https://doi.org/10.1130/G46732Y.1

Millennial-scale climate changes manifest Milankovitch combination tones and Hallstatt solar cycles in the Devonian greenhouse world

A.C. Da Silva[1], M.J. Dekkers[2], D. De Vleeschouwer[3], J. Hladil[4], L. Chadimova[4], L. Slavík[4], and F.J. Hilgen[2]
[1]Sedimentary Petrology Laboratory, Liège University, 4000 Liège, Belgium
[2]Department of Earth Sciences, Utrecht University, PO Box 80125, 3508 TC Utrecht, Netherlands
[3]MARUM–Zentrum für Marine Umweltwissenschaften, Universität Bremen, 28359 Bremen, Germany
[4]Institute of Geology of the Czech Academy of Sciences, CZ-165 00 Prague 6 – Lysolaje, Czech Republic

In his Comment, Matys Grygar (2019) puts forward two main issues: the impact of differential diagenesis on limestone-marl alternations (LMAs) in our papers (Da Silva et al., 2016, 2019), and the insufficient sampling resolution to identify some of the smallest-scale cycles in our *Geology* paper (Da Silva et al., 2019). In his Comment, Smith (2019) criticizes the use of confidence level (CL) for cycle identification. Our answers to these Comments are presented below.

Matys Grygar argues that the studied sediments would be LMAs, which may undergo differential diagenesis during which carbonates dissolve in clay-richer intervals and migrate to carbonate-rich intervals. Therefore, he advocates careful testing of the primary character of the observed bedding. We are well aware of the potential role of differential diagenesis in LMAs. Diagenesis can distort or mimic primary signals in carbonate sequences, through the redistribution of calcium carbonate, creating or enhancing the LMA expression (e.g., Ricken, 1986; Westphal et al., 2010; Nohl et al., 2018). However, we strongly emphasize that the Praha Formation portion of the Pod Barrandovem section (Prague, Czech Republic), studied by us (Da Silva et al., 2016, 2019), is not a classic LMA. Instead, the formation is dominated by limestones with minor clay contents and no cherts. The Praha Formation at Pod Barrandovem, and in other sections (e.g., Hladil et al., 2008, 2010), consists of slightly clayey offshore limestones, mostly hemipelagites and calciturbidites. Calcisiltites, calciturbidites, packstone, grainstone, and carbonate mud prevail, with only rare, very thin, levels of black shales (Hladil et al., 2010, their figure 5; Da Silva et al., 2016, our figure 2; Da Silva et al., 2019, our figure DR1). In Figure 1, we provide photos of the section showing the dominant carbonate lithology. It is unlikely that differential diagenesis played a role in the Praha Formation, with its rather small concentration of clay.

Matys Grygar also advocates that diagenesis could affect immobile elements such as Ti, and that following Westphal et al. (2010), we should use element ratios rather than individual element concentrations. We provide a comparison between the spectral analysis on the logTi data (as in Da Silva et al., 2019) with the spectral analysis of the Ti/Al data on Interval 1 and Interval 2 (Figs. 2 and 3). On both intervals, one observes high spectral power in the multitaper method (MTM) and wavelet for the same spectral peaks. As Matys Grygar writes: This “could definitely show whether the nature (grain size, provenance, mineralogy) of the clastic components changed periodically, as would be expected for a climatic signal.”

Furthermore, the Praha Formation includes carbonate beds with nodular structures, or knobbly bedding surfaces (sensu Mikuláš and Hladil, 2015; see also Fig. 1). Praha Formation trace fossils found in the outcrops in the Prague Basin intersect the nodules. Intersections also occur the other way around, with nodules partly intersecting the trace fossils. This is unambiguous evidence for the simultaneous occurrence of the biogenic activity and the formation of the undulatory surfaces on the sea floor (Mikuláš and Hladil, 2015). The fact that these syn- or early post-depositional features are preserved makes differential diagenesis clearly not a prominent player in this setting.

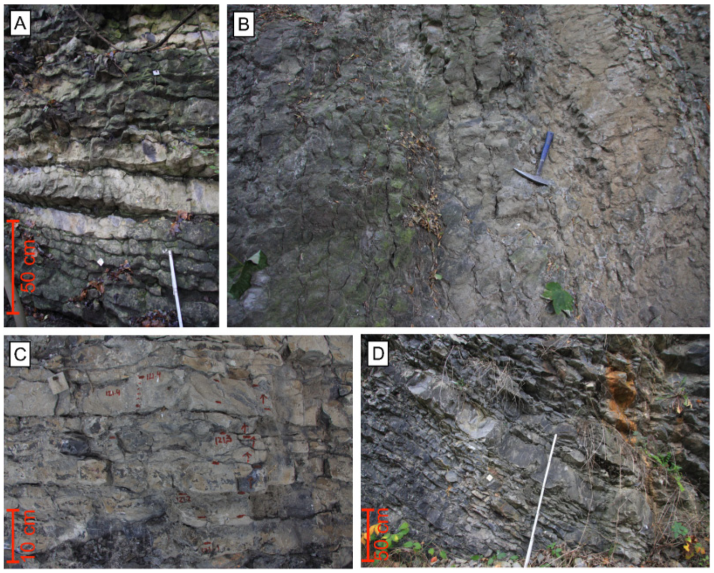

Figure 1. Photos of the Pod Barrandovem section (stratigraphic interval from the Praha Formation, Pragian and Emsian). The bedding dips ~45–60°N, so some of the photos were taken with a tilted angle. (A,B) Photos between 7 and 8 m stratigraphic level and near 18 m (hammer for scale), showing the nodular limestones. (C,D) Photos at ~121 m stratigraphic level and at ~152 m showing the limestone lithology, with thin (~7 cm to ~20 cm) limestone beds.

