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Long-term eustatic cyclicity in the Paleogene: a critical assessment

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ABSTRACT

Global sea level has changed cyclically throughout Earth's history due to a variety of mechanisms that operate on a variety of timescales. Here we attempt to place constraints on the "actual" number of sea-level cycles that can be interpreted directly from the eustatic reconstructions. We apply an interpretative algorithm to Paleogene sea level records and identify three orders of eustatic cycles longer than 1 Ma. However, the three-ordered cyclicity might not represent cycles of global eustatic change. First, only cycles of the highest of the established orders (with a timescale of 10 s of Ma) are coherent among different sea-level records. Second, the interpreted cycles are not supported by the compilation of the regional maximum flooding surfaces. Third, climatic history alone cannot explain the eustatic changes. Fourth, the interpreted cyclicity differs significantly from what is known about the tectonic control of eustasy. Fifth, there may be other orders higher than those established. The problem is rooted in (1) the fact that eustatic curves might not necessarily reflect global events (e.g., fluctuations shown on these curves may be artifacts related to regional tectonic activity) and (2) the possible weakness of Paleogene (especially Eocene) eustatic cyclicity and its significant "overprint" by regional tectonic activity. Our attempted analysis claims for significant improvement of the available eustatic reconstructions. Unfortunately, the regional stratigraphical data remain still insufficient to develop any alternative eustatic curve that can be further interpreted to understand the number of "actual" cycle orders.

1. Introduction

Global sea level changed dramatically during the Paleogene, and these changes are documented by the available eustatic curves (Vail and Hardenbol, 1979; Hallam, 1984; Haq et al., 1987; Abreu and Anderson, 1998; Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008; Müller et al., 2008; Ruban et al., 2012; Spasojevic and Gurnis, 2012; Ruban, 2016). Although aspects of the chronology, magnitude, and mechanisms of these fluctuations remain controversial (Müller et al., 2008; Ruban et al., 2012), all above-mentioned curves indicate cyclic patterns of Paleogene eustatic change (Fig. 1). This cyclicity (to be distinguished from rhythmicity and periodicity) is typically linked to a fixed hierarchy of cyclic processes that affect eustatic change (Read, 1995; Veeken, 2006; Haq, 2014). For instance, global sea-level changes occurring over hundreds of millions of years have been attributed to the so-called "Wilson's cycles" (e.g., Cogné and Humler, 2008), whereas cyclicity occurring over tens and hundreds of thousands of years has been linked to changes in the Earth's astronomical parameters and the so-called "Milankovitch cycles" (e.g., Miller et al., 2005a; Boulila et al., 2011; Coughenour et al., 2013; Hinnov, 2013; Ruban, 2015). Moreover, an interplay between glacioeustatic and tectonic mechanisms may affect global sea-level change on different time scales (e.g., Lovell, 2010; Conrad, 2013; Rowley et al., 2013), producing a complex cyclic pattern. Particularly, it cannot be excluded that the "actual" number of cycle orders may differ from the "ideal" number inferred from the expected number of sea-level change mechanisms operating simultaneously. This idea does not mean that the various mechanisms that define the "ideal" sea-level cycle hierarchy are not operating with their expected magnitudes and rates (e.g., Gale et al., 2008; Boulila et al., 2011). Instead,

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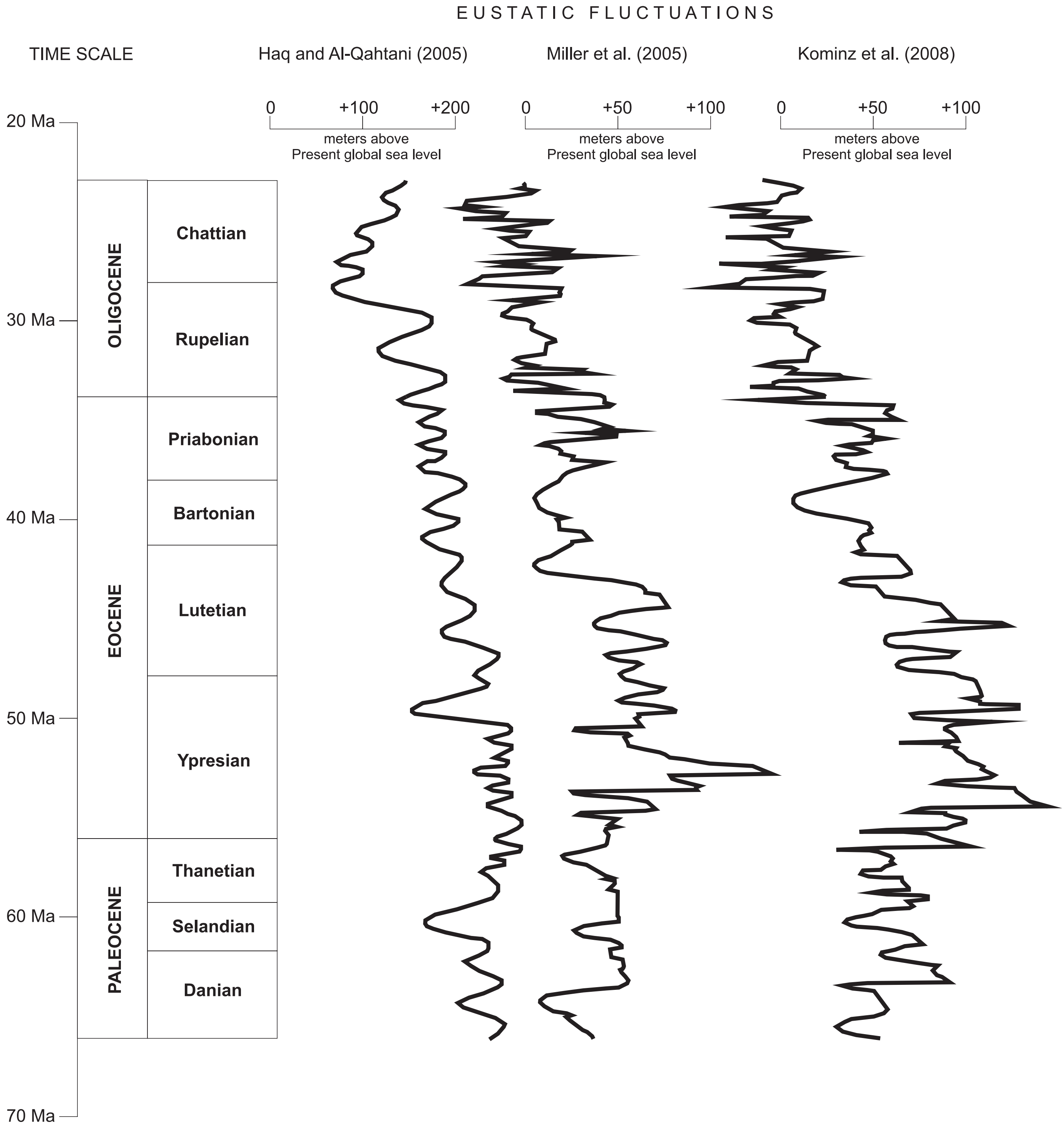

