EUSTASY, ITS CONTROLLING FACTORS, AND THE LIMNO-EUSTATIC HYPOTHESIS – CONCEPTS INSPIRED BY EDUARD SUESS

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> *„Wenn man aber nun, mit dieser neutralen Terminologie ausgerüstet, an eine ernste Prüfung der Sachlage zu schreiten versucht, tritt eine solche Fülle den Meeresspiegel beeinflussender Umstände, so vielfache Unsicherheit in den vorliegenden Angaben und eine solche Mannigfaltigkeit der Fehlerquellen hervor, dass endlich als das Ergebniss der jahrelangen Arbeit nicht viel Anderes bleibt als die Ueberzeugung von der Irrthümlichkeit mancher Sätze, welche trotz der Warnungen vorurtheilsfreier Männer zu herrschenden Schulmeinungen geworden sind, und die Hoffnung, dass es der hinter uns aufstrebenden Generation gelingen werde, zu einer genaueren Erkenntniss der Statik der Meere zu gelangen.“*
> *(Suess, 1888a, p. 29)*

> *“But if, equipped with this neutral terminology, we now attempt to proceed to a serious examination of the position, we find ourselves confronted with so many circumstances which may exert an influence on the sea-level, by so much uncertainty in the existing data, and by so many sources of error, that finally little remains as the result of many years' labour, but a conviction that many doctrines which in spite of the warnings of unprejudiced authorities have become accepted dogmas are erroneous, and a hope that the rising generation will succeed in obtaining a more exact knowledge of the laws which govern the statics of the seas.”*
> *(Suess, 1906, p. 24, translated by Hertha B.C. Sollas)*

ABSTRACT

For many years Eduard Suess dealt with the phenomenon of displaced shorelines and the search for explanations for their genesis and the controlling factors. In the year 1888 Suess introduced the term "eustatic movements" referring to the global synchroneity of marker events in marine successions of the Earth history. Since the times of Suess, rapid scientific progress has considerably widened our understanding of the processes involved in changing sea levels. Eustasy now describes global sea-level changes that play a major role in controlling the development, structure and distribution of marine sedimentary successions.

Relative (regional and local) and global (eustatic) sea-level fluctuations are controlled by a variety of endogenic and exogenic processes. Mantle convection and resulting gravity anomalies and tectonism, and climate changes are the main drivers, and apply at different temporal and spatial scales. The long-term sea-level record, i.e. 1st to 2nd order cycles and stratigraphic sequences, occurring over millions to tens of millions of years, is mainly controlled by the internal dynamic history of the Earth, e.g., the changing rates of ocean crust production. Short-term eustatic sea-level changes during ice house phases of Earth's climate are clearly controlled by waxing and waning of continental ice sheets. However, significant short-term, i.e. 10s kyr to a few Myr (3rd to 4th order cycles), sea-level changes during greenhouse episodes of Earth history are still enigmatic. Such cycles are often explained by the presence of ephemeral ice sheets even during the hottest greenhouse phases (“hothouse periods”) of the Phanerozoic climate history such as the mid-Cretaceous.

We argue that the effect of groundwater storage and release on sea-level change, particularly important during ice-free greenhouse-phases, has been and is widely underestimated in its order of magnitude. It is considered to constitute a water volume that is about equivalent to today's ice volume, thus corresponding to a potential sea-level change of up to ca. 50 m applying isostatic adjustment. Groundwater storage, including both freshwater and saline pore waters, strongly exceeds lake and river storage capacities.

We introduce the term “limno-eustatic” to describe the effect of water volumes that are bound to groundwater and lake storage on sea-level fluctuations and cycles during major greenhouse phases of Earth history. Based on these terms the dimension of purely ice-driven glacio-eustatic processes can be better differentiated.

The limno-eustatic hypothesis may be testable given high-resolution stratigraphic correlations between marine and continental lake archives during supposed ice-free periods of Earth history. Lake-level and sea-level fluctuations should be in an out of phase relation, i.e. a major marine sea-level lowstand should correspond to a lake-level highstand, and vice versa. Preliminary tests using selected stratigraphic levels of the Late Cretaceous record of the long-lived lacustrine Songliao basin in China indicate such an out-of-phase relation, and thus support the limno-eustatic hypothesis as a mechanism to explain significant short-term sea-level fluctuations during greenhouse climate phases.

Nach langjährig wiederholter Auseinandersetzung mit dem Phänomen verstellter Strandlinien und der Suche nach einem Erklärungsmuster für deren Genese und der sie bedingenden Faktoren hat Suess 1888 unter Hinweis auf die sich über globale Distanzen in marinen Abfolgen vergangener Zeitabschnitte wiederholt abzeichnende Gleichzeitigkeit identer Leitereignisse den Begriff „eustatische Bewegungen“ eingeführt. Der seitdem eingetretene rasante wissenschaftliche Fortschritt hat unser Verständnis, welche Faktoren bestimmend auf die (wechselnde) Positionen des Meeresspiegels Einfluss nehmen, bedeutend erweitert. Der Begriff Eustasie beschreibt heute globale Meeresspiegelschwankungen, die eine bedeutende Kontrolle über die Entwicklung, die Strukturen und die Verteilung mariner Sedimentabfolgen ausüben.

Kontrolliert werden sowohl der relative (regionale bzw. lokale), wie auch der globale (eustatische) Meeresspiegel, durch eine Vielzahl endogener und exogener Faktoren. Änderungen in der Schwereverteilung innerhalb der Erdkruste durch Mantelkonvektion und oberflächennahe Horizontaltektonik, wie auch Änderungen des Klimas, sind in diesem Geschehen, auf unterschiedlichen zeitlichen und räumlichen Skalen, die wichtigsten Antriebskräfte.

Dabei wird die in Zyklen und stratigraphischen Sequenzen erster und zweiter Ordnung mit der zeitlichen Dauer von einigen Millionen bis Zehnermillionen Jahren ablaufende langfristige Entwicklung des Meeresspiegels vor allem durch die interne dynamische Entwicklung der Erde gesteuert, zum Beispiel durch Änderungen der Raten der Ozeankrustenbildung. Kurzfristige eustatische Meeresspiegeländerungen in Eishaus-Klimaphasen der Erdgeschichte werden eindeutig durch den Auf- und Abbau kontinentaler Eisschilde kontrolliert. Einigermaßen enigmatisch bleiben Vorgänge, die während längerer Perioden mit Treibhaus-Klima kurzfristig, mit Zyklen dritter und vierter Ordnung und einer Zeitdauer von einigen Zehntausend bis wenige Millionen von Jahren, für signifikante Meeresspiegeländerungen gesorgt haben. Zumeist wird der Versuch unternommen, derartige Zyklen mittels Annahme kurzlebiger Eisschilde zu erklären. Träfe dies zu, würde das bedeuten, dass selbst während der heißesten Treibhaus-Klimaphasen ('Hothouse-Perioden') des Phanerozoikums, wie etwa in der mittleren Kreide, lokale Eisschilde angenommen werden müßten.

Wir argumentieren, dass, speziell für eisfreie Treibhaus-Klimaphasen, der Effekt von Grundwasserspeicherung und –freisetzung in seiner Größenordnung bisher stark unterschätzt wurde. Dieser Speichereffekt stellt ein Wasservolumen dar, welches annäherend dem heutigen Eisvolumen entspricht. Unter Annahme isostatischer Kompensation könnte dieses im Untergrund gespeicherte Wasservolumen Meeresspiegeländerungen bis zu einer Größenordnung von ca. 50 m bewirken. Der Grundwasserspeicherungseffekt, sowohl von Süßwasser als auch mit beträchtlicher chemischer Lösungsfracht behafteter Porenwässer, übersteigt damit bei weitem die Speicherungskapazitäten von Seen und Flüssen. Im folgenden wird der Begriff 'limno-eustatisch' eingeführt - vor allem, um den Einfluss hervorzuheben, welchen Speicherung und Freisetzung dieser in flüssiger Form festlandgebunden Wasservolumina in Perioden mit Treibhaus-Klima auf Änderungen des Meeresspiegels zu nehmen vermag. Auf der Grundlage dieser begrifflichen Verfeinerung sollte es in Zukunft möglich sein, die Dimension rein Eis-gesteuerter glazio-eustatischer Prozesse klarer festzulegen.

