Upper Cretaceous paleoenvironmental changes and petrophysical responses in lacustrine record (Songliao Basin, NE China) and marine sedimentary deposit (Goban Spur Basin, NW Europe)

Kouamelan Serge Kouamelan¹, Changchun Zou¹,*, Konan Roger Assie², Cheng Peng¹, Koffi Alexis N’dri³ and Ohouo Rebecca Mondah³

¹ School of Geophysics and Information Technology, China University of Geosciences, Beijing 100083, China
² Institute of Earth Sciences, China University of Geosciences, Beijing 100083, China
³ School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China

*Corresponding author: Changchun Zou. E-mail: zoucc@cugb.edu.cn

Received 23 April 2020, revised 7 September 2020
Accepted for publication 3 December 2020

Abstract
The Cretaceous interval is marked by several important geological changes whose prints are buried in both continental and marine systems. Although significant paleoenvironmental details of this period have been inferred from biological and geochemical indicators, little is known about the physical proxies. Through scientific borehole data, petrophysical properties of Upper Cretaceous Songliao Basin (SB) in NE China and Goban Spur Basin (GSB) in NW Europe were intercorrelated to investigate the critical geological paleoenvironmental shifts and their petrophysical responses, through statistical, wavelet and spectral approaches. The results demonstrated that petrophysical features, particularly gamma-ray and resistivity reactivities, were responsive to past environmental changes in both terrestrial and marine systems. Shifts in organic-rich shale deposition and brine bearing shale showed a correlation to a probable period of seawater incursion in SB, while the gamma log, resistivity and density reactivities were interrelated to the basin paleo-structuration. At GSB, the gamma-ray and resistivity reactivities are tied-up to the Mid-Atlantic seabed motion, marine-water level shifts and paleoceanographic instabilities. In both paleo-basins, a decrease in the gamma-ray reactivity occurred from Turonian to Maastrichtian and is consistent with a regional or global increase in hydrodynamic energy. The oceanic/lacustrine anoxic events related to low sedimentation rate occurred in both basins and are associated with high gamma-ray and resistivity signals (SB); high gamma-ray and low resistivity signals (GSB). These changes correlated with geochemical evidence, suggesting that gamma-ray and resistivity can represent alternative means for marine and continental paleoenvironmental comparison.

Keywords: Songliao Basin, Goban Spur Basin, Upper Cretaceous paleoenvironment, petrophysical properties, electro-facies analysis

© The Author(s) 2021. Published by Oxford University Press on behalf of the Sinopec Geophysical Research Institute. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

The Cretaceous represents in the geological record by far the last and extensive unit of the whole Mesozoic. Constituting the warmest period in the Mesozoic, this is a key period where the Earth has undergone major geological changes such as high sea level and oceanic anoxic events (OAEs), large-scale volcanic activities and Late Cretaceous mass-eradication episode (Jones 2001; Schulte et al. 2010; Haq 2014; Witts et al. 2018). The traces of these events are concealed in both marine and terrestrial proxies that are mostly chemical, biological and physical indicators, which, when analysed, provide some valuable details on paleoenvironmental fluctuations.

However, a substantial part of our current knowledge of the Cretaceous paleoclimate and paleoenvironmental alterations is mainly one-sided since previous investigations have focused principally on marine datasets (Hasegawa 2003; Wang et al. 2013a; Wu et al. 2014; Yoshino et al. 2017), and are generally based on biological or geochemical parameters through core analysis. With time, problems such as the difficulty of drilling continuous and complete cores, and limited outcrop make it sometimes challenging to obtain continuous, high-resolution and long geological time-span data. Besides, well logging data is another valuable alternative.

Lately, through international scientific cooperation, terrestrial Cretaceous investigations have emerged. However, although previous paleoenvironmental studies have gradually enhanced our knowledge of Cretaceous changes in both terrestrial and marine systems, few Cretaceous terrestrial and marine correlative studies have been conducted (Wang et al. 2013b), and the comparison based on petrophysical properties has not yet been explored.

Intended for oil research in the early stages, petrophysical properties are no longer limited to hydrocarbon studies, but are increasingly becoming more useful in investigating past environmental shifts (Chow et al. 2005; Williams et al. 2012; Peng et al. 2017; Jafarian et al. 2018). Unlike core sample study, well logging has the following advantages (Goldberg 1997; Peng et al. 2017): it is possible to carry out high-precision continuous sampling, measurement of in situ properties, analysis of a volume of a rock that is often greater than the one represented by a core or plug and the acquisition processes are impacted less by human factors, reducing the effects of contamination. Therefore, studies of well logs in past environmental change research can provide useful details that are of interest to geoscientists.

To understand the changes in petrophysical properties tied to the Upper Cretaceous paleoenvironmental variations in both terrestrial and marine systems, petrophysical datasets from both milieus need to be intercorrelated. In the current study, well logging data from ocean and continental drilling projects where an Upper Cretaceous sediments have been drilled were used. This attempt was achieved by correlating the non-marine Cretaceous Songliao Basin in NE Asia with the Goban Spur paleo-basin located in NW Europe. The responses obtained were then compared to a geochemical dataset.

Leg 80 in GSB was prearranged to probe into the European continental margin evolution (De Graciansky et al. 1985). During this scientific project, Upper Cretaceous sediments were recorded from shallow and deep marine settings throughout two drilling sites (S49 and S50B). The project highlighted several significant findings, such as the accumulation of organic-rich carbon, expansion of the seafloor and the accumulation and erosion of continental margin debris.

The Songliao paleo-basin is an important non-marine Cretaceous paleo-basin filled with an impressive volume of deposits (Wang et al. 2013b), including a nearly entire Cretaceous lacustrine records. Planned to recover continuous and complete non-marine Cretaceous sediments under the umbrella of international collaboration, the Chinese Continental Scientific Drilling Project carried out the first scientific investigation (SK1) throughout two main boreholes, namely the north borehole (SK1N) and south borehole (SK1S).

The studied paleo-basins were located within the middle latitudes climate zones of the Northern Hemisphere during the Upper Cretaceous, making them comparable (figure 1a). This investigation contributes to the advancement of our understanding of the possible paleoenvironmental changes related to global or regional factors in the middle latitudes region and their petrophysical responses throughout the Late Mesozoic era.

2. Geological setting

2.1. Songliao Basin (SB)

The SB, located in NE of China, covers roughly a total area of 260 000 km² across Heilongjiang, Jilin, and Liaoning provinces (Wang et al. 2013a). The basin is geographically situated at mid-latitudes between 119°40’ and 128°24’E, 42°25’ and 49°23’N and subdivided into six first-order structural segments (figure 1c).

The tectonic framework of SB can be summarised into four different stages: pre-rifting, syn-rifting, post-rifting and compression. The basin is filled with a substantial volume of deposits (up to 9000 m thick), which are mainly Cretaceous volcaniclastic, fluvial and lacustrine sediments (Wang et al. 2002). According to Wu et al. (2009), a regional unconformity sub-divides the Late Jurassic and Cretaceous strata into two stratigraphic sequences. The upper section representing the SB’s well-known sequence is upwardly composed of Denglouku (K1d), Quantou (K2q), Qingshankou (K2qn), Yaojia (K2y), Nenjiang (K2n), Sifangtai (K2s) and Mingshui
Figure 1. (a) Northern hemisphere paleogeography and paleoclimate during the Late Cretaceous (80 Ma) and location of study area (modified from scotese.com/cretcli.htm); (b)–(e) Borehole locations and geological map of the Songliao Basin and the Goban Spur Basin (modified from Yang et al. (2018) and Luft de Souza et al. (2018), respectively, with permission from Elsevier).

(K₂m) lithofacies deposited from nearly Aptian for K₁d to Maastrichtian for K₂m, representing the end of the Mesozoic in SB (figures 1e and 2). K₂q is divided into three members and is essentially a deep-lake environment deposit. K₂y is composed of deltaic to lacustrine sediments with two stratigraphic members. K₂n is subdivided into five members containing an upward sequence of lacustrine to fluvial facies with some probable marine evidence in the first two (Wang et al. 2013b). K₂s is dominated by fluvial facies. The stratigraphic sequence ends with K₂m, composed of formations alternating between fluvial and shallow lake deposits. The SB experienced some episodes of oil shale deposition with the
most important and well-known episodes occurring during the Turonian (in K2qn) and late Santonian (in K2n) (Wang et al. 2013b; Xu et al. 2015).

Detailed drill core analyses indicated that deposits associated with marine and brackish water developed in the paleo-basin. Marine ingress was probably a consequence of five marine transgressive episodes from Valanginian to late Santonian (Sha 2007; Xi et al. 2011a), originating from the northwestern Paleo-Pacific Ocean.

The Cretaceous’s paleoclimate in the paleo-SB was chiefly temperate and humid with relatively abundant rainfall coupled with some rapid environmental change episodes (Wang et al. 2013a). Paleomagnetic studies revealed approximately a paleolatitude of 40–50° N (Fang et al. 1990), which is similar to the basin’s actual position making SB a potential candidate for terrestrial paleoenvironment investigation.

