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NEW EUSTATIC MODEL FOR THE ORIGIN OF CARBONATE CYCLIC SEDIMENTATION

BY

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ABSTRACT

The two end-member models, eustatic and autocyclic, proposed until now to explain the repetition of carbonate shallowing-upward sequences lead to an apparent dilemma when carbonate cycles which consist of a slow shallowing-upward phase (apparent regression), followed by a rapid deepening phase (apparent transgression), are compared with Vail's worldwide eustatic cycles which display a pattern of slow rising sea level (transgression), followed by a rapid fall (regression).

The pattern of carbonate cycles has to conform to Vail's curve based mainly on siliciclastic sedimentation because carbonates not only share many basins with the former, but they belong also to the same oceanic realm.

A new eustatic model is proposed which eliminates the above dilemma. It is based on the fact that the rate of carbonate productivity on ramps and platforms can be shown to have the capacity to exceed easily the rate of any eustatic rise of sea level due to long-term geologic processes. Hence, the carbonate shallowing-upward sequence is an illusion of interpretation. In reality, it takes place during the slow rise of sea level, that is during a transgression, as a reaction of carbonate productivity versus eustatism. The existence in all carbonate series, regardless of geologic age and geotectonic location, of a hierarchy of three types of asymmetric cycles: microcycles, cycles, and megacycles, similar to the paracycles, cycles, and supercycles of eustatic sea level changes, contributes to set carbonate sedimentation in agreement with global processes.

Integration with biostratigraphic data shows that for the lower Carboniferous, for instance, typical examples of large-scale shallowing-upward sequences correspond indeed to major rises of sea level or transgressions.

RÉSUMÉ

Les deux modèles opposés, eustatique et autocyclique, proposés jusqu'à présent pour expliquer la répétition des séquences carbonatées à profondeur décroissante vers le haut conduisent à un dilemme apparent quand les cycles carbonatés qui sont formés par une phase lente de profondeur décroissante vers le haut (régression apparente), suivie par une phase rapide de profondeur croissante (transgression apparente), sont comparés aux cycles eustatiques globaux de Vail qui sont formés de phases de montée lente du niveau de la mer (transgression) suivies par des phases de chute rapide (régression).

L'organisation des cycles carbonatés doit suivre la courbe de Vail, basée surtout sur les sédiments siliciclastiques, car les carbonates non seulement partagent avec ceux-ci de nombreux bassins, mais appartiennent aussi au même domaine océanique.

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Un nouveau modèle eustatique est présenté qui élimine le dilemme présent. Il est basé sur le fait que l'on peut démontrer que la vitesse de productivité carbonatée sur les rampes et plateformes est capable de dépasser la vitesse de n'importe quel type de montée eustatique du niveau de la mer provoqué par des phénomènes géologiques de longue durée. Par conséquent, la séquence carbonatée à profondeur décroissante vers le haut est une illusion d'interprétation. En réalité elle s'effectue pendant la montée lente du niveau de la mer, c'est-à-dire pendant une transgression, par l'effet d'une réaction de la productivité carbonatée vis-à-vis de l'eustatisme. La présence dans toutes les séries carbonatées, indépendamment de leur âge géologique et de leur contexte géotectonique, d'une hiérarchie de trois types de cycles assymétriques: microcycles, cycles et mégacycles, semblables aux paracycles, cycles et supercycles des changements eustatiques du niveau de la mer, contribue à placer la sédimentation carbonatée en accord avec les phénomènes globaux.

L'intégration avec les données biostratigraphiques montre que pour le Carbonifère inférieur, par exemple, les cas typiques de grandes séquences carbonatées à profondeur décroissante vers le haut correspondent en effet aux phases principales de montée du niveau de la mer ou transgressions.

INTRODUCTION

Thirty years of microfacies studies of shallow-water carbonate successions of Phanerozoic age and worldwide distributed, and based on the analysis of more than 50,000 thin sections, confirm the fact that they all consist of superposed shallowing-upward sequences. Regardless of geologic age and geotectonic setting, these sequences belong to a hierarchy of asymmetric microcycles, cycles, and megacycles (Figure 1). They can be theoretically described as follows (Figure 2). An *asymmetric cycle* consists of a relatively slow shallowing-upward sequence of microfacies (with or without subaerial exposure), followed by a relatively rapid deepening represented by a hiatus or a very thin sequence of microfacies with no well-defined sequential order. In many instances, the shallowing-upward sequence of such a cycle displays a number of *asymmetric microcycles* which consist of short shallowing-upward episodes followed by equally short deepening episodes or by a minor hiatus.

Asymmetric cycles are generally associated in *asymmetric megacycles* consisting of a variable number of superposed asymmetric cycles which begin and terminate in gradually shallowing conditions. Asymmetric megacycles may or may not terminate with subaerial exposure.