Die limno-eustatische Hypothese kann mit Hilfe von hochauflösenden Korrelation zwischen marinen und kontinentalen Sedimentarchiven in Seen während angenommener eisfreier Perioden der Erdgeschichte überprüft werden. Zu diesen Zeiten sollten Seespiegel und Meeresspiegel gegenläufig und phasenverschoben verlaufen, das heißt bedeutende marine Meeresspiegeltiefstände sollten Seespiegelhochständen entsprechen und umgekehrt. Vorläufige Resultate für ausgewählte stratigraphische Horizonte der späten Kreide in einem Vergleich mit dem Langzeitarchiv des lakustrinen Songliao-Beckens in China zeigen eine gegenläufige Entwicklung und unterstützen damit die limno-eustatische Hypothese als eine Möglichkeit, signifikante kurzzeitige Meeresspiegelschwankungen während Treibhaus-Klimaphasen zu erklären.

1. INTRODUCTION

Sea level constitutes a fundamental boundary for life on our planet, and changes in sea level drive major shifts in the landscape (Suess, 1888a, b; Conrad, 2013). The recent rise in sea-level in response to rising levels of atmospheric greenhouse gases and the associated global warming is a primary concern for society, especially to peoples of low-lying countries. Evidence from Earth’s history indicates that deep-time global and thus “eustatic” sea-level changes occurred at rates an order of magnitude or more higher than that observed at present. To predict future sea-levels the record of past sealevel change has to be evaluated and causes and consequences have to be analysed in detail.

The term eustasy dates back to Eduard Suess (1888a: p. 677 ff., 1888b). Suess’ idea of eustasy was based on the observations of flooding of continents, i.e. transgressions and regressions. The term eustasy was subsequently used to denote global and coeval changes in sea-level with time as they are preserved in the stratigraphic record of Earth’s history (e.g. Haq, 2014).

As a concept originally deduced from geological evidence and Earth history, eustasy connects to the recent rise in sea level as a consequence of the anthropogenic rise in greenhouse gases concentration, such as carbon dioxide, and the resulting global warming. The IPCC (2007) predicted sea level to rise between 0.4 m and 1 m until the end of this century. The current rate of sea-level rise is about 1 - 3 mm/yr (e.g. Miller et al., 2011). Evidence from Earth's history indicates past sea-level change rates an order of magnitude or more higher than the current rate (Miller et al., 2005a). Clearly, there is a need to better understand the record of past sea-level changes and their causes, and the consequences for the Earth's system to better predict future global environmental change. This paper gives an introductory review on Suess ideas and today's usage of eustasy and various processes related to sea-level fluctuations. The main focus is on sea-level changes in a greenhouse world.

2. Suess and the term Eustasy

The term eustasy and the presence of eustatic sea-level changes ("eustatische Bewegungen" = "eustatic movements") was introduced by Suess (1888a, b, translated and published in English in 1906). In writing his encyclopaedic, monumental work on the complete representation of the surface geology of the Earth (Das Antlitz der Erde/ The Face of the Earth; 1883–1909), Suess often found himself obliged to specify the discussion of complex subject matters with the help of terminology adequate for the issue (see excerpt at the very beginning of this article). Among the many newly-coined specialized terms created by Suess for this purpose, most of which have passed the test of time and are thus still in use today, the term "eustatic movements" (Suess, 1888a, p. 680 ff), which he was first to introduce into earth science literature, is of special significance. This is because with this term Suess describes a process of which the governing factors remained unclear to him to the end. Nevertheless this term has imposed itself. Released from its original definition and expanded by the presen-tday knowledge of further major factors determining the (changing) position of the sea level, almost as if by metamorphosis the dry descriptive shell of an originally only very poorly-defined term turned into the now indispensible process term of "eustasy".

Suess original definition of eustasy is based on the observations of flooding of continents, i.e. transgressions ("eustatic positive movement", Suess, 1906) that moved fossil shorelines continentwards, and the drawback of oceans from continents, i.e. regressions ("eustatic negative movement"), that moved the shoreline seawards. Suess (1888a, b, 1906) indicated a purely descriptive meaning of the term "eustatic" to avoid discussions on, in his view, somehow dubious processes suggested during this time. Suess (1888a, b) original ideas involved mainly regional mechanisms such as (1) the sinking of ocean basins as the main cause for negative eustatic change, and (2) the filling of ocean basins by sediments as the cause for positive eustatic change. Suess (1888a) of course could not include a mobilistic view of the Earth as it is now based on plate tectonics, including the Wilson cycle of ocean evolution in time (Wegener published his ideas in 1915; but see Sengör, 2014).

Raised beaches above the prevailing sea-level were recognized early by man, and their significance pondered. The conclusion drawn, namely that the level of the sea as well as the boundaries of its edges are subject to constant change, can thus be counted as one of mankind's earliest items of geologic knowledge. Regardless, since antiquity such observations from the Mediterranean coastal regions were the subject of detailed comments (Suess, 1888a cum lit.; Pfannenstiel, 1971). In the 18th century interest in this subject matter was centered on the Baltic Sea, where work had just begun to obtain, by means of a tight network of gauges and specifically emplaced markers, measurements aiming at understanding the order of magnitude of the coastal retreat which had occurred within a few generations. Already at this time either (tectonic) movements within the land mass or a change in the volume of seawater were considered as explanations for these shoreline shifts. It was also already known by then that the level of the ocean and that of the seas dependent upon it could vary from one place to another (Suess, 1887), which needed to be taken into account when undertaking a global comparison of the gauge levels.

It was with this knowledge level that Suess began to deal with this subject matter. According to what he indicated in his autobiography (Suess, 1916, p. 681) he was first confronted with the question of the factors controlling the shifting of coastlines at the beginning of his academic career, while undertaking fieldwork in the area of Eggenburg (Lower Austria). However, the commented data collection on this subject, assembled with exemplary diligence in the 3rd part of his "The Face of the Earth", hardly contributes to its clarification. Despite having begun grappling at an early date with this subject matter the results assembled until his death remain curiously vague - apart from the important fact that Suess rejected, with good reason, the idea going back to Leopold von Buch that periodic uplift and sinking of the continents were the sole factor responsible for coastal shifts (see also Sengör, 2014).

In the end, there are several reasons why the original definition of "eustatic movements" remained so empty of interpretative content, despite the author's decades-long dealing with this subject matter. It was not a lack of detailed information on the subject; on the contrary, it was the plethora of divergent observations, which at the time could not be melded into a comprehensible whole, which hindered Suess. Yet some of the ideas mooted by Suess (1888a, 1893) are surprisingly modern: for instance, when Suess speaks of climate cycles lasting 25 900 years, which result from the parameters of Earth's orbit around the sun, and the resulting variations in intensity of solar radiation on the Earth's surface, or when he reflects upon the widespread influence of sea-level changes upon the shape of submarine sediment deposits. These sudden inspirations, unexpectedly occurring in several places in his description of the seas, encompassed in over 700 printed pages, point to a much larger concept, the resolution of which eluded Suess. Or rather, had to elude him, since several issues of general importance had not yet been clarified. Research on the topography of the oceans was still in its infancy and the great significance of isostatic processes for the formation of the Earth's surface not even realised. Thus, the question concerning the genesis of oceanic realms perforce remained unanswered, as did that of the permanence of deep oceanic basins (Suess, 1893). In addition, in his thinking Suess was a prisoner of the obsolete contraction theory, the concepts of which could in some fashion explain sea-level drops; in order to explain movements in the opposite direction (uplift, transgression) it was necessary to call upon more adventurous and imaginative mechanisms. His son, who later followed him to his university chair, was also still influenced by similar views (F.E. Suess 1920, and in Neumayr et al., 1920).

The dissemination of the term "eustatic variability" in ist present-day meaning was strongly aided by its concise formulation in numerous following textbooks on general geology (Geikie, 1903, 42 f.; Kaiser, 1905, 674; Kober, 1923, 168; von Bubnoff, 1931, 231; Cloos, 1936, 361; Cornelius, 1953, 138). The term eustasy as based on Suess (1888a, b) thus changed accordingly to today's usage to denote global and coeval changes in sea-level with time (e.g. Simmons et al., 2007; Conrad, 2013; Haq, 2014).

