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Tides and Tidal Currents of the Yellow and East China Seas during the Last 13000 Years

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In order to investigate the paleotidal structure and current pattern in the Yellow and East China seas (YECS) since the late Wisconsin, which is the last glacial maximum period, a two-dimensional version of the Princeton ocean model is used. We assume that subtracting the sea-level differences from the present one can produce paleobasins and that the paleotide did not differ greatly from the present one in the adjacent deep seas, the northwestern Pacific Ocean and the East Sea. We could successfully simulate the paleo-M_2 tides and tidal currents of 9000, 11000 and 13000 yr B.P. The result of the model shows considerable differences in the tidal pattern in each period. As the eustatic sea level rose, the amplitudes of the paleotides and the number of the amphidromic points generally increased, but the tidal currents in each paleobasin were strong and about the same order as the present day's. Based on these paleotide calculations, we suggest that there should have been active erosion in the paleobasin as in the present YECS, and the erosion should have played an important role on widening the paleobasin to the present shape, YECS.

INTRODUCTION

The present Yellow and East China seas (YECS) have many particular characteristics in the shape and the composition of bottom sediments. They occupy a very large semi-closed continental shelf area surrounded by the eastern China and the Korean Peninsula, and their average depths are only about 45 m. The East China Sea is the gateway through which the Kuroshio branch water flows in and the Yellow Sea shelf water flows out. The west and south coasts of Korea are drowned ria-type with many small estuaries, bays, islands, and peninsulas. The coastline is highly crenulate, even though it has been simplified in many segments by development of large intertidal mudflats and sand barriers and by construction of artificial dikes and other embankments across former bays. The history of Late Holocene submergence of the Korean Yellow Sea and South Sea bottoms has been recorded in the prism of estuarine mud that filled the floors of numerous small valleys that were eroded due to the lower sea level of glacial times (Lee, 1987). A part of the geomorphic evolution was probably due to episodes of periglacial mass-movement during the full glacial intervals, when the seas were drained by the eustatic lowering of sea level and the Korean region was no longer a peninsula but part of the east Asian mainland (Fig. 1).

It is interesting to study the evolution of the YECS from the last glacial maximum to the present. It seems to be not so simple as the area is filled with seawater due to the sea level rise. The bottom and landward boundaries of the paleobasin are considered to interact strongly and continuously with the tidal current in the basin. We can deduce this from the present basin, YECS. The tidal effect in the present YECS is one of the most dominant physical environment factors. Especially, the Yellow Sea is one of the most tide-dominated depositional environments on the earth, with a tidal range of 4—8 m. Near the Korean coast the sediment is sandier with common current-swept rocky areas, and mud flats of several kilometers wide at low tide are also ubiguitous. The erosion, transport and deposition of marine sediments in the study area during the last 16000 years is considered to be very active (Lee, 1987). In these respects, understanding of the paleotides in the area is one of the crucial clues to appreciate its sedimentation processes.

The purpose of this study is to numerically simulate the paleotide and tidal currents during the last 13000 years in the YECS and to find their characteristics for each geological period. We will

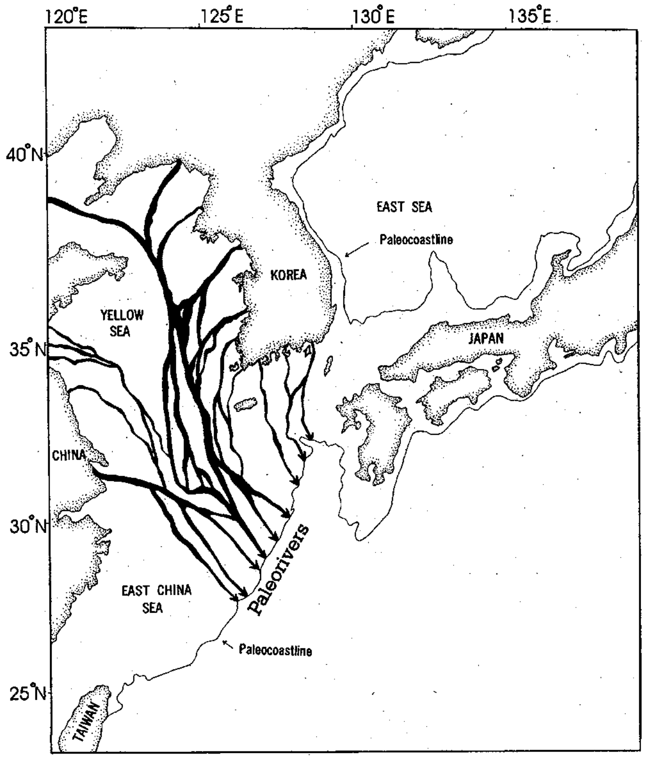

Fig. 1. Paleocoastline (135—150 m isobaths below the present sea level) and inferred paleoriver channels during the period of the maximum lower stand of sea level in the last glacial age (after Park, 1987).

try to describe not any sedimentation processes but the main driving force, *i.e.* tidal currents, for maneuvering of the marine sediments.

