Supplementary information on “Long-term Aptian marine osmium isotopic record of Ontong Java Nui activity”

Hironao Matsumoto^{1*}, Rodolfo Coccioni², Fabrizio Frontalini³, Kotaro Shirai¹, Luigi Jovane⁴, Ricardo Trindade⁵, Jairo F. Savian⁶, Maria Luisa G. Tejada⁷, Silvia Gardin⁸, Junichiro Kuroda¹

¹*Atmosphere and Ocean Research Institute, Japan, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8564, Japan*

²*University of Urbino, Carlo Bo, 61029 Urbino, Italy*

³*DiSPeA, University of Urbino Carlo Bo, Italy, Campus Scientifico Enrico Mattei, Località Crocicchia, 61029 Urbino, Italy*

⁴*Instituto Oceanográfico, Universidade de São Paulo, Praça do Oceanográfico, 191 - São Paulo, SP 05508-120, Brazil*

⁵*Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão, 1226 - São Paulo, SP 05508-090, Brazil*

⁶ *Departamento de Geologia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Avenida Bento Gonçalves, 9500 – Porto Alegre, RS 91501-970, Brazil*

⁷*Institute for Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima-cho, Yokosuka-city, Kanagawa, 237-0061, Japan*

⁸*Centre de Recherche en Paléontologie-Paris, UMR 7207, Sorbonne Université - MNHN-CNRS, 4, Place Jussieu, 75005, Paris, France*

LITHOLOGY AND MATERIALS

The sedimentary rock samples for Os and C isotopic analyses were collected from the Poggio le Guaine (PLG) section and the PLG core drilled nearby, located on the Monte Nerone ridge of the Umbria–Marche Basin in central Italy (Coccioni et al., 2012; Figs. 1 and DR1). The upper Barremian to lowermost Aptian interval belongs to the Maiolica Formation and consists of white limestone with cyclic intercalation of black shale layers (Fig. 2) (Coccioni et al., 2012; Savian et al., 2016). Since the Global Stratotype Section and Point for the base of the Aptian Stage has not yet been defined, the Barremian-Aptian boundary here is provisionally placed in the uppermost part of the *Globigerinelloides aptiensis* planktonic foraminiferal Zone based on recent findings (Coccioni, 2020) at the Gorgo a Cerbara section (Figs. 2 and 3). The ~2 m-thick organic-rich Selli Level, which is the regional expression of OAE1a, occurs at the base of the Marne a Fucoidi Formation (0 m in Fig. 2: Coccioni et al., 1987; Coccioni, 2020). Above the Selli Level, the main lithologies of Lower to mid-Aptian stage are greenish-gray mud/marlstone, reddish marlstone, and minor siliceous sediments. A 20 cm-thick black shale horizon occurs ~1 m above the Selli Level and a 6 cm-thick black shale horizon occurs ~10 m above the Selli Level (Fig. 2). The lithology of the PLG core is comparable to that of nearby outcrops, namely the PLG section (Coccioni et al., 2014) and Gorgo a

Cerbara sections (Coccioni et al., 1987). We correlated the three sedimentary records with biostratigraphy, chemostratigraphy (Os and $\delta^{13}\text{C}_{\text{carb}}$), and lithological features. The sedimentary rock samples were collected from just above the Selli Level to ~11 m above it in the PLG core (Coccioni et al., 2012). Sedimentary rock samples were also collected from the lowermost part of the PLG section that overlaps with the uppermost parts of the studied interval in the PLG core (Matsumoto et al., 2020). Since the black shales at ~3 and ~12 m of the composite depth scale were fractured during the drilling activity, these were not used for Os and C isotopic analyses. Instead, marlstone samples from just above and below the black shale horizons were used.

METHODS

Cleaned samples were dried and powdered in an agate mill. After spiking, Re and Os in the hydrogenous fraction of the carbonate rocks were extracted using inverse aqua regia digestion. Abundances and isotopic compositions of Os were determined by negative thermal ionization-mass spectrometry (TRITON, Thermo Fisher Scientific, USA) at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, Japan). The Re abundances were determined by a quadrupole inductively coupled plasma-mass spectrometer (iCAP Qc, Thermo Fisher Scientific, USA) at JAMSTEC. The average procedural blanks of Os was 0.5 ± 0.3 pg and $^{187}\text{Os}/^{188}\text{Os}$ was 0.11 ± 0.03 . The average Re

procedural blank was 4 ± 2 pg. Initial $^{187}\text{Os}/^{188}\text{Os}$ values (Os_i) were calculated from the measured $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ values, the age-depth model of the sediments (Table DR1), and the ^{187}Re decay constant ($1.666 \times 10^{-11} \text{ yr}^{-1}$; Smoliar et al., 1996). Detailed analytical methods for Os isotopic analysis were as described by Matsumoto et al. (2020). A marlstone sample at 4.1 m showed an extremely whitish color and had an anomalous high Os_i (~ 1.35) value. Since this sample could have experienced different diagenesis or alternation compared to other samples, it was considered to be an outlier and discarded thereof (Fig. DR3, Table DR1).

