An introduction to causes and consequences of Cretaceous sea-level changes (IGCP 609)

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Abstract: The International Geoscience Programme Project IGCP 609 addressed correlation, causes and consequences of short-term sea-level fluctuations during the Cretaceous. Processes causing several ka to several Ma (third- to fourth-order) sea-level oscillations during the Cretaceous are so far poorly understood. IGCP 609 proved the existence of sea-level cycles during potential ice sheet-free greenhouse to hothouse climate phases. These sea-level fluctuations were most probably controlled by aquifer-eustasy that is altering land-water storage owing to groundwater aquifer charge and discharge. The project investigated Cretaceous sea-level cycles in detail in order to differentiate and quantify both short- and long-term records based on orbital cyclicity. High-resolution sea-level records were correlated to the geological timescale resulting in a hierarchy of sea-level cycles in the longer Milankovitch band, especially in the 100 ka, 405 ka, 1.2 Ma and 2.4 Ma range. The relation of sea-level highs and lows to palaeoclimate events, palaeoenvironments and biota was also investigated using multiproxy studies. For a hothouse Earth such as the mid-Cretaceous, humid–arid climate cycles controlling groundwater-related sea-level change were evidenced by stable isotope data, correlation to continental lake-level records and humid–arid weathering cycles.

The United Nations Educational, Scientific and Cultural Organization and the International Union of Geological Sciences foster, under the umbrella of the International Geoscience Programme (IGCP), large cooperative and international projects on global issues such as climate change. IGCP 609 on ‘Climate–environmental deteriorations during greenhouse phases: Causes and consequences of short-term Cretaceous sea-level changes’ was active between 2013 and 2019. The project gathered together more than 150 scientists from 43 countries to discuss and elaborate on the topic of sea-level changes in the Cretaceous hothouse natural laboratory, linking deep-time evidence to today’s global change. Recent global warming in response to enhanced atmospheric greenhouse gases and the consequent sea-level rise have become issues of continuously growing interest for the scientific community as well as subjects of rising public awareness for a greenhouse to hothouse future Earth (e.g. Steffen *et al.* 2018).

Sea-level controls a critical zone for life, especially in coastal megacities where a global sea-level rise on the scale of tens of centimetres has major impact on mankind and society. The main drivers of recent sea-level rise are the accelerated discharge of melt water from continental ice reservoirs into the oceans and the thermal expansion of the warming seawater (e.g. Church *et al.* 2013; Conrad 2013). Thus, sea-level in an ice-free greenhouse future world would be at least 45 m higher than today, including isostatic compensation (Conrad 2013).

The Cretaceous greenhouse period provides a deep-time view of greenhouse-phase Earth system processes and fossilized planetary boundaries (e.g. Hu *et al.* 2012; Hay 2017). The Cretaceous World natural laboratory in its stratal record provides invaluable data for a better understanding of the

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causes and consequences of global (eustatic) short-term sea-level changes over a very long time interval with different, intermittently ‘extreme’ climates. Thus, the Cretaceous greenhouse, especially the mid-Cretaceous (Aptian to Turonian, *c.* 126–90 Ma) hothouse period serves as an experimental laboratory to test and learn for a future greenhouse Earth system on its way out of the ice age cyclicity of the Quaternary.

IGCP 609 ‘Climate–environmental deteriorations during greenhouse phases: Causes and consequences of short-term Cretaceous sea-level changes’

IGCP 609 (Li *et al.* 2016; Wagreich *et al.* 2016; Hu *et al.* 2017) addressed the correlation, causes and consequences of significant short-term (cycles of third- and fourth-order, i.e. about 0.5–3.0 myr and a few tens of thousands to 0.5 myr, respectively) sea-level changes which are recorded in Cretaceous sedimentary sequences worldwide. Such cyclic sea-level changes and their corresponding stratal sequences are usually explained by the waxing and waning of continental (polar) ice sheets. However, although Cretaceous eustasy involves processes like brief glacial episodes for which evidence has been given (and resulting glacio-eustasy models, e.g. Miller *et al.* 2005), the presence of continental ice sheets during the Cretaceous is still disputed, and remains particularly enigmatic for the mid-Cretaceous hothouse episodes and global average temperature maxima during the Cenomanian to Turonian (Hu *et al.* 2012; Huber *et al.* 2018). IGCP 609 placed emphasis on the causes and mechanisms of short-term eustatic sea-level changes in the mid-Cretaceous hothouse during which continental ice sheets are highly improbable and, thus, other mechanisms have to be taken into consideration to explain significant short-term eustatic changes.