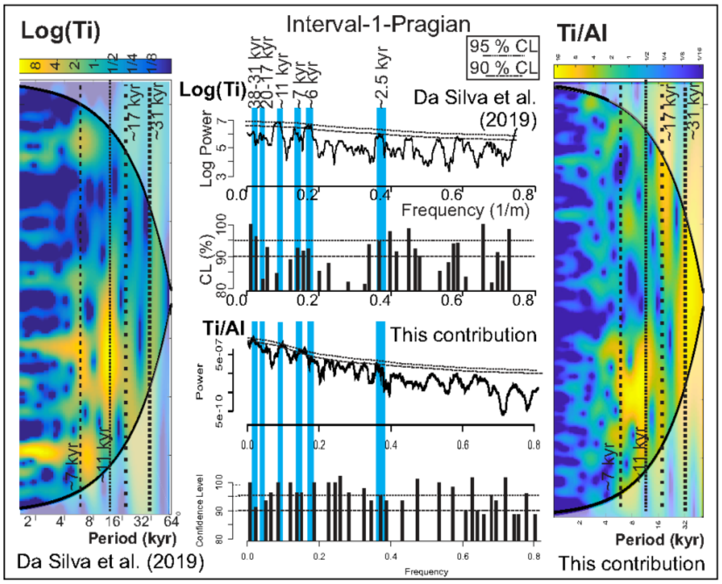

Figure 2. Spectral analysis of interval 1 from the Pragian portion of the Pod Barrandovem section (Czech Republic), including continuous wavelet transform and multitaper method (MTM) spectra (two tapers) of tuned log(Ti) and Ti/Al records (with 90%–95% confidence level, 90%–95% CL). On the MTM spectra, the blue color bars highlight the cycles that are considered significant.

Matys Grygar’s second comment concerns the sampling resolution in Da Silva et al. (2019). He mentions that some of the very short cycles found, lasting 1.5 k.y. and 0.8 k.y., include on average only two or three data points per cycle. He claims that our sampling resolution is insufficient to

https://doi.org/10.1130/G46732Y.1

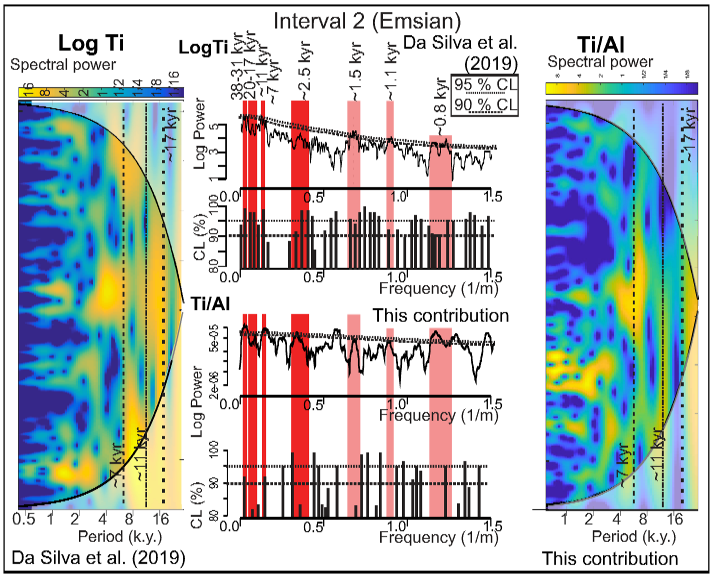

Figure 3. Spectral analysis of interval 2 from the Emsian portion of the Pod Barrandovem section, including continuous wavelet transform and multitaper method (MTM) spectra (two tapers) of tuned log(Ti) and Ti/Al records (with 90%–95% confidence level, 90%–95% CL). On the MTM spectra, the red color bars highlight the cycles that are considered significant.

detect these short cycles. This issue was actually clearly addressed in Da Silva et al. (2019): "In the Emsian interval 2, there are at least five samples per 1.5 k.y. cycle; these cycles are visible in the bandpass-filtered data (Fig. DR2). In the Pragian interval 1, the sampling interval is not sufficient and the bandpass-filtered log(Ti) doesn't catch significant variations (Fig. DR2). We note that this 1.5 k.y. periodicity is very close to the Pleistocene Dansgaard-Oeschger cycles (Dansgaard et al., 1989). However, we refrain from making firm inferences (on these cycles) because the periodicity is detected in only one of our records." In other words, the sampling resolution in Interval 2 is sufficient for 0.8 and 1.5 k.y. cycle interpretations. Matys Grygar is correct in noting that the sampling resolution is insufficient to recognize these cycles in Interval 1, but this was clearly identified in the original manuscript.