The stable carbon isotope ratio of carbonate ($\delta^{13}\text{C}_{\text{carb}}$) was determined using isotope ratio-mass spectrometry (Delta V plus, Thermo Fisher Scientific, USA), equipped with an automated carbonate reaction device (GasBench II, Thermo Fisher Scientific, USA), at the Atmosphere and Ocean Research Institute, University of Tokyo (Japan). All isotope values are reported using delta notation with respect to PeeDee Belemnite (PDB), based on an NBS-19 value of -2.20‰ for $\delta^{18}\text{O}$ and $+1.95\text{‰}$ for $\delta^{13}\text{C}$. External reproducibility was estimated from the repeated analysis of the NBS-19 standard ($n=20$) within an analysis batch and the typical values are better than 0.05‰ and 0.08‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, respectively (1 SD) (Table DR2). Detailed analytical conditions are reported in Shirai et al. (2018). One sample (PLG-C 86.17) with extremely low $\delta^{18}\text{O}_{\text{carb}}$

value was excluded from the discussion as an outlier.

WEZEL LEVEL

The black shale horizon located around 3 m of the composite depth scale falls in the Ap7 carbon isotopic segment and the upper part of the *Leupoldina cabri* planktonic foraminiferal Zone. At the present state of knowledge, a similar and coeval horizon is recorded in the Piobbico and Cismon cores (Tornaghi et al., 1989; Erba et al., 1999) and Gargano Promontory (Luciani et al., 2001) in Italy, but on the basis of the available stratigraphic data, it could also be recognized in the Vocontian Basin (Köbller et al. 2001; Herrle et al., 2004; Heimhofer et al., 2006), in southern Spain (De Gea et al., 2003; Quijano et al., 2012; Aguado et al., 2014), in northeastern Tunisia (Elkhazri et al., 2013) and in central Turkey (Hu et al., 2012). It is here proposed to name this undescribed black-shale horizon as “Wezel Level”.

BOX MODEL CALCULATION

Changes in the Os flux through hydrothermal activities were calculated using a simple box model based on Tejada et al. (2009). This model assumes that the ocean is a unique Os reservoir, and marine Os abundance and $^{187}\text{Os}/^{188}\text{Os}$ reflect the balance between

continental input, hydrothermal input related to oceanic crustal production, and hydrothermal input associated with the OJN emplacement, extraterrestrial input, and a sedimentary sink. These relationships are described as:

$$\frac{dM_{ocean}}{dt} = F_{cont} + F_{hydr} + F_{cosm} + F_{OJN} - F_{sed} \quad (1)$$

$$\frac{d(M_{ocean}R_{ocean})}{dt} = F_{cont}R_{cont} + F_{hydr}R_{hydr} + F_{cosm}R_{cosm} + F_{OJN}R_{OJN} - F_{sed}R_{sed} \quad (2)$$

where M, F, and R indicate the amount, flux, and isotopic ratio of Os ($^{187}\text{Os}/^{188}\text{Os}$), and the subscripts ‘ocean’, ‘cont’, ‘hydr’, ‘cosm’, ‘OJN’, and ‘sed’ represent the oceanic reservoir, continental input, hydrothermal input, extraterrestrial input, input from the OJN, and sedimentary output, respectively. Indeed, we assumed that R_{sed} coincides with R_{ocean} . The above equations can be combined as:

$$\frac{dR_{ocean}}{dt} = \frac{[F_{cont}(R_{cont} - R_{ocean}) + F_{hydr}(R_{hydr} - R_{ocean}) + F_{OJN}(R_{OJN} - R_{ocean}) + F_{cosm}(R_{cosm} - R_{ocean})]}{M_{ocean}} \quad (3)$$

We adopted the present-day $F_{cont}=295$ t/kyr, $R_{cont}=1.54$ (Levasseur et al., 1999; Peucker-Ehrenbrink and Jahn, 2001); $R_{hydr}=0.126$ (Allegre and Luck, 1980), $F_{cosm}=17.6$ t/kyr, $R_{cosm}=0.126$ (Levasseur et al., 1999; Allegre and Luck, 1980), and $M_{ocean}=13,000$ t (Levasseur et al., 1998) for the steady background conditions before OAE1a. Also, we used $F_{hydr}=414$ t/kyr, $F_{sed}=0.056 \times M_{ocean}$, and $R_{OJN}=0.146$ based on Tejada et al. (2009). We estimated the hydrothermal Os input flux from OJN (F_{OJN}) (Fig. 3) required to

explain the simplified Os curve (the solid line in the left column of Fig. 3) using the above equations. Model calculation combining C, Li, Ca, Sr, and Os isotopic systems (Adloff et al., 2020) suggests that the intensive input of CO₂ accelerates the continental weathering which increases the radiogenic Os input ~10-100 kyr after the CO₂ input. Since the continental weathering rate is set to a constant, the calculated unradiogenic Os input from OJN in our modeling is the minimum estimate.