Fig. 1. The principal modern global sea-level curves. The geologic time scale follows Gradstein et al. (2012a,b); see also stratigraphy.org for updates. The original eustatic curves are re-scaled. Because of differences in the geologic time scales employed by different authors (see text for additional explanations), the depicted curves should not necessarily match at resolution higher than 5 (usually 1–2) Ma.

understanding the possible differences (or their absence) between the "actual" and "ideal" cycle hierarchies should facilitate further deciphering of various stratigraphic records and construction of globally consistent sea-level curves. This understanding should help us to realize how the interplay of various eustatic controls can change the "actual" signature of the "ideal" cyclicity.

In this paper, we examine several original global sea-level curves in order to recognize the possible long-term Paleogene eustatic cyclicity. Our goal is to establish the number of orders of "actual" sea-level cycles, i.e., those directly interpreted from the eustatic curve. Although it is difficult to guarantee that the available curves actually represent global sea-level variations (e.g., Müller et al., 2008; Ruban, 2015; Ruban, 2016), the urgency of such an analysis is underlined by recent eustasy-related disputes (Müller et al., 2008; Ruban et al., 2012), recent claims for global sedimentation periodicity (Melott et al., 2012), and the need to establish useful and reliable sequence hierarchies (Catuneanu, 2006; Catuneanu et al., 2011, 2012). We seriously consider possible uncertainties linked to the available eustatic reconstructions, and also discuss the validity of the interpreted "actual" cyclicity, especially in light of the primary stratigraphical data.

2. Materials and methods

2.1. Eustatic curves

From many available Paleogene eustatic curves (e.g., Vail and Hardenbol, 1979; Hallam, 1984; Haq et al., 1987; Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008; Müller et al., 2008; Spasojevic and Gurnis, 2012), we choose only those recent, high-resolution records that are based on field geologic data (not modeling). Additionally, only curves indicating absolute global sea-level changes are chosen. Three reconstructions are considered for the purposes of the present analysis, namely those made by Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008).

Haq and Al-Qahtani (2005) not only provide important data on sea-level changes on the Arabian Platform, but also update the famous global curve proposed 25 years ago by Haq et al. (1987). The reconstruction by Kominz et al. (2008) is based on data and methods other than those by Miller et al. (2005a), and thus the two can be considered independent of each other. The original reconstruction by Haq et al. (1987) was criticized, particularly, by Miall (1992) and Hallam (2001) for the possible regional tectonic influences on sea-level changes judged to be global, the reconstruction by Miller et al. (2005a) was questioned by Müller et al. (2008) and Kominz et al. (2008), who noted that local vertical motion of the New Jersey shoreline may affect the interpretation of this record in terms of global eustasy. It seems to be difficult, perhaps impossible, to avoid the influence of individual regional records (affected by tectonic activity and sedimentation dynamics) on the data employed for development of the modern eustatic curves (Moucha et al., 2008; Lovell, 2010). Nevertheless, such curves must serve as indicators of eustatic fluctuations until "new-generation" curves, which avoid regional effects, can be developed (e.g., Ruban et al., 2012). It should be added that, in our opinion, eustatic curves developed on the basis of a "single" locality or region may have more "problems" than those based on the global synthesis of data. However, if the reconstruction is aimed essentially to be of global importance, it can be considered so until it will be disproved.

The chosen eustatic curves differ in their temporal resolution. The reconstruction by Haq and Al-Qahtani (2005) is less detailed than those presented by Miller et al. (2005a) and Kominz et al. (2008). It appears that the resolution of the former is approximately ~0.5 Ma, whereas the resolution of the two latter is ~0.1 Ma. We thus suppose that the eustatic fluctuations described by Haq and Al-Qahtani (2005) may be one order higher than those described by Miller et al. (2005a) and Kominz et al. (2008). It should be added that the "long-term" eustatic curve also shown by Haq and Al-Qahtani (2005), which is constrained as a line connecting successive "short-term" highstands, is not useful for our study, because we aim to interpret original eustatic reconstructions using a different method (see below).

