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Marine rapid environmental/climatic change in the Cretaceous greenhouse world

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ABSTRACT

The Cretaceous Period serves as a relevant model to understand greenhouse climate evolution. As atmospheric CO_2 concentrations continue to rise in the twenty-first century, critical questions put forward are 1) how the Cretaceous Earth System could have been maintained in the "greenhouse" state, if there are some variations, 2) why and how fast did climatic and palaeoenvironmental changes happened during the Cretaceous, and 3) what records were preserved in the Earth's archives that enable the comparison of Cretaceous rates of paleoenvironmental changes with today's global changes. In fact, rapid and severe global environmental and climatic changes happened in the Cretaceous greenhouse world including oceanic anoxic events, oceanic red beds, "cold snaps" or glaciations and carbonate platform drowning events. This special issue originated from the final workshop of UNESCO International Geoscience Program IGCP 555 and the Pardee session of the Geological Society of America 2010 annual meeting. Participants and contributors mainly focused on the causes, processes, and consequences of rapid environmental/climatic changes that happened in the Cretaceous greenhouse world.

1. Introduction

Among the geosciences communities it has been recognized that the Earth System was in a "greenhouse state" during the Cretaceous time, which led to the distinctive term of "Cretaceous World" (Skelton, 2003). The Cretaceous is also best known as the time for occurrences of major geological events, such as Large Igneous Provinces (LIPs) (Larson, 1991), Oceanic Anoxic Events (OAEs, Schlanger and Jenkyns, 1976), Cretaceous Oceanic Red Beds (CORBs, Hu et al., 2005; Wang et al., 2005), and carbonate platform drowning events (Schlager, 1989). As atmospheric CO_2 concentrations rise during the twenty-first century, the "Cretaceous World" will serve as a relevant model for a return to greenhouse climates (Jenkyns, 2003; Hay, 2011). People are interested to know how the Earth System could have been maintained in the "greenhouse" state for a significant time interval, if there are distinct variations, and how and why rapid climate changes happened during Cretaceous. As the Earth System is essentially composed of oceans and continents, then the sedimentary records from marine and terrestrial geological archives are widely investigated to resolve these problems. Since 2006, the UNESCO International Geoscience Program IGCP 555 was devoted to the study of the marine and terrestrial records in order to document the rapid climate environmental change in the Cretaceous World. First results of this project were published in a special issue of Sedimentary Geology (Wagreich et al., 2011).

The final workshop of IGCP 555 was held on October 31, 2010 during the Geological Society of America annual meeting in Denver, Colorado, USA. A half-day GSA Pardee session was sponsored by the IGCP 555 and SEPM titled "Rapid Environmental/Climatic Change in the Cretaceous Greenhouse World". Over twenty persons contributed and discussed the causes, processes, and consequences of rapid environmental/climate changes in the Cretaceous greenhouse world, from both marine and terrestrial records.

Two special issues were scheduled related to the IGCP 555 final workshop and the GSA Pardee session. One special issue mainly focuses on the Cretaceous continental record titled as "Environmental/climate change in the Cretaceous greenhouse world: records from terrestrial scientific drilling of Songliao Basin and adjacent area of China" which will be published in the journal Palaeogeography, Palaeoclimatology, Palaeoecology. The present special issue in Cretaceous Research focuses on the marine record on the topic of rapid environmental/climate change in the Cretaceous greenhouse world.

2. Debate on Cretaceous temperature

Marine sediments are usually more complete and widely distributed than terrestrial records, and have principally more

