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Viewpoint

In quest of Paleocene global-scale transgressions and regressions: constraints from a synthesis of regional trends

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ABSTRACT

Chronostratigraphically-justified records of regional transgressions and regressions are important for understanding the nature of the Paleocene shoreline shifts on a global scale. Review of previously synthesized data from 7 tectonically "stable" regions, namely the eastern Russian Platform, Northwestern Europe, Northwestern Africa, Northeastern Africa, the Arabian Platform, the northern Gulf of Mexico, and Southern Australia, allows a comparison of transgressions and regressions interpreted in these regions. No common patterns are found in the early Danian and late Selandian, which reflects small or zero eustatic fluctuations that are overwhelmed locally on coastlines by regional tectonic motions and local changes in dynamic support of surface topography by mantle flow. Sea level was stabilized during these stages by a warm climate and a lack of planetary-scale tectonic changes. We have detected a middle–late Danian regression that occurred in 5 of 7 study regions, and can be explained by glacial advance at ~62–63 Ma or by concurrent subduction of the Izanagi–Pacific ridge beneath eastern Asia. An early–middle Selandian transgression also occurred in 5 regions, probably, as a result of a hyperthermal at ~61 Ma that coincided with emplacement of large igneous provinces in the oceanic domain. Both events are characterized by significant diachroneity, which can also be explained by the influence of regional tectonic subsidence or uplift. Results of the present study permit us to propose a tentative framework for a new Paleocene eustatic curve that is constrained globally using available records of transgressions and regressions.

1. Introduction

The Danian, which started at 65.5 Ma and ended at 61.1 Ma, and the Selandian, which extended from 61.1 Ma to 58.7 Ma, together encompassed 6.8 Ma (Ogg et al., 2008). Chronostratigraphy of this time interval is well established (Berggren et al., 1995; Galbrun and Gardin, 2004; Dinarès-Turell et al., 2007, 2010; Ellwood et al., 2008; Ogg et al., 2008; Steurbaut and Sztrákos, 2008; Westerhold et al., 2008) and permits accurate dating and correlation of geologic events. The catastrophe that marks the start of the Danian, regardless of its true causes (Hallam and Wignall, 1997; Courtillot, 2007; Alvarez, 2008; Keller, 2008; Schulte et al., 2010), was followed by a rapid recovery of Earth's environments that enhanced the entire Paleocene geologic evolution. There were no significant tectonic re-organizations during the Danian–Selandian, although gradual changes in plate motions re-shaped the world (Golonka, 2004; Scotese, 2004; Müller et al., 2008). Global temperatures, however, did change (Zachos et al., 2001), as did sea level (Haq et al., 1987; Briskin and Fluegeman, 1990; Haq and Al-Qahtani, 2005; Miller et al., 2005; Kominz et al., 2008; Müller et al., 2008; Harris et al., 2010), although both remained relatively high. Currently, there is general agreement about the overall picture of the early–middle Paleocene world, but at a higher precision, many particular questions appear.

In particular, Danian–Selandian sea-level fluctuations remain a debated subject. Two alternative eustatic curves, one proposed by Haq and Al-Qahtani (2005), who updated a previous reconstruction of Haq et al. (1987), and another one proposed by Kominz et al. (2008), who updated a pervious reconstruction of sea level fluctuations on the New Jersey coastline by Miller et al. (2005), do not coincide well. It has become evident that no single location on Earth is suitable for reconstructing global sea-level fluctuations because changing mantle flow can uplift or depress Earth's surface, creating changing dynamic topography even in regions that are otherwise "tectonically stable" (e.g., Lithgow-Bertelloni and

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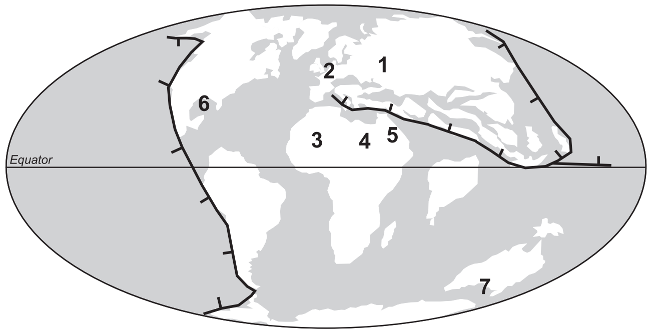

Fig. 1. Location of studied regions in the mid-Paleocene (~60 Ma). Plate tectonic map is simplified from Scotese (2004). Primary active subduction zones are shown schematically (see www.scotese.com for reference). Regions: 1 – eastern Russian Platform, 2 – NW Europe, 3 – NW Africa, 4 – NE Africa, 5 – Arabian Platform, 6 – northern Gulf of Mexico, 7 – Southern Australia.

Gurnis, 1997; Lithgow-Bertelloni and Silver, 1998; Conrad and Gurnis, 2003; Conrad et al., 2004; Moucha et al., 2008; Heine et al., 2008; Müller et al., 2008; Spasojevic et al., 2008, 2009; Al-Hajri et al., 2009; Conrad and Husson, 2009; DiCaprio et al., 2009; Lovell, 2010; Ruban et al., 2010a,b).

An interregional correlation, which involves comparing data from widely-separated regions with different tectonic and depositional settings, can permit the recognition of common patterns that reflect global-scale changes in the sea-level (cf. Bond, 1978, 1979). This type of approach was recently considered by Kominz et al. (2008), and its efficacy demonstrated for the Paleocene epoch by Zorina and Ruban (2008a,b) and Ruban et al. (2010b). Evidently, such a study should be based on review of more or less "fresh", but previously published data. The aim of the present paper is to synthesize representative already-described stratigraphic records to facilitate an understanding of the Danian–Selandian global-scale transgressive–regressive (T–R) cycles.

2. Materials and methods

This study of Danian–Selandian sea level utilizes the same material and approach as previous work devoted to interregional correlations of trangressive–regressive cycles in the Thanetian (Ruban et al., 2010b). However, some key issues, such as the geologic context of continental margins in the Danian–Selandian, should be explained clearly.

Seven exceptional (as defined by the accuracy of their chronostratigraphic frameworks) regional records are considered herein. These records are from the eastern Russian Platform, Northwestern Europe, Northwestern Africa, Northeastern Africa, the Arabian Platform, the northern Gulf of Mexico, and Southern Australia (Fig. 1), and representative sections of Danian–Selandian deposits are documented in each of them (a few examples are given in Fig. 2). Previously-interpreted and already-published information was preferred in this study (Table 1). Meanwhile, some regional T–R cycles were deduced directly from the available stratigraphical charts (Table 1). This paper utilizes these published data in order to evaluate their implications for our understanding of global Danian–Selandian T–R cyclicity. For this reason, we do not attempt to illustrate or discuss particular stratigraphic records here (for this purpose, the reader may consult the literature sources summarized in Table 1).

