Prof. Hugues Goosse

Editor

Climate of the Past

November 18, 2015

Dear Prof. Goosse,

Responses to reviewers' comments

We would like to thank you for your time, efforts, and encouragement as well as three reviewers Drs. Licht, Rolf, and Jovane for their insightful and constructive comments that are very helpful for improving the manuscript. We have addressed all the reviewers' comments in the revision and believe that the revised manuscript has become a much better paper. Hope you would be pleased to see the improvements we have made for this paper. Below are our point-by-point responses (in blue) to reviewers' comments.

Best regards,

Sincerely,

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On behalf of all coauthors

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1. Dr. Licht's comments

The paper provides interesting new paleomagnetic data from the Maoming Basin, China, to locate the stratigraphic interval of the critical Eocene-Oligocene Transition (EOT). I must first say that I am sympathetic with the effort made by the authors to identify and study the EOT in the East Asian sedimentary record, because this event is virtually undocumented in continental Southeast Asia and is particularly critical to understand the impact of Eocene Greenhouse conditions on the proto-monsoons. Accordingly, the topic of this paper is potentially suitable for CotP. However, I think that the manuscript still needs a fair amount of work to make it ready for publication. First, many important details about the sedimentology and the biostratigraphy of the localities are lacking. I acknowledge that a big part of this initial work seems to have been previously published in Chinese journals, but this work is not available for the common, non-Chinese reader and needs to be synthesized and summarized (at least in the introduction of the paper). Moreover, this paper has some critical issues with specific scientific points that significantly weaken their paleomagnetic correlations and I am not sure that there is the potential for the authors to address these concerns by reorganizing their arguments or providing more data.

We thank Dr. Licht for his helpful comments and encouragement, and we are grateful for his time, efforts, and suggestions. Dr. Licht has two major comments: 1) many important details about sedimentology and the biostratigraphy are lacking; 2) paleomagnetic correlations are weakened by some specific scientific points.

For the first comment, we have provided a synthesis of sedimentology of Maoming Basin focusing on the Youganwo Fm and the Huangniuling Fm in Section 2 of the revision. In addition, more sedimentologic details of the investigated section of the Youganwo Fm and the Huangniuling Fm are added in Section 4.1 of the revision to further substantiate the basis for the interpretations of paleoenvironmental changes in Maoming Basin. For biostratigraphy, the age of the Youganwo oil shale is defined in the revision based on the comprehensive age analysis of fossil mammal *Lunania* in Section 2. For the second comment, with the improved sedimentologic and biostratigraphic controls, paleomagnetic correlations in Section 5.3 are further strengthened. Below are our responses to each comment.

1. Sedimentological interpretations

The main -and critical- sedimentary change in the studied section is a shift from lacustrine to deltaic conditions, eventually attributed to the EOT. But the sedimentological part of the paper is very weak, and most of the sedimentary interpretations are referred to a Chinese MS thesis. The results of this previous study must be synthesized, with a clear explanation of the different lithofacies / architectural units that are found in the basin. Among the questions that remain unanswered:

1) What is the environmental interpretation of the different facies that are described

by the authors? "lacustrine" and "deltaic" are too vague and do not qualify facies. For instance, how are the "massive sandstone" beds of the Haungniuling Fm interpreted? Are those channel body, mouth bar, or delta front deposits? What is their lateral extent?

We appreciate this comment. The majority of the Youganwo Fm is interpreted to be profundal facies and only the uppermost part of the Youganwo Fm represents shallow lake deposits (Guo, 2006). The massive sandstone beds at the base of the Huangniuling Fm extend hundreds of meters laterally with uniform thickness in the open mine pit. Based on the nature of gradual transition at the interface between the Youganwo Fm and the Huangniuling Fm, the massive sandstone may be deposited in prodelta to delta front environment when lake level dropped.

2) How do the authors interpret their "parasequences" in terms of deltaic environment? note that fining-upward sequences as they are described in the paper are not very common in deltaic setting. The few information provided in this paper would rather suggest sequences made of stacked channel bodies, and thus a fluvial environment.

Because the sandstone and mudstone beds in a parasequence are nearly flat and extend laterally for hundreds of meters in the lower part of the Huangniuling Fm, the fining-upward trend within a parasequence and the repeated occurrence of the parasequence may suggest that they were deposited in an interdistributary bay environment or a prodelta environment with fluctuating lake levels. In the upper part of the Huangniuling Fm, lense-shape channels are occasionally observed, suggesting that delta plain deposits gradually became dominant in the upper section.

3) the authors described a colored mudstone layer at the interface between both Paleogene units. Could it be a paleosol? If so, that would significantly change their paleomagnetic correlation; if not, what is it?

The interface between the two units shows a gradual transition. The light brown oil shale at the uppermost of the Youganwo Fm gradually gives rise to a pale grey mudstone layer that is capped by siltstone and sandstones, displaying a coarsening upward trend of grain sizes. This gradual transition indicates that lake level gradually dropped. The pale grey mudstone layer may represent lacustrine deposition and/or muddy prodelta deposition, and the coarsening upward of siltstone and sandstone could represent a transition from prodelta to delta front environment. Also, there is no evidence of subaerial exposure for this interval. So it is not a paleosol.

4) Whatever is the origin of the "parasequences" in the Haungniuling Fm (fluvial or deltaic), channel / delta mouth migration is not necessarily controlled by orbital forcing. Avulsions /migrations can be endogenic as well. Orbital forcing must be shown, for example by proving that parasequences alternate with a regular period

that corresponds to one of the Milankovitch periods. But there is no data about the frequency of parasequences in the Haungniuling Fm, neither a clear log of the unit.

While channel/delta mouth migration may produce “delta cycles”, each of these cycles would tend to show a coarsening-up delta-lobe succession (Nichols, 2009). As mentioned above, a parasequence consists of a fining-up succession and the formation of parasequences may be associated with lake level fluctuation, which could be forced by orbital variations. Also, orbital forcing could take place via different feedbacks. This notion of orbital forcing is supported by the persistent pattern of rhythmic occurrence of the parasequences. This notion is also strengthened by the demonstrated orbital forcing of the deposition in marine (e.g., the Eocene/Oligocene boundary GSSP section in Italy, Jovane et al., 2006) and lacustrine (e.g., the Green River Fm, Meyers, 2008) settings during the similar time interval.

We agree that it is the best to determine the period represented by a paraseuqence and then compare this period with Milankovitch periods. To determine the period of a parasequence, one needs to know at least two numerical ages bracketing the parasequence. But even the age of the Huangniuling Fm remains controversial and we are not aware of any numerical ages available from the Huangniuling Fm that can be used for such a calculation. In fact, one purpose of this study is to establish a refined chronostratigraphic framework for the Huangniuling Fm.

Nichols, G. Sedimentology and stratigraphy. Second Edition, Wiley-Blackwell. 2009.
Jovane, L., F. Florindo, M. Sprovieri, and H. Pälike: Astronomic calibration of the late Eocene/early Oligocene Massignano section (central Italy), Geochem. Geophys. Geosyst. 7, Q07012, doi:10.1029/2005GC001195, 2006.
Meyers, S.R.: Resolving Milankovitchian controversies: The Triassic Latemar Limestone and the Eocene Green River Formation. Geology 36, 319–322, doi: 10.1130/G24423A.1, 2008.

2. Weaknesses of the paleomag correlation

The chronostratigraphic correlation proposed in this paper is based on several assumptions that are not very well addressed and should be discussed in more details.

1) The authors claim a "late Eocene" age (what is their definition of "late" Eocene? Upper Eocene?) based on one fossil mammal: Lunania youngi. I cannot read the original papers relating this discovery (in Chinese), but Russell and Zhai attributed this taxa to the Middle and Upper Eocene of China in their anthology of 1984 ("The Paleogene of Asia"). Note that Lunania are still poorly described and understood (Remy et al., 2005, CR Palevol), as well as their exact stratigraphic range. Moreover, the study of pollens from the Maoming Basin by Aleksandrova et al (2014, Stratigraphy and geological correlation) attributed the Youganwo Fm to the Lutetian / Bartonian and the Haungniuling Fm to the Priabonian. It thus

appears to me that the biostratigraphic context contradicts the authors' correlation.

The late Eocene age is defined as including the Bartonian to Priabonian stages based on the analysis of fossil mammal Lunania in Section 2 of the revision. Although the systematic position of the genus Lunania is still not well understood, increasing evidence appears to point its age at Bartonian to Priabonian. To date, two species in total were reported: *Lunania zhoui* from the Yuanqu Basin of central China (Huang, 2002), and *Lunania youngi* from Yunnan (Chow, 1957; Zong et al., 1996) and Maoming (Wang et al., 2007) of southern China, respectively. *Lunania zhoui* was collected from the Hedi Fm (Huang, 2002). Plenty of fossil mammals were found from this formation, i.e. the Yuanqu Fauna. According to the latest study on land mammals, the geological age of this fauna is regarded to be no earlier than Bartonian and no later than Priabonian (Tong et al., 2005, p.111). This is highly consistent with our assumption that the Youganwo Fm with *Lunania* fossils in Maoming Basin was largely deposited during the Bartonian to Priabonian.

For the *Lunania youngi* from Yunnan, fossils were collected from the Xiangshan Fm of Lijiang Basin (Zong et al., 1996), and Lumeiyi and Caijiacong formations of Lunan Basin (Chow, 1957). According to Zong et al. (1996), the Lijiang Fauna is of the Sharamurunian age in the Asian Land Mammal Ages, largely spanning from the Bartonian to Priabonian (Li and Ting, 1983; Russell and Zhai, 1987; Wang, 1992; Qiu and Wang, 2007) or the Bartonian (Tong et al., 1995).

Fossil tapir assemblage from the Lumeiyi Fm suggests that its geological age is most probably the early Late Eocene (Huang and Qi, 1982, p.324), while the Caijiachong fauna is considered to be survived in the latest Eocene (Tong et al., 2005, p110-111; Wang, 1997, p.88).

Regarding the pollen study of Aleksandrova et al. (2015), the ages for the Youganwo Fm and the Huangniuling Fm were based on comparison of their pollen data with pollen assemblages from southern China. However, the ages of most of pollen assemblages in southern China, to which they compared their pollen data, are poorly constrained and are loosely attributed to late Eocene to early Oligocene (Song et al., 1999). Also, pollen results by other authors reported rather different ages for the Youganwo Fm. The pollen study of Yu and Wu (1983, p.115-116) concluded an early Oligocene age for the Youganwo Fm, whereas the pollen study of Li et al. (2006, p.939-940) preferred the late Eocene age for this formation. Despite the fact that the neither of the two studies concluded a middle Eocene age for the Youganwo Fm, Aleksandrova et al. (2015) cited these two studies as evidence for "middle Eocene-early Oligocene" age, which we found is troubling. Below is the quote from Aleksandrova et al (2015):

> "The Youganwo Formation was considered to be the middle Eocene–early Oligocene in age on the basis of palynological data (Yu and Wu, 1983; Li et al.,

2006) or late Eocene in age on the basis of mammal *Lunania* cf. *youngi* remains (Wang et al., 2007; Jin, 2008)"

Nevertheless, pollen data appear to give a rather wide range of age estimates. It is generally accepted that fauna data provide better age constraints than pollen data. As mentioned above, a number of studies consistently constrain the age of Lunania to the Bartonian to Priabonian. A review of fossil data from the Youganwo Fm also shows that NONE of the reptile, fish, and mammal fossils indicates a middle Eocene age (Jin, 2008).

Given the large age uncertainty of pollen data and the fact that mammal fossils usually provide tighter age constraint than pollen data, Aleksandrova et al. (2015)'s biostratigraphic assignment does not necessarily contradict with our assumption of Bartonian to Priabonian age for the investigated, mammal fossil-bearing Youganwo Fm. Our assumption for the age of the sampled Youganwo Fm (Bartonian to Priabonian) is supported by the available paleontological data from Maoming Basin (Jin, 2008; Wang et al., 2007).

References (all of the Chinese literatures have English summary):

Aleksandrova G.N., Kodrul T.M, Jin J.H. 2015. Palynological and paleobotanical investigations of Paleogene sections in the Maoming basin, South China. Stratigraphy and Geological Correlation, 2015, 23: 300-325.

Chow M.C., 1957. On some Eocene and Oligocene mammals from Kwangsi and Yunnan. Verterbrata PalAsiatica, 1(3): 201-214 (in Chinese with English summary).

Huang X.S., 2002. New emoropid (Mammalia, Perissodactyla) remains from the middle Eocene of Yuanqu Basin. Verterbrata PalAsiatica, 40(4): 286-290 (in Chinese with English summary).

Jin J., 2008. On the age of the Youganwo formation in the Maoming Basin, Guangdong Province. Journal of Stratigraphy, 32:47-50 (in Chinese with English summary).

Li C., Ting S., 1983. The Paleogene mammals of China. Bull. Bulletin of Carnegie Museum of Natural History, 21: 1-93 (in Chinese with English summary).

Qiu Z.X., Wang B., 2007. Paracerathere fossils of China. Palaeontoligca Sinica, New Ser. C, 29: 1-188 (in Chinese with English summary)

Russell D.E., Zhai R.J., 1987. The Paleogene of Asia: mammals and stratigraphy. Memoires du Museum National d'Histioire Naturelle, 52: 1-490.

Song, Z.C., Zheng, Y.H., Li, M., Zhang, Y., Wang, W.M., Wang, D., Zhao, C.B., Zhou, S., Zhu, Z., and Zhao, Y., 1999. Fossil spores and pollen of China. Vol.1. Late Cretaceous and Tertiary Spores and Pollen: Beijing, Science Press, 910 (in Chinese with English summary).

Tong Y., Zheng S., Qiu Z., 1995. Cenozoic mammal ages of China. Verterbrata PalAsiatica, 33(4): 290-314 (in Chinese with English summary).

Tong Y.S., Li Q., Wang Y.Q., 2005. A brief introduction to recent advance in the

Paleogene studies. Journal of Stratigraphy, 29 (2): 109-1133 (in Chinese with English summary).
Wang B., 1992. The Chinese Oligocene: A preliminary review of mammalian localities and local faunas. In: Prothero D.R., Berggren W.A., eds. Eocene-Oligocene Climatic and Biotic Evolution. Princeton: Princeton University Press, 529-547 (in Chinese with English summary).
Wang B., 1997. Problems and recent advances in the division of the continental Oligocene. Verterbrata PalAsiatica, 21(2): 81-90 (in Chinese with English summary).
Wang Y.Y., Zhang Z.H., Jin J., 2007. Discovery of Eocene fossil mammal from Maoming Basin, Guangdong. Acta Scientiarum Naturalium Universitatis Sunyatseni, 46: 131-133 (in Chinese with English summary).
Zong G., 1996. Cenozoic Mammals and Environment of Hengduan Mountains Region. China Ocean Press, Beijing, 279 (in Chinese with English summary).

