Carbon-isotope, petrological and floral record in coals

Guo, Biao; Eley, Yvette; Hilton, Jason; Zhou, Mingjun; Wang, Qingwei

DOI:

[10.1016/j.coal.2020.103417](https://doi.org/10.1016/j.coal.2020.103417)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Guo, B, Eley, Y, Hilton, J, Zhou, M & Wang, Q 2020, 'Carbon-isotope, petrological and floral record in coals: implication for Bajocian (Middle Jurassic) climate change', *International Journal of Coal Geology*, vol. 220, 103417, pp. 1-15. <https://doi.org/10.1016/j.coal.2020.103417>

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Carbon-isotope, petrological and floral record in coals: Implication for Bajocian (Middle Jurassic) climate change

Biao Guo^{a,*}, Yvette Eley^b, Jason Hilton^b, Mingjun Zou^a, Qingwei Wang^a

^a *College of Geosciences and Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, Henan, PR China*

^b *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*

* Corresponding author.

E-mail address: guobiao@ncwu.edu.cn (B. Guo).

ABSTRACT

Much of our existing knowledge of Middle Jurassic paleoclimate is based on well-dated marine isotopic records that show fluctuations between warm (greenhouse effected) and cool climates. In contrast, much less is known from contemporaneous terrestrial deposits that are often difficult to correlate stratigraphically with marine successions, and are typically considered as showing regional rather than global signals. In this paper we show that the carbon-isotopic, petrological and floral record through 20 m thick coals in the Northern Qaidam Basin (NW, China) represents a relatively comprehensive northern hemisphere Bajocian (Middle Jurassic) record for terrestrial climatic change. $\delta^{13}\text{C}_{\text{coal}}$ values for 88 samples from the Yuqia area in Northern Qaidam Basin range from -25.3‰ to -22.5‰ , indicating that C3 plants were the main coal-forming vegetation in the region during the Middle Jurassic. This isotopic variation follows fluctuations in the composition of ferns and gymnosperms, where higher ratios correspond to more negative $\delta^{13}\text{C}$ values. The similar carbon isotope values of gymnosperms and coal from the Yuqia area indicate that the coal comprises a high proportion of organic material derived from gymnosperm taxa, which is consistent with

the very high abundance of diterpenoids in coal and especially pimarane and abietane that are produced primarily by gymnosperms. Results from the coal matrix provide an opportunity to record paleoclimate changes, showing several striking and regular coal-forming cycles with distinct long- and short-term variations. Trends of $\delta^{13}\text{C}_{\text{coal}}$ values changes coupled with the evolution of coal-forming plants may record a gradual increase in paleo- CO_2 ($p\text{CO}_2$) concentration, water-table level changes and the decrease in abundance of *Classopollis* conifer pollen through Bajocian. This result is in accordance with the published marine carbonate records for this time, with correlation enabled through matching carbon isotope curves from the terrestrial succession at Yuqia and marine records. The similarity of the terrestrial and marine geochemical and floral record is an indication that the observed paleoclimate signal is a global phenomenon. Furthermore, the high-frequency fluctuation of $\delta^{13}\text{C}_{\text{coal}}$ values, along with the coal petrologic variations may record short-term changes of environmental factors (e.g. temperature or humidity/precipitation), especially during intervals when palaeobotanical composition has not fluctuated intensely.

Keywords: Bajocian; terrestrial; carbon isotope; palynology; maceral; paleoclimate

1. Introduction

The paleoclimatic record of the Middle Jurassic (Bajocian) is comparatively well-documented from marine carbonates and organic matter proxies (O'Dogherty et al., 2006; Dera et al., 2011; Korte et al., 2015). Although an increasing amount of data on the isotopic composition of fossil wood, coal and other terrestrial material exists (e.g., Hesselbo et al., 2003; Sun et al., 2007; Yan et al., 2009; Lu et al., 2014), it is still essential to expand the study of terrestrial environments and climates to see how these differ from marine records, to aid understanding of both regional and global climate patterns. As a biochemical sediment with terrestrial origins, coal preserves a detailed record of paleoclimate change (Bohacs and Suter, 1997; Diessel, 2007). However, our understanding of the paleoclimatic record within coal is sparse (Gröcke, 2001; Holdgate et al., 2009). Here we investigate Bajocian (Middle Jurassic) aged coals from the

Northern Qaidam Basin in NW China's Qinghai Province to evaluate terrestrial palaeoclimatic signals.

Isotope analyses of coal have been used to reconstruct climatic changes associated with temperature, humidity, water-table, and atmospheric CO₂ levels (Kürschner, 1996; Lücke et al., 1999; Bechtel et al., 2008; Holdgate et al., 2009). Furthermore, petrographic analyses of coal can provide sensitive records of water-table or base-level fluctuations that occurred during peat accumulation (Bohacs and Suter, 1997; Diessel, 2007). However, geological information recorded by these analyses might be both consistent (e.g., Hesselbo et al., 2003) and/or contradictory due to the interaction of environmental parameters (e.g., Lücke et al., 1999; Holdgate et al., 2009), making paleoclimate interpretation from coal controversial in some instances. Within the Northern Qaidam Basin, there remains a discrepancy between megafossil and microfossil evidence within coal seams. Based on studies of palynological data, it has been inferred that a large proportion of peat biomass was derived from fern-dominated vegetation in the basin during the Bajocian (Li et al., 1988; Zhang et al., 1998; Wang et al., 2005). This finding is contrary to the abundance of large gymnosperm fossil wood samples and the high content of diterpenoids found in the coal seams (Ritts, 1998; Zhang et al., 1998; Wang et al., 2005). One explanation for the absence of fern fossils may be taphonomic, relating to different degrees of degradation during peat accumulation. Controversy about the principle coal-forming plants during the Middle Jurassic is common, with these providing potentially different climate signals.

Transient negative carbon isotope excursions in most carbonate reservoir rocks have been interpreted as warming events caused by rises both in atmospheric pCO₂ and other greenhouse gases for instance as seen within the Jurassic during the early Toarcian, early Bajocian and middle Oxfordian (Jenkyns, 2003; Hesselbo et al., 2007; Dera et al., 2011). A significant negative carbon isotope excursion within British coals at about the Aalenian-Bajocian boundary has been clearly defined as a global phenomenon and been interpreted as a shift to a more continuously warm and humid climate in the Early Bajocian (Hesselbo et al., 2003). In coals from the Northern Qaidam Basin, two significant negative carbon isotope excursions exist at the Aalenian-Bajocian boundary

interval (Lu et al., 2014). However, it remains to be seen whether these carbon-isotopic excursions represent global climate or local paleoenvironmental, taphonomic or diagenetic phenomena.

The aims of this paper are to examine Bajocian coals in the Northern Qaidam Basin in order to: 1) clarify the parameters controlling the carbon isotopic composition of coal; 2) interpret the main coal-forming plants; 3) establish a comprehensive record of Bajocian terrestrial environments including carbon isotopic, petrological and paleobotanical trends; and 4) evaluate climate changes during the Bajocian stage and where possible, correlate these to the marine record.

2. Geologic setting

The Qaidam Basin is a large Mesozoic-Cenozoic intermontane basin (Halim et al., 2003) situated in Qinghai Province, NW China. The Northern Qaidam Basin is one of the secondary-level tectonic units in the Qaidam Basin and is surrounded by the Altun Mountains in the northwest, the Saishiteng Mountains and Qilian Mountains in the north, and the Maoni� Mountains in the east (Dai et al., 2003; Fig. 1). Continuous sedimentation in the Northern Qaidam Basin occurred throughout the Mesozoic, resulting in fluvial-deltaic-lacustrine deposits primarily composed of gravels, sands, muds and peats, later lithified through diagenesis to conglomerates, sandstones, mudstones, and coals. The main period of peat formation spans the Lower-Middle Jurassic during the deposition of the Xiaomeigou, Dameigou and Shimengou formations.

Palynological studies of the Dameigou Formation yielded rich, age-diagnostic assemblages useful in dating and correlating the stratigraphic sections from the Northern Qaidam Basin (Ritts, 1998; Zhang et al., 1998; Ritts and Biffi, 2001; Wang et al., 2005; Jian et al., 2013). Age-diagnostic assemblages were interpreted in the context of previous biostratigraphic studies in central Asia and northwest China (Vakhrameyev, 1982) and more complete Lower and Middle Jurassic sections in northern Qaidam and parts of the Tarim Basin (Hendrix, 1992; Sobel, 1995; Ritts, 1998). All of studies indicate a Bajocian to early Bathonian age for the coal measures from Dameigou Formation. Moreover, thermochronologic and Zircon U-Pb dating data have also confirmed the age

of the Dameigou Formation (Delville et al., 2001; Jolivet et al., 2001). The Mesozoic tectonic settings of the Qaidam Basin are often linked with the evolution of the Mesotethys, Neo-Tethys and the Mongol-Okhotsk Ocean, and the collisions of the related blocks (Ritts and Biffi, 2001; Kravchinsky et al., 2002; Kapp et al., 2007; Gehrels et al., 2011; Fig. 2). These tectonic events are well-dated and provide good stratigraphic control on the ages of tectonic unconformities affecting the strata (Ritts and Biffi, 2001; Gehrels et al., 2011). The detrital zircon U-Pb dating data of sediments also constrains the geochronology of the Dameigou Formation. The youngest detrital Zircon U-Pb dating ages of sandstones from coal seam roof and floor samples were ascertained to be 168Ma and 170Ma, respectively (Yang et al., 2017; Yu et al., 2017; Fig. 2).