3. EUSTATIC AND REGIONAL SEA-LEVEL CHANGES IN DEEP-TIME

In principle, global eustatic sea level can vary due to two major groups of processes, (1) changes in the volume of water within the ocean basins, or (2) changes of the net volume of the ocean basins itself (e.g. Conrad, 2013; "ocean container volume" of Haq, 2014). Furthermore, regional and diachronous processes of "relative" sea-level change have to be distinguished from global synchronous "eustatic" processes. Eustatic (global) sea level can be defined as the globally averaged level of the sea surface measured relative to a fixed reference such as Earth's center (e.g. Conrad, 2013). In contrast, relative (regional or "eurybatic" of Haq, 2014) sea level can be defined as the local elevation of the sea surface relative to the solid surface of Earth (Conrad, 2013).

Furthermore, different time scales of (relative and global) sea-level changes have to be considered, which can be separated in general into: (1) Short-term sea-level changes in the time range of up to 10 kyr including mainly elastic and viscous deformations of the solid Earth due to glacial loading and unloading (Conrad, 2013). In the following deep-time context these effects are not considered further, although they play a major role for measuring and interpreting the recent sea-level history. (2) Long-term sea-level changes, mainly from 100 kyr to Myr time scales (3rd order sea-level changes, e.g. Haq, 2014), which are controlled mainly by climate variations, plate tectonics and mantle processes. In this deep-time context, eustatic sea level can rise due to changes of the net volume of the ocean basins because of:

- mid-ocean ridge expansion associated with faster spreading (e.g. Pitman, 1978; Larson, 1991; Conrad, 2013)
- expansion of continental areas (e.g. Conrad, 2013) including mountain-building processes
- increasing submarine sediment volumes (e.g. Conrad, 2013, as originally also envisaged by Suess, 1888a, as the main process to raise sea level)
- addition of volcanic rocks within ocean basins (e.g. Larson, 1991; Ruban et al., 2010a; Conrad, 2013)
- dynamic uplift of the seafloor by mantle flow ("dynamic topography", e.g., Moucha et al., 2008; Conrad and Husson, 2009) – this includes also a regional component by deflecting the Earth surface locally (see also Petersen et al., 2010; Lovell, 2010).

Regional and local effects on (relative) sea level can be, in addition, assigned to regional tectonic processes such as intraplate deformation, i.e. intraplate stress changes (e.g., Cloetingh et al., 1985; Cloetingh, 1986) and lithospheric buckling (e.g., Cloetingh et al., 2013). However, two arguments stand against a purely tectonic control on a purely regional sea-level history: (1) The synchroneity of at least parts of sequence boundaries and sea-level changes within different plates of the Earth (e.g. Wilmsen and Nagm, 2013; Haq, 2014); (2) the observed cyclicity of relative sea-level changes inferred from sequence stratigraphy cannot be explained easily except using the assumption that tectonic regimes, intraplate stress, and lithospheric buckling changes rhythmically within several 100 kyrs to a few Myrs at places. Furthermore, even in tectonically highly active basins such as the classical Neogene Vienna pull-apart basin with high, episodic subsidence and intermittent and spatially distributed fault activity (e.g. Wagreich and Schmid, 2002; Hölzel et al., 2008) it has become clear with increasing precision of stratigraphic dating that major sequence boundaries are tied to global sea-level lows (e.g. Strauss et al., 2006; Hohenegger et al., 2014), although individual in-sequence geometries may be strongly influenced by tectonics and resulting accommodation changes at individual fault blocks.

The concept and reality of eustasy has recently been criticized as well (e.g., Moucha et al., 2008; Lovell, 2010; Ruban et al., 2010a, b, 2012), based essentially on the fact that *"all observations of relative sea level are sensitive to both changes in eustatic sea level as well as to local uplift or subsidence at the measurement location"* (Conrad, 2013, p. 1029). Every location on Earth, and thus every single stratigraphic archive of sea-level fluctuations, is influenced by processes of changing dynamic topography as evidenced by the analyses of new global geophysical databases (e.g., Divins, 2003), new tectonic reconstructions of the seafloor (e.g., Müller et al., 2008; Ruban et al., 2010a), and numerical models of global mantle convection (e.g., Moucha et al., 2008). Thus, as Conrad (2013, p. 1029) states *"…. the solid Earth exerts a first-order and time-dependent influence on both the measurement and interpretation of eustatic change."* However, Conrad (2013) in his summary on the solid Earth influence on sea level still uses the term eustatic, as well as Haq (2014) in his justification for eustatic sea-level changes during the Cretaceous.

The long-term Phanerozoic sea-level record (1st to 2nd order cycles of Haq, 2014; several Myr to 100 Myr) is clearly controlled by the internal dynamic history of the Earth and reflects primarily plate tectonics and mantle dynamics, e.g., changing rates of oceanic crust production, mantle upwelling and downwelling, subduction, and collision processes (Larson, 1991; Müller et al., 2008). The short-term sea-level changes (3rd to 4th order cycles of Haq, 2014; several 10 kyr to a few Myr) are in the focus of the following chapters, i.e. those time ranges of regional sea-level fluctuations where processes of dynamic topography and tectonics overlap with eustatic sea-level fluctuations controlled by climate changes.

3.1 CHANGES IN THE VOLUME OF WATER IN THE OCEANS

Changes in the volume of water on land and in the oceans are primarily connected to climate and climate changes and involve two main processes: (1) changes in the storage of water on land, mainly in the form of continental ice sheets during cold periods and ice ages of Earth's history, and (2) changes due to thermal expansion of the sea water itself due to (global) warming.

In addition to these climatically induced processes, sea level also rises if water exchange rates with the deep mantle change, either because of increased outgassing or diminished loss due to subduction. However, these processes are reported to work on significantly longer time scales of at least 100s Myr with a low-amplitude (a maximum of ca. 1 m/Myr according to Conrad, 2013), and thus are not considered any further in our work. However, such mantle processes may have been important for the long-term evolution in the billion year range of the Earth, especially during the Precambrian.

4. EUSTASY IN AN ICEHOUSE WORLD – THE QUATERNARY RECORD

The most prominent mechanism for changing the seawater volume in the oceans is the growth and decay of continental ice sheets which result in high-amplitude, rapid sea-level changes (up to 200 m in amplitude, and rates of more than 40 mm/yr rise during meltwater pulses, Miller et al., 2011). Resulting sea-level changes are termed glacio-eustatic. In addition to the melting effect (that has to be isostatically compensated) the effect of thermal expansion (and contraction for cooling episodes) of sea water has to be included (a warming of 1°C of the sea water results in a eustatic sea-level rise of about 70 cm, Conrad, 2013).

The Quaternary ice age provides the most recent and intensely studied icehouse interval in Earth's history. Sea-level variations are evident, e.g. from coastal records, and modeled via the oxygen isotope record which relates temperature and ice volume (e.g., Raymo and Huybers, 2008). The Quaternary record is mainly characterized by sea-level changes induced by climate-cycles in the 40–100 kyr range that are accompanied by spatial variations in sea level associated with the solid Earth's elastic and viscous responses to loading (Conrad, 2013). During the Last Interglacial, some 120 kyr ago, the global sea level was likely ca. 6-9 m higher than today. Subsequently, the sea level dropped during the Last Glacial, with a lowstand of ca. 120 m below today's level during the Last Glacial Maximum 20 kyr ago (e.g., Miller et al., 2011).

As an example of the magnitudes involved in glacio-eustasy, Earth's present-day ice sheets contain the seawater equivalent to 64 m of sea level which, when isostatically compensated, correlates to a eustatic sea-level rise of ca. 45 m for a future ice-free world (Conrad, 2013). In addition, warming and thermal expansion of the water will also contribute about 12 m to the rising sea-level. Observations from the last 100 yr indicate a rate of sea-level rise of ca. 1–2 mm/yr (Douglas, 1991; Conrad, 2013).