Although all continental platforms may experience slow dynamic uplift or subsidence (Moucha et al., 2008), we have attempted to select regions with relatively "stable" tectonic settings for the purposes of this study. In the early–middle Paleocene, the eastern Russian Platform experienced epeirogenic deformations and, particularly, an inversion at the Cretaceous/Paleogene boundary (Nikishin et al., 1999). Similarly "stable" geodynamics prevailed in Northwestern Europe, where vertical tectonic motions took place (e.g., Vandycke et al., 1991; Vandenberghe et al., 1998). Structural evolution of the North Sea (Clemmensen and Thomsen, 2005) probably also affected the continental margin nearby. Both Northwestern and Northeastern Africa remained "stable", although some uplifts and rifting occurred (Guiraud et al., 2005; Swezey, 2009). The Arabian Platform experienced subsidence coupled with some tectonic deformations along the plate margins (Sharland et al., 2001). Subsidence continued also in the northern Gulf of Mexico during the early–middle Paleocene, although the Laramide orogeny on the continent influenced sedimentation (Salvador, 1991; Zarra, 2007). Southern Australia experienced subsidence and an influence of subduction along the nearby West Pacific margin (DiCaprio et al., 2009).

Our interregional correlation of regional records permits the recognition of common transgressions and regressions and, thus, the identification of global-scale T–R cycles. The dispersed positioning of the study regions (Fig. 1) should prevent correlated changes in dynamic topography or local tectonics from affecting all records. For example, downwelling related to the Neo-Tethyan subduction zone could affect only the Arabian Platform, Northeastern Africa, and the northern portion of Northwestern Africa (Fig. 1). Different lithologies (Fig. 2) should prevent major biases linked to preferential preservation of shoreline shifts in particular kinds of sedimentary rocks. Thus, coherent (global-scale) T–R cycles among all, or even most, records may be treated as a globally consistent signal. We assume that coherent T–R cycles (i.e., common for most of the studied regions) are indicators of global eustatic changes. In this case, regional/local tectonics (e.g., subsidence) and sedimentation (e.g., sediment supply and dynamics of accommodation spaces) influences must be insignificant, because far-located regions with different tectonic and sedimentation regimes exhibit a common signal. This paper emphasizes such common transgressions/regressions, but does not treat their magnitude, which would require detailed stratigraphic datasets that are not available for many regions. An unnecessary mix of shoreline shifts with water depth changes is also omitted in this study, which is why new data from the New Jersey margin (Kominz et al., 2008; Harris et al., 2010) are not included in our analysis. Here, we focus on the T–R cycles of the same (usually 2nd) order, which are, therefore, approximately comparable in duration and strength.

We perform an interregional correlation as accurately as possible on the basis of the modern chronostratigraphy of the Danian and Selandian stages, which was summarized by Ogg et al. (2008). Possible uncertainties in this chronostratigraphic framework (e.g., Westerhold et al., 2008) as well as possible errors in regional datings (Table 1), are considered in our interpretations. Importantly, the Danian/Selandian boundary has recently been replaced upwards according to the decision of the International Commission on Stratigraphy (Ogg et al., 2008; Vandenberghe, pers. comm.). Thus, some deposits previously dated as earliest Selandian have become latest Danian, which required us to interpret the T–R records with care. Fortunately, the available regional records are calibrated along the numerical time scale, biozones, and/or magnetic chrons (Table 1), which permitted us to re-place (when necessary) the stage boundary accurately. Thus, all considerations presented below account for a new position of the Danian/Selandian boundary. Dinarès-Turell et al. (2010) have recently suggested a new age of the Danian/Selandian boundary, i.e., 61.641 Ma. In this paper, however, we followed the age recommended in the last reference book of the International Commission on Stratigraphy (Ogg et al., 2008).

