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Link between cyclic eustatic sea-level change and continental weathering: Evidence for aquifer-eustasy in the Cretaceous

Jens E. Wendler [a,*], Ines Wendler [a], Christoph Vogt [b], Jochen Kuss [a]

[a] *Department of Geosciences, Bremen University, P.O. Box 330440, 28334 Bremen, Germany*
[b] *Crystallography/Central Laboratory for Applied Material Sciences (ZEKAM), Department of Geosciences, Bremen University, P.O. Box 330440, 28334 Bremen, Germany*

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ABSTRACT

Cyclic fluctuations in global sea level during epochs of warm greenhouse climate have remained enigmatic, because absence or subordinate presence of polar ice during these periods precludes an explanation by glacio-eustatic forcing. An alternative concept suggests that the water-bearing potential of groundwater aquifers is equal to that of ice caps and that changes in the dynamic balance of aquifer charge versus discharge, as a function of the temperature-related intensity of the hydrological cycle, may have driven eustasy during warm climates. However, this idea has long been neglected for two reasons: 1) the large storage potential of subsurface aquifers was confused with the much smaller capacity of rivers and lakes and 2) empirical data were missing that document past variations in the hydrological cycle in relation to eustasy.

In the present study we present the first empirical evidence for changes in precipitation, continental weathering intensity and evaporation that correlate with astronomically (long obliquity) forced sea-level cycles during the warmest period of the Cretaceous (Cenomanian–Turonian). We compare sequence-stratigraphic data with changes in the terrigenous mineral assemblage in a low-latitude marine sedimentary sequence from the equatorial humid belt at the South-Tethyan margin (Levant carbonate platform, Jordan), thereby avoiding uncertainties from land–ocean correlations. Our data indicate covariance between cycles in weathering and sea level: predominantly chemical weathering under wet climate conditions is reflected by dominance of weathering products (clays) in deposits that represent sea-level fall (aquifer charge > discharge). Conversely, preservation of weathering-sensitive minerals (feldspars, epidote and pyroxenes) in transgressive sediments reflects decreased continental weathering due to dryer climate (aquifer discharge > charge). Based on our results we suggest that aquifer-eustasy represents a viable alternative to glacio-eustasy as a driver of cyclic 3rd-order sea-level fluctuations during the middle Cretaceous greenhouse climate, and it may have been a pervasive process throughout Earth history.

1. Introduction

Rhythmic fluctuation of global sea level on orbital time scales during the Cretaceous has been suggested repeatedly and demonstrated by spectral analyses (Laurin and Sageman, 2007; Wendler et al., 2010; Boulila et al., 2011; Wendler et al., 2014; Laurin et al., 2015). While, on timescales $>10^6$ years, solid Earth processes like plate tectonics influence sea level via changes in the ocean basin volume, on orbital timescales, sea level is dominated by changes in the volume of ocean water due to climate forcing (see review by Conrad 2013). The increasing evidence of a globally synchronous sea-level forcing on orbital timescales (10^4 to 10^6 years) raises the question: Which cyclic components of the hydrological cycle controlled the distribution of water between the oceans and the continents in the Cretaceous?

For icehouse climate epochs, sea-level fluctuations are explained by the repeated build-up and melting of polar ice caps. This mechanism has been proposed to control sea level also during the Cretaceous greenhouse climate, based on the assumption that it is a pervasive process in both icehouse and greenhouse (Miller et al., 2005a; Miller et al., 2005b) climate modes of the Earth (see also Wendler and Wendler, 2016). Invoking solely glacio-eustasy to explain sea-level change throughout Earth history is tempting for two reasons: 1) Storage of water in ice caps is understood and modelled relatively thoroughly due to the immense database from studies of the recent icehouse epoch. 2) The evidence of sustained warmth with ice-free poles during the Cretaceous greenhouse epoch (Huber et al., 2002; Moriya et al., 2007; Francis et al., 2008; MacLeod et al., 2013) is challenged by the possible presence of ice sheets, especially if these supposedly occurred during the warmest period of the Cretaceous, i.e. the Cenomanian and Turonian (Stoll and Schrag, 2000; Bornemann et al., 2008; Galeotti et al., 2009).

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[*] Corresponding author. Tel.: +49 421 218 65132; fax: +49 421 218 65159.
E-mail address: wendler@uni-bremen.de (J.E. Wendler).

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The controversy on glacio-eustatic sea-level control during the middle Cretaceous warm greenhouse climate raises the question whether build-up of ice sheets is the only process that can significantly change the volume of ocean water. Based on mass balance calculations, it was suggested that another important reservoir is storage of groundwater in aquifers, with a capacity that is at least as high (26.35×10^6 km^3; Trenberth et al., 2007) as the water volume currently bound in ice (Hay and Leslie, 1990). These estimates gave rise to the hypothesis that changes in the global groundwater reservoir could cause eustatic sea-level changes (Hay and Leslie, 1990; Jacobs and Sahagian, 1993, 1995; Wendler et al., 2011). The hypothesis of groundwater-forced sea-level fluctuations, termed aquifer-eustasy (Wendler and Wendler, 2016) or limno-eustasy (Wagreich et al., 2014), had been widely neglected due to underestimation of the capacity of subsurface aquifers (116×10^6 km^3; Hay and Leslie, 1990), probably by confusing it (Fig. 1 in Miller et al., 2005a) with the low water volume of $0.03–0.3 \times 10^6$ km^3 in lakes and rivers (Hay and Leslie, 1990). Because the Greek word “limne” translates as “lake”, the term limno-eustasy may provoke an association with surface aquifers only, which would disregard subsurface aquifers that are the principle storage medium for groundwater-forced sea-level fluctuations. In order to avoid such etymological confusion we prefer to use the term aquifer-eustasy.

