PNAS
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Supplementary Information for

Massive formation of early diagenetic dolomite in the Ediacaran ocean: Constraints on the "dolomite problem"

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This PDF file includes:

www.pnas.org/cgi/doi/10.1073/pnas.1916673117

Supplementary figures

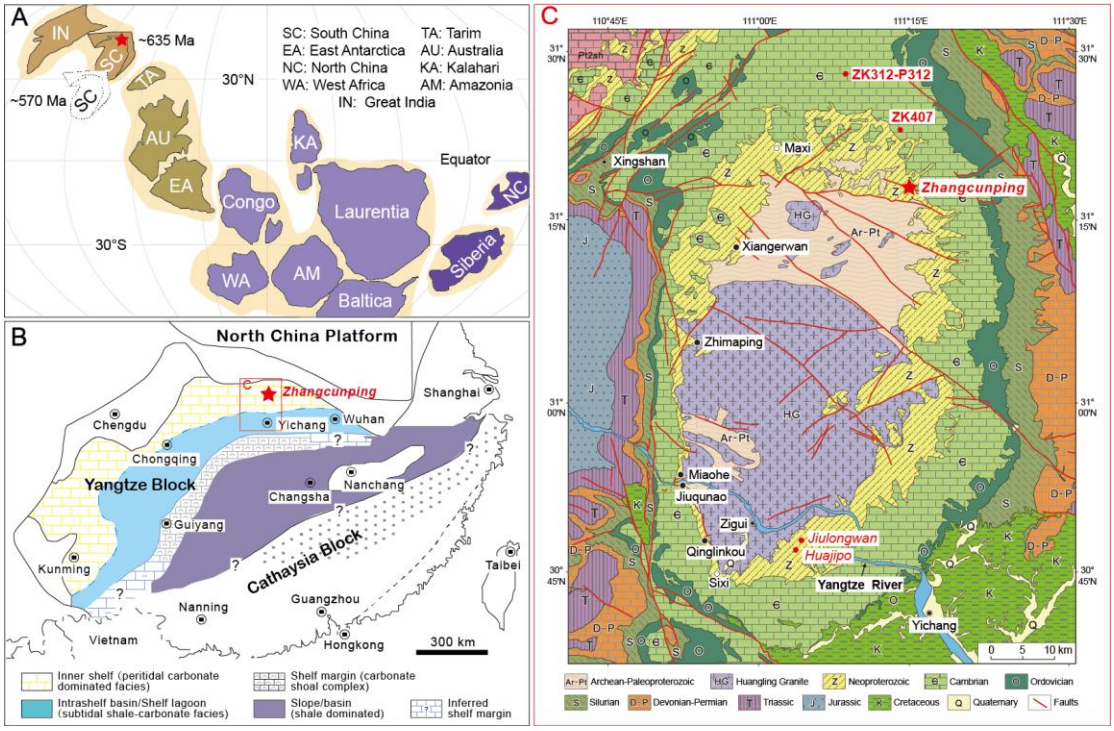


Fig. S1. Geological setting of the Ediacaran Doushantuo Formation in South China. (*A*) Location of South China (SC) in a global reconstruction at ca. 635 Ma and its latitudinal change from ca. 635 to ca. 570 Ma (dashed outline) (1). (*B*) Main facies of the Doushantuo Formation on the Yangtze Block. Location of Zhangcunping town shown as red star. (*C*) Geological map of the Yangtze Gorges area showing locations of drillcores ZK312-P312 and ZK407 as red dots close to Zhangcunping town. The Jiulongwan and Huajipo outcrop sections, which were previously studied for dolomite $T_{\Delta 47}$ (2, 3), are also marked with red dots. Subfigures (A-C) are modified from refs. 4, 5, and 6. Copyright (2013, 2011, and 2015), respectively, with permission from Elsevier.

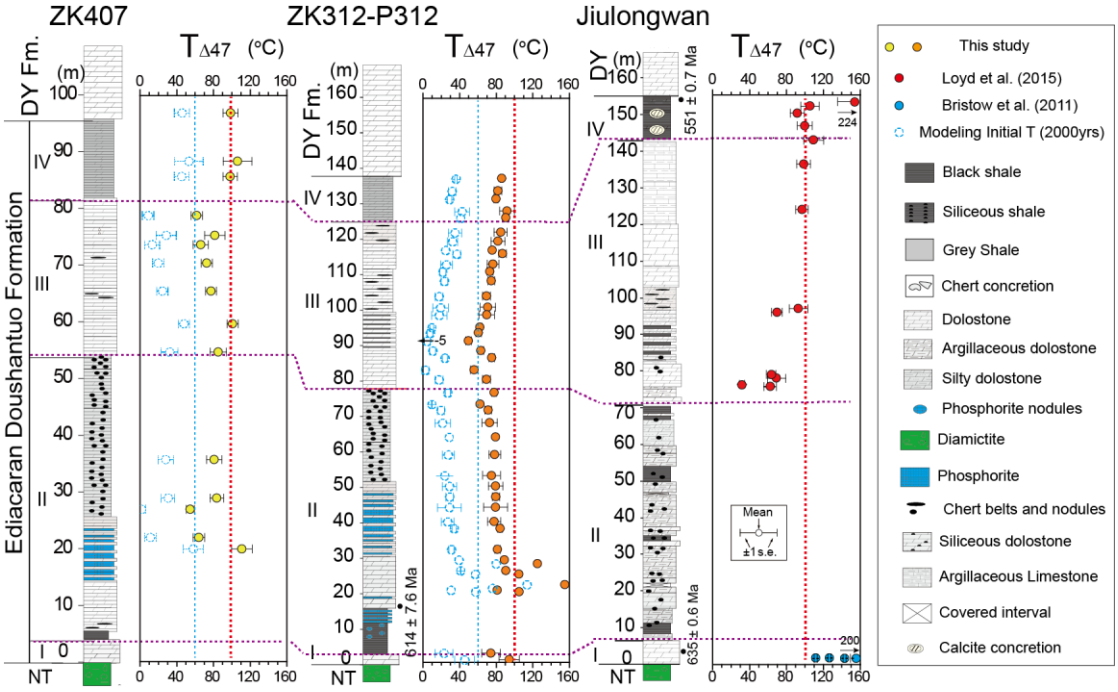


Fig. S2. Dolomite clumped isotope temperature ($T_{\Delta 47}$) profiles of the Ediacaran Doushantuo Formation in the ZK312-P312 and ZK407 drillcores, compared to a previously reported profile for the Jiulongwan section (2, 3). The initial $T_{\Delta 47}$ data (i.e., blue circles) are based on a solid-state reordering model assuming a peak heating temperature (T) of 270 °C for 2000 years. See main text for details regarding stratigraphic correlations and the solid-state reordering model. I-IV = Members I to IV of the Doushantuo Formation, NT = Nantuo, DY = Dengying, Fm. = Formation.