2.2. Goban Spur Basin (GSB)

Located at the junction between the northwest Celtic margin and the northward Porcupine Seabight and Irish margin, GSB is a marginal submarine plateau at a latitude of 49°N in NE Atlantic (figure 1b). It was formed by the establishment of the North Atlantic gateway between Europe and North America during the Cretaceous period (Bullock & Minshull 2005). The GSB is underlaid by a basement made up of pre-rifting Hercynian granites and Paleozoic forma-

![Figure 2. Synthesis of the stratigraphic column of Songliao Basin (based on Wu et al. (2013, 2014)) and Goban Spur Basin (based on De Graciansky et al. (1985)).](image-url)
Paleontological evidence (Linnert et al. 2011), revealed a paleoclimate marked by a slight cooling period throughout the Cretaceous at Goban Spur. The Upper Cretaceous, especially the latest Campanian and Maastrichtian period denoted for the first time that marine deposits were continuously and widely distributed across the whole GSB and its proximate regions (Snyder et al. 1985) coupled with carbonate accumulation. Thereby, conducting a paleoenvironmental study using Upper Cretaceous strata from GSB might be suitable for the understanding of local, regional and likely global environmental changes.

3. Data and methods

Geophysical well logs represent in situ physical and/or chemical parameters that characterise the formations crossed by the drilling and their surroundings and therefore contain geological and/or petrophysical details. Several among these logs are very useful for facies and depositional environment analysis (Table 1). Although both sites (SB and GSB) have been drilled and logged with different logging tools and in different contexts, the physical parameters recorded are mostly similar.

3.1. Data

Based on two different drilling techniques (the oil exploration drilling method in SK1S and the geologic core drilling technology in SK1N), previous significant research and the situation of drilling times, three well logging suites were applied during SK1. The geophysical logs acquired in the borehole SK1N and borehole SK1S included natural gamma-ray (GR) log, acoustic log, compensated neutron log, dual laterolog, spontaneous potential log, density log, array induction and caliper (CAL) logs.

During DSDP Leg 80, the variable length hydraulic piston corer drilling system and the rotary coring were used. At site 549 (2535.5 m water depth), four different logs were run: dual induction, GR, sonic and CAL. Only the GR log was run in the whole hole. Hole 550B was drilled to a depth of 4430 m underwater and the log data recorded included GR, neutron porosity, bulk density, resistivity, sonic and CAL.

3.2. Methods

3.2.1. Time-series analysis. The fast and robust pyramidal algorithm maximal overlap discrete wavelet transform (MODWT) implemented by Percival & Walden (2000) and the evolutive of time scale optimisation algorithm (eTimeOpt) of spectral analysis (Meyers 2015) were conducted on the petrophysical properties for data analysis in SB and GSB.

For high-resolution datasets analysis of periodicities in time-series data, diversified mathematical modus operandi such as fast Fourier transform, short-time Fourier transform, wavelet transform (WT), trend analysis, Lomb, period scanning and autocorrelation have been widely used (Gosgel & Laehne 2013; Hloupis & Vallianatos 2015) in several domains. The WT based on multi-resolution analysis is a widely used band-pass filter for nonlinear and non-stationary signal characterisation (Upadhyaya & Mohanty 2016). According to Hloupis & Vallianatos (2015), WT operates by decomposing a signal function or vector into a set of simpler, fixed blocks at different scales and positions. Percival
& Walden (2000) determined and classified two principal types of wavelets namely continuous wavelet transform and discrete wavelet transform (DWT), which uses the sequence defined essentially over a range of integers (usually $t = 0, 1, \ldots, N - 1$, where $N$ denotes the number of values in the time series). Dissimilar to the orthonormal partial DWT, the MODWT works as a highly linear redundant filtering operation that transforms a level $J_0$ of a time series $X$ in column vectors $\tilde{W}_1, \tilde{W}_2, \ldots, \tilde{W}_{J_0}$, $\tilde{V}_{J_0}$, each of dimension $N$. The decomposition of an infinite sequence $\{X_n\}$ to $J_n$ levels theoretically involves the application of $J_n$ pairs of filters (Figure 3a). Therefore, the decomposition phase at the $j$th level provides a set of wavelet coefficients ($\tilde{W}_j$) and a set of scaling coefficients ($\tilde{V}_j$) through high/low-pass filtering using equations (1) and (2), respectively.

$$\tilde{W}_{j,n} = \sum_{l=0}^{L_j - 1} h_{j,l} X_{n-l} \mod N,$$

$$\tilde{V}_{j,n} = \sum_{l=0}^{L_j - 1} g_{j,l} X_{n-l} \mod N,$$

$n = 0, \ldots, N - 1$, where $h_{j,l} \equiv \frac{h_{j,l}}{\sqrt{2}}$ (for high-pass filtering) and $g_{j,l} \equiv \frac{g_{j,l}}{\sqrt{2}}$ (for low-pass filtering).

The eTimeOpt is a statistical approach for untuned stratigraphic data that comprehensively evaluates the possible evolution of the formations deposit process (Meyers 2015). This algorithm attempts to identify the sedimentation rate for a given depth-scaled paleoclimate/paleoenvironment proxy data series ($w_{data}$) through three main phases, which independently evaluate the amplitude modulation and spectral power, and later on integrate these outcomes. By using filters and the Hilber algorithm, the observed astronomical precession-set amplitude envelope is extracted for each sedimentation rate based on equation (3), where the more suitable model at each sedimentation rate is determined throughout least squares (Meyers 2015):

$$w_{envelope} = A_e \alpha_e + \epsilon,$$

where $w_{envelope}$ represents the precession-set amplitude envelope for the temporally calibrated paleoclimate/paleoenvironment data series, $A_e$ a trigonometric matrix (cosine and sine function) predictor terms.
representing the eccentricity phases, \( \alpha_e \), a vector of regression constants for each estimator and \( \epsilon \) a vector of error terms.

Equation (3) operates across a lattice of sedimentation rates and then allow the evaluation of the quality of the fit at each sedimentation rate through a bivariate correlation between the subtracted envelope \( w_{\text{envelope}} \) and the fitted eccentricity phase, \( g(A_e, \alpha_e) \). The resulting correlation modulus namely \( r_{\text{envelope}}^2 \) represents the fraction of variance shared between the model and temporally calibrated amplitude envelope at a given sedimentation rate (Meyers 2015).

By using the linear regression (equation 4), the spectral power \( (r_{\text{spectral}}^2) \) for each temporal tuning is evaluated, with \( w_{\text{data}} \) (temporally tuned data series), \( A_{ep} \) (trigonometric matrix), \( \alpha_{ep} \) (regression coefficients vector) and \( \epsilon \) (vector of error terms).

\[
w_{\text{data}} = A_{ep} \alpha_{ep} + \epsilon. \tag{4}
\]

The final fit combining the amplitude envelope and the spectral power is estimated using equation (5), where \( r_{\text{opt}}^2 \) is the product of the fraction shared between envelope and data (Meyers 2015).

\[
r_{\text{opt}}^2 = r_{\text{spectral}}^2 r_{\text{envelope}}^2. \tag{5}
\]

This astronomical approach is accordingly useful for high-resolution evaluation of the formation sedimentation rate.

### 3.2.2. Statistical analysis.

A statistical approach based on box-plot analysis was used for data comparison. Dissimilar to the bar chart for data representation, the box plot is a powerful approach that uses statistical summaries that are robust in the presence of skewness and outliers and require no prior assumption about the samples (Nuzzo 2016). This tool presents several advantages as (i) complete details can be drawn from the full range of the data (figure 3b), (ii) can be used for small size sample data \( (n = 5) \) and (iii) quick and complete side-by-side correlation between groups (figure 3c).

### 3.2.3. Lacustrine brine shale content and organic-rich shale (OrSh) estimation.

The resistivity log is an ideal parameter that the boundary between Member 1 and Member 2 of \( K_{2n} \) formation were identified at site 550B in the Campanian deposit (Nie et al. 2017). The estimated organic-bearing shale content \( (V_{\text{shw}}) \) exhibited high values in lower Member 1 and Member 2 of \( K_{2n} \) formation, and the first member of \( K_{2n} \) unit (figure 6a and b). Similar to the GR and shale volume, the resistivity and velocity decreased from the Turonian formations to the Maastrichtian formations (figure 5a, b and e, f). The description of core samples recorded at SK1N and SK1S during SK1 showed that the formations ranged roughly from mudstone-dominated oil shale in \( K_{2n} \) formation, to colored mudstones in \( K_{2n} \) formation. The statistical evaluation of the petrophysical properties

### 4. Results

The statistical evaluation of the petrophysical properties from SK1 and Leg 80 has been assessed and displayed in figures 4 and 5, indicating that the lacustrine and marine sediments deposited in both paleo-basins during the Upper Cretaceous showed more or less variable physical properties.

Based on GR trend analysis, a regular decrease in radioactivity was identified at both the SK1 and Leg 80 sites. In SK1 the drop of GR was recorded from Turonian \( (K_{2n} \) formation) to Maastrichtian \( (K_{m} \) formation) (figure 4a and b). The boundary between Member 1 and Member 2 of \( K_{2n} \) formation at approximately 1780 m (figure 6a) and 1030 m (figure 6b) were dominated by an upward increase in the GR response (serrated bell shape) and increased resistivity responses in both north and south boreholes.