We calculated the changes in the Sr flux through hydrothermal activities using a simple box model after Blättler et al. (2011). Like the box modeling of Os, relationship of Sr flux can be described as:

$$\frac{dM_{ocean}}{dt} = F_{cont} + F_{hydr} + F_{diag} + F_{OJN} - F_{sed} \quad (4)$$

$$\frac{d(M_{ocean}R_{ocean})}{dt} = F_{cont}R_{cont} + F_{hydr}R_{hydr} + F_{diag}R_{diag} + F_{OJN}R_{OJN} - F_{sed}R_{sed} \quad (5)$$

$$\frac{dR_{ocean}}{dt} = \frac{[F_{cont}(R_{cont} - R_{ocean}) + F_{hydr}(R_{hydr} - R_{ocean}) + F_{OJN}(R_{OJN} - R_{ocean}) + F_{diag}(R_{diag} - R_{ocean})]}{M_{ocean}} \quad (6)$$

where M, F, and R indicate the amount, flux, and isotopic ratio of Sr (⁸⁷Sr/⁸⁶Sr), and the subscripts ‘ocean’, ‘cont’, ‘hydr’, ‘diag’, ‘OJN’, and ‘sed’ represent the oceanic reservoir, continental input, hydrothermal input, diagenetic input, input from the OJN, and sedimentary output, respectively. We used M_{ocean}=1.05 × 10¹³ t, R_{cont}=0.7115, R_{hydr}=0.7033, R_{diag}=0.7084, F_{cont}=1.59 × 10⁹ t/kyr, F_{hydro}=1.62 × 10⁹ t/kyr, F_{diag}=0.30 ×

140 10^9 t/kyr (Palmer and Edmond, 1989; Blättler et al., 2011) as the Upper Barremian pre-
141 OAE1a condition. In addition, we set R_{sed} and F_{sed} as $R_{\text{sed}}=R_{\text{ocean}}$ and
142 $F_{\text{sed}}=M_{\text{ocean}}\times 3.33\times 10^{-4}$ t/kyr.
143 We estimated the hydrothermal Sr flux (Fig. 3) to explain the Sr curve (the solid line in
144 the left column of Fig. 3) using the above equations.

146

147

148

149

150

151

Fig. DR1: Geological map of Poggio le Guaine (PLG) revised from Matsumoto et al. (2020). PLG section is located at lat. 43°32'29.06" N, long. 12°34'51.09" E and the drilling site of the PLG core is located at lat. 43°32'42.72" N; long. 12°32'40.92" E. The location of the Gorgo a Cerbara section is also shown.

Fig. DR2: Cross plot of $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ for sedimentary rock samples of the Poggio le Guaine core. One sample with extremely low $\delta^{18}\text{O}_{\text{carb}}$ was excluded from the discussion since it is considered as an outlier.

Fig. DR3: Os and Re data for sedimentary rock samples from the Poggio le Guaine core and section.

Fig. DR4: Age-composite depth diagram of the studied section based on Table DR3.