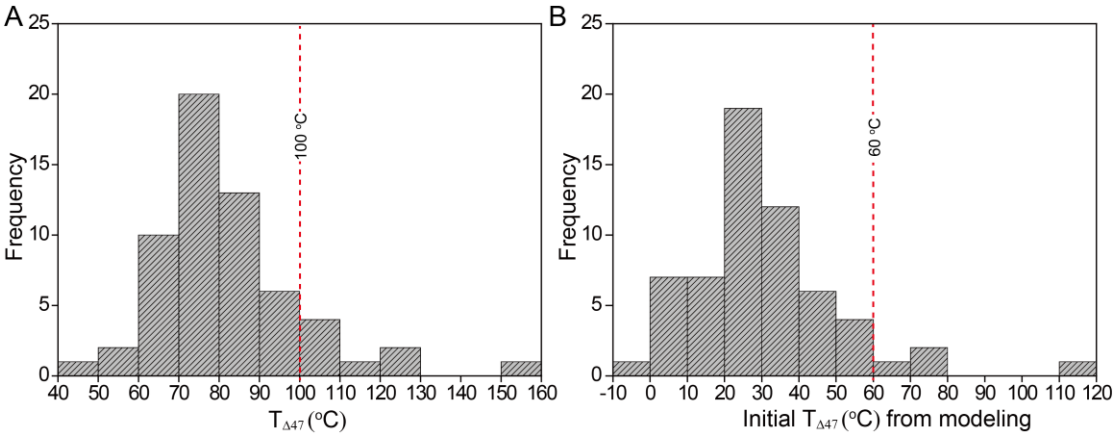
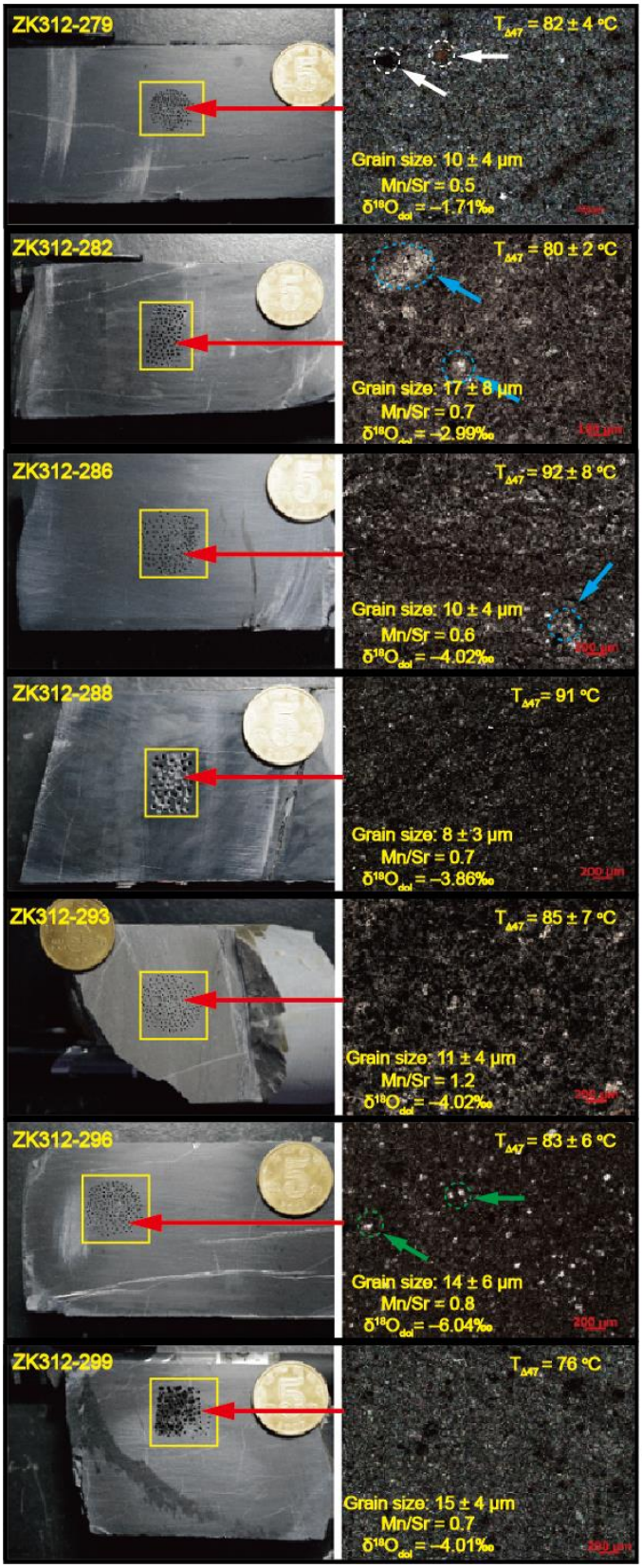


Fig. S3. Histograms of measured $T_{\Delta 47}$ values of Doushantuo dolomite (*A*) and of their initial $T_{\Delta 47}$ values from modeling (*B*). The initial $T_{\Delta 47}$ values from modeling are based on a solid-state reordering model assuming a hydrothermal event with a peak heating of 270°C for 2000 years. See text for modeling details.