The Dameigou Formation was deposited during subsidence with weak tectonic activity (Li et al., 1988). Thick coal seams were widely distributed in the Upper Member of the Dameigou Formation where they developed in lacustrine transgression systems tracts (Lu et al., 2014). The Upper Member of the Dameigou Formation varies from 20–100 m thick and contains several coal seams in which the E and F seams are the primary mineable coal beds, each varying from 2–30 m thick. In the YQ-32 borehole in the Yuqia profile, the Upper Member of the Dameigou Formation (Fig. 2) is up to 70 m thick and includes the E and F coal seams, mudstones and siltstones. The E and F coal seams attain thicknesses of 12 and 8 m, respectively (Fig. 3), and cumulative thickness of coals represents about 30% of the entire section thickness. Johnson (1984), McCabe (1984) and Collinson and Scott (1987) suggested that the compression ratios of bituminous coal, sandstone and mudstone are about 6:1, 1:1 and 2:1, respectively. According to the compression ratios of bituminous coal, sandstone and mudstone, peat may be equivalent to 60–70% of an uncompressed section (Fig. 3). In view of the much lower peat-accumulation rate in comparison to siliciclastic deposits (McCabe, 1984; 1987), peat formation may occupy about 90% of the time of deposition. Lu et al. (2018) reconstructed the deposition rate of peat in the Northern Qaidam Basin using Frequency Spectrum Analysis and indicated that peat-accumulation of the No. 6 and No. 7 coal seams from the Dameigou section may extend through the Bajocian. The No. 6 and No. 7 coal seams from the Dameigou section and E and F coal seams from the Yuqia area refer

to the same strata but with different local names (Lu et al., 2018).

Root traces occur in seat earth horizons beneath each of seams E and F. Coal seam thickness is relatively stable across the coalfield and evidence of allochthonous peat accumulation genesis, such as storms, gravity flow and underwater debris flows, are absent (Lu et al., 2014). Together these factors suggest that both seams originated from autochthonous peat accumulation and are therefore suitable for analysis of in-situ environmental trends.

3. Sampling and analytical methods

Samples were taken from the YQ-32 borehole near Yuqia in the Northern Qaidam Basin (Fig. 1). A total of 88 samples were taken from the E and F coal seams at 0.20–0.30 m intervals and immediately stored in plastic bags to minimize contamination and oxidation. Sample preparation followed ASTM D-2013/D2013-12 (ASTM, 2012). Samples were crushed and ground to 1mm maximum size, cured in epoxy resin as raw coal, then cut and polished for microscopic analysis using white-light reflectance microscopy under oil immersion. Maceral analyses are based on 500 points per sample with maceral classification and terminology based on the work of Taylor et al. (1998), ICCP System 1994 (ICCP, 1998, 2001) and Pickel et al. (2017). Mean random vitrinite reflectance was determined from 50 measurements per sample in accordance with Australian Standard guidelines (Australian Standard AS 2856.2-1998. 1998).

Stable carbon-isotope ratios for $\delta^{13}\text{C}_{\text{coal}}$ were measured at the Chinese Academy of Sciences Key Laboratory of Crust-Mantle Materials and Environments by continuous-flow mass-spectrometry using a MAT 253 isotope ratio mass spectrometer. Samples were first acidified for 24 hours with 5% dilute hydrochloric acid to remove inorganic carbon. Subsequently portions of each sample (1–2mg) with copper, copper oxide, and platinum wire were packed in vacuumized quartz combustion tubes and ignited with excess oxygen and combusted for 4 h at 850°C to generate CO_2 . The resulting CO_2 was analyzed for $^{13}\text{C}/^{12}\text{C}$ value which was compared with the corresponding ratio of USGS24 (graphite, $\delta^{13}\text{C}=-16.049\text{‰}$) and GBW04407 (Natural Gas Carbon Powder, $\delta^{13}\text{C}=-$

22.43±0.07‰). All sample carbon isotope data are reported in per mil on the V-PDB scale, and typical reproducibility of analytical replicates of the same sample was within ±0.1‰.

Pollen and spores were identified and quantified from 20 samples from the YQ-32 core. Samples were processed using standard palynological techniques with hydrochloric and hydrofluoric acids to remove mineral matter, and then oxidizing them with concentrated nitric acid. Samples were subsequently filtered through an 8 µm nylon sieve to remove the fine fraction of the residues. Finally, the remains were mounted on slides using glycerol for palynomorph identification. Spore and pollen percentages were based on counts of 300–400 palynomorphs per sample under transmitted light microscopy.

4. Results

4.1. Carbon isotope composition of coal

The $\delta^{13}\text{C}_{\text{coal}}$ values for 88 samples from the Yuqia area range from –25.3‰ to –22.5‰ (Figs. 4 and 5; Table 1), which indicate that C3 plants were the main coal-forming vegetation (Cerling et al., 1993). Striking differences in carbon isotope values exist in the coals in vertical profile through the succession (Figs. 4 and 5, Table 1). Based on the $\delta^{13}\text{C}_{\text{coal}}$ values, several coal units can be recognized with more detailed geological information within the E and F coal seams, as outlined below.

4.1.1. E coal seam

Within the coal seam E, $\delta^{13}\text{C}_{\text{coal}}$ values range from –25.3‰ to –22.5‰. Two coal units, E1 and E2, are recognized with significant isotope differences.

$\delta^{13}\text{C}_{\text{coal}}$ values for unit E1 range from –23.8‰ to –22.5‰ with an average of –23.1‰. This coal unit is characterized by an abundance of gymnosperm pollen including *Cycadopites* (5–10.3%), *Chasmatosporites* (7.6–10.5%) and *Classopollis* (5.5–

20.5%).

$\delta^{13}\text{C}_{\text{coal}}$ values for unit E2 range from -25.3‰ to -23.9‰ with an average of -24.7‰ . Fern spores including *Cyathidites* are more abundant than in the E1 coal unit. A significant negative excursion (-22.9‰ to -24.7‰) is present in the coals at the boundary between the E1 and E2 units. This trend is also reflected by a rapid increase of *Cyathidites* (from 27.4% to 53.4%; (Fig. 4, Table 1).

4.1.2. F coal seam

Within coal seam F carbon isotope values range from -25.2‰ to -23.2‰ (Table 1). Similar to the underlying E seam, two coal units, F1 and F2, are recognized with significant differences in isotope values (Fig. 4). A significant negative excursion (-23.2‰ to -25.2‰) is present between units F1 and F2. This rapid change is also reflected by an abundance shift of *Cyathidites* pollen (from 50.2% to 22.7%, and to 60.3%). The more negative isotope values continue through the upper part of unit F2 where *Cyathidites* and *Dictyophyllidites* are abundant.

4.2. Coal petrographic analysis

On the basis of the vitrinite reflectance data (Table 1), seam E (R_{max} - in %) varies in the range 0.74–0.83 and is ranked as an ortho-bituminous coal, whereas the seam F (R_{max} - in %) varies in the range 0.42–0.51, with one exception 0.64%, and is a sub-bituminous to ortho-bituminous coal. Coal seam E contains large percentages of vitrinite and moderate percentages of inertinite with reduced amounts of liptinite, and very low levels of mineral matter. Vitrinite averages 53.89% (Table 1), and is dominated by collodetrinite, collotelinite and telinite. Inertinite averages 38.55%, and is dominated by semifusinite and inertodetrinite, with lesser amounts of fusinite and macrinite (Table 1; Fig. 6). Liptinite averages 3.47%, and includes sporinite, cutinite and resinite. With some rare exceptions, liptinite and mineral matter account for less than 10% of the total volume.

Coal seam F contains moderate percentages of vitrinite and large percentages of

inertinite with reduced amounts of liptinite. Vitrinite averages 29.81% and is dominated by collodetrinite and telinite. Inertinite averages 54.11% and is dominated by semifusinite and inertodetrinite, with decreased amounts of fusinite and macrinite. Mineral matter averages 12.87%.

5. Discussion

The carbon-isotope, petrographic and palynological records from coal seams may reflect paleobotanical evolution in the source vegetation as well as paleoclimatic changes through periods of peat-formation. These paleoclimatic factors may show high consistency in response to the paleoclimatic changes, while others may be interpreted to reflect more complex depositional history. Therefore, the parameters controlling the carbon isotope and petrography from the coals should be analyzed in detail. In the following three sections, various factors controlling the carbon isotope composition and coal petrography, the interpretations of the carbon isotope and petrography data, and their differences or similarities in response to the paleoclimatic changes are considered.

5.1. Parameters controlling carbon isotope composition

5.1.1. Relationship between palynology and carbon isotopic ($\delta^{13}\text{C}_{\text{coal}}$) composition of coal

Cross-plots of $\delta^{13}\text{C}_{\text{coal}}$ values and palynological data were constructed for samples from coal seams E and F in the Yuqia profile (Fig. 4). The best correlations occur between increasing amounts of fern spores (e.g. *Cyathidites*) and lower isotope values, and between increasing amounts of gymnosperm pollen (e.g. *Cycadopites* and *Chasmatosporites*) and more positive isotope values (Fig. 4). The botanical affinity of *Cyathidites* may belong within the *Cyatheaaceae* tree ferns, while *Cycadopites* and *Chasmatosporites* may be allied with Ginkgophytes and/or Cycadalean gymnosperms (Wang et al., 2005). As shown in Figure 7, the comparison of mean carbon isotope values from different vegetation patterns shows significant trends. Effects of inter-species variations and of leaf morphology on $\delta^{13}\text{C}_{\text{coal}}$ values have already been assessed by the

use of paleobotanical data (Kolcon and Sachsenholer, 1999). Results indicate that differences in the contribution of C3 plants can largely influence carbon isotope values in coals. Lücke et al. (1999), Bechtel et al. (2008), and Holdgate et al. (2009) have undertaken stable carbon isotope investigations on fossil woods through the Cenozoic, and also evaluated the influences of changing contributions of angiosperms and gymnosperm on $\delta^{13}\text{C}_{\text{coal}}$ values. In comparison to gymnosperms, angiosperms can display 2.5‰ more carbon isotope discrimination due to differences in carbon assimilation efficiency or leaf morphology (Murray et al., 1998). Importantly, the same kinds of plants existing in different periods of geological history also show significant differences in the carbon isotope values due to the changes in $\delta^{13}\text{C}$ values of CO_2 or other environment factors through time (Arens et al., 2000). In order to interpret the carbon isotope data from coal seams E and F, it is therefore necessary to discuss the differences of carbon isotope discrimination within ferns and gymnosperms that co-existed during the Middle Jurassic.

