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Late Cenozoic history of sea level changes documented from high-resolution seismic data on the Northern Sunda Shelf, South China Sea

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Abstract: In the paper, a quantitative model is presented to estimate the magnitudes of eustatic sea level rises and falls by seismic data in an effort to consider the variables such as erosion, subsidence, compaction, and paleo-water depth, etc. As an application of the model, a eustatic curve of sea level changes since Pliocene is deduced from high-resolution air gun seismic lines acquired by German Sonne 115 Cruise in 1997. On the curve, about 36 cycles of sea level changes can be recognized with periods ranging from 0.08 Ma to 0.29 Ma, which are fallen into 4th order of sea level cycles. The curve is compared with the reprocessed deep-sea stable oxygen isotope data from benthic foraminifera on ODP sites 1,148 and 846 by resampling and filtering. Both of them matched well, which suggests that the 4th order of eustatic sea level changes during the last 5.33 Ma was probably controlled by changes in the sizes of the ice caps.

INTRODUCTION

Sunda Shelf, the largest shelf in the world, is located in the south of the South China Sea. Its wide and flat morphology made it easily submerged and exposed as a result of rising and falling of sea level. So it is believed to be one of the good sites to document Late Cenozoic sea level fluctuations (e.g. Sea Level Working Group, 1992).

The study area is located on the northern Sunda Shelf, ranging from 2° to 6° North Latitude and from 107° to 111° East Longitude. In this area, about 3,000 km high-resolution air gun seismic lines were acquired during the Cruise 115 of German Research Vessel Sonne (SO-115) in 1997 (Stattegger *et al.*, 1997). These data provided information for us to reconstruct the framework of seismic sequence stratigraphy and to deduce the history of sea level change since Pliocene.

METHODOLOGY

The popular method used to estimate the magnitudes of sea-level rises and falls by seismic data was developed by Vail and his Exxon's coworkers in the late 1970s (Vail *et al.*, 1977). In the method, "coastal aggradation", is used to measure approximately the vertical increments of sea-level changes. The magnitude of sea level changes estimated by this method, however, is not the value of eustatic sea level but the value of sea level relative to seabed or surface of sediment. The latter is the sum of eustatic sea level and subsidence of seabed or surface of sediment. In the method, there is an inclusive assumption that identical subsidence exists between different onlap or offlap points. In addition, measurements of coastal aggradation are influenced by a series of factors such as erosion of onlap and offlap points, compaction, and paleo-water depth, etc. How to deal with these factors is not elucidated in the method. In this study, we presented a quantitative model to estimate the magnitudes of eustatic sea level rises and falls by seismic data in an effort to take the variables mentioned above into consideration.

Consider the deposition of a stratigraphic unit, *i*. There are two cases for the shift of coastal onlap points during its deposition. One is onlap, that is, the onlap point shifts landward. Another is offlap, that is, the onlap point shifts basinward. On both cases, we can easily get the expressions of eustatic increment of sea level rise or fall on the basis of definitions of both eustatic sea level and relative sea level:

$$\Delta E_i = \begin{cases} Wd_{2A} + \Delta S_A - (\Delta H_A + \Delta Y_{lA} + \Delta Y_{tA}) & \textit{(for onlap case)} \\ -Wd_{1B} - (\Delta Y_{lB} + \Delta Y_{tB}) & \textit{(for offlap case)} \end{cases}$$

Where, ΔE_i and Wd are the increment of eustatic sea level and the paleo-water depth during the deposition of the unit *i*, respectively; ΔS is the depositional thickness of unit *i*; ΔH is the compaction subsidence of underlain strata during the deposition of unit *i*; ΔY_l and ΔY_t are the loading subsidence and the tectonic subsidence during the deposition of unit *i*, respectively; subscripts *A* and *B* denote the original (depositional) position of onlap or offlap points at the bottom and top boundaries of unit *i* respectively; subscripts 1 and 2 indicate the inception and the end time of deposition