A

Core sample and corresponding photomicrograph



Lithologic description

ZK312-279:
Microcrystalline dolomite and dolosparite containing phosphatic grains (white arrows)

ZK312-282:
Microcrystalline dolomite containing dolosparite particles (blue arrows) and dispersed phosphatic grains

ZK312-286:
Microcrystalline dolomite containing dolosparite particles (blue arrows) and dispersed phosphatic grains

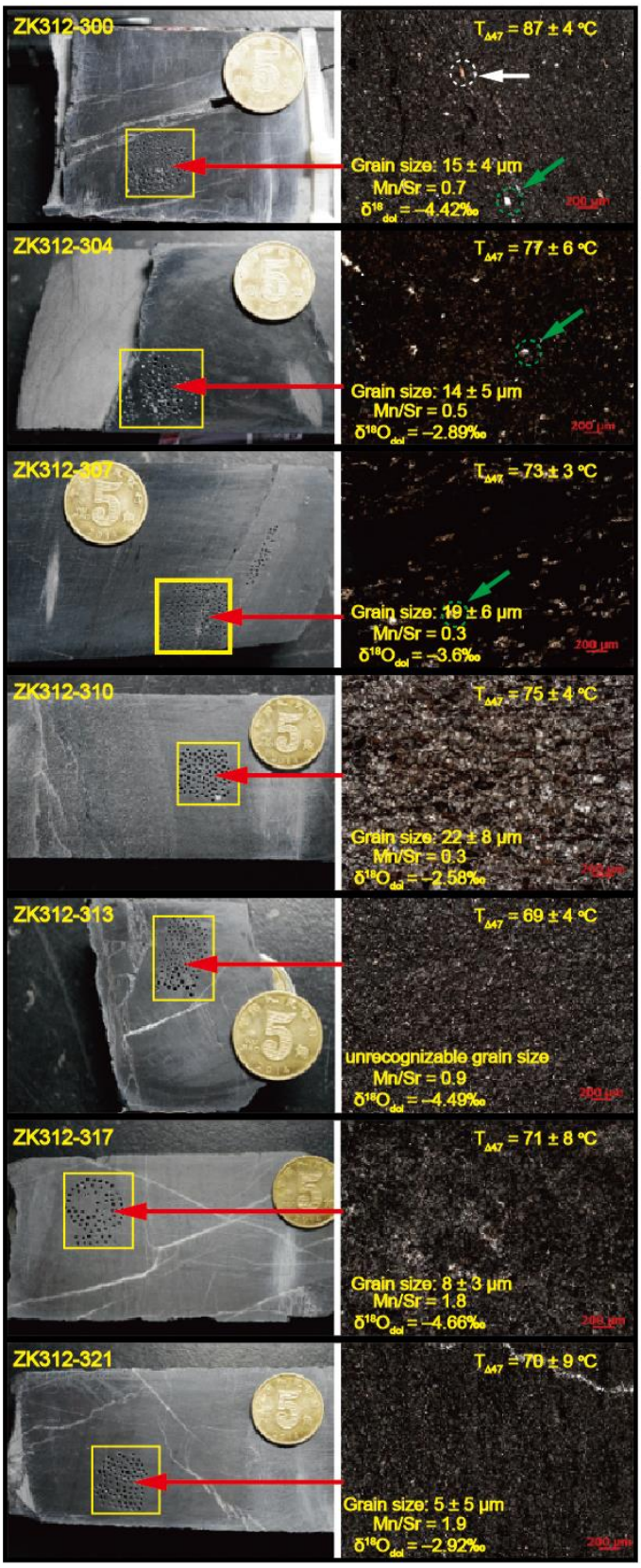
ZK312-288:
Microcrystalline dolomite and dolosparite containing phosphatic grains

ZK312-293:
Microcrystalline dolomite containing dolosparite patches and dispersed phosphatic patches

ZK312-296:
Microcrystalline dolomite containing dolosparite and calcisparite partches (green arrows) and dispersed phosphatic grains

ZK312-299:
Microcrystalline dolomite containing dolosparite particles and phosphatic grains

B Core sample and corresponding photomicrograph



Lithologic description

ZK312-300:
Microcrystalline dolomite and dolosparite containing calcisparite patches (green arrows) and phosphatic grains (white arrows)

ZK312-304:
Microcrystalline dolomite and dolosparite containing calcisparite patches (green arrows)

ZK312-307:
Microcrystalline dolomite and dolosparite containing calcisparite patches (green arrows)

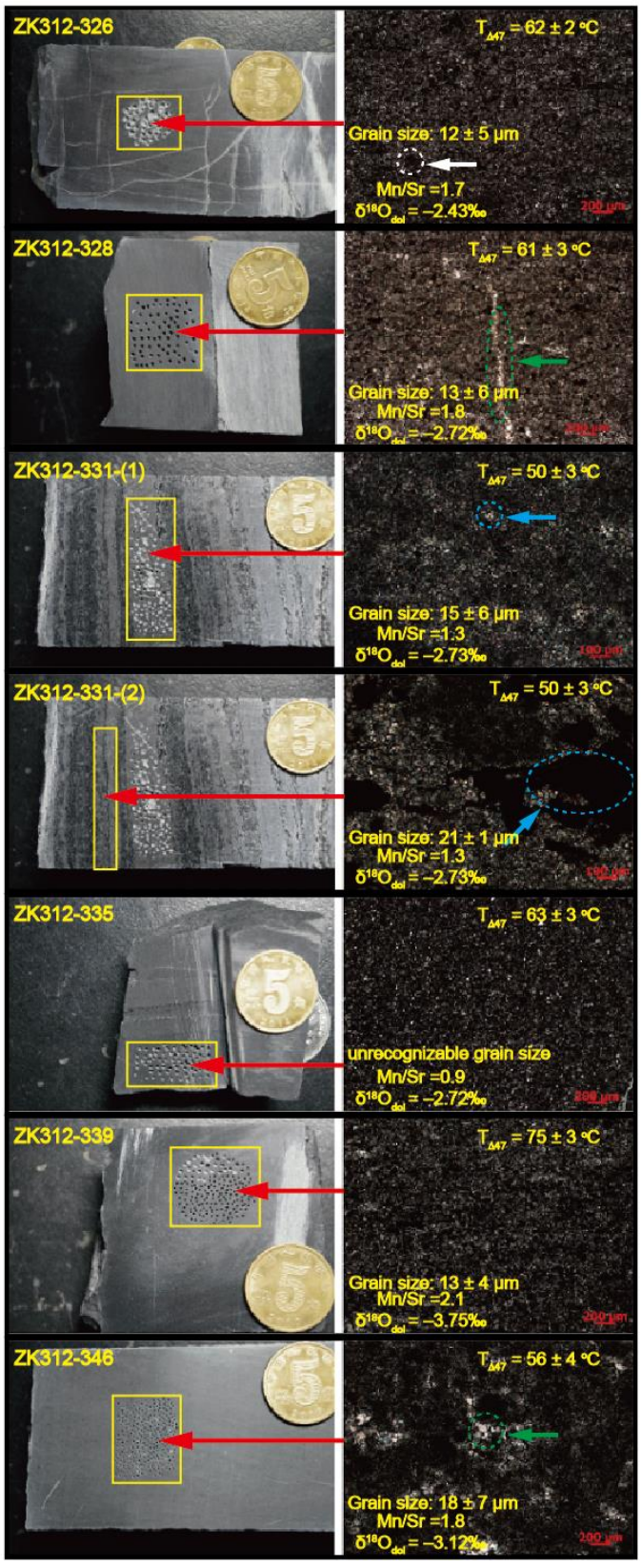
ZK312-310:
Microcrystalline dolomite containing dolosparite particles and dispersed phosphatic grains