Within the last six years, major achievements of the IGCP 609 community in understanding Cretaceous sea-level changes include the following topics:

- Cretaceous sequence stratigraphy put into a numerical time frame (e.g. Haq 2014; Haq & Huber 2017). Major mechanisms for global and regional sea-level changes were identified, and regional, tectonically induced v. global mechanisms for sea-level change were discussed and quantified (e.g. Sames *et al.* 2016, **2020**, and references therein; see Fig. 1).
- Various proxy correlations, such as oxygen and carbon isotopes, and interpretations for sea-level reconstructions in the Cretaceous were challenged and feedback mechanisms were evaluated in detail (e.g. Föllmi 2012; Wendler & Wendler 2016; **Wagreich & Koukal 2019**; **Zakharov *et al.* 2019**).

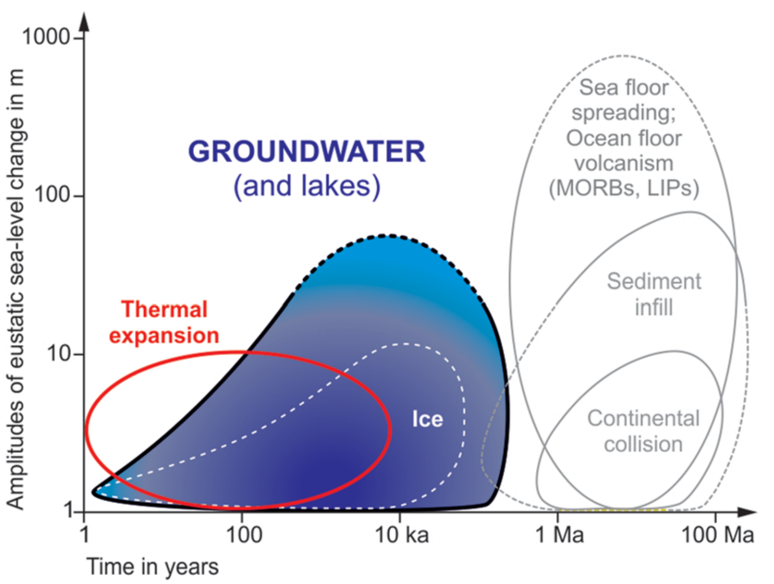

Fig. 1. Log-scale diagram sketches of the timing and amplitudes of major geological mechanisms for driving eustatic sea-level changes during greenhouse climate phases of the Earth system (modified from Sames *et al.* 2016). Aquifer-eustasy is suggested as the main driver during hot greenhouse times with no continental ice shields on Earth.

- Orbital forcing in the (long) Milankovitch band was identified as the main driver of sea-level cycles also during greenhouse times (e.g. Wendler *et al.* 2014, 2016*a*), pointing to climate control of continental water storage.
- Processes and triggering mechanisms of short-term sea-level fluctuations during greenhouse periods remain controversial, but evidence is growing for the revival of the 'aquifer-eustasy' (Fig. 1) or 'limno-eustasy' hypotheses (Hay & Leslie 1990; Föllmi 2012; Wagreich *et al.* 2014).
- Against the background that short-term cyclic sea-level changes are climate driven and, thus, ultimately orbitally controlled – and that, besides the characteristic remanent magnetization, this is the only signal potentially recorded in contemporaneous non-marine deposits as well – the stratigraphic application of short-term climate cycles comes under ever more scrutiny as a promising tool for non-marine to marine correlations (e.g. Sames 2017).

Case studies within the project came from various regions of the world, exemplifying the global character of sea-level change. Published studies out of the IGCP 609 community include contributions from, e.g. Austria (Neuhuber *et al.* 2016; Wolfgring *et al.* 2018*b*), China (Xi *et al.* 2016; Wu *et al.* 2017; Li *et al.* 2018; **Xu *et al.* 2019**), Egypt (Fathy *et al.* 2018), NW Europe (Hart *et al.* 2016; **Hart & Fox 2019**), Jordan (Wendler *et al.* 2016*b*), Nigeria (Gebhardt *et al.* 2019), Pakistan (Iqbal *et al.* 2019), Spain (Socorro *et al.* 2017), Russia (Zorina 2016; Zorina *et al.* 2017; **Zakharov *et al.* 2019**; **Vishnevskaya & Kopaevich 2020**), Tanzania (Wendler *et al.* 2016*a*), Turkey (Yilmaz *et al.* 2018; Wolfgring *et al.* 2018*a*, 2020; **Mulayim *et al.* 2019**) and the USA (Ross *et al.* 2017, **2020**; **Joeckel *et al.* 2019**).