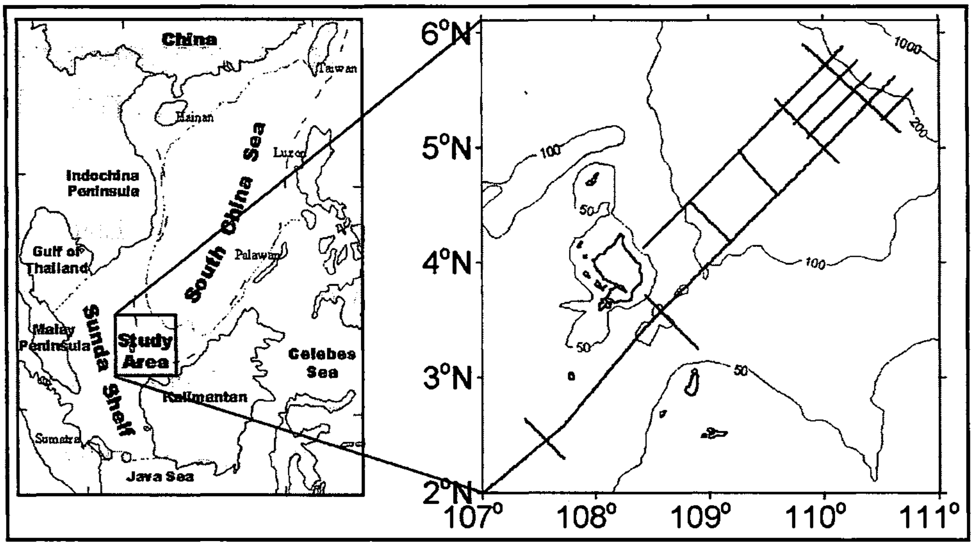

Figure 1. Location of the study area and the seismic lines used (after Stattegger *et al.*, 1997).

of unit *i* respectively. In the equation, ΔS_A and ΔH_A can be calculated by backstripping and decompaction algorithm; ΔY_{lA} and ΔY_{lB} can be calculated by local or flexural isostatic model; ΔY_{tA} and ΔY_{tB} are estimated by regional tectonic subsidence model; Wd_{2A} and Wd_{1B} are estimated by paleo-water-depth model, which is approximated by water depth on the modern Sunda Shelf in this study. It is very important that the original position for the removed onlap or offlap points need to be recovered by lateral extrapolation using thickness in nonerosional area (Zhong *et al.*, in press).

When the increments ΔEi of eustatic sea level changes for all the strata are calculated, eustatic sea level changes with time *t*, i.e. *E(t)*, can be expressed as:

$$E(t) = \sum_{i=1}^{n} \Delta E_i$$

where *i=1, 2, ..., n_n* is the total number of stratigraphic units.

The procedure used in charting the curve of magnitude of eustatic sea level rises and falls consists of three steps as follows: 1) selecting a typical updip seismic section crossing the basin margins on the basis of regional seismic sequence analysis, tracing the reflectors, and picking up their marginal onlap, offlap or truncated points, and dating the reflectors; 2) calculating increment of eustatic sea level rise or fall during deposition of each layer between adjacent two reflectors according to the model discussed above; 3) compiling the sea level curve from calculation of successive layers in step 2, plotted in absolute time.

RESULTS AND DISCUSSION

The curve of eustatic sea level changes obtained in this study is shown on Figure 2. In the chart, the vertical coordinate is the linear time scale in million years before present. The horizontal coordinate in meters represents

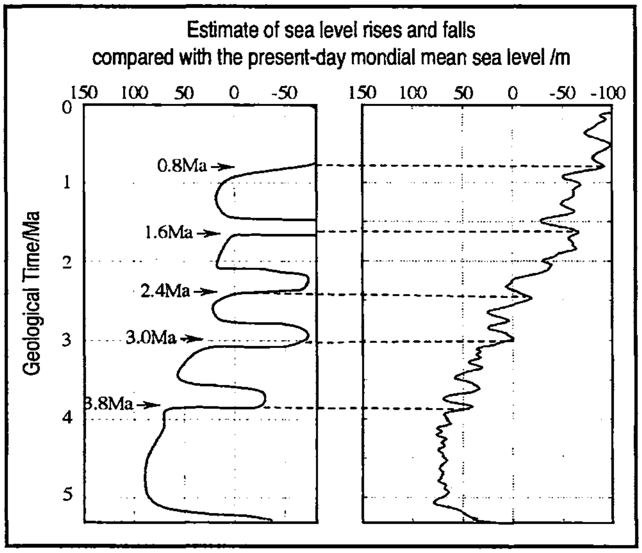

Figure 2. Eustatic curve from this study (right) compared with Haq *et al.*'s (1987, 1988) curve (left).

estimate of sea level rises and falls relative to the present-day mondial mean sea level.

According to this curve, the history of eustatic sea level changes during the past 5.33 Ma began with a transient but rapid rise in the initial stage of the Pliocene (from 5.33 Ma B.P. to 5.1 Ma B.P.±). It was close to the peak of high sea level at about 5.1 Ma B.P., and lasted through the Early Pliocene (from 5.1 Ma B.P. to 3.7 Ma B.P. or so). From the Middle Pliocene (3.7 Ma B.P. or so), eustatic sea level began to fall. This falling trend continued to the Early Pleistocene [3.7~0.9 (±0.1) Ma B.P.]. Then the sea level fluctuated at a generally low sea level through much of the Late Pleistocene (from 0.9 Ma to the end of Pleistocene).

