Author's response: Batenburg et al., 2016

J. Laurin

Dear authors,
Congratulations on excellent data and an interesting paper. This study is an important contribution, although it might benefit from a better explanation of your approach to astronomical tuning. Could you please comment on the following points?
Published studies (Mitchell et al. 2008; Lanci et al. 2010) suggest relatively uniform sedimentation rates throughout the Furlo section (except of the Bonarelli L.). Your tuning options 1 and 2 imply markedly increased sedimentation rates (or reduced compaction) in the uppermost ∼3 m beneath the Bonarelli Level (from ∼1 cm/kyr to approximately 1.5 cm/kyr) and results in a ∼100 kyr difference relative to the published age models. I realize that this part of the Furlo section is particularly difficult to interpret. Your L* data look great, and after examining your figures in detail I believe your age model might be correct (the apparent increase in both spacing and thicknesses of organic-rich beds in this interval are consistent with your interpretation). As it is, however, your tuning in this interval does not look very convincing. In section 3.3, lines 20-21 you explain that the identification of 405-kyr maxima and minima is based on a 3-5 m bandpass of L* data at Furlo. In both tuning options, however, the uppermost bandpassed maximum below the Bonarelli Level is out-of-phase relative to the 405-kyr maximum in La2011 to which it is correlated. You are apparently using other criteria, but they are not explained. I assume the correlation is based on the bundling of organic-rich beds. This aspect is, however, also problematic, because your lithological log for this interval shows important differences from L*, and it is not clear which of these two is used to define the bundles. For example, the circumflex that should mark the uppermost organic-rich bundle beneath the Bonarelli Level is centered at an exceptionally thick limestone in the lithological log (Fig. 3); this seems to contradict the definition of organic-rich bundles. It would be very helpful if you could show the detail of this part of the section and comment on the differences between your lithological log and color reflectance data. This is particularly important considering the disagreement between your interpretation and published age models.

We apologise for the lack of clarity in the tuning of the beds directly underlying the Livello Bonarelli. As this interval is at the edge of the band-pass filter, we prefer to base our tuning on the lithological pattern. The spacing of dark beds is in agreement with the reflectance record, and shows a bundle with thicker cherts and limestones. However, the use of circumflexes to indicate bundles and 100 kyr eccentricity maxima is unclear and introduces some ambiguity. In a revised version of the manuscript, we restrain from using circumflexes. Instead, we use brackets such as "}" spanning whole bundles and their centres as interpreted 100 kyr eccentricity maxima, and we discuss this specific interval in more detail.

Could you please explain why do you prefer tuning option #1 over tuning #2? I believe you have good reasons. Without an explanation (which I cannot find in your manuscript), however, the reader is puzzled especially when considering that your tuning #1 appears incompatible with some of the published radioisotopic/astrochronological estimates for the age of the C/T boundary (cf. Eldrett et al. 2015).

Tuning option #1 is in best agreement with the radioisotopic age for the Mid-Cenomanian event, presented in this study, and the intercalibrated ages for "Ash A" at the base of the *Whiteinella archaeocretacea* zone and the Cenomanian-Turonian boundary. However, tuning #2 is in better agreement with the recently published age of the C/T boundary of Eldrett et al. (2015). Based on our data, we cannot exclude either tuning option, but we discuss the differences with other timescales in more detail.

Your argument for a Myr eccentricity node prior to OAE II is based on the observed gap in the black shale occurrence at 483-485 m (page 8, lines 30-31). According to your tuning options, however, this interval experienced a 50-60% increase in sedimentation rates (or decrease in compaction) compared to the rest of the section beneath BL. If you apply correction for this change in sedimentation rate, then the thickness of the shale-free interval decreases by c. 35 %. Such a correction would make this interval comparable to other 405-kyr minima in this section (e.g., ∼471-472 m) and disqualify the argument for a Myr node. The exceptional thickness of dark levels above this interval (page 8, lines 31-32) can be attributed to the overall increase in (compacted) sedimentation rates as well.

When applying such a correction, the gap in black shale occurrence would indeed be similar in thickness to 405 kyr minima lower down in the Furlo section. What makes this interval remarkable, however, is that the number of black levels generally increases upsection, and that more black levels occur per bundle.

Recent papers (Jenkyns et al. 2007; Gambacorta et al. 2015) reinterpreted the timing of Bonarelli Level at Furlo and Bottaccione relative to the phases of OAEII. Osmium-isotope excursion marking the onset of the event starts immediately beneath the Bonarelli Level at Furlo (du Vivier et al. 2014). Thus, the possibility that Bonarelli Level represents only the second buildup phase and plateau (page 7, lines 30-31) seems to be outdated (see, for example, figure 12 in Gambacorta et al. 2015). Does this change affect your estimate of the OAE II duration?

As our age model is not based on chemostratigraphic correlation, our estimate of OAE2 duration is not affected. The duration between the start of the $\delta^{13}C$ excursion and the C/T boundary is estimated at 490 kyr. We came to this value by taking into account the estimated duration of the Livello Bonarelli (based on time series analysis of high resolution XRF data), and the 405-kyr tuning for the interval between the top of the Livello Bonarelli and the C/T boundary. We do not consider a large hiatus as proposed by Gambacorta et al (2015) likely, as we have the first occurrence of *Quadrum gartneri* (see also next paragraph). A duration of 490 kyr between the onset of OAE2 and the C/T boundary is, within our stratigraphic uncertainty, in good agreement with the estimate of 538 kyr by Laurin et al. (2016), adapted from the work of Ma et al (2014) and Sageman et al (2006).