Stable oxygen isotope ratios, i.e. $\delta^{18}O$ values of marine carbonates, are widely used in the Quaternary and older archives to assess ocean temperature and global ice volume. Based on the oxygen isotope fractionation cycle ice volume changes are recorded mainly by $\delta^{18}O$ values of deep-sea benthic foraminifera (e.g. Emiliani, 1954; Shackleton and Kennett, 1975). For example, the 120 m of sea-level fall during the Last Glacial ice sheet growth increased global seawater $\delta^{18}O$ values by ~ 1.2‰. Melting present-day global volume of ice would raise oceanic $\delta^{18}O$ values by ~ 0.9‰ (Shackleton and Kennett, 1975, Miller et al., 2011). Oxygen isotopes measured in marine carbonates vary with periods that mirror orbital Milankovitch cyclicity, and constitute an important proxy for deciphering Quaternary cycles (e.g., Hays et al., 1976). During the Pleistocene, ice volume controlled two-thirds of the measured variability in benthic foraminiferal $\delta^{18}O$ records, while temperature variations accounted for the other one-third (Miller et al., 2011). Thus, cyclic changes in stable oxygen isotope ratios connected to sea-level changes were used also to argue for glacio-eustasy in deep-time (e.g., Miller, 2005a, b; Haq, 2014).

5. EUSTASY IN A GREENHOUSE WORLD - THE CRETACEOUS RECORD

In contrast to glacial eustasy controlled mainly by the waxing and waning of continental ice sheets during icehouse periods of the Earth's climate, short-time sea-level changes during the warmer times of Earth's history, i.e. the greenhouse periods (Fischer, 1982), are still poorly understood. The Cretaceous period provides the youngest prolonged greenhouse interval in Earth history, and therefore constitutes a well studied period in regard of palaeoclimate and palaeoceanographic evolution (e.g., Skelton et al., 2003; Hay, 2008; Hay and Floegel, 2012). Despite former thoughts on a warm equable Cretaceous (e.g. Barron, 1983) more recent research indicates a segmentation into 3-4 climate states (Kidder and Worsley, 2010, 2012; Hu et al., 2012; Hay and Floegel, 2012), i.e. a cooler greenhouse early Early Cretaceous, a very warm greenhouse mid-Cretaceous including short-lived hothouse periods with widespread anoxia and a possible reversal of the thermohaline circulation (HEATT episodes of haline euxinic acidic thermal transgression, see Hay and Floegel, 2012), and a Late Cretaceous evolution from warm to cool greenhouse. In addition, more and more short-term climatic events within the longer term trends are reported for the Cretaceous (e.g. Hu et al., 2012). Regarding sea-level changes, major efforts have been made already for the Cretaceous, i.e. Immenhauser (2005), Miller et al. (2005a,b), Miller (2009), Kominz et al. (2008), Müller et al (2008), but (global) correlation and significance of these sea-level changes is still doubtful in many cases, and is strongly debated (see, e.g., Zorina et al., 2008; Lovell, 2010; Petersen et al., 2010; Boulila et al., 2011; Haq, 2014). Also, the impact of sea-level changes on evolution and biodiversity through time (e.g. Smith et al., 2001) and the carbonate sediment factory response (e.g., Yilmaz and Altiner, 2006; Schlager, 2005) are related to this complex topic.

Investigation of the timing, the causes, and the consequences of significant short-term (i.e. several kyr to 100s of kyr) sea-level changes during the last major greenhouse episode of Earth history, the Cretaceous, is a strongly debated issue. A major episode of oceanic crust production led to long-term sea-level rise and the highstand during Cretaceous times. Peak sea level during the Cretaceous is estimated between 85 and 280 m, with best estimates between 170 and 250 m above today's sea level (Müller et al., 2008; Miller et al., 2011; Conrad, 2013; Haq, 2014). However, short-term, 3rd to 4th order sea level changes, recorded in Cretaceous strata, could be in the lower range of the order of magnitude known from Pleistocene glacial-interglacial episodes, i.e. 15-50 m (Miller et al., 2005b; Voigt et al., 2006; Kominz et al., 2008). Significant investigations have already been undertaken into this topic, mostly based on regional data. Two mechanisms have been proposed, including short glacial episodes (Stoll and Schrag, 1996, 2000; Miller et al., 2005a, b; Maurer et al., 2013) or the alternating charge and discharge of aquifers (e.g. Jacobs and Sahagian, 1993; Wendler et al., 2011, 2014): Given the advancing evidence that at least some if not all 3rd order sequences of the Cretaceous, even during the extreme hothouse episode of the mid-Cretaceous (e.g. Hay and Floegel, 2012) were synchronous (see most recent compilation by Haq, 2014; Wilmsen and Nagm, 2013), and therefore record eustatic, globally synchronous sea-level changes, there evolved two theories: either (1) to invoke the presence of ice on continents even during some of the hottest greenhouse periods of the Phanerozoic, or (2) to explain sea-level changes by some (speculative) mechanisms that influence the amount of water in the oceans in the same manner and rate (but maybe not the same magnitude) as the waxing and waning of ice sheets on continents. In general, as Haq (2014) states for the Cretaceous, eustasy cannot be dismissed in this prolonged and partly extreme greenhouse period.

5.1. GLACIO-EUSTASY DURING THE CRETACEOUS GREENHOUSE

Arguments for the presence of ice during the Cretaceous are mostly indirect (e.g., Miller et al., 2005a, b, 2011; Simmons, 2012). The only clear-cut evidence for glacier transport in the form of tillites (diamictites) was so far only described from southern Australia by Alley and Frakes (2003) from the Berriasian to Valanginian. Frakes and Francis (1988) gave information on ice-rafted blocks for the Early Cretaceous, referring to the possibility of "cold snaps" in the early Early Cretaceous. This fact has also been stated by ample indirect evidence such as the presence of glendonites (Price, 1999; Price and Nunn, 2010), migrations of cold-water biota into lower latitudes (e.g., Mutterlose et al., 2009), the occurrence of CORBs (Cretaceous Oceanic Red Beds; Wagreich, 2009; Wang et al., 2010) or other evidence such as carbonate platform cycles (Greselle and Pittet, 2010). Some records of stable oxygen isotopes also do indicate the presence of short cooler episodes and possibly also ice during this time interval (e.g., Stoll and Schrag, 1996; McArthur et al., 2007).

Therefore it can be concluded that during the Early Cretaceous, before the Aptian, ephemeral ice shields may have been present on Antarctica based on the direct evidence by Frakes and Francis (1988) and proxy data including the presence of glendonites. However, various data (e.g. Jenkyns et al., 2012), and especially plant fossil evidence from high northern and southern areas still show continuously warm and equable conditions for most of the Cretaceous. Although those records are inevitably episodic, no cold flora was found even for the Early Cretaceous so far (for a review see Price and Grimes, 2007). This may be related to a sampling bias where plant fossils from these short "cold snaps" are largely missing due to short durations of these cold events, the problem of exact dating of terrestrial strata, and unfavorable conditions for preservation of plant fossils due to high sedimentation rates and predominantly coarse sediments in such periglacial environments (e.g. Price and Grimes, 2007). The Early Cretaceous and possibly also the later part of the Late Cretaceous can thus be identified as times of a cool(er) greenhouse climate with the possibility of ice on Antarctica and maybe also on parts of Siberia (Miller et al., 2005b; Flögel et al., 2011; Hay and Floegel, 2012; Bowman et al., 2013).

