

# Calculating eustatic amplitude of Middle Permian from reefs

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**Abstract** Methods for calculating ancient eustatic change amplitudes according to reef fabric-facies are proposed, with a new method for determining sediment-loading subsidence. Compared with methods based on non-reefal deposits, these methods are more accurate in restoration of original sediment thickness, determination of sediment-loading subsidence, as well as restoration of ancient water depth. According to the reef in Guangxi, China, the amplitude of sea-level rise during Middle Permian (*Neoschwagerina-Yabeina* zone) is 249.5 m. According to the coeval reef of the Guadalupe Mountains, New Mexico and Texas, the coeval sea-level rise is 247 m. With these effective methods available, it is feasible to establish more accurate eustatic curve of Phanerozoic.

**Keywords:** sea-level changes, eustatic change, reef, fabric-facies, subsidence.

To predict the future change of the global climate necessitates the understanding of the history and tendency of the global climate changes. In order to determine the distribution of ore and resources, it is necessary to restore climate history, since the distribution of sedimentary ores is mostly controlled by sea-level changes. It is shown that hydrocarbon reservoir of clastic rocks generally formed in the passive continental margins during sea-level falls, while reefal hydrocarbon reservoir mostly formed in the passive continental margins during sea-level rises<sup>[1]</sup>. Sea-level changes are the key problem of sequence stratigraphy, since the attributes of sea-level changes are the base of sequence stratigraphic division and correlation.

## 1 Some conceptions about sea-level changes

Sea-level changes include two types: eustasies and relative sea-level changes. Eustasies are global sea-level changes caused by changes in global seawater volume or changes in the volume of mid-oceanic ridges. The term "relative sea-level change" has two usages. One implies the absence of permanent reference point for measuring sea-level changes. The other means the change in water depth, which can be caused by either eustatic changes or tectonic subsidence of basin base, or by both of them.

Eustatic changes include three types: ice-eustasies caused by changes in ice sheet volume, mid-ridge eustasies caused by changes in mid-oceanic ridge volume, and ice-ridge eustasies caused by both of them.

Studies of sea-level changes involve two aspects: directions (rises or falls) and amplitudes.

Amplitudes can be relative or absolute. Relative amplitudes reflect the relative magnitudes of different sea-level changes. Absolute amplitudes are expressed in such length units as meters.

## 2 Outline of methods for determining sea-level changes

Many methods have been proposed to determine the relative magnitude of sea-level changes. A classical one is Vail et al.'s (1977). This method estimated the magnitude of sea-level changes according to the vertical component of the overlapped seismic reflectors<sup>[2-4]</sup>. Some researchers used hypsometric curves to determine the amplitude of eustatic changes according to the changes in the continental area covered by marine sediments<sup>[5-8]</sup>. Some researchers used paleobathymetric markers reflecting ancient strand-line positions, such as peat and reef terraces, to estimate the magnitude of sea-level changes<sup>[9-11]</sup>. Some researchers attempted to determine the magnitude of sea-level changes according to changes in the oxygen isotopic composition of seawater<sup>[12,13]</sup>. Cisne et al. (1984) proposed a method to determine the sea-level change magnitude using the relation between carbonate deposition rate and water depth<sup>[14,15]</sup>. Fischer (1964) proposed a method, called Fischer plotting by following researchers, to determine the sea-level change magnitude<sup>[16]</sup>. Some researchers established the sea-level change curve using water depth-time curve<sup>[17-19]</sup>. Some researchers calculated sea-level change magnitudes according to the strength features of cephalopod shells<sup>[20]</sup>.

As evaluated by Kendall and Lerche (1988), these methods depend on some assumptions not necessarily true and thus reliable absolute sea-level change magnitudes cannot be obtained from them. Recently, Soreghan and Giles (1999) stated: "Actual measurement of paleoeustatic amplitude, however, remains elusive owing in part to the difficulty in preserving unambiguous evidence for changes in water depth, as well as the problem of distinguishing eustatic from relative sea-level changes"<sup>[21]</sup>.

This paper is attempting to present a method to calculate the absolute amplitude of ancient eustatic changes according to reefs, including the method to determine paleo-water depth according to reef fabric-facies, and the method to calculate sediment-loading subsidence so as to distinguish eustatic changes from relative sea-level changes.

## 3 Responses of reef growth to sea-level changes

To understand the responses of reef growth to relative sea-level changes is the precondition for determining the directions and amplitudes of sea-level changes.