2) The authors argue that sedimentation rates in the Haungniuling Fm should be higher than in the Youganwo Fm because of "changes of lithology" and coarser grain-size. This assumption is clearly incorrect. Changes in lithology and grain-size increase can be caused by simple paleoenvironmental changes (lake level fall, for example) without any change of sedimentation rate.

We believe that this is an appropriate assumption in a general sense. Let us take sandstone and mudstone as an example to explain the reasoning behind this assumption. During deposition, clays generally take longer time than sands to get settled. Also, in the subsequent lithificational compaction stage, clay-rich sediments would have more volume loss than sand-rich sediments (sands act as skeletons and are thus less compactable than clays), and thus represent more condensed time interval. Therefore, for the same thickness of mudstone and sandstone, mudstones generally represent longer time than do sandstones, i.e., the sedimentation rate for mudstone is generally slower than that of sandstone. Because the Youganwo Fm is dominated by oil shale and the Huangniuling Fm is dominated by sandstone, it is reasonable to assume a faster sedimentation rate for the Huangniuling Fm than for the Youganwo Fm.

3) Finally, the authors argue that accumulation rates above 1.5 cm.kyr-1 are too high for oil shales. This is incorrect as well. In lacustrine context, accumulation rates can be up to 5-10 times higher. See, for example, the accumulation rates in Paleogene deposits of the Greenriver Basin, Wyoming. For all these reasons, it appears to me that almost all the other chronostratigraphic hypotheses introduced in the paper are as pertinent as the one that is eventually proposed. Actually, Hypothesis 1 (previously rejected) seems the most reliable, because it works with Aleksandrova et al’s pollen study and yields reasonable accumulation rate estimates.

It is true that sedimentation rates in a lacustrine environment are overall faster than in a marine setting. But sedimentation rates can vary widely among different types of lacustrine environment. For example, playa/evaporative lithofacies have higher sedimentation rates than profundal lithofacies (e.g., Smith et al., 2003). Even within a lacustrine environment, sedimentation rates at littoral zones are generally faster than at profundal zones. For the Paleogene deposits in Green River Basin, sedimentation rates also vary depending on the type of lacustrine environment and/or subfacies. For example, the Wilkins Peak member the Green River Fm contains playa lithofacies (e.g., Eugster and Surdam, 1973) and oil shale in this member is often sandwiched into calcareous siltstone and sandstone (e.g., Pietras et al., 2003). Because of the presence of siltstone and sandstone, the overall sedimentation rates of this member must be higher than for oil shale-only interval alone. Oil shale in the Youganwo Fm was formed in a semi-deep to deep lake environment (Guo, 2006) and the lithology of the investigated interval of the Youganwo Fm is monotonic, consisting of only oil shale. We use the well-dated organic rich black shale in the mid-Cretaceous as an analogue to constrain the sedimentation rates for the Youganwo Fm.

As to the correlation, multiple scenarios are possible due to the lack of an anchoring point. Our approach is to use all the known constraints jointly, not in isolation, to find the most viable correlation that can satisfy most, if not all, the known constraints. We analyzed six scenarios (Section 5.3, Table 1) and found that Ensemble 6 meets the criteria and thus is our preferred correlation.

Eugster, H.P. and Surdam, R.C., 1973. Depositional environment of the Green River Formation, Wyoming: A preliminary report. Geological Society of America Bulletin,84, 1115-1120.

Guo, M. 2006. Characteristics and mineralization controlling factors of oil shale in Maoming Basin. M.sc. Thesis, Jilin University, p 86.

Pietras, J.T. Carroll, A.R., Singer, B.S. Smith, M.E. 2003. 10 k.y. depositional cyclicity in the early Eocene: Stratigraphic and $^{40}Ar/^{39}Ar$ evidence from the lacustrine Green River Formation. Geology 31, 593–596.

Smith, M.E., Singer, B.S., and Carroll, A.R., 2003, $^{40}Ar/^{39}Ar$ geochronology of the Eocene Green River Formation, Wyoming: Geological Society of America Bulletin, 115, 549–565.

3. Paleoclimatic discussion

The paleoclimatic interpretation of the correlation proposed in the paper is virtually non-existent.

We appreciate this comment and we have elaborated on the paleoclimatic interpretation of the correlation in the revision (Section 5.4).

Among the questions that should be addressed:

1) How do the authors explain the shift from lacustrine to deltaic at the EOT? What does this mean for the hydrological cycle?

In terms of the implications for hydrological cycle, the shift in low-latitude Asia may represent a transition from humid to dry conditions in response to global cooling at EOT.

2) How to explain the impressive increase of accumulation rates at the EOT, if their correlation is right? -How does it compare with other records in East Asia?

As dry conditions prevailed, lake area may have shrunk. The increase in sedimentation rate is dictated by the depositional environment change from lacustrine environment to deltaic environment. Enhanced erosion of upland in the arid and cold conditions may have also contributed to the increase in sedimentation rates. Similar depositional environmental change and sedimentation rate increase between 34.5 and 31 Ma are observed in Xining Basin and the E/O climatic transition is also considered as a possible cause (Dai et al., 2006).

Dai, S., X. Fang, G. Dupont-Nivet, C. Song, J. Gao, W. Krijgsman, C. Langereis, and W. Zhang (2006), Magnetostratigraphy of Cenozoic sediments from the Xining Basin: Tectonic implications for the northeastern Tibetan Plateau, J. Geophys. Res., 111, B11102, doi:10.1029/2005JB004187.

3) What does the hypothetical eccentricity signal found in their section mean in terms of paleoclimate? How does it compare with other contemporaneous orbital record?

The recognition of eccentricity signal in Maoming Basin suggests that sedimentation in Maoming Basin during this time interval may have been modulated by orbital variations and the terrestrial responses in low-latitude Asia to the EOT may be superimposed on the long-term variations at orbital frequency. The long and short eccentricity signals are also detected from the Eocene/ Oligocene Massignano section, Italy (Jovane et al., 2006), which is the GSSP section for the Eocene/Oligocene boundary. The eccentricity signals are also found in other marine successions (e.g., Westerhold et al., 2014) and lacustrine deposits (e.g., Meyers, 2008; Okacoğlu et al., 2012) at the similar age.

Jovane, L., F. Florindo, M. Sprovieri, and H. Pälike: Astronomic calibration of the late Eocene/early Oligocene Massignano section (central Italy), Geochem. Geophys. Geosyst. 7, Q07012, doi:10.1029/2005GC001195, 2006.

Meyers, S.R.: Resolving Milankovitchian controversies: The Triassic Latemar Limestone and the Eocene Green River Formation. Geology 36, 319–322, doi: 10.1130/G24423A.1, 2008.

Ocakoğlu, F., Açıkalın, S., Yılmaz, I.Ö., Safak, Ü., and Gökçeoglu, C.: Evidence of orbital forcing in lake-level fluctuations in the Middle Eocene oil shale-bearing lacustrine successions in the Mudurnu-Göynük Basin, NW Anatolia (Turkey). Journal of Asian Earth Sciences 56, 54–71, 2012.

Westerhold, T, U. Röhl, H. Pälike, R. Wilkens, P. A. Wilson, and G. Acton: Orbitally tuned timescale and astronomical forcing in the middle Eocene to early Oligocene. Clim. Past, 10, 955–973, doi:10.5194/cp-10-955-2014, 2014.

4. Finally, a few additional comments:

1) The authors state that the magnetostratigraphy of the area was already study by Wang et al. (1994). They should clearly indicate what has been done in that study and where, and how it overlaps with their own work.

The locations of the study sites of Wang et al (1994) are marked in Fig. 1 and more details about Wang et al. (1994) are included in Section 2 of the revision.

2) Table 1 should be reorganized (It is unclear, too much infos in parentheses), Fig. 2 should be enlarged (and subfig 2d should be explained).

Table 1 has been re-organized in the revision. Fig. 2d is explained in the revision. As to the size of Fig. 2, the submitted Fig. 2 was large. The size of Fig. 2 was set by the CP copy-editing office.

3) The scientific English writing is for me comprehensible. I am not a native English speaker so I leave this to the discretion of the editor. I have noticed a few spelling mistakes, as well as unclear statements, suggesting that the manuscript should be proof-read by an English speaker. My feeling is that I am not sure that this manuscript can be saved, unless the authors succeed to clean their sedimentological interpretations and strengthen their correlation by additional biostratigraphic data.

The English language of the revision has been polished by a native English speaker to make it more readable than the initial version.

We hope you would be pleased to see the improvements that we have made for this paper.

2. Dr. Rolf's comments

In my review I will concentrate on the rock- and palaeomagnetic part. For the sedimentological and biostratigraphic part I am not a specialist but I feel the discussion stimulated by the comments of Prof. Licht and the future response by the authors will considerably improve the paper. This is true also about Prof. Licht's comments on the weakness of the palaeomagnetic correlation. The topic of the paper fits the framework of CotP. However, I am not fully convinced by the presented results, especially on the palaeomagnetic part of the paper. In this part the paper needs more work before it is ready for publication.

We thank Dr. Rolf for his constructive comments and we are very grateful for his time, efforts, and suggestions. Dr. Rolf's comments are mainly focused on the rock magnetic and paleomagnetic part of the manuscript. Dr. Rolf criticized that 1) our interpretations of rock magnetic data are not fully convincing; and 2) the description of correlations of magnetozones with the standard geologic polarity time scale (GPTS) is lengthy and is hard to follow.

In the revision, 1) we have provided additional rock magnetic data including more K-t curves, ZFC and FC low temperature measurements, and thermal demagnetization of composite IRM (Sections 3 and 4.2.2, and Fig. 5). These additional rock magnetic data provide further constraint on our interpretation of magnetic mineralogy (Section 4.2.2); 2) we have shortened the lengthy description of the correlations and presented the correlations in a more concise way (Section 5.3). Along this line, we have also re-organized Table 1. The revised Table 1 significantly improves the clarity of correlations (Table 1) and complements the description of correlations in Section 5.3. Below are our detailed responses to Dr. Rolf's comments.

The applied methods in palaeomagnetism are well described and fulfil modern standards. The thermal behaviour of susceptibility was only measured for two samples in the whole profile. In my opinion this should be enlarged by measuring many more samples to have a well-established rock magnetic profile. The described lithological units are not homogeneous enough to be thoroughly described by only two samples. I am sure that the authors have measured more K/T curves; did they all show the same behaviour?

We appreciate this comment. We have measured k-t curves of additional samples from both the Huangniuling mudstone (Fig. 5a,b) and the Youganwo oil shale (Fig. 5e). There is overall similarity among samples of the same lithology. For example, the Huagiuling mudstones show rapid increase in magnetic susceptibility (MS) between 450 and 500°C during heating (Fig. 5a,b), whereas all the oil shale samples show increases in MS starting at the similar temperature of around 250°C (Fig. 5d,e). For oil shale, the increase in MS at 250°C is more pronounced, diagnostic of hexagonal pyrrhotite, at some level (Fig. 5d) than at other levels, which may suggest varying abundance of hexagonal pyrrhotite in oil shale.

What is the reason for the repeated occurrence of sedimentary rhythms and why are they correlated to peaks in susceptibility? If the reddish colour represents weathering, is there some hematite formed colouring the beds? The fact that fresh exposure of the beds shows no reddish colour hints on a present event. Why did you not investigate the rock magnetic characteristic of these rhythmic occurring beds?

The reddish color likely represents recent weathering because fresh exposure of these beds does not show reddish color. Also, it is reasonable to believe that hematite may have been formed during weathering based on the facts that reddish color occurs and magnetic susceptibility values increase in these beds. Weathering may have enhanced the subtle changes in lithology by making them more distinctly visible. The repeated occurrence of sedimentary rhythms is intriguing and was probably related to fluctuating lake levels that can cause subtle changes in deposition, thus in lithology. We did not specifically investigate the rock magnetic properties of these reddish beds because, at the time of sampling, our primary goal was to collect fresh rock samples to obtain reliable paleomagnetic data for the magetostratigraphic study.

Remarks about the rock magnetic chapters

4. IRM for oil shale did not enter saturation before 800 mT. - The dominant magnetic minerals show coercivity around 40 mT. I am not at all convinced by your interpretation of Fig. 4b. Peaks of the heating and cooling curves show quite different characteristics between 500 and 580˚C. Your K/T curve also shows a newly-formed phase (due to heating of the sample) and it is not dominated by the phase that was studied by the IRM acquisition. Your interpretation of titanomagnetite is not convincing. Do all K/T curves show similar behaviour? Is the K/T curve that you present in the paper the best? Conversion at 400˚C during heating more likely represents the formation of a new magnetic phase than in situ titanomagnetite. The clearly higher K signal at room temperature after the heating cycle hints at newly-formed magnetic minerals.

Yes. The clearly high MS values at room temperature after the heating-cooling cycle suggest that new magnetic mineral phases were formed during heating. To better constrain the interpretation of magnetic mineralogy, thermal demagnetization of composite IRM acquired along three orthogonal axes, i.e., Lowrie test (Lowrie, 1990), and low-temperature experiments have been conducted. The IRM acquisition data (Fig. 5f) show that low coercivity magnetic minerals dominate the samples. Thermal demagnetization of the composite IRM shows that the low coercivity component unblocked at 580°C, indicating that the low coercivity phase is magnetite.

Lowrie, W. (1990), Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, Geophys. Res. Lett., 17, 159–162.

Your interpretation of the K/T curve of the oil shale (17.2 m) also raises questions. Again your susceptibility value at room temperature is near to zero – this is suspicious of newly-formed minerals during the K/T experiment. In the case of hexagonal pyrrhotite, which is characterized by the sharp peak at 240◦C, you should see the λ-transition to monocline pyrrhotite. This alone is distinctive and diagnostic of hexagonal pyrrhotite (Dunlop and Özdemir 1997). During further heating the irreversible oxidation of monocline pyrrhotite to magnetite should occur. This is not shown in your K/T curve. In your paper you argue that the sharp decay at 350°C - derived from your first differentiate, which, in my opinion, is dispensable here (no additional information in comparison to fig. 4c) - indicates the presence of greigite. Roberts et al. 2011 name different parameters (Mrs/Kappa; hysteresis parameters; no low temperature transition) to be diagnostic of greigite, but this is not addressed in your rock magnetic chapter. In my opinion your evidence of greigite is not convincing enough and should be better justified.

We appreciate this comment. Magnetic mineralogy of oil shale at around 17.2 m is now much better constrained with the additional experiments including low-temperature measurements and Lowrie test (Fig. 5i, n). The magnetic susceptibility (MS) peak at ~250°C in the heating curve (Fig. 5d) is diagnostic of hexagonal pyrrhotite (Dunlop and Özdemir 1997). The subsequent rapid increase in MS at ~400°C (Fig. 5d) probably indicates transformation of iron sulfides to magnetite during heating. The dominance of iron sulfides is indicated by the sharp drop of the composite IRM at ~400°C (Fig. 5n). Low-temperature data show marked difference between the zero-field cool (ZFC) curve and the field cool (FC) curve (Fig. 5i), which is diagnostic of pyrrhotite (Snowball and Torii, 1999) and may suggest the absence of greigite (Chang et al., 2007).