In SK1, the highest value of GR and shale volume in the studied interval have been recorded in the south borehole precisely in \( K_{2n} \) formation (figure 4b and d), which is Turonian and Coniacian in age. On the other hand, the lowest GR and shale content are recorded in north borehole namely in \( K_{m} \) formation deposited during the Maastrichtian (figure 4a and c). The analysis of the GR log showed that particular picks of GR counts appear almost in the lower Member 1 and Member 2 of \( K_{2n} \) formation, and the first member of \( K_{2n} \) unit (figure 6a and b). Similar to the GR and shale volume, the resistivity and velocity decreased from the Turonian formations to the Maastrichtian formations (figure 5a, b and e, f). The description of core samples recorded at SK1N and SK1S during SK1 showed that the formations ranged roughly from mudstone-dominated oil shale in \( K_{2n} \) formation, to colored mudstones in \( K_{2n} \) formation. The estimated organic-bearing shale content \( (V_{\text{shw}}) \) exhibited high values in lower Member 1 and Member 2 of \( K_{2n} \) formation, and the first member of \( K_{2n} \) unit (figure 7a). The brine bearing shale content of the Songliao paleo-lake was estimated and correlated to the carbon and oxygen stable isotopes (figure 7b–g). In borehole south, the box plots show that the mean of the evaluated \( V_{\text{shw}} \) closely mimics the variation of \( \delta^{18}O \) in the whole section of the intervals studied (figure 7c and e).

In Goban Spur, the log gamma reflects a consistent decrease in radioactivity from the bottom to the top intervals with some higher gamma responses in some of the in-between intervals (figure 8a and b). The resistivity response shows a shift in resistivity across these intervals. The maximum GR count and shale volume through the intervals studied were identified at site S50B in the Campanian deposit.
Figure 4. Statistical analysis of the petrophysical properties (gamma-ray (GR) and shale volume) in Songliao Basin (a–d) and Goban Spur Basin (e–h) at different periods (Maast = Maastrichtian, Camp = Campanian, Sant = Santonian, Con = Coniacian, Tur = Turonian, Cen = Cenomanian and Und = undetermined).
Figure 5. Statistical analysis of the petrophysical properties (resistivity, velocity and porosity) in Songliao Basin (a, b, e, f) and Goban Spur Basin (c, d, g, h) at different periods (Maast = Maastrichtian, Camp = Campanian, Sant = Santonian, Con = Coniacian, Tur = Turonian and Cen = Cenomanian).
Figure 6. Well logs responses correlated to oxygen and carbon isotopes data in SK1N (a) and SK1S (b). For resistivity log, blue = RD, orange = RS and light orange = RM.

(figure 4f and 4h) (approximately 574–573 mbsf). The estimated mean of shale volume was around 0.5%. Through this short-term depositional interval, the deposit is mostly dominated by a massive non-calcareous mudstone. The increasing trend of the GR value is related to the deposition of fine-grain size deposits.

At site 549, the GR log exhibited a decreasing trend from Cenomanian to lower Paleocene (figure 8a), from approximately 480 to 383 mbsf. Particularly, a peak of radioactivity associated with low resistivity was observed in a Turonian-Santonian deposit at nearly 436 mbsf (figure 8a). The lowest GR value in this paleo-basin was read in Maastrichtian deposits at site 549, while the lowest shale content was recorded through the Cenomanian formations at drilling site 549 (figure 4e and 4g). The resistivity response showed an increasing mean resistivity from Cenomanian to Turonian deposits and later a decreasing trend for the Coniacian-Santonian and Maastrichtian deposits at drilling site 549 (figure 5c). At site 550B, the mean resistivity decreased from Cenomanian to Coniacian-Santonian formations and increased through the Campanian to Maastrichtian formations (figure 5d). The GR decreased from Cenomanian to Maastrichtian (680 to 465 mbsf) (figure 8b), except for 594.3 to 570.68 mbsf. In both boreholes, the porosity and velocity
Figure 7. Scaling coefficient of the estimated OrSh and changes in Vshw in Songliao Basin. (a) Correlation between the estimated OrSh deposition and marine bio-marker (data from Hu et al. (2015)) and (b–g) correlation between the estimated brine bearing shale content based on resistivity log and oxygen and carbon isotopes data.
Figure 8. (a, b) Well log responses in Goban Spur Basin; correlation of scaling coefficient of GR response with Mn and Fe content variation at site S49 (c, e) and site S50B (d, f). For resistivity log, blue = RD, orange = RS and light orange = RM.
responses increased from Cenomanian to Campanian deposits and dropped through Maastrichtian formations (figure 5g and 5h). The mean resistivity at this site was lower compared to site 549 (figure 5c and 5d).

5. Discussion

5.1. Petrophysical properties as indicator of paleo-lake environment changes

5.1.1. Deposition of OrSh. The sedimentary history of the non-marine Songliao Basin has shown that the basin experienced some periods of oil shale deposition most importantly throughout the depositional time of K2qn and K2n formations (Xu et al. 2015), and are mainly Turonian and late Santonian in age. The GR reactions have been used to explore and examine changes in paleo-depositional facies and sequences in marine-organic-rich settings (Luning & Kolicic 2003), due to its spontaneous sensitivity to sequence boundaries and/or organic materials. It represents one of the generally used physical parameter in the evaluation of organic-rich deposits (Kamali & Allah Mirshady 2004). However, the response of GR log in lacustrine systems can present a significantly different trend from marine records (Bohacs 2012; Tänavsuu-Milkeviciene et al. 2017). Resistivity is another important log for organic matter identification (Nie et al. 2017).

The estimated $V_{\text{sho}}$ in SK1 firmly supports the existence of OrSh deposition in lower Member 1 of both K2n and K2qn formations and was well expressed in south borehole (figure 6) and correlated well with the changes in the lithology (figure 6). Due to its organic matter content, the lacustrine OrSh can exhibit low bulk density and high porosity (Burton et al. 2014). The evaluation of the density (DEN) and porosity (CN) log responses indicated a dense and porous deposit, in the identified high $V_{\text{sho}}$ intervals (figures 6 and 7a), which seems to suit the work of Burton et al. (2014) also conducted in a non-marine system. The variation of $V_{\text{sho}}$ shows that the deposition of OrSh was lower in Member 4 of the K2q formation, increased during the early stage of K2qn formation (Member 1) and decreased in Members 2 and 3 of K2qn formation (figure 7a), which may be due to the changes in the depositional environment. Similar trends have been described by Wang et al. (2013b) and Peng et al. (2017). The OrSh tends to settle in deep depositional environments. The paleoenvironmental studies referred to by Wu et al. (2013) showed that Member 4 of K2q, Member 1 of K2qn and Members 2 and 3 of K2qn were deposited in the meandering river, deep-lacustrine and sub-deep-lacustrine settings, respectively. This description ties with the variations recorded in the estimated $V_{\text{sho}}$.

Other significant intervals of OrSh deposition occurred throughout Members 1 and 2 of the K2n formation (Wu et al. 2013; Xu et al. 2015). Previous studies have shown that during the deposition of these layers, the paleo-basin passed from shallow lake in the K2y formation to a deep-lake environment (Wu et al. 2013). The downward decrease in the porosity of the formation (a function of hydrogen index) in lower K2n Member 2 may indicate that the hydrogen concentration decreased before an abrupt shift at the base of the section (figure 6a). The drop in porosity suggests the weakening of OrSh, oxygenation dominated deposits, and hence the lowering of the water depth during the deposition of this interval. This seems consistent with some scholars who described that Songliao paleo-lake experienced relatively shallower episodes during the deposition of Members 1 and 2 of K2n (Xi et al. 2011b; Bechtel et al. 2012). The deposition of the low porosity interval is preceded by high porosity deposits from roughly 1787 to 1775 m (bottom of the interval), which is associated with high radioactivity, high resistivity and high transit time features, showing that this section is organically rich and accordingly was deposited in deep-lacustrine paleo-settings (Burton et al. 2014). This correlated with the increase in OrSh content and consequently a deepening of the paleo-lake in upper Member 1 and lower Member 2 of the K2n formation (figure 7a).

Therefore, the variations in the OrSh content obtained through resistivity log data may be as a consequence of past environmental changes in SB. During the deposition of Member 1 of K2qn and Members 1 and 2 of the K2n formations, the deepening of the paleo-lake induced by rapid basin subsidence and/or marine-water ingressin (Wang et al. 2013b) generated an oxygen-depleted water bottom (anoxic environment) in the lake. The anoxic bottom water would have favored the deposition and/or preservation of OrSh during the deposition of lower K2qn and K2n formations that affected the physical properties, especially the resistivity.

5.1.2. Brine bearing shale ($V_{\text{shw}}$) content, paleoclimate and sea-water ingress. Climatic changes easily affect the lacustrine constituents, i.e. water flux level and deposits (Risacher & Fritz 2009). The periodical shifts in the climate alter the cycles of the sediments and the volume of water in the lake, which tends to increase with the increase in precipitation. The brine content (pore-water salinity) included in the deposits can fluctuate as the climate oscillates (Lowenstein et al. 1994). For instance, increasing aridity with high evaporation intensifies the salinity of water (Lowenstein et al. 1994; Risacher et al. 2003). Similarly, geochemical elements such as stable isotopic elements ($\delta^{18}$O and $\delta^{13}$C) rise with enhanced salinity (Keith & Weber 1964; Cao et al. 2015). Here, the changes in the computed brine bearing shale content were in parallel with the past environmental fluctuations. The use of brine bearing shale content to connect with past environmental changes in lacustrine settings was motivated by the work of Tomonaga et al. (2017) who found a clear rapport
between paleo-lake environmental changes and pore-water salinity, highlighting the potential of brine content to infer paleoenvironmental fluctuations.