Of the marine ecosystems, reefs are the most sensitive to environmental changes, especially to sea-level changes. Under particular sea-level conditions, particular reef community evolutionary series and particular fabric-facies series will form.

(1) Under condition of stable sea level, reefs will grow upward till their reaching the sea level (fig. 1(a)-1, (a)-2)). During reef growth the water depth on reefs decreases and the shoaling-up reef community series and the shoaling-up fabric-facies series form.

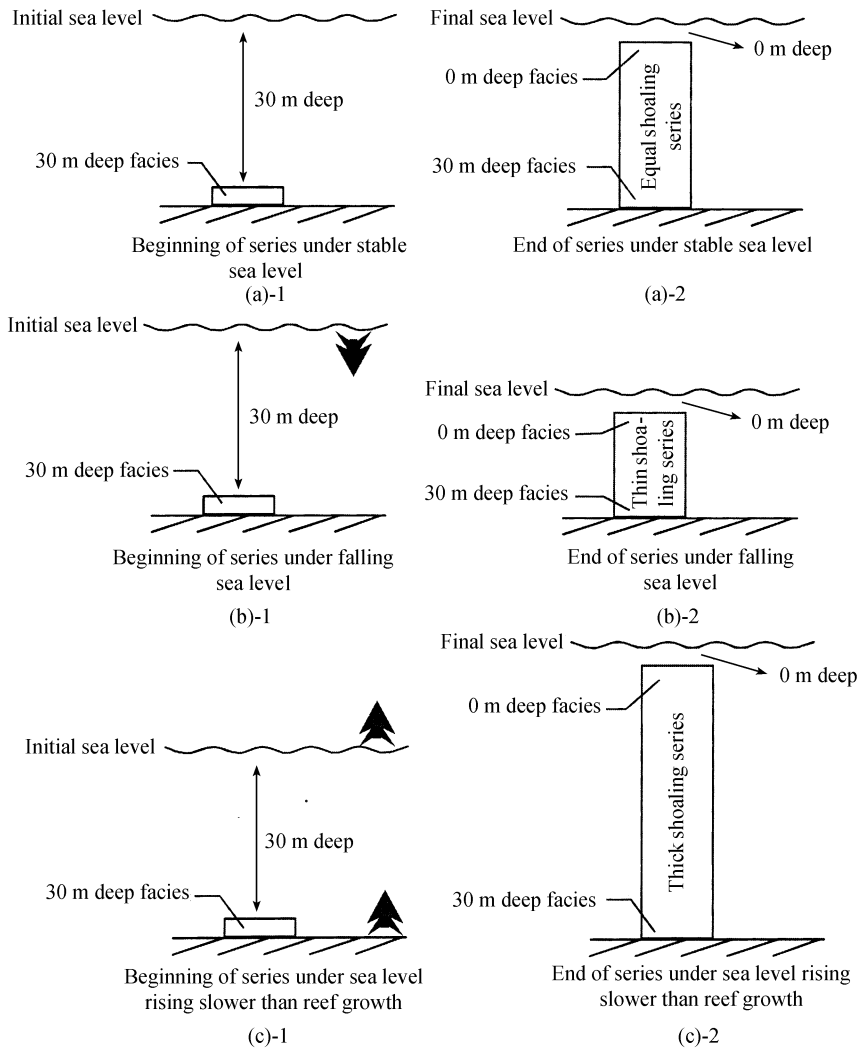


Fig. 1. Responses of reef growth to sea level changes. Water depth before sea level changes is assumed to be 30 m. Each arrow represents one velocity unit of sea-level change or reef growth.

(2) During sea-level falling, shoaling-up community series and shoaling-up fabric-facies series form in a similarly way. But the thickness of the series is much smaller (fig. 1(b)-1, (b)-2).

(3) During sea-level rising slower than reefal growth, a shoaling-up community series and a shoaling-up fabric-facies series form. But, the thickness of the series is much greater, as compared with the case of (1) (fig. 1(c)-1, (c)-2).

(4) During the sea-level rising that is as fast as reefal growth, the reef community and fabric-facies remain unchanged and "even community series" and "even fabric-facies series" form (fig. 2(a)-1, (a)-2).

(5) During the sea-level rising that is faster than reefal growth, the reef community and fabric-facies change gradually to deeper water types, forming "deepening community series" and

“deepening fabric-facies series” (fig. 2(b)-1, (b)-2).