Xiao et al. (2017) evaluated the $\delta^{13}\text{C}$ values of the Gymnosperm *Ginkgoites* in the Middle Jurassic Xishanyao Formation in the Turpan-Hami Basin (NW, China). These ranged from -23.83‰ to -23.26‰ with an average of -23.55‰, which are roughly the same values from *Ginkgo* and *Ginkgoites* from the European Middle Jurassic (Bocherens et al., 1993) (Fig. 7). Although ferns, especially the *Cyatheaceae*, were widespread in the Jurassic, $\delta^{13}\text{C}$ values from this plant group have not been evaluated systematically. One reason for the insufficient research on $\delta^{13}\text{C}$ values of ferns may be due to a poorer preservation potential compared to gymnosperms. However, the $\delta^{13}\text{C}$ values from modern ferns have been measured, and range from -32.21‰ to -28.03‰ with an average of -28.58‰ (Ren and Yu, 2011; Song et al., 2013; Werth et al., 2015; Xiao et al., 2017; Fig. 7).

Willis and McElwain (2002), Royer et al. (2003), and Sun et al. (2003) compiled a large database of fossil and modern plants and suggested that plants named as 'living fossils' (including *Ginkgo biloba* and *Alsophila spinulosa*) could be phylogenetically and ecologically conservative. This infers these plants may preserve relatively invariant information with their fossil relatives as they have not been affected by extinction. On

this basis, these 'living fossils' can provide an opportunity to predict carbon isotopic signatures from preserved fossil plants.

Farquhar et al. (1982, 1989) established a conceptual model to describe carbon isotope discrimination in C3 vascular land plants defined as:

$$\delta^{13}\text{C}_\text{P} = \delta^{13}\text{C}_\text{a} - a - (b - a)(p_i/p_a) \text{ (Eq. 1)}$$

where $\delta^{13}\text{C}_\text{P}$ and $\delta^{13}\text{C}_\text{a}$ are the isotopic composition of the plant-based (p) carbon and of the atmospheric (a) CO₂, 'a' is the diffusional fractionation (4.4‰), 'b' is carboxylation fractionation, usually taken as 27‰, and 'p_a' and 'p_i' are the ambient and intercellular partial pressures of CO₂, respectively. As shown from the format, $\delta^{13}\text{C}_\text{a}$ is one of the principle factors controlling $\delta^{13}\text{C}_\text{P}$. While changing through the geological time, $\delta^{13}\text{C}_\text{a}$ values during the early Middle Jurassic have been reconstructed by Beerling et al. (2002) through analysis of calcium carbonate fossils, which ranged from -5.6‰ to -4.6‰. Xiao et al. (2017) also evaluated $\delta^{13}\text{C}_\text{a}$ using *Ginkgoites* and *Cladophlebis* leaves fossils from the Middle Jurassic aged Xishanyao Formation, which ranged from -4.63‰ to -4.37‰. On this basis, we can calculate the p_i/p_a value in *Ginkgoites* during the Middle Jurassic, which is about 0.6 and hence approximately same as the p_i/p_a value (ca. 0.63) in extant *Ginkgo biloba* (Xiao et al., 2017). The similarity between the Middle Jurassic *Ginkgoites* and modern *Ginkgo biloba* p_i/p_a values seems to support the principle of phylogenetic and ecological conservation of *Ginkgo* as a 'living fossil' (Willis and McElwain, 2002; Royer et al., 2003). For *Alsophila spinulosa* (modern) or *Cyatheaceae* (Middle Jurassic), we evaluated the p_i/p_a (ca. 0.7-0.8) according to Eq. 1, and estimated the $\delta^{13}\text{C}_\text{P}$ values from *Cyatheaceae* from the Middle Jurassic according to the format shown in Figure 7. As shown in Figure 7, a very striking feature of the Middle Jurassic macrofossils and modern plants record is the pronounced difference between the $\delta^{13}\text{C}_\text{P}$ values of gymnosperms compared to ferns. Even if the physiological causes of that carbon isotope difference are not fully understood, the offset between inter-species $\delta^{13}\text{C}_\text{P}$ values may be used as a differentiating factor in palaeoecological studies (Lücke et al., 1999).

5.1.2. Maceral components as controls on carbon isotope composition

Bulk maceral and mineral composition in terms of vitrinite, inertinite, liptinite and mineral matter contents (in vol. %) and $\delta^{13}\text{C}_{\text{coal}}$ values throughout the E and F coal seams are presented in Fig. 5. Correlations between maceral components and $\delta^{13}\text{C}_{\text{coal}}$ values are given in Fig. 8. Coal seams that have been investigated in the past show pronounced negative relationships between liptinite content and carbon isotope values of the coal (Bechtel et al., 2008). The enhanced yields of extractable organic matter from liptinite-rich samples have already demonstrated this. However, a cross-plot of the Northern Qaidam Basin $\delta^{13}\text{C}_{\text{coal}}$ values and liptinite content fails to show a relationship (Fig. 8C). This indicates that there may be other factors that control the carbon isotope composition, or that the liptinite content may be too low to affect the carbon isotopes in these particular coals.

As seen from Figure 8, relationship between the $\delta^{13}\text{C}_{\text{coal}}$ values and vitrinite or inertinite content from the study area shows two types of diverse trend. For coal seam E, the higher the inertinite content, the higher the $\delta^{13}\text{C}$ values. Similar results were obtained on maceral groups from Permian aged coals from the Bowen and Blair Basins in Australia, including the expected Gondwana isotope-offset (Whiticar, 1996). For unit F2, this characteristic is the opposite, namely that the higher inertinite content, the lower the $\delta^{13}\text{C}$ values. In unit F1, there is no $\delta^{13}\text{C}$ versus inertinite correlation. Figure 8A, shows that $\delta^{13}\text{C}$ values in the E2 unit become lower and lower (more negative) with increasing vitrinite content. This $\delta^{13}\text{C}$ versus vitrinite content correlation corresponds to the $\delta^{13}\text{C}$ versus inertinite content correlation because more vitrinite typically means less inertinite and *vice versa* (more negative $\delta^{13}\text{C}$ values are characteristic for the high vitrinite - low inertinite samples of the E2 unit, and *vice versa*). In the F2 unit, oppositely, $\delta^{13}\text{C}$ values become higher and higher (less negative) with increasing vitrinite content. This $\delta^{13}\text{C}$ versus vitrinite correlation for unit F2 also corresponds to the inertinite/ $\delta^{13}\text{C}$ correlation because more vitrinite mostly means less inertinite and *vice versa*, but in this case less negative $\delta^{13}\text{C}$ values are characteristic for the high vitrinite - low inertinite samples of the F2 unit. A similar $\delta^{13}\text{C}$ versus vitrinite content correlation as for unit F2 exists for unit F1 (with about 1 ‰ less negative $\delta^{13}\text{C}$ values). All these contradictions show that the relationship between $\delta^{13}\text{C}$ values and vitrinite or inertinite content from

the F coal seam is different to that in coal seam E, implying that carbon isotopic composition is not univocally dependent on maceral composition. A few studies have evaluated the relationship between maceral components and the carbon isotope composition in coals, indicating that there is no systematic change of the initial carbon isotope composition of organic matter during sedimentation and coalification (Smith et al., 1982; Lücke et al., 1999). Whiticar (1996) reported that the maturity of coal does not seem to influence $\delta^{13}\text{C}$ until the meta-anthracite rank. On this basis, the ambiguous relation between maceral components and carbon isotope composition within the E and F coals might be affected by other environmental factors.

5.2. Paleoclimate records within the coal

As a biochemical sediment, coal preserves a detailed record of paleoclimate changes at the time of its deposition from which meaningful information can be obtained from petrological and carbon isotope analyses of coal at sample intervals in the centimeter or even millimeter ranges (e.g., Diessel, 2007). Such low orders of magnitude are generally not resolved by conventional sequence stratigraphy of siliciclastic sediments.

5.2.1. Carbon isotopic composition and floral records from coal as paleoclimate proxies

The carbon isotope composition of coal seams is the result of multiple factors acting through geological time (Lücke et al., 1999; Bechtel et al., 2008; Holdgate et al., 2009). The major factor affecting the carbon isotopic fluctuation within coal is the organic matter origin. Since peat-forming plants consist of different taxa, a change of the fern:gymnosperm ratio, for example, an increase in the percentage of ferns such as *Cyatheaceae*, can easily decrease carbon isotope values in the coal (Fig. 4).

More significant information can be obtained through the analysis of coal (peat)-forming plants, as recorded by carbon isotope values and palynomorphs in the coal. As seen from Figure 4, two striking negative excursions of $\delta^{13}\text{C}_{\text{coal}}$ values (red arrows) can be recognized and correlated with palynological changes. Transient negative carbon isotope excursions occurring in most carbonate reservoirs have been interpreted as

warming events caused by rises both in atmospheric pCO₂ and other greenhouses gases (e.g., during the early Toarcian, early Bajocian and middle Oxfordian; Jenkyns, 2003; Hesselbo et al., 2007; Ruebsam et al., 2018). Woodward (1987), Beerling and Woodward (1995), and Wagner et al. (1996) suggested that long-term changes of atmospheric pCO₂ can affect the stomatal index of leaves of plants thus changing photosynthetic ¹³C isotope discrimination. Kürschner (1996) conducted greenhouse experiments with Oak trees and indicated that an atmospheric CO₂ increase of 100 ppm can cause an additional discrimination of approximate 0.75‰.

