Continental Drift and Phanerozoic Carbonate Accumulation in Shallow-Shelf and Deep-Marine Settings

Luke J. Walker, Bruce H. Wilkinson, and Linda C. Ivany[1]

Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063, U.S.A.
(*e-mail: eustasy@umich.edu*)

ABSTRACT

Knowledge of past rates of transfer of rock-forming materials among the principal geologic reservoirs is central to understanding causes and magnitudes of change in earth surface processes over Phanerozoic time. To determine typical rates of global sediment cycling, we compiled information on area, volume, and lithology of shallow-water sediments by epoch for both terrigenous clastics and marine carbonates. Data on amounts of surviving continental terrigenous rock (as opposed to deep oceanic, and including "terrestrial," "marginal marine," and "marine" deposits) exhibit positive age/area trends wherein greatest areas and volumes of conglomerate, sandstone, and shale are represented by younger sequences. Global volumes of terrigenous-clastic sediment yield a mean cycling rate of 0.00124/m.yr., similar to that determined for Eurasian (0.00127), North American (0.00058 [A. B. Ronov], 0.00352 [T. D. Cook and A. W. Bally]), African (0.0017), and South American (0.0021) clastic sequences. Surficial erosion results in the mean destruction of ~0.124% of terrigenous rock volume per million years of reservoir age. In contrast, surviving epicratonic and shelf-margin carbonate sequences yield negative cycling rates of about −0.164%/m.yr. Surviving areas and volumes increase with sequence age; that is, the amount of limestone and dolostone preserved in shallow-water settings increases back in time to maximal areal extents in the Middle and Upper Cambrian. Mass/age data on terrigenous-clastic successions indicate generally constant rates of crustal erosion over Phanerozoic time. Decrease in size of the shallow-marine carbonate reservoir forward in time therefore suggests generally invariant rates of global limestone accumulation and a shift in sites of accumulation from shallow-cratonic to deep-oceanic settings over much of the past 540 m.yr. Causes of this eon-scale depositional translocation of carbonate sediment from shallow- to deep-marine settings cannot be satisfactorily linked to either changes in global sea level or the evolution of carbonate-producing plankton because neither exhibits a pattern of unidirectional change in position or abundance since the Early Phanerozoic. However, tabulation of long-term variation in areas of continental shelves from paleogeographic maps reveals a generally uniform decrease in low-latitude (<30°) platform area with decreasing age over most of the Phanerozoic. Moreover, rate of change of low-latitude shelf area (~52.6 × 10^3 km^2/m.yr.) is almost exactly the rate of change in the area of shallow-water carbonate sequences (~63.0 × 10^3 km^2/m.yr.) over the same interval. This agreement suggests that poleward movement of the major continents over the past 540 m.yr. has had a substantial impact on patterns of global carbonate accumulation. The long-term effect of decreasing low-latitude shelf area has been augmented, particularly over the last 100 m.yr., by eustatic sea level fall and the diversification of open-ocean calcifiers. The evolution of calcareous plankton in the Late Paleozoic or Early Mesozoic may have been facilitated, or at least permitted, by increasing saturation state of the oceans associated with progressive decline in shallow-water carbonates.

Introduction

The cycling of sedimentary components via erosional and depositional processes represents the largest and geologically most important flux of materials through earth surface exogenic systems. Many individuals have attempted to quantify rates of mass transfer through the various sedimentary reservoirs (e.g., Gilluly 1969; Veizer and Jansen 1979; Gregor 1985; Berner 1991, 1994; Bleuth and Kump 1991). Moreover, knowledge of relations between the surviving volume and/or area of various sedimentary bodies and their age of accumulation provides important constraints for inferences con-

Manuscript received August 8, 2000; accepted June 7, 2001.

[1] Department of Earth Sciences, Syracuse University, Syracuse, New York 13244.

[The Journal of Geology, 2002, volume 110, p. 75–87] 0022-1376/2002/11001-0004$01.00

cerning present and past magnitudes of different cycling processes. The utilization of such data to better understand the evolution of the major sedimentary rock reservoirs has an equally interesting history (e.g., Garrels and Mackenzie 1969; Blatt and Jones 1975; Hay 1985; Wilkinson and Walker 1989; Wold and Hay 1990; Veizer and Ernst 1996). These and other studies have demonstrated that data on variation in sizes of extant sedimentary systems as a function of their age allow for estimation of first-order rates of transfer into and out of each sedimentary reservoir.

Distribution of reservoir amount versus age can be conceptualized through constant-mass models (e.g., Garrels and Mackenzie 1971; Veizer and Jansen 1985) that generally presume that (1) secular variation in total reservoir size (total amount of a sedimentary rock type at a given time, independent of age) is insignificant and that (2) rates of destructional cycling via erosion, metamorphism, and melting are directly proportional to reservoir size. These rates are therefore taken to be relatively constant. Such models presuppose that the various masses of sedimentary rock formed relatively early in earth history and that this material has been cycled through the major reservoirs at a generally constant rate. In other words, rate of cycling, manifest as the probability of any part of a reservoir being destroyed by any one of several crustal processes, is generally independent of geologic age and is only a function of (proportional to) the size of the reservoir in question.

In detail, constant-mass models of sediment cycling are probably overly simplistic, in part because of short- and long-term variations in flux and in part because the sedimentary reservoir has probably grown somewhat over geologic time. In the latter case, however, the residence time for sedimentary rocks is on the order of only several hundred million years. As a result, sediment cycling is something like at least 90% cannibalistic, and recycling easily overwhelms any net addition to the sedimentary reservoir from the weathering of other rock types.

Numerically, the remaining amount (A_r) of some portion of the total sedimentary rock reservoir that was originally deposited at some time (t) can be expressed as

$$A_r = A_o e^{-kt},$$

where A_o is equal to the amount present (either area or volume) at the beginning ($t = 0$) and k is the proportional amount of the total reservoir destroyed per unit time. Because A_o is also the system flux (net mass added to and removed from per unit time), total reservoir amount at any time is equivalent to A_o/k, and the amount of time needed to cycle one total reservoir volume (the residence time) is equal to $1/-k$. In such systems, regression of age versus the natural log of surviving amount yields a line with slope equal to $-k$ and an intercept equal to the flux of material through the reservoir in question.

The validity of such assumptions can be readily challenged at shorter durations of observation and with respect to different portions of the global rock reservoir, where secular variation in rates of sediment deposition or subsequent destruction impart noise on surviving amount-age relations. However, over longer durations, many studies have now concluded that eon-scale estimates of reservoir size versus age yield trends in reasonably good agreement with those from such simple, first-order cycling models (e.g., Veizer and Jansen 1985; Veizer et al. 1992; Berry and Wilkinson 1994).

To further evaluate the validity of constant-mass cycling models and to investigate differences in cycling rates between different rock types, we examine available data on surviving areas and volumes of Phanerozoic epicontinental (as opposed to deep-marine) terrigenous-clastic and shallow-marine carbonate successions. We show, as have others before (e.g., Hay and Southam 1976; Ronov 1980; Veizer and Jansen 1985), that clastic sediments decrease backward through geologic time, while carbonates show the opposite pattern. Continuous erosion of older rock and deposition of younger sediment should result in ever-increasing amounts of younger material. It appears that amounts of terrigenous-clastic rocks through time may well reflect this expected first-order influence of the geologic cycle.

In contrast, the greater amount of shallow-marine carbonate in older successions poses a more interesting interpretational problem. We propose that movement of the continents away from the equator has significantly decreased the low-latitude shelf area available for accumulation of shallow-water carbonates. Decrease in low-latitude shelf area through the Phanerozoic could have resulted in the deepening of the carbonate compensation depth (CCD) and a concomitant increase in the net accumulation of deeper oceanic carbonate oozes. This would have shifted carbonate sedimentation from shallow- to deep-ocean settings and may have facilitated (or at least allowed for) the evolutionary radiation of open-ocean planktonic calcifiers.

