		Tsugaru	Pacific	116 m	19 km
		Korean	East China	131 m	116 km
East China Sea*	1500	Tokara	Pacific	>1000 m	
		Kemara	Pacific	>1000 m	
South China Sea	820	Taiwan	East China	70 m	130 km
		Bashi	Pacific	2600 m	370 km
		Mindoro	Sulu	420 m	125 km
		Balabac	Sulu	100 m	50 km

* The Okhotsk Sea and East China Sea have a quite open connection with the Pacific, hence only major deep-water passages are shown here.

In contrast, the Oyashio Cold Water, a western boundary flow in the subpolar gyre, originates in the Bering Sea and flows southwest off Kamchatka Peninsula where it is known as the East Kamchatka Current. A part of the Oyashio cold water enters the Okhotsk Sea through the Kruzenshtern Straits and then mixes with the Soya Warm Current and finally returns back to the Pacific through the Kuril straits, mainly the Bussol Strait (Figure 8A; Table 3) [*Talley,* 1996; *Talley and Nagata,* 1995]. The East Kamchatka Current entrains the water returning from the Okhotsk Sea to the Pacific and flows further south as the Oyashio Cold Water. Offshore eastern Japan, between 37°N and 40°N, both the western boundary currents flow eastwards in parallel: the Oyashio on the north and the Kuroshio on the south (Figure 9B). In the mixed water region between the separated Kuroshio and Oyashio Currents, the North Pacific Intermediate Water is formed [*Talley*, 1996], which then spreads to almost the entire North Pacific (Figure 10) .

The western Pacific is unique in the modern ocean in having its marginal seas connected by western boundary currents that comprise a complete oceanographic system (Figure 9C). The majority of the Kuroshio Current flows into the Pacific east of Japan after departure from the East China Sea. Nonetheless, that part of the Kuroshio Warm Water that flows inside the marginal seas provides an effective mechanism for ocean-continent exchanges. Flowing poleward, the subtropical waters of the Pacific exchange with coastal waters in the marginal seas and finally mix with the subpolar waters in the mixed water region. In doing so they produce intermediate waters of low salinity that returns back to the subtropical region. Because the marginal seas cover many latitudes from the tropics to the Arctic Circle, the system of boundary currents is also crucial in heat transfer between the lower and higher latitudes.

5.3. Different Modes of Sea-Land Interactions

A large proportion of the East Asian marginal seas is shallow and subject to emergence during periods of sea level lowstand. In addition, many of the gateways are narrow or/and shallow. This bathymetry has made the boundary current strength in the marginal seas vulnerable to sea-level changes during glacial cycles or to tectonic changes in the gateways. Paleontological and isotopic data now show that warm water of the Kuroshio Current and its branches drastically reduced in the marginal seas during the last glacial maximum. In the East China Sea the Kuroshio Current was attenuated in or even removed from the Okinawa Trough where its axis is now located [Figure 11; *Ujiie et al.*, 1991; *Jian et al.*, 1996; *Li et al.*, 1997]. The absence of the Tsushima Warm Current led to the dilution of surface water and the stratification of water column in the Japan Sea [*Oba et al.*, 1991].