Yiotis et al. (2017) suggested that there are striking differences in the photosynthetic plasticity of ferns (e.g. *Cyathea australis* or *Osmunda claytoniana*) and gymnosperms (e.g. *Ginkgo biloba*) grown in experimentally controlled low O₂:CO₂ ratio atmospheres, which may properly explain their different ecological fate across the Triassic-Jurassic boundary mass extinction event. During this extinction event, plants experienced global disturbance and a major turnover, but this was less profound than experienced in the stratigraphically earlier Permian-Triassic mass extinction event. Yiotis et al. (2017) concluded that the observed photodamage hinders the ability of *Ginkgo* to transfer excess photosynthetic electron flow to sinks other than the downregulated C3 and the diminished C2 cycles under low O₂:CO₂ conditions (Yiotis et al. 2017). This conclusion, along with the striking physiological plasticity of ferns, provides insights into the underling mechanism of near extinction of the *Ginkgoales* and the proliferation of ferns as atmospheric CO₂ increased to maximum levels across the Triassic-Jurassic boundary mass extinction (Yiotis et al., 2017). On this basis, the sharp variations in fern and gymnosperm content that are also recorded in the carbon isotope values within the coal may reflect vegetation responses to changes in the proportions of O₂ and CO₂ in atmosphere. Therefore, for the E and F coal seams from Northern Qaidam Basin, the striking trend of δ¹³C_{coal} values changes coupled with the evolution of coal-forming plants may record the relatively long-term pCO₂ changes through the Bajocian stage in the Middle Jurassic.

Except for the striking negative excursion of δ¹³C_{coal} values, the high-frequency fluctuation of δ¹³C_{coal} values within coal seams E and F may record short-term changes

of environmental factors, especially when the paleobotanical data have not fluctuated significantly. Bechtel et al. (2008) reconstructed the magnitudes of $\delta^{13}\text{C}_{\text{coal}}$ variations in low-rank coals caused by environmental changes during the Cenozoic, and concluded that the carbon isotope record generally co-varies with the estimated variability in mean annual temperatures. Bechtel et al. (2008) further noted that variation in humidity may be responsible for excursions between the $\delta^{13}\text{C}_{\text{coal}}$ trend and the paleotemperature curve during the Miocene. Additionally, relatively heavy carbon isotope values can be produced by plants growing in water-stressed or saline environments (e.g., the humidity coefficient of about -0.17‰ ; Monti et al., 2006). However, it is difficult to definitively evaluate the influence of the complicated and interactional environmental factors on the carbon isotope values in coals (Lücke et al., 1999). Therefore, interpretation of short-term climatic conditions (e.g., temperature or humidity) from these isotope signals can only be attempted with great caution and should be coordinated with other paleoclimatic factors such as coal petrology.

5.2.2. Paleoclimate significance of petrology

The most widely used criteria to record the depositional conditions at the peat stage is inorganic mineral content that consists of authigenic and detrital minerals (Ward and Swaine, 1995). Although differing genetically, authigenic minerals are not easy to distinguish from detrital minerals. Nevertheless, as outlined by Moore et al. (1996) in Holocene mires of southeast Asia, authigenic mineral content tends to be quite low unless peat ablation was excessive. Whether generally syngenetic or mostly water-borne minerals concentrated in coals depends on conditions of the relationship between accommodation rate and the rate of peat accumulation (Bohacs and Suter, 1997). A relatively lower detrital mineral content occurs in coal when the ratio of accommodation nearly balances the rate of peat accumulation. Clymo (1987), Staub (1991) and Diessel (2007) suggested that a detrital mineral proportion of $< 10\%$ can be interpreted as ombrotrophic peat-forming conditions. In planar mires, for example the distal, permanently flooded papyrus marshes around delta plains (McCarthy et al., 1989; Diessel, 2007), low-ash topogenous peat can form where peat accumulation might be

free from the influx of clastic sediment. Detrital mineral contents ranging from 10–30% by volume have been interpreted as eutrophic, limnotelmatic peat-forming conditions where water encroachments were intermittent and frequent so that water-borne minerals could easily migrate into the accumulating peat.

The mineral content of coal seams E and F shows significant differences (Fig. 5). Mineral matter averages 12.87% (max: 32.76%, min: 4.75%) in seam F which is much higher than in seam E with an average of 3.2%. Therefore, mires during the time of peat-formation for seam F may be interpreted as low-lying, rheotrophic (ground water-fed) mires, which easily accumulated detrital mineral matter due to fluvial inundation (Staub, 2002). In contrast, E seam with a low mineral content (ca. 3.2%) could be interpreted as the product of an ancient ombrotrophic (rain water-fed) mire building up above the regional water-table (Clymo, 1987; Staub, 1991; Diessel, 2007).

5.2.3. Comprehensive interpretation of carbon isotope composition, petrography and palynology

The combination of coal petrography, biomarker and carbon isotope data, and palynology has become an important tool for the reconstruction of paleoclimate, paleoenvironment and floral changes (Bechtel et al., 2008; Gross et al., 2015; Eble and Greb, 2018). As discussed above, palynological data within the coals reflect paleobotanical composition, which is also recorded by the carbon isotopes in the coals. However, more meaningful information can be obtained through a comprehensive analysis of the carbon isotope composition, petrography and palynology. Palynology of the E and F seams indicates that ferns were dominant plants (ca. >50%) during the Middle Jurassic and might comprise the major coal (peat)-forming vegetation (Li et al., 1988; Wang et al., 2005). However, the significant difference between carbon isotope values from gymnosperms and ferns provides an opportunity to infer the composition of the E and F coals. The similar carbon isotope values of gymnosperms and coals (especially E1 and F1; Fig. 7) suggests the coal from the Dameigou Formation is comprised to a very high degree from organic material derived from gymnosperms, which is consistent with the very high abundance of diterpenoids (especially pimarane

and abietane, which are primarily produced by gymnosperms) in coals from the northern Qaidam Basin (Hendrix, 1992; Ritts, 1998). This result is also supported by the high inertinite contents (ca. >50%; Fig. 5) indicative of oxidizing conditions associated with a low mire water-table. The different vegetation taxa recorded by the palynology and carbon isotope values can be explained that great portion of the palynomorph population from the coals might be enthetic (transported from the hinterland plants into the gymnosperms-rich peat-land. In addition, differential pollen and spore production rates in ferns and gymnosperms may also be a factor.

The two striking negative excursions of carbon isotopic values are significant characteristics of coal seams E and F. Though not shown by the petrography, these excursions are reflected by the palynological data which might be interpreted to reflect a change in paleoclimate. Except for the two significant negative excursions, the carbon isotope values within the four units (E1, E2, F1, and F2) may record the short-term or high-frequency paleoclimate fluctuations through time. There was no intense change of plant patterns in each unit, and this may provide an opportunity to explore the changes of paleoclimate (e.g., temperature and humidity or precipitation). The trend of $\delta^{13}\text{C}_{\text{coal}}$ values negatively correlating with changes in vitrinite content in the E coal seam (see section 4.3 and Fig. 8A) appears to support the relationship between carbon isotope and paleoclimatic factors in the sense that higher vitrinite content and lower $\delta^{13}\text{C}_{\text{coal}}$ values mean warmer climate. However, a significant positive correlation between carbon isotope values and vitrinite exists in the F coal seam (Figs 5 and 8). One explanation for this contradiction may be related to the mire pattern associated with the depositional environment. The Upper Member of the Dameigou Formation developed during the sequence stratigraphic transgressive system tract (TST), with coal seam E occurring in the early TST, and coal seam F occurring in the middle of the TST (Lu et al., 2014). The water-table rose more slowly during the early TST relative to that during the middle TST. The E coal, with a lower mineral matter content (ca. 3%), may have resulted from ancient ombrotrophic (rain water-fed) mires building up above the regional water-table. A domed, ombrotrophic origin is more likely to preserve a climate record without the effect of eustasy and basin subsidence. During the middle TST, the water-table rose and

mires during the F coal-forming period may be interpreted as low-lying, rheotrophic (ground water-fed) mires, which easily accumulated detrital mineral matter due to fluvial inundation (Staub, 2002). The fluvial conditions with oxygenated water strongly affected the maceral composition and disturbed the relationship between carbon isotope and paleoclimatic factors.

5.3. Climate change in the Bajocian

Detailed Bajocian carbon isotope data from marine lithologies and terrestrial bulk organic matter both agree that some observed isotopic patterns are caused by global rather than local paleoenvironmental, taphonomic or diagenetic factors (Jenkyns et al., 2002; Hesselbo et al., 2003; O'Dogherty et al., 2006; Dera et al., 2011; Korte et al., 2015). In view of the much lower peat-accumulation rate than siliciclastic deposits (McCabe, 1984; 1987), the formation of coal seams E and F may occupy about 90% of the Bajocian time of deposition (Lu et al., 2018; Fig. 3). Lu et al. (2018) suggested that the formation of coal seam E might require approximately 0.65-0.77 Ma for peat accumulation—if taking into account the hiatal events during peat accumulation which may be characterized by the existence of exposure or oxidation organic partings in the coal (Diessel, 2007; Guo et al., 2018), this interval must be longer. According to the stratigraphic chronology from Ritt (1998), Hesselbo et al. (2003), Yu et al. (2017), and Lu et al. (2018), the negative isotopic values excursion as seen in coal seam E is very similar to the marine carbonate (Dera et al., 2011) and bulk organic matter (Hesselbo et al., 2003) records for this time (Fig. 9), which may indicate a global change in the coal. Furthermore, the palynological records also appear to have a global extent. For example, steadily increasing ferns:gymnosperms ratio is recorded in the latest Early Bajocian strata in the Swabia Borehole, southwest Germany (Wiggan et al., 2017, 2018), the Inner Hebrides, northwest Scotland (Riding et al., 1991) and the south Junggar and south Tarim Basins, northern China (Hendrix, 1992).