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accurate and precise age control by biostratigraphy and other stratigraphic methods; thus, most of the information about Cretaceous climate is provided from the marine sediments up to now. Among many other properties, stable oxygen isotope compositions of marine sediments are extremely useful in reconstructing of the long-term paleoenvironmental change (e.g. Clarke and Jenkyns, 1999; Huber et al., 2002), especially those oxygen isotopes from glassy foraminiferal calcite from deep sea drilling cores (Pearson et al., 2001; Norris et al., 2002; Wilson et al., 2002; Moriya et al., 2007; Friedrich et al., 2012). Based on oxygen isotopic data of planktonic foraminifers, the Cretaceous can be divided, in the first order, into three stages (Huber et al., 2002): the cooler Early Cretaceous, the hot mid-Cretaceous, and the warm Late Cretaceous, though there are sub-cycles within each period. The Cenomanian-Turonian appears to have been the warmest interval on Earth for at least the past 100 myr, at that time tropical sea surface temperatures may have reached above 35 °C and therefore surface ocean temperatures were at least ~7–8 °C warmer than today (Pearson et al., 2001; Norris et al., 2002; Wilson et al., 2002). New benthic isotope compilation separated the Cretaceous (115–65 Ma) into four intervals (Friedrich et al., 2012): (1) the increasing temperatures before 97 Ma (Early Cenomanian); (2) the subsequent hot greenhouse interval (Late Cenomanian-Early Turonian) – intermediate to bottom waters in the southern high latitudes and the Pacific Ocean were as warm as 20 °C, whereas the tropical proto–North Atlantic shows even higher temperatures; (3) the long-lasting cooling trend between 91 Ma and 78 Ma (Early Campanian); (4) the last 13 myr of the Cretaceous (78-65 Ma) are characterized by small inter-basin gradients with relatively cool temperatures of intermediate to bottom waters.

The Early Cretaceous was generally regarded as a relatively cool time compared to the rest of the Cretaceous as indicated by the inferred presence of glacial and cool-water deposits (diamictites and glendonites) in high-latitude regions (e.g. De Lurio and Frakes, 1999; Alley and Frakes, 2003; Price and Nunn, 2010). However, recently, TEX_{86} palaeotemperature proxy records indicated that sea surface temperatures during the Early Cretaceous may have exceeded 32 °C at 15–20 N and ~ 26 °C at ~53 S (Littler et al., 2011), and 26–30 °C at ~60 S (Jenkyns et al., 2012). These temperatures substantially exceed modern temperatures at equivalent latitudes, and are even compatible with the paleotemperature reconstruction by the same method of TEX_{86} from the mid-Cretaceous (Fig. 1; Table 1; Schouten et al., 2003; Wagner et al., 2008; Mutterlose et al., 2010). Glendonites are pseudomorphs of the cool-temperature form of hydrated calcium carbonate, ikaite, which typically forms at temperatures no greater than ~7 °C (De Lurio and Frakes, 1999). As explained by Jenkyns et al. (2012), the ikaite is an early diagenetic mineral growing by displacement within sediment; it may not give much information on sea surface temperature. Föllmi (2012) emphasized arid and humid climate fluctuations during reinforced greenhouse conditions in the Early Cretaceous. Humid periods were associated with intensified monsoon conditions and strong winds, arid periods were associated by intensive evaporation. Humid conditions and intensified coastal upwelling caused some regions to become seasonally cooler because of dense cloud cover, the loss of energy by latent heat transfer and cooler ocean surface waters. Therefore unequal distribution of colder and warmer areas was present.

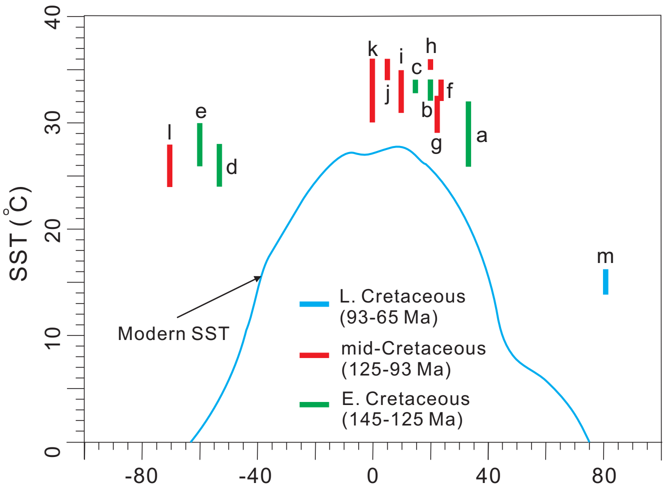

Fig. 1. Cretaceous meridional sea surface temperature gradients based on the available TEX_{86} data. The location number and references refer to the Table 1.

However, studies in the Late Cretaceous display a cooling trend in the Late Campanian and Maastrichtian (Jarvis et al., 2006; Keller, 2008; Wagreich, 2009). Given these strongly debated, contradictory data the need for more and multiproxy, high-resolution, continuous temperature records is obvious; however, short-term, but significant temperature variations in the Cretaceous are very likely based on these data.