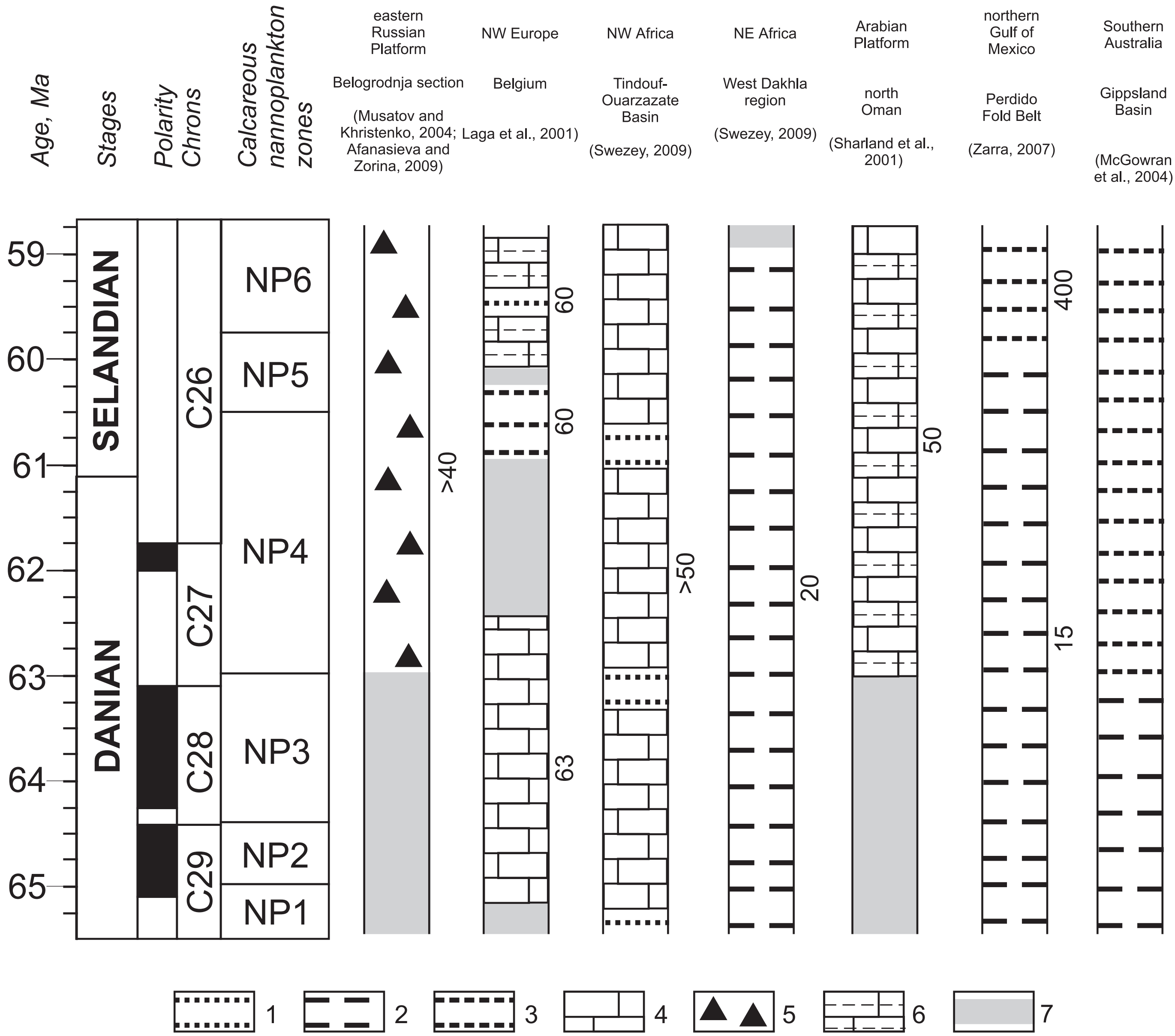

Fig. 2. Selected Danian–Selandian reference sections of the studied regions (only very general correlations are possible, and detailed chronostratigraphy is given here only for reference). When available, approximate (maximum when considered) thickness (in meters) is indicated along each column. Lithologies: 1 – sandstones and all siliciclastics excluding shales, 2 – shales (and mudstones for the northern Gulf of Mexico), 3 – undifferentiated/mixed siliciclastics, 4 – carbonates (limestones), 5 – siliceous rocks, 6 – marlstones and carbonate mudstones, 7 – hiatuses. More lithologic data are available within the sources of information (see Table 1). Chronostratigraphy after Ogg et al. (2008). Lithologic information for Southern Australia is given very schematically on the basis of Fig. 14 in McGowran et al. (2004). Larger data sets were used for T–R cycle interpretations (see Table 1), whereas this figure shows differences of sedimentary successions between the regions. Thus, incompleteness of the depicted sections does not affect our analysis.

3. Review of regional syntheses

3.1. Regional syntheses with originally-interpreted T–R cycles

Three regional syntheses, which contain interpretations of Danian–Selandian T–R cycles, characterize the eastern Russian Platform, Northwestern Europe, and Southern Australia. Interpretations attempted in these syntheses are relatively accurate and, even if they are based on application of slightly different tools, the reconstructed curves give valuable evidence of T–R patterns (Table 1).

Zorina and Ruban (2008b, Fig. 1) presented the Paleocene T–R curve for the eastern Russian Platform, which is well justified using chrono- and biostratigraphic scales (Table 1). This curve depicts 3 cycles, which embraced the early–middle Danian (transgression peak occurred at ~64 Ma), the late Danian–early Selandian (transgression peak occurred at ~60.5 Ma), and the middle–late Selandian (transgression peak occurred at ~59.3 Ma) (Fig. 3). The last cycle ended already in the Thanetian (Ruban et al., 2010b).

Hardenbol et al. (1998) presented the Mesozoic–Cenonzoic T–R curve for Northwestern Europe. Ogg et al. (2008, Fig. 13.4) put this curve and, particularly its Paleogene part, into the new chronostratigraphic context (Table 1), and the latter interpretation is followed herein. No complete T–R cycles embraced the Danian–Selandian time interval according to this interpretation. Long-term regression, which started in the Cretaceous, reached its peak at 61.1 Ma to be followed by a transgression (Fig. 3), which ended in the Thanetian (Ruban et al., 2010b).

McGowran et al. (2004, Fig. 5) presented a Southern Australian Cenozoic T–R curve anchored to detailed chrono- and biostratigraphic frameworks (Table 1). This interpretation suggests no complete regional T–R cycles during the Danian–Selandian time

Table 1
Sources of information used in this study for interregional correlation of Danian–Selandian T–R cycles (detailed data on each region can be found in the sources indicated below). These sources should be consulted for more data on particular stratigraphic records and sections. Description and critical evaluation of these records is not an objective of the present review paper. For all regions, only cycles of the same magnitude (commonly 2nd-order) are included in order ensure sufficient data consistency to make the comparison.

Region	Main source(s)	Type of information from the main source(s) used in this study	Stratigraphic control on T–R interpretation	Resolution of T–R interpretation (very approximate possible uncertainties in regional datings are given in square brackets)	Additional source(s)
Eastern Russian Platform	Zorina and Afanasieva (2006), Afanasieva and Zorina (2008), Zorina and Ruban (2008b)	Interpreted T–R cycles (on the basis of facies analysis and maximum flooding surfaces identification)[a]	Diatom- and nannoplankton-based biozonation; regional data are presented along the numerical time scale	Moderate [<0.5 Ma]	Distanov et al. (1970), Sahagian and Jones (1993), Akhmetiev and Beniamovskij (2003), Musatov and Khristenko (2004), Afanasieva (2004), Afanasieva and Zorina (2009), Zorina and Ruban (2008a)
Northwestern Europe	Ogg et al. (2008)	Interpreted T–R cycles, coastal onlap record, sequence stratigraphic surfaces (on the basis of detailed sequence stratigraphic constraints)[a]	Foraminifera- and nannoplankton-based biozonation, polarity chrons; regional data are presented along the numerical time scale	Moderate [<0.3 Ma]	Hardenbol et al. (1998), Michelsen et al. (1998), Vandenberghe et al. (1998), Laga et al. (2001)
Northwestern Africa	Guiraud et al. (2005)	Unconformities, lateral facies distribution (interpretations of T–R cycles are based on observed changes in the lateral distribution of marine and continental facies, and on the spatial extent of hiatuses)[b]	Only general chronostratigraphic scales are available (Guiraud et al. (2005) presented sedimentary records of various NW African basins on charts, where the Paleocene stages can be traced)	Low [<1.0 Ma]	Swezey (2009)
Northeastern Africa	Guiraud et al. (2005), Swezey (2009)	Unconformities, lateral facies distribution (interpretations of T–R cycles are based on observed changes in the lateral distribution of marine and continental facies, and on the spatial extent of hiatuses)[b]	Only general chronostratigraphic scales (within the numerical time scale) are available (Guiraud et al. (2005) presented sedimentary records of various NE African basins on charts, where the Paleocene stages can be traced)	Low [<0.7 Ma]	
Arabian Platform	Sharland et al. (2001), Simmons et al. (2007)	Lateral facies distribution, sequence stratigraphic surfaces (interpretations of T–R cycles are based on the documented sequence boundaries, on maximum flooding surfaces, and on the observed spatial extent of non-deposition)[b]	Foraminifer-based biozones, various chronostratigraphic data (referred, but not specified by Sharland et al. (2001) and Simmons et al. (2007)); regional data are presented along the numerical time scale	High [<0.1 Ma]	Le Nindre et al. (2003)
Northern Gulf of Mexico	Zarra (2007)[c]	Coastal onlap record, 2nd-order sequence stratigraphic surfaces (interpretations of T–R cycles are based on the documented sequence boundaries, on maximum flooding surfaces, and on observed lateral distribution of facies)[b]	Foraminifera-based biozons, polarity chrons; regional data are presented along the numerical time scale	High [<0.1 Ma]	Galloway et al. (1991), Mancini and Tew (1991), Salvador (1991), Xue and Galloway (1993), Galloway et al. (2000)
Southern Australia	McGowran et al. (1997, 2004), McGowran (2005)	Interpreted 2nd-order T–R cycles (on the basis of facies sequence stratigraphic constraints, observed lateral distribution of marine facies, and the spatial extent of hiatuses)[a]	Foraminifer-based biozonation, polarity chrons; regional data are presented along the numerical time scale	Moderate [<0.5 Ma]	DiCaprio et al. (2009)

[a] For these regions, previously-attempted and published (in the main source(s)) interpretations of T–R cycles are utilized for the purposes of this study.
[b] For these regions, interpretations of T–R cycles are made in this study on the basis of information from the sources.
[c] Only a high-resolution coastal onlap record (with no accounting for data on deep-water deposition) was used from this source.