In the marine record (Fig. 9), the negative carbon-isotopic excursion at the latest

Early Bajocian (*humphresianum* Zone) that is accompanied by a marked oxygen-isotopic negative excursion, has been interpreted as global warming event (Dera et al., 2011; Korte et al., 2015). The higher kaolinite content of the *Stephanoceras humphrieisianum* ammonite biozone of the Paris Basin may also be indicative of a warm and humid climate (Brigaud et al., 2009). In the Tethyan realm, a maximum third-order transgression happened at this time (Jacquin et al., 1998; Hallam, 2001). Though Hesselbo et al. (2003) argued that the Bajocian negative carbon-isotopic excursion may reflect changes in the abundance of organic components from terrestrial to marine dominance, the temporal coincidence between transgression and palynological evidence in the *humphresianum* Zone indicates climatic warming in the northwest Tethyan realm.

In the Northern Qaidam Basin, the long-term paleoclimatic change through this period was characterized by a gradual rise of pCO₂ and also rising water-table levels (Lu et al., 2014). Within coal seam E, the higher carbon-isotopic values (E1) are associated with a high content of conifer-Ginkgophyte-Cycadophyte-*Classopollis* palynomorph assemblages (upland origin). The lower carbon isotope and floral factors represent the humid climate that is believed to have existed during the E2 peat-forming period. Coupling with evidence of gradual increase in pCO₂ concentration, water-table level changes and the palynomorph assemblages through the northwest China including the Jungger, Tarim, Qaidam and Yaojie Basins (Hendrix, 1992; Ritt, 1998; Zhang et al., 1998), the terrestrial realm (northeast Tethyan) also shows obvious climate change—becoming warmer and more humid in the latest Early Bajocian. The similarity of the terrestrial and marine geochemical records, and their similarity with the floral record is an indication that the observed paleoclimate signal is a global phenomenon.

6. Conclusions

In the Northern Qaidam Basin, the Bajocian terrestrial carbon isotopic variation follows fluctuations in fern spore/gymnosperm pollen, where higher ratios correspond with lower $\delta^{13}\text{C}$ values. The similar carbon isotope values of gymnosperms (Middle Jurassic) and coals may indicate that the coals from the Dameigou Formation are

comprised to a very high degree from organic material derived from gymnosperm taxa, which is consistent with the very high abundance of diterpenoids in the coal (especially pimarane and abietane, which are primarily produced by gymnosperms). The different condition recorded by the palynology and carbon isotope can be explained that some portion of the palynomorph assemblages from the coals might be enthetic (transported).

Two striking negative excursions of carbon isotopic values are significant characteristics of coal seams E and F. The trend of $\delta^{13}\text{C}_{\text{coal}}$ values changes coupled with the evolution of peat-forming vegetation may be indicative of an obvious climate change—becoming warmer and more humid, in the latest Early Bajocian in the terrestrial realm (northeast Tethyan).

Except for the striking negative excursion of $\delta^{13}\text{C}_{\text{coal}}$ values, the high-frequency fluctuation of $\delta^{13}\text{C}_{\text{coal}}$ values, along with the coal petrologic variation within coal seams E and F may record short-term changes of environmental factors, especially when the paleobotanical data have not fluctuated.

Acknowledgements

This research is supported by the High-level Talent recruitment Project of North China University of Water Resource and Electric Power (No. 40481) and the National Natural Science Foundation of China (No. 41702168). We thank Lu Jing (China University of Mining and Technology, Beijing) for discussion, and Jianhan Huang, Hongjian Wang and Yazhou Fan for help with sample preparation. The text has been greatly improved as a result of insightful comments from Cortland Eble and an anonymous reviewer.

References

Arens, N.C., Jahren, A.H., Amundson, R., 2000. Can C3 plants faithfully record the carbon isotopic composition of atmospheric carbon dioxide? *Paleobiology* 261, 137–164.

- ASTM D2013/D2013M-12, 2012. Standard Practice for preparing Coal Samples for Analysis. ASTM International, West Conshohocken, PA, USA. www.astm.org.
- Australian Standard AS 2856,2-1998, 1998. Coal petrography. Part 2: Maceral analysis. Standards Association of Australia, North Sydney (32 pp)
- Bechtel, A., Gratzner, R., Sachsenhofer, R.F., Gusterhuber, J., Lücke, A., Püttmann, W., 2008. Biomarker and carbon isotope variation in coal and fossil wood of Central Europe through the Cenozoic. *Palaeogeog., Palaeoclimatol., Palaeoecol.* 262, 166–175.
- Beerling, D.J., Woodward, F.I., 1995. Leaf stable carbon isotope composition records increased water-use efficiency of C3 plants in response to atmospheric CO₂ enrichment. *Funct. Ecol.* 9, 394–401.
- Beerling, D.J., Lake, J.A., Berner, R.A., Hickey, L.J., Taylor, D.W., Royer, D.L., 2002. Carbon isotope evidence implying high O₂/CO₂ ratios in the Permo-Carboniferous atmosphere. *Geochim. Cosmochim. Acta* 66(21), 3757–3767.
- Bocherens, H., Friis, E.M., Mariotti, A., Pendersen, K.R., 1993. Carbon isotopic abundances in Mesozoic and Cenozoic fossil plants: palaeoecological implication. *Lethaia* 26(4), 347–358.
- Bohacs, K.M., Suter, J., 1997. Sequence stratigraphic distribution of coaly rocks: fundamental controls and examples. *AAPG Bull.* 81, 1612–1639.
- Brigaud, B., Durlet, C., Deconinck, J.F., Vincent, B., Pucéat, E., Thierry, J., Trouiller, A., 2009. Facies and climate/environmental changes recorded on a carbonate ramp: a sedimentological and geochemical approach on middle Jurassic carbonates (Paris Basin, France). *Sediment. Geol.* 222, 181–206.
- Cerling, T.E., Wang, Y., Quade, J., 1993. Expansions of C4 eco-systems as an indicator of global ecological change in the late Miocene. *Nature* 361, 344–345.
- Cernusak, L.A., Ubierna, N., Winter, K., Holtum, J.A.M., Marshall, J.D., Farquhar, G.D., 2013. Environmental and physiological determinants of carbon isotope discrimination in terrestrial plants. *New Phytol.* 200, 950–965.
- Cernusak, L.A., Winter, K., Aranda, J., Turner, B.L., 2008. Conifers, angiosperm trees, and lianas: growth, whole-plant water and nitrogen use efficiency, and stable isotope composition ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of seedlings grown in a tropical environment. *Plant Physiol.* 148, 642–659.
- Cernusak, L.A., Winter, K., Aranda, J., Turner, B.L., Marshall, J.D., 2007. Transpiration efficiency of a tropical pioneer tree (*Ficus insipida*) in relation to soil fertility. *J.*

631   Exper. Bot. 58, 3549–3566.

632   Clymo, R.S., 1987. Rainwater-fed peat as a precursor of coal. In: Coal and Coal-Bearing
633   Strata: Recent Advances (Ed. A.C. Scott), Geol. Soc. Lond. Spec. Pub. 32, 107–125.

634   Collinson, M.E., Scott, A.C., 1987. Implications of vegetal change through the geological
635   record on models for coal-forming environments, In: Coal and Coal-Bearing Strata:
636   Recent Advances (Ed. A.C. Scott), Geol. Soc. Lond. Spec. Pub. 32, 67–85.

637   Dai, J.S., Ye, X.S., Tang, L.J., Jin, Z.J., Shao, W.B., Hu, Y., Zhang, B.S., 2003. Tectonic units and
638   oil-gas potential of the Qaidam Basin. Chinese J. Geol. 38(3), 291–296 (in Chinese
639   with English abstract).

640   Delville, N., Arnaud, N., Montel, J.M., Roger, F., Brunel, M., Tapponnier, P., Sobel, E., 2001.
641   Paleozoic to Cenozoic deformation along the Altyn Tagh fault in the Altun Shan
642   massif area, eastern Qilian Shan, northeastern Tibet, China, Paleozoic And Mesozoic
643   Tectonic Evolution of Central Asia: From Continental Assembly To Intracontinental
644   Deformation. Geological Society Of America Memoir 194, 265–292.

645   Dera, G., Brigaud, B., Monna, G., Laffont, R., Pucéat, E., Deconinck, J.-F., Pellenard, P.,
646   Joachimski, M.M., Durlet, C., 2011. Climatic ups and downs in a disturbed Jurassic
647   world. Geology 39, 215–218.

648   Diessel, C., 2007. Utility of coal petrology for sequence-stratigraphic analysis. Int. J. Coal
649   Geol. 70, 3–34.

650   Ding, S.T., Sun, B.N., Wu, J.Y., Li, X.C., 2010. Cuticular composition and carbon isotope
651   characteristics of Jurassic *Phoenicopsis* (*Phoenicopsis*) *angustifolia* Heer from
652   Huating in Gansu province, China. J. Lanzhou Univ. (Nat. Sci.) 46(1), 14–21 (in
653   Chinese with English abstract).

654   Eble, C.F., Greb, S.F., 2018. Geochemical, petrographic and palynologic characteristics of
655   two late middle Pennsylvanian (Asturian) coal-to-shale sequences in the eastern
656   Interior Basin, USA. Int. J Coal Geol. 190, 99–125.

657   Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and
658   photosynthesis. Ann. Rev. Plant Physiol. Plant Mol. Biol. 40, 503–537.

659   Farquhar, G.D., O’Leary, M.H., Berry, J.A., 1982. On the relationship between carbon
660   isotope discrimination and the intercellular carbon dioxide concentration in leaves.
661   Aust. J. Plant Physiol. 9(2), 121–137.

662   Gehrels, G., Kapp, P., DeCelles, P., Pullen, A., Blakey, R., Weislogel, A., Ding, L., Guynn, J.,
663   Martin, A., McQuarrie, N., Yin, A., 2011. Detrital zircon geochronology of pre-

Tertiary strata in the Tibetan-Himalayan orogen. *Tectonics* 30, TC5016.

Gröcke, D.R., 2001. The carbon isotope composition of ancient CO₂ based on higher plant organic matter. *Phil. Trans. Roy. Soc., Lond. A* 360 (1793), 633–658.