Feasibility of aquifer-eustatic forcing of cyclic 3rd-order sea-level changes in the Cretaceous can be tested with numerical model approaches and by identification of sedimentological evidences for varying transfer of water from the oceans to the continents. Modelling the rate of charge and discharge of aquifers for the Cretaceous has been difficult because of three main unknowns (Hay and Leslie, 1990): 1) the unknown potential of Cretaceous aquifers that mostly got eroded or buried, 2) uncertainty about possible climate fluctuations that could change evaporation/precipitation sufficiently on the required time-scales, and 3) effectiveness of infiltration and discharge of any given aquifer. In the present study, we follow the alternative approach of an empirical test, by using direct observations in the sedimentary record that indicate changes in precipitation and weathering. A causal link between sea level and precipitation is expected to generate a sea-level rise during precipitation decrease, and vice versa. Variability in precipitation can be assessed qualitatively from the mineral-assemblage signal of weathering intensity of the eroded rocks and soils that are transported as siliciclastic input into the marine sediments.

For such analyses, shallow-marine settings are well suited, because they are close to the source of terrestrial influx and most sensitive to sea-level fluctuations. However, in these sequences it has been difficult to proof the presence of astronomical cycles and their relation to sea level, because of unsteady sedimentation and absence of radio-isotopic constraints. Using Evolutive Average Spectral Misfit time series analysis, specifically designed to rigorously test for astronomical forcing under such conditions, a major advance was achieved in a recent study (Wendler et al., 2014) of a shallow-water carbonate section from the Levant Platform in Jordan. For that same sequence-stratigraphically and astrochronologically well-constrained section, we employ a full quantification of the mineral assemblage in order to test for synchronicity in precipitation-related weathering of minerals and sea-level fluctuations.

We explore such changes in hinterland weathering intensity over four 3rd-order sea-level cycles of a marine Cenomanian–Turonian carbonate platform section that spans ~5 Myr (Wendler et al., 2014). Importantly, this approach has the advantage of studying both terrestrial (siliciclastics) and marine (carbonates and evaporites) signals from mineral assemblages as climate proxies in one and the same section, thereby avoiding correlation uncertainties between marine and continental (e.g. lake levels) records. Furthermore, the investigated section is particularly suitable for our approach for two reasons: 1) It has a paleogeographic position (Fig. 1) that restricts possible source areas for terrigenous siliciclastics (weathered material) to the tropical humid belt; 2) It was positioned in the northern hot arid belt (Hay and Floegel, 2012) during the Cenomanian–Turonian, so that the marine sediments yield indicators for evaporation changes in relation to sea level. While the carbonates and evaporites represent the climate conditions and sea level on the platform, the siliciclastic components reflect the climate conditions in the hinterland. Determination of the complete siliciclastic assemblage enables us to record both the source minerals and the weathering products (clays). The relative contribution of these two mineral groups is used as an indicator for weathering intensity.

2. Material and methods

Section GM3 in Jordan (Ghawr Al Mazar or Ghor al Mazrar: 31°15′34′′ N; 35°35′41′′ E) represents a platform carbonate sequence that was deposited on the rimmed Levant Carbonate platform at approximately 100 km distance from the palaeo-coastline of the Arabian Shield (Fig. 1). The section contains open-marine subtidal to supratidal deposits and was sampled at a sample interval of 10 to 30 cm. More detailed information on the lithology and biostratigraphy is given in Wendler et al. (2014) and references therein. Stable carbon-isotope

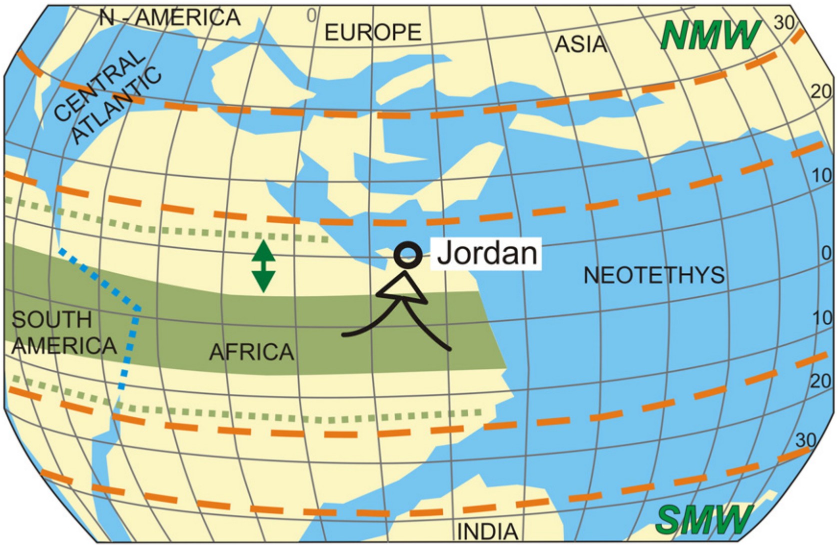

Fig. 1. Paleogeography of the studied GM3 section in Jordan (after Cavazza et al., 2004). Circle: section position; arrow indicates origin of siliciclastic input. Approximate Turonian–Santonian climate belts (Chumakov, 1995; Hasegawa et al., 2012; Hay and Floegel, 2012); green: equatorial humid belt with maximal expand (green dotted lines, green arrow); orange dashed lines: northern and southern hot arid belts; NMW = Northern Mid-latitude Warm humid belt, SMW = Southern Mid-latitude Warm humid belt.