In K2qn formation, the Vshw content decreased from Member 1 to Member 2, and increased through Member 2 and 3. From Member 1 to Members 2 and 3 of K2qn, the Songliao passed from subtropical semi-humid to tropical warm humid climate (Wang et al. 2013a), which likely led to the shift in stable isotope δ18O and δ13C contents (figure 7c and g), and most probably in the drop of Vshw. This environmental changes are also supported by the presence of the red bed record considered as an arid print in Members 2 and 3 of K2qn, while in Member 1 these deposits are missing (Xi et al. 2011b; Wang et al. 2013a). The arid episode prolonged to Members 2 and 3 of K2y formation, and probably would have led to an increase in the degree of evaporation as the climate became dry and hot (Xi et al. 2011b). Consequently, an increasing long trend Vshw occurred from Member 2 of K2qn to Member 2 of K2y formation, and was associated with an increase in δ18O (figure 7c and e). Through the late stage of K2y formation (Member 3) and early stage of K2n (Member 1), the Vshw as well as δ18O dropped, although these layers were formed in subtropical semi-humid conditions with a slightly dry and hot episode in Member 3 of K2y. The climatic context changed from arid to humid, likely leading to the decrease in evaporation and thus the drop in Vshw. Based on Wang et al. (2013a), SB experienced a drop in temperature from late K2y to Members 1 and 2 of K2n formation. This drop in temperature correlates to the fall in temperature records from the Far East Cretaceous climate (Wang et al. 2013a).

The Vshw content increases from Member 1 of K2n formation to Member 2 as do δ18O and δ13C (figure 7c, e and g). However, the climatic context remained as subtropical humid to semi-humid during the deposition of Member 2 of K2n formation. Therefore, the significant changes in the recorded Vshw content and stable isotopes may not be due to the climate, but either acid rain or the introduction of saline water, which helped the rise of the paleo-lake salinity. Through its long evolution, the Earth has undergone large volcanic eruptions that could have generated acid rain and lake acidification (Bailey et al. 2005; Varekamp 2008), including some parts of NE China during the Early Cretaceous (Zhou et al. 2016). However, though the volcanic events have been admitted as normal events in SB during the Upper Cretaceous, according to Li et al. (2017) they probably happened during K2qn formation deposition. Therefore, lake acidification due to probable acid rain caused by volcanic events may not be the result of increased Vshw and stable isotopes observed from Member 1 of K2n to Member 2 of K2n formations.

Many studies have reported the relationship between paleoclimate and salinity. For example, Cao et al. (2015) claimed that in a relatively humid climatic context, paleosalinity is lower, and in relatively hot and arid conditions, paleosalinity is high due to increased evaporation. Following this line of thought, a second member of K2n was deposited in humid to sub-humid context (Wang et al. 2013b), which should have result in low salinity and low Vshw content accordingly. However, the brine content was amplified indicating that the increased Vshw content in Member 2 of K2n was more likely not due to the paleoclimate.

Most brines in paleo-sedimentary basins are related in some way to seawater phenomena (Sanders 1991; Birkle et al. 2009; Lüders et al. 2010; Bagheri et al. 2014). Indeed, based on sedimentary details, anterior research showed an enhanced salinity and anoxic bottom-water strata in Members 1 and 2 of K2n (Wang et al. 2011), which promoted the settling of organic-rich deposits. These organic-rich source rocks were, in some way, the consequence of seawater ingestion. If our dataset is accurate, we speculate that during the deposition of Member 2 of K2n formation, the salinity of the paleo-lake increases. This increase in paleosalinity may likely be related to an uncommon change in the basin, such as seawater ingestion.

The seawater would have favored an establishment of a brackish water environment leading to an enhanced salinity stratified water column, which helped the development of OrSh during the formation of Members 1 and 2 of K2n. This matches with the analysis of specific marine evidence (figure 7a), where the peaks of these biomarkers show that Members 1 and 2 of the K2n formation were affected by seawater ingestion. Subsequently, the sediments deposited in such milieu for an extended period can archive the change in the salinity in their pore space (Strassmann et al. 2005). Therefore, we correlated the increase in Vshw content associated with increasing δ18O and δ13C isotopes in Member 2 of K2n formation to a seawater event during the deposition of K2n 1 and 2, as described in several studies (Xi et al. 2011a; Hu et al. 2015), which contributed to the brine bearing shale enrichment and deposition of OrSh.

During the deposition of mid-K2n (Members 3 and 4), the Vshw content drops as well as δ18O and δ13C, and later increases through late K2n (Member 5), implying that the phenomenon responsible for their rise ceased in the mid-K2n. From mid-K2n through to the late K2n, Songliao went from subtropical humid to the subtropical semi-arid environment (Wang et al. 2013b), which led to the paleo-lake to go through increased evaporation and accordingly an increased Vshw. This increasing tendency is also evident in δ18O and δ13C contents (figure 7b, d and f). The Vshw decreases in Ks formation, and also δ18O and δ13C contents, although the paleoenvironment remains subtropical semi-arid (Wang et al. 2013b). From Ks to the first member of Km formation, Vshw content decreases and correlates well with a decrease in δ13C and an increase in δ18O. The paleo-lake shifted from subtropical semi-arid to subtropical humid, and ended
up as warm temperate semi-humid in late K2m (Wang et al. 2013b). The $\delta^{13}$C was still dropping during the deposition of late K2m, whereas the $V_{shw}$ content and $\delta^{18}$O increased. Since isotopes $\delta^{18}$O and $\delta^{13}$C did not undergo important fluctuations, but kept increasing and decreasing, respectively, the changes in $V_{shw}$ content from K2s formation to late K2m may not have been due to the climatic variation only. According to previous studies, the paleo-basin underwent a period of basin restructuring where the paleo-lake shrunk gradually from K2s to the end of K2m formation (Bechtel et al. 2012). This reorganisation would have affected the changes in $V_{shw}$ content.

In the north borehole where the upper K2n is well explored, the result of the wavelet decomposition showed a decrease in radioactivity from Member 2 of K2n toward the top, which seemed to indicate that the hydrodynamic energy increases from the Member 2 up to K2m formation and then decreases in shale content. As the shale is predominantly made up of fine-grain size fractions of sediments and sedimentary rocks, they are mostly deposited in a deep environment or fare from the wave zone in the aquatic environment. In line with this argument, the Songliao paleo-lake became shallower during its late stage. A similar trend has been described by several scholars such as Wu et al. (2009), and Wang et al. (2013a), who have suggested that the Late Cretaceous strata of SB (K2s and K2m formations) were deposited in a shallow environment, during the waning of the basin’s life. Thus, the variation in $V_{shw}$ content may be the consequence of paleoclimatic fluctuations and basin reorganisation.

5.1.3. Timing of the Lake Anoxic Events (LAEs) and petrophysical responses. In SB, intervals with enhanced organic carbon described as deposited in anoxic water context under high productivity and/or preservation conditions have been recorded in Member 1 of K2qn formation, and Members 1 and 2 of K2n formation (Xi et al. 2011a, 2018; Wu et al. 2013; Xu et al. 2015). The stratigraphic details showed that these layers were deposited when the paleo-basin was enlarged (Feng et al. 2010), thus limiting the entry and deposition of detrital clastic sediments, which helped the organically rich settling in the paleo-basin.

These LAEs strata are associated with high GR, high resistivity, high shale volume and high OrSh (figure 9a–c) in Member 1 of K2qn Formation and Members 1 and 2 of K2n formation. This may suggest increased organic-rich deposition under strong productivity and/or preservation (Robinson et al. 2004). Additionally, the increased GR count, shale volume and presence of OrSh demonstrates that the LAEs occurred when the paleo-lake was deep environment. This is supported by the porosity, neutron log responses and the lithology, which is mainly organic shale (Wan et al. 2013). Indeed, according to Burton et al. (2014), in deep-lacustrine environments, the lithofacies are defined by the presence of laminated organic shale and fine-grained carbonate deposits with high neutron porosity and low density. Therefore, the high porosity and low density (figure 9a–c), associated with the presence of marly organic shale, especially in lower K2qn, supports our assumptions that the changes in porosity and density are tied to changes in the paleofacies. With the description of specific marine evidence, i.e. C30 steranes (Hu et al. 2015) in these LAE intervals (figures 7a and 9), it has been suggested that seawater helped in the setting-up of an anoxic system in SB (Xi et al. 2011a; Wang et al. 2013b).

Previous LAEs investigations have proven that an elevated $p_{CO_2}$ due to volcanic events promoted the development of anoxic conditions in a vast lacustrine system in SW China (Xu et al. 2017), indicating that terrestrial LAEs can be initiated by volcanic activities. The massive volume of CO2 produced during the eruptions can affect the hydrological cycles and accordingly intensify the flux of nutrients toward the lakes boosting the lacustrine bioproduction and sediment storage (Xu et al. 2017). However, in SB the prints of volcanic activities during the Upper Cretaceous were observed only in lower Member 3 of K2qn formation (Li et al. 2017). The existence of LAEs in K2qn first Member and K2n Members 1 and 2 implies that their deposition and volcanic activities may not be coeval. Moreover, the weak petrophysical features, especially GR and resistivity, show no evidence of volcanic ash deposition since these deposits are indicative of typically high GR and resistivity response. Thus, the LAEs developed in deep-lacustrine paleoenvironment with likely small scale marine ingress into the paleo-basin, which helped to increase the bio-productivity of the surface waters of the paleo-lake, and subsequently led to the establishment of weakly oxidized or dysoxic to anoxic water bottom (Xi et al. 2011b). This probably contributed to the settling and/or preservation of OrSh with typically high GR, high resistivity, high porosity, low density and low velocity. The peaks of OrSh content and shale volume appear in lower Member 2 of K2n and correlate well with the increase in marine biomarkers (figure 7a), suggesting that deep water under probable strong seawater ingress development in lower K2n than lower K2qn formation during the LAE periods (Xi et al. 2016).