Cycling Rates and Phanerozoic Rock Reservoirs

Sources of Data. Estimates of surviving amounts of Phanerozoic sediment were derived from two sources. The first comprised a tabulation of data from Ronov and coworkers (Ronov and Khain 1954, 1955, 1956, 1961, 1962; Ronov et al. 1974*a*, 1974*b*, 1976; Khain et al. 1975; Khain and Seslavinskiy 1977; Khain and Balukhovskiy 1979 [hereafter referred to collectively as the Ronov data]). These sources include surviving sediment areas, thicknesses, and volumes for shallow-marine settings from all continents exclusive of Antarctica, partitioned by epoch. Based on lithology and depositional setting, these are further divided into as many as 20 different facies associations. Ronov (1980) published a synopsis of these tabulations and then a later summary of the maps (Ronov et al. 1989). For comparison with other sources of data, we combined volumes of different facies associations into terrigenous-clastic, marine-carbonate, and other (phosphate, chert, evaporites) lithofacies reservoirs.

The other source of information on surviving sediment amount and composition was derived from isopach and lithofacies maps in Cook and Bally (1975). The paired thickness and lithofacies maps for 39 epoch-scale time intervals allow for determination of the volumes of a variety of rock types. The volume of each rock type was determined by planimetering both isopach and lithofacies maps and assuming that the fraction of total sequence volume represented by each rock type is proportional to the areal extent of that rock type on lithofacies maps. More detailed descriptions of methodologies used is given in Berry and Wilkinson (1994).

Comparison of data on amounts of surviving sediment in North America from Ronov (1980) and from Cook and Bally (1975) suggests that the global estimates from Ronov (1980) are fairly precise. Volumes of clastic, carbonate, and other sediment types from Ronov (1980) and Cook and Bally (1975) are 52.1, 26.2, and 2.9 versus 50.5, 20.4, and 1.5×10^6 km^3, respectively. Hence, the Ronov (1980) estimates are ~10% larger than those from Cook and Bally (1975), an excellent agreement considering the fact that they are independent geological estimates of continental sediment volumes. However, this good precision alone is no guarantee that these data also enjoy a similar degree of accuracy. Sediment areas and volumes determined from both studies suffer from a variety of uncertainties such as those associated with postdepositional basin deformation, present continental margin submergence, and differences in quality of regional coverage. Nonetheless, these are the best data sets presently available on surviving amounts of sedimentary rock at continental scales of consideration and serve as a starting point for the evaluation of eon-scale change in patterns of sediment accumulation.

Terrigenous Clastics versus Marine Carbonates. Based on data in these sources, epoch-interval sizes of terrigenous-clastic and marine-carbonate Phanerozoic sedimentary reservoirs can be compared with amounts anticipated from constant-mass/age cycling models (fig. 1). The most obvious characteristic of these comparisons is that amounts of surviving sediment exhibit considerable scatter about long-term trends, regardless of rock composition. Not surprisingly, regressions of age versus surviving amount of terrigenous-clastic and carbonate rock yield low R^2 values (table 1). Conversely, most P values indicate significance of these trends at >90% confidence levels (table 1). In short, correlation of ages versus the natural logs of both areas and volumes of surviving terrigenous and carbonate sediment yields low but generally significant slopes. Differences between estimates of actual surviving amount of sediment and those anticipated from longer-term first-order trends undoubtedly reflect some combination of epoch-scale secular variation in sediment flux to various depositional settings, in differential amounts of postdepositional sediment destruction, and in imprecision in estimates of reservoir sizes.

Despite scatter in the data, it is striking to note that terrigenous-clastic (gravel- to clay-sized siliceous material) and shallow-marine carbonate (limestone and dolostone) reservoirs exhibit distinctly different size/age trends. Sequences of terrigenous-clastic sediment exhibit negative age versus amount slopes that reflect exponentially decreasing survival with linearly increasing age. This trend is equally apparent in estimates of reservoir volumes (fig. 1*A*) and areas (fig. 1*C*) at a global scale, from different continents (fig. 1*E*, 1*G*), and from different data sources (fig. 1*G*, 1*I*). As might be expected from a qualitative appreciation of the geologic cycle, both areas and volumes show an exponential decrease with linear increase in sequence age, reflecting the gradual destruction of terrigenous-clastic sequences over geologic time. On the basis of these data, it is a relatively straightforward exercise to determine that residence times ($1/-k$) for the cycling of continent-scale masses of terrigenous-clastic sediment typically span several hundred million years.