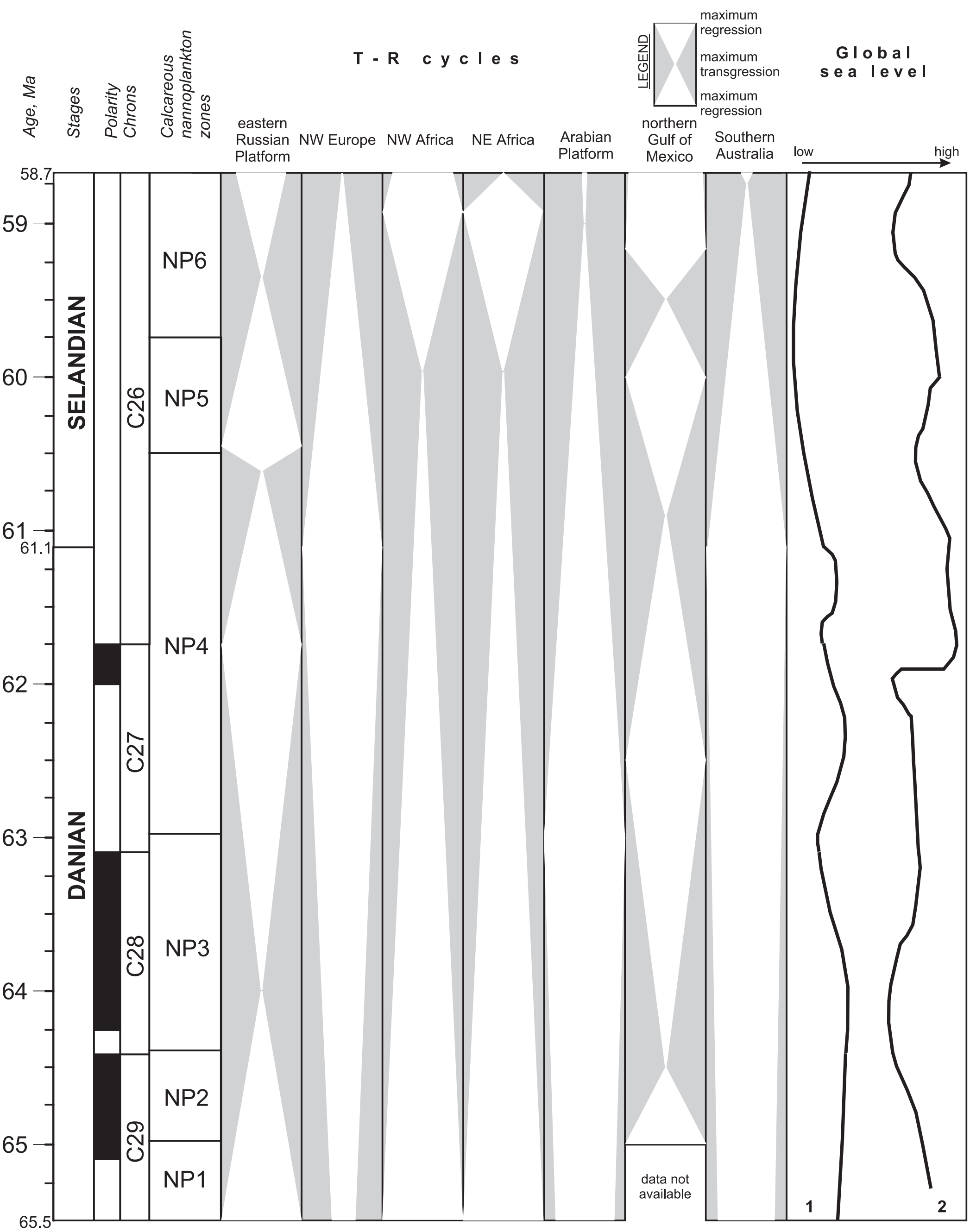

Fig. 3. Correlation of the Danian–Selandian regional T–R cycles and global sea-level curves (1) after Haq and Al-Qahtani (2005), (2) after Kominz et al. (2008). Note the relatively low resolution of the global sea-level curves. The curve suggested by Kominz et al. (2008) may be unjustified at the Cretaceous–Paleogene transition, and thus it is considered herein since 65 Ma. Table 1 lists sources of information. Chronostratigraphy after Ogg et al. (2008); Westerhold et al. (2008) presented an alternative timing of events.

interval. Long-term regression lasted during the entire Danian, reached a maximum at ~61.1 Ma, and was followed by a more rapid transgression that peaked near the end of the Selandian, at ~58.7 Ma (Fig. 3). New regression gained strength only in the Thanetian (Ruban et al., 2010b).

3.2. Regional syntheses with no interpretations of T–R cycles

Four regional syntheses, which summarize the lithostratigraphical data from Northwestern Africa, Northeastern Africa, the Arabian Platform, and the northern Gulf of Mexico, provide sufficient material for straightforward interpretations of Danian–Selandian T–R cycles. Data on some North African basins are low-resolution and do not provide details on bio- or magnetostratigraphic controls (Table 1). We consider these data, however, for three reasons (cf. Ruban et al., 2010b). First, the northern part of Africa was large and "stable" in the Paleogene. And, thus, the relevant geological records provide important information on shoreline shifts that occurred on the generally low-lying margin of this continent. Second, the synthesis of Guiraud et al. (2005) generates a comprehensive regional stratigraphic framework, which permits evaluation of T–R cycles with an uncertainty smaller than one half of a stage. Third, data from Africa are new (Guiraud et al., 2005) and are attached to a current chronostratigraphic scale, which speaks to their importance for global reviews such as the one attempted here. By contrast, both the Arabian

Platform and the northern Gulf of Mexico feature high-resolution lithostratigraphical data that have already been interpreted partly using the tools of sequence stratigraphy, which simplifies recognition of T–R cycles in this paper (Table 1).