In the lacustrine environment, previous studies reported a relationship between paleo-redox conditions and the changes in the sedimentation rate (Ding et al. 2015). As the change in the paleo-redox state is vital during the anoxic event (Jenkyns 2010), a relationship exists between the sedimentation rate and LAEs. Based on time scale optimisation, the high-resolution sedimentation estimated by using the GR log correlated these LAEs sections to a high frequency of power spectrum and low sedimentation rate (figure 9d). This indicates that the sedimentation process declined during the LAEs in both K2n and K2qn formations. In Wu et al. (2013) study, a similar correlation was described in SB, indicating that valuable information concerning the sediment
accumulation during LAEs can be drawn from petrophysical properties.

5.2. Impact of Sea Environmental Changes on the Petrophysical Properties

5.2.1. Seafloor spreading. At GSB, De Graciansky et al. (1985) categorised the Upper Cretaceous lithological units into two units, namely lower Unit 4 and Unit 5 in hole 549, and three units in hole 550B, i.e. Unit 3, Unit 4 and Unit 5. At site 549, the GR indicated changes in the sedimentary environment from Cenomanian to lower Paleocene. This interval includes two depositional stages associated with low and extremely low radioactivity and is characterised by a serrated cylindrical shape (figure 8a), which may indicate uniform lithology and constant energy overall (Emery & Myers 1996; Nazeer et al. 2016), with some increasing phase in Cenomanian–Turonian. This trend seems to be consistent with the lithology composed chiefly of nannofossil chalk with black shale intercalation at approximately 436.6 mbsf, deposited through Cenomanian–Turonian. The deposition of this interval with high radioactivity marks a significant changes in the paleo-basin, as also described by Luft de Souza et al. (2018) in the similar depositional interval.

From Coniacian–Santonian to Maastrichtian, the radioactivity presents a smooth decreasing trend (figures 4e and 8a), showing that either the content of radioactive elements decreased or the deposited materials are coarse sediments. However, the mean of the shale volume increased from Coniacian–Santonian to Maastrichtian (figures 4g and 8a),
which was further revealed by the decrease in the resistivity. This is consistent with the work of De Graciansky & Bourbon (1985), implying that the grain size is probably not the main factor controlling the GR response. Similarly, from Cenomanian to Turonian, the radioactivity displayed a decreasing trend as the shale volume increased (figure 4e and g). These changes are not arbitrary, but are related to variations in the sedimentary environment.

According to Andrianiazy & Renard (1985), the North Atlantic seabed dynamism experienced several variations. During the Cretaceous, the seabed extension was rapid through the Aptian-Albian time due to an active rifting. This extension rate declined during the Late Cretaceous and approached zero, and later reopened during the early Paleocene. This trend correlates well with the changes in the radioactivity activity, as shown by the results of the WT (figure 8c) and the statistical analysis (figure 4e). Therefore, the GR reactivity is compared to the Mn and Fe variation, because based on Renard et al. (1979); Corbin et al. (2000), these geochemical elements are useful proxies for evaluating the seafloor spreading. Figure 8c and e point out that the scaling coefficient of GR reactivity relatively mimics the trend of Mn and Fe distribution. The Mn and Fe contents roughly decrease from Cenomanian to Maastrichtian and increase during the Paleocene, and they correlate well with North Atlantic seafloor spreading (Andrianiazy & Renard 1985), which controls the deposition of materials. Therefore, if our data are correct, then there is a correlation between the North Atlantic seafloor motion and the decrease in radioactivity from Cenomanian to Maastrichtian and the abrupt change at early Paleocene highlighted by the scaling coefficients and the box plot. This can also be explained by the variation in shale volume and CaCO₃ deposition. During the time of spreading, the deposition of sediments ceases or decreases, leading to the absence of sediments or deposition of thin sediments, which affect the shale volume and the CaCO₃ deposition. By examining the shale volume, associated with CaCO₃ tendency (figure 8a), it is clear that the shale volume, CaCO₃ and GR response are approximately inversely proportional. The interval of high GR correlates to a time of decreasing shale volume and CaCO₃ content. The development of the Mid-Atlantic seafloor seems to have affected the accumulation of the radioactive elements and sediments deposition, with high GR and declined deposits during the active spreading phases, resulting in a low sedimentation rate. This is consistent with the works of De Graciansky et al. (1985), who reported that during the Upper Cretaceous, site 549 in GSB underwent sediments cut off on several times, causing a drastic decrease in the sedimentation rate.

The velocity log evaluation showed an increasing velocity trend from Cenomanian to Campanian deposits and later decreased toward the Danian sediments. According to Nelson (2010), velocity response is affected by several factors; among them, silica and carbonate elements tend to increase the velocity while clay content, porosity, microfissures, current and paleo-overpressure tend to decrease the sonic log values. The velocity tendency from Cenomanian to Campanian is more likely related to the lithological variation because, based on De Graciansky et al. (1985), CaCO₃ content varies from 65 to 90% through unit 5 to 90–95 in unit 4. However, although characterised by high carbonate concentration, the sonic velocity drops from Campanian to Maastrichtian and the velocity–shale volume crossplot displays a weak interrelation between clay distribution and velocity indicative of a weak influence of these factors on the velocity (figure 10a). Therefore, the variation of the sonic velocity from Campanian to Maastrichtian may likely be due to the porosity, low silica content or microfractures.

At site 550B, the changes in GR is more likely interrelated to the shale content (figure 4c and 4f). The radioactive activity of this site located on the oceanic basement is higher than that of site 549 nearly located on a slope, which could either be due to its proximity from the extension and therefore archived more radioactive elements or due to its setting in a deep marine milieu, which is suitable for deposition of fine-grain size deposits. The shale proportion indicates the same trend. Furthermore, by intercorrelating Mn and Fe distribution and GR reactivity, a light correlation was exhibited (figure 8d and 8f). In conclusion, because site 550B is located in the deep environment and has undergone different sedimentary processes due to the basin build-up (De Graciansky et al. 1985), the changes in the water energy and the carbonate compensation depth (CCD) could affect the grain size of the sediments and consequently the GR reactivity.

5.2.2. OrSh deposition, sea-level change and carbonate compensation depth (CCD). The sediments at GSB accumulated under various paleoenvironmental conditions (De Graciansky et al. 1985), with deposition of some organic-rich intervals. In borehole 549, the radioactivity increased through the upper Cenomanian-lower Turonian deposit, and was associated with black shale deposition (Luft de Souza et al. 2018). This indicates that the sharp rise in the GR radiation is a consequence of OrSh deposition, which fall in line with Luning & Kolonic (2003). The presence of OrSh suggests that this sedimentary interval has probably accumulated in deep-water settings. Through this interval, the CaCO₃ content is low, indicating that it was deposited in a deep environment (likely below the CCD) where the proportion of carbonate input was lower.

At site 550B, an interval with a high radioactivity correlated with slightly high TOC and low CaCO₃ content dating from Coniacian-Santonian with dark mudstone as lithology (figures 8b and 10d). This period indicates the deposition of faint OrSh. The modest TOC count adjoined with low CaCO₃ and the depositional details (De Graciansky et al.
Figure 10. (a) Velocity–Vsh crossplot of Campanian–Maastrichtian sediment at site 549 using Kermel density; (b) statistical analysis of the formations resistivity response at site 550B; TOC and carbonate content variation at site 549 (c) and site 550B (d) (data from Luft de Souza et al. (2018)) used for comparison and (e) geological model of the Goban Spur Basin from Campanian to Maastrichtian.
high CaCO3 contents from 510 to 470 mbsf, mainly from shallow water settings. The accumulation of fine-size sediments marks the deep-water deposition in a high water energy environment at both sites. In the Campanian–Maastrichtian, the GR reactivity and shale content declined, and was tied to a decrease in TOC content, while the CaCO3 content exhibited a high value (figures 8a, b and 10c, d), indicating that the sediments were most likely deposited in a high water energy environment at both sites. Indeed in shallow water settings, usually, the current flow is high and hence suited for coarse sediments settling, while accumulation of fine-size sediments marks the deep-water settings.

By comparing our well log data to the lithology composed of chalks interbedded with mudflow and turbidites, with high CaCO3 contents from 510 to 470 mbsf, mainly from the Maastrichtian age, and dark mudstones at approximately 600 to 570 mbsf deposited from the Coniacian–Santonian to Campanian (De Graciansky & Bourbon 1985), the response of the GR was consistent with the hypothesis that in deep marine settings, the upward coarsening reflects a gradual change from clastic to carbonate deposition (Emery & Myers 1996).