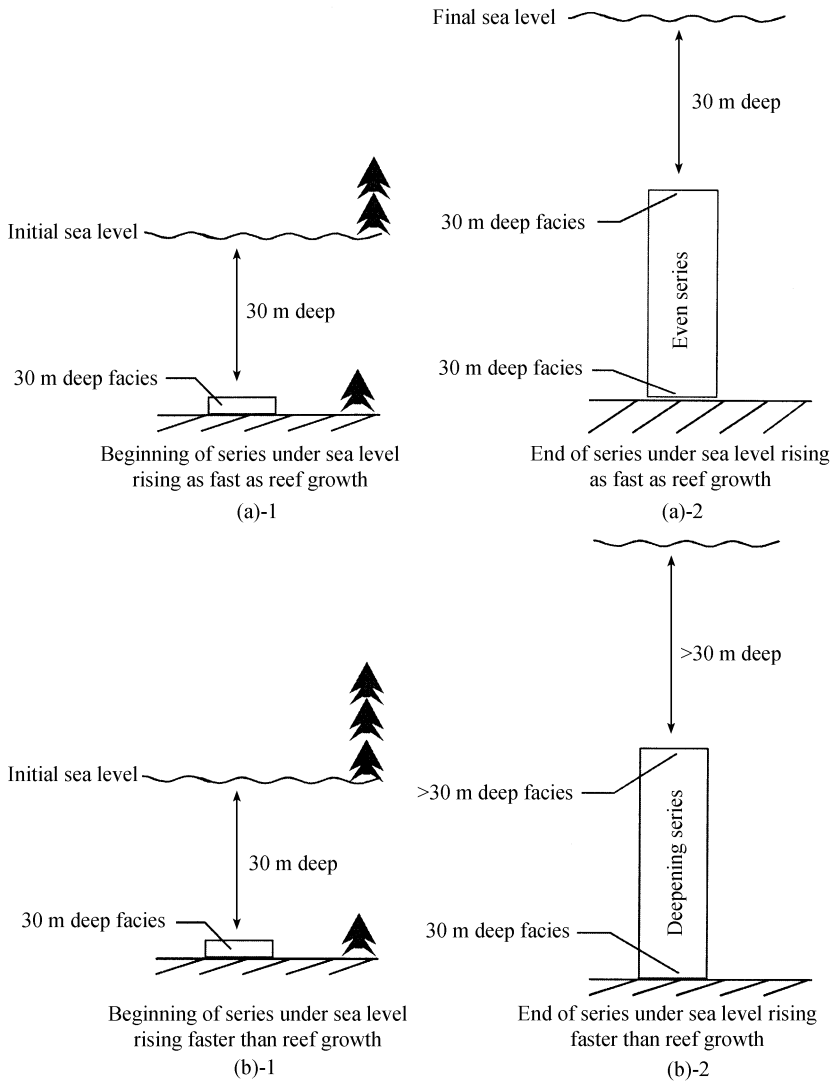


Fig. 2. Responses of reef growth to sea level changes. Water depth before sea level changes is assumed to be 30 m. Each arrow represents one velocity unit of sea-level change or reef growth.

#### 4 Fabric-facies of reefs

In order to describe the fabrics of reefs and the 3-D variation of reef fabrics in more details, Wu (1992)<sup>[22, 23]</sup> proposed the conception of reef fabric-facies. Reef fabric-facies are divided according to the fabrics of reefs formed in particular environments. The main reef fabric-facies are as follows.

(1) Biolain facies: Mainly composed of turned-down and broken skeletons of reef-builders, generally formed on reef flat or in the vicinity of reef flat.

(2) Boulded facies: Mainly composed of boulders of large reef-builders (such as massive corals) or reef rocks, forming a reef crest on reef-flat.

(3) Bioruded facies (or reeferred facies): Mainly composed of sands or / and gravels of reefbuilders (or reef rocks), including biosandstones, biogravelstones, reefsandstones, and reefgravelstones, formed in the vicinity of reef flat.

(4) Framed facies: Composed of framestones including sparry cemented framestones and micritic framestones with interstice-filling micrites. Both cemented framestones and micritic framestones form in the “growth zone” of reefs, the photic shallow water environments. Cemented framestones form in water shallower than that micritic framestones form in.