3. Cretaceous rapid environmental/climate change

During the Cretaceous Period, rapid environmental/climatic changes are manifest as the OAEs, CORBs, cold snaps or glaciations, global eustatic changes, and carbonate platform drowning events, among other events (Fig. 2).

3.1. Oceanic anoxic events (OAEs)

Environmental changes are strongly connected to the carbon cycle; therefore, strong emphasis has been put on the Cretaceous oceanic anoxic events, when organic-carbon rich sediments were widely deposited in the global ocean basins (Schlanger and Jenkyns, 1976; Jenkyns, 1980). These events have also been one of the hottest topics of Earth Sciences for over 35 years (Jenkyns, 2010). OAEs record profound changes in the climatic and paleoceanographic state of the planet and represent major disturbances in the global carbon cycle. Up to now, four main periods of oceanic anoxic events have been recognized, i.e., the Valanginian (Weissert OAE), Late Hauterivian (Faraoni OAE), Aptian-Albian (OAE1a, 1b, 1c, 1d), Cenomanian-Turonian (OAE2), and Coniacian–Santonian (OAE3), respectively (Jenkyns, 1980; Bralower et al., 1994; Erba, 2004; Jenkyns, 2010). Well known by the major $\delta^{13}C$ excursion (Arthur et al., 1988), and marine biota extinction (Leckie et al., 2002), it has been widely suggested that OAEs are associated with a decrease in dissolved oxygen in the deep water (Schlanger and Jenkyns, 1976), or a significant increase in the oceanic productivity (Leckie et al., 2002; Erba, 2004). Currently available data suggest that the major forcing function behind OAEs was an abrupt rise in temperature, induced by rapid influx of CO_2 into the atmosphere from volcanogenic and/or methanogenic sources (Adams et al., 2010; Barclay et al., 2010; Jenkyns, 2010).

3.2. Oceanic red beds (ORBs)

CORBs have become one of the more recent hot topics in the field of paleoclimate and palaeoceanography (Hu et al., 2005, 2006, 2009; Wang et al., 2005, 2009, 2011; Wagreich, and Krenmayr, 2005; Wagreich et al., 2011; Neuhuber et al., 2007; Neuhuber and Wagreich, 2011). It has been proven that CORBs generally occurred after OAEs (Hu et al., 2005; Wang et al., 2011; Trabucho-Alexandre et al., 2011). Brief occurrences of ORBs can be found within the

Table 1
Available TEX_{86} data from the Cretaceous sediments.

Number	Place	Paleolatitute	Epoch	Age	SST by TEX86	Reference
m	Arctic ocean	80 N	Late Cretaceous	Campanian-Maastrichtian	14–16	Jenkyns et al., 2004
l	DSDP 693A East Antarctic	70 S	Mid-Cretaceous	L. Aptian - E. Albian	24–28	Jenkyns, 2010
k	ODP 1207 central Pacific	0 (equatorial)	Mid-Cretaceous	E. Aptian	30–36	Dumitrescu et al., 2006
j	DSDP 367 North Atlantic	5 N	Mid-Cretaceous	latest Cenomanian OAE2	34–36	Schouten et al., 2003
i	ODP 1258-1259 North Atlantic	15 N–4 N	Mid- to Late Cretaceous	Albian-Santonian	31–35	Forster et al., 2007
h	DSDP 603B North Atlantic	20 N	Mid-Cretaceous	latest Cenomanian OAE2	35–36	Schouten et al., 2003
g	DSDP 545 central Pacific	22 N	Mid-Cretaceous	Early Albian	29–32.5	Wagner et al., 2008
f	ODP1049C North Atlantic	23 N	Mid-Cretaceous	Early Albian	32–34	Wagner et al., 2008
e	DSDP 511 South Atlantic	60 S	Early Cretaceous	Callovian-Aptian	26–30	Jenkyns, 2010
d	ODP 766 Indian Ocean	53 S	Early Cretaceous	Valanginian-Barremian	24–28	Littler et al., 2011
c	DSDP 534 North Atlantic	15 N	Early Cretaceous	Valanginian-Barremian	33–34	Littler et al., 2011
b	DSDP 603 North Atlantic	20 N	Early Cretaceous	L. Berriasian-Hauterivian	32–34	Littler et al., 2011
a	NW Germany	33 N	Early to mid-Cretaceous	Barremian-E. Aptian	26–32	Mutterlose et al., 2010