2.2. Long-term cycle interpretation

The eustatic curves by Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008) provide clear evidence of multi-ordered cyclicity (Fig. 1). Taking into account their resolution, we can use these curves to delineate long-term cycles of global sea-level change (provisionally, we will consider cycles with durations of 1 Ma and more as "long-term cycles"). Here we consider not only global sea-level highstands, which was preferred by Haq and Al-Qahtani (2005), but lowstands as well, in order to constrain the total magnitude of eustatic fluctuations of multiple orders.

We use an interpretative algorithm as follows. For each original eustatic curve, successive highstands and lowstands (maximal and minimal global sea levels) are connected by the curves HS and LS, respectively. Then, midpoint positions (between the HS and LS curves) of sea level are determined for time slices corresponding to every highstand and lowstand. The curve for the next order of sea-level cycling is generated by connecting these midpoint positions. This procedure is repeated until the curve ceases to display a cyclic pattern. The number of interpreted curves indicates the number of orders of the eustatic cyclicity. This simple approach permits us to establish "actual", or "natural" long-term sea-level cyclicity. However, this cyclicity actually represents eustatic changes only if all sea-level changes shown on the original curves were correctly interpreted and really global (of course, it is difficult to guarantee this). We do not give numbers to the interpreted orders of eustatic cyclicity (that is, we avoid labels like "first-order", "second-order", etc.), because the number of orders is taken as unknown by definition.

A serious challenge for the present analysis is linked to stratigraphy. Each original eustatic curve (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) is justified along its own time scale. Although these time scales are more or less comparable with one another and also with the modern internationally adopted Paleogene chronostratigraphy (Gradstein and Ogg, 2004; Gradstein et al., 2004, 2012a,b; Ogg et al., 2008; see on-line: stratigraphy.org), certain differences are inevitable (see review of this problem in Ruban, 2016). The chronostratigraphical frameworks (chiefly the series, stages, and absolute time scales) presented in the original publications of these eustatic reconstructions (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) do not permit precise correlation. The resulting error in direct correlation of the chosen curves (Fig. 1) may reach 2 Ma. Unfortunately, this error cannot be minimized, but it is not significant with regard to the present study: we aim to constrain the number of cyclicity orders and not the temporal coherence of the original curves. Thus, it should be sufficient to consider only the errors noted in interpretations and discussions presented below. In the other words, we consider each eustatic reconstruction with its own (original) time scale. Generally, the nomenclature of the Paleogene series and stages and the absolute ages of their boundaries established presently by the International Commission on Stratigraphy (Gradstein et al., 2012a,b; see on-line: stratigraphy.org) are followed in this paper.

3. Results

The eustatic curve proposed by Haq and Al-Qahtani (2005) permits us to interpret three orders of long-term cyclicity in the Paleogene (Fig. 2). Order A corresponds to the shortest of the long-term cycles visible on the original reconstruction. These are more or less symmetrical. Order B of the long-term eustatic cyclicity is constituted of about a dozen cycles, which differ strongly in their duration and magnitude. This cyclicity remains almost invisible during the late Eocene interval. The only cycle started and ended beyond the limits of the Paleogene is Order C, which peaked as a prominent global sea-level highstand in the early Eocene.

The curve proposed by Miller et al. (2005a) also allows us to interpret three orders of the Paleogene long-term cyclicity (Fig. 2). The cycles that constitute eustatic fluctuations shown on the original reconstruction are not considered, because their duration is not "long-term" (they are recognized at the scale of 0.1 Ma). The long-term cycles of Order A are both symmetrical and asymmetrical, and they differ strongly in absolute duration. Some of them lasted for only ~1 Ma, whereas others were longer (up to 5 Ma and even more). However, the majority of these cycles were 1–2 Ma in