The three types of asymmetric cycles appear to have, in order of higher hierarchy, thicknesses ranging from less than a meter to hundreds of meters. Their horizontal extension shows a similar trend and ranges from less than one kilometer to tens and hundreds of kilometers across entire ramps and platforms.

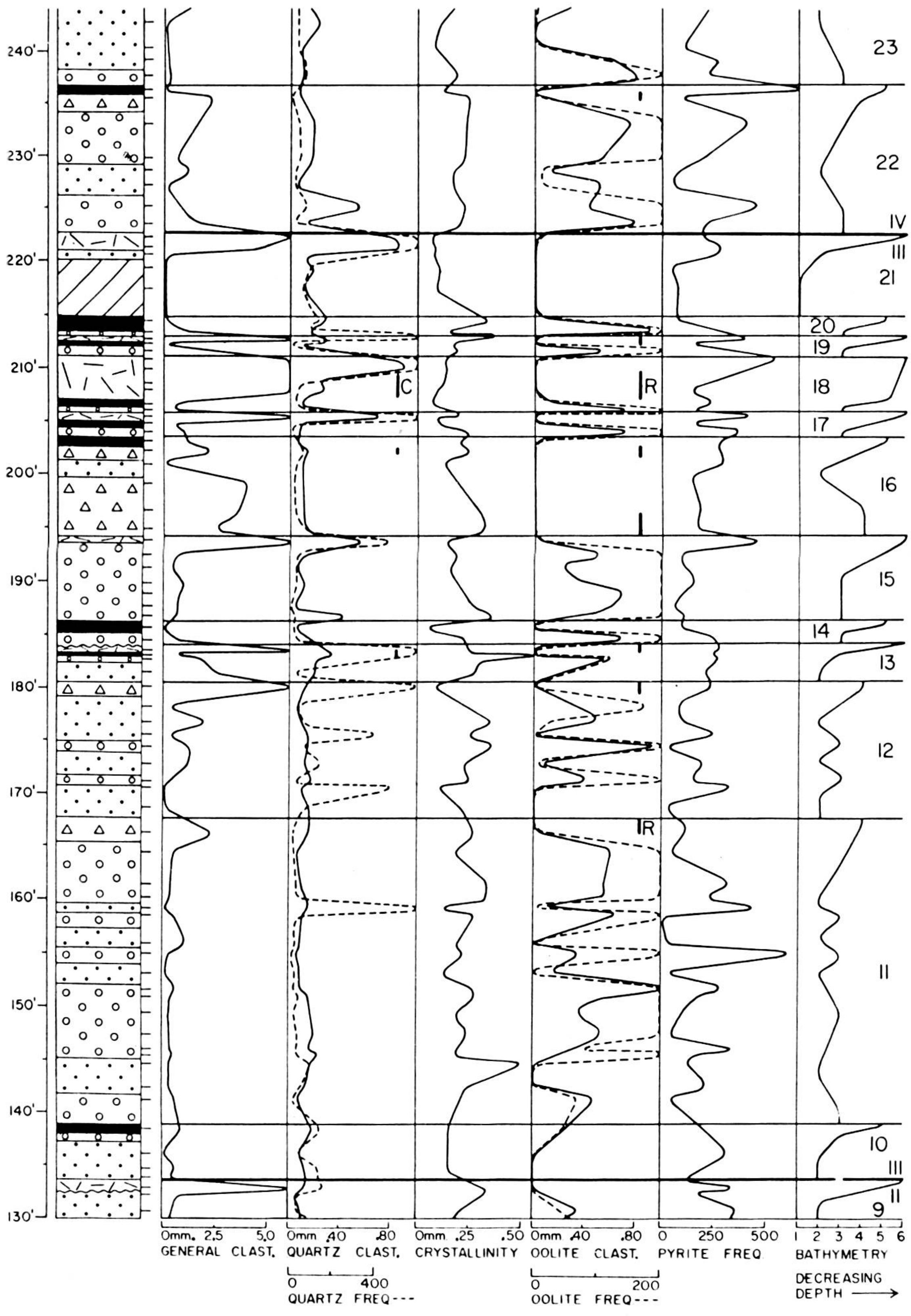

FIG. 1.

Allentown Dolomite, Upper Cambrian of New Jersey, USA.
Typical example of microfacies succession and microscopic parameter variations showing asymmetric cycles (10 through 21) with several displaying microcycles (11, 12, and 16), and associated in an asymmetric megacycle (III). From Zadnik and Carozzi (1963).

