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Global carbonate accumulation from 145 Ma to Present (Cretaceous–Cenozoic): a new continental-scale analysis

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Analysis of continental-scale lithostratigraphic data may facilitate an understanding of global sedimentary processes. The number of carbonate-bearing formations established in northern Eurasia (430 in total), northern Africa and Arabia (47 in total), and India (98 in total) is calculated per epochs for the last 145 Ma. The results show maxima in the Late Cretaceous, the Eocene, and the Miocene and minima in the Paleocene, the Oligocene, and the Pliocene. The Quaternary records are somewhat ambiguous. The similarity of the patterns established in the three regions argues for a single global-scale mechanism of carbonate accumulation. The noted patterns also coincide well with some modeled changes in the global amount of carbonates accumulated by epoch. Moreover, increases in the amount of carbonates in the Late Cretaceous and the Eocene, and a decrease in the Paleocene, reflect true changes in the accumulation rates. The global process of carbonate accumulation might have been controlled, at least, by eustatic changes (sea-level rise led to broad transgressions on continental margins and consequently to expansion of shelfal paleoenvironments) and climate dynamics (warm water facilitated carbonate production). Interestingly, no dependence between the global carbonate accumulation and marine biodiversity dynamics is established.

Key words: carbonate, northern Eurasia, northern Africa, Arabia, India, eustasy, climate, Cretaceous, Cenozoic.

Introduction

Carbonates (limestone, dolostone, and marlstone) are common in the global Phanerozoic sedimentary rock record. However, the dynamics of their

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accumulation from 145 Ma to Present remains debated (Ronov 1980; Ronov et al. 1980; Opdyke and Wilkinson 1988; Nakamori 2001; Peters 2006; Ruban 2009). The curves reflecting changes in the carbonate accumulation rate differ (Nakamori 2001). It thus remains unclear whether 1.) the amount of carbonate rocks increased or decreased in the Cretaceous and 2.) their deposition in the latest Cenozoic was significant (Fig. 1). Global-scale compilation of lithostratigraphic data can help to prove or disprove the available models of carbonate accumulation (Opdyke and Wilkinson 1988; Nakamori 2001).

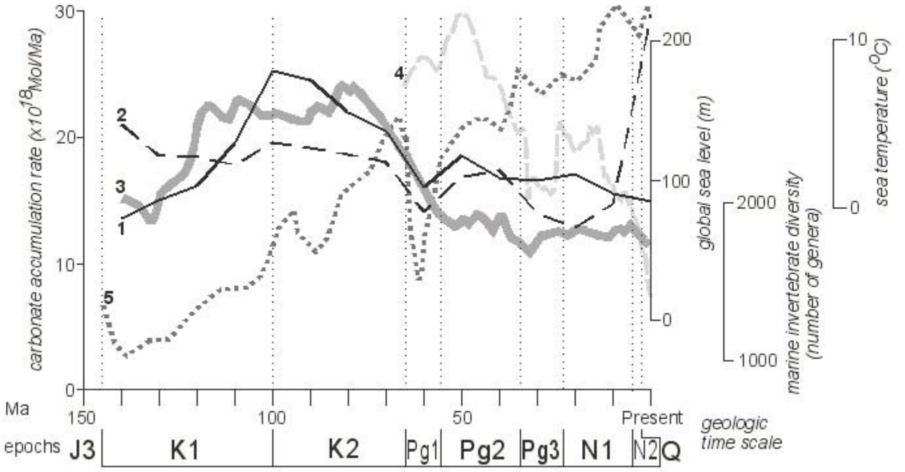

Fig. 1
Global carbonate accumulation rate (1. after Opdyke and Wilkinson 1988, 2. after Nakamori 2001), eustatic changes (3. after Müller et al. 2008), sea temperature (4. after Zachos et al. 2001), and biodiversity (5. after Purdy 2008). Note that the sea temperature is interpreted using oxygen isotopes; its values are meaningful only for ice-free ocean (Zachos et al. 2001) and should consequently be considered with great caution

The present paper focuses on the last 145 Ma of the geologic history (Cretaceous–Cenozoic). On the one hand, some extensive syntheses of lithostratigraphic data from some continental masses (Eurasia, Africa, Arabia, and North America) permit documenting and measuring the distribution of carbonate-bearing formations in this interval (see below). On the other hand, the knowledge of Cretaceous–Cenozoic paleoenvironments has been updated significantly during the past decade, with new eustatic curves (Haq and Al-Qahtani 2005; Miller et al. 2005; Kominz et al. 2008; Müller et al. 2008) and climatic reconstructions (Zachos et al. 2001) having been proposed (Fig. 1). An absence of simple coincidence of these curves reveals the highly complex nature of the Earth's evolution. The main goals of the present paper are 1.) recognition of the patterns of carbonate accumulation on the basis of large lithostratigraphic datasets, 2.) comparison of these patterns with the available global reconstructions of carbonate accumulation, and 3.) discussion of the possible environmental controls on these patterns.