Necessary assumptions in advance

The environment we try to simulate is paleo-environment, which we can not measure or observe directly. Therefore, two inevitable assumptions in the following are required:

(1) In order to simulate the paleotide of the study area, we need detailed geometry and bottom topography of the YECS for each geological period. Unfortunately, we could not get this information from anywhere. Instead, we could solve it by assuming that there were no serious crustal movements during the interglacial period. In this way, we reconstructed the geometry and bottom topography of the paleobasin for each period by lowering sea levels from the present YECS level. This assumption seems to be reasonable for our purpose because the Korean peninsula became its present shape by the end of Cretaceous to early Paleogene (Lee, 1987).

(2) We also need to know the paleotide patterns of the northwestern Pacific Ocean and the East Sea during the interglacial period for setting up the open-boundary conditions of the present numerical model. We assume that the tidal patterns in the Pacific Ocean and the East Sea were not altered much due to the interglacial sea level rise. This assumption seems to be reasonable because the Pacific Ocean is so deep and wide that the oceanic tide can not be affected significantly by the sea level change of the order of 10 m. For the East Sea, the tidal action is very weak as compared with that of the YECS.

Table 1. Eustatic sea levels used for the present experiments (read from Park, 1992)

Experiment no.	Years before the present time	Sea level (m) below the present level
1	0	0
2	9000	28
3	11000	54
4	13000	80

Sea level changes

According to Park (1992), about 15000 yr B.P., which is called the Wisconsin, the last glacial maximum, the most part of the Yellow Sea bottom was a dry land because the sea level was about 150 m lower than the present one. It is reasonable to consider and define the following features (Fig. 1): (1) The lowest sea level in the last glacial time might be 135—150 m lower than the present one. (2) Rapid rise of the sea level between 15000 and 6500 yr B.P. is conceived, (3) The possibitiky of higher sea level stand than the present between 6500 and 1000 yr B.P. is still in question. Based on the study above, we picked up three time points for the computation of paleotides. The first one is 13000 yr B.P. The sea level was about 80 m below the present one and the Yellow Sea was just a small gulf. For about 4000 years from that time, the sea level had risen rather fast at a rate of 13 cm/kyr (Table 1). After the first 2000 years, the sea level in the Yellow Sea increased by 26 cm, and the channel-shape Yellow Sea became wider and wider as the sea level rose. Another 2000 years later, the old Yellow Sea extended to the primitive Bohai Bay. Fig. 2 shows the paleocoastlines for each period.

NUMERICAL MODEL

For the present study, a two-dimensional version

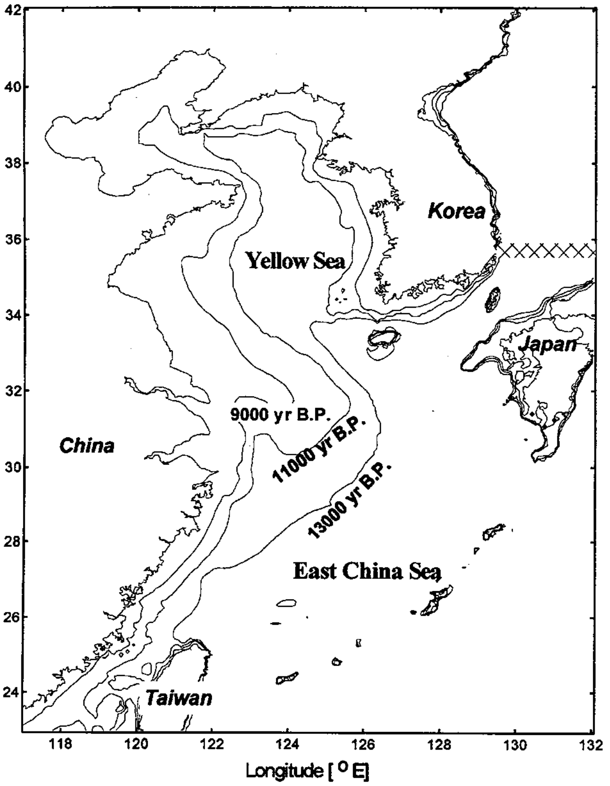

Fig. 2. Coastlines of 9000 yr B.P., 11000 yr B.P., and 13000 yr B.P. The paleocoastlines are estimated by lowering the present sea level.

of the Princeton ocean model is used. In the model, depth-integrated equations of motions and mass conservation in spherical coordinate system are used. The hydrodynamic assumption and the β-plane approximation are the important simplifications, and the density differences are neglected. The governing equations together with their boundary conditions are solved by finite difference scheme and leapfrog technique for time stepping. Detailed description of the model may be found elsewhere (Blumberg and Mellor, 1983, 1987; You and Oh, 1993).

The calculation is conducted by considering only the M_2 constituent for the domain from 23°N to 42°N and from 117°E to 132°E and having 1/12° grid resolution in both E-W and N-S directions. In considering the CFL condition, time step is chosen to be 27 seconds. The parameters that are used for the present study are listed in Table 2.

There are three open boundaries: southern boundary along 23°N line, eastern boundary along 132°E line, and East Sea boundary in Korean Strait. The amplitudes and phases of the M_2 tide were specified along the boundaries by approximating from the observational data which had been used by Choi (1980) and from the numerical results (Kantha, 1995). For the efficiency and stability of the model, the minimum water depth was set to be 5 m.

