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Interactive comment on "Astronomical calibration of the geological timescale: closing the middle Eocene gap" *by* T. Westerhold et al.

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Climate of the Past Discussions

Reply to Interactive comment of Anonymous Referee 1 on "Astronomical calibration of the geological timescale: closing the middle Eocene gap" by T. Westerhold, U. Röhl, T. Frederichs, S. Bohaty, and J. Zachos.

We thank Anonymous Referee 1 for taking the time and effort to review our manuscript. The referee states that the data should be reported to the scientific community but feels the manuscript in its current form is flawed primarily due to the absence of a complete comparison with and discussion of terrestrial radioisotopic chronologies. This assessment, however, is expressed as a general statement on the strategy and is not

supported by specific examples. We would appreciate if the referee would provide details of these specific issues as they relate to this study.

Anonymous Referee 1 main point of criticism is that the manuscript does not include any comparison and discussion of the Geomagnetic Polarity Time Scale (GPTS) calibrations from high-resolution radio-isotopic dating of Eocene terrestrial strata. As indicated by the referee, there has been much recent work on radio-isotopic dating of terrestrial Eocene records. The Green River Formation, in particular, has been utilized during the last 20 years towards improving the Eocene GPTS. We agree that it would be beneficial to discuss our results in the context of the most recently developed GPTS of the Green River Formation (e.g. Smith et al. 2010; Machlus et al. 2008, 2015; Tsukui and Clyde 2012). Therefore, in the revised version of the manuscript we will add a paragraph or two to discuss this issue including modifying Figure 7 as shown below. A very detailed comparison between marine and terrestrial records is well beyond the scope of this paper, which is intended to focus on marine Eocene records. A more in-depth synthesis and discussion of terrestrial and deep-sea GPTS for the Eocene will be better addressed in synthesis papers similar to the Paleogene chapter in the GTS2012 (Vandenberghe et al. 2012) or ongoing efforts of the wider community toward the ATS2020. Such an effort would likely require interaction of experts both on terrestrial and deep-marine Paleogene geochronology as the stratigraphy of terrestrial successions, and specifically correlation of sections and accurate age dating of ash layers, is highly complex (for example see discussion in Clyde et al., 1997, 2001, 2004; Machlus et al., 2004, 2008, 2015; Smith et al., 2003, 2004, 2006, 2008, 2010; Tsukui and Clyde 2012; Westerhold and Röhl 2009). Here, we illustrate this by adding the GPTS calibrations from Smith et al. 2010 and Tsukui and Clyde 2012 to Figure 7 of our manuscript (see Figure below). Considering the latest Green River Formation GPTS calibrations (all adjusted and reported by Smith et al. 2010 and Tsukui and Clyde et al. 2012 to FCT 28.201 Ma of Kuiper et al. 2008), it is clear that substantial differences in calibration and interpretation exist based on very similar data sets (across Chron C20 and C21, for example).

How complex the GPTS calibrations in terrestrial records are can be grasped looking at the discussion in Tsukui and Clyde (2012) comparing their results to those of Smith et al. (2010): ”Smith et al. (2008a, 2010) recalibrated the interval, C24 through C20 based on 40Ar/39Ar ages of ash beds, existing magneto-stratigraphic data, NALMA biostratigraphy from the Bighorn Basin, Wind River Basin, Greater Green River Basin, Uinta Basin, Devil’s Graveyard Formation in Texas, and Absaroka volcanic province, as well as marine biostratigraphy from San Diego region (see table 4 in Smith et al., 2008a). However, uncertainties remain in the correlation of some of the tuffs to local magnetostratigraphic records (e.g., Layered tuff, Sixth tuff, and Continental Peak tuff). This model implies the presence of several short- duration polarity chrons that are not shown in the original marine magnetic anomaly records of Cande and Kent (1992). Smith et al. (2008a) attributed those to tiny wiggles described in Cande and Kent (1992).”