Materials and methods

The present paper deals with the lithostratigraphic datasets relevant to three large regions. The Cretaceous-Cenozoic lithostratigraphic data of northern Eurasia (territory of the ex-USSR) were summarized by Prozorovskaya (1979) and Mironova (1982). Their validity appears to be generally the same as that of the COSUNA charts (Childs 1985) currently used by Peters (2006). The Cenozoic lithostratigraphic data on northern Africa and Arabia are modern. They were summarized by Sharland et al. (2001) and Swezey (2009) respectively, and the data for these two regions are used together in this paper. Finally, the Cretaceous-Cenozoic lithostratigraphic data for India (continental India and the Himalaya) are also recent. They were summarized by Raju (2007).

A total of 575 carbonate-bearing formations (430 from northern Eurasia, 47 from northern Africa and Arabia, and 98 from India) are considered. The age of each formation is established at the level of epochs. The resolution of the analysis is, therefore, moderate. It is impossible to increase this resolution because 1.) the age of some formations is not justified at the level of stages, and 2.) many formations of northern Eurasia are dated with the regional stages, the correlation of which with the standard time units is often uncertain. The epoch-limited resolution, preferred in this paper, also permits avoiding problems linked to current changes in the Cenozoic chronostratigraphy (Ogg et al. 2008). When a carbonate-bearing formation was deposited during two or more epochs, the presence of carbonate rocks is indicated for each of these epochs. In some cases, there is information available that carbonates were accumulated during only one particular epoch. This paper employs the geologic time scale adopted by the International Commission on Stratigraphy (Ogg et al. 2008) (see www.stratigraphy.org for the most recent update). It should be noted, however, that the regional lithostratigraphic data are justified along slightly different time scales. In all cases, the boundary between the Neogene and Quaternary systems was established at a level higher than that in the modern geologic time scale (Ogg et al. 2008). In some areas of northern Eurasia (the territory of the Paratethys), the Miocene/Pliocene boundary was established slightly lower than that in the modern geologic time scale (Nevesskaja et al. 2005; Ogg et al. 2008); one should also note an uncertainty in the correlation of the Paratethyan and standard units of the Neogene, which has been only recently improved (e.g. Krijgsman et al. 2010; Vasiliev et al. 2011). However, these differences are not sufficiently large to cause large errors in the long-term analysis of carbonate accumulation.

The number of carbonate-bearing formations in epochs of the last 145 Ma (only the Quaternary is not differentiated into epochs) is measured for each of the three above-mentioned regions. It is presumed that the more carbonates accumulated, the more carbonate-bearing formations appeared during the given epoch, and vice versa. Thus, in measuring the quantity of carbonate-bearing formations through the Cretaceous–Cenozoic time interval, we evaluate the dynamics of the carbonate accumulation. Of course, it would be more exact to calculate the volume (in km^3) of carbonates existing in these carbonate-bearing formations. However, this is impossible with the available data for three reasons: 1.) the areas of distribution of each formation are unknown; 2.) formations do not necessarily include only carbonates; 3.) some formations were accumulated during more than one epoch. If this is the case, then even consideration of the formation thickness does not make sense.

The regions considered in the present analysis, are related to large continental masses (but they are not the entire continents themselves); their Cretaceous–Cenozoic history differed because of differences in tectonic, paleoclimatic, and depositional setting (Laz'ko 1975; Sharland et al. 2001; Scotese 2004; Guiraud et al. 2005; Raju 2007; see also www.scotese.com). If common patterns of carbonate accumulation are observed in these large regions with different geologic settings, it is highly probable that these continental-scale patterns reflect a single global-scale mechanism. The above-mentioned approach permits recognizing only some very general patterns of broad carbonate deposition, because differences between local topography, tectonic setting, sea-level changes, etc., influence the number of formations in a given region, which produces some uncertainty.