Snowball I. F. and Torii, M., Incidence and significance of magnetic iron sulphides in Quaternary sediments and soils, in Quaternary Climates, Environments and Magnetism, edited by B.A. Maher and R. Thompson, pp. 199-230. Cambridge Univ. Press, Cambridge, U.K., doi:10.1017/CBO9780511535635.009, 1999

Chang, L., Robert, A.P., Rowan, C.J., Tang, Y., Pruner, P., Chen, Q., and Horng, C.S., Low-temperature magnetic properties of greigite (Fe_3S_4). Geochem. Geophys. Geosyst., 10, Q01Y04, doi:10.1029/2008GC002276, 2007.

Please use mA/m instead of A/m, because it is better to read.

This has been revised as suggested.

The discussion of your demagnetization experiments is comprehensible. But its interpretation depends on your rock magnetic statements and that should be strengthened.

5. Your discussion of your magnetozones is transparent. The correlation of these magnetozones to the standard GPTS is difficult to follow. The problems recognised by Prof. Licht in relation to your basic assumptions, i.e. the correlation of the magnetozones to chronostratigraphy seem to me to be correct, and I do not feel competent enough to argue for or against that argument. Why not try a cyclostratigraphic study, especially in the oil shale, to estimate the sedimentation rates based on susceptibility values, for example (keyword sliding window technique)?

We appreciate this comment. In the revision, we have performed spectral analysis of the depth series of magnetic susceptibility of the Youganwo Fm. The spectral analysis detected dominant sedimentary cycles with cycle wavelength ratios in orbital frequency bands (Section 4.1).

Your construction of a geomagnetic polarity timescale is hard to read. I suggest you describe your technique on one example and then refer to this and describe in few words your data listed in Table 1. This would make your discussion more readable.

We appreciate this comment. Following your suggestion, we have shortened the description of the correlations (Section 5.3) and re-organized Table 1 in the revision to improve the clarity of presentation.

6. The missing palaeoclimatic discussion is well described by Prof. Licht. I have nothing more to add.

We have elaborated on the paleoclimatic discussions in the revision (Section 5.4).

Final comments:

The results of the study carried out by Wang et al. (1994) should be taken into account and/or matches and contradictions should be described.

More details of Wang et al. (1994) are included in Section 2 of the revision.

Shorten the discussion of the magnetozones and their stratigraphic correlations, by using a better constructed Table 1, and avoid the lengthy descriptions of your different correlation possibilities.

We appreciate this comment. We have re-organized Table 1 to make it easier to follow. Accordingly, the description of different correlations is shortened (Section 5.3) as well.

Since I am not a native English speaker myself I have had good experience of using professional journal experts to edit my texts. This should be considered in this case too.

Thank you. The English language of the revision has been polished by a native English speaker to make it more readable than the initial version.

The paper deserves to be published after a thorough revision.

Thank you. We hope you would be pleased to see the improvements that we have made for this paper.

3. Dr. Jovane's comments

The paper is well written and fluid. The topic is interesting and deserves to be published.

We thank Dr. Jovane for his helpful comments and we are grateful for his time, efforts, and suggestions. Dr. Jovane's comments are mainly focused on the cyclostratigraphic component of the manuscript. Dr. Jovane questioned that 1) details of our "close inspection" of reddish layers in the Youganwo Fm are lacking; and 2) statistical analysis of cycles is lacking.

In the revision, 1) we have clarified our field investigation of lithology and interpretation of the rhythmic occurrence of the reddish layers in the Youganwo Fm in Section 4.1; 2) we have performed spectral analysis of the depth series of magnetic susceptibility (MS) data of the Youganwo Fm (Sections 3 and 4.1) and added a new figure (Fig. 3), showing the dominant sedimentary cycles that display cycle wavelength ratios in the orbital frequency bands. Below are our detailed responses to Dr. Jovane's comments.

However, the paper does not present at this stage a mature study. This study pretends to show a lacustrine response to global paleoclimate in a continental Asia stratigraphy sequence based on paleomagnetism and cyclostatigraphy. The paleomagnetic work is reliable and solid. Nevertheless, the cyclostratigraphy is not ready yet.
There are two major lacks in this study:

- The poorness of the phase relation. They associate the cycles to couplets of red beds, which they states, without any proof, that are represented as to weathered bands related to fresh exposure. They says that this is build up from a "close inspection" but I do not see any sedimentological data to show this inspection. If cycles are represented by red beds, then the authors really have to make an effort to explain the environmental process that is behind the cycles and red beds, which they just go around avoiding a real explication of the phase relation.

The confusion probably arose from the wording of "close inspection". The rhythmic occurrence of reddish layers on the outcrop is striking at distance (Fig. 2). The wording "close inspection" was meant to say that when we approached the outcrop and looked at these reddish layers closely, we found that reddish color occurs only at the surface of these layers because once the reddish surface is hammered off, fresh exposure of the same layer does not show reddish color. Therefore, the reddish color should represent recent weathering, not the depositional signature. But weathering did help enhance the expression of subtle changes in lithology and make the subtle lithological changes more distinctly visible on the outcrop. The repeated occurrence of these sedimentary rhythms was probably related to fluctuating lake levels that can cause subtle changes in deposition, thus in lithology. In the revision, we have clarified this issue and provided an explanation for the processes that caused the sedimentary rhythms in Section 4.1

- The absence of spectrum, tuning and the wrong calibration. The cycles must be expressed as simple statistical analysis of a depth or temporal series as a frequency analysis, which they do not make neither on the magnetic susceptibility nor to the lithology. This quick exercise is needed to support the cycle analysis they underway. The mathematical approach would also allow them to attempt a tuning of the sequence to the target cycles of Laskar. Surprisingly, at the end of the magnetotratigraphy they show an astronomical calibration of the EO boundary, which is completely non-sense since they even do not show a spectrum of the depth or time sequence.

In the revision, we have performed spectral analyses of the depth series of magnetic susceptibility data of the Youganwo Fm and added a new figure (Fig. 3). Spectral analysis reveal dominant sedimentary cycles with cycle wavelength ratios in the orbital frequency band, suggesting that the observed sedimentary rhythms likely represent orbital cycles.

As to calibration, maybe it was not presented clear enough because we did not intend to calibrate the EO boundary per se. Our goal was to find the best correlation that can satisfy most, if not all, of the constraints by examining six possible correlations. Ensemble 6 happens to present a correlation that places the transition at the EO boundary and yields sedimentation rates, using which the observed sedimentary rhythms would be in short and long eccentricity bands. Since orbital cycles have been observed from records of similar time intervals in other regions, this line of evidence adds more weight to Ensemble 6 and makes it the preferred correlation.

The paper should not be accepted if those two major issues are resolved.

Then, minor corrections are also requested to improve the paper:

The title

They uses "responses" should be singular because they study only one process. If there are different processes aging in the upper and lower part of the section they have to study them sepatelly.

"of low-latitude Asia" should be "at low-latitude". Is the English correct?

All the language related concerns are taken care of in the revision. The English language of the revision has been polished by a native English speaker.

I do not see much integrated chronostratigraphy because I see a quick lithology description and not a lithostratigraphic analysis, the biological part is quite poor and uses previously published data and the cyclostratigraphy is completely lacking. Consequently, I only see a tentative magnetostratigraphy and not an "integrated chronostratigraphy".

The reason why we think an integrated chronostratigraphy is better because none of the lithostratigraphy, biostratigraphy, or cyclostratigraphy *alone* can provide a refined chronological framework for the studied section. For example, magnetostratigraphy *alone* will only yield magnetozones that cannot be exclusively correlated with the standard GPTS. Similarly, biostratigraphy *alone* cannot provide adequate temporal resolution needed. Cyclostratigraphy *alone* will only provide duration estimates, thus can only serve as a floating timescale, if there is not an anchoring point. However, if these different types of records are used jointly, i.e., integrated, it is possible to establish a refined chronological framework. As we show in this study, 6 ensembles of correlations are possible and Ensemble 6 is preferred because it can satisfy most, if not all, of the constraints from the different types of records.

In the revision, the lithostratigraphy and biostratigraphy parts have been strengthened (Sections 2.0 and 4.1) following Dr. Licht's suggestions. Also, we have strengthened the cyclostratigraphic component by adding spectral analyses of depth series of magnetic susceptibility of the Youganwo Fm and improving the description of sedimentary rhythms (Section 4.1 and Fig.3).

Abstract

Line 1: "clues to the impacts" not correct

Line 15; "reduction in hydrodynamics in low-latitude regions", their results do not show this! This sentence is not true! The abstract should re-written on the base of the two major improvements needed.

In the revision, this phrase has been changed to "drying conditions in the low-latitude". This statement is based on the fact that a drastic change in lithology is observed between the oil sale dominated Youganwo Fm and the overlying siltstone and sandstone dominated Huangniuling Fm. The drastic change in lithology indicates that the depositional environments changed from deep lake, shallow lake, to delta front to delta plain settings, suggesting the overall shrinkage of the lake and most likely implying a gradually prevailing drying condition of the region.

The abstract has been revised.

Results

Line 22: how MS can facilitate the characterization of sedimentary rhythms? Here they need spectral analyses to proof it!

The reddish layers correspond to high magnetic susceptibility (MS) values. Less reddish levels display relatively lower magnetic susceptibility values. Thus, MS facilitates the characterization of sedimentary rhythms. In the revision, spectral analysis of the depth series of the magnetic susceptibility data of the Youganwo Fm are performed and detected dominant sedimentary cycles in the orbital frequency bands.

Line 25: which close inspection? Show some sedimentological data!

The sedimentary rhythms are best seen at distance (Fig. 2c, e). When we came closer to the outcrop and examined the reddish layers, we found that the reddish color of these layers only occurs at the surface. When the reddish surface of these layers is hammered off, the fresh exposure of these layers show no reddish color. So the weathering is recent and the rhythmic occurrence of reddish color reflects rhythmic subtle lithologic changes, which would otherwise be difficult to discern at the outcrop.

Thanks to the recent weathering that makes the subtle lithological changes distinctly and expressively visible, our high-resolution measurements of magnetic susceptibility at the outcrop surface can capture the subtle lithological changes.

Line 26: weathering banding means continental exposure like paleosols? In this case the environmental interpretation is completely different!

As mentioned above, weathering bandings of the Youganwo Fm are the surficial features that were recent not during deposition. These surficial features enhance the subtle lithological changes and make them well expressed by distinct rhythmic occurrence of reddish color. Since the banding was not depositional in origin, it is not related to continental exposure.

Page 2819 line 1: the beds are red or not? Unclear sentence and scientifically weak! This is a major point!

The surface of the beds is reddish and the fresh exposure of the beds is not reddish.

Line 2: subtle compositional of what?

This was meant to say subtle lithological changes. This has been revised (Section 4.1).

Line 4: which depositional environment? What cause the cycles? This is not explained at all! Is the level of the lake changing in elevation exposing sometimes this area? At this point is fundamental that they show some pictures and geology of the area where they show that the strata are really continuous and horizontal. The lower part of the session, which is supposed to be deeper water, how can express paloesols?

In the revision, we have explained that lake level fluctuation was likely the cause for the sedimentary cycles. The investigated Youganwo Fm was deposited in a semi-deep to deep lake environment. As mentioned above, recent weathering makes the subtle lithological changes distinctly and expressively visible. So the reddish layers are not paleosols. The field photos of these strata are shown in Fig. 2 c-e.

Line 7: what makes them consolidated? $CaCO3$? Should be good to compare magnetic susceptibility with $CaCO3$ to build up the phase relation.

It is by the appearance of this layer because it often sticks out the outcrop, indicating that this layer is more resistant to weathering than the neighboring sandstones.

Line 11: rewrite the sentence: “massive sandstone cycles vary”

From line 10 to line 11, we describe the thickness of the massive sandstone, not the cycle, varies from decimeters to meters. The massive sandstone together with a red layer and a thin mudstone bed constitute a parasequence, or a cycle (lines 13-14).

Line 12: thinner mudstones bed… is it a cycles? They have much better to explain this too!

Lines 13-14 provide the explanation that a thin mudstone bed is part of a parasequence, or a cycle.

Lines 17-20: this sentence is already said before. Line 21: what they mean for “ traced to the center of the basin”? ~50 cm seem to me quite abrupt for a geological change also if continue… have they considered a tectonic uplift?

These have been revised (Section 4.1). The ~50 cm interval presents a gradual transition from brown grey mudstone to pale grey mudstone. And the pale grey mudstone is capped by siltstones and sandstones that show a coarsening upward trend. These features suggest that gradual environmental transition was the most likely cause because tectonic uplift would lead to sharp changes, not a gradual transition.

Line 27: I really do not see any data that show the lacustrine environment and the sedimentological characteristics of the transition. This point is fundamental and need to be resolved!

Detailed sedimentary facies analyses were carried out by Guo (2006), which we cited in the paper to interpret the depositional environment. The lithological changes of the transition are described in Section 4.1 and are shown in Fig. 2d.

Page 2820 line 24: the curie temperature of ~500C?? what is this? Wrong statement!
Line 26: it is not clear which are the proof to affirm that is it titanomagnetite and not only magnetite?
Page 2821 line 7: it does not seems to me that it is a "rapid increase between 580-500". Line 21: write "the NRM intensity f the samples…" It does not seams to me they spell NRM.

In the revision, we have added more k-t curves, ZFC and FC low temperature measurements, and thermal demagnetization of composite IRM (Sections 3 and 4.2.2). These additional rock magnetic data help better constrain the interpretation of magnetic mineralogy of the samples (Section 4.2.2). Also, NRM has been spelled out at its first occurrence in the revision (Section 4.3).

Discussions

Page 2822 line 3: they stated before that there is titanomagnetite as main magnetic carrier and now they say iron sulfides? I do this that there is still lot of magnetite carrying the characteristic magnetic signal… but if they really think that the main carrier is iron sulfides they have to do more magnetic researches. Line 25: prolate occurrence is written in a weird way.

In the previous version, these refer to different segments of the succession. Titanomagnetite was for the uppermost part of the Youganwo Fm and the Huangniuling mudstones (Lines 4-6), whereas iron sulfides were for the Youganwo oil shale (Line 3). As mentioned above, additional rock magnetic data (k-t, ZFC and FC low temperature experiments, and Lowrie test) are obtained to further constrain the interpretation of magnetic mineralogy of the samples in the revision (Section 4.2.2).

Page 2824 line 4 and 27: "late" or "middle" Eocene are not capital letters.
Line 10: "pebbly coarse sandstone" that means that a strong energy depositional process was aging meaning that probable also a lot of erosion… this must be considered in the cycle reconstruction.

We appreciate this comment. It is possible that erosion could take place at the edge of the lake during the same time interval. Since the investigated section is located at a depositional center of the basin, erosion at the study site during this stage of the Huangniuling Fm would be less likely.

Line 14: “sediment composition”… where? Do I miss something? I have not seen any sedimentological or compositional analyses like XRD or XRF. Each affirmation must be scientifically proven!