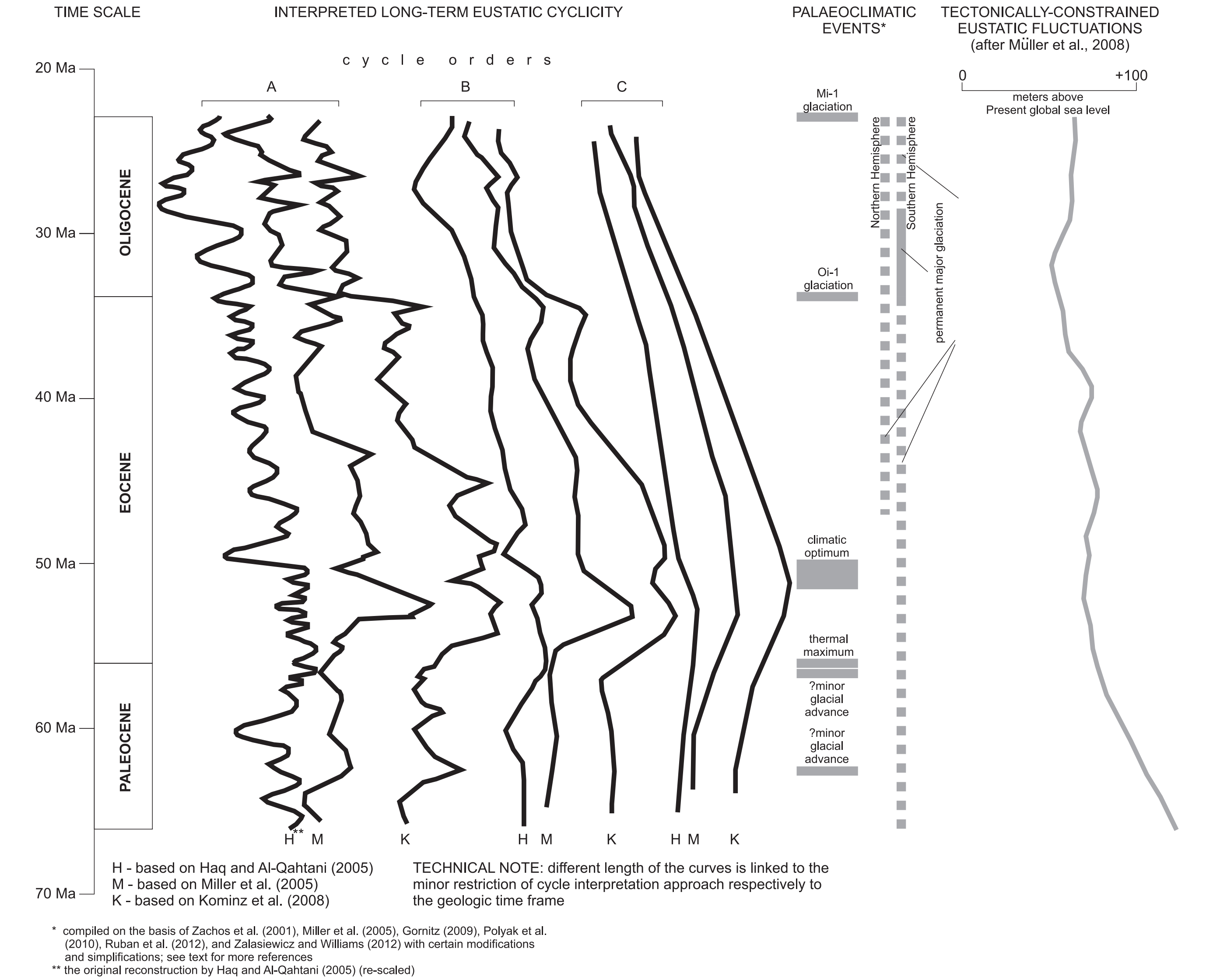

Fig. 2. Long-term eustatic cycle interpretations and the palaeoclimatic and tectonic evidence. The simplified geologic time scale follows Gradstein et al. (2012a,b).

duration. A few cycles of Order B were often asymmetrical, and their duration reached 9 Ma, although they were shorter in the Oligocene. The only long-term cycle of Order C indicates an early Eocene highstand. The preceding global sea-level rise was less gradual than the forthcoming fall.

The curve proposed by Kominz et al. (2008) depicts eustatic fluctuations, for which three orders of long-term cycles can be interpreted (Fig. 2). As in the previous case, the global sea-level changes demonstrated by the original curve cannot be considered "long-term". The cycles of Order A were both symmetrical and asymmetrical. Their duration varied between ~1 Ma and ~5 Ma. About five cycles of Order B can be established in the Paleogene. Their symmetry and duration (from ~3 Ma to ~15 Ma) differ markedly, but the magnitude of the relevant global sea-level changes was more or less comparable. The only asymmetrical cycle within the early Eocene highstand marks Order C of the long-term eustatic cyclicity.

Comparison of the three above-presented interpretations (Fig. 2) permits us to make some interesting observations. All three original curves (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) indicate three "actual" orders of long-term eustatic cyclicity, which are named provisionally as Orders A, B, and C. The lower resolution of the reconstruction by Haq and Al-Qahtani (2005) permits us to relate the cycles outlined by their curve to Order A interpretations from the curves of Miller et al. (2005a) and Kominz et al. (2008).

4. Discussion

4.1. An absence of coherence

The interpretations based on all three original curves (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) indicate strong similarity of only the C-order long-term cycle (Fig. 2). In all cases, the relevant highstand occurred in the early Eocene, and the registered changes in its absolute age (Fig. 2) lie within the possible correlation error (see above). In other words, despite differences in the data and the methods used by the separate authors, all reconstructions permit us to identify the early Eocene highstand. The latter is an evidently coherent feature. This also means that the available eustatic reconstructions permit unambiguous representation of only the longest-term global sea-level changes, because no such coherence is recorded at the lower orders. The above-said allows us to question whether the Paleogene cyclicity was really multi-ordered. On the one hand, the absence of coherence of the A and B-order long-term cycles may mean these are "artificial", i.e., they inherit peculiarities of the different methods employed by the different specialists. On the other hand, it is possible that different A- and B-order cyclicity derived from the available eustatic reconstructions indicates the very weak appearance of such cyclicity. The latter idea requires explanation, which is given below.

The dynamics of planetary climate (shifts from "greenhouse" conditions to glaciations, and vice versa) and planetary interiors (plate tectonic processes, mantle dynamics, plume emplacement, etc.) are thought to exert important controls on the global sea-level changes (e.g., Miller et al., 2005a,b; Catuneanu, 2006; Veeken, 2006; Müller et al., 2008; Lovell, 2010; Ruban et al., 2010a,b, 2012; Anjos Zerfass et al., 2013; Conrad, 2013; Haq, 2014; Ruban, 2016). The above-mentioned absence of correspondence of the A- and B-order long-term eustatic cyclicity between the interpretations based on the curve of Haq and Al-Qahtani (2005) on the one side and the curves of Miller et al. (2005a) and Kominz et al. (2008) on the other side may be explained potentially in the terms of palaeoclimate. "Greenhouse" conditions diminish the importance of glacioeustatic mechanisms, and tectonic mechanisms for global sea level change typically operate on timescales much longer than those of the A and B cycles (Conrad, 2013). These factors minimize the Earth's potential for global eustatic change, and instead establish conditions where the regional records of sea-level changes are not coherent because of differences in the tectonic evolution of particular regions (Ruban, 2010; Ruban et al., 2010a, 2012). The reconstructions by Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008) may be overwhelmed by regional signals. This echoes the earlier critique expressed by Miall (1992) and Hallam (2001), and also matches the explanations of Müller et al. (2008). The regional records employed for the development of the eustatic curves can provide an eustatic signature that is altered or masked significantly by regional tectonic influences (e.g., in the form of dynamic topography). Several authors (e.g., Kominz et al., 2008; Moucha et al., 2008; Müller et al., 2008; Spasojevic et al., 2008) have warned about such a possibility.