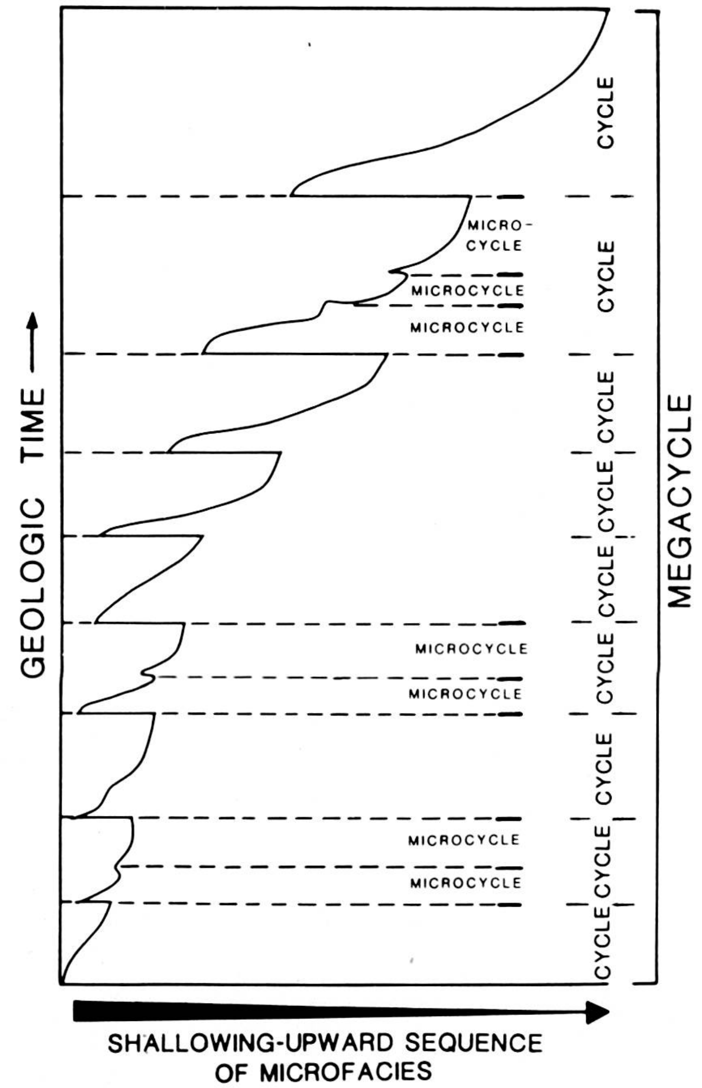

FIG. 2.

Theoretical relationship between asymmetric microcycles, cycles, and megacycle.

EUSTATIC AND AUTOCYCLIC MODELS

Two end-member models have been proposed to explain the repetition of shallowing-upward sequences (Wilkinson, 1982; James, 1984). According to these authors, the rate of carbonate sedimentation in the *eustatic model* is considered constant while the rate of subsidence or the absolute position of sea level change periodically. During periods of stability or slowly rising sea level, the carbonate sedimentation accretes or progrades generating a typical shallowing-upward sequence. This pattern is interrupted by a sudden and rapid period of deeper water with reduced deposition or interruption of sedimentation. Sea level remains relatively stationary in this new position and progradation of the carbonates begins again depositing a new shallowing-