We meant that the Youganwo Fm is predominately oil shale and lithological changes within the Youganwo Fm are subtle. This has been revised (Section 5.2). So, compositional analyses such as XRD and XRF would be beyond the scope of this study. However, we measured high-resolution magnetic susceptibility (MS) of surface of the outcrop and the MS data can capture the subtle lithological changes within the Youganwo Fm.

Page 2825 line 6: here too they must specify which orbital cycle because each one act in a different way on the climate and environment… spectral analyses can explain which is the orbital forcing.

Spectral analyses of the depth series of the MS data of the Youganwo Fm has been performed and detected the dominant sedimentary cycles that are in orbital frequency bands (Section 4.1 and Fig. 3).

Line 23: avoid using “+” sign

This has been replaced with “and” in the revision (Section 5.3).

Line 27: late Eocene
Page 2826 line 1 and 4: late Eocene, middle Eocene. Ensemble 5 and 6: I liked the effort they make to build up their model using a logical exclusion process.

Thank you. This is one of the thrusts of this study. Unlike many marine records that are relatively long in time and magnetostratigraphy can be relatively easier to be defined with the help of paleonotologic data, terrestrial records however are usually short in time, i.e., fragmentary, and it is often difficult to establish a high-resolution timescale for this type of terrestrial records. Here we demonstrate that it is possible to establish a refined timescale for the fragmentary terrestrial records when different types of datasets of the terrestrial records are integrated synergistically.

However, I do not agree with their conclusion. It seems to me that the strongest model is the ensemble 5. All their thoughts on the changes in sedimentary rate are wrong because N2 and N3 can be C16N or 16N and 17N since there might be a gap which is very common also at sea in this period. So, I think they have to reconsider most of their discussions and conclusions. They must also consider that main lithological changes in the Tethys realm occur before that the EO boundary (namely Scaglia variegata FM-scaglia cinerea FM)

Magnetozone N3 cannot be used for correlation to the standard GPTS because its lower bound is not well defined. Its low bound is "0"m in our study because our studied section starts from "0" m. Its real lower bound could well be below the studied section. This is why we did not use the magnetozone N3, but only used the well-defined N1, R2, and N2 zones for correlations (Table 1).

As to the comment about "a gap", the studied Youganwo Fm including the N2-N3 portion show predominately oil shale that was deposited in semi-deep to deep lake environments (Guo, 2006). Previous workers did not recognize sedimentary hiatus in the Youganwo Fm and we did not see any sedimentary hiatus in the studied Youganwo oil shale either. The "gap" was probably common in marine records from Tethys realm and was probably associated with oceanographic changes such as circulation and/or carbonate compensation depth (CCD) that can cause sedimentary "gap". We do not think that the occurrence of a sedimentary "gap" in marine records from Tethys realm would necessarily also warrant a sedimentary hiatus in a lacustrine record from an intramontane basin in low-latitude Asia. As such, we believe Ensemble 6 is the best among these six possible correlations and is used to establish the refined timescale.

Page 2827 line 1: something wrong with the "by".

It is a part of the phrase "by and large".

Page 2829 line 13-23: This part should be completely cancelled. The do not show any spectral analyses and they end up building a astronomical calibration… this is completely wrong. Worst… they are so many uncertainties in they work starting from the lack of the phase analyses based on any environmental assumption and, them, serious mistakes in the magnatostratigraphy interpretation. So, all the rest of the text need to revised after having solved those two major issues first.

Lines 13-23 are deleted in the revision (Section 5.3). As mentioned above, spectral analyses of the depth series of the MS data of the Youganwo Fm are performed and a new figure (Fig. 3) is added in the revision. Other comments regarding calibration and phase relation have been replied at the beginning of the response to Dr. Jovane's comments.

Thank you for your comments. And we hope you would be pleased to see the improvements that we have made for this paper.

A list of relevant changes made in the revision

(P4=page no. 4; L4=Line no.4)

1. The abstract is expanded to incorporate the changed made in the revision;
2. P4, L7-20: Comprehensive age analysis of fossil mammal *Lunania* is added to define the age of Youganwo oil shale;
3. P4, L27--P5, L13: A synthesis of sedimentology of Maoming Basin focusing on the Youganwo Fm and the Huangniuling Fm is added; In addition, more sedimentologic details of the investigated section of the Youganwo Fm and the Huangniuling Fm are added in Section 4.1
4. P5, L19--P6, L10: More details of the previous paleomagnetic study by Wang et al (1994) are added. The locations of the study sites of Wang et al (1994) are marked in Fig. 1;
5. Methods: the spectral analysis approach (P6, L17-18) and additional rock magnetic experiments (P7, L11-23) are added;
6. Section 4.1: more sedimentologic details of the Youganwo Fm (P8, L14—P9, L12), the contact between Youganwo Fm and the Huangniuling Fm (P9, L14-L27), and the Huangniuling Fm (P10, L6-20) are provided; Spectral analyses results of the Youganwo Fm are presented (P8, L23-30) and a new figure (Fig. 3) is added;
7. Section 4.2.2: This section is expanded in light of the additional rock magnetic data to better constrain the magnetic mineralogy.
8. P14, L2-6: In light of new rock magnetic data, the revision is made to better constrain the magnetic remanence carriers;
9. P16, L24-27: Spectral analysis results are presented to support the constraint that sedimentary rhythms probably represent orbital cycles;

10. Section 5.3 (P17, L12—P19, L17): The description of different ensembles of correlations of magnetozones with geomagnetic polarity chrons is shortened. Also, Table 1 is re-organized to make it easy to follow. The shortened description together with the re-organized Table 1 significantly enhanced the clarity of correlations;
11. P20, L25—P21, L3: these lines are deleted following Dr. Jovane’s comments;
12. Section 5.4 (P21, L20---P22, L19): Paleoclimatic implications are significantly expanded.
13. P22, L24—P23, L6: Conclusions are modified to reflect changes made in the revision.

Terrestrial responses of low-latitude Asia to the Eocene-Oligocene climate transition revealed by integrated chronostratigraphy

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Abstract

The Paleogene sedimentary records from southern China hold important clues to the impacts of the Cenozoic climate changes on low-latitudes. However, although there are extensive Paleogene terrestrial archives and some contain abundant fossils in this region, few are accurately dated and have a temporal resolution adequate to decipher climate changes. Here we present a detailed stratigraphic and paleomagnetic study of a fossiliferous late Paleogene succession in the Maoming Basin, Guangdong Province. The succession consists of oil shale of the Youganwo Formation (Fm) in the lower part and ~~massive pebbly coarse sandstones of~~ the overlying sandstone-dominated Huangniuling Fm in the upper part. Fossil records indicate

that the age of the succession possibly spans from late Eocene to Oligocene. Both the Youganwo Fm and the Huangniuling Fm exhibit striking sedimentary rhythms, and spectral analysis of the depth series of magnetic susceptibility of the Youganwo Fm reveals dominant sedimentary cycles at orbital frequency bands. The ~~conformable~~ transition from the Youganwo oil shale to the overlying Huangniuling sandstones is conformable and represents a major depositional environmental change from a lacustrine to a deltaic environment. Integrating the magnetostratiphic, lithologic, and fossil data allows establishing a ~~The~~ substantially refined chronostratigraphic framework ~~is established based on the litho-, bio-, cyclo-, and magnetostratiphic data~~ that places the major depositional environmental ~~transition~~ change at 33.88 Ma, coinciding with the Eocene–Oligocene climate transition (EOT) at ~33.7 to ~33.9 Ma. We suggest that the transition from a lacustrine to deltaic environment in Maoming Basin represents terrestrial responses to the EOT and indicates ~~a significant reduction in hydrodynamics~~ prevailing drying conditions in low-latitude regions during the global cooling at EOT.

1 Introduction

The Late Paleogene witnessed one of the most prominent climatic changes in the Cenozoic, a transition from greenhouse to icehouse world. The transition is climaxed at the Eocene–Oligocene boundary when marine sediments registered a large, widespread, and rapid cooling in oceans (e.g., Zachos et al., 2001; Liu et al., 2009; Bohaty et al., 2012), which was accompanied by a sudden deepening of the carbonate compensation depth (CCD) by ~1.2 km (Pälike et al., 2012) in oceans and a severe calamity in the marine community that gave rise to the largest marine mass extinction since the end of Cretaceous (e.g., Prothero, 1994; Pearson et al., 2008; Cotton and Pearson, 2011). On land, this transition is expressed as rapid ice sheet growth over Antarctic (e.g., DeConto and Pollard, 2003; Coxall et al., 2005; Goldner et al., 2014) and large-scale cooling (e.g., Zanazzi et al., 2007; Dupont-Nivet et al., 2007; Hren et al., 2013). While the transition is widely recognized in the marine realm (Zachos et al., 2001; Jovane et al., 2006; Liu et al., 2009; Pälike et al., 2012; Westerhold et al., 2014) and is increasingly well-defined in terrestrial records from the Atlantic region (e.g., Zanazzi et al., 2007; Hren et al., 2013), its impacts on Asian environment remain poorly understood. This is largely because the concomitant tectonism, i.e., the Tibetan plateau uplift, and the development of monsoonal climate may also impose strong influence on Asian environment (e.g., Dupont-Nivet et al., 2007; Quan et al., 2012, 2014; Wang et al., 2013; Licht et al., 2014, 2015; Shukla et al., 2014).

There are numerous basins in southern China that host conspicuous Cenozoic sedimentary archives documenting the Cenozoic climate changes in the region. The late Paleogene sedimentary records from this region are of particular interest because they hold clues to the dramatic shift of climates in low-latitude Asia (Quan et al. 2012; Wang et al., 2013; Licht et al., 2014, 2015), where the influence of the Tibetan Plateau uplift should be minimal in comparison to the Asian interior. However, although abundant Paleogene sedimentary successions were developed here (e.g., Tong et al., 2005; 2013), their age controls are generally poor. Despite the fact that some successions contain vertebrate and/or plant fossils (e.g., Tong et al., 2005; 2013), the indicative age ranges of these fossils are often too broad to date climate changes with satisfactory accuracy and precision.

In this paper, we present a detailed stratigraphic and paleomagnetic study on the fossiliferous Eocene to Oligocene succession in the Maoming Basin of Guangdong Province, southern China to construct a new chronostratigraphic framework that is based on an integrated litho-, bio-, magneto-, and cyclostratigraphy. The new chronology not only greatly reduces the uncertainty but also significantly refines the available fossil-based timescale of the succession. In particular, the substantially refined chronology permits establishing the link between the dramatic environmental change in the basin and the global Eocene-Oligocene climatic transition, and thus provides a critical chronological basis for further detailed examination of climate changes in this region.

2 Geologic setting

The Maoming Basin is an intramontane basin situated in the southwestern part of Guangdong Province, southern China (Fig. 1). The Cenozoic succession of the basin consists of, from the bottom to the top, the Shangdong Formation (Fm), Youganwo Fm, Huangniuling Fm, Shangcun Fm, Laohuling Fm, and Gaopengling Fm (BGMRGP, 1988, 1996). Among these units, the Eocene to Oligocene strata concern the Youganwo Fm and the Huangniuling Fm (Fig. 2).

The Youganwo Fm is characterized by the occurrence of siltstones and shales containing coal seams in the lower part and the predominant occurrence of oil shales in the upper part (Fig. 2). The Youganwo Fm contains abundant vertebrate and plant fossils including turtles of *Anosteira maomingensis, Isometremys lacuna* and *Adocus inexpectatus* (Chow and Liu, 1955;

Chow and Yeh, 1962; Claude et al., 2012; Danilov et al., 2013), crocodiles of *Tomistoma petrolica* and Alligatoridae (Yeh, 1958; Li, 1975; Skutschas et al., 2014), fish of *Cyprinus maomingensis* (Liu, 1957), mammals of *Lunania* cf. *L. youngi* (Wang et al., 2007), and wood of *Bischofia maomingensis* and *Myrtineoxylon maomingensis* (Feng et al., 2012; Oskolski et al., 2013). The age of the formation is controversial, varying from Eocene to Oligocene (e.g., Liu, 1957; Yeh, 1958; Yu and ~~Zu~~Wu, 1983). A comprehensive review of the fossil records suggests that the Youganwo Fm was most likely deposited in the ~~Late~~ late Eocene (Jin, 2008). The late Eocene age is interpreted to include both Priabonian stage and the Bartonian stage of the Eocene based on recent advances in understanding fossil mammals of *Lunania*. Although the systematic position of the genus *Lunania* is still not fully understood, increasing evidence appears to point its age at Bartonian to Priabonian stage of the Eocene. To date, two species in total were reported: *Lunania zhoui* from the Yuanqu Basin of central China (Huang, 2002), and *Lunania youngi* from Yunnan (Chow, 1957; Zong et al., 1996) and Maoming (Wang et al., 2007) of southern China, respectively. The geological age of *Lunania zhoui* is regarded to be no earlier than Bartonian and no later than Priabonian (Tong et al., 2005). For the *Lunania youngi* from Yunnan, its age spans from the Bartonian to Priabonian (Li and Ting, 1983; Russell and Zhai, 1987; Wang, 1992; Qiu and Wang, 2007), the Bartonian (Tong et al., 1995), the early Late Eocene (Huang and Qi, 1982), or the latest Eocene (Tong et al., 2005; Wang, 1997). Therefore, the late Eocene age of the mammal fossil in Maoming Basin should be understood as including both the Priabonian stage and the Bartonian stage of the Eocene.

The overlying Huangniuling Fm consists mainly of sandstones and siltstones (Fig. 2). The lower part of the Huangniuling Fm is dominated by massive, pebbly coarse sandstones interbedded with thinly bedded, grey, silty mudstones. This formation contains plenty of plant macrofossils such as fruits, leaves and reproductive remnants (e.g., Feng et al., 2013). The age of the Huangniuling Fm has been ascribed to late Eocene to Oligocene, or even to the Miocene (Yu and ~~Zu~~Wu, 1983; Wang et al., 1994; Guo, 2006; Aleksandrova et al., 2012).

The areal extent of these two formations and other Cenozoic architectural units in the Maoming Basin was mapped by Guo (2006) that compiled stratigraphic data from drill cores and outcrops. Sedimentary facies analyses of these sedimentary units indicate that alluvial fan and fan delta were initially developed in the north-eastern part of the basin, which gradually gave rise to lacustrine environment that expanded to the whole basin and alternated with deltaic environment as lake area waxed and waned (Guo, 2006). Accordingly, successions

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that were accumulated in the lacustrine and deltaic environments often exhibit various subfacies and microfacies. For instance, subfacies/microFfacies analysis indicates that the lower part of the Youganwo Fm was initially formed in a littoral zone to shallow lake environment that was replaced by a prodelta environment and subsequently by a shallow lake environment (Guo, 2006). The oil shale dominated upper part of the Youganwo Fm was deposited mainly in semi-deep or deep lake environments that gave rise to a shallow lake environment at the uppermost of the Youganwo Fm. The Huangniuling Fm was deposited predominately in deltaic environments that vary from prodelta, delta front to delta plain environments lacustrine environment, while the overlying Huangniuling Fm was deposited in a deltaic environment (Guo, 2006). The uppermost part of the Huangniuling Fm, which consists of mainly muddy siltstone and mudstones, was deposited in a prodelta environment that transitioned to a shallow lake environment where the younger Shangcun Fm was deposited.