Table 2. Parameters used for the present model

Time step	Grids	Domain	Bottom friction coefficient	Horizontal eddy viscosity
27 sec	$\Delta x=\Delta y=1/12°$ EW 181 grids NS 229 grids	117°E—132°E 23°N—42°N	0.0025	0.05 m^2/s

EXPERIMENTS AND RESULTS

Experiments for model verification

Before applying our model to the eustatic YECS, it is necessary to verify whether the model operate properly in the case of the present time. Since we do not have eustatic tidal data for such a long time, direct comparison of our model results was not possible. Instead, the verification of the experiments should be achieved in some indirect ways.

The stability of the model was tested on an arbitrary point, Kunsan outer port, by running the model for sufficiently long time (more than 10 days). Fig. 3 shows that the model became stable after about 2 days. We also compared the computed and observed amplitudes and phases of the M_2 component. Fig. 4 shows the locations of forty-one tidal stations for comparisons. In Fig. 5a, the calculated amplitudes for each station are plotted against the observed ones. There is a correspondence between the two (correlation coefficient=0.945). The calculated phases are plotted against the observed ones (Fig. 5b). They also show good agreements (correlation coefficient=0.964). The computed rms errors of amplitude and phase angle for the 41 stations are 19.9 cm and 19.3°, respectively.

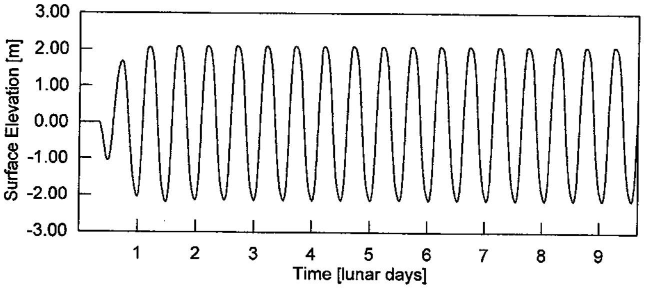

Fig. 3. Time series of model M_2 tidal elevation for 10 days at an arbitrary point off Kunsan.

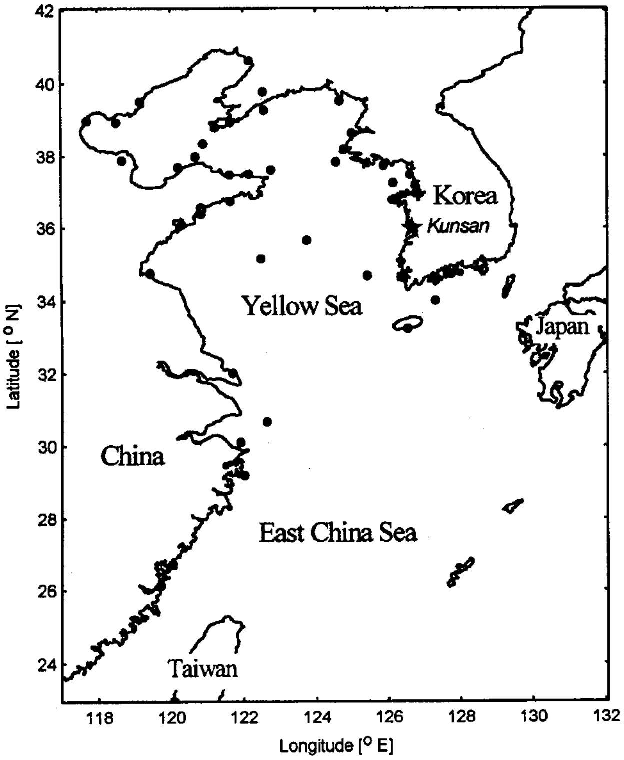

Fig. 4. Selected grid points (●) at which the observed and calculated harmonic constants are compared. A point where the time series of model M_2 tidal elevation is monitored in Fig. 3 is denoted by ★.

The overall patterns and characteristics of the calculated tide are compared with the previous studies. Fig. 6a is a computed co-tidal and co-range chart of the M_2 tide using the present day's geometry and bottom topography. Fig. 6b describes the calculated M_2 tidal ellipses at every six-grid point. The positions of three amphidromic points and the pattern of co-tidal lines as well as the coastal tidal ranges seem to be in a good agreement with others (Choi, 1980; Fang, 1994). We believe that this model is ready to simulate the paleotides and tidal currents of the old basins.

Eustatic experiments

The paleotides and tidal currents at the present time, 9000 yr B.P., 11000 yr B.P., and 13000 yr B.P. are simulated. Since the sea level was lowered by 24 m, 54 m, and 80 m from the present sea level for each case, much of the Yellow Sea bottom was exposed. There was no significant area that can be called as Yellow Sea in 13000 yr B.P. (Fig. 2). A narrow channel-shape Yellow Sea appeared in 11000 yr B.P. The similar-shaped Yellow Sea to the present form appeared from 9000 yr B.P., but it was much narrower than the present Yellow Sea. In these old basins, the patterns of the tidal-range distribution might be quite different from the present day's. We will explain the paleotides from 13000 yr B.P. to the present. In this way, we can focus our attention on the changes of tidal pattern as the sea level rises.

