Author’s response: Batenburg et al., 2016

<u>Reviewer #2</u>

This study can be regarded as an extension of an earlier investigation on cyclicity and astrochronology of the same successions, published by Mitchell et al. 2008. This study includes a detailed C-isotope data set and it adds new radioisotope data. The results of this study are mostly in agreement with the earlier study. Additional information is gained on the mode of circulation during OAE2 and on the behaviour of the global carbon cycle before, during and after OAE2.

Carbon isotopes and carbon cycle:
Since the carbon isotope data are the most relevant new data in this study, the carbon isotope results deserve more in-depth discussion. The authors see an obliquity pattern in their data but they do not really discuss these data. In most Cretaceous data sets available from the literature, the obliquity pattern seems not preserved in C-isotope records, in few others there is some evidence, especially in the amplification of the signal within longer cycles (see Laurin et al.: .... "net transfers between reservoirs are plausibly controlled by ~1 Myr changes in the amplitude of axial obliquity”). The authors may add some comments on the obliquity – carbon residence time enigma in this study (see also Laurin et al. 2015).

The potential ~1 Myr cycle in the carbon isotope curve is very interesting and we are happy to include this in the discussion of long term orbital forcing and the carbon cycle in a revised version of the manuscript. In general, it seems that the trends in the carbon cycle follow a ~1 Myr pacing, whereas sharp excursions occur at ~2.4 Myr intervals superimposed on this pattern. The high resolution XRF data from the Livello Bonarelli show a likely obliquity pacing, as detected previously during OAE2 by Meyers et al. (2012). This observation likely reflects a long-term (~2.4 Myr) minimum in eccentricity-modulated precession, during which obliquity can become the dominant astronomical parameter driving changes in insolation, as was observed in the Eocene by Westerhold et al. (2014).

They may also discuss possible causes of the remarkable changes in the C-isotope pattern through time. The Turonian C- isotope curve is, across several long eccentricity cycles much more stable than the Cenomanian curve.
The authors may also comment on possible reasons, why the C- isotope pattern remains quite noisy throughout two eccentricity cycles from 476m to 484 m.

The Cenomanian carbon isotope curve indeed seems much more strongly paced by the 405 kyr cycle of eccentricity modulated precession than the Turonian $\delta^{13}C$ curve. A similar phenomenon was observed for the end of the Albian, and interpreted to reflect a change to a more stable ocean circulation pattern (Giorgioni et al., 2012). For the Cenomanian/Turonian, the carbon cycle may have become more stable as CO2 may have been drawn down by black shale formation and volcanic activity, delivering nutrients, may have decreased.
The high variability in $\delta^{13}C$ values from 476 to 484 m coincides with the frequent occurrence of organic-matter rich intervals. Potentially, this may have influenced the $\delta^{13}C$ values of, for example, early diagenetic cements.

Climate and oceanography:
It will be important to integrate new information on ocean chemistry, including new Nd- isotope data, into new ocean circulation models. It seems remarkable, that OAE 2 was characterised by a change in Tethys-Atlantic circulation, if Nd-isotope data are integrated into circulation reconstructions (e.g. Martin et al., 2012). An integration of geochemistry into improved circulation models will add value to this study which otherwise may be regarded just as a repetition of the Mitchell et al study. Carbon isotopes and oceanography (p.6): Relatively low values of δ13C are be associated with stratification of the water column and reduced yearly integrated primary productivity (Sprovieri et al., 2013): » Do these peculiar water mass conditions in the western Tethys control the C-isotope composition of the global marine carbon pool, or do you suggest “global stratification”? Conversely, high δ13C values likely do reflect good bottom water ventilation during eccentricity minima, with a prolonged avoidance of seasonal extremes, allowing for more stable primary productivity over the annual cycle which may have caused the increase

in marine δ13C Âˇn see e.g. Nd-isotope work by e.g. Martin et al (2012) and others on deep-water formation during OAE 2.

We agree with the reviewer that new Nd-isotope data are essential for a better understanding of ocean circulation before and during OAE2. Although beyond the scope of this manuscript, this is part of the ongoing research by S. J. Batenburg. The Nd-isotope of Martin et al (2012) and others indicates a change in deep water formation and exchange at the Cenomanian-Turonian transition, which may have driven the transport of nutrients and black shale deposition. Such a change in circulation may have resulted from astronomically-forced changes in seasonality and the hydrological cycle.
As mentioned in the reply to reviewer #1, we highlight the differences between our manuscript and the Mitchell et al. (2008) study in the revised version of the manuscript. The remarks on the patterns in $\delta^{13}C$ values refer to the western Tethys, where regional anoxia already developed episodically before OAE2.

Figures
Please, add a stratigraphy figure to the chapter “geological setting” and to the regional map. This is fundamental information for the reader.

We gladly include a generalised stratigraphy of the Umbria-Marche basin next to the regional map in a revised version of the manuscript.

References

Giorgioni, M., Weissert, H., Bernasconi, S. M., Hochuli, P. A., Coccioni, R., and Keller, C. E.: Orbital control on carbon cycle and oceanography in the mid-Cretaceous greenhouse, Paleoceanography, 27, 10.1029/2011PA002163, 2012.

Martin, E. E., MacLeod, K. G., Jiménez Berrocoso, A., and Bourbon, E.: Water mass circulation on Demerara Rise during the Late Cretaceous based on Nd isotopes, Earth and Planetary Science Letters, 327–328, 111-120, http://dx.doi.org/10.1016/j.epsl.2012.01.037, 2012.

Meyers, S. R., Sageman, B. B., and Arthur, M. A.: Obliquity forcing of organic matter accumulation during Oceanic Anoxic Event 2, Paleoceanography, 27, 10.1029/2012pa002286, 2012.

Mitchell, R. N., Bice, D. M., Montanari, A., Cleaveland, L. C., Christianson, K. T., Coccioni, R., and Hinnov, L. A.: Oceanic anoxic cycles? Orbital prelude to the Bonarelli Level (OAE 2), Earth and Planetary Science Letters, 267, 1-16, DOI 10.1016/j.epsl.2007.11.026, 2008.

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