mid-Cretaceous strata interbedded with black shales in the Tethyan realm (Hu et al., 2006). After OAE2, CORBs became the predominant deep oceanic sediment type in the Late Cretaceous, from Turonian to Campanian, with their global distribution maximum in Santonian–Campanian times (Wang et al., 2009). The most characteristic features of CORBs are their extremely low level of organic carbon and higher content of iron oxides (mainly hematite) (Hu et al., 2005; Cai et al., 2009). Various proxies indicate that CORBs were deposited in the well-oxygenated environment with much less nutrient recycling efficiency, i.e., less oceanic productivity (Neuhuber et al., 2007; Hu et al., 2009; Wang et al., 2009).

3.3. *Cretaceous glaciations and sea-level change*

It has been argued that ice sheets may have been present at particular times during the Cretaceous, based on the following evidences (see overview by Hay, 2008): 1) cold-climate-related sediments including ice dropstone, glendonites and diamictite (e.g., De Lurio and Frakes, 1999; Alley and Frakes, 2003; Price and Nunn, 2010). 2) Evidence of significant, short-term sea-level changes from sequence stratigraphy and coastal offlap and onlap. During the Cretaceous greenhouse interval, sea-level fluctuations of tens of metres occurred over periods of less than 1 myr, and thus, to our knowledge, can only be explained by growth and delay of continental ice sheets. However, in a warm equable greenhouse world, sea-level changes of this magnitude would not be expected to occur, but stratigraphic evidence indicates the occurrence of tens of short-term sea-level swings (Miller et al., 2003; Yilmaz et al., 2004; Yilmaz and Altiner, 2006; Gale et al., 2008; Galeotti et al., 2009) that can clearly be traced especially within the shallow-water peritidal carbonates. 3) Paleothermometry using mainly $\delta^{18}O$ and TEX_{86} proxies suggest that four cooling pulses occurred even within the Cenomanian-Turonian hottest greenhouse interval (Voigt et al., 2004; Forster et al., 2007; Bornemann et al., 2008). However, two oxygen isotopic studies by Moriya et al. (2007) and Ando et al. (2009) provide evidence against the interpretation of ice-sheet growth as a driver of the sea-level change during these extreme greenhouse periods.

Up to now, the debate of Cretaceous glaciations and sea-level change is ongoing. Some believe that the Cretaceous greenhouse world may have had “cool snaps” with the occurrence of ephemeral continental ice sheets near or at Polar Regions. Others tend to believe that the observed sea-level changes in the Cretaceous greenhouse world need a new theory to explain.

3.5. *Cretaceous carbonate platform drowning events*

The drowning events of Cretaceous carbonate platforms and their associated drowning unconformities play a significant role in the stratigraphic organization of shallow platform carbonates (Schlager, 1989; Weissert et al., 1998; Masse and Fenerci-Masse, 2011). In sequence stratigraphy such unconformities are usually interpreted as “drowning unconformities” (Catuneanu, 2006), which represent the key sequence boundaries (Type 3 sequence boundaries of Schlager, 1999). Weissert et al. (1998) proposed that the Early Cretaceous carbonate carbon isotope record characterized by three positive high-amplitude excursions (>1.5‰, late Valanginian–Hauterivian, early and late Aptian age) had a coincidence with black shale formation, and widespread carbonate platform drowning events. However, the temporal correlation of oceanic anoxia and platform drowning has not been rigorously tested and evidence indicating causality is debated. Recently, Huck et al. (2011) reported a high-resolution carbon- and strontium-isotope chronostratigraphy applied to the Barremian–Aptian Urgonian carbonate platform in France, and found that shallow-water carbonate production in the Urgonian platform ceased about 300 kyr before the onset of OAE 1a.

4. Contribution of this special issue

A total of fourteen manuscripts were submitted to this special issue. Among them, eight papers were finally accepted after reviewers’ and guest editors’ comments. Below is a brief introduction to each paper.

Yongjian Huang, Chengshan Wang and Huaichun Wu investigate the mechanism responsible for the regulation of long-term climate stability by spectrum analysis on the global marine phosphorus burial records of the Cretaceous and compare these data with paleoclimates, mainly the long-term oxygen isotope record. They found four periodicities, with a strong 34–38 myr frequency in both the carbon-phosphorous cycle and the paleoclimate evolution, and they relate these cycles to tectonic activity.