In contrast to the amount/age relations exhibited

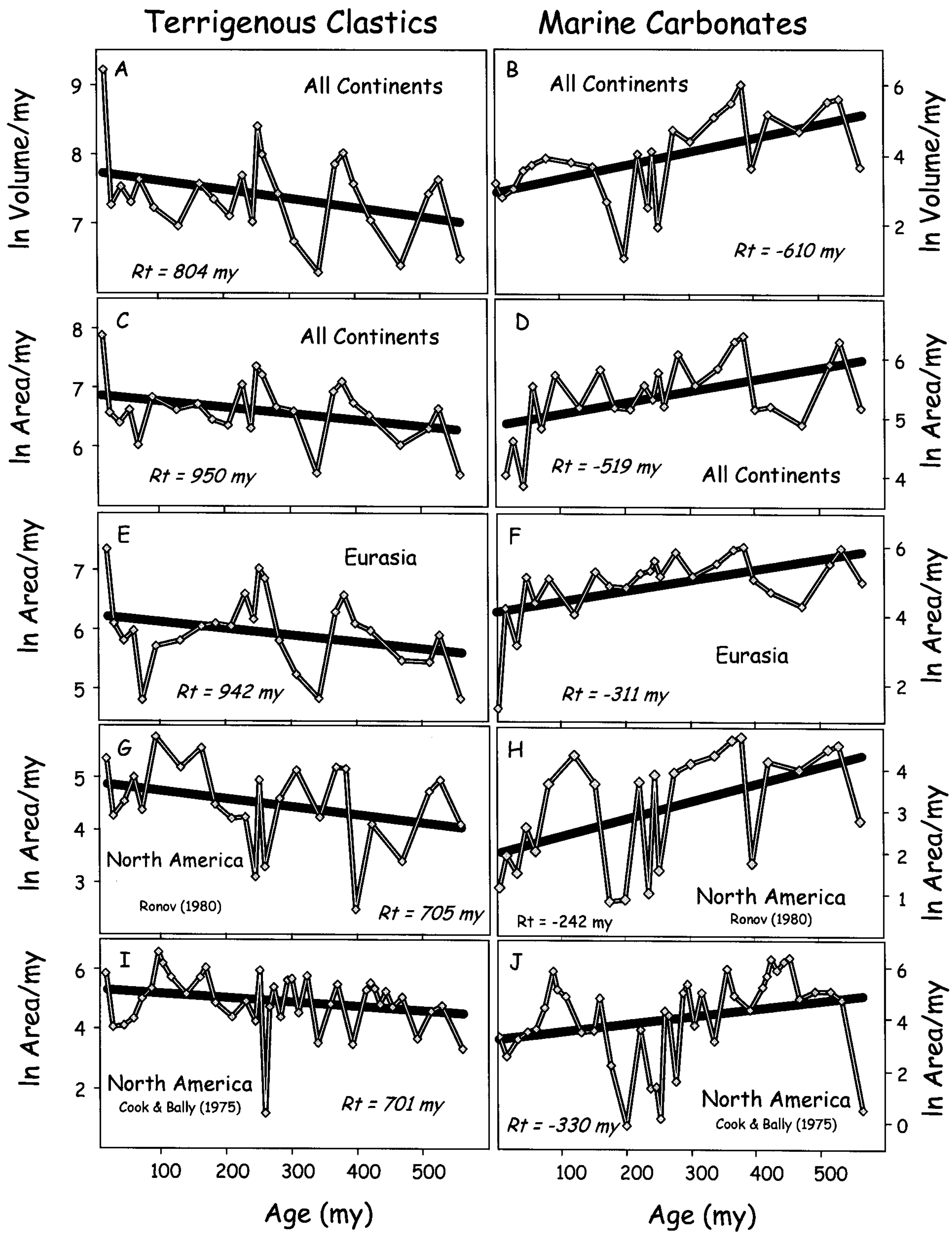

Figure 1. Surviving amount (*vertical*) versus age (*horizontal*) distributions for Phanerozoic epicontinental terrigenous-clastic (*left*) and marine-carbonate (*right*) sedimentary reservoirs. All data are expressed as the natural log of surviving amount of sediment deposited over some (generally epoch-duration) time interval, normalized by the du-

by terrigenous-clastic successions, sequences of shallow-marine carbonates exhibit exponentially increasing amounts of surviving material with linearly increasing age. This trend is apparent in data on global reservoir volumes (fig. 1*B*) and areas (fig. 1*D*), from different continental masses (fig. 1*F*, 1*H*), and on the same continental mass but from different sources (fig. 1*H*, 1*J*). As a result, volume and area for most shallow-water carbonate reservoirs exhibit negative residence times. On the basis of these data, it seems clear that traditional assumptions about invariance of total reservoir mass with time are inadequate when applied to shallow-marine carbonate successions. Moreover, unless we are willing to accept the nonsensical presumption that carbonate rock sequences inflate as they get older, these measures of limestone and dolostone quantity require that shallow-water carbonate fluxes and reservoir sizes have been decreasing over a nontrivial portion of Phanerozoic time. This shrinkage has occurred at a rate of ~0.164%/m.yr. (fig. 1*B*; table 1).

Recognition of this trend in carbonate abundance was discussed as early as 1941 by Kuenen (1941). Bramlette (1958), Berger and Winterer (1974), Southam and Hay (1977), Sclater et al. (1979), and Hay (1988) have largely interpreted this pattern as recording the transfer of sites of carbonate accumulation from shallow-epicontinental to deeper-oceanic settings. Lower accumulation of carbonate in shallow waters forward in time is presumably balanced by greater accumulation of carbonate in the deep sea. Such an eon-scale change in the locus of shallow-marine carbonate accumulation is supported by estimates of deep-marine carbonate masses by Milliman (1974), Davies and Worsley (1981), Gregor (1985), and Hay (1985, 1988). All of these studies indicate that shelfal deposits accounted for a significantly larger portion of the total global carbonate flux in the Paleozoic and Mesozoic than they have over most of the Cenozoic.

Mechanisms of Craton-to-Ocean Carbonate Transfer

Eustatic Partitioning. One scenario for the Phanerozoic transfer of carbonate from shelfal/cratonic to pelagic/oceanic reservoirs maintains that the decline of shallow-water carbonates through time reflects a decrease in shelf area available for deposition and that this reduction is largely associated with a lowering of global sea level. Patterns of change in Mesozoic-Cenozoic positions of global sea level (Haq et al. 1987) and the CCD (Van Andel 1975) suggest the efficacy of this mechanism for at least the past 120 m.yr. However, most longer-term reconstructions of Phanerozoic change in continental freeboard (e.g., Vail et al. 1977; Hallam 1984; Algeo and Seslavinskiy 1995) depict two major intervals of continental flooding spanning Early to Middle Paleozoic and Middle to Late Mesozoic intervals. This bimodal pattern is somewhat apparent in data on surviving carbonate abundance from North America (e.g., fig. 1*H*–1*J*) but is not nearly as similar to the rather monotonic long-term trends in global data.

While Phanerozoic change in global sea level almost certainly had some influence on patterns of carbonate accumulation in shallow- versus deep-marine settings, this process alone seems incapable of explaining the longer-term trends of increasing amount with increasing age apparent in figures 1*B* and 1*D*. In addition, data on the nature of sedimentary components of Phanerozoic ophiolite suites and on the Phanerozoic distribution of chalks suggest that despite continental emergence during the Middle to Late Paleozoic, pelagic carbonate did not begin to accumulate in any significant quantities in deep-sea settings until the Late Mesozoic (Boss and Wilkinson 1991). It therefore seems clear that factors in addition to net area of continent flooded by shallow marine water have served to regulate the amounts of carbonate de-

ration of time represented by that portion of the reservoir, versus mean sequence age from Harland et al. (1982). *A*, *B*, Surviving volumes (10^3 km^3/m.yr.) of global clastic and carbonate sediment from Ronov data (numerous citations; see "References Cited"). *C*, *D*, Areas (10^3 km^2/m.yr.) of global clastic and carbonate sediment from Ronov data. *E*, *F*, Areas (10^3 km^2/m.yr.) of Eurasian sediment from Ronov data. *G*, *H*, Surviving areas (10^3 km^2/m.yr.) of North American clastic and carbonate sediment from Ronov data. *I*, *J*, Surviving areas (10^3 km^2/m.yr.) of North American sediment from data in Cook and Bally (1975). Note that terrigenous-clastic volumes and areas decrease exponentially with linearly increasing age; residence times (*Rt*) for terrigenous units are on the order of several hundreds of millions of years. In contrast, carbonate reservoirs exhibit a trend of apparently increasing size with age; residence times calculated for carbonate units are actually negative and imply a gradual decrease in material flux to epicontinental carbonate reservoirs over most of the Phanerozoic.

Table 1. Cycling Rates for Terrigenous-Clastic and Carbonate Sediments on the Major Continents

	k (%/m.yr.)	Residence times (m.yr.)	Figure	R^2	P
Clastics by volume:					
All continents	.124	804	1*A*	.110	.1048
Eurasia	.127	786	...	.097	.1294
North America:					
Ronov 1980	.058	1719	...	.012	.5021
Cook and Bally 1975	.352	284	...	.281	.0004
Clastics by area:					
All continents	.105	950	1*C*	.117	
Eurasia	.106	942	1*E*	.079	.1723
North America:					
Ronov 1980	.142	705	1*G*	.091	.1439
Cook and Bally 1975	.143	701	1*I*	.053	.1533
Carbonates by volume:					
All continents	−.164	−610	1*B*	.194	.0276
Eurasia	−.227	−440	...	.201	.0246
North America:					
Ronov 1980	−.406	−246	...	.322	.0032
Cook and Bally 1975	−.103	−966	...	.009	.5544
Carbonates by area:					
All continents	−.193	−519	1*D*	.263	.0087
Eurasia	−.322	−311	1*F*	.296	.0049
North America:					
Ronov 1980	−.413	−242	1*H*	.260	.0092
Cook and Bally 1975	−.030	−330	1*J*	.080	.0776

posited in shallow- and deep-marine settings throughout the Phanerozoic.

Biologic Partitioning. Kuenen (1941) proposed another idea concerning the partitioning of carbonate sediment between shallow- and deep-marine settings, that the post-Paleozoic evolution and diversification of planktonic calcifiers may have given rise to an oceanic "lime famine," which then led to a substantial decrease in rates of epicratonic limestone and dolostone accumulation since that time (see also Kuenen 1950; Poldervaart 1955; Hay and Southam 1976; Sibley and Vogel 1976). Because planktonic foraminifera and coccolithophorids are primarily responsible for the generation of calcareous oozes in modern oceans, their absence in pre-Mesozoic oceans would have had a profound effect on the mechanism, and perhaps rate, of carbonate-sediment generation.