Since the sea level of the Yellow Sea in 13000 yr B.P. was 80 m lower than the present level, there was no Yellow Sea. The phase and amplitude pat-

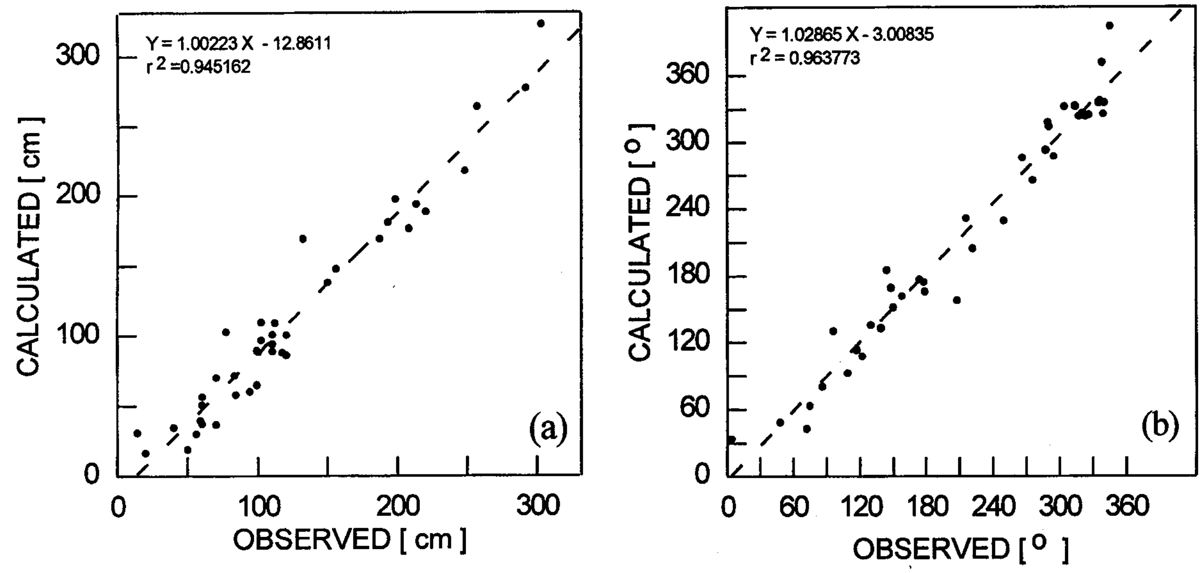

Fig. 5. (**a**) Comparison of the calculated and observed amplitudes of the M_2 tide for 41 grid points. (**b**) Comparison of the calculated and observed phase angles of the M_2 tide for 41 grid points.