ZK312-313:
Microcrystalline dolomite containing dolosparite particles and dispersed phosphatic grains

ZK312-317:
Microcrystalline dolomite containing dolosparite particles and dispersed phosphatic grains

ZK312-321:
Microcrystalline dolomite and dolosparite containing phosphatic grains

C Core sample and corresponding photomicrograph



Lithologic description

ZK312-326:
Microcrystalline dolomite and dolosparite containing phosphatic grains (white arrows)

ZK312-328:
Microcrystalline dolomite and dolosparite containing sparry calcite patches (green arrows) and dispersed phosphatic grains

ZK312-331-(1):
Microcrystalline dolomite containing dolosparite particles (blue grrows) and dispersed phosphatic grains

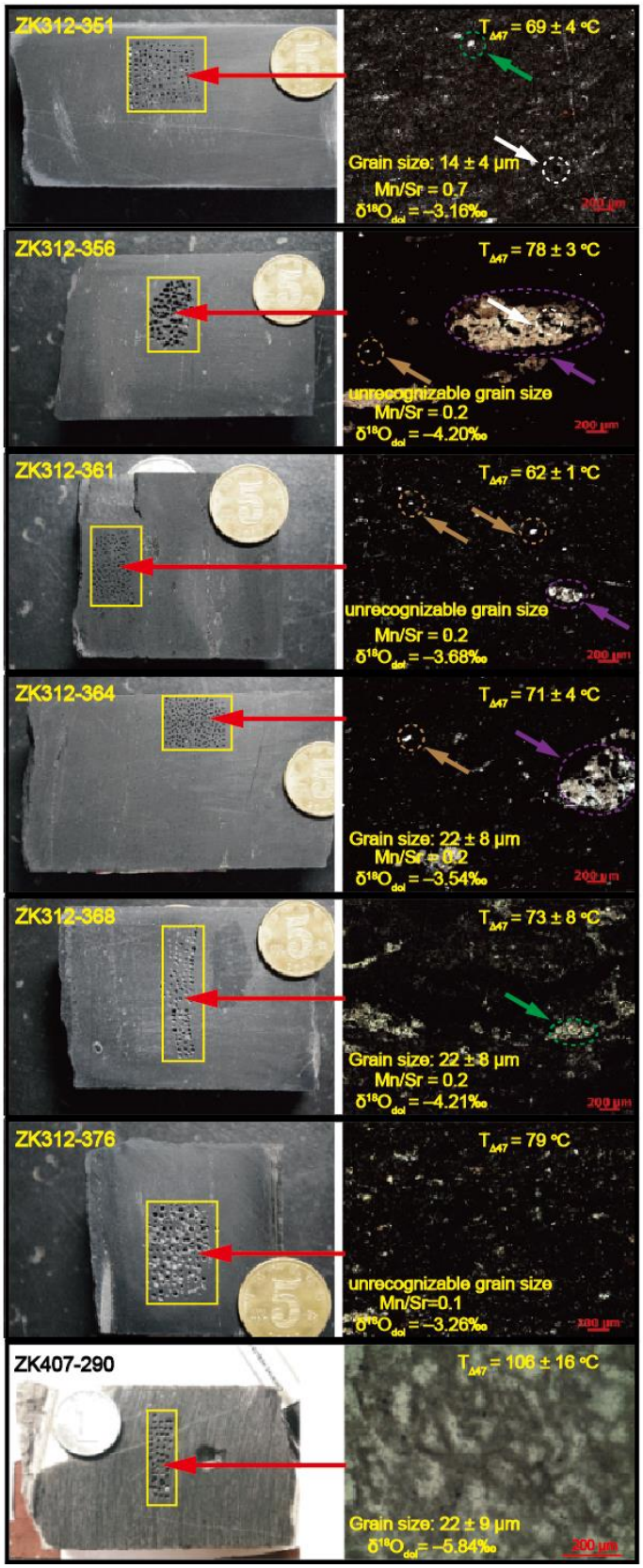
ZK312-331-(2):
Microcrystalline dolomite and containing dolosparite particles and phosphatic grains (blue arrows)

ZK312-335:
Microcrystalline dolomite and dolosparite containing dispersed phosphatic grains

ZK312-339:
Microcrystalline dolomite and dolosparite containing dispersed phosphatic grains

ZK312-346:
Microcrystalline dolomite and dolosparite containing sparry calcite patches (green arrows) and phosphatic grains

D Core sample and corresponding photomicrograph



Lithologic description

ZK312-351:
Microcrystalline dolomite and dolosparite containing calcsparite (green arrows) phosphatic particles (white arrows)

ZK312-356:
Microcrystalline dolomite containing chalcedony block (purple arrows) and dispersed phosphatic particles (white arrows) and pyrite (brown arrows)

ZK312-361:
Microcrystalline dolomite containing chalcedony block (purple arrows) and pyrite (brown arrows)