However, areas and volumes of shelfal carbonate began to decline early in the Phanerozoic (fig. 1). Although global subduction has resulted in a rarity of pre-Jurassic pelagic sediment, there is little evidence to suggest that pelagic calcifiers played any significant role in carbonate sedimentation prior to their explosive radiation in the later part of the Mesozoic (Lipps 1970; Tappan and Loeblich 1973). Unconfirmed reports of Late Paleozoic coccolithophorids exist (e.g., Pirini-Radrizzani 1971; Gartner and Gentile 1972; Minoura and Chitoku 1979; Siesser and Haq 1987), but true calcareous nannoplankton are not seen until the Triassic (DiNocera and Scandone 1977; Jafar 1983) and do not become volumetrically significant until the Jurassic (Siesser and Haq 1987). Similarly, planktonic foraminifera do not appear until the Middle Jurassic (Grigelis and Gorbatchik 1980; Culver 1987). Although measures of taxonomic abundance are a rather unsatisfactory proxy for carbonate-producing biomass, this lack of concordance between diversity of planktonic calcifiers and the decreasing area of shallow-water carbonates prior to the Cretaceous necessitates an additional control on the partitioning of carbonate between shallow and deep depositional settings.

Phanerozoic Paleogeography. If available data on Phanerozoic sea levels and the diversity of pelagic calcifiers are insufficient to explain fully Phanerozoic-scale trends in amounts of surviving shallow- and deep-marine carbonate deposits, what other earth surface process might exhibit a pattern of variation similar to that seen in surviving platform-carbonate sequences? Modern carbonates accumulate preferentially on tropical to subtropical shelves (Emery 1968; Lees 1975) where seawater reaches its highest degree of saturation with respect to calcite and aragonite (Morse et al. 1980). Available data suggest that ancient limestone and dolostone deposits exhibit a similar distribution (e.g., Briden and Irving 1964; Parrish 1982; Ziegler et al. 1984), accumulating within ~30° of the equator. It therefore follows that net accumulation of shallow-water carbonate might be linked to areas of low-latitude continental crust flooded by shallow seas. As noted above, data on amounts of surviving carbonate from North America (fig. 1*H*, 1*J*) exhibit a pattern similar to reconstructions of positions of global sea level, suggesting that some amount of change in shelf-carbonate accumulation may indeed be linked to differences in low-latitude areas of flooded craton. Moreover, paleomagnetic and other paleogeographic data indicate a more or less continuous northward migration of the major continental blocks over much of the last 500 m.yr. (e.g., Denham and Scotese 1988; Allison and Briggs 1993), with the major continents crossing up to 110° of latitude. Given this significant displacement through time, areal extents of low-latitude shelves may have been related to the paleopositions of continental plates.

In the following section, we test the hypothesis that abundance of shallow-marine carbonate sediments in the oceans throughout the Phanerozoic is correlated with paleogeography and continental drift. We first ask how much areas of low-latitude shelves have changed during the general northern migration of continents. We can then ask how the area of low-latitude carbonate shelves has changed over this same interval. If there is concordance in the two trends, then there is strong evidence to support the importance of plate tectonics in determining where carbonate sediments accumulated through the Phanerozoic.

Shelf Areas, Latitude, and Lithology

Paleogeographic Database. We used Scotese and Golonka's (1992) paleogeographic atlas of the world as a source of data on latitudinal distributions of flooded continental crust over the past 547 m.yr. The atlas integrates plate tectonic, paleomagnetic, and paleogeographic data compiled over the last 25 yr and includes data on areal distributions of deep ocean, shallow shelves, subaerial low lands, and mountain ranges. The 29 reconstructions in the atlas are available in a digital format; we imported files into a commercially available image analysis software package (Adobe Photoshop), tabulated areas of these four paleogeographies at intervals of 10° latitude, and then normalized each by the actual area of that band at the earth's surface. Specifically, contiguous areas of open ocean, shallow shelves, continental landmasses, and mountain ranges were identified within each latitudinal band, and the number of pixels within that region was recorded. We assumed that total area of the globe has remained constant throughout the Phanerozoic and then converted pixelated map areas for each of the 18 latitudinal bands to actual areal extents. This process was repeated for all of the 29 paleogeographic reconstructions. The net result is a tabulation of global areas of deep ocean, shallow shelf, land, and mountains over Phanerozoic time.

Areas of Low-Latitude Shelves and Shelf Carbonates through Time. Shelf area within 30° of the equator (fig. 2) declines more or less monotonically throughout the Phanerozoic, defining a trend that is qualitatively similar to that exhibited by shallow-marine carbonate successions (fig. 1*B*, 1*D*). However, the direct comparison of secular variation in low-latitude shelf area with trends based on surviving volumes or areas of shelfal carbonate rocks is inappropriate because variable portions of the carbonate reservoir have presumably been destroyed by erosion. Even though older Phanerozoic carbonate sequences cover greater areal extents (fig. 1*D*), they almost certainly underrepresent amounts of carbonate that accumulated over these time intervals. Older portions of the reservoir have been subjected to exogenic cycling processes for considerably greater spans than experienced by younger successions, thereby producing a bias toward younger rocks (e.g., Tardy et al. 1989). This bias must be corrected to make meaningful comparisons between low-latitude shelf area and area of shallow-marine carbonates through time.

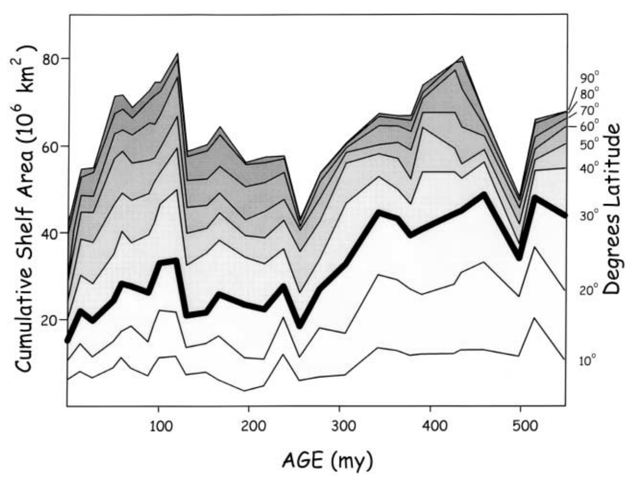

Figure 2. Areas of shallowly flooded global shelf area versus age; each interval represents cumulative shelfal area equatorward of each successive 10° band of latitude. The dark heavy line is total shelf area within 30° of the equator, here taken as generally equivalent with the zone of potential carbonate generation. Note the generally linear decrease in tropical shelf areas over Phanerozoic time.