Gross, D., Bechtel, A., Harrington, G.J., 2015. Variability in coal facies as reflected by organic petrological and geochemical data in Cenozoic coal beds offshore Shimokita (Japan)—IODP Exp.337. *Int. J. Coal Geol.* 152, 63–79.

Guo, B., Shao, L.Y., Hilton, J., Wang, S., Zhang, L., 2018b. Sequence stratigraphic interpretation of peatland evolution in thick coal seams: Examples from Yimin Formation (Early Cretaceous), Hailaer Basin, China. *Int. J. Coal Geol.* 196, 211–231.

Halim, N. Chen, Y., Cogné, J.P., 2003. A first palaeomagnetic study of Jurassic formations from the Qaidam Basin, Northeastern Tibet, China—tectonic implications. *Geophys. J. Int.* 153, 20–26.

Hallam, A., 2001. A review of the broad pattern of Jurassic Sea-level changes and their possible causes in the light of current knowledge. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 167, 23–37.

Hendrix, M.S., 1992. Sedimentary basin analysis and petroleum potential, Mesozoic strata, northwest China: Ph.D. thesis, Stanford University, Stanford, California, 192–198.

Hesselbo, S.P., Morgans-Bell, H.S., McElwain J.C., Rees, P.M., Robinson, S.A., Ross, C.E., 2003. Carbon-cycle perturbation in the Middle Jurassic and accompanying changes in the terrestrial paleoenvironment. *J. Geol.* 111, 259–276.

Hesselbo, S.P., Jenkyns, H.C., Duarte, L.V., Oliveira, L.C.V., 2007. Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal). *Earth Planet. Sci. Lett.* 253, 455–470.

Holdgate, G.R., McGowran, B., Fromhold, T., Wagstaff, B.E., Gallagher, S.J., Wallace, M.W., Sluiter, I.R.K., Whitelaw, M., 2009. Eocene-Miocene carbon-isotope and floral record from brown coal seams in the Gippsland Basin of southeast Australia. *Glob. Planet. Change* 65, 89–103.

International Committee for Coal and Organic Petrology (ICCP), 1998. The new vitrinite classification (ICCP System 1994). *Fuel* 77, 349–358.

International Committee for Coal and Organic Petrology (ICCP), 2001. The new inertinite classification (ICCP System 1994). *Fuel* 80, 459–471.

Jacquin, T., Dardeau, G., Durlet, C., de Graciansky, P.C., Hantzpergue, P., 1998. The North

- Sea cycle: an overview of 2nd-order transgressive/regressive facies cycles in western Europe. In: de Graciansky, P.C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Spec. Pbb. 60, pp. 445-466.
- Jenkyns, H.C., 2003. Evidence for rapid climate change in the Mesozoic-Palaeogene greenhouse world: *Phil. Trans. Roy. Soc. Lond. A* 361, 1885–1916.
- Jenkyns, H.C., Clayton, C.J., 1997. Lower Jurassic epicontinental carbonates and mudstones from England and Wales: chemostratigraphic signals and the early Toarcian anoxic event. *Sedimentology* 144, 687–706.
- Jenkyns, H.C., Jones, C.E., Gröcke, D.R., Hesselbo, S.P., Parkinson, D.N., 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *J. Geol. Soc. Lond.* 159, 351–378.
- Jian, X., Guan, P., Zhang, W., Feng, F., 2013. Geochemistry of Mesozoic and Cenozoic sediments in the northern Qaidam basin, northeastern Tibetan Plateau: Implications for provenance and weathering. *Chem. Geol.* 360-361, 74–88.
- Johnson, D.P., 1984. Development of Permian fluvial coal measures, Goonyella, Australia, In: Rahmani, R.A., and Flores, R.M., (Eds.), *Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7*, 149–162.
- Jolivet, M., Brunel, M., Seward, D., Xu, Z., Yang, J., Roger, F., Tapponnier, P., Malavieille, J., Arnaud, N., Wu, C., 2001. Mesozoic and Cenozoic tectonics of the northern edge of the Tibetan plateau: fission-track constraints. *Tectonophysics* 343, 111-134.
- Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., Ding, L., 2007. Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area of central Tibet. *Geol. Soc. Am. Bull.* 119, 917-932.
- Kolcon, I., Sachsenhofer, R.F., 1999. Petrography, palynology and depositional environment of the early Miocene Oberdorf lignite seam (Styrian Basin, Austria). *Int. J. Coal Geol.* 41, 275–308.
- Korte, C., Hesselbo, S.P., Ullmann, C.V., Dietl, G., Ruhl, M., Schwerdt, G., Thibault, N., 2015. Jurassic climate mode governed by ocean gateway. *Nature Comm.* 6: 10015.
- Kravchinshy, V.A., Cogne, J.P., Harbert, W.P., Kuzmin, M.I., 2002. Evolution of the Mongol-Okhotsk Ocean as constrained by new palaeomagnetic data from the Mongol-Okhotsk suture zone, Siberia. *Geophys. J. Int.* 148, 34-57.

730 Kürschner, W.M., 1996. Leaf stomata as biosensors of palaeoatmospheric CO₂ levels. LPP
 731 Contributions Series, vol. 5. LPP Foundation, Utrecht, pp. 153.

732 Li, P.J., He, Y.L., Wu, X.W., Mei, S.W., Li, B.Y., 1988. Early and Middle Jurassic strata and
 733 their floras from Northeastern border of Qaidam Basin, Qinghai, Nanjing University
 734 Press, Nanjing (in Chinese with English summary).

735 Lu, J., Shao, L.Y., Wang, Z.G., Li, Y.H., Wang, S., 2014. Organic carbon isotope composition
 736 and paleoclimatic evolution of Jurassic coal seam in the northern Qaidam Basin. J.
 737 China Univ. Mining & Tech. 43(4), 612–618. (in Chinese with English abstract)

738 Lu, J., Yang, M.F., Sun, X.Y., Shao, L.Y., Zhang, F.H., 2018. Jurassic coal maceral and
 739 deposition rate of peat in the northern Qaidam Basin. J. Mining Sci. Technol. 3(1), 1–
 740 8. (in Chinese with English abstract)

741 Lücke, A., Helle, G., Schleser, G.H., Figueiral, I., Mosbrugger, V., Jones, T.P., Rowe, N.P., 1999.
 742 Environmental history of the German Lower Rhine Embayment during the Middle
 743 Miocene as reflected by carbon isotopes in brown coal. Palaeogeog., Palaeoclimatol.,
 744 Palaeoecol. 154, 339–352.

745 McCabe, P.J., 1984. Depositional environments of coal and coal-bearing strata, In:
 746 Rahmani, R.A., and Flores, R.M., (Eds.), Sedimentology of Coal and Coal-bearing
 747 Sequences: International Association of Sedimentologists Special Publication 7, 13–
 748 42.

749 McCabe, P.J., 1987. Facies studies of coal and coal-bearing strata, In: Scott, A.C., (Ed.),
 750 Coal and coal-bearing strata: Recent advances. Geol. Soc. Lond. Spec. Pub. 32, 51–
 751 66.

752 McCarthy, T.S., McIver, J.R., Cairncross, B., Ellery, W.N., Ellery, K., 1989. The inorganic
 753 chemistry of peat from the Maunachira channel-swamp system, Okavango Delta,
 754 Botswana. Geochim. Cosmochim. Acta 53, 1077–1089.

755 Monti, A., Amaducci, M.T., Pritoni, G., Venturi, G., 2006. Variation in carbon isotope
 756 discrimination during growth and at different organs in sugar beet (*Beta vulgaris*
 757 L.). Field Crops Res. 98 (2-3), 157–163.

758 Moore, T.A., Shearer, J.C., Miller, S.L., 1996. Fungal origin of oxidized plant material in the
 759 Palangkaraya peat deposit, Kalimantan Tengah, Indonesia: implications for
 760 ‘inertinite’ formation in coal. Int. J. Coal Geol. 30, 1–23.

761 Murray, A.P., Edwards, D., Hope, J.M., Boreham, C.J., Booth, W.E., Alexander, R.A.,
 762 Summons, R.E., 1998. Carbon isotope biogeochemistry of plant resins and derived

- hydrocarbons. *Organic Geochem.* 29, 1199–1214.
- O'Dogherty, L.O., Sandoval, J., Bartolini, A., Bruchez, S., Bill, M., Guex, J., 2006. Carbon-isotope stratigraphy and ammonite faunal turnover for the Middle Jurassic in the Southern Iberian palaeomargin. *Palaeogeog., Palaeoclimatol., Palaeoecol.* 239, 311–333.
- Pickel, W., Kus, J., Flores, D., Kalaizidis, S., Christanis, K., Cardott, B.J., Misch-Kennan, M., Rodrigues, S., Hentschel, A., Hamor-Vido, M., Crosdale, P., Wagner, N., ICCP, 2017. Classification of liptinite—ICCP System 1994. *Int. J. Coal Geol.* 169, 40–61.
- Ren, S.J., Yu, G.R., 2011. Carbon isotope composition ($\delta^{13}\text{C}$) of C3 plants and water use efficiency in China. *Chinese J. Plant Ecol.* 35(2), 119–124 (in Chinese with English abstract).
- Riding, J.B., Walton, W., Shaw, D., 1991. Toarcian to Bathonian (Jurassic) palynology of the Inner Hebrides, Northwest Scotland. *Palynology* 15, 115–179.
- Ritts, B.D., 1998. Mesozoic tectonic and sedimentation, and petroleum systems of the Qaidam and Tarim Basins, NW China: Ph.D. thesis, Stanford University, Stanford, California, 53–500.
- Ritts, B.D., Biffi, U., 2001. Mesozoic northeast Qaidam basin: response to contractional reactivation of the Qilian Shan, and implications for the extent of Mesozoic intracontinental deformation in central Asia. *Mem. Geol. Soc. Am.* 194, 293–316.
- Royer, D.L., Hickey, L.J., Wing, S.L., 2003. Ecological conservatism in the 'living fossil' *Ginkgo*. *Paleobiology* 29, 84–104.
- Ruebsam, W., Müller, T., Kovács, J., Pálfi, J., Schwark, L., 2018. Environmental response to the early Toarcian carbon cycle climate perturbations in the northeastern part of the West Tethys shelf. *Gondwana Res.* 59, 144–158.
- Smith, B.N., Gould, K.W., Rigby, D., 1982. Tree cellulose $^{13}\text{C}/^{12}\text{C}$ isotope geochemistry of Australian coals. *Organic Geochem.* 3, 111–131.
- Sobel, E.R., 1995. Basin analysis and apatite thermochronology of the Jurassic-Paleogene Western Tarim Basin: Ph.D. thesis, Stanford University, Stanford, California, 10–308.
- Song, J., Li, R.H., Zhu, S.D., Ye, Q., 2013. Leaf functional traits of ferns from different habitats in monsoon evergreen broad-leaved forest in Dinghushan Mountain. *J. Tropical Subtropical Bot.* 21(6), 489–495 (in Chinese with English abstract).
- Staub, J.R., 1991. Comparisons of central Appalachian Carboniferous coal beds by benches and a raised Holocene peat deposit. *Int. J. Coal Geol.* 18, 45–69.