The presence of ice during the main warm greenhouse to hothouse period of the mid-Cretaceous (Aptian to Turonian) is more enigmatic. Arguments in favor of ice have been summarized by Miller et al. (2005b, 2011), and case studies relating sea-level changes to continental ice storage include both the Cenomanian (Maurer et al., 2013) and the Turonian (Bornemann et al., 2008) as the hottest times of the Cretaceous hothouse period with reconstructed ocean surface water temperature in the range of 32-37°C (e.g. Huber et al., 2002; Steuber et al., 2005). Arguments are mainly based on interregional correlateable high-amplitude sea-level changes based on sequence stratigraphic studies. Evidence for ice is inferred from proxies like oxygen isotopes (Stoll and Schrag, 2000), especially in combination with independent temperature proxies (Ca/Mg ratios, e.g. Miller et al., 2011; TEX86, e.g. Bornemann et al., 2008) which allow the separation of temperature and salinity (ice) components in stable oxygen isotope records, especially from benthic foraminifera. However, some of the presumably best preserved and continuous stable oxygen isotope records for these extremely warm time intervals from excellently preserved glassy foraminifera, e.g. for the Cenomanian from the Atlantic Ocean (Demerara Rise, Moriya et al., 2007) and for the Turonian from Tanzania (McLeod et al., 2013), do not show any of these inferred ice-induced oxygen isotope shifts and strongly argue against a global ice signature in stable oxygen isotope record for the Cretaceous hothouse. Also, climate models indicate that, given those high hothouse temperatures reconstructed and resulting high carbon dioxide levels, ice sheets could not form in Cretaceous hothouse climates (e.g. Hay, 2008; Hay and Floegel, 2012). This leaves the debate open and fosters further studies on extremely well preserved material and especially polar regions from the Cretaceous hothouse to evaluate the possibility of the presence of ice during these intervals.

5.2 AN ALTERNATIVE, "LIMNO-EUSTATIC" PROCESS: GROUNDWATER AND LAKE STORAGE

In recent years more and more studies have proven the interrelation of climate cycles and sea-level fluctuations, based on sequence stratigraphy and mainly platform depositional cycles, even during Cretaceous hothouse times. Essentially, arguments come from statistically proven Milankovitch-type of cyclicities of sea-level changes during the Cenomanian-Turonian hothouse, from various areas and basins of the world, e.g. Jordan-Egypt-Arabia (Maurer et al., 2013; Wilmsen and Nagm, 2013; Wendler et al., 2014) to Europe (e.g., Galeotti et al., 2009; Sprovieri et al., 2013). This record can be also connected to the stable oxygen isotope record which often shows a similar cycling (e.g. Wendler et al., 2014; summarized also by Haq, 2014). Although reasons for cycles in stable oxygen isotopes may be complex, and diagenetic influence is ubiquitous, the similarities are often appealing, and give the same Milankovitch-types of bands in the longer (>100 kyr) range, e.g. 405 kyr eccentricity, 1.2 Myr obliquity and 2.4 Myr obliquity (e.g., Gale et al., 2002; Immenhauser, 2005; Wendler et al., 2014). Longer-term cycles, e.g. a 4.7 Myr band, are also archived in the carbon isotope records (e.g., Batenburg et al., 2012; Sprovieri et al., 2013).

Given the fact that there is a Milankovitch-driven climate cyclicity in sea-level changes even during mid-Cretaceous hothouse, and referring to arguments that there is no significant continental ice possible during those times (e.g. Hay and Floegel, 2012), the search for other climate related processes that result in changes in the ocean's water volume has to be made, i.e. alternatives for ice shield control on sea-level changes during extreme greenhouse phases of Earth history.

Two main processes can be envisaged influencing global sea-level on a climate-cyclic Milankovitch-type of scale if we consider climate changes in a completely ice-free world:

(1) Climate-related differences in sediment input into the oceans, with times of high sedimentation marked by sea-level rise and times of low sediment input marked by sea-level falls, as envisaged already by Suess (1888a). However, to affect sea level significantly, such changes in worldwide sediment input must be extremely high within short time periods of a maximum of a few 100 kyr. Effects are in the range of a few meters in maximum (Conrad, 2013), but may provide an additional process adding to induced sea-level change. Interestingly, such a mechanism may contribute to the recent sea-level rise given the anthropogenic rise in sedimentation rates due to deforestation and other anthropogenic processes (e.g., Wilkinson, 2005).

In general, eustatic sea-level changes in a sequence stratigraphy framework provide an intrinsic feedback mechanism for increasing sediment input into oceanic basins, and thus rising eustatic sea level, via shelf erosion during lowstands as opposed to sea-level highstands with sediments captured at shorelines and deeper water condensed sections. Thus, both positive (e.g. delta progradation during highstands raise the sea level) and negative feedbacks (shelf erosion during lowstands and lowstand-slope fan sedimentation may raise sea level) relate to this. This relates also to the hydrological cycle, when accelerated, strongly humid conditions bring more sediment into the ocean and when lowered during more arid conditions with low input of sediments into the oceans. But this process then seems to be more a result of a sea-level fluctuation and not its triggering mechanism.

(2) As continents provide the main storage capacity to effectively remove water from the oceans the only other reservoir apart from major ice shields are lakes and – much more important as to storage capacity – groundwater in porous sediments (Wendler et al., 2011, 2013, 2014; Note: Wendler et al., 2013 somewhat misleading used the term "freshwater", but freshwater only comprises less than 50% of all groundwater – today estimated at 23.4 × 10^6 km^3, e.g. Gleick, 1996).

To differentiate groundwater and lake storage induced sea-level fluctuations from ice-induced glacio-eustatic cycles we propose the term "limno-eustatic" for this process and the resulting cycles ("limno" since the 1970's the term limnology was extended to cover all study of inland waters, whether lotic, i.e., flowing water, or lentic, i.e., standing or still waters, and whether being located on the surface or underground - e.g., Elster, 1974; Wetzel, 2001), to underline the importance of the groundwater storage in contrast to ice-storage mechanism. Thus, limno-eustatic constitutes a newly defined process in addition to thermo-eustatic, glacio-eustatic and tectono-eustatic components of sea-level fluctuations.

The order of magnitude to which particularly groundwater reservoir filling and draining can contribute to eustatic sea-level changes is controversial and presumably still been underestimated to a large extent by many researchers to date. Miller et al. (2005a, Fig. 1 therein) published a scheme (given modified in Fig. 1 herein) informatively illustrating the timing and amplitudes of mechanisms influencing global eustatic seal-level change. However, such a scheme can easily be misinterpreted if read as diagram depicting a relation based on exact values, which it is obviously not (Moreover, the original scheme of Miller, 2005a, raises several questions remaining unanswered thus far, e.g.: about the ellipsoidal shape of some of the areas depicted). It thus only gives rough estimates of the orders of magnitude in time and amplitude. This scheme is used as basis for a modified sketch herein (Fig. 1) focusing on the calculations given by Hay and Leslie (1990) to visualise the dimension of groundwater contribution to global sea-level change in relation to other mechanisms, particularly in comparison with ice, and its potential scales of dimension against the background of different calculations for groundwater storage capacity (pore space in aquifers) and residence time (the time to fill and empty a groundwater reservoir). With respect to groundwater volumes and residence time, Miller et al. (2005a), for example, gave quite low volumes for lake and groundwater affecting global sea-level change and relatively short time periods for the mechanisms behind it.

However, studies by Hay and Leslie (1990) and Jacobs and Sahagian (1993) calculated the storage capacity of inland basins and continental sediments in general. This relates mainly to the global sediment porosity above sea level and lake level in closed inland continental basins. Lakes and rivers today only contain a minor volume of water of ca. 0.29 × 10^6 km^3 (Hay and Leslie, 1990). Jacobs and Sahagian (1993) estimated the total change of sea level due to lakes and groundwater by only considering large internally drained basins at 4–8 m, and considered a strongly seasonal climate (“mega monsoon”) especially for supercontinent stages of the Earth. Jacobs and Sahagian (1993) already concluded that cyclic lake and groundwater storage may probably have been the main contribution to Late Triassic greenhouse sea-level fluctuations.

Hay and Leslie (1990) indicated the portion of pore space in the groundwater system available for changes during climate cycles may be 25 × 10^6 km^3 (i.e., pore space in aquifers within the upper 1 km of average elevation on the continents of a global total of pore space in sediments of 116 × 10^6 km^3). This volume constitutes a water reservoir that is about equivalent to today’s ice volume of ca. 25 × 10^6 km^3 (Miller et al., 2011) and corresponds to a sea-level change of over 76 m without or ca. 50 m applying isostatic adjustment (Hay and Leslie, 1990). While response times for changes in the groundwater reservoir after a (step function) change in climate were estimated by Hay and Leslie (1990, p. 170) to be in the order of 10s to 1000s of years, the residence time, i.e., the time to fill and empty a groundwater reservoir after a step function change in the global hydrologic cycle, is estimated to be in the order of some 10 kyr to 100 kyr by these authors (Hay and Leslie, 1990, p. 166–167). Global groundwater and lake water storage occurs if the filling processes exceed the draining on a global scale of consideration, and the other way round regarding the emptying of the reservoirs. Since these hydrological systems are in constant flow, the response times are short. The times to fill or empty the continental water reservoirs in an order of magnitude that changes global seawater volumes, however, take considerably longer (in contrast to e.g. glacio-eustatic sea-level changes).