Furthermore, the low TOC value in subunit 3b compared to the underlying subunit 4a (De Graciansky et al. 1985) points out to a probable gradual drop in anoxicity from the lower section toward the top of the interval studied, and is related to a significant decrease in radioactivity. Moreover, Emery & Myers (1996) described the upward coarsening in the deep marine environment might be as a result of a gradual drop in anoxicity and neither necessarily interrelated to an ascending shallowing or a progradation of a depositional facies. However, some previous analyses showed a marine level decline from Campanian to Maastrichtian in North Atlantic (Haq 2014; Luft de Souza et al. 2018), after long stability throughout the Campanian. If our data are correct, the decrease in radioactivity and shale content, associated to the decrease in TOC trend and increase in CaCO3 from Campanian to Maastrichtian, seems to correlate with seawater lowering. This is consistent with the works of Christian (2008), who, based on nannofossil observations, showed that the Late Cretaceous deposits in GSB accumulated in shallow water. During the Campanian, where the seawater was high, the sediments were mainly fine-grain sediments and were deposited in deep water, as shown by dark claystone and high shale content, associated with a high GR log count. With the lowering of the sea level, the depositional environment became more oxygenated with the deposition of light sediments characterised by the low GR response. Furthermore, the drop in the sea level could affect the deep water pressure and, consequently, the deepening of the CCD, leading to deposition of carbonate and likely to the slump in the basin slope. This slumping may be responsible for the turbidites formation during the Late Campanian–Early Maastrichtian (figure 10e), and seems to affect site 549 with the deposition of some slumped beds (De Graciansky et al. 1985).

From 578.40 to 573 mbsf (unit 4a), the resistivity is low (figure 10b), although it has been described as high TOC content (De Graciansky et al. 1985; Alves et al. 2018; Luft de Souza et al. 2018). This trend appears as a result of the immaturity of the organic content (De Graciansky et al. 1985), which seems to be affected by the quality of the preservation or the sedimentation process, probably due to the CCD or sea-level change. Alves et al. (2018) depicted almost the same section (between 578.40 and 575.40 mbsf) as barren in calcareous nannofossils, although with a slightly higher TOC and lower CaCO3, and attributed this to many factors, namely sea-level fluctuation or CCD. The decrease in the resistivity from Unit 3b Campanian section to unit 4a Campanian deposit is related to the change in the lithology from chalk to mudstone (figure 8b). However, the variation in the resistivity between the Campanian deposits and the Maastrichtian sediments within unit 3b is more complex and challenging to explain lithologically. We speculate that the lower resistivity from Unit 3b Campanian sediments to those deposited through the Maastrichtian may be related to the provenance of the sediments as depicted by Thiede et al. (1980) or likely local chemical changes.

The changes in the GR reactivity and shale content are well recorded in TOC and CaCO3 distribution from Cenomanian to Maastrichtian deposits at GSB and may be likely related to the significant paleoenvironmental changes such as rifting, sea-level variations and paleoceanography event (CCD) during the Upper Cretaceous. This is consistent with the observations made by Thiry & Jacquin (1993), by centering on the clay minerals dispersal from the north and south Atlantic Cretaceous deep ocean deposits. While the variations observed in the resistivity and sonic velocity logs are more likely related to the changes in the lithology however, the impact of the paleoenvironmental changes cannot be neglected.

5.2.3. Timing of oceanic anoxic events (OAEs) and petrophysical responses. At GSB, based on δ13C dataset at site 549, Linnert et al. (2011) described an interval with high organic carbon deposition at nearly 436.25 mbsf, likely as the consequence of OAE 2. This interval belongs to the magnetic reversal C34n and is Cenomanian–Turonian in age (figure 11a).

Brewton (2008), while studying the log signature for OAEs in several ODP holes, found a significant increase in the GR response through the interval related to OAEs. Other
research interrelated high resistivity with the time of OAEs interpreted as due to increased productivity (Robinson et al. 2004). The petrophysical properties analysis across the OAE interval in the Goban Spur paleo-basin indicates that the OAE deposit displays high GR reactivity and shale proportions, coupled with decreased resistivity and velocity responses (figure 11a). The increase in the GR reactivity and shale content correlates well with deposition of OrSh shown.
by a high TOC value and an abrupt shift of the carbon isotope, likely resulting from turbulence in the carbon provenance (figure 11a) across this depositional interval. The positive $\delta^{13}$C deviation that occurred near the Cenomanian–Turonian boundary suggests that the change in the GR reactivity, shale content and velocity responses is a consequence of far-reaching OAE2, which induced global carbon storage (Jenkyns 2010) and black shale accumulation.

However, the resistivity reactivity did not pair with the organic material content. The low resistivity may be a consequence of low maturation of the organic matter as described by Hartung et al. (1985), and correlates with an intense power spectrum in the GR reactivity and feeble to moderate sedimentation rate (figure 11b). Consequently, the high GR radiation would seem to correspond to a mixture of clay minerals and immature organic content, which, based on its low maturity, shows a weak influence on the resistivity reactivity. The presence of OrSh and the result of the estimated high-resolution sedimentation rate based on the GR response suggests that during the deposition of the OAE 2 interval, a probable deep environment with increasing productivity under low to moderate sedimentation process was developed in the Goban Spur paleo-basin. This interval going from Late Cenomanian–Early Turonian corresponds to a period of increased marine-water level (Haq 2014), which would have contributed to the increase in the marine bio-productivity.

Other studies have cited the possible link between volcanism and Cretaceous marine OAEs (Leckie et al. 2002; Jenkyns 2003; Bauer et al. 2017). However, physical properties reactivity shows no manifestation of volcanic ash accumulation. Furthermore, the organic-rich carbon segment seems to represent the termination of the OAE 2 interval in the Goban Spur paleo-basin (Linnert et al. 2011), and therefore cedes the paleoenvironmental setting of this layer with more questions.

6. Conclusions

Based on the petrophysical analysis of scientific drilling dataset from marine and lacustrine Upper Cretaceous records in NE China and NW Europe, the following conclusions can be drawn:

(1) Although physical proxies have shown little interest in marine and terrestrial paleoenvironmental correlation, the physical attributes, especially GR and resistivity, have proven alternative means for comparison and intercorrelation of marine and non-marine past environments. Indeed the GR and resistivity reactivities have shown that both paleo-basins in the mid-latitude undergo OrSh deposition during the Turonian and late Santonian, which seems to correlate with large-scale trend. These changes were also observed with the geochemical dataset.

(2) Environmental shifts were recurring events in both lacustrine and marine paleo-systems and induced some significant changes in the petrophysical properties. At the Songliao Basin, the variation in brine bearing shale content estimated based on the resistivity was tied to climate fluctuation and probable marine incursion. Furthermore, a period of basin reorganisation correlated with changes in the GR, brine-bearing shale content and density logs, while in the GSB the variation in GR, shale volume and resistivity responses were associated with frequent and gradual changes, probably as a result of the Mid-Atlantic Ridge activity, sea-level variation and paleoceanography events such as CCD. These changes had a high correlation with the geochemical dataset.

(3) The OAE and LAEs related to rising water level and low sedimentation rate occurred in both lacustrine and marine environments at different epochs and corresponded to significant changes in the well log signature. In Songliao Basin, a Turonian and late Santonian LAEs occurred in K$_2$q$_1$ and K$_2$n$_1$ and 2, respectively, and were associated with high GR count, high resistivity, low velocity and high OrSh. While in GSB, the OAE (Cenomanian-Turonian limit) was related to high GR count, low resistivity and low-velocity responses, and seemed to be synchronous with the K$_2$q$_1$ 1 LAE.

Acknowledgements

We acknowledge the members of the CCSD-SK project team, including Chengshan Wang, Pujun Wang, Jinchang Zhang, Hengqian Ran, Yongyi Zhu and Wenshi Wang, for their outstanding support. This work was jointly supported by the National Natural Science Foundation of China (grant no. 41790455) and the ‘China Continental Drilling Program of Cretaceous Songliao Basin (CCSD-SK)’ of China Geological Survey (grant no. 12120113017600). We also thank the members of the Division of Marine and Large Programs (Lamont-Doherty Earth Observatory, Columbia University) for making the marine geophysical data accessible.

Conflict of interest statement: None declared.

References

Alves, A.N., Bruno, M.D.R., Do Monte Guerra, R. & Fauth, G., 2018. Biostratigraphy and paleoecologic inferences during the late Campanian–Maastrichtian interval: evidence based on calcareous nannofossils from Goban Spur, Marine Micropaleontology, 142, 40–47.

Andrianiazy, A. & Renard, M., 1985. Trace Element Contents of Carbonates from Holes S49 and S50B (Leg 80): Comparison with Some Tethyan and Atlantic Sites, Vol. 80, U.S. Government Printing Office.

Bagheri, R., Nadri, A., Raeisi, E., Kazemi, G.A., Eggenkamp, H.G.M. & Montaseri, A., 2014. Origin of brine in the Kangan gasfield: isotopic and
Corbin, J.-C., Cohen, A.S. & Kring, D.A., 2005. Lacustrine fossil preservation in acidic environments: implications of experimental and field studies for the Cretaceous–Palaeogene boundary acid rain trauma, PALAIOS, 20, 376–389.

Bauer, K.W., Zeebe, R.E. & Wortmann, U.G., 2017. Quantifying the volcanic emissions which triggered Oceanic Anoxic Event 1a and their effect on ocean acidification, Sedimentology, 64, 204–214.

Bechtel, A., Jia, J., Strobl, S.A.I., Sachsenhafer, R.F., Liu, Z., Gratzer, R. & Püttermann, W., 2012. Palaeoenvironmental conditions during deposition of the Upper Cretaceous oil shale sequences in the Songliao Basin (NE China): implications from geochemical analysis, Organic Geochemistry, 46, 76–95.