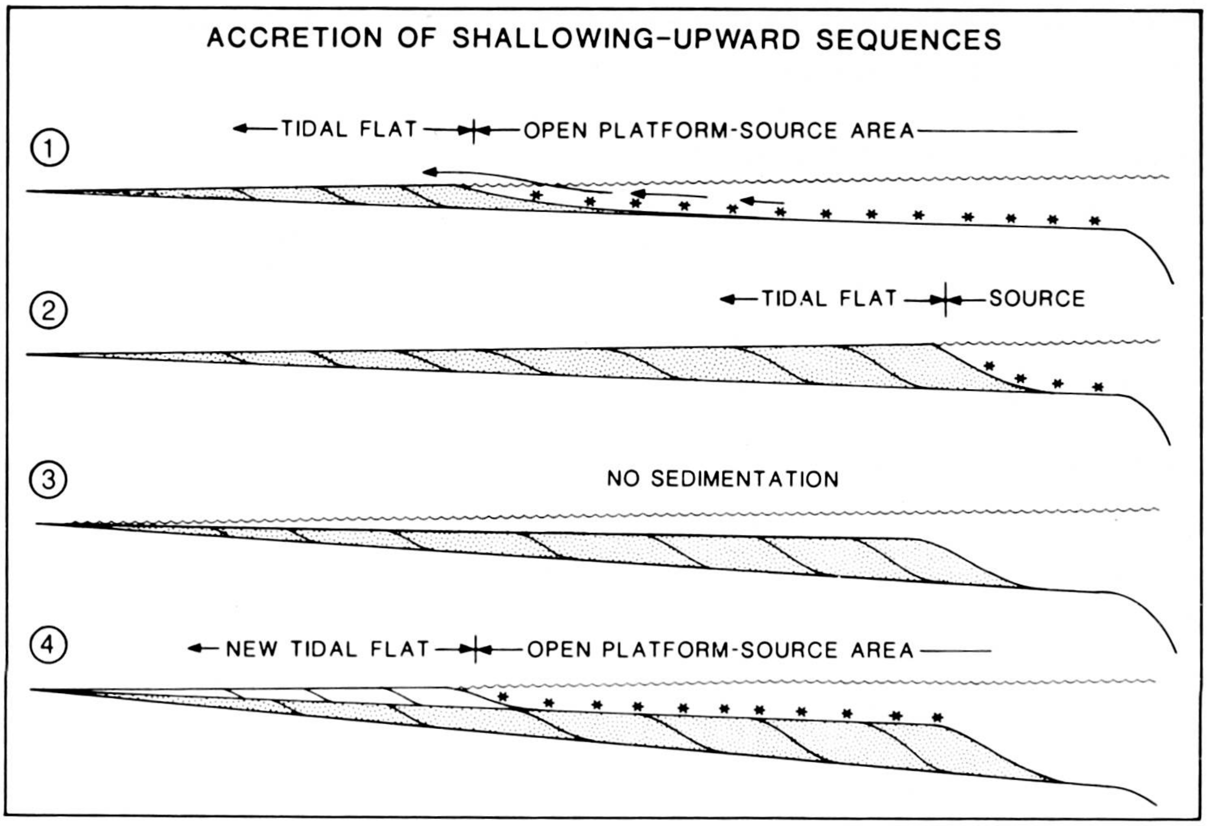

FIG. 3.

Diagram illustrating how two shallowing-upward sequences can be produced by progradation of a tidal flat wedge. These general conditions apply to both eustatic and autocyclic models. From James (1984).

upward sequence on top of the preceding one. In the *autocyclic model* (Ginsburg, 1971) as in the eustatic one, carbonate deposition is assumed to take place on a gently inclined ramp or on a platform under conditions of gradual subsidence or slowly rising sea level, or some combination of both. The control is within the model and consists of a variable rate of carbonate sedimentation controlled by the extent of the subtidal source area. The latter produces carbonate sediments which move shoreward by wind-driven, tidal, or estuarine-like circulation and a seaward progradation of the carbonate wedge takes place. This progradation gradually reduces the surface of the sediment-producing subtidal area until carbonate production no longer exceeds subsidence. Since relative rise of sea level continues, the entire platform becomes again subtidal and deep enough to resume sediment production and a new progradation phase begins.

However, both the eustatic model which implies a constant rate of carbonate production and the autocyclic model which assumes a variable rate of carbonate production take into account only either *a stable sea level or repeated episodes of slow or rapid rate of sea level rise* (Figure 3). Furthermore, the autocyclic model based on the Florida Bay lagoon and the tidal flats of the Bahamas and the Persian Gulf suffers from its uniformitarian character, restricted depositional environment, and from the fact that the landward movement of carbonate sediments is not a common mechanism of deposition in ancient carbonate models. In fact, ancient carbonate sediments are either formed and deposited almost *in situ* or transported in a seaward direction except when storm-influenced. In addition, the eustatic and autocyclic models do not account for the observed hierarchy of microcycles, cycles, and megacycles.

WORLDWIDE EUSTATIC CHANGES OF SEA LEVEL

At present, eustatic changes of sea level are known to have taken place during at least the Phanerozoic on a worldwide basis. The eustatic oscillations of sea level follow a well-established pattern of repeated episodes of slow rises or transgressions, stillstands, and rapid falls or regressions (Vail *et al.,* 1977). This pattern displayed by the siliciclastic sedimentation has to be recorded in some manner by the carbonate sediments which not only share many basins but which also belong to the same oceanic realm and display a hierarchy of microcycles, cycles, and megacycles comparable to Vail's paracycles, cycles, and supercycles of eustatic changes of sea level (Figure 4).

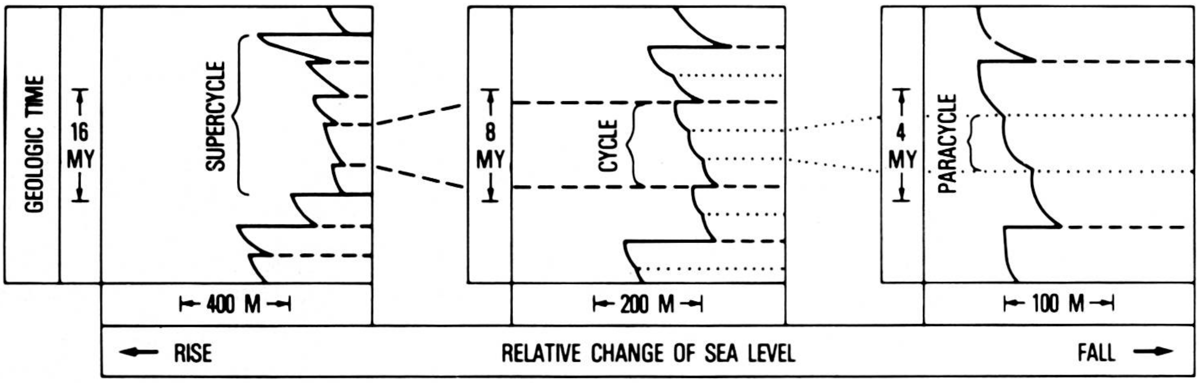

FIG. 4.