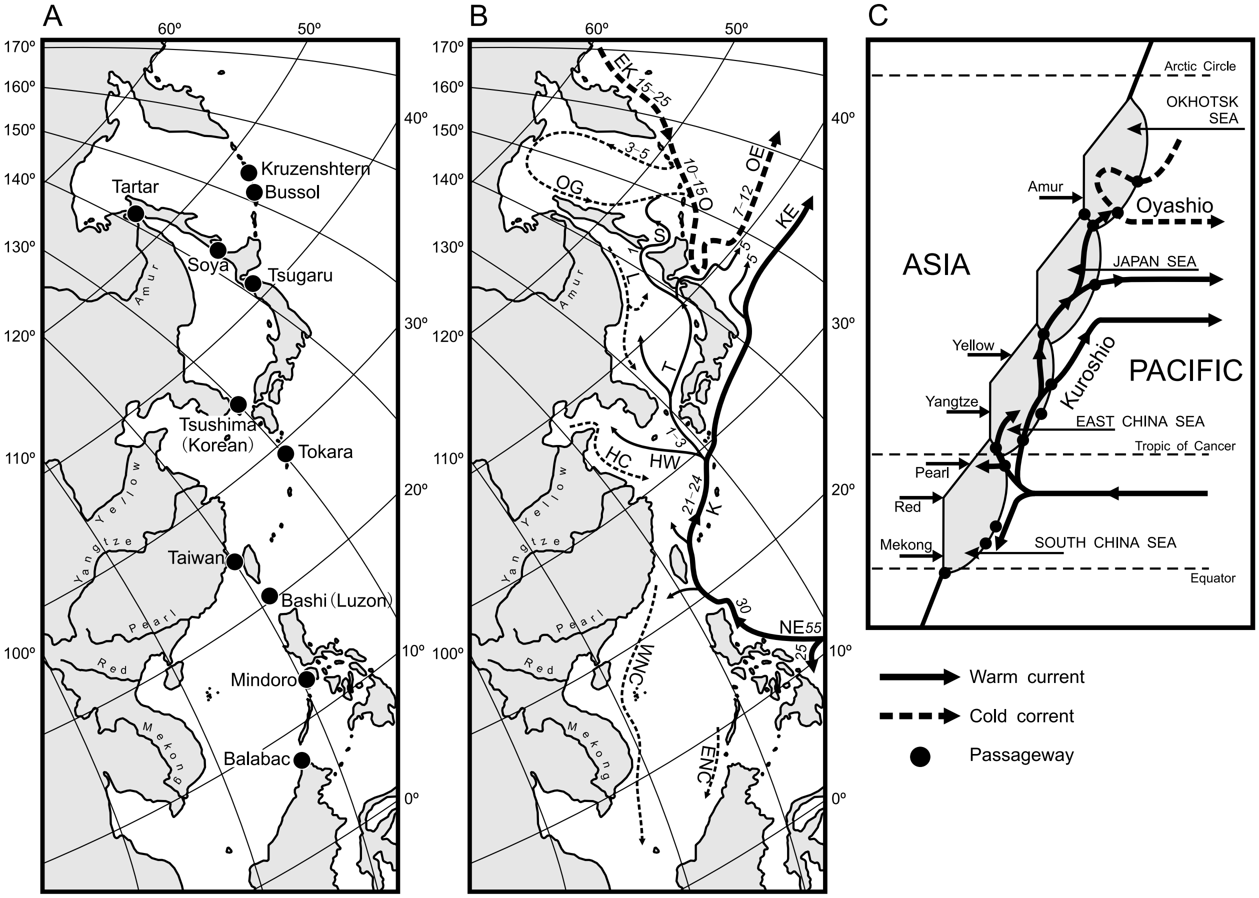

Figure 9. The system of Western Pacific marginal seas between the Asian continent and Pacific Ocean (Okhotsk, Japan, East China and South China Seas), as well as the Western Boundary currents. (A) Main passageways (Table 3) and rivers emptying into the marginal seas. (B) Western boundary currents flowing through the marginal seas. Numbers give the water transport in Sv (1 Sv = 10^6 km^3/sec). EK: East Kamchatka Current; NNC: East Nansha Coast Current; HC: Huanghai (Yellow Sea) Coastal Current; HW: Huanghai (Yellow Sea) Warm Current; K: Kuroshio Current; KE: Kuroshio Extension; NE: North Equatorial Current; O: Oyashio Current; OE: Oyashio extension; OG: Okhotsk Gyre; S: Soya Current; T: Tsushima Current. (C) Diagram showing the hydrographic system in the marginal seas.

Similar changes occurred in the Oyashio Current system. Because of shelf exposure and the expansion of sea-ice coverage in the glacial Okhotsk Sea, it might be expected that the Oyashio Current would have had more restricted access to the Okhotsk Sea. This hypothesis is supported by a decrease of biogenic components and an increase in the proportion of terrigenous clastic material found in sediments deposited during the last glacial maximum in the Okhotsk Sea [*Gorbarenko,* 1996]. Two alternative modes of western boundary currents may have operated during glacial cycles: A glacial mode with boundary currents flowing only outside the marginal seas, and an interglacial mode with currents partially running through the marginal seas (Table 4). Switching between the two modes can result in different climates in East Asia and in different water mass structures of the northern Pacific.

The reduction of the Kuroshio warm water in the marginal seas during glacial times decreased the heat and humidity

Table 4. Two modes of the boundary current system in Western Pacific Marginal Sea

Mode	Western boundary currents	Exchanges between. continent and ocean
Interglacial	Partially flow through marginal seas	Mainly in marginal seas
Glacial	Only flow through the ocean	Mainly in open ocean