TABLE DR1. CARBONATE CARBON AND OXYGEN ISOTOPIC RATIO OF SEDIMENTARY ROCK SAMPLES OF PLG CORE

Sample Name	Lithology	$\delta^{13}\text{C}_{\text{carb}}$ (‰VPDB)	$\delta^{18}\text{O}_{\text{carb}}$ (‰VPDB)	$\delta^{13}\text{C-1SD}$ (‰VPDB)	$\delta^{18}\text{O-1SD}$ (‰VPDB)	Depth (Core) (m)	Depth (Composit) (m)	Comment
PLG-C 90.98	Marlstone	4.65	-1.69	0.09	0.05	89.20	2.34	
PLG-C 90.85	Marlstone	4.23	-2.28	0.06	0.05	89.08	2.46	
PLG-C 90.58	Mudstone	4.37	-1.89	0.06	0.05	88.82	2.72	
PLG-C 90.42	Marlstone	4.44	-2.10	0.06	0.05	88.67	2.87	
PLG-C 90.32	Mudstone	4.75	-2.06	0.06	0.05	88.57	2.97	
PLG-C 90.13	Marlstone	4.24	-1.86	0.06	0.05	88.39	3.15	
PLG-C 89.93	Marlstone	4.32	-2.19	0.06	0.05	88.19	3.35	
PLG-C 89.53	Marlstone	3.94	-2.07	0.06	0.05	87.80	3.74	
PLG-C 89.26	Marlstone	4.66	-1.78	0.06	0.05	87.53	4.01	
PLG-C 89.06	Marlstone	4.10	-2.10	0.06	0.05	87.33	4.21	
PLG-C 88.92	Marlstone	4.49	-2.10	0.06	0.05	87.19	4.35	
PLG-C 88.52	Marlstone	4.64	-1.96	0.06	0.05	86.79	4.75	
PLG-C 88.33	Mudstone	4.64	-2.18	0.06	0.05	86.60	4.94	
PLG-C 87.99	Marlstone	4.53	-1.57	0.07	0.07	86.26	5.28	
PLG-C 87.79	Marlstone	4.44	-1.50	0.08	0.05	86.06	5.48	
PLG-C 87.67	Marlstone	4.56	-1.91	0.08	0.05	85.94	5.60	
PLG-C 87.60	Mudstone	3.96	-1.59	0.08	0.05	85.87	5.67	
PLG-C 87.41	Marlstone	3.90	-1.99	0.08	0.05	85.68	5.86	
PLG-C 87.17	Marlstone	3.86	-2.47	0.08	0.05	85.44	6.10	
PLG-C 87.03	Marlstone	4.09	-1.55	0.08	0.05	85.30	6.24	
PLG-C 86.99	Marlstone	4.02	-1.62	0.08	0.05	85.26	6.28	
PLG-C 86.92	Mudstone	3.97	-1.90	0.08	0.05	85.19	6.35	
PLG-C 86.84	Marlstone	3.84	-1.87	0.08	0.05	85.11	6.43	
PLG-C 86.79	Mudstone	3.89	-1.86	0.08	0.05	85.06	6.48	
PLG-C 86.68	Marlstone	3.60	-1.62	0.08	0.05	84.95	6.59	
PLG-C 86.54	Marlstone	3.57	-1.83	0.06	0.05	84.81	6.73	
PLG-C 86.44	Marlstone	3.64	-1.89	0.06	0.05	84.71	6.83	
PLG-C 86.38	Mudstone	3.43	-1.83	0.06	0.05	84.65	6.89	
PLG-C 86.17	Marlstone	3.56	-3.28	0.06	0.05	84.44	7.10	Excluded
PLG-C 86.01	Marlstone	3.62	-1.70	0.06	0.05	84.28	7.26	
PLG-C 85.94	Mudstone	3.69	-1.62	0.06	0.05	84.21	7.33	
PLG-C 85.89	Marlstone	3.73	-1.70	0.06	0.05	84.16	7.38	
PLG-C 85.77	Mudstone	3.37	-1.79	0.06	0.05	84.04	7.50	
PLG-C 85.48	Marlstone	3.43	-1.80	0.06	0.05	83.75	7.79	
PLG-C 85.05	Mudstone	3.33	-2.29	0.06	0.05	83.32	8.22	
PLG-C 84.90	Marlstone	3.37	-1.91	0.06	0.05	83.17	8.37	
PLG-C 84.78	Marlstone	3.33	-1.72	0.08	0.05	83.05	8.49	
PLG-C 84.70	Mudstone	3.36	-1.77	0.08	0.05	82.97	8.57	
PLG-C 84.51	Marlstone	3.35	-2.17	0.08	0.05	82.78	8.76	
PLG-C 84.40	Mudstone	2.95	-2.44	0.08	0.05	82.67	8.87	
PLG-C 84.36	Mudstone	2.93	-1.92	0.08	0.05	82.63	8.91	
PLG-C 84.27	Marlstone	3.23	-1.92	0.08	0.05	82.54	9.00	
PLG-C 84.08	Marlstone	3.32	-2.02	0.08	0.05	82.35	9.19	
PLG-C 83.92	Mudstone	2.93	-1.91	0.08	0.05	82.19	9.35	
PLG-C 83.67	Marlstone	3.17	-1.97	0.08	0.05	81.94	9.60	
PLG-C 83.47	Mudstone	3.37	-1.98	0.08	0.05	81.74	9.80	
PLG-C 83.37	Marlstone	3.12	-1.64	0.08	0.05	81.64	9.90	
PLG-C 83.05	Mudstone	3.33	-1.81	0.06	0.05	81.32	10.22	
PLG-C 82.86	Mudstone	3.32	-1.74	0.06	0.05	81.13	10.41	
PLG-C 82.73	Marlstone	3.27	-1.72	0.06	0.05	81.00	10.54	
PLG-C 82.61	Marlstone	3.32	-1.80	0.06	0.05	80.88	10.66	
PLG-C 82.48	Marlstone	3.26	-1.68	0.06	0.05	80.75	10.79	
PLG-C 82.32	Marlstone	3.30	-1.85	0.06	0.05	80.59	10.95	
PLG-C 82.15	Mudstone	3.25	-2.03	0.06	0.05	80.44	11.10	
PLG-C 82.01	Mudstone	3.07	-2.27	0.06	0.05	80.28	11.26	
PLG-C 81.91	Mudstone	2.97	-1.68	0.06	0.05	80.18	11.36	
PLG-C 81.82	Mudstone	3.09	-1.64	0.06	0.05	80.09	11.45	
PLG-C 81.61	Marlstone	3.20	-1.86	0.06	0.05	79.88	11.66	
PLG-C 81.56	Marlstone	3.22	-1.92	0.06	0.05	79.83	11.71	
PLG-C 81.47	Marlstone	3.18	-1.97	0.08	0.05	79.74	11.80	
PLG-C 81.35	Marlstone	3.07	-1.87	0.08	0.05	79.66	11.88	
PLG-C 81.23	Marlstone	3.08	-1.89	0.08	0.05	79.50	12.04	
PLG-C 81.12	Marlstone	3.14	-1.91	0.08	0.05	79.39	12.15	
PLG-C 80.96	Marlstone	3.15	-1.81	0.08	0.05	79.23	12.31	
PLG-C 80.92	Marlstone	3.21	-1.88	0.08	0.05	79.19	12.35	
PLG-C 80.71	Marlstone	3.15	-1.71	0.08	0.05	78.98	12.56	
PLG-C 80.67	Marlstone	3.24	-1.64	0.08	0.05	78.94	12.60	
PLG-C 80.49	Marlstone	3.20	-1.73	0.08	0.05	78.76	12.78	
PLG-C 80.35	Marlstone	3.16	-1.92	0.08	0.05	78.62	12.92	
PLG-C 80.23	Marlstone	3.07	-1.67	0.08	0.05	78.50	13.04	
PLG-C 80.12	Marlstone	3.11	-1.74	0.08	0.05	78.39	13.15	