Chart of relative changes of sea level. Cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller pulses of relative rises to stillstands. Several cycles usually form a higher order cycle (supercycle) with pattern of successive rises between major falls. Note asymmetry of gradual rises and abrupt falls at each scale. From Vail *et al.* (1977).

APPARENT DILEMMA OF CARBONATE CYCLES

There is an *apparent dilemma* (Figure 5) when carbonate cycles which consist of a slow shallowing-upward phase (apparent regression), followed by a rapid deepening phase (apparent transgression), are compared with worldwide eustatic cycles which

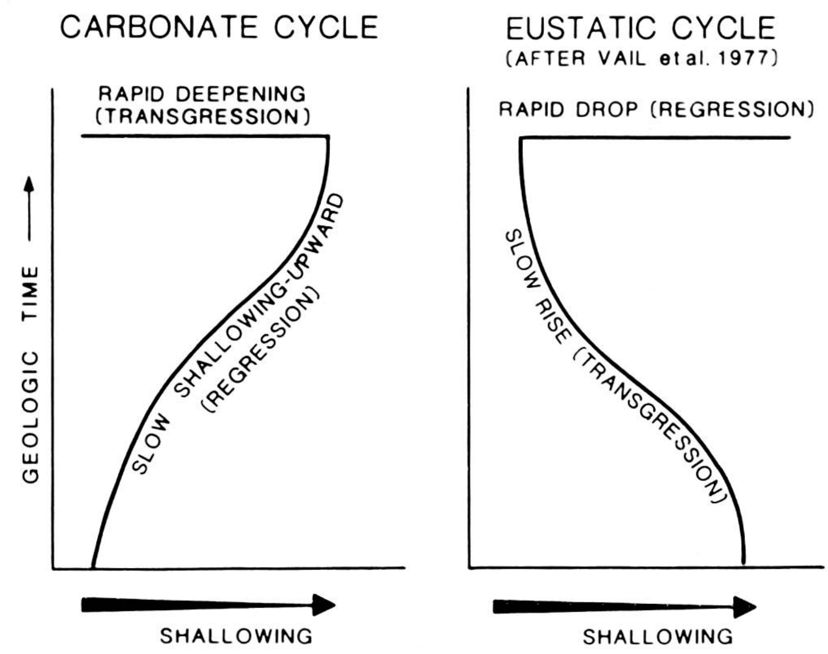

FIG. 5.

Theoretical illustration of the apparent dilemma between carbonate cycle and Vail's eustatic cycle.