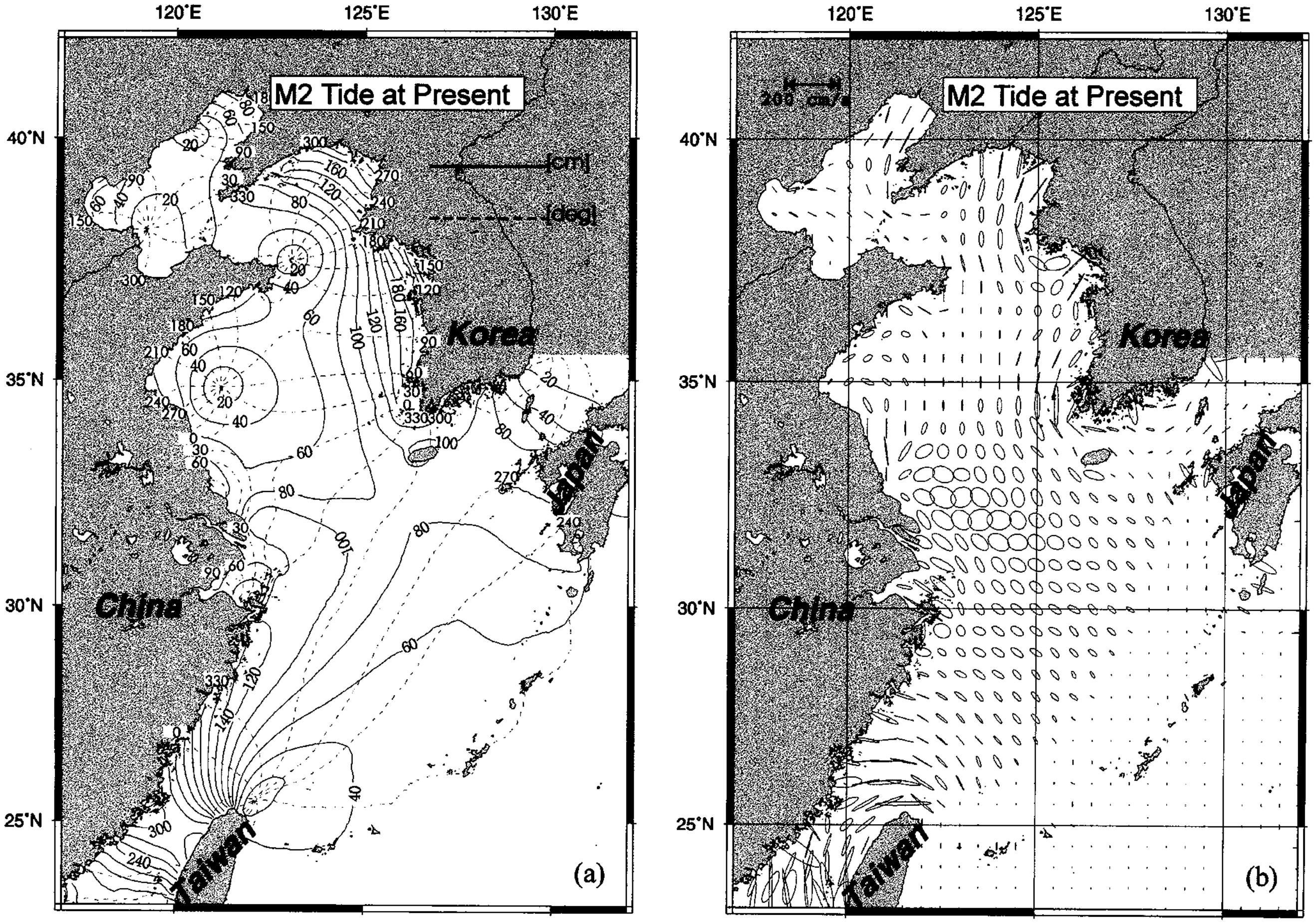

Fig. 6. (**a**) Lines of coamplitude (solid line) in cm and cophase (broken line) in degree (referred to 135°E) of the M_2 tide at the present time. (**b**) Tidal ellipses of the M_2 tide at the present time.

tern at that time were quite different from the present day's (Fig. 7a). Fig. 7b shows tidal current pattern. The overall tidal pattern was very simple because the coastline was very simple; however, the current speeds were comparable to the present day's. New high tidal amplitude area of over 2 m appeared along the Chinese coast between 27°N to 30°N. This is rather high value as compared with the tidal amplitude of the Chinese coast of the present day. The area between the Cheju Island and Japan had very large tidal amplitude of 2 m. The amplitudes decreased rapidly from the south of Cheju island towards the north and towards the Korea Strait. There can be some argues on magnitudes of the tidal amplitude of Korea Strait, *i.e.*, the large tidal amplitudes in the east of Cheju Island may not appear if the open boundary in Korea Strait is not specified as we did in this study. We agree this argument. However, we do not know better open boundary condition for the paleobasin than we used. Another thing we can point out is that the geometry of the East Sea has not been changed significantly (Fig. 1). Thus, the paleotidal pattern in the East Sea may not be much different from the present one. Therefore, at this moment, the present boundary condition seems to be the best choice. We can solve this problem rather easily by expanding our computational domain to include the East Sea. We reserve this for the next study subject.

The Yellow Sea became a narrow channel in 11000 yr B.P. (Fig. 8a). The tidal pattern was much different from that of 13000 yr B.P., but the overall pattern became somewhat similar to the present day's. Two amphidromic points appeared in the northernmost part of the channel, near the present-day Shandong peninsula. The tidal amplitude of the western part of Cheju Island had the maximum value of 180 cm, and it was gradually reduced as we went into the channel. The amphidromic points were shifted to the west; therefore, the coastal tidal amplitudes of the Korean side were larger than those of the Chinese side. Compared with the pre-