The curve is generally in agreement with Haq *et al.*'s (1987, 1988) curve as shown in Figure 2. Several major low peaks on Haq *et al.*'s curve, such as those at 3.8 Ma, 3.0 Ma, 2.4 Ma, 1.6 Ma, 0.8 Ma, have corresponding peaks on our curve. Interestingly, our curve shows some peaks that are missing on Haq *et al.*'s curve, which may indicate that the resolution of our curve is higher.

It is generally agreed that the oxygen isotope records recovered by analyzing foraminifera in deep-sea sediment cores gives a history of global continental ice volume and hence of the glacio-eustatic component of sea-level change (e.g. Mattews, 1984; Chappell and Shackleton, 1986; Shackleton, 1987). To verify our curve, we compare it with the deep-sea stable oxygen isotope records from benthic foraminifera on ODP sites 1148 (Jian *et al.*, 2001) and 846 (Shackleton *et al.*, 1995; Mix and Shackleton, 1995), which are located in the northern South China Sea and in the east Pacific respectively (Fig. 3).

On our curve, about 36 cycles of sea level fluctuations can be recognized with periods ranging from 0.08 Ma to 0.29 Ma, which are fallen into 4^{th} order of cycles defined by Vail *et al.* (1991). The time resolution of deep-sea oxygen isotope records from benthic foraminifera, however, is generally scaled in millennium. In order to compare them on the same time scale, and to eliminate errors caused by casual factors during the documentation of these data, we reprocessed the two sets of data following the same procedures. Each data set is resampled with a time interval of 0.01 Ma. Then the resampled data are moving-averaged by a filter with window width specially chosen as 0.1 Ma, which is equal to the upper limit of 4th order of eustatic cycles defined by Vail *et al.* (1991). This way, we can compare our eustatic curve with the oxygen isotope records on the same time scale of 4^{th} order of cycle. To our satisfaction, the results matched well (Fig. 3). This result suggests that the 4th order of eustatic sea level fluctuations during the last 5.33 Ma was probably controlled by changes in the sizes or the volumes of the ice caps.

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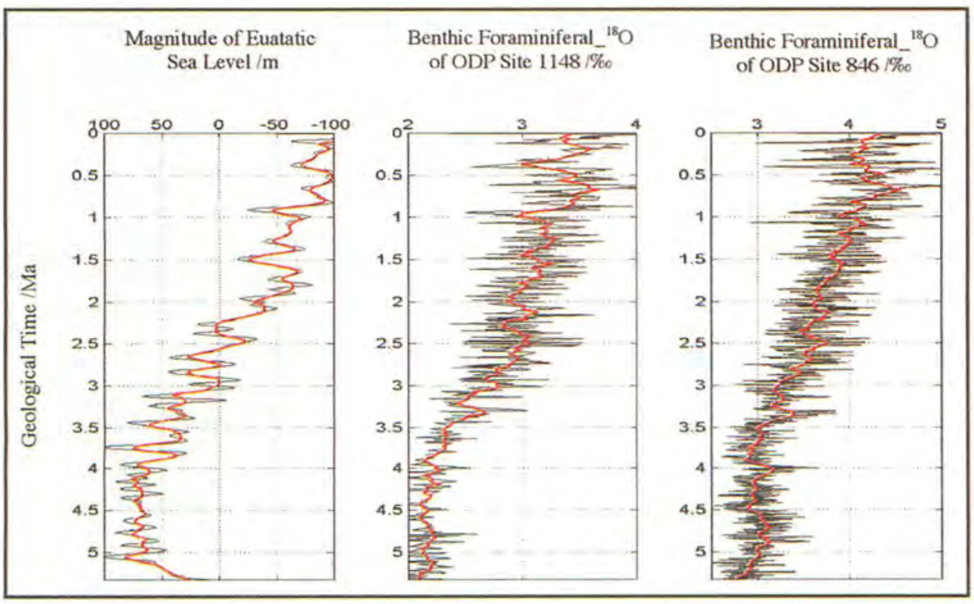

Figure 3. Eustatic curve from this study (left) compared with the deep-sea stable oxygen isotope records from benthic foraminifera on ODP sites 1148 (middle) (Jian *et al.*, 2001) and 846 (right) (Shackleton *et al.*, 1995; Mix and Shackleton, 1995).

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