Further comparison of the regional patterns of carbonate accumulation with global ones is a serious challenge. The results of the present analysis reflect the amount of carbonates per epoch. In contrast, the global reconstructions by Opdyke and Wilkinson (1988) and Nakamori (2001) deal with the accumulation rates (calculated as Mol/Ma; Mol = mole, a chemical expression of the amount of substance; Ma = millions of years), which were established for equal time slices (of 10 Ma each) for the 140–0 Ma time interval. It is impossible to measure the number of carbonate-bearing formations per 10 Ma in each region, and thus it is better to convert the global accumulation rates into the amount of carbonates accumulated per epoch. For this purpose, the average carbonate accumulation rates established for each epoch on the basis of information from Opdyke and Wilkinson (1988) and Nakamori (2001) was multiplied by the epoch duration to establish the amount of carbonates. The observed changes in these amounts, accumulated both regionally and globally, may be strongly affected by significant differences in the absolute duration of the epochs (Ogg et al. 2008). However, for the purposes of the present study, the comparison of regional and global changes for each pair of successive epochs is more important. For instance, if the available global curve indicates a rise of the amount of carbonates from one epoch to another, the simultaneous rises of the amount of carbonates registered regionally will prove the noted global change.

Results

The number of carbonate-bearing formations in northern Eurasia increased from the Early Cretaceous to the Upper Cretaceous (Fig. 2). Thereafter it was strongly reduced in the Paleocene. The two next maxima are observed in the Eocene and the Miocene, whereas the Oligocene and the Pliocene–Quaternary are characterized by a relatively small number of formations. In northern Africa and Arabia, the number of carbonate-bearing formations was low through the entire Cenozoic (Fig. 2). However, the small peaks are registered in the Eocene and the Miocene. In India, the number of carbonate-bearing formations was relatively low during the Cretaceous, but rose significantly in the Eocene (Fig. 2). Thereafter it decreased stepwise, and two minor peaks are observed in the Miocene and the Quaternary.

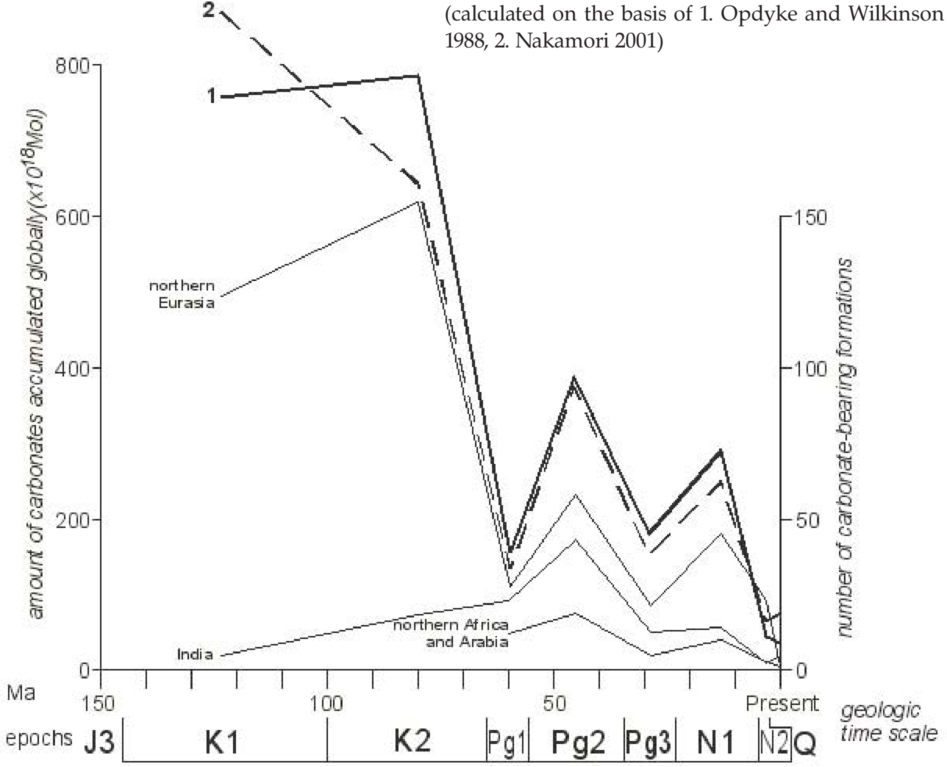

Fig. 2
Number of carbonate-bearing formations in the Cretaceous–Cenozoic epochs in the study regions and amount of carbonates accumulated globally (calculated on the basis of 1. Opdyke and Wilkinson 1988, 2. Nakamori 2001)