In addition, the database and methodology applied in obtaining the above-mentioned curves is distinct. Haq and Al-Qahtani (2005) justified the sea-level curve based on data from the Arabian Platform (although their curve is not based solely on data from Arabia). Miller et al. (2005a) dealt with data from the coastal plain of New Jersey (USA) and used techniques of backstripping, as say, the effects of sediment compaction and thermal subsidence were modeled, and the paleodepth was taken into account as well. An updated version of the latter work was presented by Kominz et al. (2008), who included new wells and different treatment of the data. As some data of Haq and Al-Qahtani (2005) by one side, and Miller et al. (2005a) and Kominz et al. (2008) by the other, are from different plate tectonics contexts, it is possible that the uncorrelated cycles represent the influence of regional effects, with a probable tectonic origin. Of course, such phenomena cannot occur on very long scales because of global tectonic influences, but previous studies of the Paleocene global transgressions and regressions (Ruban et al., 2010a, 2012) permit us to hypothesize that these phenomena can be documented at the level of stages and, probably, series. In such a case, the documented A and B orders of eustatic cyclicity may represent regional uplift and subsidence patterns at the observation locations. If this idea is confirmed, it means automatically that there is only one order (the C order in this paper) that can be confirmed to be part of the long-term eustatic cyclicity.

4.2. An evidence from the summary of regional data

The most objective knowledge about eustasy can be compiled from the regional records (e.g., Hallam, 2001; Ruban et al., 2010a, 2012). In such a case, it is sensible to compare the interpreted long-term eustatic cycles with the shoreline shifts established regionally. A preference should be given to major platform regions that are more "stable" than active island arcs or orogenic belts. Unfortunately (and surprisingly), the available stratigraphical data for the entire Paleogene is limited, and, thus, we cannot repeat the approach employed earlier by Ruban et al. (2010a, 2012). However, some appropriate data can be found in four major regions, namely Northwestern Europe (the sea-level curve of Hardenbol et al. (1998) was adapted to the modern time scale by Gradstein et al. (2012a,b)), Northern Africa (interpretations are possible on the basis of the composite stratigraphical schemas presented by Guiraud et al. (2005)), Arabia (new interpretation of maximum flooding surfaces and sequence boundaries was presented by Simmons et al. (2007)), and Southern Australia (shoreline shifts were interpreted by McGowran et al. (2004)). In order to make the data compatible and to avoid uncertainties linked to different geologic time scales used by the specialists and changes in this scale in the past years, we (1) emphasize on the only maximum flooding surfaces, (2) consider the only B- and C-level cyclicity, and (3) deal with those maximum flooding surfaces that match the levels of cyclicity.

The results of the comparison of the cyclicity interpreted from the original eustatic curves and the regional maximum flooding surfaces are highly ambiguous (Fig. 3). The correspondence of some regional maximum flooding surfaces indicates possible nearly global eustatic peaks. But these peaks do not coincide well with the B- and C-order cycle peaks. There are also regional maximum flooding surfaces that do not coincide. Finally, there are cycle peaks that are not associated with common maximum flooding surfaces. What is especially surprising is the absence of concentration of regional maximum flooding surfaces in the early and middle Ypresian, where the great C-order highstand is registered. Taken together, these observations suggest that the interpreted B- and C-order cycles are not well supported by the regional data.

The above-presented observations allow yet another important inference. "Greenhouse" conditions of the early Eocene (Zachos et al., 2001; see Fig. 2) were favorable for the "overprint" of the climatic controls of the global sea-level changes by the regional tectonic activity (such a possibility is demonstrated by Ruban et al. (2010a, 2012) by example of the Paleocene), and this resulted in the absence of the coherent maximum flooding surfaces. If so, there might have been no such thing as well-pronounced eustatic cyclicity in this time. Moreover, we think that individual maximum flooding surfaces should not necessarily be present (or at least not easily recognized) in the stratigraphic record of the Ypresian because of the same reason, although this requires further examination.

4.3. Sea-level cycles in a greenhouse world?

According to the available palaeoclimatological data (Kennett and Stott, 1991; Zachos et al., 2001; Miller et al., 2005b; Sluijs et al., 2005, 2008; Zachos et al., 2008; Gornitz, 2009; Zalasiewicz and Williams, 2012), the Paleogene was a period dominated by "greenhouse" conditions, although two glaciations (the so-called "Oi-1" and "Mi-1") marked the beginning and the end of the Oligocene Epoch. The full strength of the Cenozoic glaciation was reached in the last few millions of years of this era (Ehlers and Gibbard, 2007), but some glaciation persisted through the Paleogene Period in the Southern Hemisphere, where relatively short-termed glacial advances occurred (Zachos et al., 2001; Miller et al., 2005a; Ruban et al., 2012), and the first ice sheet appeared in the Northern Hemisphere in the middle Eocene (Polyak et al., 2010). Two remarkable events were the Paleocene–Eocene