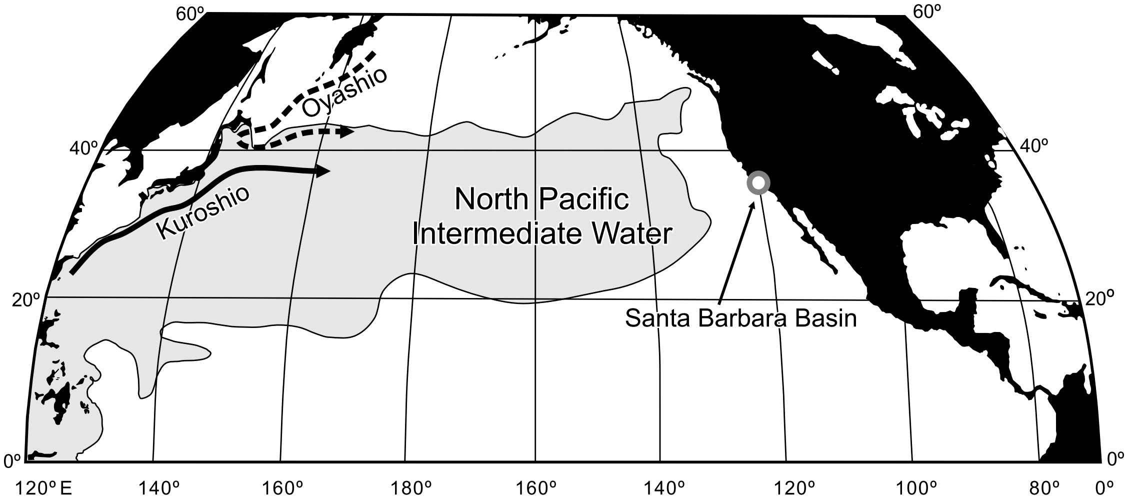

Figure 10. Distribution of the North Pacific Intermediate Water in the modern Pacific [after *Talley,* 1993]. Solid and dashed arrows show the extensions of the Kuroshio and Oyashio Currents, respectively; circle indicates the location of Santa Barbara Basin.

supply to East Asia. At the same time, this flow regime may have favored intensified production of North Pacific Intermediate Water. The North Pacific Intermediate Water is now the main salinity minimum in the subtropical North Pacific and is formed by mixing of the subtropical and subpolar waters in the mixed water region between the Oyashio and Kuroshio Currents. Its distribution is confined primarily to the North Pacific subtropical gyre (Figure 10) [*Talley,* 1993]. During glacial times, the boundary currents flowed outside the marginal seas, and their direct mixing would have increased Intermediate Water production and thus broadened its influence, possibly reaching the eastern margin of the Pacific. This process could have suppressed the California Current, the Eastern Boundary Current of the North Pacific.

Indeed, the cold-water California Current is known to have collapsed during the last glacial maximum [*Herbert et al.*, 2001], while enhanced production of North Pacific Intermediate Water provided well-oxygenated water to the California margin, including the Santa Barbara Basin. The sediments in the Santa Barbara Basin are laminated during interglacial periods, but are bioturbated during glacial periods, so recording oscillations between low-oxygen and higher-oxygen benthic conditions. *Kennett and Ingram* [1995] found that changes in the source of the bottom water were responsible for the oxygen content: a distal source in the North Atlantic brought low-oxygen intermediate water to the basin and led to formation of laminated sediments, while relatively young intermediate water from proximal sources provided more oxygen to the basin bottom and produced non-laminated deposits. Most probably, enhanced North Pacific Intermediate Water in glacial periods was the proximal source for the bottom water of the Santa Barbara Basin. If so then this is an example of teleconnection where bottom water conditions in the Eastern Pacific are causally related to changes in Western Pacific boundary currents.

It remains unclear whether the shift of the main route in the Kuroshio Current during glacial times was caused by a local factor, thus causing a change in the Eastern Pacific, or if the changes of boundary currents in Western and Eastern Pacific were manifestations of a single process, such as a draw-back of the North Pacific Subtropical Gyre. In any case, new data suggest that both western and eastern boundary currents have waxed and waned during glacial cycles [e.g., *Doose et al.*, 1997; *Ujiie and Ujiie*, 1999; *Mangelsdorf et al.*, 2000]. Climate modeling shows that the wind system during the glaciation was also less favorable for the development of eastern and western boundary currents [*Kutzbach,* 1987].

In summary I conclude that the Western Pacific marginal seas and the Western Boundary currents comprises a vulnerable system of sea-land interactions, sensitive to tectonic and eustatic sea level changes. Because of their relatively smaller size and of their narrow and/or shallow passages, the marginal seas can amplify the climate signal of the open ocean. Their proximal position means that the marginal seas have a strong impact on the terrestrial climate.