Because most of the radio-isotopic dates for ash layers in the Green River Formation are based on 40Ar/39Ar ages, they are directly dependent on the absolute age of the FCT standard (see discussion in Westerhold and Röhl 2009 and Westerhold et al. 2012). High quality U/Pb ages are also available for some ash layers (Smith et al. 2010 [Analcite and Firehole tuff] and Machlus et al. 2015 [Sixth, Layered, Main, Grey, Second, Firehole and 1448 Tuff]). The Firehole tuff has a consistent U/Pb age of 51.66 ± 0.19 Ma in Smith et al. (2010) and 51.528 ± 0.061 Ma in Machlus et al. 2015. The 40Ar/39Ar age of the Firehole Tuff is 51.40 ± 0.25 Ma (FCT 28.201 Ma) (Smith et al. 2010). The Firehole tuff, however, was not included by Smith et al. (2010) for recalibrating the GPTS. According to Tsukui and Clyde (2015) the Firehole tuff is in a paleomagnetic reversal, likely C23r (See table DR4 in Tsukui and Clyde). Unfortunately, the Analcite Tuff (U/Pb 49.23 ± 0.12 Ma, Smith et al. 2010) has not clear paleomagnetic polarity (Tsukui and Clyde 2015). Comparing the radioisotopic ages used by Smith et al. (2010) and their paleomagnetic pattern with the astronomically calibrated GPTS (see figure) shows consistent results for the Mission Valley ash (in C20n), the Montanari ash (in C21n), the Blue Point Marker ash (in C21r), the Continental tuff (in

C22n), the Firehole tuff (in C23r) and the Willwood ash (in C24n). Inconsistencies are apparent for the Sixth tuff and Layered tuff which have a normal polarity but correlate to C22r in the astronomical GPTS. Tsukui and Clyde (2012) utilized more ash layers for their calibration that has substantial differences to the GPTS by Smith et al. (2010) from C21n to C24n (see figure). Some ash layers, for example in C21r and C23n of the GPTS of Tsukui and Clyde (2012), have an opposite polarity although they are of similar age. The GPTS of Tsukui and Clyde (2012) is more consistent with the astronomical GPTS for Chron C22 and C23, but the Sixth ash, the Layered tuff and the Main tuff occur in an interval of normal polarity correlate to C22r in the astronomical GPTS. In contrast, the Firehole tuff, located in an interval of reversed polarity, is positioned in C23n according to the GPTS of Tsukui and Clyde (2012). We would argue here that the calibration of Tsukui and Clyde (2012) for the duration of C23n is probably too long. A detailed comparison of the GPTS for Chrons C22 and C23 between terrestrial and deep-sea records is difficult at the moment because the deep-sea and the terrestrial GPTS still need to be scrutinized in the early Eocene, as described in our submitted manuscript. This is subject of an ongoing study. Nevertheless, it seems at present the records do fit for Chron C24n suggesting that both astrochronology and radio-isotopic dating of terrestrial successions are in agreement at least for this time interval.

For a revised manuscript we will add the GPTS calibrations from selected terrestrial sections to figure 7 of the submitted manuscript and make a comparison chapter in the discussion. We have to point out here again that the goal of our study is, as explicitly described in the abstract and introduction, to develop a robust Astronomical Time Scale (ATS) for the Paleocene and Eocene that is not dependent on radio-isotopic ages and unstable parts of the astronomical solutions. We have chosen the state-of-the-art approach by establishing a complete stratigraphic framework for the Cenozoic that is based on the identification of the stable 405-kyr eccentricity cycle and is rooted in the Neogene to late Eocene where all components of the orbital solutions are stable and uncertainties in radio-isotopic ages are negligible.

More specifically we like to reply to some comments and statements of anonymous Referee 1 here: 1) “If this paper were resubmitted, it should include a robust discussion/comparison of existing geochronologic data with their interpretations.” – We agree this is an important and ambitious task, one that is beyond the focus and reach of this study. Given the complexity of such an endeavor, it will require a collaborative community effort aim for a synthesis toward the next generation of ATS.

2) “The paper should also consider the potential effects of changes in sedimentation rate, lacunae, and the possibility that some of the observed facies variability is not the direct consequence of orbital fluctuations (i.e., stochastic variations due to local effects).” – To start, the isotope records from ODP Sites 702 and 1263 are the first high-resolution chemostratigraphic records for the Chron C20r interval, a time interval that usually is characterized by stratigraphic gaps in many marine sections. Average resolution reached for Site 702 is âĹij13 kyr and for Site 1263 as good as 5 kyr. Comparing two deep-sea records about 3500 km apart indicates that these monitor global rather than local variations in the, e.g., carbon isotope inventory. In this way, the stable carbon isotope data, when integrated with magnetostratigraphy, can be used to correlate sites with high confidence and identify potential stratigraphic issue, an approach routinely used throughout the Cenozoic. In Figure 5 A of our manuscript the 702 and 1263 bulk δ13C records show similar patterns. The slight offset between records from 44.5 to 48 Ma is not uncommon and could be related to regional or local effects (e.g. ocean circulation, local productivity, etc.). However, the overall pattern used for cyclostratigraphy is similar and highly suitable for time scale construction as outlined in the submitted manuscript. Our two records characterized by unprecedented completeness and data resolution 3500 km apart allow to identifying potential stratigraphic gaps in the records. But, of cause, if a stratigraphic gap is present in both records at the same position then we will not detect this. To check the completeness of the record new sites have to be drilled at other locations of the world ocean. Besides our new, unique deep-sea sections presented in the manuscript, only IODP Exp. 342 (Newfoundland margin, NW Atlantic) has possibly recovered comparable sequences covering Chron C20. Studies on these records are at a relatively early stage and can eventually be compared with the results from Sites 702 and 1263 in South Atlantic. Hence, our presented data are only available state of the art record and provides first insights to the Chron C20 cyclostratigraphy at short eccentricity resolution and higher.