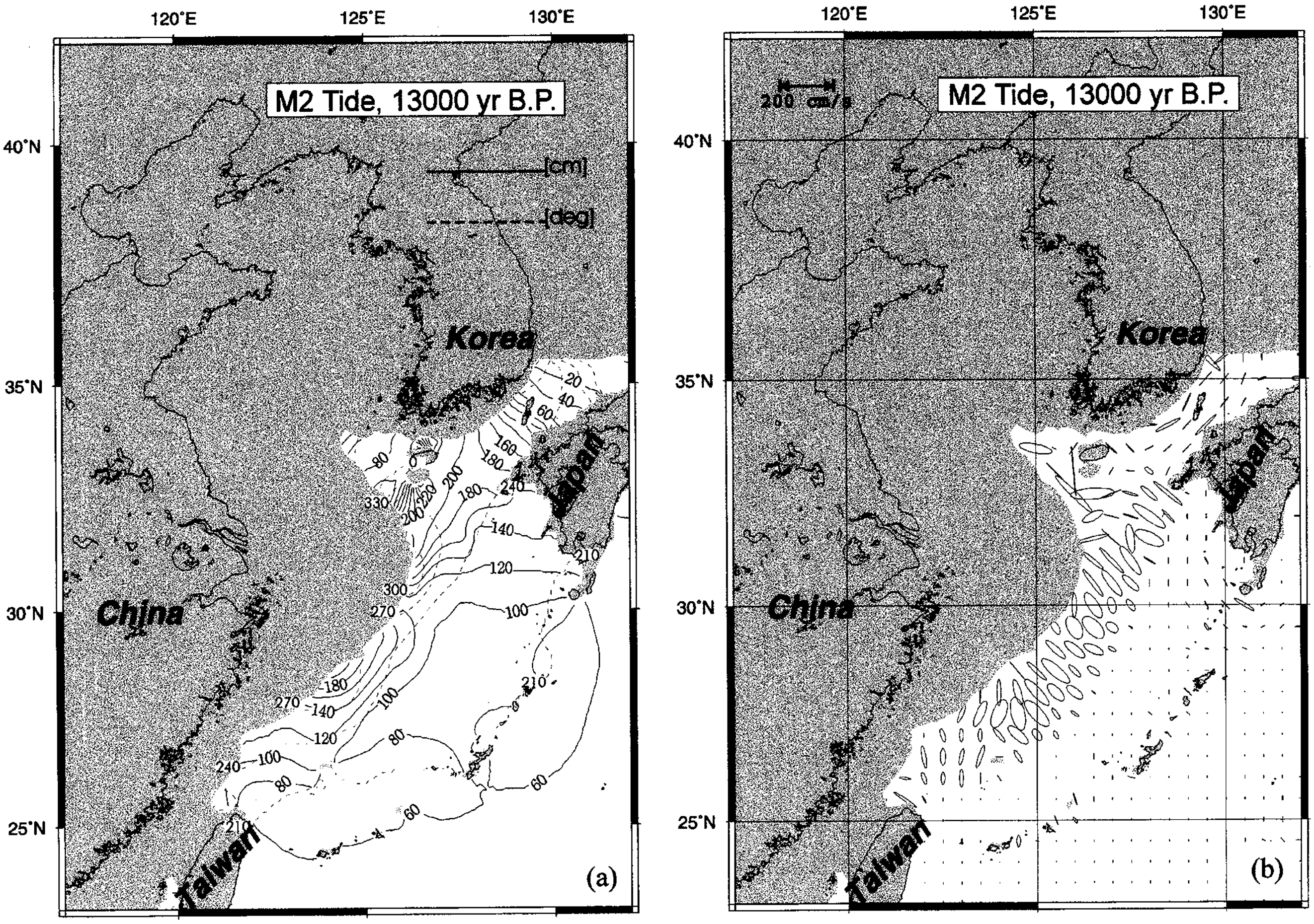

Fig. 7. (**a**) Lines of coamplitude (solid line) in cm and cophase (broken line) in degree (referred to 135°E) of the M_2 tide in 13000 yr B.P. (**b**) Tidal ellipses of the M_2 tide in 13000 yr B.P.

sent pattern, tidal amplitude seems to have become smaller near the Yantze River mouth at 30°N, but the northeastern part of the coast at 31°N had the maximum amplitude of over 180 cm. The main axis of tidal current ellipses coincided with the main axis of the channel and the speeds were very strong (over 200 cm/s near the southwestern tip of Korean peninsula) in the southern part of the channel (Fig. 8b). This suggests that there would be active erosion in the area, so that the Yellow Sea would be wider for the next 2000 years.

Figure 9a shows the M_2 tide in 9000 yr B.P. The width of the Yellow Sea became wider in 9000 yr B. P. in which the sea level was lower by 28 m than the present level. The overall pattern of the tide for this time was much similar to the present day's. The northern amphidromic point moved westward to the eastern tip of Shandong peninsula, and the southern amphidromic point moved southwestward about 250 km near 35°N where the present day's one is located. There developed a sign for future amphidromic point at the entrance of primitive Bohai Bay. The tidal amplitudes along the western Korean coast were greatly increased (by over 200%) as compared with those of 11000 yr B.P. The tidal amplitudes along the northern Chinese coast (from 32°N to 38°N) were relatively unchanged, but the amplitudes of the southern Chinese coast were changed considerably, especially much changes appeared near the Taiwan Strait. The strait was to be of almost the same width as the present's. New amphidromic point was formed near the northern tip of Taiwan Island.

The M_2 tidal ellipses in 9000 yr B.P. are shown in Fig. 9b. The current speeds in the northern part of the basin became stronger as compared with those of 11000 yr B.P. Especially the entrance of the primitive Bohai Bay had very strong tidal current. On the southwestern coast of the Korean peninsula, strong tidal currents appeared. The current speed in the southwestern part of the YECS near the Yantze River mouth was larger than the present day's and