TABLE DR2. Os AND Re DATA OF SEDIMENTARY ROCK SAMPLES OF PLG RECORD.															
Sample Name	Lithology	Os	1SD	¹⁸⁷ Os/ ¹⁸⁸ Os m	1SD	Re	1SD	¹⁸⁷ Re/ ¹⁸⁸ Os	1SD	Osi	1SD	Age	Depth(core)	Depth(composit)	Comments
		(pg g ⁻¹)				(pg g ⁻¹)						(Ma)	(m)	(m)	
PLG core															
PLG-C 90.98	Marlstone	116.8	0.5	0.952	0.007	6.74.E+03	6.E+01	308	3	0.338	0.009	119.6	89.20	2.3	
PLG-C 90.85	Marlstone	69.5	0.4	1.058	0.010	3.52.E+03	9.E+01	274	7	0.513	0.019	119.6	89.08	2.5	
PLG-C 90.58	Mudstone	97.6	0.4	0.933	0.006	3.66.E+03	1.8.E+02	199	9.9	0.536	0.02	119.5	88.82	2.7	
PLG-C 90.42	Marlstone	89.6	0.6	1.295	0.013	7.14.E+03	1.7.E+02	442	11	0.414	0.03	119.4	88.67	2.9	
PLG-C 90.32	Mudstone	135.2	0.9	0.796	0.011	5.21.E+03	9.E+01	202	4	0.395	0.013	119.3	88.57	3.0	
PLG-C 90.13	Mudstone	59.1	0.4	0.490	0.007	1.257.E+03	1.8.E+01	107	2	0.277	0.008	119.3	88.39	3.2	
PLG-C 89.93	Marlstone	52.1	0.3	0.404	0.007	8.06.E+02	1.3.E+01	77.2	1.3	0.251	0.007	119.2	88.19	3.3	Just below Wezel Level
PLG-C 89.53	Marlstone	18.0	0.2	0.361	0.013	1.41.E+02	3.E+00	38.7	1.1	0.284	0.013	119.0	87.80	3.7	Just above Wezel Level
PLG-C 89.26	Marlstone	37.6	0.18	0.565	0.006	1.045.E+03	1.6.E+01	142	2	0.284	0.008	118.9	87.53	4.0	
PLG-C 89.06	Marlstone	36.5	0.30	1.131	0.019	2.046.E+03	1.9.E+01	305	4	0.504	0.02	118.8	87.33	4.2	
PLG-C 88.92	Marlstone	49.6	0.19	2.156	0.013	3.20.E+03	1.7.E+02	393	21	1.378	0.05	118.7	87.19	4.4	Excluded
PGL-C 88.52	Marlstone	43.1	0.39	0.464	0.010	1.54.E+02	1.0.E+01	17.9	1.2	0.427	0.011	118.4	86.79	4.8	
PLG-C 88.33	Mudstone	153.4	0.7	0.454	0.003	8.53.E+02	1.1.E+01	27.9	0.4	0.399	0.003	118.2	86.60	4.9	
PLG-C 87.60	Mudstone	20.4	0.2	0.440	0.011	6.E+00	1.0.E+01	2	3	0.437	0.012	117.6	85.87	5.7	
PLG-C 86.99	Marlstone	21.2	0.14	0.479	0.007	1.1.E+01	8.E+00	2.6	1.8	0.474	0.008	117.5	85.26	6.3	
PLG-C 86.54	Marlstone	19.5	0.18	0.473	0.009	4.7.E+00	1.1.E+00	1.2	0.3	0.471	0.009	117.4	84.81	6.7	
PLG-C 85.89	Marlstone	22.8	0.14	0.476	0.007	3.E+00	5.E+00	0.6	1.0	0.475	0.007	117.3	84.16	7.4	
PLG-C 85.05	Mudstone	35.0	0.3	0.477	0.013	6.E+00	2.E+00	0.9	0.3	0.475	0.010	117.1	83.32	8.2	
PLG-C 84.47	Mudstone	45.5	0.2	0.512	0.005	1.17.E+01	1.0.E+00	1.30	0.11	0.509	0.005	117.0	82.74	8.8	
PLG-C 83.37	Marlstone	18.6	0.1	0.538	0.007	8.9.E+00	1.0.E+00	2.4	0.3	0.533	0.007	116.8	81.64	9.9	
PLG-C 82.48	Marlstone	25.4	0.2	0.536	0.009	8.E+00	9.E+00	1.6	1.8	0.533	0.010	116.6	80.75	10.8	
PLG-C 81.82	Marlstone	18.3	0.10	0.473	0.007	7.8.E+00	1.0.E+00	2.2	0.3	0.469	0.007	116.5	80.09	11.4	
PLG-C 81.35	Marlstone	23.1	0.14	0.414	0.006	9.E+00	6.E+00	1.9	1.3	0.410	0.007	116.4	79.66	11.9	
PLG-C 81.12	Marlstone	20.3	0.12	0.487	0.007	2.50.E+02	5.E+00	62.1	1.4	0.367	0.008	116.3	79.39	12.1	Just below Fallot Level
PLG-C 80.96	Marlstone	18.1	0.10	0.478	0.007	6.1.E+00	1.2.E+00	1.7	0.3	0.475	0.007	116.3	79.23	12.3	Just above Fallot Level
PLG-C 80.49	Marlstone	18.9	0.14	0.433	0.008	7.1.E+00	1.3.E+00	1.9	0.4	0.430	0.008	116.2	78.76	12.8	
PLG-C 80.12	Marlstone	23.6	0.2	0.518	0.015	4.E+00	6.E+00	0.9	1.2	0.516	0.015	116.1	78.39	13.1	
PLG section															
PLG-9	Marlstone	22	0.16	0.448	0.009	7.8.E+00	1.3.E+00	1.8	0.29	0.445	0.009	116.2	Depth (outcrop) 9 m		12.5