The transition from a lacustrine environment to a deltaic environment indicates reduced hydrodynamic conditions that may be associated with regional climate changes as inferred from other parts of southern China (Wang et al., 2013). However, because the ages of the two formations are poorly constrained, age estimates for the Youganwo-Huangniuling boundary can be as large as over 10 Myrs, ranging from the Late Eocene to the Miocene, which makes it difficult to relate the transition to any major climate events. Although a paleomagnetostratigraphicie work study, of drill cores from Maoming Basin was previously conducted in the Maoming Basin (Wang et al., 1994). The paleomagetic data were collected from three different sites, drill cores MR and MB as well as an outcrop section MS (Fig. 1b), and stratigraphic data from these three sites were compiled to obtain a composite stratigraphy that comprises the upper part of Youganwo Fm, Huangniuling Fm, Shangcun Fm, and Laohuling Fm.-. The age of the composite stratigraphy was interpreted to span from Chron 18n to Chron 12n (Wang et al., 1994). However, the magnetostratigraphy of Wang et al (1994) can only be regarded as preliminary by modern standards because of the following reasons. The mean sampling spacing is large, ~2.6 m; In addition, changes in sedimentation rates as indirectly reflected by the lithology were not taken into account. Furthermore, despite that samples of the Huangniuling Fm, Shangcun Fm, and Laohuling Fm were collected from the same core, i.e., the 874 m long MR core, samples of the Youganwo Fm were collected from both the MB core (15 samples) and the MS section (17 samples). The MB core is 567 m long, penetrates the Cenozoic strata, and reaches the Cretaceous rocks. No details were available as to how these 32 samples from two different sites were integrated to make a composite stratigraphy for the Youganwo Fm, particularly given that the MB core is relatively condensed and its base reaches the Cretaceous rocks. In particular, concerning the stratigraphic interval equivalent to that of this study, i.e., the upper Yougnawo Fm and the lower Huangniuling Fm, the sampling spacing was on average about 6.0 m (Figs 2 and 5 of Wang et al., 1994), which is too large by modern standards. ~~constructed a magnetic polarity timescale, the study was mainly focused on the Huangniuling Fm and younger units. Also, the mean sampling spacing is large, ~2.6 m, and changes in sedimentation rates as indirectly reflected by the lithology were not taken into account. The magnetic polarity timescale can only be regarded as preliminary by modern standards.~~

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3 Methods

The study section is well exposed in the cliffs of the now-abandoned open mine pit (N21° 42.3’, E110° 53.9’), located to the northwest of the Maoming City (Fig. 1). The exposed section comprises the upper part of the Youganwo Fm and the overlying Huangniuling Fm. To detect subtle changes in lithology of the exposed Youganwo Fm, magnetic susceptibility (MS) was measured with a hand-held susceptibility meter SM30, typically at every 10 to 20 cm. Spectral analysis of the depth MS data series was performed using the technique of Muller and MacDonald (2000) to detect the dominant sedimentary cycles. For the overlying Huangniuling Fm, it is basal 30 meter was measured and major lithological changes in its upper part are noted.

Oriented paleomagnetic samples were collected from the exposed Youganwo Fm and the lower part of the overlying Huangniuling Fm at ~~the~~ a depositional center of the basin where the gradual transition between the two formations occur (see Section 4.1). For oil shales in the Youganwo Fm, samples were collected usually every ~30 to 40 cm and, where possible, 2 core samples were taken from a stratigraphic level. For the Huangniuling Fm, samples were mainly collected from the interbedded thin, gray mudstones. A gasoline-powered portable rock drill was used to collect samples and a Pomery orientation device was used to orient the samples. Oriented block samples were taken from outcrops where drilling is not possible. A total of 109 core samples and 66 block samples from 122 stratigraphic levels were collected from this section.

In the laboratory, the samples were trimmed to standard cylindrical paleomagnetic specimens or cut into 2cm × 2cm × 2cm cubes. Anisotropy of magnetic susceptibility (AMS) of all specimens was measured with a KLY-3 Kappabridge. The specimens were then subjected to progressive thermal or AF (alternating field) demagnetization. The AF demagnetization was performed with a Molspin demagnetizer and the thermal demagnetization was conducted with an ASC TD48 thermal demagnetizer. The remanence of specimens was measured with a three-axis, 2G Enterprise Inc. 755 rock magnetometer. To constrain the magnetic mineralogy, isothermal remanent magnetization (IRM) acquisition was conducted with an ASC impulse magnetizer (IM-30) for selected samples. In the IRM acquisition experiments, each sample was magnetized in a forward field that progressively increases from 20 mT to 1.2 T. The sample was then progressively demagnetized in a backward field to estimate the coercivity of magnetic minerals. Between each magnetization/demagnetization treatment, the remanece of the sample was measured with an AGICO JR6A magnetometer. In addition, selected samples were subjected to a Lowrie test (Lowrie, 1990) to further constrain the magnetic mineralogy. In the Lowrie test, the samples were first magnetized sequentially along their Z, Y, and X axes with fields of 1.2 T, 0.6 T, and 0.125 T, respectively, and the composite IRM was then thermally demagnetized up to 640 °C. To further aid in magnetic mineralogy determination, thermal changes of magnetic susceptibility of representative two samples from the Youganwo Fm and the Huangniuling Fm were measured with a MFK Kappabridge equipped with CS4 apparatus. The magnetic susceptibility of the samples was measured while the samples were heated and cooled between the room temperature and 700 °C in an argon environment. In addition, Zero-field-cooled (ZFC) and field-cooled (FC) low-temperature measurements were conducted with a MPMS system at the Paleomagnetism Laboratory of Chinese Academia of Science. The magnetic susceptibility of the samples was measured while the samples were heated and cooled between the room temperature and 700 °C in an argon environment. All the demagnetization experiments and remanence measurements were conducted in a magnetically shielded room (residual field < 300 nT) in the Paleomagnetism Laboratory of Nanjing University, China.

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The demagnetization data were analyzed using the principal component analysis technique (Kirschvink, 1980). The demagnetization data are presented graphically with vector end point diagrams (Zijderveld, 1967). Software packages Puffinplot (Lurcock and Wilson, 2012) and PMGSC (by Randy Enkin) were used for paleomagnetic data analysis. The defined polarity zones, together with constraints from the paleontologic and lithologic data, are compared with the Geomagnetic Polarity Time Scale (GPTS) of Ogg (2012) to establish a chronologic framework for the investigated section.

4 Results

4.1 Sedimentary rhythms

The lithostratigraphy of the investigated section is summarized in Fig. 2. The lithology difference of the Youganwo Fm at the lower part and the Huangniuling Fm at the upper part of the section is dictated indicated by the distinct color contrast (Fig. 2c-e). The overall light brownish color in the lower part characterizes the exposed Youganwo oil shale, while the overall pale grey to light yellowish color in the upper part characterizes the overlying, sandstone-dominated Huangniuling Fm (Fig. 2e). One of the most striking features of the outcrop is the occurrence of sedimentary rhythms, which are impressively expressed as the repeated occurrence of beds with distinct reddish color, in both the Youganwo Fm and the Huangniuling Fm (Fig. 2c, e). In the Youganwo Fm, there are more than a dozen of beds displaying distinct reddish color (Fig. 2a). The sedimentary rhythm is particularly well expressed between ~11 m and 30 m, where the average spacing between two neighboring reddish beds is about 1.0 to 1.5 m (Fig. 2a). Inspection of the beds with reddish color at the outcrop found that the reddish coloration only occurs at the surface and should represent weathering banding of the beds because the fresh exposure of these beds does not show reddish color. Despite that the reddish color represents recent weathering, not the depositional signature, weathering enhanced the expression of changes in lithology and made the subtle lithological changes more distinctly and expressively visible on the outcrop. Because the reddish layers correspond to higher magnetic susceptibility (MS) values and less reddish levels display relatively lower magnetic susceptibility values, MS data can facilitate the characterization of sedimentary rhythms in the Youganwo Fm. Indeed, our high-resolution MS data also exhibit meter-scale cyclicity (Fig. 2b). Spectral analysis of the MS data reveals dominant sedimentary cycles with a cycle wavelength of ~252 cm, 127 to 107 cm, and ~30 cm (Fig. 3). The 127 to 107 cm cycle and the ~30 cm cycle have a cycle wavelength ratio of 3.6 to 4.2:1, which is similar to the periodicity ratio of 4:1 for the long eccentricity and the short eccentricity. The ~252 cm cycle and the 127 to 107 cm cycle have a cycle wavelength ratio of 1.98 to 2.35:1, probably representing the harmonics of the 127 to 107 cm cycle. Therefore, the dominant sedimentary cycles are probably in the orbital frequency bands and the meter-scale cycles may represent the long eccentricity cycle. Since the Youganwo oil shale was formed in a lacustrine environment (Guo, 2006), the subtle lithological changes in a repeated fashion as exemplified by the occurrence of the meter-scale sedimentary rhythms were probably related to fluctuating lake levels, which can cause subtle changes in deposition, thus in lithology. Fluctuations of lake level in Maoming Basin may have been modulated by orbital variations because the dominant sedimentary cycles appear to be in the orbital frequency bands. Magnetic susceptibility (MS) data can facilitate the characterization of sedimentary rhythms in the Youganwo Fm. High-resolution MS measurements show that the MS peaks generally correspond to the beds with reddish color and also exhibit meter-scale cyclicity (Fig. 2b). Close inspection of the beds with reddish color found that the reddish coloration represents weathering banding of the beds because fresh exposure of these beds does not show reddish color. Regardless of the origin of the reddish color, its meter-scale rhythmic occurrence exemplifies subtle compositional changes of the Youganwo oil shale in a repeated fashion, which could be due to cyclic variations in the depositional environment during oil shale formation in Maoming Basin.

The contact between the Youganwo Fm and the overlying Huangniuling Fm is sharp at many locations around the edge of the open mine pit where the siltstone and sandstone dominated Huangniuling Fm directly sit atop of brown grey to dark grey mudstones of the upper part of the Youganwo Fm. However, when the contact is traced toward the center of the basin, the interface between the two formations is represented by a ~ 50 cm thick layer that displays a continuous, gradual change from brown grey mudstones at the uppermost Youganwo Fm to pale grey mudstones at the base of the Huangniuling Fm (Fig. 2d). Above the pale grey mudstone are siltstones and sandstones, exhibiting a coarsening upward trend in grain size. Further upsection, the siltstones and sandstones are interbeded with thin layers of pale grey mudstones in the lower part of the Huangniuling Fm. These features suggest that the deposition was continuous at the study site when the Maoming Basin experienced the transition from a shallow lacustrine environment, as represented by the upper part of the Youganwo Fm to a prodelta environment, as represented by the lower part of the Huangniuling Fm (Guo, 2006), while the lake level was probably dropping.

In the Huangniuling Fm, the distinct red layer consists of coarse sandstones. It occurs at the base of the pale grey massive coarse sandstone and is typically a few centimeters thick. Because it is much more consolidated than the rest of the massive sandstones, tThe basal red sandstones are more resistant to weathering than the rest of the massive sandstones and commonly stick out of the surface of the outcrop, making the distinct red layers readily recognizable at distance (Fig. 2c). The thickness of the massive sandstone varies largely from decimeters to meters, occasionally up to decameters. Above massive sandstones is typically a relatively thinner mudstone bed (Fig. 2c). A red layer, massive sandstones, and a thin mudstone bed appear to form a parasequence that occurs repeatedly across the Huangniuling Fm (Fig. 2a, b, c). In the lower part of the Huangniuling Fm, the sandstone and mudstone beds in a parasequence are nearly flat and extend laterally with uniform thickness for hundreds of meters, and there is a fining-upward trend within a parasequence, suggesting that this part of the Huangniuling Fm was deposited in a prodelta to delta front or an interdistributary bay environment. Given the gradual nature of the transition from the Youganwo Fm to the Huangniuling Fm, the repeated occurrence of the parasequence in the lower part of the Huangniuling Fm was probably associated with fluctuating lake levels that may have been forced by orbital variations as well. This notion of orbital forcing is supported by the persistent pattern of rhythmic occurrence of the parasequences. This notion is also strengthened by the demonstrated orbital forcing of the deposition in marine (e.g., the Eocene/Oligocene boundary GSSP section in Italy, Jovane et al., 2006) and lacustrine (e.g., the Green River Fm, Meyers, 2008) settings during the similar time interval. In the upper part of the Huangniuling Fm, lense-shaped channelized sandstones are occasionally observed, suggesting that delta front to delta plain deposits gradually became dominant in the upper section. Using the distinct red layer in a parasequence as a marker bed, we have counted 19 parasequences, representing 19 sedimentary cycles, in the exposed Huangniuling Fm (Fig. 2a, b).

The contact between the Youganwo Fm and the overlying Huangniuling Fm is sharp at many locations around the edge of the open mine pit where coarse sandstones of the Huangniuling Fm directly sit atop of brown grey to dark grey mudstones of the upper part of the Youganwo Fm. However, when the contact is traced to the center of the basin, the transition is represented by a ~ 50 cm thick layer that displays a continuous, gradual change from brown grey mudstones at the uppermost Youganwo Fm to pale grey mudstones at the base of the Huangniuling Fm (Fig. 2d). Above the pale grey mudstone are siltstones and sandstones, exhibiting a coarsening upward trend in grain size. These features suggest that the deposition was continuous at the study site when the Maoming Basin experienced the transition from a lacustrine environment as represented by the Youganwo Fm to a deltaic environment as represented by the Huangniuling Fm (Guo, 2006).

4.2 Rock magnetic data

4.2.1 Anisotropy of magnetic susceptibility (AMS)

The AMS data of the Youganwo samples show predominantly oblate fabrics with the minimum axes perpendicular to the bedding and the maximum and intermediate axes parallel or subparallel to the bedding (Fig. ~~3a~~4a,b). The degree of anisotropy (Pj) ranges from 1.0 to 1.232 (Fig. ~~3b~~4b). The AMS data of the Huangnuling samples display mainly oblate fabrics (Fig. ~~3d~~4d), but also show a weak prolate fabric with the maximum axes trending SE and the minimum and intermediate axes girdling along the NE-SW direction (Fig. ~~3c~~4c). In addition, the degree of anisotropy of the Huangniuling samples is low, varying from 1.0 to 1.089, and mostly below ~1.03 (Fig. ~~3d~~4d).