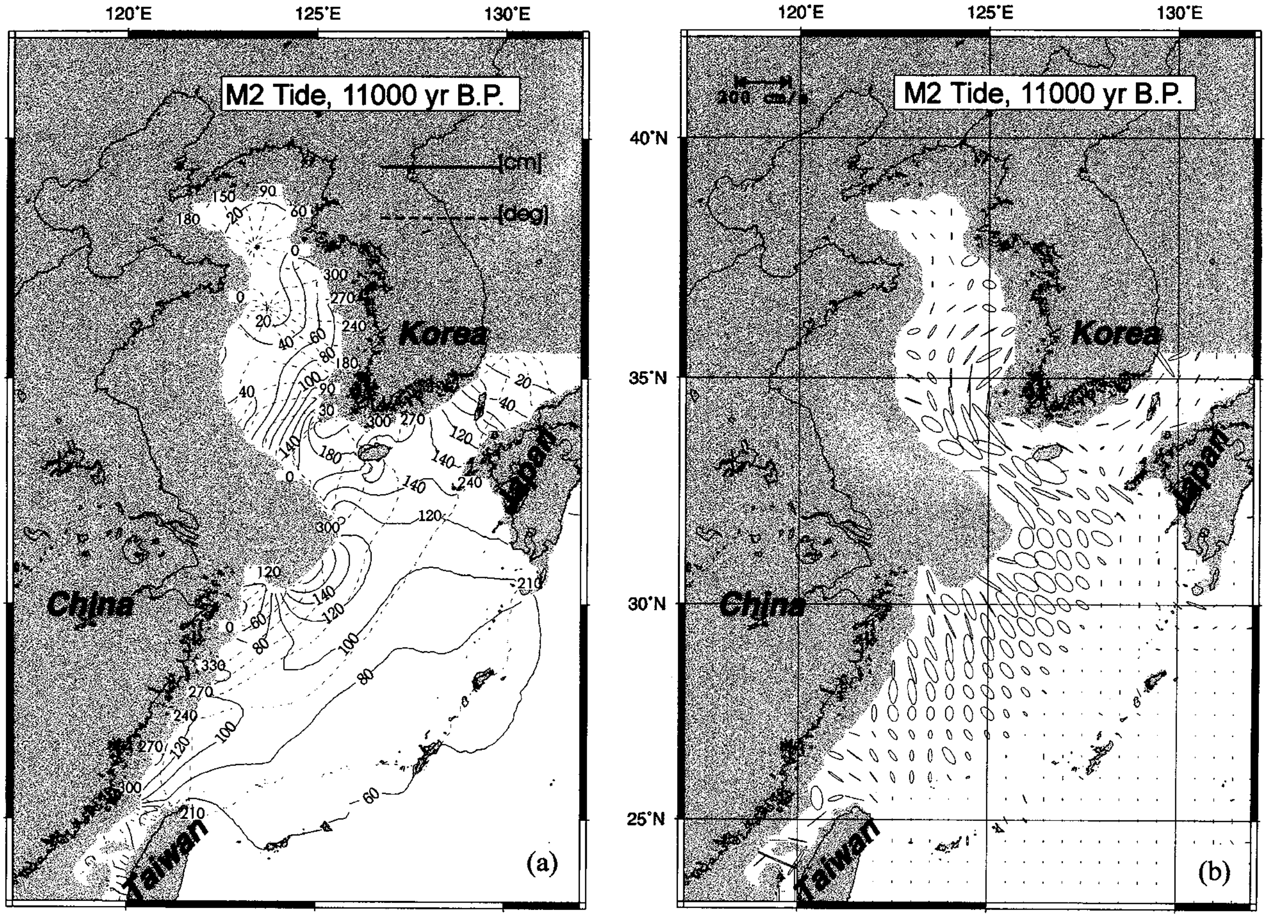

Fig. 8. (**a**) Lines of coamplitude (solid line) in cm and cophase (broken line) in degree (referred to 135°E) of the M_2 tide in 11000 yr B.P. (**b**) Tidal ellipses of the M_2 tide in 11000 yr B.P.

that of 11000 years B.P. This suggests that there would be active erosion in those areas, so that the Yellow Sea would be wider for the next 9000 years.

By comparing the computed tidal patterns all together, we could see some interesting results. The geometry and bottom topography of the paleobasin have been changed considerably for the last 13000 years due to the eustatic sea level rise, and the amplitudes of the tides are generally increased, and the number of the amphidromic points is also increased and their positions are shifted.

The reason for the gradual increase of the tidal amplitudes of the paleobasin seems to be as follows. The basin became a more suitable place for resonance of the M_2 tide signal as the sea level rose. In the present Yellow Sea, for instance, the water depth averaged from the amphidromic point near the eastern tip of Shandong Peninsula to the area of high tidal range over 8 m near Inchon is about 30 m. The tidal wave would propagate with the speed of $\sqrt{gh}$ where g is gravity and h is average water depth, thus the resonance distance for the M_2 tide with 30 m depth would be about 380 km. The actual distance from the amphidromic point to Inchon is about 350 km, which is close enough. In case of the 11000 yr B.P., the corresponding water depth would be about the same, but the distance from an amphidromic point to a point of the maximum tidal amplitude was too short for the tide to be resonated. Such a distance for 9000 yr B.P. was even shorter than that of 13000 yr B.P. Therefore, the tidal amplitudes were increased with increasing sea level, *i.e.*, as the sea level rises; the more water the ancient Yellow Sea was filled with, it became a more proper place for the M_2 to be resonated.