Gambacorta et al. (2015) interpret hiatuses in the upper part of the Bonarelli Level at Furlo and other sites in the Umbria-Marche Basin. Could you please indicate how are these hiatuses considered in your age model?

Hiatuses could occur at the sharp shifts in sedimentary facies at the base and the top of the Livello Bonarelli. If such hiatuses are (together) near 405 kyr in duration, they could result in a similar sedimentary rhythm and go unnoticed in our analyses. However, we would expect such a hiatus to have a more pronounced sedimentary expression. The potential for a hiatus at the base of the Livello Bonarelli was previously recognised by Jenkyns et al. (2007), and estimated to be on the order of 20 kyr. Such a hiatus would be small relatively to our tuning target, the 405 kyr periodicity of eccentricity. We would be happy to include a short paragraph on this issue in the revised version of the manuscript.

Let me add a note on the paper by Lanci et al. (2010), which is criticized in your text. The phase calibration in this paper was based on a previous astronomical solution (La2004), and is probably incorrect as you noted. The change of interpretation is, however, not due to an incorrect sampling strategy by Lanci et al. (2010). We recently revisited the topic using the same data and simple numerical models. The results suggest that the omission of precession-paced organic layers in Lanci et al. (2010) does not distort the 100-kyr and 400-kyr eccentricity signatures to a degree that would prevent detection of 405-kyr eccentricity phases (Fig. S1.5 in the supporting information of Laurin et al., in press). I would not say that the sampling in Lanci et al. (2010) was “incorrect” (page 6, line 23 in your paper). It was correct considering that the authors needed to avoid lithological bias to focus on the record of changing bottom-water oxygenation in rock-magnetic properties. They just could not have assessed precession-scale variability, which is a major advantage of your color reflectance data.

We changed the wording of our criticism. However, in the revised version of the manuscript, we are still making clear that, if one does not take into account chert samples, the precession signal is largely eliminated in the intervals of the chert bundles while the weaker precession signal in the limestone beds in between is kept. This is the reason why the precession filtered signal (Fig. 4b in Lanci et al., 2010) suggests the opposite (wrong) phase relation with eccentricity.

I believe the above issues can be fixed. Your paper includes important data and interpretations, and I am hoping to see the final version published soon.
Yours sincerely, Jiˇrí Laurin (Institute of Geophysics ASCR, Prague; laurin@ig.cas.cz)

References

Eldrett, J. S., Ma, C., Bergman, S. C., Lutz, B., Gregory, F. J., Dodsworth, P., Phipps, M., Hardas, P., Minisini, D., Ozkan, A., Ramezani, J., Bowring, S. A., Kamo, S. L., Ferguson, K., Macaulay, C., and Kelly, A. E.: An astronomically calibrated stratigraphy of the Cenomanian, Turonian and earliest Coniacian from the Cretaceous Western Interior Seaway, USA: Implications for global chronostratigraphy, Cretaceous Research, 56, 316-344, http://dx.doi.org/10.1016/j.cretres.2015.04.010, 2015.

Gambacorta, G., Jenkyns, H. C., Russo, F., Tsikos, H., Wilson, P. A., Faucher, G., and Erba, E.: Carbon- and oxygen-isotope records of mid-Cretaceous Tethyan pelagic sequences from the Umbria – Marche and Belluno Basins (Italy), Newsletters on Stratigraphy, 48, 299-323, 10.1127/nos/2015/0066, 2015.

Jenkyns, H. C., Matthews, A., Tsikos, H., and Erel, Y.: Nitrate reduction, sulfate reduction, and sedimentary iron isotope evolution during the Cenomanian-Turonian oceanic anoxic event, Paleoceanography, 22, n/a-n/a, 10.1029/2006PA001355, 2007.

Lanci, L., Muttoni, G., and Erba, E.: Astronomical tuning of the Cenomanian Scaglia Bianca Formation at Furlo, Italy, Earth and Planetary Science Letters, 292, 231-237, http://dx.doi.org/10.1016/j.epsl.2010.01.041, 2010.

Laurin, J., Meyers, S. R., Galeotti, S., and Lanci, L.: Frequency modulation reveals the phasing of orbital eccentricity during Cretaceous Oceanic Anoxic Event II and the Eocene hyperthermals, Earth and Planetary Science Letters, 442, 143-156, http://dx.doi.org/10.1016/j.epsl.2016.02.047, 2016.

Ma, C., Meyers, S. R., Sageman, B. B., Singer, B. S., and Jicha, B. R.: Testing the astronomical time scale for oceanic anoxic event 2, and its extension into Cenomanian strata of the Western Interior Basin (USA), Geological Society of America Bulletin, 10.1130/b30922.1, 2014.

Sageman, B. B., Meyers, S. R., and Arthur, M. A.: Orbital time scale and new C-isotope record for Cenomanian-Turonian boundary stratotype, Geology, 34, 125-128, Doi 10.1130/G22074.1, 2006.