(5) Baffled facies: Composed of bafflestones in which reefbuilders generally have intervals of more than 0.2 m, generally formed in deeper water, compared with framed facies.

(6) Prebaffled facies: Composed of bafflestones in which reefbuilders have intervals of more than 0.5 m, formed in much deeper water, compared with baffled facies.

Besides these reefal facies, non-reefal facies, including packed facies composed of packstone, wacked facies composed of wackestones and grained facies composed of grainstones, can occur in reef complexes, too. They form in inter-reef places or non-reefal episodes.

## 5 Paleodepth of reef fabric-facies

Interpretation of the water depth of different reef fabric-facies is the basis for determining ancient sea-level change amplitude according to reefs.

### 5.1 Water depth of fabric-facies of modern coral reefs

According to our survey of modern coral reefs in the South China Sea as well as observation of these reefs by other researchers, biolain facies, boulded facies, bioruded facies and reeferred facies form in the vicinity of reef flat at depth of 0—2 m under wave action. Framed facies forms in the upper part of the “growth zone” of reefs. According to Lü et al. (1981)<sup>[24]</sup>, the “growth zone” of the coral reefs in the South China Sea is 3—18 m deep. According to Dodd and Stanton (1981)<sup>[25]</sup>, hermatypic corals reach greatest abundance in the water less than 15 m deep. So we believed that framed facies forms in the water 2—18 m deep. Sparry cemented framed facies forms in the upper part of the unda (the depth above wave base). The wave base is generally 20 m deep<sup>[26]</sup>. It is obvious that, in the unda the more upper the part of growth zone the greater the wave action is, and the greater the volume ratio of sparry cemented framestone to micritic framestone. So sparry cemented framestones occur in the upper part of the unda, at depth of 2—10 m, while the micritic framestone in the lower part of the unda, at 10—18 m depth. According to Barnes and Hughes (1982)<sup>[27]</sup>, on the coral reefs in the Indian Ocean the reef biota reaches its acme in diversity at 20 m depth, with diversity decreasing at 20—40 m depth. So we believe that the framed facies forms in the water less than 20 m deep, the baffled facies forms in the water 20—30 m deep, and the prebaffled facies forms in the water 30—40 m deep.

## 5.2 Paleodepth of the fabric-facies of calcisponge reefs

Permian reefs were mostly calcisponge reefs. The fabric-facies in Permian reefs mainly include: (1) biolain facies composed of turned-down calcisponge skeletons, (2) bioruded facies mainly composed of sorted sands or/and gravels of reefbuilder skeletons and reeferred facies mainly composed of sorted sands or/and gravels of reef rocks, (3) sparry cemented framed facies generally having algal encrusting and sparry cements, (4) micritic framed facies with interstice-filling micrites, (5) baffled facies composed of bafflestones, and (6) prebaffled facies composed of prebafflestones. The biolain facies formed in the vicinity of sea level. The bioruded facies and reeferred facies formed in the vicinity of sea level by wave action. The three facies formed in the vicinity of reef flat. According to Flugel (1982)<sup>[28]</sup>, the water depth of reef flat is 0—3 m. Then we can conclude that the three facies formed at 0—3 m depth. The series “framed facies-baffled facies-prebaffled facies” is a spectrum with reefbuilders decreasing, representing a spectrum from the environments the most suitable for reef growth to the environments the least suitable. The framed facies occurs in the upper part of the photic zone and unda; the baffled facies occurs in the middle part of the photic zone with little wave action; the prebaffled facies occurs in the lower part of the photic zone almost without wave action. It is known that the presence of symbiotic zooxanthellae in the tissue of hermatypic corals can greatly increase the rate of carbonate secretion. Some researchers believed that the hexacorals in Triassic reefs had symbiotic zooxanthellae. Calcareous algae occur abundantly in Permian reefs. Because of this, Flugel et al. (1984)<sup>[29]</sup> called Permian calcisponge reef “calcisponge/algal/cement reef”. We know that light is essential to algal life. Calcareous algae need light to perform photosynthesis. So the Permian reefs with calcareous algae lived within the photic zone. The depth of the photic zone is generally 0—30 m. So it is reasonable to infer that the Permian calcisponge reefs with calcareous algae formed in the water 0—30 m deep. Since the framed facies represents the upper part of the photic zone, in modern reefs the framed facies form in the water less than 20 m deep. According to Barnes and Hughes (1982)<sup>[27]</sup>, in modern reefs, sponges are sparse at 0—10 m depth, increasing in abundance at 10—15 m depth, the most abundant at 20 m depth, decreasing in abundance to very sparse at 20—35 m depth. It is believed that in Permian reefs the role of the coral with zooxanthellae in modern reefs was played by calcisponges. So we infer that the “growth zone” in Permian reefs was generally at depth of 3—20 m and dominated by calcisponges. In the “growth zone” the main reefbuilders calcisponges had the greatest abundance and formed framed facies. Similarly, the sparry cemented framed facies formed in the upper part of the “growth zone” where the wave action was relatively strong and the micritic framed facies formed in the lower part of the “growth zone” where the wave action was relatively weak and fine sediments and micrites remained. So, we divided the “growth zone” into two parts: the upper part 3—10 m deep is the place where the sparry cemented framed facies formed but the lower part 10—20 m deep is the place where the