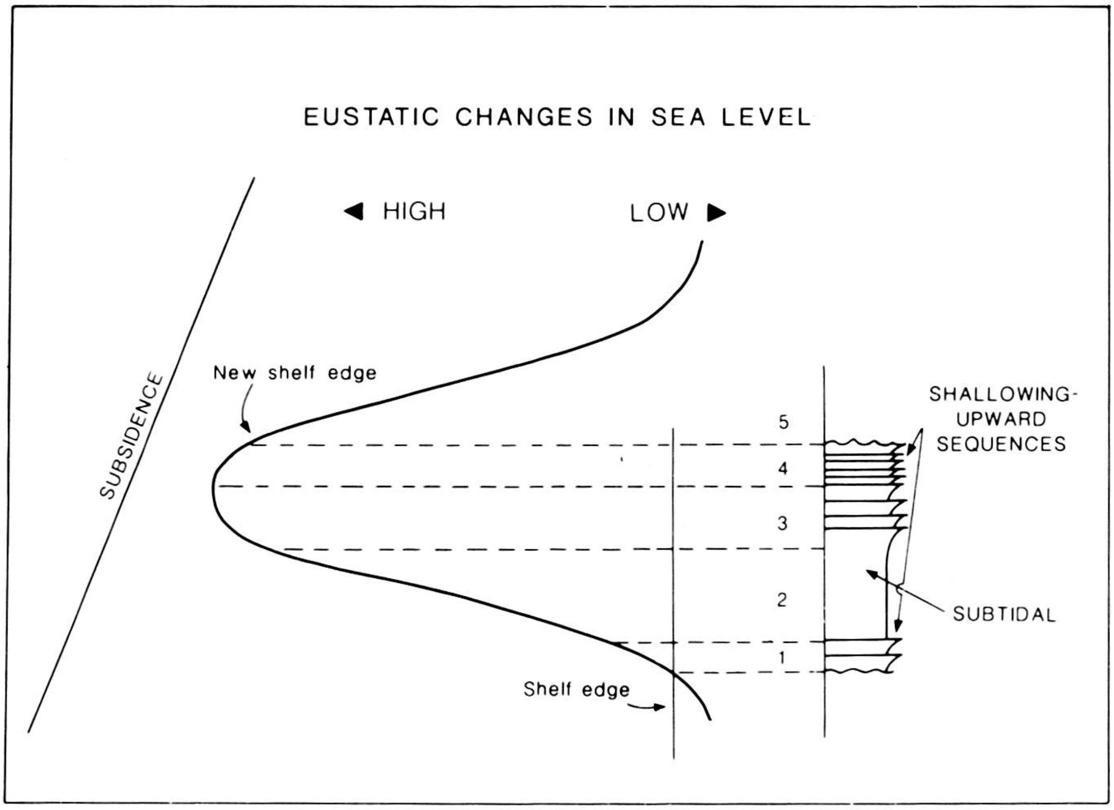

FIG. 6.

Diagram illustrating how a large-scale shallowing-upward sequence is produced under conditions of slow platform subsidence and a uniform rise and fall in eustatic sea level. From James (1984).

display a pattern of slow sea level rising (transgression), followed by a rapid fall (regression). Wilkinson (1982) took the unrealistic position of considering that the shapes of worldwide eustatic cycles are simply wrong and that carbonate cyclicity can only be explained by the eustatic model based on sudden and repeated sea level rises. James (1984) tried to solve the apparent dilemma of large-scale carbonate cycles by assuming a constant rate of subsidence and by combining it with a slightly modified Vail curve which consists of a *more or less symmetric worldwide rise and fall of sea level* (Figure 6). According to this hypothesis, the rising sea level initially floods the platform and carbonate accretion can outpace sea level rise so that shallowing-upward sequences develop. During the long period of relatively rapid sea level rise, and depending upon the rate between this process and subsidence, either subtidal conditions are maintained or a few thick shallowing-upward sequences occur. When the rate of sea level rise decreases, several shallowing-upward sequences are formed. When sea level begins to fall and subsidence continues, the net result is a stillstand generating numerous thin shallowing-upward sequences separated by long episodes of subaerial exposure. The final rapid fall of sea level outpaces subsidence and the carbonate platform is entirely exposed. The main point in James' hypothesis is to show that a large-scale asymmetric carbonate cycle may be produced by a uniform eustatic rise and fall of sea level. It is certainly a bold idea although not in agreement with the asymmetric pattern of eustatic oscillations of sea level.

CARBONATE PRODUCTIVITY AS KEY FACTOR

Unquestionably, the origin of carbonate cycles is a complex interplay of eustatic sea level oscillations, subsidence (tectonism), and the fundamental property of carbonate ramps and platforms which consists mainly of *in situ* carbonate sediment production by benthic and planktic organisms. It is possible that the rate of carbonate productivity has been underestimated.

According to Schlager (1981, p. 204), "A platform with a sediment-covered flat top that simultaneously builds upward and progrades basinward must produce more sediments than it needs to match the relative rise of sea level. Consequently, its growth potential must be greater than its vertical growth rate". The latter can be estimated by the study of pre-Holocene prograding platforms which reveals accumulation rates (not corrected for compaction) ranging from 30 to 500 μm/y. and average growth potential probably on the order of a thousand microns per year (Schlager, 1981). Taking into account figures provided by Schlager (1981) such as a maximum accumulation rate of 500 μm/y. and a basin subsidence averaging 10 to 100 μm/y., it is safe to say that a carbonate platform has the capacity to build upward at a rate exceeding any eustatic rise of sea level. Such a rise caused by increases in the rate of sea-floor spreading, changes in subduction and spreading pattern, or other long-term geologic processes is estimated to range between 10 and 90 μm/y.

NEW EUSTATIC MODEL

In the light of the data presented above, and under the most conservative conditions, the origin of carbonate cycles can be approached as an interplay between global