History and significance of eustasy

The term eustasy dates back to Eduard Suess (Suess 1888), who introduced 'eustatic movements' based on the observations of globally synchronous flooding of continents in the Phanerozoic, i.e. transgressions that displaced fossil shorelines landwards, and the drawback of oceans from continents, i.e. regressions, that shifted the shoreline seawards. The term eustasy was subsequently used to denote global and coeval changes in sea-level in time, preserved in the stratigraphic record (e.g. Conrad 2013; Haq 2014).

The most prominent eustatic mechanism for changing the seawater volume in the oceans is the waxing and waning of continental ice sheets, which result in high-amplitude, rapid sea-level changes (up to 120 m in amplitude, and rates of more than 40 mm a^{-1} rise during melt water pulses; Miller *et al.* 2011). Suess (1888) did not involve glacio-eustasy as one of his proposed processes responsible for transgressions and regressions. Exploring the Quaternary ice ages, it soon became clear that the sea-level fluctuations were significant from glacial stages to inter-glacial stages, linked to ice-sheet growth and decay (glacio-eustasy), and thermal expansion and contraction of seawater (thermo-eustasy). Accordingly, glacio-eustasy, depending on the presence of large ice shields on continents, was not applicable to sea-level fluctuations recorded in stratal archives of supposedly ice-free greenhouse climate intervals of the Phanerozoic such as the Cretaceous hothouse phases.

The hypothesis of a groundwater- and aquifer-related eustasy process was put forward during the 1990s by Bill Hay (Hay & Leslie 1990) and Jacobs & Sahagian (1993, 1995) relating enhanced continental (ground) water storage and mega-monsoon phases to sea-level fall and regressions. This idea was revived when it became clear that during the Cretaceous hothouse climate the presence of ice sheets on the Earth was highly unlikely (e.g. Hay & Floegel 2012). Jens Wendler (Wendler *et al.* 2011) and Karl Föllmi (Föllmi 2012) were the first to re-introduce the concept of humid–arid climate cycles, to investigate processes and models, and to quantify the magnitude of aquifer continental water storage during the Cretaceous. In the following years, partly within the IGCP 609 scientific community, partly from other working groups, the aquifer-eustasy hypothesis was formulated and tested, and evidence was brought forward by stable isotope cycling (e.g. Föllmi 2012; Wendler & Wendler 2016; Brikiatis 2019; Laurin *et al.* 2019), weathering on carbonate platforms (e.g. Wendler *et al.* 2014, 2016*b*) and lake-level to sea-level correlations (Wagreich *et al.* 2014). At the same time, GRACE (Gravity Recovery and Climate Experiment) satellite data gave evidence for enhanced land-water storage as a result of recent climate change (e.g. Reager *et al.* 2016), thus linking the aquifer-eustasy hypothesis from deep-time to today's global change in the Earth system, making a direct link from the Cretaceous hothouse to our Anthropocene future (see **Sames *et al.* 2020** for details).

Tests on Cretaceous hothouse eustatic cycles showed theoretically predicted out-of-phase relationships between sea- and lake-level changes in the mid-Cretaceous on 1.2 myr Milankovitch scales (Wagreich *et al.* 2014). We suggest the following scenario for sea-level fluctuations during an ice-free greenhouse world: stronger humid conditions result in greater storage in groundwater reservoirs and higher lake levels, thus filling up the continental aquifers as discharge into the ocean cannot keep up. This lowers sea-level during times of lake-level highstands. In contrast, more arid conditions result in lesser aquifer storage and low lake levels, and thus a rise in sea-level. In addition, the thermo-eustatic effect of water expansion owing to warming may add a few more metres to such a mechanism, if warming occurs during times of aridity.