TABLE DR3. AGE MODEL

Horizons	Age (Ma)	Depth (m)
Base of the Urbino Level	111.10	36.7
LO <i>M. renilaevs</i>	113.10	28.2
LO <i>M. miniglobularis</i>	113.40	27.0
Base of the Jacob Level	114.50	24.0
LO <i>P. rohri</i>	115.26	20.0
HO <i>G. algerianus</i>	115.74	15.0
LO <i>G. algerianus</i>	117.64	5.6
HO <i>L. cabri</i>	118.74	4.4
Top of the Selli Level	119.65	2.3
Base of the Selli Level	120.76	0.3
LO <i>L. cabri</i>	120.80	0.2
Top of CM0r	121.05	-1.2
Base of CM0r	121.54	-3.6

Note1. *G.*=*Globigerinelloides*, *L.*=*Leupoldina*,

P.=*Paraticinella*, *M.*=*Microhedbergella*,

LO= Lowest occurrence, HO=highest occurrence

Note2. Age is based on Malinverno et al. (2012), Coccioni (2020), and Matsumoto et al. (2020)

REFERENCE

- Adloff, M., Ridgwell, A., Monteiro, F.M., Parkinson, I.J., Dickson, A., Pogge von Strandmann, P.A., Frantle, M.S., and Greene, S.E., 2020, Inclusion of a suite of weathering tracers in the cGENIE Earth System Model—muffin release v. 0.9. 10: Geoscientific Model Development Discussions, p. 1–48, doi: 10.5194/gmd-2020-233.
- Allegre, C.J., and Luck, J.M., 1980, Os isotopes as petrogenetic and geological tracers: Earth and Planetary Science Letters, v. 48, p. 148–154, doi: 10.1016/0012-821X(80)90177-6.
- Aguado, R., de Gea, G.A., Castro, J.M., O'Dogherty, L., Quijano, M.L., Naafs, B.D.A., and Pancost, R.D., 2014, Late Barremian–early Aptian dark facies of the Subbetic (Betic Cordillera, southern Spain): Calcareous nannofossil quantitative analyses, chemostratigraphy and palaeoceanographic reconstructions: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 395, p. 198–221, doi: 10.1016/j.palaeo.2013.12.031.
- Blättler, C.L., Jenkyns, H.C., Reynard, L.M., and Henderson, G.M., 2011, Significant increases in global weathering during Oceanic Anoxic Events 1a and 2 indicated by calcium isotopes: Earth and Planetary Science Letters, v. 309, p. 77–88, doi: 10.1016/j.epsl.2011.06.029.