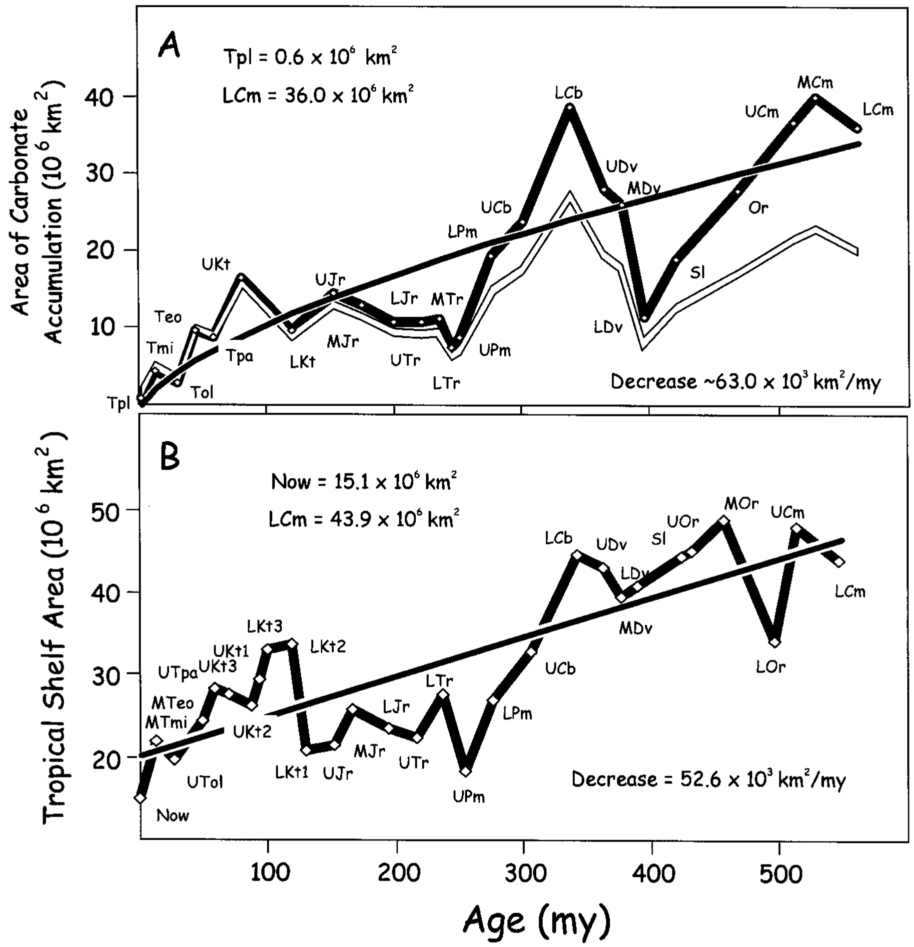

Figure 3. *A*, Restored areal extents of Phanerozoic cratonic carbonate accumulation (*heavy black line*) inferred from present distributions of limestone and dolostone sequences (*white line*) assuming postdepositional destruction by subaerial erosion at a rate of 0.105%/m.yr. Areas of shelfal carbonate accumulation have decreased from an inferred lower Cambrian extent of ~36.0 × 10^6 km^2 (~18% of continental crust, the size of continental Africa) to a present extent of some 0.6 × 10^6 km^2. *B*, Areal extents of tropical (<30° lat.) Phanerozoic shelves. These have decreased from a lower Cambrian extent of ~44.0 × 10^6 km^2 to a present area of ~15.1 × 10^6 km^2.

If exogenic cycling of terrigenous-clastic and marine-carbonate successions have proceeded at comparable rates over the Phanerozoic, the sedimentary cycling rate derived from surviving areas of global terrigenous-clastic sequences can be used to estimate original areas of Phanerozoic low-latitude shelf-carbonate sequences. Based on area-versus-age relations from terrigenous sandstones and shales, this rate is ~0.105%/m.yr. (table 1). These restored values decrease, albeit irregularly, from a Lower Cambrian depositional area of ~36.0 × 10^6 km^2 to a Pliocene extent of some 0.6 × 10^6 km^2.

This trend compares quite well with that defined by the entire area of low-latitude shelf through the Phanerozoic. Global areas of shallow-marine carbonate accumulation have decreased over the Phanerozoic at a rate of ~63.0 × 10^3 km^2/m.yr. (fig. 3*A*). Similarly, areas of low-latitude shelves decrease from a Cambrian high toward the present at a rate of ~52.6 × 10^3 km^2/m.yr. (fig. 3*B*). On the basis of this correlation, we suggest that the decrease in low-latitude shelf area associated with Phanerozoic poleward drift of the major continental land masses was likely responsible for the observed decrease in the areal extent of shallow-water carbonate accumulation through the Phanerozoic.

Shelf Sedimentation. Globally, the area of Phanerozoic flooded shelf has averaged ~64 × 10^6 km^3 but exhibits a distinct bimodality with Silurian and Cretaceous maxima of ~80 × 10^6 km^3 (fig. 4*A*), a pattern similar to that in Phanerozoic sea levels of Vail et al. (1977) and Hallam (1984). On the basis

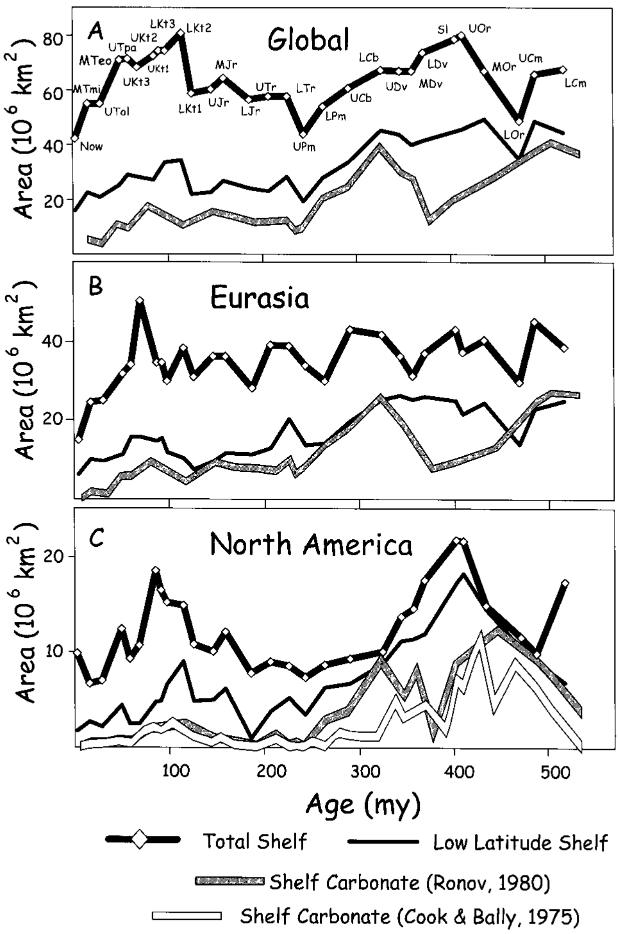

Figure 4. Phanerozoic variation in inferred (see fig. 3) areas of shallowly flooded continent (*thick black lines and diamonds*), tropical flooded continent (*thin black lines*; cf. fig. 3*B*), and carbonate accumulation (*gray lines*; cf. fig. 3*A*) for global continents (*A*), Eurasia (*B*), and North America (*C*). Note similar patterns of variation in all three panels with respect to all three types of earth surface area.

of this apparent agreement, absolute area of shallowly flooded continental crust was more closely related to global tectono-eustasy than to the aggregate effect of localized tectonism along individual margins. Comparison of total low-latitude shelf area and estimated extent of carbonate sediment indicates that limestone and dolostone accumulation predominated on global shelves throughout much of the Early Phanerozoic, at times blanketing some 80%–90% of tropical shelves (fig. 4*A*). This pattern is equally apparent for Eurasia (fig. 4*B*) and North America (fig. 4*C*), where independent estimates of carbonate amounts are available from both Cook and Bally (1975) and the Ronov data.

What is somewhat surprising, however, is that although the proportion of tropical shelves serving as sites of carbonate accumulation has decreased at a constant rate over the past ~100 m.yr., the area of shelfal carbonate accumulation has decreased much more rapidly than has the rate of drift to northern latitudes (fig. 5). Whereas rate of change in area of tropical shelf has remained generally constant over the past 540 m.yr., decrease in carbonate accumulation has been significantly greater since the Cretaceous. The percentage of tropical shelf receiving carbonate sediment (PSC) is best represented as a power function wherein

$$\mathrm{PSC} = 0.0556 \times \mathrm{age}^{0.414}.$$

Such a relation suggests that even though eon-scale change in areas of low-latitude shelves has occurred at rates comparable to decrease in inferred areas of carbonate accumulation, rate of transfer to deep oceans over the past ~100 m.yr. has increasingly exceeded that anticipated solely from change in tropical shelf area.