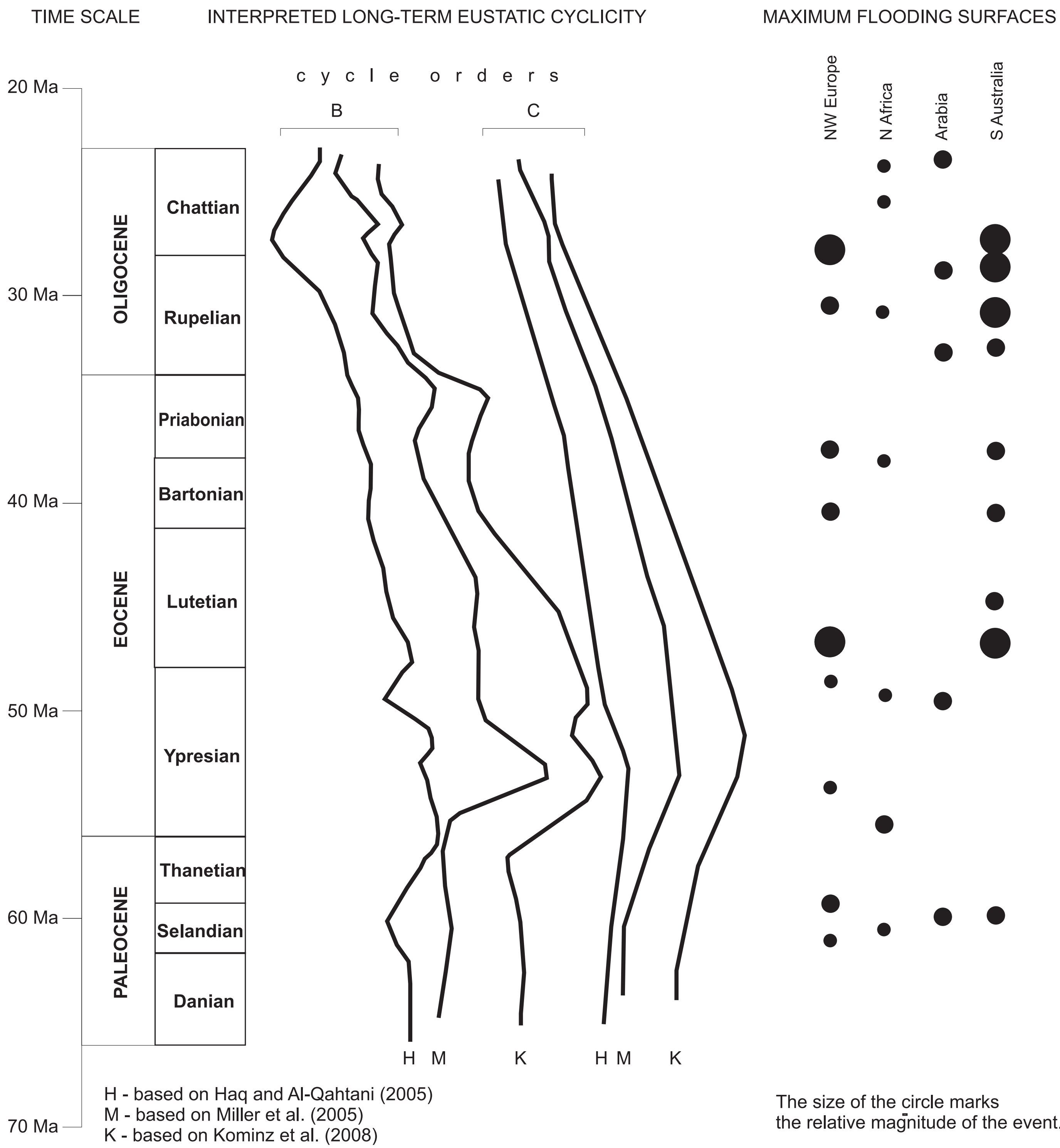

Fig. 3. Long-term eustatic cycle interpretations and regional major flooding surfaces (established provisionally on the basis of data from McGowran et al. (2004), Guiraud et al. (2005), Simmons et al. (2007) and Gradstein et al. (2012a,b)). The simplified geologic time scale follows Gradstein et al. (2012a,b).

Thermal Maximum and the early Eocene climatic optimum (Zachos et al., 2001; Kent et al., 2003; Cohen et al., 2007; Pearson et al., 2007; Weijers et al., 2007; Moore and Kurtz, 2008; Retallack, 2008; Gornitz, 2009; Roberts et al., 2009; Westerhold et al., 2009; Eberle et al., 2010; Hodgson et al., 2011; Bowen, 2013; Chew and Oheim, 2013; Hyland and Sheldon, 2013; Pujalte et al., 2014). There were some other potentially significant events such as the early Paleocene hyperthermal (Ali, 2009; Bornemann et al., 2009).

Undoubtedly, glacial advances facilitated global sea-level falls, and the thermal expansion of the seawater at the times of significant warming facilitated global sea-level rises on different time scales. A comparison of the Paleogene palaeoclimatic history with the long-term eustatic cyclicity (Fig. 2) implies that the recorded C-order long-term cycle peaked in the early Eocene, and it can be linked to the extraordinary warmth of either the Paleocene–Eocene Thermal Maximum or the early Eocene climatic optimum (or, most probably, both). Sluijs et al. (2008) postulated that the onset of the Paleocene–Eocene sea-level rise preceded the Paleocene–Eocene Thermal Maximum, which led the authors to consider a tectonic origin to the transgression, possibly the ocean floor uplift in the North Atlantic Igneous Province. It should be noted, however, that the early Eocene world did not remain abnormally warm at its entire interval; some cooling also took place (Jolley and Widdowson, 2005). A problem with climate change as an explanation for this Order C variation is that the ice sheets and seawater warming together only account for about 50–60 m of higher sea level (e.g., Lemke et al., 2007; Conrad, 2013), even if the presence of polar ice provides better conditions for the regional appearance of the "ideal" cyclicity (Boulila et al., 2011). If so, the amount of sea level change due to this mechanism in the early Cenozoic, when the volume of landed ice was smaller, might be even more limited, and tectonic controls on the eustatic fluctuations should be of more importance. This means that the Paleogene climate history cannot explain (at least fully) the interpreted C-order cyclicity by definition.