The paper by ***Ismail O. Yilmaz, D. Altiner, U. K. Tekin, F. Ocakoglu*** studied the stratigraphic transition from Hauterivian carbonate platform to Aptian shale deposition in the Sakarya zone of western Turkey, which is a general feature of western Tethys. They successfully demonstrated the late Hauterivian platform drowning event through the presence of hardgrounds, glauconite- and phosphate-bearing facies over the platform carbonates, and the successive transition to the pelagic limestones. They found a black shale level with rich ammonites, manganese, iron, pyrite, and glauconite minerals, which was deposited around the early Barremian-late Barremian boundary, and which they interpreted as the “mid-Barremian” oceanic anoxic event.

Xiumian Hu, Kuidong Zhao, Ismail O. Yilmaz, and Yongxiang Li carried out a detailed study on the stratigraphic transition and the paleoenvironmental changes from the early Aptian oceanic anoxic event OAE 1a to oceanic red beds 1 (ORB1) along a pelagic section in

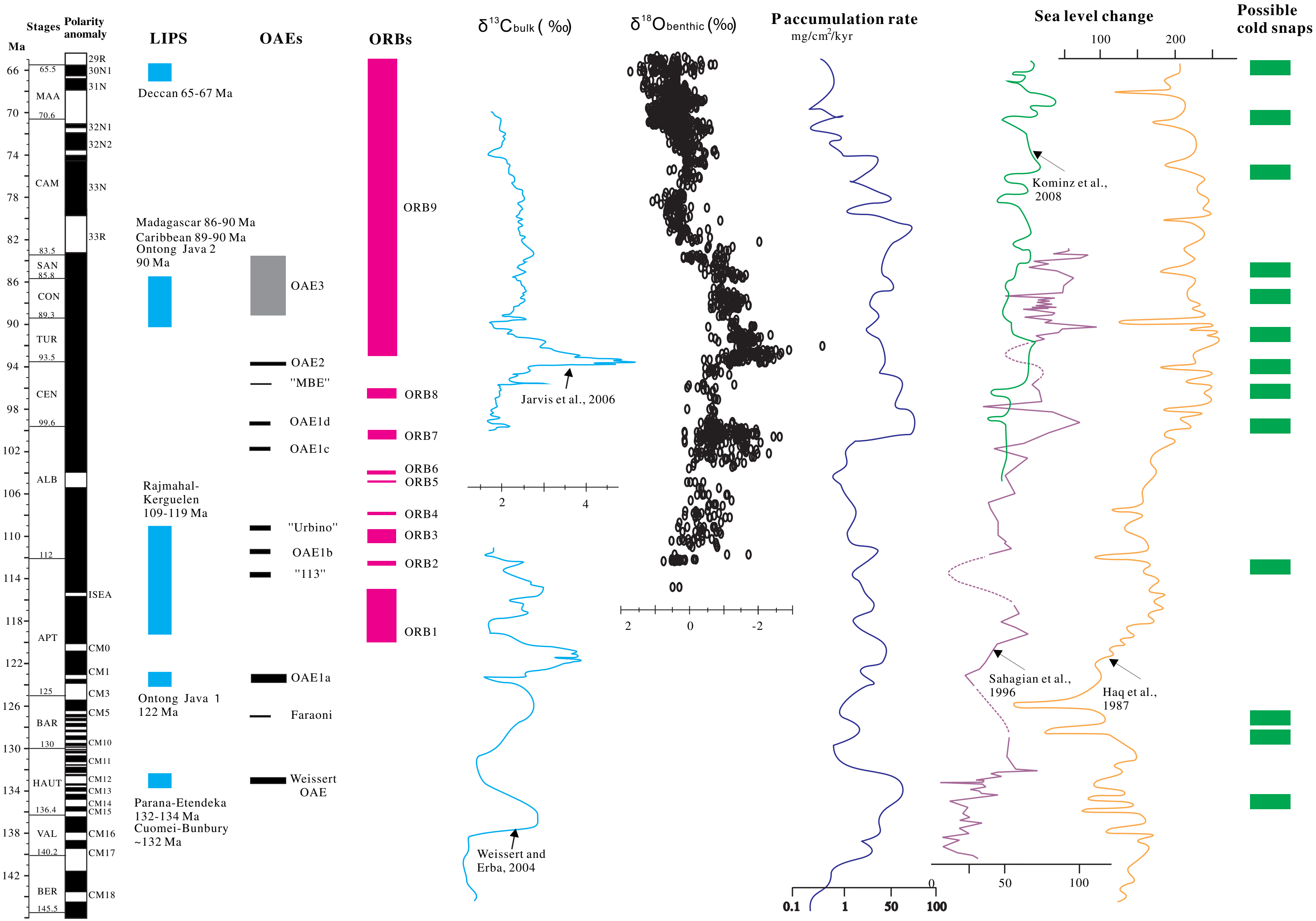

Fig. 2. Summary of the Cretaceous rapid climatic/environmental changes, showing LIPS (Larson, 1991), OAEs (Schlanger and Jenkyns, 1976; Jenkyns, 1980; Bralower et al., 1994), ORBs (Hu et al., 2005, 2006), δ^{13}C of bulk rocks (Weissert and Erba, 2004 and references therein; Jarvis et al., 2006), δ^{18}O of benthic foraminifers (Friedrich et al., 2012), P accumulation rate (Huang et al., 2012), global sea-level changes (Haq et al., 1987; Sahagian et al., 1996; Kominz et al., 2008), and possible cold snaps (reviewed by Chen et al., 2011). Ages follow to the geological time scale of Gradstein et al. (2004).

Turkey. Changes in redox conditions from anoxic to highly oxic with hematite formation are evident. Cyclicity and stable isotope records are discussed and a scenario of enhanced volcanic CO_2 emission and/or pulsed methane dissociation for OAE 1a is discussed.

Relu-Dumitru Roban and Mihaela C. Melinte-Dobrinescu studied the Lower Cretaceous lithofacies spanning the the Late Barremian-Late Albian interval of the Audia Formation, Tarcău nappe, eastern Carpathians. From a regional tectonic context, they propose that the sedimentation of black and grey shales in the outer nappes, i.e., Moldavides, of the Eastern Carpathians, during the Barremian-Albian interval, was a consequence of the intermittent isolation of the basin, leading to periods of restricted circulation.