micritic framed facies formed. The lower limit of the occurrence of the framed facies is the upper limit of the baffled facies. Since in modern reefs the abundance of sponges declines in the water 20—30 m deep, we believed that the occurrence of the baffled facies is at 20—30 m depth. The lower limit of the occurrence of the baffled facies is the upper limit of the occurrence of the pre-baffled facies. According to Basile et al. (1984)<sup>[30]</sup>, modern calcisponges mainly occur at depth of less than 35 m, very sparsely at depth of 40—50 m. So we suppose that the prebaffled facies mainly occurred at depth of 30—40 m, typically at depth of 35 m.

## 6 Calculating ancient eustatic change amplitudes according to reefs

As stated above, particular sea-level conditions lead to particular reefal community series and particular reefal fabric-facies series. Conversely, particular reefal community series or fabric-facies series recorded the particular sea-level change history. So we can restore the ancient sea-level change history from reefal community series or reefal fabric-facies series. Our study showed that it is possible to calculate ancient sea-level change amplitude according to reefal fabric-facies series. The method includes the following cases.

(1) Equal shoaling series. It means the shoaling series with original thickness similar to the water depth of the bottom of the fabric-facies series. This series is formed under stable sea level (fig. 1(a)-1, (a)-2). So the sea-level change amplitude is 0.

(2) Thin shoaling series. It means the shoaling series with original thickness much smaller than the water depth of the fabric-facies of the bottom of the series. This is the series formed under falling sea level (fig. 1(b)-1, (b)-2). Evidence of exposure often occurs on the top of the series. The calculation of the sea-level falling amplitude will be dealt with in a separate paper.

(3) Thick shoaling series. It means the shoaling series with original thickness greater than the water depth of the fabric-facies of the bottom of the series. This series is formed under the sea level rising slower than reef growth (fig. 1(c)-1, (c)-2). The sea-level rise amplitude is

$$R = T_s - (D_b - D_t),$$

where  $T_s$  is the original stratum thickness of the series,  $D_b$  the water depth of the fabric-facies of the bottom of the series, and  $D_t$  the water depth of the top of the series.

(4) Even series. This series is formed under the sea level rising as fast as reefal growth (fig. 2(a)-1, (a)-2). The sea-level rise amplitude is

$$R = T_s,$$

where  $T_s$  is the original stratum thickness of the series.

(5) Deepening series. This series is formed under the sea level rising faster than reefal growth (fig. 2(b)-1, (b)-2). The sea-level rise amplitude represented by this series is

$$R = T_s + (D_t - D_b),$$

where the meanings of  $T_s$ ,  $D_b$  and  $D_t$  are the same as above.

Actually most reef sequences are different stacked fabric-facies series. The sea-level change

amplitude represented by stacked series is the sum of the sea-level change amplitudes represented by all single fabric-facies series.

## 7 Restoration of the original thickness of series

Restoring the original thickness of series is the precondition for determining ancient sea-level change amplitude.

The following formula has been used to calculate the original thickness of strata<sup>[31]</sup>:

$$S_0 = S (1 - \Phi) / (1 - \Phi_0),$$

where  $S$ ,  $S_0$ ,  $\Phi$  and  $\Phi_0$  represent current thickness, original thickness, current porosity, original porosity of strata, respectively. The assumption behind the formula is that the ratio of the original porosity to the current porosity is equal to the ratio of the original thickness to the current thickness. But we believe that this relationship is not applicable to reefal rocks, since compaction is obvious in some reef rocks but unobvious or ignorable in some other reef rocks and the compaction of carbonate rocks is different from that of clastic rocks. Thus we propose that: (i) since sparry cemented framestone and grainstone are resistant to compaction, their original thickness can be represented by their current thickness; (ii) the original thickness of other rocks can be calculated using Goldhammer's (1997) method<sup>[31]</sup>.