In his Comment, Smith (2019) highlights that we focus on cycles identified through MTM and reaching ~95% CL. This approach would lead to overestimates of significant frequencies and may increase the risk of false-positive cycle identification. An exhaustive and clear reply to essentially the same Comment was already provided by Hinnov et al. (2016). Furthermore, in Da Silva et al. (2019), we focus on three specific ranges of cyclicities: 10–12 k.y., 6–8 k.y., and 2.5 k.y. These cycles have been considered as significant because they correspond to peaks in the MTM of two short records and in both logTi and Ti/Al proxies (Fig. 2). The cycles are also identified through wavelet analysis. Furthermore, we also confirm that they are not an artifact of spectral analysis through bandpass filtering. By comparing the filtered components with the log(Ti) time series, we ascertain these quasi-periodicities to be real. The 10–12 and 6–8 k.y. were also identified in the 5.7 m.y. magnetic susceptibility record (Da Silva et al., 2016; its resolution was not sufficient to identify the 2.5 k.y. cycle), through MTM analysis, as well as through bispectra. All these arguments point to stable and pervasive cycles. These cycles consistently emerge when put to the test of different methods, which makes them highly unlikely to be artifacts.

REFERENCES CITED

Dansgaard, W., White, J.W.C., and Johnsen, S.J., 1989, The abrupt termination of the Younger Dryas climate event: Nature, v. 339, p. 532–534, https://doi.org/10.1038/339532a0.

Da Silva, A.C., Hladil, J., Chadimova, L., Slavík, L., Hilgen, F.J., Bábek, O., and Dekkers, M.J., 2016, Refining the Early Devonian time scale using Milankovitch cyclicity in Lochkovian–Pragian sediments (Prague Synform, Czech Republic): Earth and Planetary Science Letters, v. 455, p. 125–139, https://doi.org/10.1016/j.epsl.2016.09.009.

Da Silva, A.C., Dekkers, M.J., De Vleeschouwer, D., Hladil, J., Chadimova, L., Slavík, L., and Hilgen, F.J., 2019, Millennial-scale climate changes manifest Milankovitch combination tones and Hallstatt solar cycles in the Devonian greenhouse world: Geology, v. 47, p. 19–22, https://doi.org/10.1130/G45511.1.

Hinnov, L.A., Wu, H., and Fang, Q., 2016, Reply to the comment on Geologic evidence for chaotic behavior of the planets and its constraints on the third-order eustatic sequences at the end of the Late Paleozoic Ice Age by Qiang Fang, Huaichun Wu, Linda A. Hinnov, Xiuchun Jing, Xunlian Wang: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 461, p. 475–480, https://doi.org/10.1016/j.palaeo.2016.07.030.

Hladil, J., Slavík, L., Schnabl, P., Koptíková, L., Frana, J., Vacek, F., and Bábek, O., 2008, The gross environmental phenomenon of the classical Pragian stage (hot lowstand), in Bjorlykke, A., et al., eds., 33rd International Geological Congress in Oslo, Abstract CD-ROM, HPF-01, 1343454.

Hladil, J., Vondra, M., Cejchan, P., Vich, R., Koptikova, L., and Slavik, L., 2010, The dynamic time-warping approach to comparison of magnetic-susceptibility logs and application to Lower Devonian calciturbidites (Prague Synform, Bohemian Massif): Geologica Belgica, v. 13, p. 385–406.

Matys Grygar, T., 2019, Millennial-scale climate changes manifest Milankovitch combination tones and Hallstatt solar cycles in the Devonian greenhouse world: Comment: Geology, v. 47, p. e487, https://doi.org/10.1130/G46452C.1.

Mikuláš, R., and Hladil, J., 2015, A Large Trace Fossil in Nodular Limestones (Lower Devonian, Czech Republic): Sedimentological Consequences, Ethology and Taphonomy: Ichnos, v. 22, p. 69–76, https://doi.org/10.1080/10420940.2015.1035436.

Nohl, T., Jarochowska, E., and Munnecke, A., 2018, Revealing the diagenesis of limestone-marl alterations: A taphonomic approach: Palaios, v. 34, p. 15–31, https://doi.org/10.2110/palo.2018.062.

Ricken, W., 1986, Diagenetic bedding: A model for limestone–marl alternations: Lecture Notes in Earth Sciences 6: Berlin, Springer, 210 p.

Smith, D.G., 2019, Millennial-scale climate changes manifest Milankovitch combination tones and Hallstatt solar cycles in the Devonian greenhouse world: Comment: Geology, v. 47, p. e488, https://doi.org/10.1130/G46475C.1.

Westphal, H., Hilgen, F., and Munnecke, A., 2010, An assessment of the suitability of individual rhythmic carbonate successions for astrochronological application: Earth-Science Reviews, v. 99, p. 19–30, https://doi.org/10.1016/j.earscirev.2010.02.001.