The reasons for this difference most probably relate to the importance of changing sea level and diversification of planktonic calcifiers in augmenting carbonate accumulation as deep-sea calcareous ooze. Although low-latitude and carbonate-covered

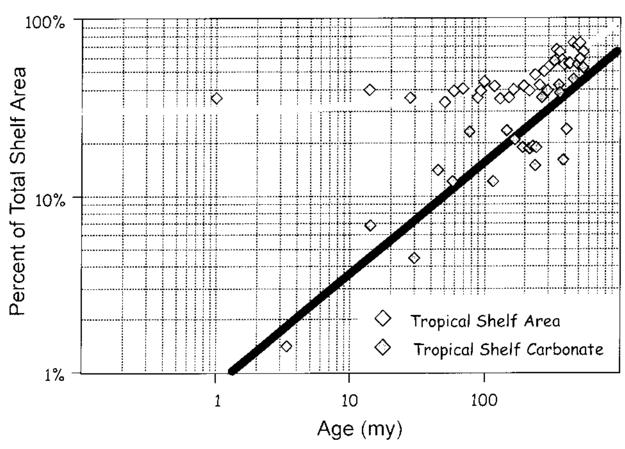

Figure 5. Log-log plot of relative proportion of total global shelves as tropical shelf (*light gray*) and carbonate-covered shelves (*dark gray*) versus sequence age. Note generally similar rates of decrease of low-latitude and carbonate shelf areas until ~100 Ma and an ever greater loss of carbonate extent since that time. Note that ~36.0 × 10^6 km^2 of lower Cambrian limestone and dolostone occupied ~56% of low-latitude shelves, whereas ~0.6 × 10^6 km^2 of Pliocene deposits cover some 1.4% of tropical platforms.

shelf areas decreased at comparable rates over most of the Phanerozoic (fig. 6), loss of shelfal carbonate accumulation has accelerated significantly since ~100 Ma (fig. 5), an interval that corresponds with the onset of Cretaceous-Cenozoic fall of sea level as well as the diversification of planktonic foraminifera and calcareous nannoplankton. These factors may have served to exacerbate the loss of shallow-water carbonate related to the poleward drift of continental crust.

Modern versus Ancient Accumulation Rates. The potential for carbonate generation over low-latitude shelves is widely perceived as significantly exceeding rates of passive-margin shelf subsidence (e.g., Sadler 1981; Schlager 1981; Enos 1991; Bosscher and Schlager 1993). Many Proterozoic and Phanerozoic successions comprise relatively thick intervals, reflecting millions of years of carbonate accumulation, that are composed entirely of subtidal lithofacies (Elrick and Read 1991; Osleger 1991; Holland et al. 1997). If the potential for sediment generation has always generally exceeded subsidence, how then was it that accommodation space was never filled during the accumulation of many Phanerozoic carbonate successions?

In light of available data on change in Phanerozoic low-latitude shelf area, one possibility is that carbonate accumulation rates determined from Holocene settings are not at all typical of those that existed throughout much of the past 540 m.yr. Estimates of areal extent of carbonate in the Ronov data indicate that Pliocene carbonate deposits occupy some 2.35% of their Paleozoic maxima and that these values are 0.60% and 1.85% for Eurasia and North America, respectively. The latter value is virtually identical to that derived for North America from data in Cook and Bally (1975). Regardless of period-scale differences in areal extent (fig. 4), it seems apparent that areal extents of shallow-marine carbonate accumulation are now only a small fraction of earlier Phanerozoic maxima. Data on surviving terrigenous successions suggest that this decrease in extent of carbonate accumulation was not the result of any eon-scale change in weathering rate, and the delivery of calcium and carbonate ions to global oceans' net rates of carbonate generation have remained more or less constant over Phanerozoic time. It therefore follows that in addition to the greater delivery of carbonate sediment to the deep sea, lesser Holocene areal extents of low-latitude carbonate accumulation may also be balanced in part by significantly higher rates of vertical accumulation. Conversely, the greater area of tropical shelves in the Paleozoic would have given rise to lower rates of vertical accumulation. Under such conditions, long-term subsidence and sedimentation rates would be more similar, and significant successions of subtidal carbonate could accumulate.

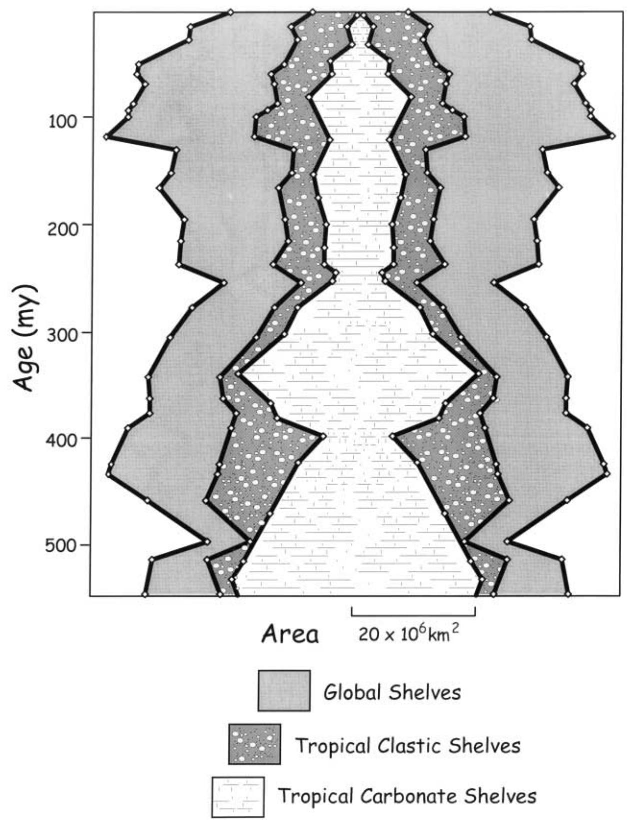

Figure 6. Summary of eon-scale trends in total and tropical shelf areas and extents of low-latitude carbonate accumulation. Total shelf area (fig. 2) ranges over ~30 × 10^6 km^2. Based on hypsometric data in Harrison et al. (1983), this suggests ~300 m of Phanerozoic sea level change. Low-latitude shelf (fig. 3*B*) decreases linearly from a lower Cambrian extent of 43.9 × 10^6 km^2 at a rate of 52.6 × 10^3 km^2/m.yr. Carbonate shelf area changes more irregularly but generally decreases from a lower Cambrian extent of 36.0 × 10^6 km^2 as area = 0.407 × $age^{0.673}$.

Conclusions

We suggest that extratropical migration of continental landmasses has had a profound influence on the sites of carbonate accumulation in Phanerozoic oceans. Long-term decreases in areas of tropical shelf and in areal extent of cratonic carbonates were similar throughout the Paleozoic and much of the Mesozoic, which suggests that continental drift has limited the size of depositional surfaces available for shallow-water carbonate accumulation. On the scale of eons, poleward migration of the major continental blocks has been significantly more important in predicting sites of carbonate accumulation in shallow- and deep-marine settings than either biologic evolution or eustatic change in sea level. Only since the Cretaceous has the rate of loss of carbonate shelves (and hence the transfer of carbonate to deep-sea settings) significantly exceeded the loss of tropical shelfal platforms. This offset in rates is likely due to the combined effects of eustatic sea level fall and evolutionary radiation of planktonic calcifiers, both of which can augment the transfer of carbonate from shallow shelves to the deep sea.