4.2.2 ~~IRM acquisition and~~ Temperature-dependence ~~thermo~~magnetic properties and IRM

Thermomagnetic curves of the samples show that all the low-field magnetic susceptibility values at the end of the experiments are higher than those at the beginning of the experiments, suggesting that transformation of magnetic mineral phases occurred during heating (Fig. 5a-e). Because the cooling curves generally show a rapid increase in susceptibility from 580°C to 500°C (Fig. 5a-e), magnetite were probably produced during the experiments, leading to elevated susceptibility values by the end of the experiments. The mudstone at the lower part of the Huangniuling Fm (Fig. 5a,b) and the brown grey shale of the uppermost Youganwo Fm (Fig. 5c) show overall similar features with an increase in magnetic susceptibility between 450°C and 500°C during heating, whereas the oil shale samples show an increase in magnetic susceptibility at ~250°C and another major increase between 400°C and 450°C (Fig. 5d,e) during heating. For the oil shale samples, the magnetic susceptibility increase at ~250°C (Fig. 5d,e) is diagnostic of hexagonal pyrrohtite due to thermally activated vacancy ordering (Dunlop and Özdemir, 1997), and the subsequent increase in magnetic susceptibility between 450°C and ~500°C probably indicates transformation of pyrrohtite to magnetite during heating (Fig. 5d,e).

IRM acquisition of the samples shows that these samples are mostly saturated at fields above 200 mT (Fig. 5f). The demagnetization of IRMs in the backward DC fields suggests that the coercivity of the magnetic minerals is around 40 mT (Fig. 5f). The ZFC and FC low-temperature data of the samples show that the Huangniuling mudstone and the brown grey shale of the uppermost part of the Youganwo Fm exhibit similar features that are characterized by a small difference between the ZFC and FC curves (Fig. 5g, h). In addition, the Huangniuling mudstone shows a subdued transition at ca. 120 K (Fig. 5g), indicative of the presence of magnetite (Verwey, 1939; Özdemir et al., 1993). Thermal demagnetization of the composite IRM of the Huangniuling mudstone and the brown grey shale of the Youganwo Fm shows that the low coercivity component (0.125 T) unblocked at 580°C, confirming that magnetite is the major magnetic mineral phase in the Huangniuling mudstone and the brown grey shale of the uppermost of the Youganwo Fm. For the Youganwo oil shale, in addition to the presence of pyrrhotite as indicated by the rapid increase in magnetic susceptibility at ~250°C (Fig. 5d,e), magnetite is present as well, which is evidenced by the 580°C unblocking temperature of the composite IRM (Fig. 5o). At some oil shale levels such as around 17.2 m, iron suphide phases become predominant, which is indicated by the sharp drop of the composite IRM between 350°C and 400°C (Fig. 5n). ZFC and FC low-temperature measurements show that there is a marked difference between the ZFC and FC curves (Fig. 5i, j), indicating the presence of pyrrhotite (Snowball and Torii, 1999). The Mr/χ ratio of the Youganwo oil shale is typically around 0.5 x 10^3 to 1.0 x 10^3 A/m, which is low in comparison to the ~ 70 x10^3A/m for greigite (Snowball and Thompson, 1990). Also, greigite tends to display little difference between ZFC and FC curves (Chang et al., 2007; Roberts et al., 2011). Therefore, greigite may not be present in Youganwo oil shale. Pyrrhotite is the dominant iron sulphide phases in the Youganwo oil shale.

~~IRM acquisition of samples from the oil shale and the brown grey shale from the uppermost of the Youganwo Fm as well as the mudstone at the lower part of the Huangniuling Fm show that these samples are largely saturated at fields above 200 mT (Fig. 4a). The demagnetization of IRMs in the backward fields suggests that the coercivity of the magnetic minerals is around 40 mT (Fig. 4a). Thermomagnetic properties of the brown grey shale show that the low-field magnetic susceptibility gradually increases from the room temperature to ~480 °C, then increases rapidly and peaks at ~500 °C, and subsequently decreases to the background level at ~580 °C. The cooling curve of the magnetic susceptibility is characterized by a sharp increase at 580 °C, followed by a gradual decay with the decreasing temperature (Fig. 4b). The cooling~~

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curve displays an overall similar pattern to that of the heating curve, but shows higher susceptibility values than those of the heating curve (Fig. 4b), suggesting that magnetite was formed during heating. In addition, the Curie temperature of ~500 °C is shown on both heating and cooling curves. These features suggest that the main magnetic phase is likely titanomagnetite (Hrouda, 2003). Since the two mudstone samples (31.9 m and 32.5 m) from the lower part of the Huangniuling Fm exhibit similar IRM acquisition features to those of the dark grey shale in the uppermost part of the Youganwo Fm (Fig. 4a), titanomagnetite is probably the main magnetic phase in the Huangniuling mudstones as well. The sample (17.2 m) from the Youganwo oil shale displays a unique pattern of thermal changes in magnetic susceptibility (Fig. 4c). The heating curve is characterized by a sharp peak at ~260 °C and a broad peak between 450 °C and ~500 °C, and the cooling curve is featured by a rapid increase between 580°C and 500 °C, a broad peak between 500 °C and 400 °C, and a subsequent gradual decay (Fig. 4c). For the heating curve, the peak at ~260 °C is diagnostic of hexagonal pyrrohtite due to thermally activated vacancy ordering (Dunlop and Özdemir, 1997). The susceptibility decay following the ~260 °C peak appears to smooth (Fig. 4c). However, the first derivative of this decay segment of the heating curve shows a relatively rapid decrease at ~350 °C (Fig. 4d), indicating the possible presence of greigite (Roberts et al., 2011). The absence of a clear drop at ~320 °C (Fig. 4d), diagnostic of monoclinic pyrrhotite (Hrouda et al., 1997; Dunlop and Özdemir, 1997) suggests that the sample may not contain monoclinic pyrrohtite. The broad peak between 450 °C and ~500 °C probably indicates transformation of iron sulfides such as pyrrohtite and greigite to magnetite, which is evidenced by the rapid increase in susceptibility during cooling from 580 °C to 500 °C (Fig. 4c).

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4.3 Paleomagnetic data

Natural remanent magnetizations (NRMs) of the samples range between 3 × 10^{-6-3} and 20 × 10-2 mA/m with the majority being at the orders of 10^{-5-2} to 10^{-4-1} mA/m. About half of the specimens are magnetically unstable, displaying erratic directions upon demagnetization. For the rest of the samples, the AF demagnetized samples generally show demagnetization trajectories decaying toward the origin (Fig. 5a6a, b, c) and the thermally demagnetized samples generally show relatively stable demagnetization trajectories below 400 °C (Fig. 5d6d, e, f), above which erratic directions occur. For most samples, the linear segment of the demagnetization trajectory with coercivities > 15 mT or with a temperature range from ~150 °C to ~340°C or 380°C that decays toward the origin is regarded as a characteristic

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remanence (ChRM). The demagnetization data together with the rock magnetic data (Section 4.2.2) suggest that the remanence of the samples mainly resides in magnetite and pyrrhotite becomes the dominant magnetic mineral phase in the Youganwo oil shale~~ is mainly carried by iron sulfides, probably greigite, while titanomagnetite is probably also the remanence carrier of the brown grey shale in the uppermost part of the Youganwo Fm and the mudstones of the overlying Huangniuling Fm~~.

To obtain reliable estimates of the ChRMs, the following criteria are also used to scrutinize the data: a) we generally accept ChRMs of higher coercivity/unblocking temperature component decaying toward the origin with at least four data points; b) ChRMs with a maximum angular deviation (MAD) greater than 16° are rejected; c) if two samples from the same stratigraphic level yield similar ChRMs, the sample that has a better definition of the ChRM is used. Following the above treatments, we obtain reliable paleomagnetic data from 63 stratigraphic levels. Among these data, ChRMs from 46 stratigraphic levels have their corresponding virtual geomagnetic pole (VGP) within 45° from the mean of VGPs. These 46 ChRMs show both normal and reversed polarities (Fig. ~~6~~7). A reversal test was performed and passed at 95% confidence level with class "C" (McFadden and McElhinny, 1990). Therefore, the quality of the 46 ChRMs is ranked at "A" and the remaining 17 ChRMs are ranked at "B" in quality. Changes in inclinations and VGP latitudes of these ChRMs with depth are shown in Fig. ~~7c~~8c, d.

5 Discussions

5.1 Definition of magnetozones

Oil shales in the Youganwo Fm exhibit predominantly oblate AMS fabrics (Fig. ~~3~~4), indicative of a depositional origin of the fabrics. Silty mudstone layers in the Huangniuling Fm also show mainly oblate AMS fabrics, and prolate fabrics occur as well, though weak. These features indicate depositional type of fabrics developed in the presence of currents flowing at a moderate speed (Tauxe, 1998), which is consistent with a deltaic depositional environment for the Huangniuling Fm. In addition, reversed polarities are present and a reversal test passed (Section 4.3). Taking together, the occurrence of depositional type fabrics, the presence of reversed polarities, and the passage of a reversal test suggest that the remanence is likely primary. Therefore, both the VGP latitudes and inclinations are used to define magnetozones of the investigated section (Fig. ~~7~~8e). Also, definition of magnetozones is primarily based on the "A"-quality ChRM data and the "B"-quality ChRM data are only used as a second-order constraint for intervals where "A"-quality data are sparse (Fig. 7c8c, d). In addition, a polarity zone is defined by at least two consecutive levels of similar polarities. Changes in inclinations and VGP latitudes with depth are largely in concert, which allows us to define two reversed polarity zones (R1 and R2) and two main normal polarity zones (N1 and N2) (Fig. 7e8e). Among these magnetozones N1 and R2 are better defined. N1 is defined between 32.2 m and 51.0 m, and R2 is defined from 25.0 m to 32.2 m (Fig. 7e8e). Below 25.0 m is dominated by the normal polarities except at ~ 10 m where isolated negative inclinations and VGP latitudes occur (Fig. 7c8c, d). Although these negative values do not occur consecutively in depth (Fig. 7c8c, d), the trend of shift toward negative values in both inclinations and VGP latitudes is evident and is consistent, suggesting that a reversed polarity probably exists at ~10 m (Fig. 7e8e). This possible reversed polarity zone is tentatively defined between ~11.0 m and ~8.5 m and separates the lower 25 m section into two short normal polarity zones, N2 and N3 (Fig. 7e8e).

5.2 Major constraints on a geomagnetic polarity timescale (GPTS)

Correlation of these magnetozones to the standard GPTS is not unique due to the lack of numerical ages serving as anchor points. However, several constraints exist for the investigated section. When these constraints are used collectively and in conjunction with the defined magnetozones (Fig. 7e8e), it is possible to establish a reliable polarity time scale for this section.

The major constraints are as follows. First1), the studied oil shales contain abundant vertebrate and plant fossils (Chow and Liu, 1955; Liu, 1957; Yeh, 1958; Chow and Yeh, 1962; Li, 1975; Yu and ZuWu, 1983; Wang et al., 2007; Claude et al., 2012; Feng et al., 2012, 2013). In particular, the mammal fossil (*Lunania* cf. *L. youngi*) (Wang et al., 2007), which was unearthed from the studied oil shale of the Youganwo Fm, provides the most definitive evidence for a late Eocene age (Wang et al., 2007; Jin et al., 2008). Accordingly, the Youganwo oil shale was formed sometime in the Priabonian stage and/or Bartonian stage of the Eocene that could span from magnetic chrons Chrons C18r to C13r, i.e., 41 to 34 Ma (Fig. 7f8f). Second2), the marked difference in lithology of the Youganwo Fm and the Huangniuling Fm suggests drastic difference in sediment accumulation rates. The sampled Youganwo Fm consists predominantly of brown oil shales; , whereas the overlying Huangniuling Fm comprises dominantly massive pebbly coarse sandstones and siltstones.

Therefore, the sediment accumulation rates for the Huangniuling Fm were much faster than those for the Youganwo Fm. In addition, although organic matter and silt content decreases upsection and grey mudstones occur at the uppermost of the Youganwo Fm, changes in ~~sediment composition~~lithology within the Youganwo Fm are subtle. This suggests that sediment accumulation rates of the studied Youganwo Fm should not change drastically. ~~Third~~3), the deposition between the Youganwo and Huangniuling Fms is continuous. The contact between the two formations displays a continuous, gradual change from brown grey mudstones at the uppermost Youganwo Fm to pale grey mudstones at the base of the Huangniuling Fm within an interval of ~50 cm. In addition, siltstones and sandstones overlying the basal pale grey mudstone exhibit a coarsening upward trend in grain size, indicating a continuous deposition during the transition from the Youganwo Fm to the Huangniuling Fm. ~~Fourth~~4), the characteristic sedimentary rhythms of the investigated section may also be used as an additional constraint. In fact, ~~T~~the occurrence of sedimentary rhythms is not unique at the studied section. A marine succession of similar age in Massignano, Italy also displays striking limestone/marl cycles (Jovane et al., 2006). Cyclic lithologic patterns are also seen in the ~~Middle~~ middle Eocene oil shale-bearing lacustrine succession in the Mudurnu-Göynük Basin, Turkey (Ocakoğ~~g~~lu et al., 2012), the Eocene oil shale-bearing Green River Formation in the United States (Meyers, 2008), and other terrestrial records of similar ages in Asia (e.g., Dupont-Nivet et al., 2007; Xiao et al., 2010). All these lithologic cycles are attributed to orbital forcing and represent orbital cycles (Jovane et al., 2006; Dupont-Nivet et al., 2007; Meyers, 2008; Xiao et al., 2010; Ocakoğ~~g~~lu et al., 2012). The strong lithologic expression of orbital variations in both marine and terrestrial records, particularly those containing oil shales, from widespread regions at similar ages leads us to believe that the sedimentary cycles of the studied section likely represent orbital cycles as well. In particular, spectral analysis of magnetic susceptibility depth series of the Youganwo Fm reveals dominant sedimentary cycles with a cycle wavelength ratio of ~4:1, which is in the orbital frequency bands. Therefore, ~~A~~although it is not certain yet as to exactly which orbital cycle(s) (i.e., eccentricity, obliquity, or precession) these sedimentary rhythms may represent, the frequency of these lithologic cycles should be within the orbital frequency bands, which can be used as an additional, first-order constraint when establishing a time scale for the studied section. Based on the definition of the magnetozones (Fig. ~~7~~8), there are ~3.5 sedimentary cycles in N1. Because a sedimentary cycle in the Huangniuling Fm is represented by a sequence of red layer, massive sandstone, and a thin mudstone, one red layer marker at 40 m might be unidentified, where the accompanied thin mudstone bed did occur (Fig. ~~7~~8). Therefore, there are probably 4 sedimentary cycles in N1 zone. Similarly, there are ~ 3 sedimentary cycles in R2 zone and ~8.5 sedimentary cycles in N2 zone, respectively (Fig. ~~7~~8).

5.3 Construction of a geomagnetic polarity timescale (GPTS)

With the aforementioned 4 constraints, correlations between the four polarity zones (Fig. ~~7e~~8e) and the magnetochrons C18r to C13r (Fig. ~~7f~~8f) can be examined and unrealistic correlations can be rejected. Because polarity zones N1 and R2 are better defined than other two polarity zones, correlation is thus constructed mainly between the N1~~+~~ and R2 pair and the consecutive normal ~~+~~ and reversed magnetochrons of the GPTS. To facilitate the analyses, the N2 zone is also used, but as a secondary constraint, in establishing the correlations.