Birkle, P., García, B.M. & Milland Padrón, C.M., 2009. Origin and evolution of formation water at the Jujo–Teconomicán oil reservoir, Gulf of Mexico. Part 1: chemical evolution and water–rock interaction, Applied Geochemistry, 24, 543–554.

Bohacs, K.M., 2012. Relation of hydrocarbon reservoir potential to lake-basin type: an integrated approach to unravelling complex genetic relations among fluvial, lake-plain, lake margin, and lake center strata, Lacsutrine Sandstone Reservoirs and Hydrocarbon Systems, pp. 13–56, ed. Baganz O.W., Bartov Y., Bohacs K. & Nummedal D., vol. AAPG Memoir, The American Association of Petroleum Geologists, USA, 95.

Brewton, A., 2008. Development of a borehole log signature for oceanic anoxic events and its application to the Gulf of Mexico, Theses and Dissertations, University of New Orleans, USA, pp. 1–167.

Bullock, A.D. & Minshull, T.A., 2005. From continental extension to seafloor spreading: crustal structure of the Goban Spur rifted margin, southwest of the UK, Geophysical Journal International, 163, 527–546.

Burton, D., Woolf, K. & Sullivan, B., 2014. Lacustrine depositional environments in the Green River Formation, Uinta Basin: expression in outcrop and wireline logs, AAPG Bulletin, 98, 1699–1715.

Cao, H., Guo, W., Shan, X., Ma, L. & Sun, P., 2015. Palaeoceanological environments and organic accumulation of the Nenjiang formation in the southeastern Songliao Basin, China, Oil Shale, 32, 5.

Chow, J.J., Li, M.-C. & Fuh, S.-C., 2005. Geophysical well log study on the paleoenvironment of the hydrocarbon producing zones in the Erchangchi Formation, Hsinyin, SW Taiwan, Terrestrial, Atmospheric and Oceanic Sciences, 16, 531.

Christian, M.R., 2008. Mature oceans in a context of plate divergence, in Chow, J.J., Li, M.-C. & Fuh, S.-C., 2005. Geophysical well log study on the paleoenvironment of the hydrocarbon producing zones in the Erchangchi Formation, Hsinyin, SW Taiwan, Terrestrial, Atmospheric and Oceanic Sciences, 16, 531.

Christian, M.R., 2008. Mature oceans in a context of plate divergence, in Global Sedimentology of the Ocean: An Interplay between Geodynamics and Paleoenvironment, pp. 175–237, ed. Christian M.R., Elsevier.

Colin, J.-P., Ioannides, N.S. & Vining, B., 1992. Mesozoic stratigraphy of the Goban Spur, offshore south-west Ireland, Marine and Petroleum Geology, 9, 527–541.

Cool, T.E., 1982. Sedimentological evidence concerning the palaeoenography of the Cretaceous western North Atlantic ocean, Palaeogeography, Palaeoclimatology, Palaeoecology, 39, 1–35.

Corbin, J.-C., Person, A., Fatzoura, A., Ferré, B. & Renard, M., 2000. Manganese in Pelagic carbonates: indication of major Tectonic events during the geodynamic evolution of a passive continental margin (the Jurassic European Margin of the Tethys–Ligurian Sea), Palaeogeography, Palaeoclimatology, Palaeoecology, 156, 123–138.

De Graciansky, P.C. & Bourbon, M., 1985. The goban spur of the northeast-atlantic margin during late cretaceous times, Initial Reports, DSIP, 80, 863–883.

De Graciansky, P.C. et al., 1985. The Goban Spur transect: geologic evolution of a sediment-starved passive continental margin, Geological Society of America Bulletin, 96, 58.

Ding, X. et al., 2015. Relationship between total organic carbon content and sedimentation rate in ancient lacustrine sediments, a case study of Erlian basin, northern China, Journal of Geochemical Exploration, 149, 22–29.

Dingle, R.V. & Scrutton, R.A., 1979. Sedimentary succession and tectonic history of a marginal plateau (Goban Spur, southwest of Ireland), Marine Geology, 33, 45–69.

Emery, D. & Myers, K.J., 1996, Sequence Stratigraphy, Wiley-Blackwell.

Fang, D.J., Wang, Z.L., Jin, G.H., Gao, R.Q., Ye, D.Q. & Xie, J.L., 1990. Cretaceous magnetostratigraphy in the Songliao Basin, China, Science in China, 33, 246–256.

Feng, Z., Jia, C., Xie, X., Zhang, S., Feng, Z. & Cross, T.A., 2010. Tectonostратigraphic units and stratigraphic sequences of the nonmarine Songliao Basin, northeast China, Basin Research, 22, 79–95.

Goldberg, D., 1997. The role of downhole measurements in marine geology and geophysics, Reviews of Geophysics, 35, 315–342.

Gossel, W. & Laehne, R., 2013. Applications of time series analysis in geosciences: an overview of methods and sample applications, Hydrology and Earth System Sciences Discussions, 10, 12793–12827.

Haq, B.U., 2014. Cretaceous eustasy revisited, Global and Planetary Change, 113, 44–58.

Hartung, B., Mukhopadhyay, P.K., Rullkötter, J., Schaefer, R.G. & Welte, D.H., 1985. Petrography and geochemistry of organic matter in Cretaceous sediments from the Goban Spur, Initial Reports, DSIP, 80, 983–991.

Hasegawa, T., 2003. Cretaceous terrestrial palaeoenvironments of north-eastern Asia suggested from carbon isotope stratigraphy: increased atmospheric pCO2-induced climate, Journal of Asian Earth Sciences, 21, 849–859.

Hloupis, G. & Vallianatos, F., 2015. Wavelet-based methods for rapid calculations of magnitude and epicentral distance: an application to earthquake early warning system, Pure and Applied Geophysics, 172, 2371–2386.

Hu, J.F., Peng, P.A., Liu, M.Y., Xi, D.P., Song, J.Z., Wan, X.Q. & Wang, C.S., 2015. Seawater incursion events in a Cretaceous paleo-lake revealed by specific marine biological markers, Scientific Reports, 5, 1–6.

Jafarian, A., Javanbakht, M., Koeshidayatullah, A., Pimentel, N., Salad Hersi, O., Yahyaei, A. & Beigi, M., 2018. Palaeoenvironmental, diagenetic, and eustatic controls on the Permo-Triassic carbonate-evaporite reservoir quality, Upper Dalan and Kangan formations, Lavan Gas Field, Zagros Basin, Geological Journal, 53, 1442–1457.

Jenkyns, H.C., 2003. Evidence for rapid climate change in the Mesozoic–Palaeogene greenhouse world, Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 361, 1885–1916.

Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events: review, Geochemistry, Geophysics, Geosystems, 11, 1–30.

Jones, C.E., 2001. Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous, American Journal of Science, 301, 112–149.

Kamali, M.R. & Allah Mirshady, A., 2004. Total organic carbon content determined from well logs using AstlogR and neuro fuzzy techniques, Journal of Petroleum Science and Engineering, 45, 141–148.

Keith, M.L. & Weber, J.N., 1964. Carbon and oxygen isotopic composition of selected limestones and fossils, Geochimica et Cosmochimica Acta, 28, 1787–1816.

Leckie, R.M., Bralower, T.J. & Cashman, R., 2002. Oceanic anoxic events and plankton evolution: biotic response to tectonic forcing during the mid-Cretaceous: oceanic anoxic events and plankton evolution, Paleoceanography, 17, 13–11–13–29.

Li, F., Li, W., Yu, Z., Liu, N., Yang, H. & Liu, L., 2017. Dawsonite occurrences related to the age and origin of CO2 influx in sandstone reservoirs: a case study in the Songliao Basin, NE China: age and origin of CO2 influx, Geochemistry, Geophysics, Geosystems, 18, 346–368.
Linnert, C., Mullerlose, J. & Herrle, J.O., 2011. Late Cretaceous (Cenomanian–Maestrichtian) calcareous nannofossils from Goban Spur (DSDP Sites 549, 551): implications for the palaeoceanography of the proto North Atlantic, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 299, 507–528.

Lowenstein, T.K., Spencer, R.J., Wenbo, Y., Casas, E., Pengzi, Z., Baozhen, Z., Haibo, F. & Krouse, H.R., 1994. Major-element and stable-isotope geochemistry of fluid inclusions in halite, Qaidam Basin, western China: implications for late Pleistocene/Holocene brine evolution and paleoclimates, *Geological Society of America Special Papers*, 289, 19–32.

Luft de Souza, F., Kahrl, G. & Fauth, G., 2018. Late Cretaceous (Cenomanian–Maestrichtian) planktic foraminifera from Goban Spur (DSDP sites 549 and 550): biostatigraphic inferences, *Cretaceous Research*, 86, 238–250.

Luning, S. & Kolonic, S., 2003. Uranium spectral gamma-ray response as a proxy for organic richness in black shales: applicability and limitations, *Journal of Petroleum Geology*, 26, 153–174.

Meyers, S.R., 2015. The evaluation of eccentricity-related amplitude modulation and bundling in paleoclimatic data: an inverse approach for astrochronologic testing and time scale optimization: astrochronologic testing and optimization, *Paleoclimatology*, 30, 1625–1640.