Guiraud et al. (2005) synthesized various data on lithostratigraphy and facies from Northwestern Africa and presented them within the modern chronostratigraphic framework (Table 1). An interpretation of T–R cycles from this synthesis is possible from an examination of major fluctuations in the areas of marine deposition and the stratigraphic distribution of hiatuses/disconformities. Generally, the marine deposition embraced large areas in Northwestern Africa during the Paleocene (Guiraud et al., their Fig. 57A; compare also with their Figs. 49B and 57B). Fig. 26 of Guiraud et al. (2005) depicts: 1) a decrease in area with non-deposition through the Paleocene (including the Thanetian) in the Oued Mya Basin of the Algerian Sahara, 2) local disconformities at the base-Paleocene and in the mid-Paleocene (possibly prior to, or contemporaneous with, the base of the Thanetian boundary) and an increase in marine deposition area between these interruptions of the sedimentary record in the Senegal–Mauritania region, 3) an early Paleocene (most or all of the Danian) interruption of the stratigraphic record on the eastern margin of the Taoudenni area and in the Iullemmeden and Tim Mersoi areas, 4) a slight increase in marine sedimentation in the mid-Paleocene in the Iulemmeden and Tim Mersoi areas, 5) a base-Paleocene disconformity in the Termit area of eastern Niger and in the territory of Chad, and 6) mid-Paleocene laterites in the Termit area of eastern Niger. Additionally, Swezey (2009) mentioned an unconformity between the Cretaceous and Paleocene deposits in the Iullemmeden Basin. Taken together, these constraints from particular basins of the region can be interpreted unambiguously to establish a transgressive trend throughout the Danian–Selandian for the entirety of Northwestern Africa (Fig. 3). The beginning of the Paleocene was, undoubtedly, a time during which this trend was established. A minor regressive episode, which occurred sometime during the Selandian (as suggested by information from the Senegal–Mauritania region and Termit), interrupted this trend, and a regression phase should be postulated. Taking into account the lateral shifts of facies and the area of non-deposition in the Oued Mya Basin, Senegal–Mauritania, Illeummeden and Tim Mersoi, one may conclude that the change from transgression to regression occurred in the Selandian. Another transgression started in the late Selandian (Fig. 3), or maybe even at the Selandian–Thanetian transition, which partly improves the interpretation of Ruban et al. (2010b). As suggested by facies changes (Guiraud et al., 2005, Fig. 26), the peak of this transgression was reached at about the Paleocene–Eocene transition (see also Ruban et al., 2010b).

The same Guiraud et al. (2005) synthesized various data on lithostratigraphy and facies from Northeastern Africa and presented them on a modern chronostratigraphic basis (Table 1). An interpretation of T–R cycles from this synthesis is possible as an examination of major fluctuations in the areas of marine deposition and stratigraphic distribution of hiatuses/disconformities. Fig. 27 of Guiraud et al. (2005) depicts 1) a striking hiatus at the lower Danian boundary in Southeastern Sirt, the North-Western Desert, and the Nile delta and 2) no major changes in all regions until the late Paleocene regression. Fig. 48 of Guiraud et al. (2005) suggests that distal marine facies appeared in the Sirt Basin of Libya during the earliest Paleocene. Swezey (2009) indicated 1) an unconformity between the Cretaceous and Paleogene deposits in northern and central Egypt and 2) an end-Selandian unconformity in central Egypt. Taken together, this information permits delineation of a transgression since the early Danian and a regression peak in the late Selandian (Fig. 3). If so, two trend changes (from transgression to regression) should be suggested: one around the Danian–Selandian transition or later (by analogy with Northwestern Africa – see above), and another at the Selandian–Thanetian transition because Guiraud et al. (2005) provide evidence of regression since at least the early Thanetian.

For the Arabian Platform, we used the sequence stratigraphic interpretations first made by Sharland et al. (2001) and then improved by Simmons et al. (2007) (Table 1). The latter authors corrected the absolute ages of the key sequence stratigraphic surfaces. The original information is gathered (and presented along the numerical time scale) by Sharland et al. (2001) on their Fig. 3.38 and by Simmons et al. (2007) on their Fig. 1. The Pg10sb sequence boundary (63.0 Ma, Danian) and the Pg 10 maximum flooding surface (59.0 Ma, Selandian) are reported from the Danian–Selandian succession (Simmons et al., 2007). In the underlying strata, the K180 maximum flooding surface (70.0 Ma, Maastrichtian) was determined by Simmons et al. (2007), whereas Ruban et al. (2010b) presented the T–R pattern interpretation for the overlying strata (regressive trend from the beginning of the Thanetian). The ages of the horizons given above are evaluated with biostratigraphic tools (see references in Sharland et al., 2001 and updates by Simmons et al., 2007). Sharland et al. (2001) indicated a transgressive systems tract between the Pg10sb and the Pg10 maximum flooding surface, and a highstand systems tract above the Pg10 maximum flooding surface. On the basis of the above-mentioned information, it is sensible to delineate a regressive trend starting in the Maastrichtian and lasting until 63.0 Ma, a transgressive trend between 63.0 Ma and 59.0 Ma, and also a new regressive trend beginning in the very end of the Selandian (Fig. 3). The latter culminated only after the Paleocene (Ruban et al., 2010b).

Zarra (2007) discussed with precision the sequence stratigraphic interpretations for the northern Gulf of Mexico. From his interpretations, we chose the sequence stratigraphic model that deals with the coastal zone (Zarra, 2007) (Table 1). It should be noted that his paper is generally devoted to deep-marine deposition, but the above-mentioned model depicts sequence stratigraphy of the coastal zone. Zarra (2007) and earlier Galloway et al. (2000) did not provide data on the lowest Danian, i.e., strata older than 65.0 Ma. A total of 4 sequence boundaries with ages of 65.0 Ma, 62.5 Ma, 60.0 Ma, and 59.2 Ma, and 3 maximum flooding surfaces with ages of 64.5 Ma, 60.9 Ma, and 59.5 Ma shown by Zarra (2007, Fig. 3) are relevant to our interpretations. These ages are established with the help of bio- and magnetostratigraphy (numerical time scale is also given by Zarra on his Fig. 3). Sequence boundaries mark maxima in the basinward shoreline shifts, whereas maximum flooding surfaces mark maxima in the landward shoreline shifts. Thus, the former indicate peaks of regressions, whereas the latter indicate peaks of transgressions. For the purposes of the present study, we delineated transgressive trends between the sequence boundaries and the maximum flooding surfaces, and regressive trends between the maximum flooding surfaces and the sequence boundaries. As a result, 3 T–R cycles can be delineated (Fig. 3). The first cycle embraced the early–middle Danian (transgression peak occurred at ~64.5 Ma). The second cycles encompassed the late Danian–early Selandian (transgression peak occurred at ~60.9 Ma). The third cycle took place in the middle Selandian (transgression peak occurred at ~59.5 Ma). A new transgression started in the late Selandian, but it peaked only in the mid-Thanetian (Ruban et al., 2010b).

4. Interpretations and inferences

4.1. Common T–R patterns

Our interregional correlation of regional T–R cycles (Fig. 3) permits detection of two common patterns, which we interpret as global-scale cycles. The first pattern is the middle–late Danian regression, which is evident from five regions, namely the eastern Russian Platform, Northwestern Europe, the Arabian Platform, the northern Gulf of Mexico, and Southern Australia. This regression started at different times in different regions, but culminated before or near the Danian/Selandian boundary with a certain degree of diachroneity. The Arabian Platform and the northern Gulf of Mexico experienced this regressive peak earlier than did the other three regions. In Northwestern Europe and Southern Australia, this regression occurred synchronously (Fig. 3). The second common pattern is the early–middle Selandian transgression, which took place in five regions, namely Northwestern Europe, Northwestern Africa, Northeastern Africa, the Arabian Platform, and Southern Australia. The peak of this transgression was reached with a significant diachroneity: in Northwestern Europe the peak occurs at the very end of the Selandian, while Northwestern Africa and Northeastern Africa experienced the transgression maximum synchronously in the mid-Selandian. It should be noted that in two other regions, i.e., the eastern Russian Platform and the northern Gulf of Mexico, the transgression began in the late Danian, but this trend was interrupted in the early and middle Selandian, respectively (Fig. 3). Therefore, we cannot exclude the possibility that the noted early–middle Selandian transgression influenced these two regions.