## 8 From relative sea-level change amplitudes to eustatic amplitudes

Using the method introduced above, we can calculate the relative sea-level change amplitudes. To obtain eustatic change amplitudes, we must exclude the subsidence or rise of the basin base of sediment-loading or tectonic origin from the relative sea-level change amplitude.

### 8.1 Sediment-loading subsidence

Some researchers ignored the subsidence caused by sediment-loading; some other researchers calculated sediment-loading subsidence using formula

$$S = H_w \rho_w / \rho_m + T_s \rho_s / \rho_m,$$

where  $S$ ,  $H_w$ ,  $\rho_w$ ,  $\rho_m$ ,  $T_s$  and  $\rho_s$  represent respectively the base subsidence, change in water depth, the density of sea water, the density of the mantle, the thickness of the sediments and the density of the sediments. The assumption behind this formula is that the weight of the deposits makes the mantle under the earth crust move aside and the weight of the mantle moved aside is equal to the weight of the deposits on the basin bottom. The basis of the formula is isostasy, which can be easily understood from Archimedes' formula for calculating buoyancy. According to this formula, 10 m thick deposits will cause 6.7 m deep subsidence of the basin base.

Base subsidence caused by very great thickness of ice sheet is really present. But we have never found that 100 m thick deposits can cause 67 m deep subsidence. So we believe that sediment-loading subsidence is really present and is obvious when the thickness of the sediments is great. But if the thickness of the sediments is not great, say, less than 500 m, the subsidence is not so great as calculated from the above formula and the assumption of isostasy is not true.

Since the base subsidence is caused by the weight of the deposits, the magnitude of the subsidence should be in proportion to the weight of the deposits (which can be represented by the thickness of the deposits): the greater the deposit weight, the greater the magnitude of the subsidence. To several stratigraphic sections under the same tectonic settings (so as to exclude the difference in their vertical tectonic motions), the ratio of the difference in the original thickness of the sediments of any two sections to the difference in their subsidence magnitudes should be a constant, which can be called sediment-loading subsidence coefficient and can be calculated easily. With the sediment-loading subsidence coefficient at hand, we can calculate the basin subsidence for each section via multiplying the original thickness of the section with the sediment-loading subsidence coefficient.

For example, three stratigraphic sections a, b and c under the same tectonic settings have original thicknesses of 150, 100 and 50 m, respectively. The relative sea-level change magnitudes represented by them are  $X_1$ ,  $X_2$  and  $X_3$ , respectively. Then we get

$$(150-100) / (X_1-X_2) = (150-50) / (X_1-X_3) = (100-50) / (X_2-X_3) = f,$$

where  $f$  is the sediment-loading subsidence coefficient. With  $f$  available, we can calculate the sediment-loading subsidence magnitudes of sections a, b and c, being  $150f$ ,  $100f$ , and  $50f$ , respectively. Then we can obtain  $X_1-150f$ ,  $X_2-100f$ , and  $X_3-50f$ , the sum of the eustatic change amplitude and possible vertical tectonic motions of each section, respectively. Since reefal strata and the adjacent inter-reef strata differ greatly in thickness, we can select reefal sections and adjacent (so as to exclude the difference in their tectonic subsidence magnitudes) reefal or non-reefal sections to calculate sediment-loading subsidence.

## 8.2 Tectonic subsidence

If we select the reefal series formed under tectonically stable region, the affection of tectonic motions on sea-level change magnitude may be avoided. If tectonic motions are present, we can calculate and exclude them from the relative sea-level change magnitude through the comparison of the relative sea-level change magnitudes of several distantly located reefal sections.

Cisne and Gildner (1988)<sup>[15]</sup> believed that the accordance between the relative sea-level change magnitudes of several distantly located stratigraphic sections should indicate the eustatic change. Conversely, local tectonically vertical motions of basin base will cause the sea-level change magnitude recorded in the section to be "abnormal". In this way we can recognize and exclude the affection of tectonic motions on eustatic change magnitude.