ZK312-364:
Microcrystalline dolomite containing chalcedony block (purple arrows) and pyrite (brown arrows)

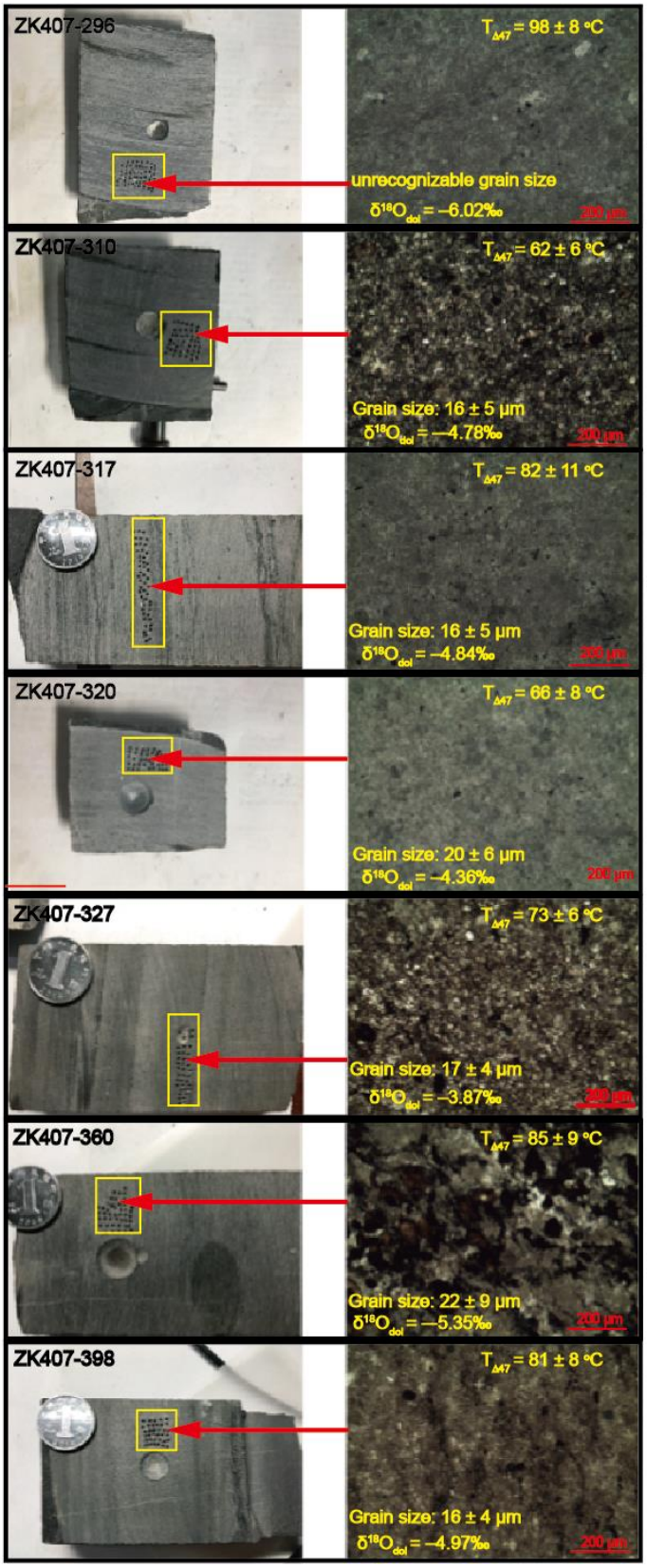
ZK312-368:
Microcrystalline dolomite containing calcsparite (green arrows) and dispersed phosphatic grains

ZK312-376:
Microcrystalline dolomite containing calcsparite and dispersed phosphatic grains

ZK407-290:
Microcrystalline dolomite and dolosparite containing dispersed phosphatic particles

E Core sample and corresponding photomicrograph

Lithologic description



ZK407-296:
Microcrystalline dolomite containing phosphatic particles

ZK407-310:
Microcrystalline dolomite and dolosparite containing phosphatic particles

ZK407-317:
Microcrystalline dolomite containing phosphatic particles

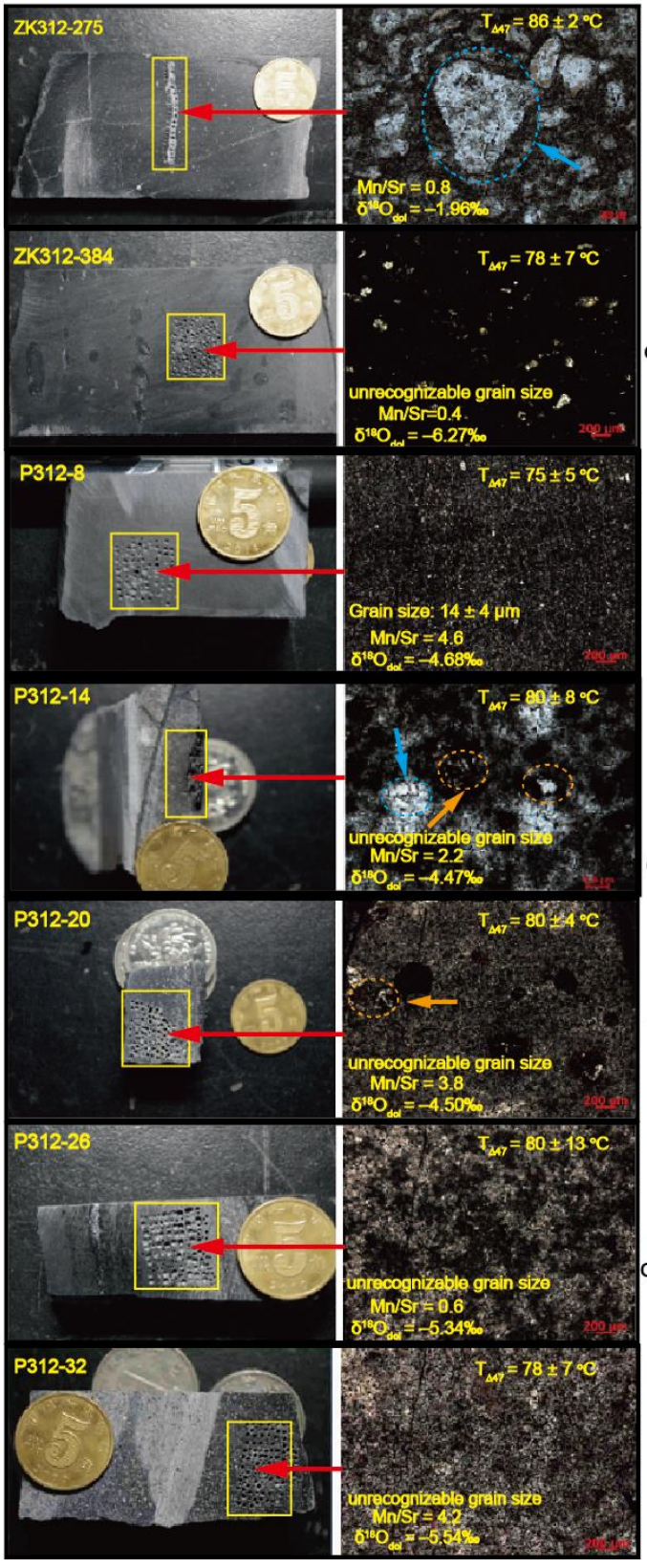
ZK407-320:
Microcrystalline dolomite containing dispersed phosphatic grains