Our interregional correlation also suggests that no common T–R patterns, and therefore no global-scale transgressions or regressions, can be found in the early Danian and the late Selandian (Fig. 3). In the first case, transgressions on the eastern Russian Platform, Northwestern Africa, Northeastern Africa, and the northern Gulf of Mexico coincided with regressions in Northwestern Europe, the Arabian Platform, and Southern Australia. In the second case, regression trends or maxima on the eastern Russian Platform, Northwestern Africa, Northeastern Africa, and the northern Gulf of Mexico coincided with transgression trends or maxima in Northwestern Europe, the Arabian Platform, and Southern Australia. The absence of correspondence between the regional T–R cycles during these noted time intervals resembles that observed by Ruban et al. (2010b) in the early–middle Thanetian.

4.2. Comparison with eustatic curves

Global-scale T–R patterns should reflect the global sea-level fluctuations driven by either glacioeustatic mechanisms or planetary tectonic processes. If so, transgressions and regressions common for the regions considered in this study can be brought into correspondence with two available eustatic curves. Haq and Al-Qahtani (2005) suggest a gradual fall in the global sea level through the Danian–Selandian interval with 3 highstands in the Danian and a prominent lowstand in the mid-Selandian (Fig. 3). Trends and events delineated by this curve coincide with neither the middle–late Danian regression nor the early–middle Selandian transgression. The other reconstruction attempted by Kominz et al. (2008) reveals Danian sea level fluctuations about a constant average level, and a slight eustatic fall during the Selandian. This curve demonstrates partial, although not complete, agreement with our T–R interpretations: the late Danian regressive maximum coincides with a remarkable global sea-level fall (Fig. 3).

The early Danian, where no common T–R patterns are found, corresponds to a period of relative eustatic stability that is indicated by both Haq and Al-Qahtani (2005) and Kominz et al. (2008). In contrast, the late Selandian interval, also with no common T–R patterns, was a time of either global sea-level rise according to Haq and Al-Qahtani (2005) or major eustatic fluctuations according to Kominz et al. (2008). It should be noted that the eustatic curve by Kominz et al. (2008), which is an updated version of the Miller et al. (2005) curve, is derived from a single, although important, locality, namely the New Jersey margin of North America. Müller et al. (2008), who examined the curve by Miller et al. (2005) critically, noted the likely influence of dynamic topography on sea-level interpretations in the New Jersey area. Moreover, Kominz et al. (2008) themselves argued for interregional testing of their reconstruction.

5. Discussion

5.1. Possible controls on Danian–Selandian T–R patterns

The punctuated appearance of global-scale T–R cycles during the Danian–Selandian time interval requires an explanation. Three plausible factors should be considered, namely climate, which can change the volume of seawater (via glacioeustasy or thermal water expansion), global tectonics, which can change the "container" volume of the ocean basins, and regional/local tectonics, which can also affect T–R cycles. As discussed by the previous work (Ruban et al., 2010b), the two former mechanisms are able to produce sharp globally-correlating T–R patterns via significant rises and falls of global sea level, whereas the latter masks the relative stability of the sea level during glacier-free "hothouse" periods without major tectonic perturbations.

5.1.1. Early Danian lack of T–R cycles

During the early Danian (with the exception of a short interval following the Cretaceous/Paleogene catastrophe, when paleoenvironments were strongly perturbed), global temperatures experienced a slight increase (Zachos et al., 2001). There is no evidence of glaciation at the beginning of the Danian, whereas the possible effects of thermal expansion of seawater (Harrison, 1990; Miller et al., 2005) after slight warming should be minimal if any. Consequently, climatic conditions did not favor eustatically-driven transgressions or regressions at this time. The available plate tectonic reconstructions (e.g., Golonka, 2004; Scotese, 2004; Müller et al., 2008) also do not show any major and rapid reorganizations that could alter the global sea level during such a short interval as the early Danian. The unique exception is the activity of mantle plumes. Abbott and Isley (2002) indicate two superplume events, namely emplacement of the Deccan traps and the Peary Land dikes, around the Cretaceous–Paleogene transition, although with a significant uncertainty in their age. These plumes occurred in continental domains, and thus their influence was probably spatially restricted. But if even these plumes were so large to affect the oceanic domains, they were not located close to any of the regions considered in this study, which makes a plume influence on the observed T–R patterns unlikely.

If both global climate and global tectonics exert minimal control on global sea-level, it is not unexpected that regional/local tectonic motions become more important for T–R cycles in particular regions, even if these regions are relatively "stable". Mechanisms of dynamic topography may produce significant (up to 50–100 m/Ma) subsidence or uplift across large (1000s of km) territories (Müller et al., 2008; Spasojevic et al., 2008, 2009; Al-Hajri et al., 2009; Conrad and Husson, 2009; DiCaprio et al., 2009; Lovell, 2010). Thus, the lack of common global-scale T–R cycles in the early Danian can be explained by regional uplift or subsidence and weak eustatic fluctuations. This period may be analogous to the early–middle Thanetian (Ruban et al., 2010b).

5.1.2. Middle–late Danian regression

Zachos et al. (2001) do not indicate any significant shifts in global temperature during the middle–late Danian. However, the documented global-scale regression was a short-term event, which might have corresponded well to a glacial advance. It should be noted that ephemeral glaciations with periodic expansions and retreats persisted in Antarctica and enabled glacioeustasy since the Cretaceous (Miller et al., 2005; Galeotti et al., 2009), whereas the Arctic was ice-free until the mid-Eocene (Polyak et al., 2010; Spicer and Herman, 2010). The long-persistence of a fluctuating Antarctic ice sheet permits us to hypothesize that a glacial advance, with a peak at about 62–63 Ma, could trigger global-scale regression. This hypothesis, however, requires further testing, ideally with isotopic studies.

The relatively short duration of the middle–late Danian regression, coupled with the lack of remarkable changes in plate configurations at this time (Golonka, 2004; Scotese, 2004), limits an explanation from global tectonic forces, although some considerations are possible. Müller et al. (2008) indicate a significant decrease in seafloor crustal production within the time interval of 65–60 Ma, which is linked to subduction of the Izanagi–Pacific ridge beneath eastern Asia. This slowdown of seafloor spreading, coupled with the loss of young near-ridge seafloor to subduction, increased the mean age, and thus depth, of the ocean floor, which may have contributed to the middle–late Danian regression. The magnitudes of the associated sea-level fall indicated by Müller et al. (2008), however, do not permit Pacific–Izanagi ridge subduction to be the only mechanism for the global-scale seaward shoreline shift.