3) “A consideration of the nature radioisotopic tie points within the CK95 timescale (upon which the authors erect their chronology) should also be included. Why is it that these low resolution multi-crystal input data are considered reliable while literally tens of other newer single crystal Ar and U-Pb dates are dismissed out of hand? This sort of skepticism and interpetive caution is essential to science, and is almost completely lacking in the manuscript’s current form (other than a brief consideration - and dismissal - of a missing 18th cycle after the authors have already burrowed deeply into their interpretations)” – There is a conceptual misunderstanding here by the referee. We did not use the CK95 timescale to compile our chronology, nor are we dismissing newer single crystal dates. Indeed, we applied the CK95 time scale to demonstrate that the cycles observed in the depth domain are short and long eccentricity cycles. Choosing any of the more recent GPTS calibrations would not change this finding. We preferred to not use any of the new GPTS for this purpose to avoid bias from orbitally tuned records. The aim of this study, as mentioned in the manuscript and above, is to directly connect the middle to early Eocene and Paleocene cyclostratigraphy for the first time with the Neogene to late Eocene cyclostratigraphy based on the identification of the stable 405 kyr eccentricity cycle. We only made use of the 405 kyr cyclostratigraphic framework to circumvent the uncertainties in some components of the orbital solutions (see Westerhold and Röhl (2009) for more details). Integrating our here presented records with the section from ODP Site 1260 (Westerhold and Röhl 2013), which has been directly connected to the late Eocene 405 kyr cyclostratigraphy (Westerhold et al. 2014), provides an independent cyclostratigraphy covering the Eocene gap. Linking the older 405-kyr cyclostrati-graphies from the middle to early Eocene and Paleocene completes the 405-kyr cyclostratigraphic framework for the total of the Paleogene. No radio-isotopic age points are needed for this task. The new cyclostratigraphy gives consistent results

for e.g. the U/Pb and cyclostratigraphic age for the PETM. Remaining issues are in Chrons C22-C23 as already mentioned above due to the lack of high-quality magnetostratigraphic data both in terrestrial and deep-sea records. However, this does not affect the 405-kyr cyclostratigraphic framework, but the exact location and duration of reversals in Chrons C22 and C23 (as discussed in the submitted manuscript). It is very clear that we do not use CK95 to build our cyclostratigraphy. It is not our aim to discuss which radio-isotopic age is more reliable then the other in our manuscript. This requires contributions from the broader community including colleagues who are familiar with the stratigraphy of the terrestrial sections. We are very confident that our approach is scientifically sound and that we naturally include skepticism and caution in our interpretation of data in general.