- 796 Staub, J.R., 2002. Marine flooding events and coal bed sequence architecture in southern
797 West Virginia. *Int. J. Coal Geol.* 49, 123–145.
- 798 Sun, B.N., Dilcher, D.L., Beerling, D.J., Zhang, C.J., Yan, D.F., Kowalski, E., 2003. Variation in
799 *Ginkgo biloba* L. leaf characters across a climatic gradient in China. *PNAS* 100,
800 7141–7146.
- 801 Sun, B.N., Xiao, L., Xie, S.P., Deng, S.H., Wang, Y.D., Jia, H., Susan, T., 2007. Quantitative
802 analysis of paleoatmospheric CO₂ level based on stomatal characters of fossil
803 *Ginkgo* from Jurassic to Cretaceous in China. *Acta Geol. Sinica (English edition)*
804 81(6), 931–939.
- 805 Taylor, G.H., Teichmüller, M., Davies, A., Diessel, C., Littke, R., Robert, P., 1998. Organic
806 Petrology. Gebrüder Borntraeger, Berlin (704 pp.).
- 807 Vakhrameyev, V.A., 1982. Classopollis pollen as an indicator of Jurassic and Cretaceous
808 climate. *Internat. Geology Rev.* 24(10), 1190–1196
- 809 Wagner, F., Below, R., de Klerk, P., Dilcher, D.L., Joosten, H., Kürschner, W.M., Visscher, H.,
810 1996. A natural experiment on plant acclimation: Lifetime stomatal frequency
811 response of an individual tree to annual atmospheric CO₂ increase. *PNAS* 93,
812 11705–11708.
- 813 Wang, Y.D., Mosbrugger, V., Zhang, H., 2005. Early to Middle Jurassic vegetation and
814 climatic events in the Qaidam Basin, Northwest China. *Palaeogeog., Palaeoclimatol.,*
815 *Palaeoecol.* 224, 200–216.
- 816 Ward, C.R., Swaine, D.J., 1995. Minerals and inorganic constituents. In: *Geology of*
817 *Australian Coal Basins* (Eds C.R. Ward, H.J. Harrington, C.W. Mallett and J.W.
818 Beeston), 1, pp. 93–109. Special Publication, Geological Society of Australia Coal
819 Geology Group, Sydney.
- 820 Werth, M., Mehlreter, K., Briones, O., Kazda, M., 2015. Stable carbon nitrogen isotope
821 compositions change with leaf age in two mangrove ferns. *Flora* 210, 80–86.
- 822 Whitticar, M.J., 1996. Stable isotope geochemistry of coals, humic kerogens and related
823 natural gases. *Int. J. Coal Geol.* 32, 191–215.
- 824 Wiggan, N.J., Riding, J.B., Franz, M., 2017. Resolving the Middle Jurassic dinoflagellate
825 radiation: the palynology of the Bajocian of Swabia, Southwest Germany. *Rev.*
826 *Palaeobot. Palynol.* 238, 55–87.
- 827 Wiggan, N.J., Riding, J.B., Fransome, R.A., M., Emanuela, M., 2018. The Bajocian (Middle
828 Jurassic): A key interval in the early Mesozoic phytoplankton radiation. *Earth-Sci.*

829 Rev. 180, 126-146.

830 Willis, K.J., McElwain, J.C., 2002. The Evolution of Plants. Oxford University Press, New
831 York, 107–110.

832 Woodward, F.I., 1987. Stomatal numbers are sensitive to increases in CO₂ from pre-
833 industrial levels. *Nature* 327, 617–618.

834 Wu, J.Y., Ding, S.T., Li, Q.J., Sun, B.N., Wang, Y.D., 2016. Reconstructing paleoatmospheric
835 CO₂ levels based on fossil *Ginkgoites* from the Upper Triassic and Middle Jurassic in
836 Northwest China. *Paleontologische Zeitschrift* 90, 377–387.

837 Xiao, L., Qi, Y.L., Ma, W.Z., Li, X.C., Guo, J.F., Sun, N., Yao, X.Y., 2017. Stable carbon isotope of
838 Middle Jurassic plant fossils in the north edge of Turpan-Hami Basin, Xinjiang and
839 their palaeoenvironmental Implications. *Acta Sedimentologica Sinica* 35(3), 489–
840 498 (in Chinese with English abstract).

841 Xie, S.P., Sun, B.N., Yan, D.F., Xiao, L., Wei, L.J., 2006. Leaf cuticular characters of *Ginkgo*
842 and implications for paleoatmospheric CO₂ in the Jurassic. *Progress in Nat. Sci.*
843 16(S), 258–263.

844 Yan, D.F., Sun, B.N., Xie, S.P., Li, X.C., Wen, W.W., 2009. Response to paleoatmospheric CO₂
845 concentration of *Solenites vimineus* (Phillips) Harris (*Ginkgophyta*) from the Middle
846 Jurassic of the Yaojie Basin, Gansu Province, China. *Science in China D: Earth Sci.*
847 52(12), 2029–2039.

848 Yang, Y.T., Guo, Z.X., Luo, Y.J., 2017. Middle-late Jurassic tectonostratigraphic evolution of
849 Central Asia, implications for the collision of the Karakoram-Lhasa Block with Asia.
850 *Earth-Sci. Rev.* 166, 83-110.

851 Yiotis, C., Evans-Fitz.Gerald, C., McElwain, J.C., 2017. Differences in the photosynthetic
852 plasticity of ferns and *Ginkgo* grown in experimentally controlled low O₂:CO₂
853 atmospheres may explain their contrasting ecological fate across the Triassic-
854 Jurassic mass extinction boundary. *Ann. Bot.* 119, 1385–1395.

855 Yu, L., Xiao, A.C., Wu, L., Tian, Y.T., Rittner, M., Lou, Q.Q., Pan, X.T., 2017. Provenance
856 evolution of the Jurassic northern Qaidam Basin (West China) and its geological
857 implications: evidence from detrital zircon geochronology. *Int. J. Earth Sci.* 106,
858 2713–2726.

859 Zhang, H., Li, H.T., Xiong, C.W., Zhang, H., Wang, Y.D., He, Z.L., Lin, G.M., Sun, B.N., 1998.
860 Jurassic Coal-bearing Strata and Coal Accumulation in Northwest China. Geological
861 Publishing House, Beijing (in Chinese with English summary).

Figure and table captions

Fig. 1. Location and geology maps of the study area in the Northern Qaidam Basin. (A) Palaeogeographical map showing position of Northern Qaidam Basin in boxed area (simplified from R. Blakey's maps: <http://cpgeosystems.com>). (B) Location and tectonic divisions of the Northern Qaidam Basin and with boxed area enlarged in C (after Dai et al., 2003). (C) Geological map of the Yuqia area. Abbreviations: Q-Quaternary; N-Palaeogene; E-Neogene; J3-Upper Jurassic Hongshuigou Formation and Caishiling Formation; J2s-Middle Jurassic Shimengou Formation; J2d-Middle Jurassic Dameigou Formation; C2z-Pennsylvanian Zhongwunongshan Group; $\gamma\delta 4$ -Lower Palaeozoic granodiorite; $\Sigma 3$ -Lower Palaeozoic ultrabasic rocks; O3tj-Upper Ordovician Tanjianshan Group; Pt1dk-Proterozoic Dakendaba Group.

Fig. 2. Development and chronostratigraphic correlation of the Jurassic coal-bearing strata in the Qaidam Basin (modified from Li et al., 1988; Zhang et al., 1998; Ritts, 1998; Wang et al., 2005). Detrital Zircon U-Pb dating in Ma (million years) is from Yu et al. (2017) and Yang et al. (2017). Thermochronologic data and tectonic events are from Delville et al. (2001), Jolivet et al. (2001), and Gehrels et al. (2011). Abbreviations: TCZ=*Thaumatopteris-Cycadocarpidium* Assemblage; CAZ=*Cladophlebis* Acme Zone; CIZ=*Coniopteris* Initial Appearance; COAZ=*Coniopteris* Acme Zone; UNZ=Unnamed Plant Assemblage Zone; CDC=*Cyathidites-Dictyophyllidites-Cycadopites* Assemblage; CCQ/C=*Cyathidites-Cycadopites-Quadraeculina/Classopollis* Assemblage; MNP=*Cyathidites minor-Neoraistrickia-Piceapollenites* Assemblage; CCC=*Cyathidites-Callialasporites-Classopollis* Assemblage; CCP=*Classopollis-Cyathidites-Pinuspollenites* Assemblage

Fig. 3. Possible correlation between coal thickness and peat depositional time based on the peat compaction (blue arrow) and carbon accumulate rate (green arrow). The compression ratios of bituminous coal, sandstone and mudstone are from Johnson (1984) and McCabe (1984). Peat depositional time is based on Diessel (2007) and Lu et al. (2018).