Nazeer, A., Abbasi, S.A. & Solangi, S.H., 2016. Sedimentary facies interpretation of Gamma Ray (GR) log as basic well logs in Central and Lower Indus Basin of Pakistan, *Geodesy and Geodynamics*, 7, 432–443.

Nelson, P.H., 2010. Sonic velocity and other petrophysical properties of source rocks of Cody, Mowry, Shell Creek, and thermopiles shales, Bighorn Basin, Wyoming, in *Petroleum Systems and Geologic Assessment of Oil and Gas in the Bighorn Basin Province*, Wyoming and Montana, pp. 39, U.S. Geological Survey Bighorn Basin Assessment Team, US Geological Survey Digital Data Series DDS–69–V.

Nie, X., Wan, Y. & Bie, F., 2017. Dual-shale-content method for total organic carbon content evaluation from wireline logs in organic shale, *Open Geosciences*, 9, 133–137.

Nuzzo, R.L., 2010. The box plots alternative for visualizing quantitative data, *PM&R: The Journal of Injury, Function, and Rehabilitation*, 8, 268–272.

Peng, C., Zou, C., Pan, L. & Niu, Y., 2017. Application of geochemical logging for palaeoenvironmental research in the Late Cretaceous Qingkangou Formation from the Chinese Continental Scientific Drilling Project SK-2e, Songliao Basin, NE China, *Journal of Geophysics and Engineering*, 14, 865–877.

Pericival, D.B. & Walden, A.T., 2000. *Wavelet Methods for Time Series Analysis*. Cambridge University Press.

Renard, M., Richebois, G. & Léotelle, R., 1979. Strontium, manganese, and iron contents, and oxygen isotopes in the carbonate fractions recovered from Hole 398C, Leg 47B, Initial Reports, DSDP, 47B, 497–506.

Risacher, F., Alonso, H. & Salazar, C., 2003. The origin of brines and salts in Chilean salars: a hydrochemical review, *Earth-Science Reviews*, 63, 249–293.

Risacher, F. & Fritz, B., 2009. Origin of salts and brine evolution of Bolivian and Chilean Salars, *Aquatic Geochemistry*, 15, 123–157.

Robinson, S.A., Williams, T. & Bown, P.R., 2004. Fluctuations in biosiliceous production and the generation of Early Cretaceous oceanic anoxic events in the Pacific Ocean (Shatsky Rise, Ocean Drilling Program Leg 198): biosiliceous production and oceanic anoxic events, *Paleoceanography*, 19, 1–19.

Sanders, L.L., 1991. Geochemistry of formation waters from the Lower Silurian Clinton Formation (Albion Sandstone), Eastern Ohio, *AAPG Bulletin*, 75, 1593–1608.

Schulte, P. et al., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary, *Science*, 327, 1214–1218.

Sha, J., 2007. Cretaceous stratiographic of northeast China: non-marine and marine correlation, *Cretaceous Research*, 28, 146–170.

Snyder, S.W., Müller, C., Sigal, J., Townsend, H. & Poag, C.W., 1985. Biosratigraphic, palaeoenvironmental, and paleomagnetic synthesis of the Goban Spur Region, Initial Reports, DSDP Leg 80, 1169–1186.

Strassmann, K.M., Brennwald, M.S., Peeters, F. & Kipfer, R., 2005. Dissolved noble gases in the porewater of lacustrine sediments as palaeoecological proxies, *Geochimica et Cosmochimica Acta*, 69, 1665–1674.

Tännesvuo-Milkeviciene, K., Sarg, J.F. & Bartov, Y., 2017. Depositional cycles and sequences in an organic-rich lake basin: Eocene green river formation, Lake Uinta, Colorado and Utah, U.S.A., *Journal of Sedimentary Research*, 87, 210–229.

Thiede, J., Agdestein, T. & Strand, J.E., 1980. Depth distribution of calcareous sediments in the Mesozoic and Cenozoic North Atlantic Ocean, *Earth and Planetary Science Letters*, 47, 416–422.

Thiry, M. & Jacquin, T., 1993. Clay mineral distribution related to rift activity, sea-level changes and palaeoceneovery in the Cretaceous of the Atlantic Ocean, *Clay Minerals*, 28, 61–84.

Tonomaga, Y. et al., 2017. Powerear salinity reveals past lake-level changes in Lake Van, the Earth's largest soda lake, *Scientific Reports*, 7, 1–10.

Upadhyaya, S. & Mohanty, S., 2016. Localization and classification of power quality disturbances using maximal overlap discrete wavelet transform and data mining based classifiers, *IFAC-PapersOnline*, 49, 437–442.

Varekamp, J.C., 2008. The volcanic acidification of glacial Lake Cavihue, Province of Neuquen, Argentina, *Journal of Volcanology and Geothermal Research*, 178, 184–196.

Wan, X., Zhao, J., Scott, R.W., Wang, P., Feng, Z., Huang, Q. & Xi, D., 2013. Late Cretaceous stratigraphy, Songliao Basin, NE China: SK1 cores, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 385, 31–43.

Wang, C., Feng, Z., Zhang, L., Huang, Y., Cao, K., Wang, P. & Zhao, B., 2013a. Cretaceous paleogeography and palaeoclimate and the setting of SK1 borehole sites in Songliao Basin, northeast China, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 385, 17–30.

Wang, C. et al., 2013b. Late Cretaceous climate changes recorded in Eastern Asian lacustrine deposits and North American Eocene sea strata, *Earth-Science Reviews*, 126, 275–299.

Wang, L., Song, Z., Yin, Q. & George, S.C., 2011. Paleosalinity significance of occurrence and distribution of methyltrimethyltridecyl ammoniums in the Upper Cretaceous Nenjiang Formation, Songliao Basin, China, *Organic Geochemistry*, 42, 1411–1419.

Wang, P., Liu, W., Wang, S. & Song, W., 2002. 40Ar/39Ar and K/Ar dating on the volcanic rocks in the Songliao basin, NE China: constraints on stratigraphy and basin dynamics, *International Journal of Earth Sciences*, 91, 331–340.

Williams, T. et al., 2012. Lithostratigraphy from downhole logs in Hole AND-1B, Antarctica, *Geosphere*, 8, 127–140.

Witts, J.D. et al., 2018. The impact of the Cretaceous–Paleogene (–Pg) mass extinction event on the global sulfur cycle: evidence from Seymour Island, Antarctica, *Geochimica et Cosmochimica Acta*, 230, 17–45.

Wu, H., Zhang, S., Hinnov, L.A., Jiang, G., Yang, T., Li, H., Wan, X. & Wang, C., 2014. Cyclostratigraphy and orbital tuning of the terrestrial upper Santonian–Lower Danian in Songliao Basin, northeastern China, *Earth and Planetary Science Letters*, 407, 82–95.

Wu, H., Zhang, S., Jiang, G. & Hinnov, T., 2009. The floating astronomical time scale for the terrestrial Late Cretaceous Qingkangou Formation
from the Songliao Basin of Northeast China and its stratigraphic and paleoclimate implications, *Earth and Planetary Science Letters*, **278**, 308–323.

Xi, D. et al., 2016. Late Cretaceous marine fossils and seawater incursion events in the Songliao Basin, NE China, *Cretaceous Research*, **62**, 172–182.

Xi, D. et al., 2018. New SIMS U-Pb age constraints on the largest lake transgression event in the Songliao Basin, NE China, *PLoS ONE*, **13**, 1–11.

Xi, D., Wan, X., Feng, ZQ, Li, S., Feng, ZH, Jia, J., Jing, X. & Si, W., 2011a. Discovery of Late Cretaceous foraminifera in the Songliao Basin: evidence from SK-1 and implications for identifying seawater incursions, *Chinese Science Bulletin*, **56**, 253–256.

Xi, D., Wan, X., Jansa, L. & Zhang, Y., 2011b. Late Cretaceous paleoenvironment and lake level fluctuation in the Songliao Basin, northeastern China: Songliao Basin in Late Cretaceous, *Island Arc*, **20**, 6–22.

Xu, J., Liu, Z., Bechtel, A., Meng, Q., Sun, P., Jia, J., Cheng, L. & Song, Y., 2015. Basin evolution and oil shale deposition during Upper Cretaceous in the Songliao Basin (NE China): implications from sequence stratigraphy and geochemistry, *International Journal of Coal Geology*, **149**, 9–23.

Xu, W. et al., 2017. Carbon sequestration in an expanded lake system during the Toarcian oceanic anoxic event, *Nature Geoscience*, **10**, 129–134.

Yang, D., Huang, Y., Guo, W., Huang, Q., Ren, Y. & Wang, C., 2018. Late Santonian–Early Campanian lake-level fluctuations in the Songliao Basin, NE China and their relationship to coeval eustatic changes, *Cretaceous Research*, **92**, 138–149.

Yoshino, K., Wan, X-Q, Xi, D-P, Li, W. & Matsuoka, A., 2017. Campanian–Maastrichtian palynomorph from the Sifangtai and Ming-shui formations, Songliao Basin, Northeast China: biostratigraphy and paleoflora, *Palaeoworld*, **26**, 352–368.

Zhou, L., Algeo, TJ, Feng, L., Zhu, R., Pan, Y., Gao, S., Zhao, L. & Wu, Y., 2016. Relationship of pyroclastic volcanism and lake-water acidification to Jehol Biota mass mortality events (Early Cretaceous, northeastern China), *Chemical Geology*, **428**, 59–76.