Another interesting factor is tidal current. It is the most important factor for sedimentation in the very shallow continental shelf area such as Yellow Sea. The computation results show that the paleotidal current speeds are about the same order as the present day's. This suggests that there should have been active erosion in the area for the period, and

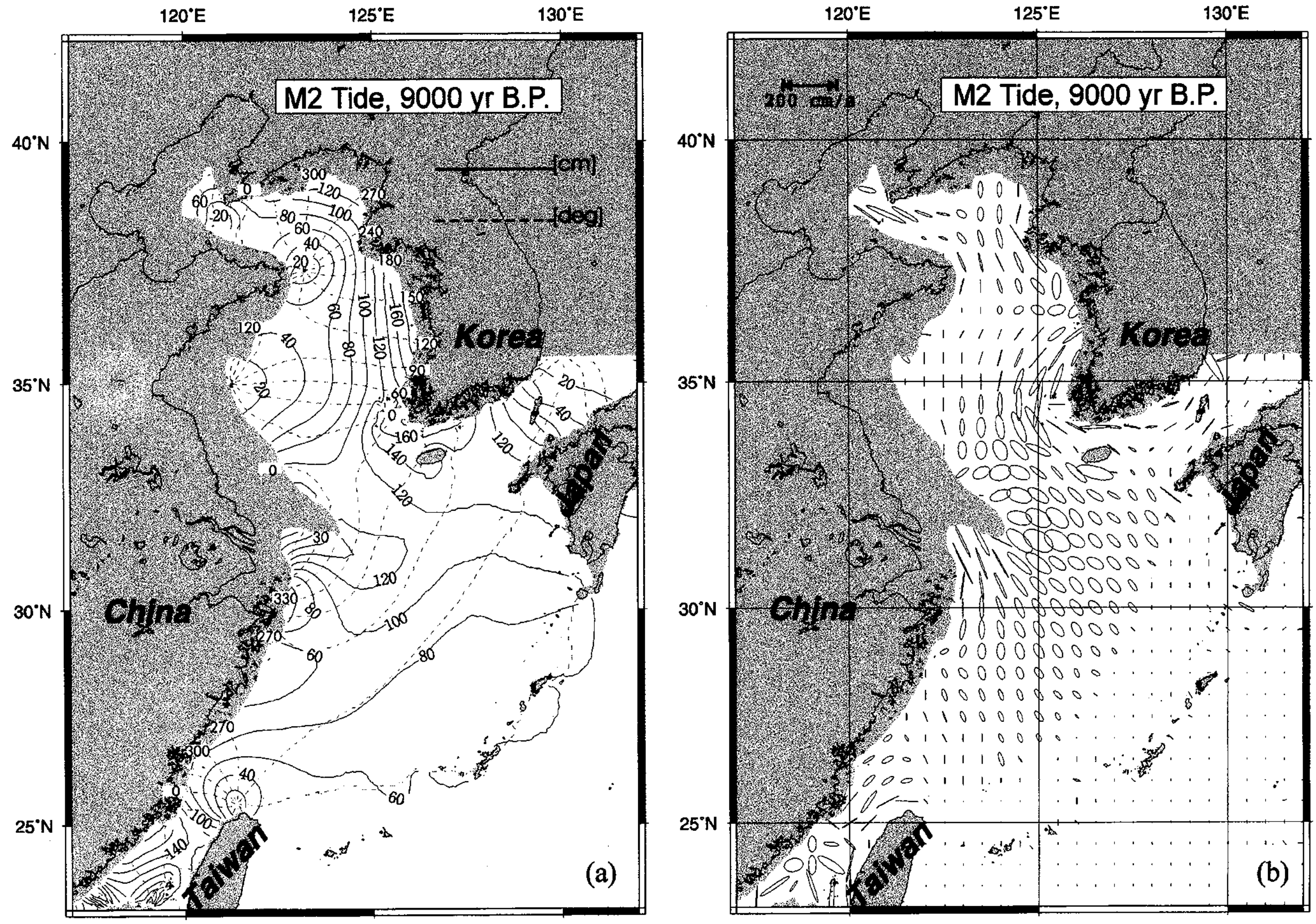

Fig. 9. (**a**) Lines of coamplitude (solid line) in cm and cophase (broken line) in degree (referred to 135°E) of the M_2 tide in 9000 yr B.P. (**b**) Tidal ellipses of the M_2 tide in 9000 yr B.P.

the erosion would have played an important role for the widening the paleobasin and making it into the present shape. With this strong tidal current and high tidal amplitude, the YECS would have been one of the most erosional areas on the earth, and the process would continue.

CONCLUSIONS

The paleo-M_2 tides and tidal currents in the YECS at the eustatic times of 9000 yr B.P., 11000 yr B.P., and 13000 yr B.P. were simulated by using a two-dimensional version of the Princeton ocean model. The results are as follows:

(1) The amplitudes of the paleotides and the number of the amphidromic points in the basin were generally increased with sea level rising. The amplitude increases were due to the fitting of the basin for the resonant condition of the M_2 tide.

(2) The magnitudes of the tidal currents in the 13000 yr B.P. as well as 9000 yr B.P. were strong and about the same order as compared with the present day's.

(3) Therefore, we can conclude that there should be active erosion in the paleobasin as in the present YECS. That erosion should have played an important role on widening the paleobasin and making it the present shape, YECS.

(4) In this study, we got the useful information about paleotidal patterns in the YECS for the last 13000 years. Future works will be extended to simulate three-dimensional tidal patterns in the YECS and the East Sea (Japan Sea) for the same geological period.

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