Fig. 4. Carbon isotopic composition ($\delta^{13}\text{C}_{\text{coal}}$ in ‰) and quantitative palynology record from the Yuqia coal. Red arrows represent the significant Carbon isotope excursions. $\Delta\delta^{13}\text{C}_{\text{coal}}$ is given as $\delta^{13}\text{C}_{\text{coal}}$ minus the respective unit (i.e. E, F) average. GR= gamma ray log; Rt=resistivity log.

Fig. 5. Carbon isotopic composition ($\delta^{13}\text{C}_{\text{coal}}$ in ‰) and petrography record from the Yuqia coal. Red arrows represent the significant Carbon isotope excursions. $\Delta\delta^{13}\text{C}_{\text{coal}}$ is given as $\delta^{13}\text{C}_{\text{coal}}$ minus the respective unit (i.e. E, F) average. GR= gamma ray log; Rt=resistivity log.

Fig. 6. Macerals and mineral matters in coal under the optical microscope (reflected white light). (A) and (B) Telinite (cell walls) and clay (cell interiors). (C) Collotelinite. (D) Collodetrinite. (E) Thickened cell walls in fusinite. (F) and (I) Semifusinite with cell structure. (G) and (H) Semifusinite. (J) Rounded to oval macrinite. (K) Clay. (L) Pyrite.

Fig. 7. Statistical box plot of carbon isotope values from gymnosperms, ferns and coals. The green, red and grey box plots for Qaidam Basin represent the median (white line), first and third quartiles (ends of boxes), and minima and maxima (horizontal lines). Black pentagon=maximum value, black square=arithmetic mean value, black circle=minimum value, a and d =plants living in Middle Jurassic (M. Jur.), b and c=modern plants. × represents the estimated $\delta^{13}\text{C}_{\text{P}}$ values from ferns (Middle Jurassic) according to Farquhar et al. (1982; 1989) and Beerling et al. (2002).

Fig. 8. Cross plots including conjoint sampling of palynological group counts, maceral composition and carbon isotope values, and correlation analysis including R-squared values and T-test for these plots.

Fig. 9. Global marine and terrestrial paleoclimate through Bajocian with tentative correlation to the terrestrial succession in the Northern Qaidam Basin from the present study. Carbon and

oxygen isotope ratios of calcareous fossils from Korte et al. (2015). Carbon isotope data of marine carbonates from Bartolini et al. (1999) and O'Dogherty et al. (2006). pCO₂ concentration for the same period derived from Xie et al. (2006), Sun et al. (2007), and Yan et al. (2009). Carbon isotope data of organic materials from Yaojie Basin from Yan et al. (2009). Carbon isotope data of fossil wood and bulk organic matter from Ravenscar group (Yorkshire, NE England) from Hesselbo et al. (2003). Ammonite data derived from O'Dogherty et al. (2006). Abbreviations: Laeviu=*Laeviuscula*, Propin=*Propinquans*, Humph=*Humphriesianum*, Niorten=*Niortense*, Garan=*Garantiana*, Parkin=*Parkinsoni*.

Table 1. Carbon isotope, quantitative palynology, and petrography data from the Yuqia coal.

Abbreviations: Vitrin=vitrinite, Inert=inertinite, Lip=liptinite, Min=mineral, Delto=*Deltoidospora*, Cyath=*Cyathidites*, Dicty=*Dictyophyllidites*, Duple=*Duplexisporites*, Psoph=*Psophosphaera*, Cycad=*Cycadopites*, Chasm=*Chasmatosporites*, Picea=*Piceapollenites*, Quadrae=*Quadraeculina*, Eucom=*Eucommiidites*, Classo=*Classopollis*. Ro_{max}=maximal vitrinite reflectance.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

Fig. 9.

Table 1

Coal	Depth (m)	δ ¹³ C (‰)	Δδ ¹³ C (‰)	Coal petrology (%)				R _{Omax}	Ferns (%)				Gymnosperms (%)						
				Vitrin	Inert	Lip	Min		Delto	Cyath	Dicty	Duple	Psoph	Cycad	Chasm	Picea	Quadrae	Eucom	Classo
F coal	179.25								1.51	45.21	4.43	0.49	10.1	2.5	5.11	4.6	2.11	2.12	0
	179.5	-24.6	-0.6	54.1	29.84	0.65	15.19												
	179.75	-24.1	-0.1	39.33	42.44	0.41	16.44	0.49	1.82	59.98	7.66	0.92	6.9	1.97	6.43	2.31	2.12	2.07	0.9
	180	-24.3	-0.3	28.2	60.29	0.98	9.91												
	180.25	-24.7	-0.7	23.21	63.42	0.59	12.03												
	180.5	-24.3	-0.3	24.79	64.91	4.58	4.94												
	180.75	-24.6	-0.6	19.31	67.94	0.88	11.26	0.47	1.79	70.43	10.2	0	2.16	0.98	5.98	0	2.13	1.02	0
	181	-24.4	-0.4	21.62	67.05	0.64	10.51												
	181.25	-24.8	-0.8	5.85	83.03	0.5	10.41												
	181.5	-24.8	-0.8	15.85	71.95	2.73	6.26												
	181.75	-24.8	-0.8	15.45	78.77	0.32	4.75	0.43	1.51	54.79	6.53	4.31	4.53	2.89	8.78	0.09	2.08	0.98	0
	182	-25.2	-1.2	22.13	34.6	1.05	32.76												
	182.25	-24.2	-0.2	51.34	34.23	3.97	9.28												
	182.5	-24.2	-0.2	53.34	30.59	1.98	14		2.08	40.17	5.01	5.99	5.33	6.21	11.29	0	3.21	0.89	1.01
	182.75	-23.2	0.8	52.71	17.92	0.91	24.84												
	183	-23.5	0.5	33.61	50.06	1.67	14.62	0.51											
	183.25	-23.2	0.8	24.95	57.3	0.84	15.94												
	183.5	-23.6	0.4	19.27	70.21	0.29	10.02		1.97	28.02	2.01	8	7.12	10.11	13.12	0.32	3.43	1.69	2.45
	183.75	-23.3	0.7	15.87	73.28	0.28	10.51	0.51											
	184	-23.5	0.5	16.7	70.07	0.6	9.11												
	184.25	-23.9	0.1	19.16	72.29	2.79	4.82		1.99	37.16	6.04	6.02	8.31	11.56	11.63	1.29	4.13	2.39	3.01
	184.5	-23.7	0.3	18.14	71.44	1.79	8.1												
	184.75	-23.7	0.3	19.17	60.2	2.24	16.46	0.64											
	185	-24	0	25.87	60.1	3.21	9.98												
	185.25	-23.9	0.1	17.97	72.45	1.36	7.33												
	185.5	-23.5	0.5	22.09	62.25	1.26	13.63	0.45											

[illegible]

216.33	-24.8	-0.81	65.57	17.12	4.3	9.87												
216.58	-25.1	-1.11	70.19	19.14	2.08	4.39												
216.83	-24.6	-0.61	79.32	16.56	2.37	1.74		1.89	46.2	4.12	0	1.09	14.07	9.21	0	2.08	3.54	4.43
217.08	-24.6	-0.61	63.98	31.42	1.46	2.39	0.8											
217.33	-25.1	-1.11	71.7	8.15	2.39	1.58												
217.58	-24.7	-0.71	50.17	44.39	3.06	2.28												
217.83	-23.6	0.39	59.29	36.54	2.8	1.25	0.76											
218.08	-22.9	1.09	24.12	69.13	2.81	3.42												
218.33	-23.2	0.79	21.73	71.15	4.05	2.9		4.17	28.34	3.41	0	4.56	15.76	11.42	0	4.81	4.67	4.51
218.58	-23.2	0.79	23.87	68.7	0.74	3.25												
218.83	-23.3	0.69	52.29	41.53	1.68	1.33												
219.08	-23.6	0.39	68.08	27.57	1.94	2.28												
219.33	-23.8	0.19	53.54	43.41	1.19	1.85												
219.58	-23.6	0.39	49.55	44.67	2.93	2.77	0.79											
219.83	-23.5	0.49	68.07	27.98	1.37	2.12		5.12	35.17	4.05	0	2.13	10.79	11.94	0	4.53	3.99	8.73
220.08	-23.2	0.79	32.89	60.1	1.21	2.11												
220.33	-23.5	0.49	25.81	70.02	0	2.44												
220.58	-23.1	0.89	65.83	30.16	0	1.98	0.81											
220.83	-22.8	1.19	39.99	55.03	2.57	1.96												
221.08	-23.2	0.79	41.37	51.97	2.7	1.68		5.89	39.77	4.07	0.01	2.11	8.18	12.14	1.01	4.76	2.98	13.01
221.33	-22.5	1.49	67.76	25.58	4.86	1.35												
221.58	-22.7	1.29	60.37	35.23	1.72	1.95												
221.83	-23	0.99	56.88	35.11	2.11	2.01												
222.08	-22.7	1.29	39.99	53.2	4.08	2.67	0.83											
222.33	-22.5	1.49	82.89	7.94	1.41	4.6												
222.58	-23.1	0.89	71.88	21.77	2.69	3.28		6.88	34.35	4.17	0.02	1.24	8.31	12.45	2.37	4.55	1.02	20.23
222.83	-22.7	1.29	48.63	39.87	3.11	6.89												
223.08	-22.6	1.39	43.57	43.41	5.08	4.6												
223.33	-22.6	1.39	39.99	51.93	6.55	1.06												
223.58	-23.1	0.89	48.24	43.83	5.32	1.7												
223.83	-22.7	1.29	58.01	21.98	2.61	1.32		8.01	34.23	4.09	2.11	3.54	10.89	6.13	1.11	3.34	1	19.21

224.08	-23.5	0.49	77.72	7.31	5.02	9.4	
224.33	-23.4	0.59	29.63	29.48	4.08	31.13	0.74