The decrease in low-latitude shelf area associated with poleward migration of the continents, and concomitant decrease in areal extent of shallow-water carbonate accumulation, may have increased the carbonate saturation state of the oceans. This may have been the trigger for the evolution of planktonic calcifying organisms. Increasing availability of carbonate through the Paleozoic may have reached a threshold above which it was possible to exploit the resource. High atmospheric P_{CO_2} (e.g., Berner 1994) and low saturation states of the oceans prior to the latest Paleozoic would have discouraged colonization of the surface ocean by calcareous plankton. The appearance of the first calcareous nannofossils appears roughly to coincide with the major sea level fall near the Permo-Triassic boundary and the associated drop in area of shelfal carbonate accumulation below the overall Phanerozoic trend (fig. 4*A*). Weathering of exposed carbonates would have enhanced the effect of decreasing shelf area to further boost the carbonate saturation of the ocean, making calcification more feasible. The combined effects of eustatic sea level fall and loss of low-latitude shelf area may therefore have permitted, if not facilitated, the evolution of open-ocean planktonic calcifiers.

ACKNOWLEDGMENTS

Many individuals have directly and indirectly contributed to the ideas presented above. B. Hay, J. Walker, and A. Ronov served as valuable sources of information and motivation during these investigations. Early versions of this article benefited from critical evaluation by M. Gamberg and two anonymous reviewers. The National Science Foundation (grant EAR-99-02849) supports research on patterns of Phanerozoic sediment accumulation at the University of Michigan.

REFERENCES CITED

Algeo, T. J., and Seslavinskiy, K. B. 1995. The Paleozoic world: continental flooding, hypsometry, and sea level. Am. J. Sci. 295:787–822.

Allison, P. A., and Briggs, D. E. G. 1993. Paleolatitude sampling bias, Phanerozoic species diversity, and the end-Permian extinction. Geology 21:65–68.

Berger, W. H., and Winterer, E. L. 1974. Plate stratigraphy and the fluctuating carbonate line. Spec. Publ. Int. Assoc. Sedimentol. 1:11–48.

Berner, R. A. 1991. A model for atmospheric CO_2 over Phanerozoic time. Am. J. Sci. 291:330–376.

———. 1994. Geocarb II: a revised model for atmospheric CO_2 over Phanerozoic time. Am. J. Sci. 291:330–376.

Berry, J. P., and Wilkinson, B. H. 1994. Paleoclimatic and tectonic control on the accumulation of North American cratonic sediment. Geol. Soc. Am. Bull. 106: 855–865.

Blatt, H., and Jones, R. L. 1975. Proportions of exposed igneous, metamorphic, and sedimentary rocks. Geol. Soc. Am. Bull. 86:1085–1088.

Bleuth, G. J. S., and Kump, L. R. 1991. Phanerozoic paleogeography. Am. J. Sci. 291:284–308.

Boss, S. K., and Wilkinson, B. H. 1991. Planktogenic/eustatic control on cratonic/oceanic carbonate accumulation. J. Geol. 99:497–513.

Bosscher, H., and Schlager, W. 1993. Accumulation rates of carbonate platforms. J. Geol. 101:345–355.

Bramlette, M. N. 1958. Significance of coccoliths in calcium-carbonate deposition. Geol. Soc. Am. Bull. 69: 121–126.

Briden, J. C., and Irving, E. 1964. Paleolatitude spectra of sedimentary paleoclimatic indicators. *In* Nairn, A. E. M., ed. Problems in paleoclimatology. New York, Wiley, p. 199–224.

Cook, T. D., and Bally, A. W. 1975. Stratigraphic atlas of North and Central America. Princeton, N.J., Princeton University Press, 272 p.

Culver, S. J. 1987. Foraminifera. *In* Lipps, J. H., ed. Fossil prokaryotes and protists—notes for a short course. University of Tennessee Department of Geological Sciences Studies in Geology 18. Knoxville, University of Tennessee, p. 169–212.

Davies, T. A., and Worsley, T. R. 1981. Paleoenvironmental implications of oceanic carbonate sedimentation rates. Soc. Econ. Paleontol. Mineral. Spec. Publ. 32:169–179.

Denham, C. R., and Scotese, C. R. 1988. Terra mobilis: a plate tectonics program for the Macintosh (version 2.1). Houston, Earth in Motion Technology.

DiNocera, S., and Scandone, P. 1977. Triassic nannoplankton limestones of deep basin origin in the central