ZK407-327:
Microcrystalline dolomite and dolosparite containing phosphatic particles

ZK407-360:
Microcrystalline dolomite and dolosparite,containing dispersed phosphatic particles

ZK407-398:
Microcrystalline dolomite containing dispersed phosphatic particles

F Core sample and corresponding photomicrograph



Lithologic description

ZK312-275:
Microcrystalline dolomite and dolosparite, containing large chalcedony block, Ca and Si intergrowth (blue arrows)

ZK312-384:
Microcrystalline dolomite containing dolosparite particles and phosphatic grains

P312-8:
Microcrystalline dolomite and dolosparite containing phosphatic particles

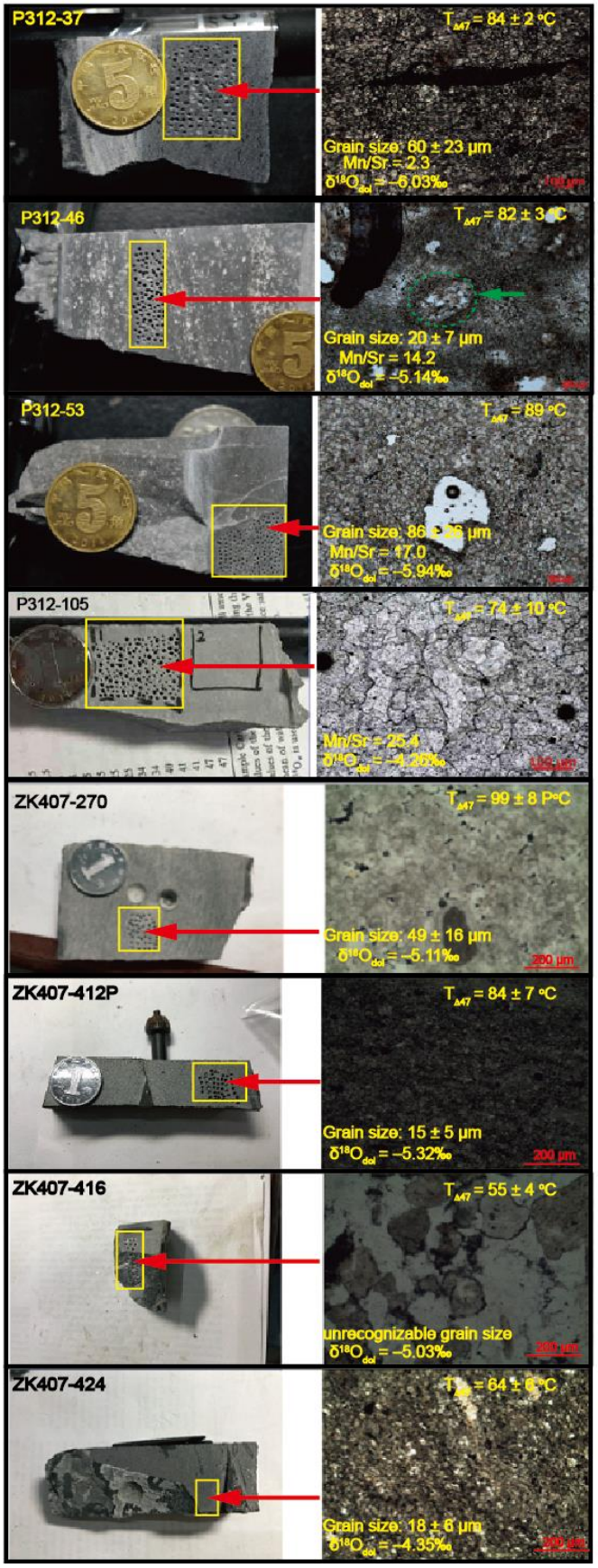
P312-14:
Microcrystalline dolomite containing dolosparite particles (blue arrows) and dispersed phosphatic patches. Phosphatic debris carbonatization (orange arrows)

P312-20:
Microcrystalline dolomite and dolosparite containing dispersed phosphatic patches. Phosphatic debris carbonat-ization (orange arrows)

P312-26:
Microcrystalline dolomite and dolosparite containing large dispergated phosphatic particles

P312-32:
Microcrystalline dolomite and dolosparite particles containing dispersed phosphatic particles

G Core sample and corresponding photomicrograph



Lithologic description

P312-37:
Microcrystalline dolomite and dolosparite particles containing dispersed phosphatic particles

P312-46:
Microcrystalline dolomite and dolosparite, containing large calcited phosphatic patches (blue arrows)

P312-53:
Microcrystalline dolomite and dolosparite, containing phosphatic patches

P312-105:
Microcrystalline dolomite and dolosparite

ZK407-270:
Microcrystalline dolomite and dolosparite containing phosphatic particles

ZK407-412:
Microcrystalline dolomite and dolosparite containing phosphatic particles

ZK407-416:
Microcrystalline dolomite and dolosparite containing phosphatic particles

ZK407-424:
Microcrystalline dolomite and dolosparite containing phosphatic particles

Fig. S4. Drillcore segments and corresponding photomicrographs of sampled areas in ZK312-P312 and ZK407 drillcores, including well-preserved samples (*A*-*E*) and potentially diagenetically altered samples (*F*-*G*). Geochemical proxies for diagenesis (i.e., Mn/Sr, $\delta^{18}O_{dol}$, and grain size) and corresponding $T_{\Delta 47}$ data are shown, as available. Scale: the 1-yuan, 5-jiao and 1-jiao coins have diameters of 2.5 cm, 2.0 cm and 1.8 cm, respectively.