## 9 Sea-level rise distance during Wordian-Capitanian (*Neoschwagerina* zone or *Polydiexodina*)

Typical Permian reefs of Maokouian Stage (i.e. the *Neoschwagerina* zone, equivalent to the Wordian and Capitanian Stages used in western countries) have been found in the Guangxi Zhuang Autonomous Region, China. According to our studies<sup>[32]</sup>, the reef is 167 m thick, consist-

ing of 101.1 m thick prebaffled facies and 2.3 m thick grained facies as well as 60.6 m thick framed facies. The bottom of the reefal series consists of micritic calcisponge framed facies; the top of it consists of calcisponge prebaffled facies. So this is a deepening series.

The burial depth is about 75 m. According to Goldhammer (1997)<sup>[31]</sup>, when the burial depth is 75 m, the original thickness of 1 m thick of a current stratum is 1.64 m. Then the original thickness of the prebaffled facies is  $101.1 \times 1.64 = 166.3$  m. The burial depth of the grained facies is about 47.8 m. At such a depth, 1 m thick grainstone facies has original thickness of about 1 m. Then the original thickness of the grained facies is 2.3 m. The framestone is resistant to compaction. So the original thickness of the framed facies is 60.6 m. Then the total thickness of the series is 229.2 m.

Since the water depth of the bottom of the series is 15 m and that of the top of the series is 35 m, the sea-level rise represented by this deepening series is

$$R = 229.2 + (35 - 15) = 249.2 \text{ (m)}.$$

So, the relative sea-level change represented by this series is 249.2 m.

According to other researchers<sup>[33]</sup>, the coeval reef of the Guadalupe Mountains of Texas and New Mexico (“Capitan Formation” with *Polydiexodina*) is 200 m thick. Its lower part (about 100 m thick) consists of bafflestone (“Floatstone and bafflestone form 80 to 95 percent of massive”). Its upper part (about 100 m thick) consists of sparry cemented framestone. Using the method of Goldhammer (1997)<sup>[31]</sup>, we calculated the original thickness (264 m). The water depth of the bottom of the series is 25 m, and that of the top is 8 m. So this is a shoaling series formed under the condition of sea-level rising slower than reefal growth. The sea-level change magnitude is

$$R = 264 - (25 - 8) = 247 \text{ m}.$$

So, the relative sea-level rise represented by this series is 247 m.

Because stratigraphic sections for calculating sediment-loading subsidence have not been measured, sediment-loading subsidence coefficient is not available. But since both of the two reefs have small thicknesses, the sediment-loading subsidence may be very small and thus ignorable. Since the two reefs located very distantly have similar sea-level magnitudes, they may be free from tectonic affection and the relative sea-level change magnitudes probably are really the eustatic change amplitude. So we can conclude that the eustatic change amplitude of Maokouian Stage is probably 247—249 m.

## 10 Conclusions

(1) Relative sea-level change magnitudes can be calculated from reef fabric-facies series. For “equal shoaling series”, the relative sea-level change amplitude is 0; for “thick shoaling series”, the relative sea-level change amplitude is  $R = T_s - (D_b - D_t)$ ; for “even series”, the relative sea-level change amplitude is equal to the original thickness of the series; for “deepening series”, the relative sea-level change is  $R = T_s + (D_t - D_b)$ , where  $T_s$  is the original stratum thickness of the series,  $D_b$  the water depth of the fabric-facies of the bottom of the series, and  $D_t$  the water depth of

the top of the series.

If the sediment-loading subsidence and vertical tectonic motions can be calculated and excluded from the relative sea-level change amplitude, the eustatic change amplitude can be obtained.

(2) Some reef rocks are resistant to compaction, which enables the restoration of the original thickness of reefal strata to be more reliable than that of non-reefal strata. Since reefal communities and reef fabrics are more sensitive to sea-level changes than non-reefal communities and fabrics, and because of the use of the method of fabric facies, water depth determinations based on reefs are more accurate than those based on non-reefal deposits. Sediment-loading subsidence coefficient makes the calculation of sediment-loading subsidence more reasonable. Vertical tectonic motions can be calculated and excluded through correlation of several distantly located reefal series. If the sediment-loading subsidence and vertical tectonic motions are calculated and excluded from the relative sea-level change magnitudes, the eustatic change amplitude is obtained.

(3) Reefs are present in most geological periods. So the eustatic change magnitudes of most geological periods can be calculated from reefs. This method, combined with other methods, makes it possible to establish a new, quantitative eustatic curve.

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