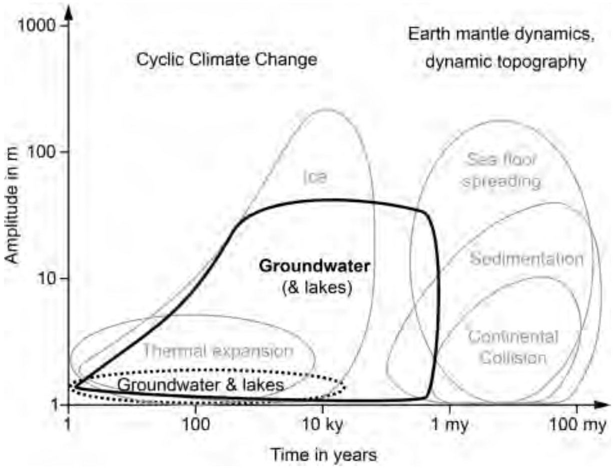

FIGURE 1: Timing and amplitudes of mechanisms influencing global eustatic seal-level change, effectively giving rough estimates of volumes affecting global seawater volume fluctuations and the time periods of the mechanisms (modified from Miller et al., 2005a). The timing and amplitudes of groundwater and lake storage (mainly controlled by cyclic climate change) as estimated by Miller et al. (2005a, dotted ellipse) in comparison to estimates based on Hay and Leslie (1990, continuous black line, after Wendler, J., unpublished), with an estimated volume of pore space in the groundwater system of 25 × 10^6 km^3 (of a global total of pore space in sediments of 116 × 10^6 km^3) as corresponding to a sea-level change of ca. 50 m applying isostatic adjustment; and as constituting a water reservoir that is about equivalent to today’s ice volume of ca. 25 × 10^6 km^3).

That is to say, given Cretaceous short-term 3rd (to 4th) order cycles in the order of 100 kyr to millions of years, the groundwater system quasi instantly responds to changes in climate but the complex of feedback mechanisms that cause noticeable sea-water volume fluctuations – and, thus, global sea-level changes – have a longer duration that fall within the (lower) order of magnitude of theses cycles. Consequently, there is a lag between a (climate induced) step-function change in the global hydrological cycle and resulting sea-level changes by groundwater storage on land or inflow into the sea. Moreover, the initial amplitude of limno-eustatic sea-level changes is probably lower compared to glacio-eustasy. These lag and overlap mechanisms must be taken into consideration when analysing sedimentary archives for cyclicity and testing these for limno-eustatic sea-level cyclicities. Therefore, our limno-eustatic groundwater and lake storage hypothesis remains to be tested thoroughly (see also Chapter 5.3. below). The causal linking of limno-eustatic sea-level changes and especially its timing and effects are not yet fully understood.

Summing up, against the background of a limno-eustatic groundwater and lake storage (and release) hypothesis, today’s calculated volume of the Earth’s groundwater exceeds that of lake water by almost a factor of 100. Based thereupon, the main element causing limno-eustatic sea-level changes is groundwater, while lake water can be almost neglected at the global scale (e.g. Jacobs and Sahagian, 1993; Miller et al., 2005a, 2011). While the calculations of pore space and groundwater volume given above are based on observations of today’s Earth, it is important to bear in mind that these have been subject to considerable change in Earth history through different continent configuration patterns, land mass size, topography, orogeneses, climate etc., which influence the available depositional space for sediments and their pore space and permeability. In certain times of the geologic past (e.g. mid-Paleozoic, late Paleozoic–early Mesozoic, mid-Cretaceous), the pore volume of sediments above sea level, thus coming into consideration as groundwater reservoirs, might have been up to twice the amount of today (Hay and Leslie, 1990; see also Hay et al., 2013 regarding the Cretaceous). Consequently, the order of magnitude of groundwater (and lake water as well) induced sea-level changes as described herein with respect to water volume and resulting amplitude of sea-level changes (Fig. 1), may be still significantly underestimated as for the Cretaceous.

5.2.1 LIMNO-EUSTATIC PROCESSES AND FEEDBACK MECHANISMS

The following scenario is envisaged for a Cretaceous ice-free world: more humid conditions give higher storage in the lake and groundwater reservoirs and higher lake levels, thus filling up the continental reservoirs as discharge into the ocean cannot keep up, which lowers sea level; vice-versa more arid conditions result in low lake levels, lower reservoir storage, and thus a rise in sea level. This is corroborated by climate modeling for the Cretaceous greenhouse which indicates the possibility of a very different hydrological situation with evenly flowing rivers (in spite of snow melt induced spring floods today), delivering less water to the ocean (Hay et al., 2013). Recent studies indicate that a warming climate resulting in a general precipitation shift from snow- towards rain-dominated regime leads to a significant decrease in streamflow (Berghuijs et al., 2014). In addition, the thermo-eustatic effect of water expansion due to warming may add a few more meters to such a mechanism, if warming occurs during times of aridity (e.g. Boulila et al., 2011).

However, there may be also negative feedback mechanisms that may dampen the effect of continental water storage on a longer time scale: (1) higher sea level means more continental areas covered by the Sea resulting in larger areas for evaporation (together with warmer shallow seas which also favor precipitation). This accelerates in principle the hydrological cycle (Jacobs and Sahagian, 1993) which then increases the input of water into continental reservoirs – a negative feedback which dampens the possible effects of groundwater and lake storage on sea level. (2) Another negative feedback mechanism may provide the sediment input cycling mentioned above where a sea-level lowstand principally increases sediment input into the oceans and thus results in sea-level rise.

Giving all this premises and feedback mechanisms and the possibly initially lower amplitude of sea-level change by these mechanisms compared to glacio-eustasy it seems probable that a short-duration overshooting mechanism can give a rapid lake-level rise and a coeval rapid sea-level fall. This may imply a different asymmetry than the slow fall to fast rise provided by the glacial-interglacial climate cycles of the Quaternary – we speculate that a sea-level cycle induced by continental water storage in lakes and aquifers may be characterized in contrast by a faster fall followed by a slow rise. We envisage a fast climate change to humid conditions and storage on continents followed by longer duration feedback mechanisms that slowly rise and equilibrate the sea level. Investigations into the asymmetry of sea-level cycles, especially in carbonate platforms, may help to separate controlling mechanisms (e.g. Greselle and Pittet, 2010).

Magnitudes and rates involved in limno-eustatic processes may be also assessed by using today's figures resulting from post-glacial warming and the anthropogenic global change