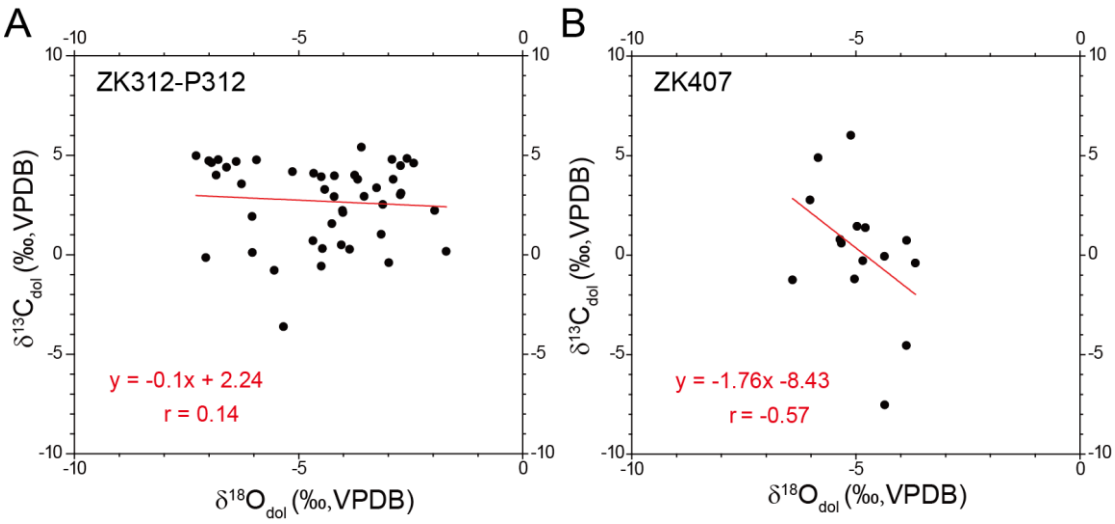


Fig. S5. Crossplots of paired carbon ($\delta^{13}C_{dol}$) and oxygen isotope ($\delta^{18}O_{dol}$) compositions of Doushantuo dolomite samples from the ZK312-P312 (*A*) and ZK407 drillcores (*B*).

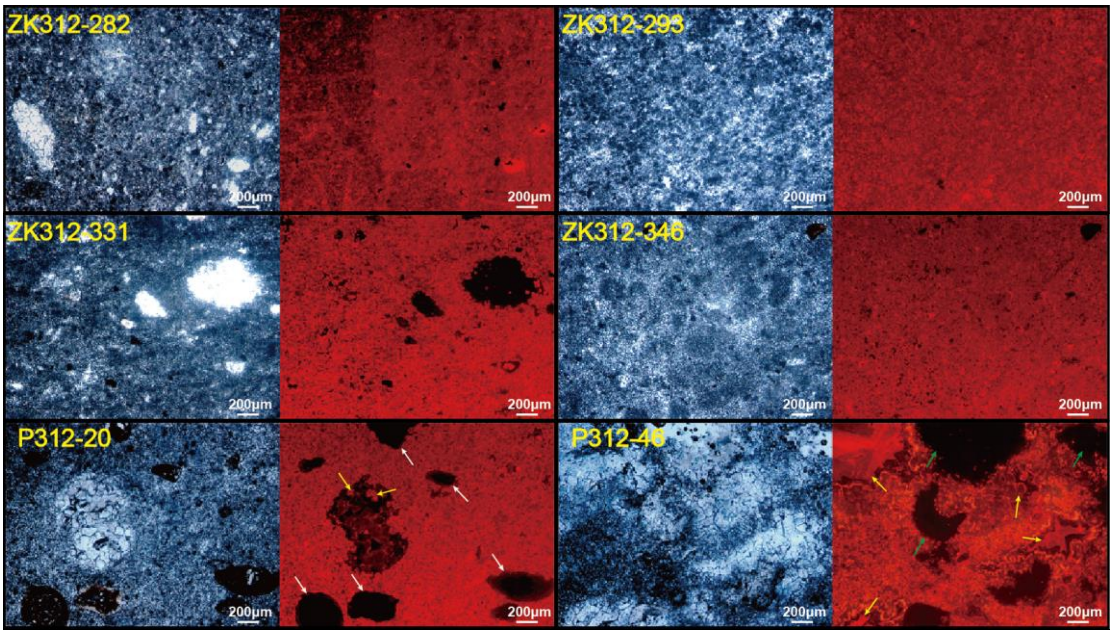


Fig. S6. Polarized light (PL; left) and cathodoluminescent (CL; right) images of four typical samples from >50 m depth (ZK312-282, ZK312-293, ZKE312-331 and ZK312-346) and 2 typical samples from <50 m depth (P312-20 and P312-46). The CL images of samples from >50 m depth show no obvious cements. The samples from <50 m depth contain large phosphatic patches (pointed by white arrows), chalcedony block (pointed by green arrows) and dolomite cements (pointed by yellow arrows).