6. CONCLUSIONS

In his keynote speech to the First Asian Marine Geology Conference, 1988, Eugen Seibold defined Marine Geology as “Geology between Sea and Land” [*Seibold*, 1990]. This definition applies particularly well to Asian marine geology,

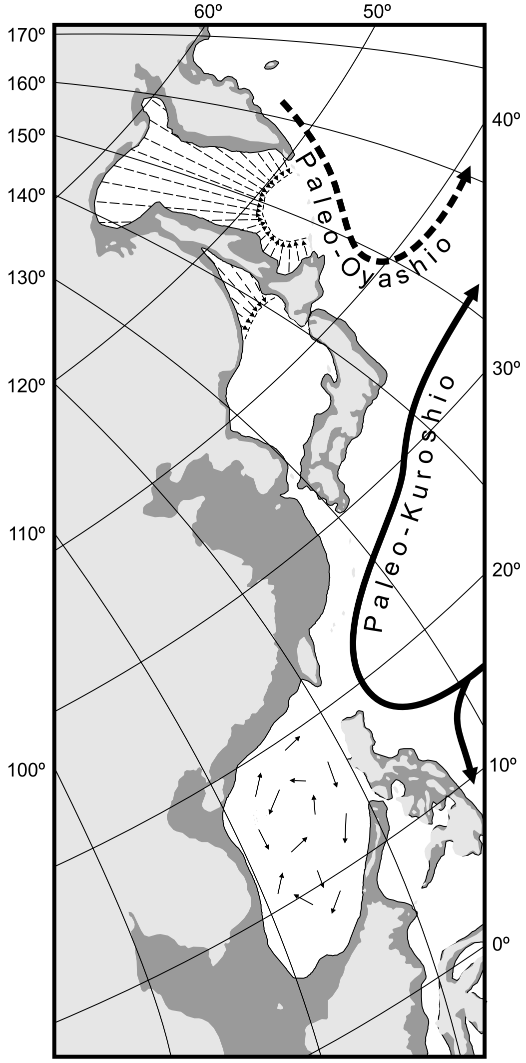

Figure 11. Hypothetical patterns of the western boundary currents in the Northwest Pacific during the last glacial maximum. Heavy arrows show the hypothetical tracks of the Paleo-Kuroshio, Paleo-Oyashio Currents and their extensions. Grey colors mark the land and exposed shelves. Thin arrows indicate surface currents in the South China Sea (based on numerical simulation after *Wang and Li* [1995]). Dotted lines with arrows show sea ice (according to *Frenzel et al.* [1992].

which surrounds the largest and highest continent on the planet. Cenozoic deformation of Asia was accompanied by changes in sea-land interactions and has impacted the regional and global climate.

Asia has experienced more significant deformation during the Cenozoic than any continental mass. Asia has been significantly enlarged between the late Eocene and the Miocene through amalgamation with Europe and India, and meanwhile it has increased its altitude, a process that continues to the present day. The uplift of Tibet and Mongolia, coupled with the opening of East Asian marginal seas has caused radical changes in regional topography and driven reorganization of the river network, resulting in a fluvial system that radiates from Central Asia. Since surface uplift has been propagating from south to northeast, the rivers discharging into the seas offshore northern and eastern Asia are very young, dating only from the late Pliocene or Pleistocene.

Asian deformation has brought about profound changes in global and regional climate. Plateau uplift may have promoted the establishment and development of the Arctic ice-sheet by alteration of atmospheric circulation, enhancement of weathering, and by formation of north-flowing Siberian rivers, which provide the Arctic Ocean with freshwater run-off. Plateau uplift and changes in sea-land distribution were responsible for the initiation of the Asian monsoon system during early Miocene, with further strengthening at ~8 Ma and ~3 Ma, also related to uplift and closure of oceanic passageways.

The formation of marginal seas along the eastern margin of Asia has modified the nature of land-sea interactions between Asia and the Pacific Ocean. The system of Western Boundary Currents in the marginal seas has switched between modes in response to tectonic or eustatic changes. The resulting amplification of global climatic signal within the marginal seas has had a strong impact on the terrestrial climate of Asia.

The role of Asia in controlling global climatic and environmental history has historically been underestimated largely because of limited studies of its vast areas. This has been exacerbated by language and/or political barriers to the work that has been done. This review shows that understanding of Asian climate and tectonic history remains largely qualitative in nature, particularly because of a lack of precise dating. However, the East Asia marginal seas are a natural laboratory for understanding a range of first order global-scale Earth science questions and must be a target for future efforts. What precisely was the relative role of Siberian rivers in the growth of the Arctic ice-sheet? Did the Western Pacific Warm Pool develop with the gradual closure of the Indonesian passageway? Is there any causal relationship of initiation of the Asian monsoons with the emergence of the Western Siberian Sea and opening of Western Pacific marginal seas?

Answers to these questions require collaborative international research. With its economic development, Asia is now becoming increasingly active in offshore and onshore research, as well as in the realm of international scientific cooperation. The time is ripe to increase the scale of collaboration and to organize well-focused and globally oriented international research projects in Asia.

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