The results of correlations are summarized in Table 1. With the first-order constraint that the Youganwo oil shales were formed in the ~~Late~~ late Eocene, i.e., from C18 to C13, six ensembles of correlations are ~~possible~~possible ~~between the N1+R2 pair and the normal-reversed magnetochron pairs in the Late Eocene, i.e., from C18 to C13~~ (Table 1). Ensemble 1 correlates N1 and R2 zones with C18n and C18r, respectively. Ensemble 2 correlates N1 and R2 zones with C17n and C17r, respectively. Ensemble 3 relates N1 to C16n.2n and R2 to C16r. Ensemble 4 links N1 to C16n.1n, R2 to C16n.1r, and N2 to C16n.2n. In Ensemble 5, N1 and R2 zones are correlated to C15n and C15r, respectively. And Ensemble 6 correlates N1 to C13n and R2 to C13r. The quality of each correlation is assessed by examin~~ed as follows~~ing whether and to what extent the above four constraints are met. The one that satisfies most or all of the constraints is preferred and is used to establish the magnetic polarity timescale for the investigated section. ~~Ensemble 1 correlates N1 and R2 zones with C18n and C18r, respectively.~~ For instance, Ensemble 1 is rejected because ~~This~~ this correlation would force the majority of the Youganwo oil shale section (N2-N3), where funa fossils of ~~Late~~ late Eocene age were discovered, to the ~~Middle~~ middle Eocene (Fig. ~~7e~~8e,f). Ensembles 2 and 3 are rejected on the grounds that the sedimentation rate for N1 in the coarse sandstones is slower than or similar to that of R2 in the oil shale, which violates constraint 2).~~Therefore, ensemble 1 is rejected~~. ~~Ensemble 2 correlates N1 and R2 zones with C17n and C17r, respectively. The corresponding sedimentation rates for N1 and R2 are 1.38 cm/kyr and 2.54 cm/kyr, respectively (Table 1). Ensemble 2 is rejected on the grounds that the 1.38 cm/kyr for N1 is too slow for the massive pebbly coarse sandstones; and 2) the 1.38 cm/kyr for N1 is slower than the 2.54 cm/kyr for R2 in the oil shales. Ensemble 3 relates N1 to~~

~~C16n.2n and R2 to C16r. Such a correlation would yield a sedimentation rate of 2.90 cm/kyr for N1 and 2.68 cm/kyr for R2 (Table 1). Because the 2.90 cm/kyr rate of N1 in coarse sandstones of the Huangniuling Fm is similar to the 2.68 cm/kyr rate of R2 in the oil shale, which is unrealistic, ensemble 3 is rejected as well. Ensemble 4 links N1 to C16n.1n, R2 to C16n.1r, and N2 to C16n.2n. This correlation leads to a sedimentation rate of 10.11 cm/kyr for N1, 4.53 cm/kyr for R2 in the upper part of the Youganwo Fm, 2.31 cm/kyr for N2.1n in the lower part of the Youganwo Fm (Table 1). Although the fact that the 10.11 cm/kyr rate for N1 is much faster than the 4.53 cm/kyr for R2 is well compatible with the lithology,~~ Ensemble 4 is also rejected because the sedimentation rate for the upper part of the Youganwo Fm (R2) is almost two times ~~of~~ that of ~~for~~ the lower part of the Youganwo oil shale, which is~~. The sedimentation rate difference is too large to be~~ incompatible with the subtle compositional change within the studied Youganwo Fm.~~ For this reason, ensemble 4 is also rejected.~~

~~In ensemble 5, N1 and R2 zones are correlated to C15n and C15r, respectively.~~ For Ensemble 5, a~~A~~ssuming that C16n.1r was not captured probably due to its relatively short duration, N2 zone would correlate to C16n. Such a correlation yields a sedimentation rate of ~ 6.37 cm/kyr for N1, ~1.75 cm/ky for R2, and ~1.51 cm/kyr for N2 (Table 1). These sedimentation rates comply with the constraints specified in Section 5.2~~, i.e., 1) the sedimentation rate for N1 in the coarse sandstones in the Huangniuling Fm should be much faster than that for R2 in the upper part of the Youganwo Fm; 2) sedimentation rates for the upper and lower part of oil shales in the Youganwo Fm should be by and large similar~~. ~~Despite these~~However, the sedimentation rates of ~1.51 to 1.75 cm/kyr are probably too fast for the investigated oil shale because oil shale in the Youganwo Fm was formed in a semi-deep to deep lake environment (Guo, 1996) and the lithology of the investigated interval of the Youganwo Fm is nearly monotonic, consisting of only oil shale. ~~–~~ A pure shale unit represents a condensed time interval and should be accumulated at very slow rates. Two well-dated organic-rich black shale intervals in the mid-Cretaceous could serve as useful analog to oil shale of the investigated section. The well-dated black shale unit at ~120 Ma is about 5 m thick and represents ~1270 kyr (Li et al., 2008), and thus was accumulated at a rate of ~0.39 cm/kyr. Similarly, the sedimentation rates of the well-dated black shale unit at ~94 Ma (Sageman et al., 2006) are estimated to be ~0.37 to ~0.50 cm/kyr. In addition, ~~ensemble~~ Ensemble 5 correlation would result in a duration of 295 kyr (C15n) for N1 zone and 411 kyr for R2 zone. Because there are ~4 and ~3 sedimentary cycles in N1 zone and R2 zone, respectively, the sedimentary cycle in N1 zone and R2 zone would represent a ~74 kyr and ~137 kyr cycle, respectively.~~ and the sedimentary cycle in R2 zone would represent a ~137 kyr cycle.~~ The ~137 kyr~~sedimentary~~ cycle in R2 zone could be a result of modulation by short eccentricity ~~cycles~~ of orbital variations. But the ~70 kyr ~~sedimentary~~ cycle in N1 zone is not in the frequency band of orbital variations and its origin is thus difficult to interpret. Therefore, ~~ensemble~~ Ensemble 5 is rejected as well ~~correlation cannot provide satisfactory accounts of the major constraints either and is thus rejected~~.

~~Ensemble 6 correlates N1 to C13n and R2 to C13r. To~~ Ensemble 6 ~~satisfy~~ satisfies the constraints on sedimentation rates for ~~that R2 zone and N2 zone should have similar sedimentation rates, N2 must correlate to magnetochrons C15n to C17n (Table 1). The corresponding sedimentation rate is 3.43 cm/kyr for N1, 0.56 cm/kyr for R2, and 0.42 cm/kyr for N2, respectively (Table 1). Clearly, the sedimentation rate of 3.54 cm/kyr for N1 zone of the coarse sandstone in~~ the Huangniuling Fm ~~is faster than the 0.56 cm/kyr sedimentation rate for R2 zone of oil shale in~~ and the Youganwo Fm. Also, ~~the sedimentation rate of 0.56 cm/kyr in R2 at the upper part of the Youganwo Fm is similar to the sedimentation rate of 0.42 cm/kyr in N2 at the lower part of the Youganwo Fm. Apart from these,~~ the sedimentation rates of 0.42 to 0.56 cm/kyr for the Youganwo Fm (Table 1) are compatible with those of the well-dated, organic-rich black shales in the mid-Cretaceous. Furthermore, this correlation would result in durations of N1, R2, and N2 zones that are largely comparable to those estimated from sedimentary cycles. With ensemble 6 correlation, N1, R2, and N2 zone would represent ~548 kyr, ~1294 kyr, and ~3334 kyr, respectively. Since N1 zone contains ~ 4 sedimentary cycles (Fig. ~~7a~~8a, b), each cycle would represent a ~137 kyr cycle, which is similar to the short eccentricity cycle E2 (95 to 125 kyr). Similarly, since there are ~3 sedimentary cycles in R2 zone (Fig. ~~7a~~8a, b), each sedimentary cycle would represent a ~431 kyr cycle, which is similar to the long eccentricity cycle E1 (405 to 413 kyr). As an additional check, the duration of the sedimentary cycles within N2 zone is calculated. There are ~8.5 sedimentary cycles in N2 zone representing ~3334 kyr and thus each sedimentary cycle has a duration of 392 kyr, which is similar to the periodicity of long eccentricity cycle E1. Therefore, the sedimentary cycles in the Youganwo Fm are consistently shown as representing the long eccentricity cycles. It is reasonable that the sedimentary cycles in N1, i.e., Huangniuling Fm, represent short eccentricity E2 and sedimentary cycles in R2~~ zone~~ represent long eccentricity E1 because the sedimentation rates of the Huangniuling Fm is much faster than that of the Youganwo Fm and orbital cycles with shorter durations can be recorded in the Huangniuling Fm. Indeed, among these six ensembles, only ~~ensemble~~ Ensemble 6 ~~correlation~~ can yield periodicities of all the sedimentary cycles, which are from different parts of the section, in the orbital frequency band within uncertainties (Table 1). Thus, taking together, ~~ensemble~~ Ensemble 6 ~~correlation~~ can satisfy different aspects of major constraints within uncertainties and thus is acceptable.

Analyses of the six possible correlations lead to a conclusion that only ~~ensemble~~ Ensemble 6 correlation offers the most realistic scenario. Therefore, the ~~ensemble~~ Ensemble 6 correlation is employed to establish a chronologic framework for the studied section (Fig. ~~7e~~8e, f). With this chronologic framework, the transition from the Youganwo Fm to the Huangniuling Fm took place within magnetochron C13r (Fig. ~~7~~8). Because the transition is represented by a ~ 50 cm thick, mudstone-dominated interval and the C13n/C13r boundary (33.705 Ma) occurs at ~70 cm above the top of the transitional interval, the age of the onset of the transition can be determined by estimating the duration of the ~ 1.2 m thick interval. There are two ways to estimate the duration of the 1.2 m thick interval. One is to extrapolate the sedimentation rate of ~0.56 cm/kyr for the uppermost part of the Youganwo Fm, i.e., R2 zone. This would lead to an estimate of ~210 kyr and the onset of the transition is then estimated to be at ~33.915 Ma. The second approach is to treat the 1.2 m thick interval as the upper part of the long eccentricity cycle at the uppermost of the Youganwo Fm (Fig. ~~7a~~8a, b). This results in an estimate of ~ 140 kyr for the 1.2 m thick interval and an onset age of ~ 33.845 Ma. Taking the average of the above two estimates, we obtain a mean age of 33.88 Ma for the onset of the transition.

In summary, ~~T~~the constructed timescale represents a significantly refined chronology for the Paleogene strata in Maoming Basin, and ~~. It not only~~ provides the tightest possible constraints on the timing of the onset of the transition from a lacustrine environment to a deltaic environment in the Maoming Basin~~, but also permits detailed dating of the studied section~~. ~~Because there are 19 parasequences, which probably represent 19 short eccentricity cycles, in the exposed Huangniuling Fm, the duration of the exposed Huangniuling Fm is estimated to be ~1.9 Myr and the age of the uppermost of the section (Fig. 2a) is estimated at ~31.98 Ma. The age of the uppermost of the magnetostratigraphic section (Fig. 7) would be ~33.2 Ma. For the Youganwo Fm, the R2 magnetozone is correlated to magnetochron C13r and the basal age of R2 magnetozone is at 34.999 Ma. Since the N2 zone is correlated to magnetochrons C15n-C17n, the basal age of N2 zone would be at 38.333 Ma. Since there are 3 or 4 sedimentary~~

cycles (Fig. 2), which probably represent long eccentricity cycles, in the lower ~11 m section below the N2 magnetozone, the basal age of the investigated section is estimated to be at ~39.73 Ma.

5.4 Paleoclimatic implications

The rapid transition from a lacustrine environment to a deltaic environment and the subsequent persistently prolonged drying conditions could be related to global climate change. In the late Paleogene, the Earth's climate underwent a major transition from greenhouse to icehouse that was climaxed at the Eocene–Oligocene boundary (Zachos et al., 2001). This climatic transition was accompanied by rapid ice sheet growth on the Antarctic (e.g., DeConto and Pollard, 2003; Coxall et al., 2005; Goldner et al., 2014) and was characterized by pronounced global cooling (e.g., Zanazzi et al., 2007; Liu et al., 2009; Bohaty et al., 2012; Hren et al., 2013). The Eocene–Oligocene transition (EOT) was dated at 33.714 Ma (Jovane et al., 2006) or 33.9 ±0.05 Ma (Brown et al., 2009) from the marine succession in Massignano, Italy, which is the Global Stratotype Section and Point (GSSP) for the Eocene–Oligocene boundary. Studies of the equatorial Pacific records constrain the EOT at ~33.79 Ma (Pälike et al., 2006) or 33.89 Ma (Westerhold et al., 2014). The rapid transition from a lacustrine environment to a deltaic environment in Maoming Basin is dated at 33.88 Ma, which coincides well with the timing of the EOT determined from marine records. The close timing suggests strong linkage between the drastic environmental transition in Maoming Basin and the EOT (Fig. 7f8f). The dramatic shift from a lacustrine to a deltaic environment at the Maoming Basin suggests that low-latitude Asia likely underwent a transition in regional hydrological cycle from humid to dry conditions in response to global cooling at the EOT. As dry conditions become prevailed, lake level likely dropped and lake area became shrunk. The prevailing drying conditions together with global cooling during EOT probably promoted erosions in upland and supplied abundant sediments to the shrinking lake, leading to the rapid increase in sediment accumulation rates after the dramatic environmental change. The dry conditions perhaps persisted in low-latitude Asia after the dramatic environmental change as the global climate continued to deteriorate following the rapid, severe, and widespread climatic transition at the Eocene–Oligocene boundary (Fig. 7f). This persisted dry condition The linkage is further strengthened by the subsequent occurrence of persistently prolonged drying conditions, which is indicated by the accumulation of the sandstone-dominated Huangniuling Fm in the Maoming Basin at relatively increased sedimentation rates, as the global climate continued to deteriorate following the rapid, severe, and widespread climatic transition at the Eocene Oligocene boundary (Fig. 7f). Indeed, similar depositional environmental change and increase in sedimentation rates between 34.5 Ma and 31 Ma are also observed in Xining Basin and the E/O climatic transition is considered as a possible cause (Dai et al., 2006).

The new, significantly refined chronology also indicates that the striking sedimentary cycles in both the Youganwo Fm and the Huangniuling Fm likely represent eccentricity cycles. The recognition of eccentricity signal suggests that sedimentation in the Maoming Basin during this time interval may have been modulated by orbital variations, probably via lake level fluctuations at orbital frequency. The occurrence of eccentricity signals in the records is consistent with the fact the Maoming Basin is situated in the low-latitude areas that are sensitive to orbital variations at eccentricity frequency bands. Indeed, modulation of orbital variations on sedimentation appeared to be widespread during this time interval. The long and short eccentricity signals are also detected from the Eocene/Oligocene Massignano section in Italy (Jovane et al., 2006). The eccentricity signals are also found in other marine successions (e.g., Westerhold et al., 2014) and lacustrine deposits (e.g., Meyers, 2008; Okacoğlu et al., 2012) at the similar ages. Therefore, the drastic environmental change in the Maoming Basin during EOT represents the terrestrial responses in low-latitude Asia to the EOT that may be superimposed on the long-term variations at orbital frequency. Therefore, the The investigated section in the Maoming Basin thus likely faithfully recorded the impacts of the EOT on low-latitude Asia. With the significantly refined chronology, future studies using various proxies shall shed new lights into understanding these regional processes.