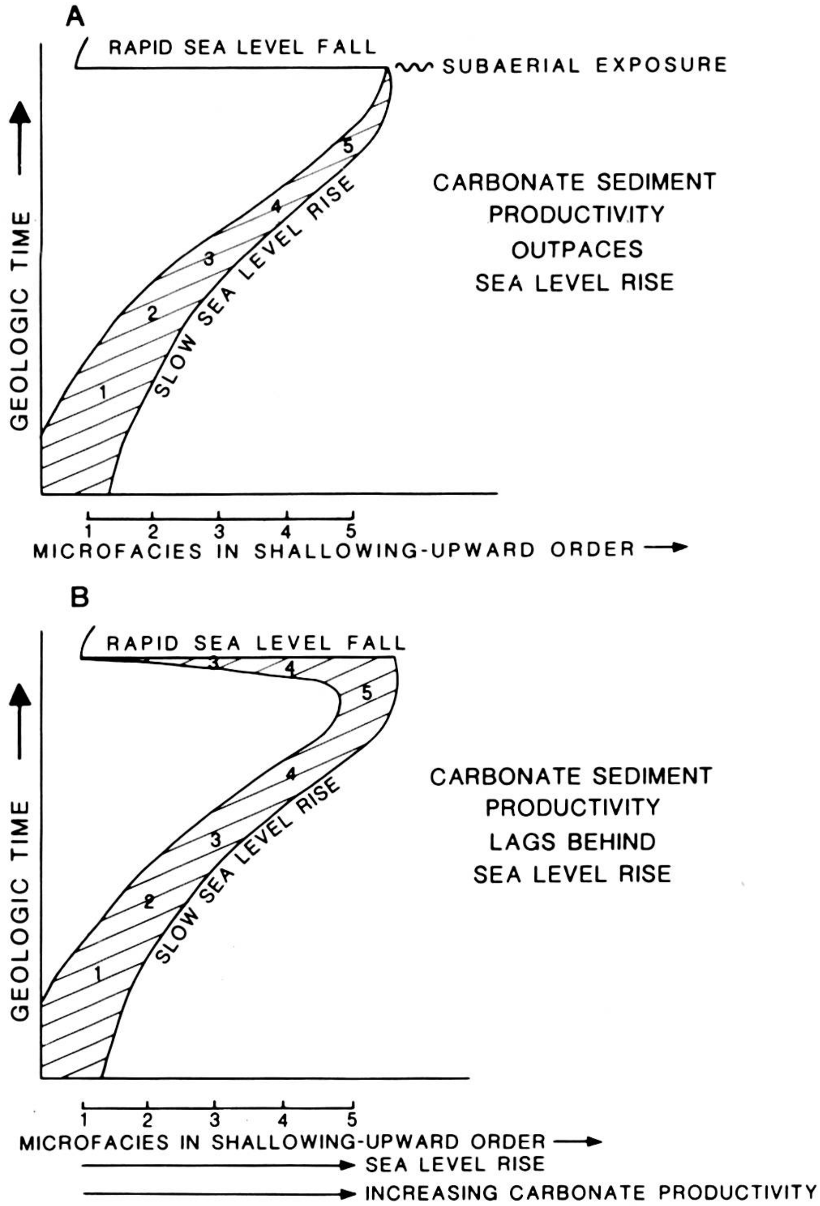

FIG. 7.

Theoretical illustration of how the two major types of asymmetric carbonate cycles are generated during a eustatic slow sea level rise followed by a rapid sea level fall.

slow rises and rapid falls of sea level and a rate of carbonate productivity resulting in vertical accretion and horizontal progradation which can easily be greater than sea level rise. Assuming a constant rate of subsidence, two possibilities can be considered. First (Figure 7A), a rate of carbonate productivity which increases with the slow rise of sea level and eventually outpaces it. A shallowing-upward sequence is generated which terminates with subaerial exposure followed by a hiatus during sea level fall. Second (Figure 7B), a rate of carbonate productivity which increases with the slow rise of sea level but which at all times lags behind. A shallowing-upward sequence is generated which does not reach subaerial exposure but is overlain during the phase of rapid sea level fall by a thin sequence of non-sequential carbonate sediments or a complex lag deposit.

This hypothesis, certainly not the final word in this complex problem, nevertheless has the advantage of resolving the above-mentioned dilemma. It shows that the shallowing-upward sequence is an illusion of interpretation. In reality, the *shallowing-upward sequence takes place during the slow rise of sea level, that is during a transgression, as a reaction of carbonate productivity versus eustatism.* Furthermore, the existence of a hierarchy of three types of carbonate cycles similar to those of eustatic sea level changes contributes to set carbonate sedimentation in agreement with global processes.

INTEGRATION WITH BIOSTRATIGRAPHY

Comparison of the hypothesis presented above with the results of Ross and Ross (1985) shows, for instance, that all the lower Carboniferous examples of large-scale shallowing-upward sequences of the Mississippi Valley investigated by microfacies techniques, such as the Burlington Limestone (Carozzi and Gerber, 1979); the Salem Limestone (Carozzi and Diaby, 1981); the St. Louis Limestone (Diaby and Carozzi, 1984); the Ste. Genevieve Limestone (Rao and Carozzi, 1971); the Glen Dean Formation (Feiznia and Carozzi, 1981, Feiznia, 1983); and the Kinkaid (Grove Church) Formation (Lasemi and Carozzi, 1981) correspond indeed to major rises of sea level or transgressions (Figure 8). Ross and Ross (1985) described more than fifty transgressive-regressive depositional sequences in Carboniferous and Permian shallow marine successions over stable cratonic shelves all over the world. Stratigraphic evidence shows the large extent of these shoreline displacements and suggests slow rises of sea level followed by rapid falls. Faunal correlations indicate that each transgressive-regressive sequence is synchronous worldwide and hence represents eustatic changes in sea level of 100 to 200 m, lasting from 1.2 to 4 m.y. with an average of 2 m.y.