It has been established presently that "greenhouse" conditions favored aquifer-eustasy, when regressions occurred despite the warmth (Sames et al., 2016; Wendler and Wendler, 2016; Wendler et al., 2016). If this occurred in the Paleogene and, particularly, Eocene, this mechanism can explain the noted absence of maximum flooding surfaces concentration. At the same time, the aquifer-eustasy questions the available eustatic reconstructions and their interpretations (in the other words, uncertainty about this mechanism means it is too early to judge about the multi-ordered cyclicity of the global sea level).

4.4. Global tectonics and sea-level cycling

The models proposed by Müller et al. (2008) and Spasojevic and Gurnis (2012) link the Paleogene eustasy to the global tectonics and the mantle convection. The both models permit the reconstruction of long-term changes of global sea level on the basis of estimates of changes in ridge volume constrained by plate tectonic reconstructions. The tectonically constrained eustatic curve of Müller et al. (2008) differs strikingly from the interpretations of the curves of Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008). For example, the early Eocene C-order long-term eustatic maximum shown by all these curves corresponds to the prominent lowstand constrained only by ridge volumes changes by Müller et al. (2008) (Fig. 2). Additionally, reconstructions of sea level based on estimates of tectonics of the time-varying influence of tectonics (e.g., Spasojevic and Gurnis, 2012; Conrad, 2013) suggest gradual long-term global sea-level fall throughout the analyzed period, and do not show the early Eocene highstand shown in our interpretations (Fig. 2).

The C-order long-term eustatic cyclicity interpreted from the original curves of Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008) indicates fluctuations that lasted on the scale of tens of millions of years. If such cycles are tectonic in origin, they seem to occur on timescales shorter than the 100 million year timescales of the so-called "Wilson's cycles" (Cogné and Humler, 2008), which mark important stages in the Earth's tectonic evolution. One may suppose that very long term sea level trends associated with supercontinent cycles (Santosh, 2010; Yoshida and Santosh, 2011; Nance and Murphy, 2013; Conrad, 2013; Nance et al., 2014) may be also reflected in the interpreted long-term eustatic fluctuations. However, the noted discrepancy between the interpretations based on the available eustatic curves (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) and the models depicting global tectonic constraints on eustasy (Müller et al., 2008; Spasojevic and Gurnis, 2012; Conrad, 2013) questions the possible relationship of long-term eustatic fluctuations and the tectonic cycles. This also questions the validity of the interpreted C-order cyclicity.

4.5. Other sea-level cycles?

If it was anyway true, the C-order long-term cyclicity interpreted in this study can be treated as first-order cyclicity, because the duration and amplitude of the interpreted cycles appear to be more or less comparable with those of the conventional "first-order cycles" (Read, 1995; Veeken, 2006; Haq, 2014). But does this mean that there were not any other long-term eustatic fluctuations? Because the present analysis is limited to the Paleogene, answering this question would require consideration of the entire Phanerozoic and Precambrian. Presentation of Paleogene eustasy in such a wider perspective is attempted below, although this is a very tentative analysis.

The Phanerozoic curves proposed by Hallam (1984) and then by Haq and Al-Qahtani (2005), Haq and Schutter (2008) and Haq (2014) indicate two outstanding global sea-level highstands that occurred in Ordovician and the mid-Cretaceous. Which of them resulted in higher absolute sea level remains a subject for debate (e.g., Ruban et al., 2010b), but these highstands were the largest in the Phanerozoic record. If so, the early Eocene eustatic peak recorded in this work (Fig. 2) may be just a "lower-level" feature on the very long-term trend stretching from the mid-Cretaceous highstand to the Quaternary glaciation-related lowstand. The model of Spasojevic and Gurnis (2012) depicting tectonically constrained global sea-level fall from the late Mesozoic to the late Cenozoic generally confirms this interpretation. However, the latter is challenged by the reconstructions of Miller et al. (2005a) and Kominz et al. (2008), which indicate the early Eocene peak as unprecedented in the Cretaceous–Quaternary history of the Earth. Several new findings should be also considered. Firstly, climatic cooling, if not minor glaciation, occurred in the mid-Cretaceous and the Late Cretaceous (Frakes and Francis, 1988; Frakes and Krassay, 1992; Alley and Frakes, 2003; Miller et al., 2005a,b; Bornemann et al., 2008; Galeotti et al., 2009; Russell, 2009; Boulila et al., 2011; Moriya, 2011; Bowman et al., 2013; Maurer et al., 2013; Peropadre et al., 2013; see also discussion in Haq, 2014). Secondly, the same took place in the Ordovician (Saltzman and Young, 2005; Gornitz, 2009; Turner et al., 2011, 2012; Cherns et al., 2013; Elrick et al., 2013; Holmden et al., 2013). If so, we can hypothesize that the Ordovician, mid-Cretaceous, and early Eocene eustatic peaks were more or less comparable, which disproves the eustatic cyclicity of order higher than the C-order documented in the Paleogene. Of course, this hypothesis should be further tested.