6 Conclusions

We have carried out aA detailed stratigraphic and paleomagnetic investigation of the upper Paleogene succession in the Maoming Basin, southern China. The investigated succession comprises oil shale dominated Youganwo Fm and the overlying sandstone dominated Huangniuling Fm. Both the Youganwo Fm and the overlying Huangniuling Fm exhibit striking sedimentary rhythms. The sedimentary rhythms of the Youganwo Fm are well expressed the high-resolution magnetic susceptibility (MS) data and spectral analysis of the MS depth series reveals that the dominant meter-scale sedimentary cycles are in orbital frequency bands. The sedimentary rhythms in the Huangniuling Fm are characterized by the repeated occurrence of a parasequence containing red sandstone layer, massive coarse sandstones, and a relatively thin mudstone. New paleomagnetic results, together with the lithologic and fossil age data, ~~-~~allows us to establish a~~n integrated litho-, bio-, cyclo-, and~~ magnetostratigraphy for the studied section that constrains the striking sedimentary rhythms of the Youganwo Fm and Huangniuling Fm to long and short eccentricity cycles, respectively. Taken together, a significantly refined chronologic framework is established for the investigated succession.~~ The Youganwo Fm in the lower part contains mainly brown oil shale and displays striking meter-scale sedimentary cyclicity that is attributed to modulation of long eccentricity (~405 kyr). The exposed Youganwo Fm is constrained to span from ~39.73 Ma to ~33.88 Ma. The overlying Huangniuling Fm is dominated by coarse sandstones and exhibit sedimentary rhythms that are characterized by the repeated occurrence of a parasequence containing red sandstone layer, massive coarse sandstones, and a relatively thin mudstone. The sedimentary cycles in the Huangniuling Fm are linked to short eccentricity cycles (~100 kyr) in the chronologic framework. The exposed Huangniuling Fm contains 19 such sedimentary cycles and is bracketed between ~33.88 Ma and ~31.98 Ma.~~

The contact between the Youganwo Fm and the Huangniuling Fm is represented by a 50 cm interval that shows a gradual change from dark grey mudstone at the uppermost of the Youganwo Fm to the grey mudstone and siltstones with a coarsening upward trend in grain size at the base of the Huangniuling Fm. This interval represents a major environment change from a lacustrine to a deltaic environment in the Maoming Basin and its onset is dated at ~33.88 Ma. The timing of the onset of the dramatic environmental change is in remarkable similarity with that of the Eocene–Oligocene transition (EOT) that is dated at 33.7 to 33.9 Ma from various marine records. The synchroniety suggests strong linkage between these two events and implies that the rapid environmental change in the Maoming Basin most likely represents terrestrial responses to the global cooling associated with the EOT. This notion is strengthened by the subsequent occurrence of the persistently prolonged dry conditions, as represented by the ~~~1.9 Myr Huangniuling coarse~~ sandstone-dominated Huangniuling Fm~~s~~, following the rapid environment change coincident with the EOT. These features are highly compatible with the continued deteriorating conditions after the EOT.

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Table 1 Correlations of magnetozones with ~~chrons~~ Chrons of C18 to C13 of the geomagnetic polarity time scale (GPTS).

		Polarity Chrons/subchrons (duration in myr)														
		C18n	C18r	C17n	C17r	C16n.2n	C16r	C16n.1n	C16n.1r	C16n.2n	C15n	C15r	C16n	C13n	C13r	C15n-C17n
Correlations	Polarity zone*	(1.529)	(1.01)	(1.363)	(0.283)	(0.649)	(0.269)	(0.186)	(0.159)	(0.649)	(0.295)	(0.411)	(0.994)	(0.548)	(1.294)	(3.334)
1	**N1**	**1.23, 382**	-													
x[a]	R2	-	0.71, 337													
2	**N1**			**1.38, 341**	-											
x[b]	R2			-	2.54, 94											
3	**N1**					**2.90, 162**	-									
x[b]	R2					-	2.68, 90									
4	**N1**							**10.11, 47**	-	-						
	R2							-	4.53, 53	-						
x[c]	**N2**							-	-	**2.31, 76**						
5	**N1**										**6.37, 74**	-	-			
	R1										-	1.75, 137	-			
x[d]	**N2**										-	-	**1.51, 117**			
6	**N1**													**3.43, 137**	-	-
	R1													-	0.56, 431	-
√[e]	**N2**													-	-	**0.42, 392**

~~Correlations~~	~~1~~		~~2~~		~~3~~		~~4~~			~~5~~			~~6~~		
~~Polarity zone\chron~~	~~C18n~~	~~C18r~~	~~C17n~~	~~C17r~~	~~C16n.2n~~	~~C16r~~	~~C16n.1n~~	~~C16n.1r~~	~~C16n.2n~~	~~C15n~~	~~C15r~~	~~C16n~~	~~C13n~~	~~C13r~~	~~C15n-C1~~
~~(Depth, n cycles)\(myr)~~	~~1.529~~	~~1.01~~	~~1.363~~	~~0.283~~	~~0.649~~	~~0.269~~	~~0.186~~	~~0.159~~	~~0.649~~	~~0.295~~	~~0.411~~	~~0.994~~	~~0.548~~	~~1.294~~	~~3.334~~
~~N1 (32.2-51.0 m, ~4)~~	~~1.23~~	~~–~~	~~1.38~~	~~–~~	~~2.90~~	~~–~~	~~10.11~~	~~–~~	~~–~~	~~6.37~~	~~–~~	~~–~~	~~3.43~~	~~–~~	
~~R2 (25.0-32.2m, ~3)~~	~~–~~	~~0.71~~	~~–~~	~~2.54~~	~~–~~	~~2.68~~	~~–~~	~~4.53~~	~~–~~	~~–~~	~~1.75~~	~~–~~	~~–~~	~~0.56~~	
~~N2 (25.0-11.0 m, ~8.5)~~	~~–~~	~~–~~	~~–~~	~~–~~	~~–~~	~~–~~	~~–~~	~~–~~	~~2.31~~	~~–~~	~~–~~	~~1.51~~	~~–~~	~~–~~	~~0.42~~
~~Periodicity of cycle (kyr)~~	~~382~~	~~337~~	~~341~~	~~94~~	~~162~~	~~90~~	~~47~~	~~53~~	~~76~~	~~74~~	~~137~~	~~117~~	~~137~~	~~431~~	~~392~~
~~Remark~~	~~x[a]~~		~~x[b]~~		~~x[b]~~		~~x[c]~~			~~x[d]~~			~~√[e]~~		

带格式的: 两端对齐, 段落间距段前: 6 磅, 行距: 1.5 倍行距

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带格式表格

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Note:

*, N1 is defined from 32.2 to 51.0 m and contains ~ 4 sedimentary cycles; R2 is defined from 25.0 to 32.2 m and contains ~3 sedimentary cycles; N2 is defined from 11.0 to 25.0 m and contains ~8.5 sedimentary cycles. Bold (regular) fonts indicate normal (reversed) polarity zones/chrons; The two numbers in each cell are sedimentation rate in cm/kyr and the perodicity of the sedimentary cycle (in kyr) calculated based on the correlation. For example, 1.23, 382 in the very first cell indicate that the sedimentation rate is 1.23 cm/kyr and the sedimentary cycle represents 382 kyr based on Correlation 1. "-" denotes "not applicable"; "x" indicates that the correlation is unrealistic and is rejected. " √ " indicates acceptable correlations; a-e provides brief comments on why the correlation is rejected or accepted. a, the correlation would place the majority of the Youganwo Fm, i.e., N2-N3, to the middle Eocene;

b, the correlation would result in sedimentation rates in R2, i.e., the Youganwof Fm, faster than or similar to those in N1, i.e., the Huangniuling Fm; c, the correlation leads to the drastic difference in sedimentation rates between the upper (R2) and lower (N2) part of the studied Youganwo Fm; d, the sedimentation rates for the Youganwo oil shale are too fast in comparison to those of well-dated organic-rich shales in deep-time; e, the sedimentation rates of the Youganwo oil shale are compatible with those of well-dated organic-rich shales in deep-time and the sedimentary cycles in both Huangniuling Fm (N1) and the Youganwo Fm (R2 and N2) are in the orbital frequency bands and likely represent eccentricity cycles.~~The black/white background stand for the normal/reversed polarity zones/chrons; Depths are in meters; n = number of sedimentary cycles; sedimentation rates in the table are in cm/kyr; "-" denotes "not applicable"; "x" indicates that the correlation is unrealistic and is rejected. " √ " indicates acceptable correlations; a-e provides brief comments on why the correlation is rejected or accepted. a, the correlation would place the majority of the Youganwo Fm, i.e., N2-N3, to the Middle Eocene; b, the correlation would result in sedimentation rates in R2, i.e., the Youganwof Fm, faster than or similar to those in N1, i.e., the Huangniuling Fm; c, the correlation leads to the drastic difference in sedimentation rates between the upper (R2) and lower (N2) part of the studied Youganwo Fm; d, the sedimentation rates for the Youganwo oil shale are too fast in comparison to those of well-dated organic-rich shales in deep-time; e, the sedimentation rates of the Youganwo oil shale are compatible with those of well-dated oragnic-rich shales in deep-time and the sedimentary cycles in both Huangniuling Fm (N1) and the Youganwan Fm (R2 and N2) are in the orbital frequency bands and likely represent eccentricity cycles. see text for details.~~

Figure captions

Figure 1 Location and regional geology of the study area. (a) Map showing the location of the Maoming Basin, Guangdong Province, southern China. (b) Simplified geological map of the Maoming Basin. 1. Precambrian; 2. Upper Cretaceous; 3. Youganwo Fm.; 4. Huangniuling Fm.; 5. Shangcun Fm.; 6. Laohuling Fm.; 7. Gaopengling Fm.; 8. Quaternary; 9. Fault; 10. Investigated Jintang section. MR, MB, and MS mark the sites where samples were collected for a magnetostratigraphic study by Wang et al. (1994). See text for details.

Figure 2 Stratigraphy of the investigated section exposed in the now-abandoned open mine pit in Maoming Basin. Lithostratigraphic column~~s~~ (a) shows that the investigated section contains the Youganwo Fm in the lower part and the Huangniuling Fm in the upper part. ~~, sedimentary cycles (b), and field photographs (c-e) of the investigated section exposed in the now-abandoned open mine pit in Maoming Basin.~~ The Huangniuling Fm part of the stratigraphic column schematically shows the overall rhythmic sedimentary feature that is characterized by the occurrence of a thin bed (shown in short red lines) of red coarse sandstone at the base, followed by massive grey sandstone that is capped by light grey clays. The Youganwo Fm also exhibits sedimentary rhythms that are characterized by repeated occurrence of the beds with distinct reddish color at distance that are indicated by the pinkish lines. Sedimentary cycles (b) are reflected by magnetic susceptibility data. The distinct reddish beds in the Youganwo Fm and the thin red sandstone layers in the Huangniuling Fm generally correspond to the magnetic susceptibility peaks. The distinct thin red sandstone layer in the Huangniuling Fm is numbered ~~(b)~~ and a total of 19 repeated sedimentary packages (cycles) are identified. ~~The beds with distinct reddish color at distance in the Youganwo Fm are indicated by the pinkish lines and these beds generally correspond to the magnetic susceptibility peaks (b)~~. Note the different scales of the magnetic susceptibility of the Youganwo Fm (the lower part) and the Huangniuling Fm (the upper part)~~ in (b)~~. Field photographs (c-e) show the major sedimentary features of the two formations and the contact between them. In (c), the red arrows indicate the red, thin marker bed of sandstone in the Huangniuling Fm. In (d), the arrow marks the contact between the two formations, displaying a continuous, gradual transition from brown grey mudstones at the uppermost of the Youganwo Fm to pale grey mudstones at the base of the Huangniuling Fm. In (e), the yellow ellipse at the lower-middle part of the picture marks a person (~1.6 m) for scale; red arrows point to several distinctive reddish layers that form the sedimentary rhythms in the Youganwo Fm. br grey = brown grey, lt grey = light grey.

Figure 3 Spectral analysis of the depth series of magnetic susceptibility the Youganwo oil shale. The analysis reveals dominant sedimentary cycles with cycle wavelength ratios similar to periodicity ratios of orbital cycles, suggesting that these sedimentary cycles are orbital frequency bands. The red curve represents the noise level above which the spectral peaks are considered statistically significant. The numbers above the spectral peaks indicate cycle wavelength (in cm) of the sedimentary cycles.

Figure ~~3~~4 Anisotropy of magnetic susceptibility (AMS) data of the Youganwanwo Fm (a, b) and the Huangniuling Fm (c, d). k1, k2, k3 are the maximum, intermediate, and minimum axis of the anisotropy ellipsoid, respectively. (a, c) are the equal area projection of these principal axes. No. is the number of specimens. T and Pj in (b, d) are the shape factor and the degree of anisotropy, respectively (Jelinek, 1981).

Figure ~~4~~ 5 Rock magnetic data of samples from the Youganwo Fm and Huangniuling Fm. (a) – (e), thermal changes of magnetic susceptibility (MS) of samples from the Huangniuling mudstone (a, b), the uppermost brown grey shale (c) and the oil shale (d, e) of the Youganwo Fm during a heating-cooling cycle between room temperature and 700 ° C; (f), IRM acquisition and the subsequent demagnetization in a backward DC field~~.~~ ; (~~b~~g-~~d~~j), ~~thermal changes of magnetic susceptibility (MS) of samples from the uppermost brown grey shale (29.3 m) and the oil shale (17.2 m) of the Youganwo Fm.~~ Zero-field-cooled (ZFC) and field-cooled (FC) low temperature measurements of the representative samples. The arrow in (g) marks the subdued Verwey transition; (~~d~~k-o) ~~shows the first derivative of the heating curve of (e) between 265 °C and 395 °C~~ thermal demagnetization of composite IRM along Z-, Y-, and X-axis at a field of 1.2T, 0.6T, and 0.125T, respectively.

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Figure ~~5~~ 6 Representative demagnetization data of samples from the studied section. Open/closed squares indicate the vertical/horizontal components.

Figure ~~6~~ 7 Characteristic remanent magnetization in stratigraphic coordinates. The solid/open symbols represent the lower/upper hemisphere projection.

Figure ~~7~~ 8 Integrated litho-, cyclo-, and magnetostratigraphy of the investigated section, and the correlation with the δ18O and δ13C records from the equatorial Pacific deep-sea sediments (ODP site 1218) (Pälike et al., 2006) that show the Eocene-Oligocene climatic transition (EOT). The legends for lithology and sedimentary cycles are the same as those in Fig. 2. In (c,d), the solid (open) symbols represent “A”(“B”)-quality ChRM data.