The revision of fundamental aspects in the context of recent and Cretaceous global sea-level shifts (Fig. 1) and its application as discussed during IGCP 609 have led to different ideas and approaches. All measurements of amplitude of sea-level changes (rises and falls measured in metres) in any given region are always local ('regional' or 'relative'), even when there is a strong underlying global signal, since they are a product of both local vertical movements (solid-Earth factors) and eustasy, or the change of ocean water volume and volume of ocean basins ('container volume'), respectively. Eustatic sea-level amplitudes cannot be measured; these are averaged global estimates of eustatic changes in relation to a fixed point, e.g. the Earth's centre. Regarding the reconstruction of sea-levels and sea-level changes from the geological record, the differentiation of relative (regional, eurybatic) and eustatic (global) sea-level changes and the respective proportion of each signal at a given locality or region is a critical issue (Haq 2014; Sames *et al.* 2016), the disregard of these factors can lead to strong over- or underestimation of respective amplitude estimates. In recent years, a complex of solid-Earth processes and feedback under the label of 'dynamic topography' has become a stronger focus of attention since it affects local measurements of sea-level and past reconstructions (Cloetingh & Haq 2015). We have learned that some of the processes mentioned above can re-fashion landscapes only regionally, and that solid-Earth processes are responsible for retaining lithospheric memory and its surface expressions. Moreover, and in contrast to previous perceptions that considered solid-Earth processes to be operative on long-term (way beyond 5 myr) scales, IGCP 609 provided evidence that it is essential to take these processes into consideration since they affect local measures of sea-level, and thus, estimated eustatic sea-levels and sea-level changes on short-term scales as well (Sames *et al.* 2016). The present volume comprises two review papers and a set of case studies on Cretaceous sea-level, palaeoclimate and palaeoceanographic evolution.

The first paper by **Sames *et al.* (2020)** reviews Cretaceous eustasy, delving deeper into aquifer-eustasy. In this topical review of Cretaceous greenhouse climate global sea-level change, Benjamin Sames, Michael Wagreich, Clinton Conrad and Shahid Iqbal identify aquifer-eustasy as the main driver of short-term (<3 Ma: *c.* 100 ka to 2.4 Ma) sea-level fluctuations during the Mesozoic hothouse. These Cretaceous third- and fourth-order sea-level changes, forming the framework for sequence stratigraphy, are linked to Milankovitch-type climate cycles of 405 ka and 1.2 Ma. Evidence for groundwater-related sea-level cycles instead includes the existence of humid–arid climate oscillations, the relationship of sea-level to the marine oxygen isotope curves, and the anti-phase relationship of sea- and lake-levels. Rates of past aquifer-eustatic sea-level change give a wide range from a conservative 0.04 mm a^{-1} to 0.7 mm a^{-1} for asymmetric cycles. The latter compares with similar values for climate- induced land water storage as obtained by satellite data for today's Anthropocene sea-level rise budget.

Michael Wagreich and Veronika Koukal give a review of sea-level proxies from pelagic marine archives. The deeper-water, more continuous rock record, in particular, preserves the signature of sea-level oscillations in the Milankovitch-band of orbital climate cyclicities. Physical proxy signals are based on higher and coarser siliciclastic input during sea-level lowstand and regressions, and include coarser grain size as well as enrichment in heavy minerals and clay content. Chemical proxies that relate mainly to siliciclastics provide manganese, titanium and zirconium, often normalized v. aluminium. From a mineralogical point of view, the total amount of siliciclastics and their diversity provide sea-level information mainly in hemipelagites, as well as the phyllosilicate content v. biogenic pelagic background deposition of carbonate and silicious pelagites. Oxygen isotope $\delta^{18}O$ values, the main sea-level proxy during glacial episodes, cannot be used reliably for deciphering changing sea-level during hothouse climates with no ice.

Jeffrey Ross, Greg Ludvigson, Claudia Schröder-Adams and Marina Suarez provide a case study on high-latitudinal continental palaeoclimates from the Cenomanian of the Canadian Arctic Archipelago, at an estimated palaeolatitude of 68–72° N and palaeotemperatures around 12–14°C. Depleted meteoric water $\delta^{18}O$ values indicate that ancient greenhouse worlds show different meteoric $\delta^{18}O$ values compared with today's relationships between local surface air temperature and local oxygen isotope ratios of precipitation. The low $\delta^{18}O$ values for palaeoprecipitation in the Sverdrup Basin cannot be explained by local to regional orographic effects, exemplifying the fundamental differences of the hothouse Earth system.

Matt Joeckel, Greg Ludvigson, Andreas Möller, Noah McLean, Marina Suarez, Celina Suarez, Benjamin Sames, Carol Hotton, James Kirkland and Brittany Hendrix present a breakthrough in the chronostratigraphy of the vertebrate-bearing Yellow Cat Member of the Cedar Mountain Formation, which provides an important archive for terrestrial environments, ecosystems and global change in the ancient North American Cordilleran foreland. The

Berriasian to Valanginian age for the Yellow Cat Member is confirmed by geochronology and palynostratigraphy such as zircon U–Pb maximum depositional ages of palaeosols around 136 Ma, constraining dinosaur evolution and interpretations of ancient palaeoclimates, palaeoenvironments and palaeoecology.