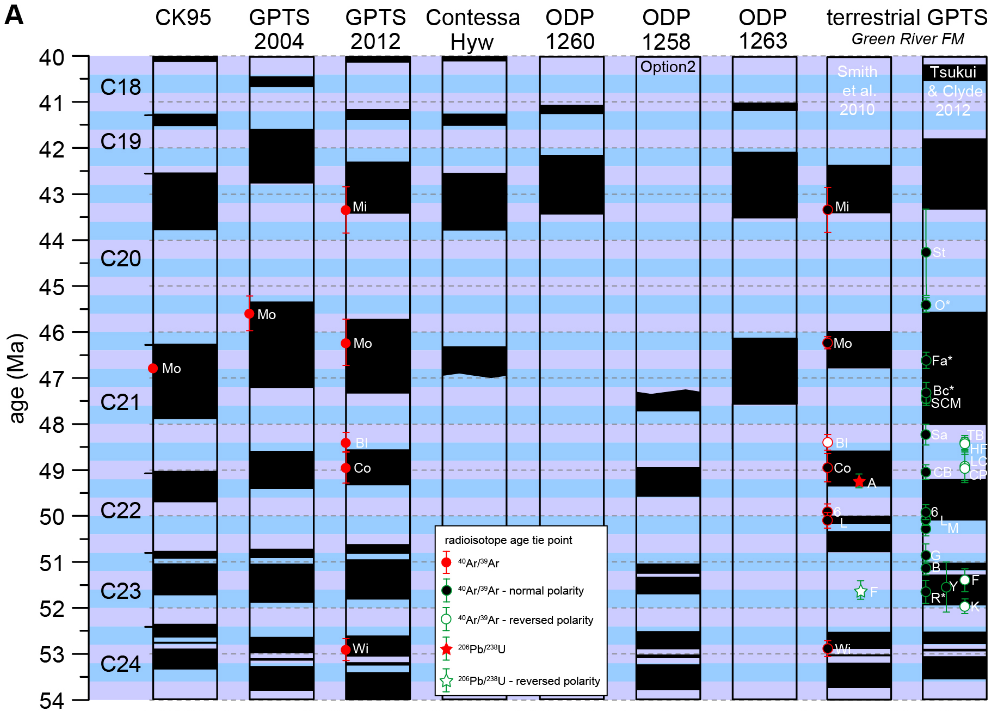
4) “I strongly suggest that this manuscript be rejected in its current form. If resubmission is considered, the manuscript should not ignore the last two decades of geochronology and focus on the high quality magnetostrat and d13C data contained within.” – We do not feel that is a fair assessment of our approach. We do not ignore the last two decades of geochronology, as demonstrated in the revised Figure 7. The most complete overview including many of the terrestrial records is provided by Vandenberghe et al. (2012). Again, a detailed discussion and review of the entire Paleogene geochronology is a major undertaking that is not the focus of this manuscript. It requires a community effort toward ATS2020. As we present the first very high-resolution δ13C stratigraphy and magnetostratigraphy for Chron C20 we do not understand the 2nd part of the referee′s statement. Other records of comparable completeness and resolution do not exist to our knowledge for terrestrial sections.

We propose to add a chapter discussing terrestrial successions and the GPTS calibrations in more detail to a revised version of the manuscript to be submitted after the discussion phase. In addition we propose to initiate a more detailed future review or synthesis paper, an advanced study similar to the Paleogene chapter in GTS2012, by making a workshop including the wider community (both marine and terrestrial

astro- and radioisotope-stratigraphy) and supported by Subcommission on Paleogene Stratigraphy.

FIGURE CAPTION: Figure – modified Figure 7 from the submitted manuscript: Geomagnetic Polarity Time Scale of CK95 (Cande and Kent, 1995), GPTS2004 (Ogg and Smith, 2004) and GPTS2012 (Ogg, 2012; Vandenberghe et al., 2012) compared to astronomical calibrations of magnetochrons from Contessa Highway (Jovane et al., 2010), PEAT sites (Westerhold et al., 2014), Site 1260 (Westerhold and Röhl, 2013), Site 1258 (Westerhold and Röhl, 2009; Westerhold et al., 2012), 1263 (this study), and now also the Green River Formation GPTS from Smith et al. (2010) as well as Tsukui and Clyde (2012) from 40–54 Ma added. Small red dots with error bars mark the radio-isotopic calibration points used for CK95, GPTS2004, GPTS2012 and Smith et al. (2010); green circles show calibration points for the terrestrial sections.

Interactive comment on Clim. Past Discuss., 11, 1665, 2015.



A=Analcite tuff; B=Boar tuff; Bc*=Blind Canyon tuff; Bl=Blue Point Marker ash; CB=Chruch Butte tuff; Co=Continental tuff; CP=Continental Peak tuff; Fa*=Fat tuff; F=Firehole tuff; G=Grey tuff; HF=Henry Fork tuff; K=K-spar tuff; L=Layered tuff; LC=Leavitt Creek tuff; M=Main tuff; Mi=Mission Valley ash; Mo=Montanari ash; O*=Oily tuff; R=Riffe tuff; Sa=Sage tuff; SCM=Sage Creek Mt. pumice; 6*=Sixth tuff; St=Strawberry tuff; TB=Tabernacle Butte tuff; Wi=Willwood ash; Y=Yellow tuff.

Note: all ages for terrestrial records from Smith et al. (2010) and Tsukui & Clyde (2012) are sanadine ^{40}Ar/^{39}Ar ages relative to 28.201 Ma for Fish Canyon sanadine (Kuiper et al. 2008); ashes markt by * are biotite ages; Analcite tuff is U/Pb age.

Fig. 1. modified Figure 7