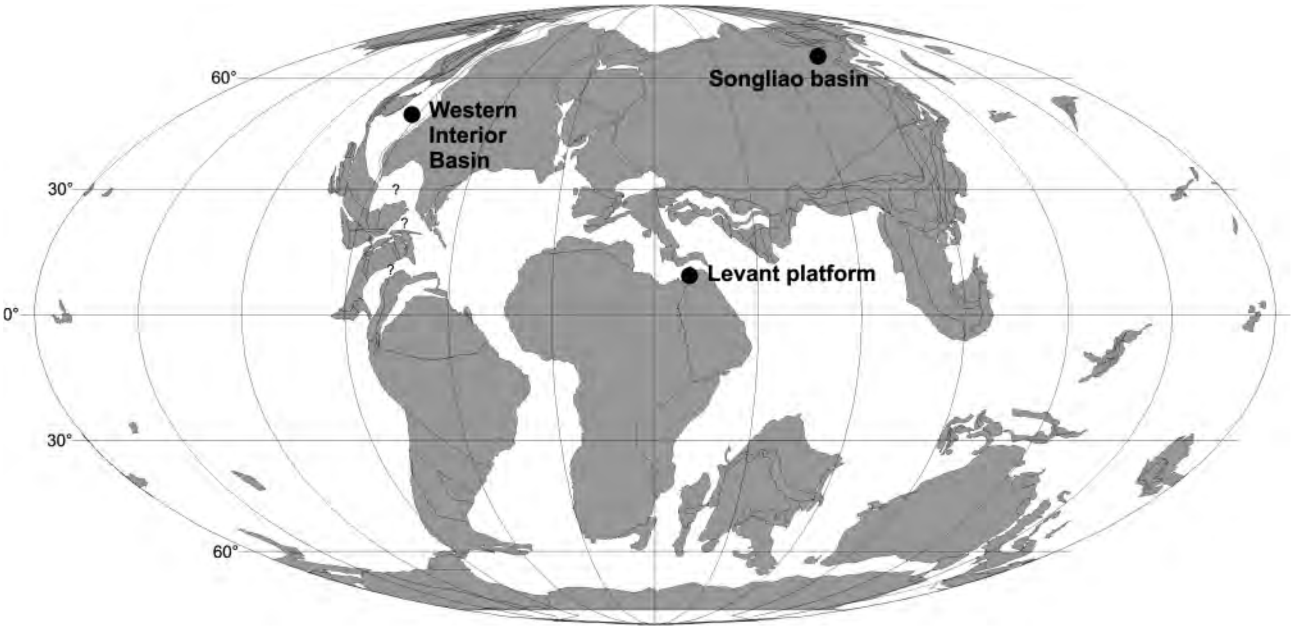

FIGURE 2: Location of Songliao basin, and correlated marine cyclic successions as used for a test of the limno-eustatic hypothesis (Coniacian-Santonian plate tectonic reconstruction based on Schettino and Scotese, 2002, and Wagreich, 2012). Grey areas denote continents and include shelf seas.

(the Great Acceleration of Steffen et al., 2007). Here, we compare the anthropogenic transformation of the continental water cycle with the proposed different hydrological cycle of greenhouse times. Based on modeling of continental ice loss an average global eustatic sea-level rise of 1.48 mm/yr is calculated (Conrad, 2013). Fiedler and Conrad (2010) calculated a coeval opposing sea-level drop of ca. 0.55 mm/yr due to the water storage in artificial reservoirs for the last 50 yr – thus, a figure of comparable and significant magnitude to the ice melting today.

5.3 TESTING THE LIMNO-EUSTATIC HYPOTHESIS

A test for the hypothesis that limno-eustatic groundwater and lake storage may be an additional and alternative climate-driven process to explain sea-level changes during greenhouse/hothouse episodes without ice may provide long-term high resolution inland lake records such as the Songliao basin for the Cretaceous (Wang et al., 2013a), and the Newark Supergroup for the Late Triassic (e.g. Jacobs and Sahagian, 1993; Whiteside et al., 2011). Following the reasoning based on Hay and Leslie (1990) and Jacobs and Sahagian (1993), non-marine sequences, and thus lake-level changes, should be within the longer Milankovitch band, but out-of-phase with sea-level changes, in that a lake-level highstand in the inland lake record should correlate to a (limno-eustatic) sea-level low in the world oceans. Testing this hypothesis is hampered by the severe problem of correlating marine with terrestrial archives in high-precision in deep time. However, based on improved biostratigraphy and correlations for the Cretaceous (e.g., Sha, 2007; Sames, 2010; Sames et al., 2010; Sames and Horne, 2012), high-precision absolute dating by geochronological methods (e.g., Meyers et al., 2012; Deng et al., 2013) and Milankovitch cyclicity and the advancing development of a common astrochronological time scale (e.g., Kuiper et al., 2008; Husson et al., 2011; Wagreich et al., 2012; Wu et al., 2013; Wendler et al., 2014), high-resolution correlations should be possible in near future with a precision in the 405 or even the 100 kyr cycle range.

The Songliao basin in NE China (Fig. 2) provides one of the best and continuous lacustrine records for the Cretaceous greenhouse climate evolution (Wang et al., 2013a, b). Although stratigraphic data and absolute ages for the Songliao basin SK1 core still vary (compare Wu et al., 2009, 2013) and orbital tuning still has to be calibrated in more detail, absolute age control by U/Pb on volcanic zircons (Deng et al., 2013) provides a robust time frame, together with palaeomagnetic data and astronomical tuning (Wu et al., 2013). Longer-term lake-level records from the Songliao basin are based on sequence stratigraphy (Feng et al., 2010) and facies interpretations (Wu et al., 2013).

A first comparison of Late Cretaceous sequences from the Songliao basin with the marine Western Interior Basin indicates non-synchroneity of sequence boundaries in general (Wang et al., 2013b). Shorter-term lake-level highstands are inferred for maximum levels of organic matter accumulation and black shale deposition under anoxic conditions of a stratified lake water body by Xi et al. (2011) and Jia et al. (2013), although Wang et al. (2013b) indicated also a possible connection to marine incursions. However, these LAE (Lake Anoxic Events, Xi et al., 2011) mark lake-level highstands, and occur (1) in the lower to middle Turonian (LAE1, originally erroneously identified as the Cenomanian-Turonian boundary OAE2 by Wu et al., 2009) and (2) in the upper Santonian (LAE2, which may be split in LAE2a and LAE2b as indicated by Xi et al., 2011). Recent U/Pb high precision zircon dating together with palaeomagnetic data (Deng et al., 2013) and astrochronology (Wu et al., 2013) refined the stratigraphy of the Songliao basin SK1 core (Wan et al., 2013) and provide absolute ages for LAE1 (91.4 Ma, with a duration of 100 to 800 kyrs according to Wu et al., 2009, 2013) and for LAE2a (84.478 Ma) and LAE2b (83.7 Ma) (see Xi et al., 2011, cor-

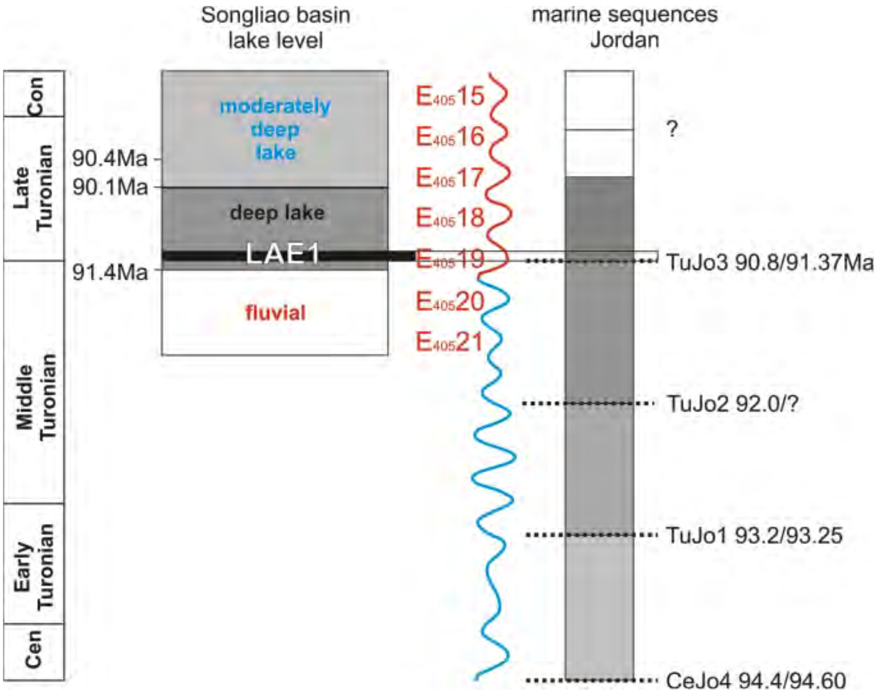

FIGURE 3: Correlation of the inferred limno-eustatic Songliao basin lake level changes with the prominent LAE1 black shale lake-level highstand at ca. 91.4 Ma (absolute ages by Deng et al., 2013; facies and lake level interpretation by Feng et al., 2010, Wang et al., 2013a, b) via 405 kyr eccentricity cycles (Wu et al., 2013) to the Cenomanian-Turonian marine sequence stratigraphy and cyclostratigraphy from the Jordanian carbonate platform (Wendler et al., 2014). Note, that LAE1 is coeval to a sequence boundary (TuJo3) in the mid/late Turonian dated as 90.8 Ma by Wendler et al. (2014) and 91.37 Ma by Gradstein et al. (2012).

rected for ages given by Deng et al., 2013, and Wan et al., 2013). A preliminary survey of the stratigraphic and lake level data from the Songliao basin and eustatic sea-level changes for these two intervals, i.e. the Turonian hothouse and the Santonian greenhouse intervals, indicates a trend to a reverse correlation as predicted if the above given limno-eustatic hypothesis on continental groundwater storage in an ice-free greenhouse world holds true.