The tectonics of ridge–trench collision in the western Pacific may also lead to eustatic sea level drop. For example, ridge–trench collision may accelerate subduction erosion of the overriding plate (Cande and Leslie, 1986; von Huene and Scholl, 1991) and uplift the forearc (Sisson et al., 2003), both of which may decrease the area of the overriding plate. The accompanying increase in ocean area should lead to net sea level drop. On the other hand, ridge subduction may also lead to slab breakoff and an associated decrease in negative dynamic topography near the trench (Burkett and Billen, 2009), which should tend to increase sea level (Conrad and Husson, 2009). Taken together, the tectonics of nearly parallel collision of a ridge with a trench, as proposed by the Müller et al. (2008) reconstruction, are likely to produce a net sea level drop, but the magnitude and duration of this drop is poorly constrained, as is the precise timing of ridge–trench subduction in the western Pacific (Müller et al., 2008).

The large spatial extent of the middle–late Danian regression, which is recorded in 5 of 7 study regions (Fig. 3), cannot be explained by regionally-restricted dynamic topography or any other regional/local-scale mechanisms. This finding echoes the note of Clemmensen and Thomsen (2005), who suggested that regionally observed sea-level changes (which should be distinguished carefully from T–R cyclicity) across the Danian–Selandian transition had a eustatic nature.

5.1.3. *Early–middle Selandian transgression*

During the latest Danian–middle Selandian, temperatures remained high and then dropped by about 1 °C (Zachos et al., 2001). These weak trends, however, were superposed by the so-called "late Danian" (probably, latest Danian–earliest Selandian, ~61 Ma) hyperthermal, when a short-term acceleration of temperatures took place (Ali, 2009; Bornemann et al., 2009). If some ice persisted in Antarctica, this hyperthermal may have been able to produce its partial melting with a consequent increase in the global sea level. A rapid and significant rise in temperatures could also stimulate thermal expansion of seawater, which may be a significant process at times of rapid heating of the ocean (Miller et al., 2005; Archer, 2008). This trend would be especially pronounced if the "late Danian" hyperthermal followed the late Danian glacial advance hypothesized above. Taken together, we can link the early–middle Selandian transgression documented above with the noted remarkable changes in global temperatures. One should note, however, that the above-mentioned hyperthermal was apparently a short-term event. If so, further discussions are necessary in order to understand whether this climatic event might have been a significant factor for the 2nd-order T–R cyclicity.

The emplacement of two large igneous provinces (the Del Cano Rise and the Mascarene Plateau) in the oceanic domain around 60 Ma might be also responsible for the global-scale transgression. These plume events added about 10 m of sea-level rise (Müller et al., 2008). It is questionable whether this effect alone would be large enough to produce a rather synchronous transgression on several continents, but, undoubtedly, it might have contributed to the eustatic rise induced by the above-noted hyperthermal, and thus it may have strengthened the eustatically-driven transgression.

5.1.4. *Late Selandian lack of T–R cycles*

During the late Selandian, global temperatures declined weakly to a local minimum, but were relatively warm throughout (Zachos et al., 2001). All changes in global temperature (excluding the rapid hyperthermal linked with possible glacial advance) did not exceed 1 °C (Zachos et al., 2001). If so, it is unlikely that climate was an important control on T–R patterns in the late Selandian. The same conclusion can be made about the importance of global tectonics, which did not undergo abrupt changes. Available absolute dating does not exclude the onset of the North Atlantic large igneous province emplacement in the Selandian (Abbott and Isley, 2002; Jolley et al., 2002), but the longevity of this process brings its contribution to global sea-level change into question.

It appears that regional/local tectonic motions, and particularly dynamic topography, masked any minor global T–R cyclicity and produced uncorrelated records of late Selandian shoreline shifts. In other words, we interpret the late Selandian as a period of relative sea level stability, similar to the early Danian (above), which persisted into the early–middle Thanetian (Ruban et al., 2010b).

5.1.5. *Concluding remarks*

Our interregional correlation for the middle Danian–middle Selandian interval identifies two T–R cycles of ~2 Ma duration that are characterized by strong diachroneity. Specifically, these cycles are the middle–late Danian regression and the early–middle Selandian transgression. The large diachroneities can be easily detected by comparing peaks of the noted regressions and transgressions on a correlation chart (Fig. 3). Although errors and uncertainties in the regional chronostratigraphical frameworks are inevitable (Table 1), it is unlikely that they solely explain the observed diachroneity. It is therefore sensible to assume that regional/local tectonic motions, including dynamic topography, significantly altered even those eustatic fluctuations that were governed by global factors and recorded by common T–R patterns. Additionally, mechanisms linked with so-called "continental freeboard" (Wise, 1972; Bond, 1979; Eriksson et al., 1999, 2006; Eriksson, 1999; Flament et al., 2008) may be geographically or temporally variable, leaving a regionally- or locally-varying signature of the sea level record (Eriksson et al., 1999).

On a long-term scale, the Paleocene world was a "hothouse" with a rather "calm" tectonic regime. Consequently, sea level was relatively stable, and deviations from this "stability" were not large. It is unlikely, for example, that the late Danian glacial advance or the "latest Danian" hyperthermal were as important climatically as were the Pleistocene glaciation or the Paleocene–Eocene Thermal Maximum. Thus, global Paleocene sea level changes (and consequently transgressions on the continental margins) could not be so large as to overwhelm all regional variations. Instead, regional tectonic alterations of global-scale T–R cycles, and the consequent diachroneity of these T–R cycles, were inevitable during the middle Danian–middle Selandian time interval. One should also note that there may be time lags between some processes and their consequences. A coincidence of different lags of tectonic and eustatic mechanisms may also lead to diachroneity.

5.2. Towards a new Paleocene eustatic curve

The absence of good correspondence between the available global sea-level curves, as well as their miscorrespondence with common shoreline shifts during both the Danian–Selandian (see above) and the Thanetian (Ruban et al., 2010b), argues for the development of a next generation eustatic curve for the entire Paleocene epoch. Minimal requirements for such an effort include 1) a foundation on data from many localities representing different tectonic and depositional settings across the globe, 2) a justified chronostratigraphic framework, and 3) a clear separation of shorelines shifts and water-depth changes as evidence of past sea levels. It seems that only globally-coherent T–R patterns may indicate eustatic fluctuations, because ground movement in any one location may leave clear km-scale signatures on the low-angle flat surfaces of "stable" platforms and "passive" margins.