Jozef Michalík, Otília Lintnerová, Daniela Reháková, Daniela Boorová, Vladimír Šimo expound on the Early Cretaceous sedimentary evolution at the margin of a pelagic basin (the Manín Unit, central Western Carpathians, Slovakia). They indicate presence of a late Valanginian anoxic oceanic event in the Butkov sections and interpreted the absence of any black shale record as a response to local oxic conditions in the marginal part of the basin. The carbon isotope excursion is interpreted as an effect of local changes. A late Aptian carbonate progradation was followed by a collapse during middle Albian.

Polina Pavlishina and Michael Wagreich documented the biostratigraphy and paleoenvironments in a northwestern Tethyan Cenomanian-Turonian boundary section (Austria) based on palynology and calcareous nannofossils. They conclude that nannofossil indices and dinoflagellate associations indicate rather low-productivity, low-nutrient settings during at least the later part of OAE 2, and display parallel interpretations based on foraminiferal assemblages.

The paper by ***Yuanfeng Cai, Xiaoxiao Hu, Xiang Li, and Yuguan Pan*** concentrated on the study of the origin of the red colour of the Scaglia Rossa from the Vispi Quarry section, Gubbio, central Italy. They studied the morphology and distribution of hematite using high-resolution transmission electron microscopy and selected-area electron diffraction. The authors indicate that nano-grains of hematite impart the limestones with a homogeneous red. This may indicate that these nano-grains of ferric minerals are authigenic, implying oxic or sub-oxic conditions at the time when the red limestones were deposited.

The paper by ***Michael Wagreich, Johann Hohenegger and Stephanie Neuhuber*** brings new and high-resolution data on the timing of the *Radotruncana calcarata* biozone within the Late Campanian interval. They studied a section in the Eastern Alps of Austria and established an integrated stratigraphy by way of plankton foraminifer and nannofossil biostratigraphy, carbon and strontium isotopic stratigraphy, and orbital cyclostratigraphy. Based on the thickness of marl-limestone cycles they found that the *Calcarata* Biozone has a duration of c. 806 kyr.

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