Comparing the LAE1 black shale lake-level highstand at ca. 91.4 Ma with the most recent Cenomanian-Turonian sequence stratigraphy and cyclostratigraphy (405 kyr cycles) from the Jordanian carbonate platform (Wendler et al., 2014) indicates that LAE1 is coeval to a sequence boundary (TuJo3) in the mid/late Turonian (Fig. 3). Although the dating is not straightforward, correlation to the eustatic curves of Haq (2014) shows a major sea-level lowstand for the early-to-mid Turonian with a sequence boundary (KTu4) at 91.8 Ma. This corresponds to the prominent sea-level lowstand recorded at Atlantic margins (dated at ca. 92-91.5 Ma at the New Jersey Atlantic margin, Miller et al., 2005b, 2011; ca. 91.2 Ma in the tropical Atlantic, Bornemann et al. 2008), Tethyan (Galeotti et al., 2009) and Jordanian (Wendler et al., 2014) carbonate platforms, although the timing is still biased due to different time scales and calibrations applied. Using the Gradstein et al. (2012) time scale and the sea-level data included into TimeScaleCreator Software (2014, Version 6.1) an age of 91.37 Ma is indicated for this marine sequence boundary, which corresponds perfectly to the 91.4 Ma dating of LAE1 in the Songliao basin.

The stratigraphic position of the lake-level highstands of LAE2a and LAE2b shows the same out-of-phase trend with eustasy as indicated above (Fig. 4). Timing of LAE2b at 83.7 Ma close to the Santonian-Campanian boundary (base of magnetochron C33r) is coeval within the range of dating and correlation errors to a sequence boundary (KSa3 at 84 Ma) and a major eustatic sea-level low peaking at around 83.6 Ma identified by Haq (2014), and a sequence boundary (Sa3) indicated at ca. 84 Ma by Gradstein et al. (2012; TimeScaleCreator Software 2014, Version 6.1). The lake-level highstand indicated by LAE2a at ca. 84.7 Ma correlates to a late phase of a sea-level low at ca. 84.8-85 Ma – however, the corresponding sequence boundary was indicated by Haq (2014) as considerably older, at 85.3 Ma, but with a doubtful global extend and correlation.

A preliminary spotlight view on the Late Triassic greenhouse indicates a similar trend as recognized in the mid-Cretaceous hothouse. Here, lacustrine cycles recorded in the Newark Supergroup and other Late Triassic - Early Jurassic lake deposits (Dam and Surlyk, 1993; Andrews et al., 2014) may be related to the global sea-level curve, despite the fact that correlations of non-marine to marine strata are still in discussion (Hillebrandt et al., 2013). We concentrate on the sea-level cycle around the precisely defined Triassic-Jurassic boundary (i.e. around the base of the Hettangian, see Deenen et al., 2010, and Ruhl et al., 2010, for astrochronology). Here, we correlate the latest Triassic sea-level fall as identified and biostratigraphically tied down in Tethyan sections, e.g., by McRoberts et al. (2012), to the Newark Supergroup evolution on Pangea (e.g. Ruhl et al., 2010). Although (lake-level) cyclicity in the Newark and related basins along the US North Atlantic coast clearly shows higher frequency fluctuations, the late Rhaetian sea-level lowstand just before the major extinction level (ca. 100 kyr before the base of the Hettangian, McRoberts et al., 2012) correlates well with grey lacustrine beds and inferred maximum wet cycles, and therefore lake-level highs in the non-marine Newark and Hartford basins given the correlations indicated by Witheside et al. (2011) and Ruhl et al. (2010). A correlation of the sea-level lowstand slightly earlier than 100 kyr before the extinction event (McRoberts et al., 2012) to the 100 kyr cyclicity (Ruhl et al., 2010) matches to a major grey interval and thus a lake-level high in the Newark Supergroup.

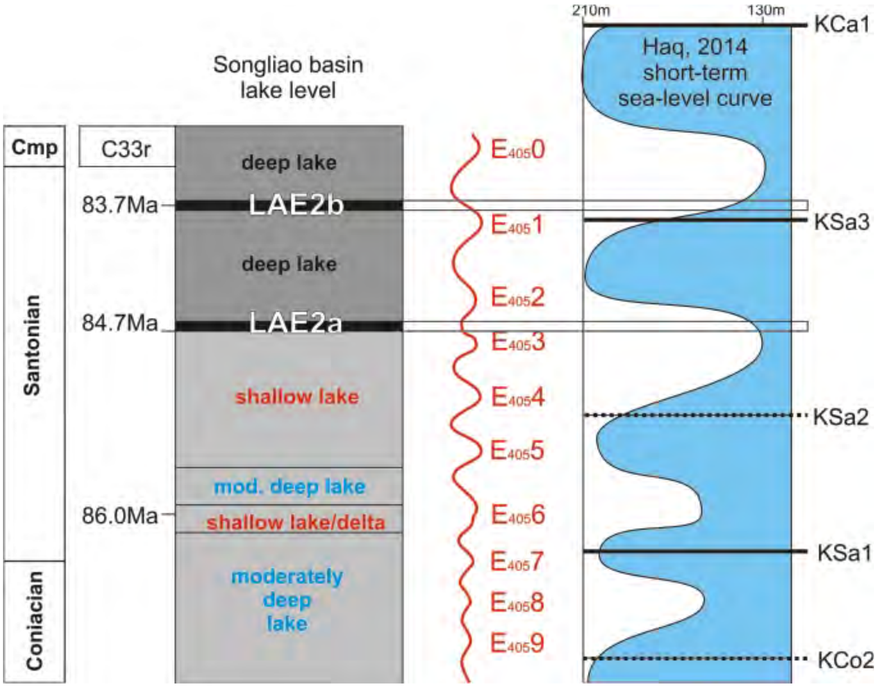

FIGURE 4: Correlation of the Songliao basin lake-level highstands of LAE2a and LAE2b to the short-term sea-level curve and sequence boundaries (KCo2 to KCa1) of Haq (2014). For references to timing and facies interpretation of the Songliao basin record see Figure 3. Both lake-level highstands correspond to marine sea-level lows.

6. CONCLUSIONS

Suess (1888a, b) introduced the term eustatic which was later on used to denote global isochronous sea-level changes. Although various processes influence sea level on a local and regional scale, such as dynamic topography and tectonics, eustatic sea-level fluctuations are present in Earth history. During icehouse times like the Quaternary and probably also during cool greenhouse times such as the early Early Cretaceous, sea-level changes are controlled mainly by continental ice sheet growth and decay, and thus are predominantly glacio-eustatic. In contrast, the main process controlling short-term, 100 kyr to several million year cycles in an ice-free world of warm greenhouse to hothouse conditions, is considered to be the climatically-induced change in groundwater storage in continental porous sediments and lakes, i.e. a limno-eustatic sea-level fluctuation, as proposed herein. With respect to volume, the groundwater proportion is by far dominant, while the lake proportion adds only a very minor proportion.

Testing the limno-eustatic hypothesis, however, is ultimately connected to the problem of high-precision correlation of marine to non-marine/continental successions, allowing to identify out-of-phase relationships between sea-level and lake-level fluctuations. Therefore, the lake water history cannot be neglected, but provides an applicable test scenario for the hypothesis. Preliminary tests using selected stratigraphic levels of the lacustrine Late Cretaceous record of the Songliao basin as well as sequence stratigraphy, cyclostratigraphic correlations and eustatic sea-level curves result in an out-of-phase relation that may support the limno-eustatic hypothesis for sea-level fluctuations in the mid-Cretaceous hothouse.

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