The amount of carbonates increased from the Early Cretaceous to the Late Cretaceous in northern Eurasia and India (Fig. 2). This was a significant change because the Late Cretaceous was shorter than the Early Cretaceous with regard to the absolute time scale (Ogg et al. 2008). The Eocene and Miocene peaks, as well as the relatively low number of carbonates in the Paleocene, the Oligocene, and the Pliocene, are recognizable in all three regions (Fig. 2). These patterns, however, may not reflect changes in the intensity of carbonate accumulation, because the Eocene and the Miocene were longer epochs than the Paleocene, Oligocene, and the Pliocene (Ogg et al. 2008). An evident similarity of the regional change in carbonate accumulation suggests the presence of the global-scale (but not truly global, because data from other continents such as South America or Australia should also be involved) mechanism of carbonate accumulation. The only principal dissimilarity is the low amount of carbonates accumulated in India during the Cretaceous in relation to the Cenozoic. This can be explained by an absence of widespread marine sedimentation in this large region before the Paleogene (Raju 2007), which itself can be related to the peculiarities of the paleotectonic setting of this continental block.

Interpretation

An increase in the number of carbonate-bearing formations in northern Eurasia and India during the Cretaceous proves a similar global pattern, which is established on the basis of carbonate accumulation rates by Nakamori (2001), but disproves the earlier results of Opdyke and Wilkinson (1988) (Fig. 2). The models of both Opdyke and Wilkinson (1988) and Nakamori (2001) permit outlining the Eocene and Miocene peaks in carbonate accumulation and the relatively low amounts of carbonates in the Paleocene, the Oligocene, and the Pliocene. The same pattern has been revealed by the comparison of the three regional records considered in the present study (Fig. 2).

It is very important that the Paleocene minimum and the Eocene maximum were also recorded directly by Opdyke and Wilkinson (1988) and Nakamori (2001) with changes in the global carbonate accumulation rate measured for equal absolute time intervals (Fig. 1). If so, these features can be also caused by the dynamics of intensity of carbonate accumulation in the regional records (i.e. they were not influenced by the differences in duration of the epochs). The two global models differ significantly during the Oligocene-Miocene time interval (Fig. 1). Where Opdyke and Wilkinson (1988) depicted a decrease in the carbonate accumulation rates, Nakamori (2001), in contrast, documented a rate increase. However, conversion to the amount of carbonates accumulated per epoch does not reveal differences between these models, which are both proven by their coincidence with the regional patterns (Fig. 2). The most striking difference between the models proposed by Opdyke and Wilkinson (1988) and Nakamori (2001) occurs during the Quaternary (Figs 1 and 2). The regional evidence produced by the present study does not clarify the situation (Fig. 2). The number of carbonate-bearing formations decreased in northern Eurasia and northern Africa / Arabia, coinciding with the pattern established by Nakamori (2001), whereas the number of such formations increased slightly in India to coincide with the results of modeling attempted by Opdyke and Wilkinson (1988). It should be noted that the data from northern Eurasia is the most representative, and this is a reason to favor the reconstruction by Nakamori (2001).

It appears important to compare conclusions made in the present study with measurements of global sedimentary rock proportions attempted earlier by Ronov et al. (1980). The latter results, however, are ambiguous in the context of the present analysis for two reasons. First, only rock proportions (i.e. percentage among all rocks), but not quantity of particular rock types, were measured by Ronov et al. (1980). Second, and more importantly, the above-mentioned authors discussed not rock types, but lithological associations, namely carbonate and carbonate-clastic. Nonetheless an analysis of a graph, presented by Ronov et al. (1980), permits outlining a decrease in carbonate accumulation in the Oligocene and an increase in the Miocene. Both patterns are known from the regional records analyzed herein (Fig. 2) and the global curves by Opdyke and Wilkinson (1988) and Nakamori (2001).

According to Peters (2006), the number of carbonate-dominated sedimentary packages increased in the Early Cretaceous and then decreased in the Late Cretaceous. This pattern differs from changes documented in northern Eurasia (Fig. 2) and globally by Nakamori (2001). The next cycle embraced the Cenozoic. The number of carbonate-dominated sedimentary packages peaked in the Eocene and then declined with no peak in the Neogene. Thus, one may recognize only a partial similarity of the above-mentioned patterns with those of northern Eurasia, northern Africa / Arabia, and India, and of the global carbonate accumulation (Opdyke and Wilkinson 1988; Nakamori 2001) (Fig. 2). Nonetheless, the Paleocene minimum and the Eocene maximum in carbonate deposition appeared in North America (Peters 2006), which coincides with observations made in the present paper.