186 Coccioni, R., 2020, Revised upper Barremian–upper Aptian planktonic foraminiferal
187 biostratigraphy of the Gorgo a Cerbara section (central Italy): Newsletters on
188 Stratigraphy, v. 53, p. 275–295, doi: 10.1127/nos/2019/0539.

189 Coccioni, R., Nesci, O., Tramontana, M., Wezel, F.C., and Moretti, E., 1987, Descrizione
190 di un livello–guida “radiolaritico–bituminoso–ittiolitico” alla base delle Marne a
191 Fucoidi nell'Appennino Umbro–Marchigiano: Bollettino della Società Geologica
192 Italiana v. 106, p. 183–192.

193 Coccioni, R., Jovane, L., Bancalà, G., Bucci, C., Fauth, G., Frontalini, F., Janikian, L.,
194 Savian, J., Paes de Almeida, R., Mathias, G.L., and Ferreira da Trindade, R.I., 2012,
195 Umbria-Marche Basin, Central Italy: A reference section for the Aptian-Albian
196 interval at low latitudes: Scientific Drilling, v. 13, p. 42–46, doi:
197 10.2204/iodp.sd.13.07.2011.

198 Coccioni, R., Sabatino, N., Frontalini, F., Gardin, S., Sideri, M., and Sprovieri, M., 2014,
199 The neglected history of Oceanic Anoxic Event 1b: insights and new data from the
200 Poggio le Guaine section (Umbria–Marche Basin): Stratigraphy, v. 11, p. 245–282.

201 De Gea, G.A., Castro, J.M., Aguado, R., Ruiz-Ortiz, P.A., and Company, M., 2003, Lower
202 Aptian carbon isotope stratigraphy from a distal carbonate shelf setting: the Cau
203 section, Prebetic zone, SE Spain: Palaeogeography, Palaeoclimatology,

204 Palaeoecology, v. 200, p. 207-219, doi: 10.1016/S0031-0182(03)00451-6.

205 Elkhazri, A., Abdallah, H., Razgallah, S., Moullade, M., and Kuhnt, W., 2013, Carbon-

206 isotope and microfaunal stratigraphy bounding the Lower Aptian Oceanic Anoxic

207 Event 1a in northeastern Tunisia: Cretaceous Research, v. 39, p. 133–148, doi:

208 10.1016/j.cretres.2012.05.011.

209 Erba, E., Channell, J.E., Claps, M., Jones, C., Larson, R., Opdyke, B., Silva, I.P., Riva,

210 A., Salvini, G., and Torricelli, S., 1999, Integrated stratigraphy of the Cismon

211 Apticore (southern Alps, Italy); a "reference section" for the Barremian-Aptian

212 interval at low latitudes: The Journal of Foraminiferal Research, v. 29, p. 371–391.

213 Heimhofer, U., Hochuli, P.A., Herrle, J. O., and Weissert, H., 2006, Contrasting origins

214 of Early Cretaceous black shales in the Vocontian basin: Evidence from palynological

215 and calcareous nannofossil records: Palaeogeography, Palaeoclimatology,

216 Palaeoecology, v. 235, p. 93–109, doi: 10.1016/j.palaeo.2005.09.025.

217 Herrle, J.O., Köbller, P., Friedrich, O., Erlenkeuser, H., and Hemleben, C., 2004, High-

218 resolution carbon isotope records of the Aptian to Lower Albian from SE France and

219 the Mazagan Plateau (DSDP Site 545): a stratigraphic tool for paleoceanographic and

220 paleobiologic reconstruction: Earth and Planetary Science Letters, v. 218, p. 149–161,

221 doi: 10.1016/S0012-821X(03)00646-0.

222 Hu, X., Zhao, K., Yilmaz, I.O., and Li, Y., 2012, Stratigraphic transition and
 223 palaeoenvironmental changes from the Aptian oceanic anoxic event 1a (OAE1a) to
 224 the oceanic red bed 1 (ORB1) in the Yenicesihlar section, central Turkey: *Cretaceous*
 225 *Research*, v. 38, p. 40–51, doi: 10.1016/j.cretres.2012.01.007.