The Precambrian record of geologic history may imply eustatic fluctuations much stronger than any of those that occurred in the Phanerozoic. The lines of evidence are as follows. Firstly, the "Snowball Earth" or the "Slushball Earth" models (Kirschvink, 1992; Hoffman et al., 1998; Kirschvink et al., 2000; Eriksson et al., 2004; Eyles and Januszczak, 2004; Eyles, 2008; Brasier, 2009; Gornitz, 2009; Hoffman and Li, 2009; Gaucher et al., 2010; Micheels and Montenari, 2010; Pierrehumbert et al., 2010; Strand, 2012; Zalasiewicz and Williams, 2012; Eriksson et al., 2013; Erwin and Valentine, 2013; Young, 2013) imply severe Neoproterozoic glaciations, which should lead potentially to extremely low global sea level, although such an interpretation depends strongly on the amount of sea ice, which is a debatable issue (e.g., Brasier, 2009; Gaucher et al., 2010). It cannot be excluded that the same might have also occurred for earlier Precambrian glaciations (Eriksson et al., 2004; Eyles and Januszczak, 2004; Gargaud et al., 2012; Strand, 2012; Hoffman, 2013; Melezhik et al., 2013; Tang and Chen, 2013; Young, 2013). Secondly, the size of lithospheric plates in the Proterozoic and, especially, the Archean and the Hadean, as well as the size of the Precambrian supercontinents, was relatively small

(Pesonen et al., 2003; Ernst, 2007, 2009; Komiya and Maruyama, 2007; Gargaud et al., 2012; Evans, 2013). This may imply a wider distribution of young domains of oceanic crust than in the Phanerozoic. As younger age of the oceanic crust is an important control on the eustatic rise (e.g., Müller et al., 2008; Anderson and Anderson, 2010), Precambrian global sea level might have reached (at least, episodically) a high position relative to the Phanerozoic and, in particular, the Paleogene, which features much larger plates (Seton et al., 2012). Such an interpretation is in agreement (at least, in part) with the outcome of modeling undertaken recently by Coltice et al. (2014). The above-mentioned and other peculiarities of Precambrian tectonics (including, first of all, the activity of mantle plumes (Gargaud et al., 2012; Gerya, 2014)) likely influenced global sea-level change on a large scale; possible changes in crust production may also induce a cyclic pattern of these changes (Eriksson et al., 2004, 2005, 2012, 2013). For the earliest times, this second line of evidence is most uncertain, because the onset of the plate tectonics on the Earth remains debatable (e.g., Hamilton, 2011; Gargaud et al., 2012; Griffin et al., 2014; Turner et al., 2014). Thirdly, the amount of water on the Earth did not remain constant at the earliest stages of the planetary evolution (Gargaud et al., 2012), which also means significant global sea-level changes (although the latter, probably, will never be modeled). Fourthly, a slow drain of water into the interiors should be considered as a long-term control on global sea-level changes (Conrad, 2013; Maruyama et al., 2014).

If the evidence given above implies Precambrian eustatic fluctuations were more "extreme" than those of the Phanerozoic, one can hypothesize the very long-term cyclicity, which can be termed "zero-order" because it exceeded (by the both duration and magnitude of cycles) what is commonly defined as the "first-order cyclicity" (Read, 1995; Veeken, 2006; Haq, 2014). The entire Phanerozoic global sea-level changes might have represented only part of any cycle, which started in the Proterozoic. Moreover, it is difficult to predict the number of such "zero" orders. As in the previous case, this preliminary idea requires further development and verification with enough data for establishment of "actual" cyclicity. However, it should not be excluded that the C-order of long-term eustatic cyclicity interpreted for the Paleogene on the basis of the available curves (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) was not the longest-lived cyclical variation. In such a case, the number of orders may vary (especially if it will be also proved that the Ordovician highstand was larger than that of the mid-Cretaceous, and that the latter was larger than that of the early Eocene). Further discussions of this issue depend strongly on the interpretation of "actual" eustatic cyclicity and its hierarchy for the Precambrian time intervals; this remains a challenging task to be achieved with the approach of sequence stratigraphy (Eriksson et al., 2004, 2005). Generally, the possibility of cyclicity orders higher than the C-order established above complicates the understanding of the Paleogene "actual" cyclicity and makes impossible to answer the question about the number of orders of this cyclicity.

5. Conclusion

The interpretation of the available global sea-level reconstructions (Haq and Al-Qahtani, 2005; Miller et al., 2005a; Kominz et al., 2008) reveals three orders of long-term eustatic cyclicity that might have operated in the Paleogene. The method of interpretation demonstrated in this paper seems to be powerful for distinction of the "actual" cycles. However, only the highest of these orders is depicted similarly by the interpretations of all chosen original curves. Moreover, there are several objections with regard to the interpreted cycles, and the issue of the number of the Paleogene long-term eustatic cycles remains uncertain because of either the non-global nature of sea-level changes reconstructed by Haq and Al-Qahtani (2005), Miller et al. (2005a) and Kominz et al. (2008), or "overprint" of the weak global fluctuations by the regional tectonic activity.

Generally, the "actual" long-term eustatic cyclicity in the Paleogene as it is currently known appears to be under question. "New-generation" eustatic curves are very necessary. These should be based on globally representative stratigraphical data and justified with global-scale modeling of palaeoclimatic and tectonic influences on the sea level. Constraining these curves is a challenge because of the serious lack of uniform stratigraphical data from many regions across the globe. Unfortunately, the now available stratigraphical data are not enough to attempt reconstruction of a new (alternative) eustatic curve like this was done in the case of the Paleocene (Ruban et al., 2012). If even there are many data from single outcrops, more important are regionally representative pieces of information, which requires significant compilation work. Assembly of several well-justified regional syntheses of data would be most helpful for the construction of "new-generation" eustatic curves.

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