Discussion

If the global carbonate accumulation from 145 Ma to present was a global-scale mechanism, which equally affected depositional systems of regions with different geologic settings, this requires a proper explanation by action of factors of the same scale. Many global controls on carbonate deposition are possible, but the present study examines only two of them, namely eustatic changes, which were very important for the evolution of large-scale depositional systems (Ruban 2009) and climate dynamics. This preference is explained by new significant achievements in studies of these factors.

The Cretaceous–Cenozoic eustatic changes were depicted by Müller et al. (2008), who updated the earlier reconstructions proposed by Haq et al. (1987), Haq and Al-Qahtani (2005), and Miller et al. (2005), accounting for the tectonic factor. The curve implied by Kominz et al. (2008) is only regional and, consequently, less suitable. The long-term eustatic changes coincided quite well with the dynamics of the global carbonate accumulation (Fig. 1). This relationship is especially well-documented when the curve by Nakamori (2001) is used. A higher global sea level always occurred together with higher carbonate accumulation rates. This coincidence might have not been only occasional. Rising global sea level leads to transgressions over continental margins and consequently to expansion of shallow-water shelfal environments, which are especially favorable for carbonate deposition (Nichols 2009). However, the noted coincidence may be indirect and rooted in the climatic mechanisms driving both the carbonate production and the sea level dynamics (the latter, however, was also controlled by tectonic forces (Müller et al. 2008)).

The precise dynamics of the Cenozoic climatic conditions was reconstructed by Zachos et al. (2001) (see also Fig. 1). Their data indicate the Eocene and Miocene warm phases and the Oligocene and Pliocene-Quaternary cool phases. The climate of the Paleocene Epoch was also relatively cool, although warmer than in some later epochs. These patterns coincide well with the regional and global carbonate records (Figs 1 and 2). It is supposed that cooler conditions are less favorable for carbonate production (Boggs 2006; Nichols 2009) and therefore that they reduce both the carbonate accumulation rate and the number of deposited carbonate-bearing formations. One should note that possible relationships between carbonate accumulation and sea temperature are complex and multi-dimensional (Mackenzie and Lerman 2006). It appears, however, that both eustasy and climate were important controls on carbonate accumulation. They experienced significant shifts during the Cenozoic (Zachos et al. 2001; Müller et al. 2008), which is why the rate of carbonate accumulation changed simultaneously in all analyzed regions in spite of the differences in their geologic setting.

The present study allows one additional inference. A comparison of the present estimates of global marine biodiversity changes (Purdy 2008) with the reconstructed dynamics of carbonate accumulation (Opdyke and Wilkinson 1988; Nakamori 2001) does not reveal any strong coincidence. The number of marine genera increased during the last 145 Ma, whereas the accumulation of carbonates, in contrast, decreased (Fig. 1). Some "local" similarities (e.g. the Paleocene and Oligocene minima) can be explained by the action of paleoenvironmental factors, such as eustatic changes and climate dynamics, which were important for the both biodiversity dynamics and carbonate deposition. If no principal dependence is established, it is also impossible to state that changes in the volume of carbonates through the Cretaceous-Cenozoic time interval affected biodiversity through preservation bias. The above-made observation also corresponds to the idea of Foote (2006), who suggested that the post-Paleozoic marine organisms were less dependent on carbonate substrates.

Conclusions

The present continental-scale analysis of the stratigraphic distribution of Cretaceous-Cenozoic carbonate-bearing formations established in northern Eurasia, northern Africa and Arabia, and India permits three important conclusions:

1.) the amount of carbonates that accumulated regionally from 145 Ma to present changed similarly in the studied regions, which indicates the presence of a global-scale mechanism of carbonate accumulation;

2.) changes in the amount of carbonates that accumulated globally measured on the basis of the model by Nakamori (2001) correspond better to the regional patterns than that measured on the basis of the model by Opdyke and Wilkinson (1988);

3.) carbonate accumulation during the past 145 Ma might have been controlled, at the very least, by global eustatic changes and climate dynamics.

Further studies should employ data from other continents and oceans in order to prove or disprove conclusions made in the present paper. In addition, the global tectonic control on carbonate production requires further discussion.

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