226 Köbller, P., Herrle, J.O., Appel, E., Erbacher, J., and Hemleben, C., 2001, Magnetic
 227 records of climatic cycles from mid-Cretaceous hemipelagic sediments of the
 228 Vocontian Basin, SE France: *Cretaceous Research*, v. 22, p. 321–331, doi:
 229 10.1006/cres.2001.0256.

230 Levasseur, S., Birck, J.L., and Allègre, C.J., 1998, Direct measurement of femtomoles of
 231 osmium and the $^{187}\text{Os}/^{186}\text{Os}$ ratio in seawater: *Science*, v. 282, p. 272–274.

232 Levasseur, S., Birck, J.L., and Allegre, C.J., 1999, The osmium riverine flux and the
 233 oceanic mass balance of osmium: *Earth and Planetary Science Letters*, v. 174, p. 7–
 234 23, doi: 10.1016/S0012-821X(99)00259-9.

235 Luciani, V., Cobianchi, M., and Jenkyns, H.C., 2001, Biotic and geochemical response to
 236 anoxic events: the Aptian pelagic succession of the Gargano Promontory (southern
 237 Italy): *Geological Magazine*, v. 138, p. 277–298.

238 Matsumoto, H., Kuroda, J., Coccioni, R., Frontalini, F., Sakai, S., Ogawa, N.O., and
 239 Ohkouchi, N., 2020, Marine Os isotopic evidence for multiple volcanic episodes

240 during Cretaceous Oceanic Anoxic Event 1b: Scientific Reports, v. 10, 12601, doi:
241 10.1038/s41598-020-69505-x.

242 Palmer, M.R., and Edmond, J.M., 1989, The strontium isotope budget of the modern
243 ocean: Earth and Planetary Science Letters, v. 92, p. 11–26, doi: 10.1016/0012-
244 821X(89)90017-4.

245 Peucker-Ehrenbrink, B., and Jahn, B.M., 2001, Rhenium-osmium isotope systematics and
246 platinum group element concentrations: Loess and the upper continental
247 crust: Geochemistry, Geophysics, Geosystems, v. 2, p. 1061, doi:
248 10.1029/2001GC000172.

249 Quijano, M.L., Castro, J.M., Pancost, R.D., de Gea, G.A., Najarro, M., Aguado, R.,
250 Rosales, I., and Martín-Chivelet, J., 2012, Organic geochemistry, stable isotopes, and
251 facies analysis of the Early Aptian OAE—New records from Spain (Western
252 Tethys): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 365, p. 276–293,
253 doi: 10.1016/j.palaeo.2012.09.033.

254 Savian, J., Trindade, R., Janikian, L., Jovane, L., de Almeida, R.P., Coccioni, R.,
255 Frontalini, F., Sideri, M., and Jenkyns, H.C., 2016, The Barremian-Aptian boundary
256 in the Poggio le Guaine core (central Italy): Evidence for magnetic polarity Chron
257 M0r and oceanic anoxic event 1a. *in* Menichetti, M., Coccioni, R., and Montanari,

258 A., eds., *The Stratigraphic Record of Gubbio: Integrated Stratigraphy of the Late*
 259 *Cretaceous–Paleogene Umbria-Marche Pelagic Basin: The Geological Society of*
 260 *America Special Paper*, v. 524, p. 57–78, doi:10.1130/2016.2524(05).

261 Shirai, K., Koyama, F., Murakami-Sugihara, N., Nanjo, K., Higuchi, T., Kohno, H.,
 262 Watanabe, Y., Okamoto, K., and Sano, M., 2018, Reconstruction of the salinity
 263 history associated with movements of mangrove fishes using otolith oxygen isotopic
 264 analysis: *Marine Ecology Progress Series*, v. 593, p. 127–139, doi:
 265 10.3354/meps12514.

266 Smoliar, M.I., Walker, R.J., and Morgan, J.W., 1996, Re-Os ages of group IIA, IIIA, IVA,
 267 and IVB iron meteorites: *Science*, v. 271, p. 1099–1102, doi:
 268 10.1126/science.271.5252.1099.

269 Tejada, M.L.G., Suzuki, K., Kuroda, J., Coccioni, R., Mahoney, J.J., Ohkouchi, N.,
 270 Sakamoto, T. and Tatsumi, Y., 2009, Ontong Java Plateau eruption as a trigger for the
 271 early Aptian oceanic anoxic event: *Geology*, v. 37, p. 855–858, doi:
 272 10.1130/G25763A.1.

273 Tornaghi, M.E., Silva, I.P., and Ripepe, M., 1989, Lithostratigraphy and planktonic
 274 foraminiferal biostratigraphy of the Aptian-Albian "Scisti a Fucoidi" in the Piobbico
 275 core, Marche, Italy: background for cyclostratigraphy: *Rivista Italiana di*