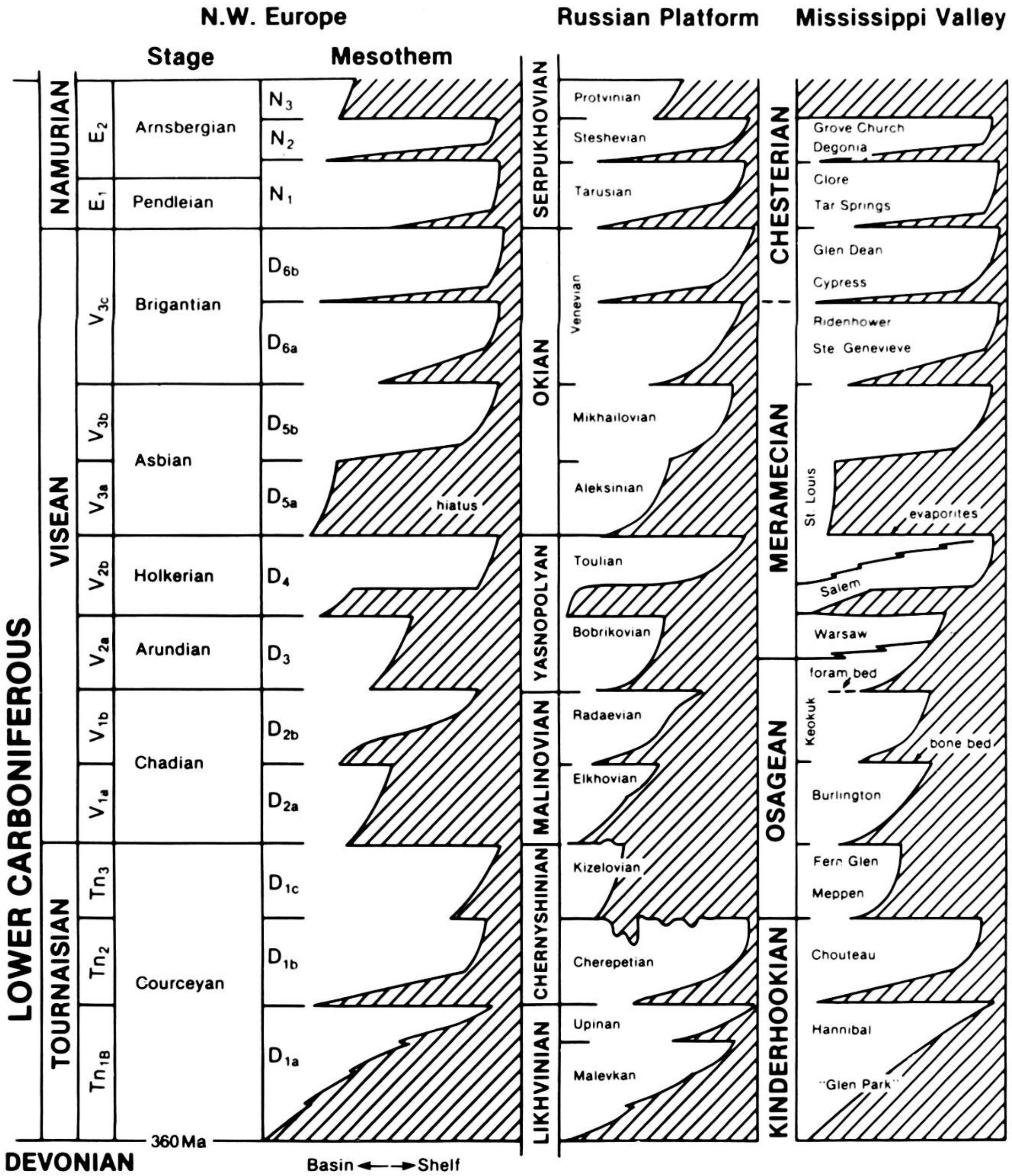

FIG. 8.

Correlation of lower Carboniferous transgressive-regressive sequences based on fossil zonations. From Ross and Ross (1985).

CONCLUSION

What lies ahead is, in essence, the testing of Vail's curve by means of a combination of detailed microfacies analysis and biostratigraphic studies of the well-exposed sedimentary record of cratons around the world. Such a combined approach can unravel the local patterns of sea level fluctuations expressed by the various types of carbonate cycles, and by comparing such patterns on a worldwide basis, establish those which are of global character.

Urbana, July 13, 1985.

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