Taking the above interpretations of the T–R global-scale cycles and those summarized by Ruban et al. (2010b) into account, a tentative framework for a Palceocene eustatic curve can be presented (Fig. 4). Diachroneity of trends and events allows us to indicate their ages very approximately via age averaging (this explains differences between the dating of T–R patterns above and those depicted in Fig. 4). The intervals where regional/local tectonics overwhelm the weak eustatically-driven shoreline shifts are considered as periods of average shoreline "stability" on a global scale. In fact, without such a mechanism as dynamic topography, transgressions and regressions, if present, would be minor during intervals of "calm" global tectonics and warm global climate. An absence of large masses of continental ice at these time intervals suggests that shoreline positions were maximally landward during these periods. Our attempted interregional correlations permit us to identify two Paleocene intervals without common T–R cycles, namely the early Danian and the late Selandian–middle Thanetian. These stable periods were separated by the middle Danian–middle Selandian and late Thanetian regression–transgression cycles, which have probably resulted from global-scale eustatic change. The latter observation matches some conclusions of Harris et al. (2010) about the validity of glacioeustatic mechanisms in the Paleocene. One may suppose that the late Thanetian event was a bit stronger, because it embraced more regions (see Ruban et al., 2010b). These considerations are presented within a global-scale T–R curve (Fig. 4). This curve

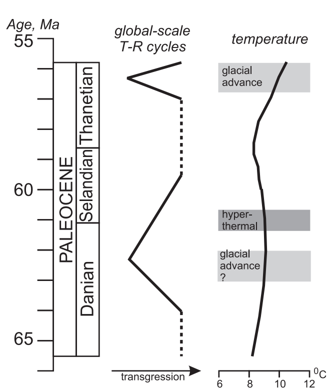

Fig. 4. Our tentative global T–R curve (dotted intervals indicate stability overwhelmed by regional/local tectonic motions), which was reconstructed from the inter-regional comparison in this study (see text for explanations) and the global $\delta^{18}O$ temperature (after Zachos et al., 2001). Hyperthermal at ~61 Ma is shown after Ali (2009) and Bornemann et al. (2009), whereas glacial advance at ~56 Ma is shown after Speijer and Morsi (2002) and Speijer and Wagner (2002).

confirms some importance to both paleoclimate (acting as glacioeustasy) for influencing Paleocene global sea-level changes and dynamic topography for affecting transgressions and regressions on a regional scale. The role of global tectonic processes should also not be dismissed (see above).

Even this tentative global T–R curve, which can be treated as indicating eustatic changes, may provide some interesting insights. For example, it suggests that the rapid diversification of marine invertebrate organisms, which occurred throughout the Paleocene as documented by Purdy (2008) on the basis of the famous paleontological database of Sepkoski (2002), was a result of recovery after the Cretaceous/Paleogene mass extinction. Thus, it was driven by "intrinsic" (or some other extrinsic) factors, and not a major eustatically-driven transgression. This confirms an absence of direct relationships between global sea level and biodiversity (e.g., Ruban, 2010).

5.3. Reliability of synthesizing syntheses

Forming general conclusions and presenting hypotheses based on analysis of previously-published syntheses presents several challenges, which are addressed below. First, it is sensible to question whether our "synthesizing syntheses" approach can generate scientifically useful results. This is a rather philosophical question. However, it is evident that recently-published regional syntheses of geological knowledge produce single fact-based datasets relevant to particular regions. If new research is only based on new field data, the importance of the previous work becomes undermined and significant gaps in knowledge can form. Furthermore, given the potentially significant influence of dynamic topography on T–R cycles in any particular location on Earth (e.g., Moucha et al., 2008), comparing studies from geographically dispersed regions is the only way to obtain information about globally-consistent T–R patterns. This effort necessarily involves utilizing and comparing regional syntheses of T–R patterns.

Another challenge is the potential inaccuracy of some regional syntheses because of data generalization and differences in the time scales along which these syntheses were constrained. Detailed chronostratigraphic frameworks available in the original sources permit corrections and somewhat precise interregional correlations. But they do not prevent errors in dating (e.g., biostratigraphic) particular rock packages or stratigraphic surfaces. These challenges can be addressed with an accounting of possible errors in all interpretations. In this study, we were able to account for the current replacement of the Danian/Selandian boundary according to Ogg et al. (2008). In addition, we accounted for possible stratigraphic uncertainties in the original syntheses as best we could. Particularly, the resolution of the regional records was considered (Table 1). When data from all syntheses are converted into a more or less comparable framework, further chronostratigraphic corrections are relatively easy to include. For instance, the new age of the Danian/Selandian stage boundary suggested by Dinarès-Turell et al. (2010) suggests that the regression peak was reached near the Danian–Selandian transition, which, however, does not significantly alter our interpretations (Fig. 4).

Probably, the most important challenge, however, concerns the possibility of coincidental similarity of the compared data. It is not possible to be certain that development of transgression in even 5 or 6 of 7 studied regions was not occasional. The larger the number of independent regions used to trace global-scale T–R cycles, the more certain we can be of discerning globally-consistent patterns in these cycles. However, the requirements for including regional datasets in a global comparison are rather restrictive ("stable" regions, "fresh" data, justification along the modern chronostratigraphical scale, etc.), and only a restricted number of regions may fulfill them. In this case, the only solution is to keep the incompleteness of the "synthesizing syntheses" approach in mind as we make conclusions.

Generally, the above-mentioned challenges appear whenever an attempt is made to discern globally-consistent patterns from a set of regional studies. For instance, difficulties similar to those discussed above are encountered in paleobiodiversity studies (Ruban and van Loon, 2008; Ruban, 2011). Therefore, if critical revision of global developments on the basis of earlier results is an efficient tool, the above-mentioned challenges are inevitable. However, they may be avoided, or at least minimized, when a degree of uncertainty (error) linked with each study is included in any interpretations that result from a synthesis. Moreover, by "synthesizing syntheses", we generate only one, although important, constraint that should be used together with the others for making final conclusions.

6. Conclusions

An interregional correlation of Paleocene T–R cycles based on a review of previously-published regional syntheses allows us to make three important conclusions:

1) No global-scale T–R cycles occurred in the early Danian and the late Selandian. Instead, regional/local tectonic motions, and particularly dynamic topography, overwhelmed any small eustatic fluctuations during these periods of relatively stable global climate and tectonics.
2) The middle–late Danian regression is common to the study regions, and it can be linked with possible glacial advance at $\sim$62–63 Ma and/or collision of the Pacific–Izanagi ridge with subduction zones in the western Pacific basin.
3) The early–middle Selandian transgression is also common among the study regions, and it can be linked with the global hyperthermal at $\sim$61 Ma and also possibly with the emplacement of large igneous provinces at the Danian–Selandian transition.

The large diachroneity of transgressions and regressions across the globe underlines the possible pitfalls of inferring eustatic constraints on the basis of data from single locations. This conclusion highlights the need for interregional correlation of eustatic constraints from multiple locations. The more regions with justified chronostratigraphical frameworks that are compared, the more precise the resulting reconstructions of global-scale shoreline shifts will be. Although such correlative approaches are already available thanks to the achievements of the International Commission on Stratigraphy (Ogg et al., 2008; see also www.stratigraphy.org), there remains a lack of high-quality regional records. This indicates an important need that can be rectified by future research and significant effort, which will be required to create a broad set of high-resolution records, well correlated with one another. It should be also noted that the approach addressed in the present paper produces only one possible constraint on global T–R cyclicity. Further comparison with results from other studies is necessary to solidify our knowledge of the global Danian–Selandian T–R cycles and eustatic fluctuations.

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