Yuri Zakharov, Vladimir B. Seltser, Mikheil V. Kakabadze, Olga P. Smyshlyaeva and Peter P. Safronov present new data on late Mesozoic trends in palaeoclimate, palaeoceanography and palaeoecology from the Volga region of Russia based on stable isotope studies from mollusc shells. Temperature trends for the epipelagic zone from the Middle Jurassic to Cretaceous in the Russian Platform–Caucasus area indicate extreme warm conditions for the middle–late Tithonian and the late early to early late Aptian, followed by late Aptian and early Campanian cooling.

The contribution by Erik Wolfgring, Michael Wagreich, Ismail O. Yilmaz, Shasha Liu and Katharina Boehm investigates a Tethyan deeper-marine Campanian–Maastrichtian section at Göynük, Turkey, from a pelagic palaeoenvironment rich in planktonic and benthonic foraminifera and calcareous nannofossils. Clastic sediment input rates constrain regional sea-level lowstands around the late Campanian *calcarata* Zone and the Campanian–Maastrichtian boundary, corresponding to the Campanian–Maastrichtian boundary event. The presence of cooler-water nannofossil taxa may suggest related cooling episodes in the northern Neo-Tethys around the Campanian–Maastrichtian boundary and in the mid-Maastrichtian.

Malcolm Hart and Lyndsey Fox confirm the hitherto controversial stratigraphical position of the Cambridge Greensand to the lowermost Cenomanian and the widespread lowstand hiatus at the Albian/Cenomanian boundary. The historical disagreements between macrofossil (Albian) and microfossil (early Cenomanian) ages are resolved using sea-level changes, planktic foraminifera and sequence stratigraphy.

Based on comprehensive microfossil data and an integrated foraminiferal–radiolarian zonation for the upper Albian–Maastrichtian of the Eastern European Platform, Valentina Vishnevskaya and Ludmila Kopaevich study the palaeogeographic and palaeoceanographic evolution of this area. The late Albian was characterized by the gradual disappearance of a meridional seaway and the opening of connections into the Tethys Ocean and parts of the Peri-Tethys seas during the Cenomanian. Carbonate sedimentation prevailed during the middle Turonian–Santonian time of high global sea-level. A cold Boreal water influence can be recognized as far south as the Northern Caucasus during latest Albian and around the Campanian–Maastrichtian boundary event, whereas the Turonian–Coniacian–Santonian and the late Maastrichtian were identified as rather warm episodes and high longer-term sea level.

Oguz Mulayim, Ismail O. Yilmaz, Bilal Sarı, K. Tasli and Michael Wagreich report a particular platform drowning event at the Cenomanian–Turonian carbonate ramp in the Adıyaman region of southeastern Turkey, part of the northern Arabian Platform. The abrupt shift from benthic carbonate deposits to pelagic deposits near the Cenomanian–Turonian boundary correlates to a distinct positive $\delta^{13}C$ excursion, linking a major transgression to Oceanic Anoxic Event 2, and thus drowning to a global sea-level event in the latest Cenomanian.

The case study by Yiwei Xu, Xiumian Hu, Marcelle BouDagher-Fadel, Gaoyuan Sun, Wen Lai, Juan Li and Shijie Zhang investigates the evolution of the 1 km-thick and at least 110 km-wide epeiric carbonate platform of the late Aptian to early Cenomanian Langshan Formation in central Tibet. Eleven distinct microfacies correspond to lagoonal, rudist bank and open marine facies belts that sensitively record regional sea-level changes. During the late Albian, at around 107 Ma, a sudden deepening event is reconstructed by the change from rudist bank to open marine sedimentation. Correlation to other sections globally indicates that this deepening event was widespread and synchronous, thus controlled by a global sea-level rise related to the decay of polar ice sheets and/or the release of water from continental aquifers.

The final case study by Holger Gebhardt, Samuel Akande and Olabisi Adekeye looks on Cenomanian to Coniacian sea-level changes in the Benue Trough of Nigeria using facies analyses, foraminiferal assemblages and planktonic deep-water foraminifera. Tectonic subsidence was superimposed by eustatic sea-level changes resulting in palaeowater depth fluctuations attributed to 405 ka eccentricity cycles. The correlation of the percentage of planktonic foraminifera and the number of keeled planktonic species can be used as a potential proxy for water depth estimations in deeper-water sections.

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