Mediterranean region. Palaeogeogr. Palaeoclimatol. Palaeoecol. 21:101–111.
Elrick, M., and Read, J. F. 1991. Cyclic ramp-to-basin carbonate deposits, Lower Mississippian, Wyoming and Montana: a combined field and computer modeling study. J. Sediment. Petrol. 61:1194–1224.
Emery, K. O. 1968. Relict sediments on continental shelves of the world. Am. Assoc. Petrol. Geol. Bull. 52:445–464.
Enos, P. 1991. Sedimentary parameters for computer modeling. *In* Franseen, E. K.; Watney, W. L.; Kendall, C. G. St. C.; and Ross, W., eds. Sedimentary modeling: computer simulations and methods for improved parameter definition. Kans. Geol. Surv. Bull. 223: 207–230.
Garrels, R. M., and Mackenzie, F. T. 1969. Sedimentary rock types: relative proportions as a function of geological time. Science 163:570–571.
———. 1971. Evolution of sedimentary rocks. New York, Norton, 396 p.
Gartner, S., and Gentile, R. 1972. Problematic Pennsylvanian coccoliths from Missouri. Micropaleontology 18:401–404.
Gilluly, J. 1969. Geological perspective and the completeness of the geologic record. Geol. Soc. Am. Bull. 80:2303–2312.
Gregor, C. B. 1985. The mass-age distribution of Phanerozoic sediments. *In* Snelling, N. J., ed. The chronology of the geological record. Memoir (Geol. Soc. Lond.), no. 10. Oxford, Blackwell Scientific for Geol. Soc. (Lond.), p. 284–289.
Grigelis, A., and Gorbatchik, T. 1980. Morphology and taxonomy of Jurassic and Early Cretaceous representatives of the superfamily Globigerinacea (Favusellidae). J. Foraminiferal Res. 10:180–190.
Hallam, A. 1984. Pre-Quaternary sea level changes. Annu. Rev. Earth Planet. Sci. 12:205–243.
Haq, B. U.; Hardenbol, J.; and Vail, P. R. 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to the present). Science 235:1156–1167.
Harland, W. B.; Cox, A. V.; Llewellyn, P. G.; Pickton, C. A. G.; Smith, A. G.; and Walters, R. 1982. Subdivisions of Phanerozoic time: a geologic time scale. New York, Cambridge University Press, 122 p.
Harrison, C. G. A.; Miskel, K. J.; Brass, G. W.; Saltzman, E. S.; and Sloan, J. L. 1983. Continental hypsometry. Tectonics 2:357–377.
Hay, H. W. 1985. Potential errors in estimates of carbonate rocks accumulating through geologic time. *In* Sundquist, E. T., and Broecker, W. S., eds. The carbonate cycle and atmospheric CO_2: natural variations, Archean to present. Am. Geophys. Union Monogr. 32: 573–583.
Hay, W. W. 1988. Paleoceanography: a review for the GSA centennial. Geol. Soc. Am. Bull. 100:1934–1956.
Hay, W. W., and Southam, J. R. 1976. Modulation of marine sedimentation by the continental shelves. *In* Anderson, N. R., and Malahoff, A., eds. The fate of fossil fuel CO_2 in the oceans. New York, Plenum, p. 569–604.
Holland, S. M.; Miller, A. I.; Dattilo, B. F.; Meyer, D. L.; and Diekmeyer, S. L. 1997. Cycle anatomy and variability in the storm-dominated type Cincinnatian (Upper Ordovician): coming to grips with cycle delineation and genesis. J. Geol. 105:135–152.
Jafar, S. A. 1983. Significance of Late Triassic calcareous nannoplankton from Austria and southern Germany. Neues Jahrb. Geol. Palaeontol. Abh. 166:218–259.
Khain, V. Y., and Balukhovskiy, A. N. 1979. Neogene lithologic associations of the world. Sov. Geol. 10: 15–23.
Khain, V. Y.; Ronov, A. B.; and Balukhovskiy, A. N. 1975. Cretaceous lithologic associations of the world. Sov. Geol. 11:10–39.
Khain, V. Y., and Seslavinskiy, K. B. 1977. Silurian lithologic associations of the world. Sov. Geol. 5:21–42.
Kuenen, P. H. 1941. Geochemical calculations concerning the total mass of sediments in the earth. Am. J. Sci. 239:161–190.
———. 1950. Marine geology. New York, Wiley, 568 p.
Lees, A. 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. Mar. Geol. 19:159–198.
Lipps, J. H. 1970. Plankton evolution. Evolution 24:1–22.
Milliman, J. D. 1974. Marine carbonates. *In* Milliman, J. D.; Mueller, G.; and Foerstner, U., eds. Recent sedimentary carbonates. New York, Springer, 375 p.
Minoura, N., and Chitoku, T. 1979. Calcareous nannoplankton and problematic microorganisms found in the Late Paleozoic limestones. J. Fac. Sci. Hokkaido Univ. Ser. IV Zool. 19:199–212.
Morse, J. W.; Mucci, A.; and Millero, F. J. 1980. The solubility of aragonite in seawater of 35‰ salinity at 25°C and atmospheric pressure. Geochim. Cosmochim. Acta 44:85–94.
Osleger, D. 1991. Subtidal carbonate cycles: implications for allocyclic vs. autocyclic controls. Geology 19: 917–920.
Parrish, J. T. 1982. Upwelling and petroleum source beds, with reference to the Paleozoic. Am. Assoc. Petrol. Geol. Bull. 66:750–774.
Pirini-Radrizzani, C. 1971. Coccoliths from Permian deposits of eastern Turkey. *In* Farinacci, A., ed. Proceedings II Plankton Conference 1970. Roma, Edizioni Tecnoscienza, p. 993–1001.
Poldervaart, A. 1955. Chemistry of the earth's crust. Geol. Soc. Am. Spec. Publ. 62:110–144.
Ronov, A. B. 1980. The earth's sedimentary shell: quantitative patterns of its structures, compositions and evolution. 20th Vernadskry Lecture, no. 1. *In* Yaroshevskiy, A. A., ed. The earth's sedimentary shell. Moscow, Nauka, p. 1–80.
Ronov, A. B., and Khain, V. Y. 1954. Devonian lithologic associations of the world. Sov. Geol. 41:47–76.
———. 1955. Carboniferous lithologic associations of the world. Sov. Geol. 48:92–117.
———. 1956. Permian lithologic associations of the world. Sov. Geol. 54:20–36.
———. 1961. Triassic lithologic associations of the world. Sov. Geol. 1:27–48.

———. 1962. Jurassic lithologic associations of the world. Sov. Geol. 1:9–34.

Ronov, A. B.; Khain, V. Y.; and Balukhovskiy, A. N. 1974*a*. Paleogene lithologic associations of the world. Sov. Geol. 3:10–42.

———. 1989. Atlas of lithological-paleogeographical maps of the world, Mesozoic and Cenozoic of Continents and Oceans. Leningrad, U.S.S.R. Academy of Sciences, 79 p.

Ronov, A. B.; Khain, V. Y.; and Seslavinskiy, K. B. 1976. Ordovician lithologic associations of the world. Sov. Geol. 1:7–27.

Ronov, A. B.; Seslavinskiy, K. B.; and Khain, V. Y. 1974*b*. Cambrian lithologic associations of the world. Sov. Geol. 12:10–33.

Sadler, P. M. 1981. Sediment accumulation rates and the completeness of stratigraphic sections. J. Geol. 89: 569–584.

Schlager, W. 1981. The paradox of drowned reefs and carbonate platforms. Geol. Soc. Am. Bull. 92:197–211.

Sclater, J. G.; Boyle, E.; and Edmond, J. M. 1979. A quantitative analysis of some factors affecting carbonate sedimentation in the oceans. *In* Talwani, M.; Hay, W. W.; and Ryan, W. B. F., eds. Deep drilling results in the Atlantic Ocean: continental margins and paleoenvironment. Maurice Ewing series, no. 3. Washington, D.C., American Geophysical Union, p. 235–248.

Scotese, C. R., and Golonka, J. 1992. Paleogeographic atlas. PALEOMAP Progress Report 20-0692. Arlington, Department of Geology, University of Texas, 34 p.

Sibley, D. F., and Vogel, T. A. 1976. Chemical mass balance of the earth's crust: the calcium dilemma and the tale of pelagic sediments. Science 192:551–553.

Siesser, W. G., and Haq, B. U. 1987. Calcareous nannoplankton. *In* Lipps, J. H., ed. Fossil prokaryotes and protists—notes for a short course. University of Tennessee Department of Geological Sciences Studies in Geology 18. Knoxville, University of Tennessee, p. 87–127.

Southam, J. R., and Hay, W. W. 1977. Time scales and dynamic models of deep-sea sedimentation. J. Geophys. Res. 82:3825–3842.

Tappan, H., and Loeblich, A. R., Jr. 1973. Evolution of the oceanic plankton. Earth Sci. Rev. 9:207–240.

Tardy, Y.; Roger, N.; and Probst, J. 1989. The global water cycle and continental erosion during Phanerozoic time. Am. J. Sci. 289:455–483.

Vail, P. R.; Mitchum, R. M.; and Thompson, S. 1977. Seismic stratigraphy and global changes of sea-level. *In* Payton, C. E., ed. Seismic stratigraphy: applications to hydrocarbon exploration. Am. Assoc. Petrol. Geol. Mem. 26:83–97.

Van Andel, T. H. 1975. Mesozoic/Cenozoic calcite compensation depth and the global distribution of calcareous sediments. Earth Planet. Sci. Lett. 26:187–194.

Veizer, J.; Bell, K.; and Jansen, S. L. 1992. Temporal distribution of carbonatites. Geology 20:1147–1149.

Veizer, J., and Ernst, R. E. 1996. Temporal pattern of sedimentation, Phanerozoic of North America. Geochem. Int. 33:64–75.

Veizer, J., and Jansen, S. L. 1979. Basement and sedimentary cycling and continental evolution. J. Geol. 87:341–370.

———. 1985. Basement and sedimentary cycling. 2. Time dimension to global tectonics. J. Geol. 93:625–664.

Wilkinson, B. H., and Walker, J. C. G. 1989. Phanerozoic cycling of sedimentary carbonate. Am. J. Sci. 289: 525–537.

Wold, C. N., and Hay, W. W. 1990. Estimating ancient sediment fluxes. Am. J. Sci. 290:1069–1089.

Ziegler, A. M.; Hulver, M. L.; Lottes, A. L.; and Schmachtenberg, W. F. 1984. Uniformitarianism and paleoclimates: inferences from the distribution of carbonate rocks. *In* Brenchley, P., ed. Fossils and climate. New York, Wiley, p. 3–27.