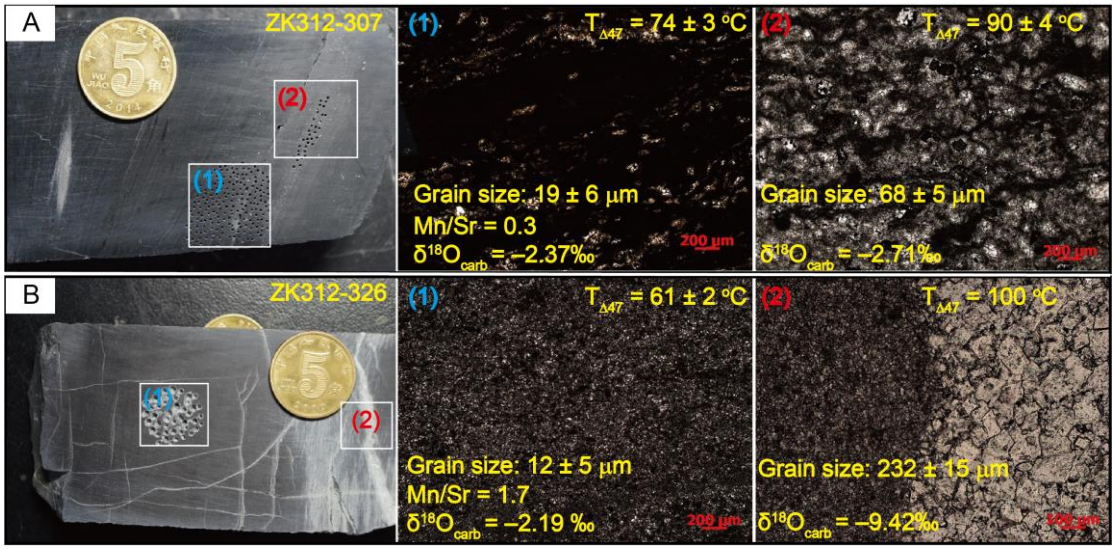


Fig. S7. Typical carbonate textures as observed in the sample slab and under microscopy. (*A*) Sample ZK312-307 includes major microcrystalline dolomite area [labeled as (1)] and minor coarse crystallite dolomite area [labeled as (2)]. (*B*) Sample ZK312-326 includes major microcrystalline dolomite area [labeled as (1)] and minor veins [labeled as (2)]. In this study, we sampled the microcrystalline dolomite area by micro-drilling while avoiding those coarse crystallite dolomites and veins for sampling. Geochemical proxies for late diagenesis (i.e., Mn/Sr, $\delta^{18}O_{dol}$, and grain size) and corresponding $T_{\Delta47}$ data are shown for references, as available. Scale: 5-jiao coin is 2.0 cm in diameter.

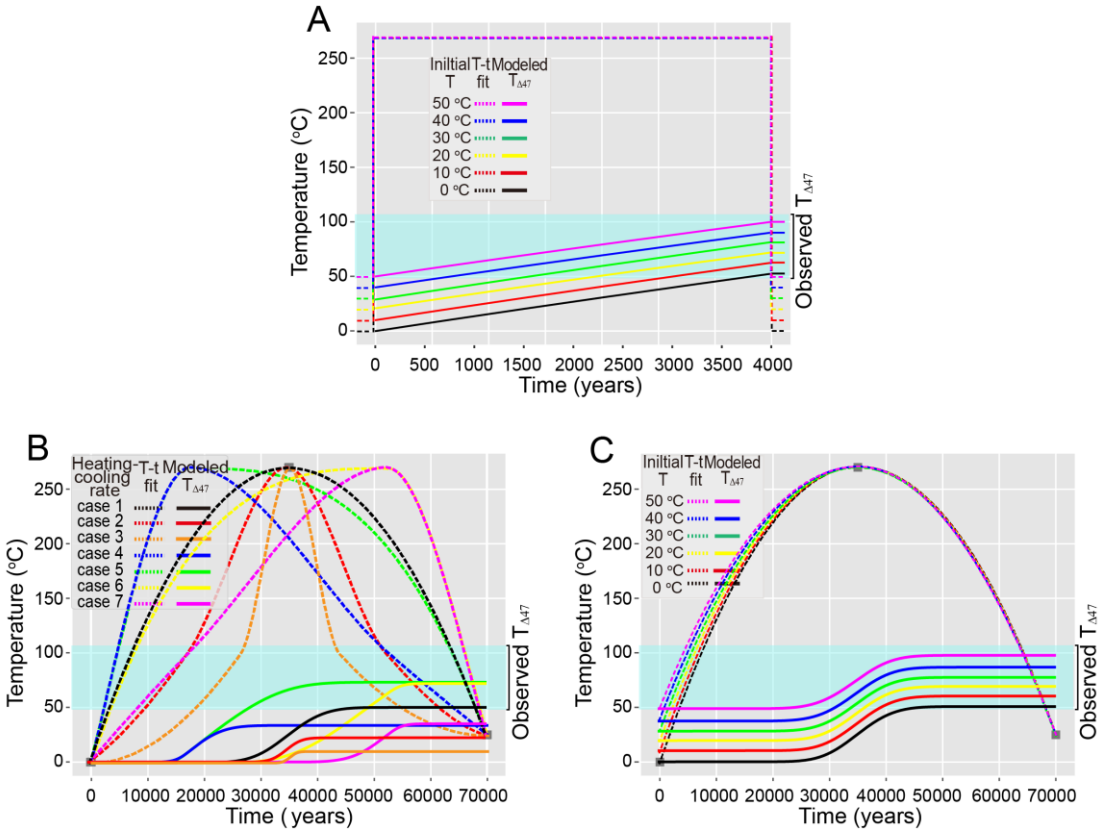


Fig. S8. Solid-state reordering modeling of the study Doushantuo Formation based on the dolomite-based "transient defect/equilibrium defect" model (7-8) and the "equilibrium defect" (9) models, which can achieve the $T_{\Delta47}$ values (50-106 °C) observed in this study. (*A*) Dolomite-based "transient defect/equilibrium defect" model (an instantaneous isothermal heating model) results assuming a varying initial temperature from 0 to 50 °C, a heating duration of 4000 years at a peak temperature of 270 °C. (B) "Equilibrium defect" model results for short-duration (70000 years) of hydrothermal events. These simulations assumed an initial temperature of 0 °C, a heating duration of 70000 years at a peak temperature of 270 °C with variable heating-cooling rates, including three symmetric heating-cooling cases (case 1-3) and four asymmetric heating-cooling cases (case 4-7). (*C*) "Equilibrium defect" model results assuming a varying initial temperature from 0 to 50 °C, a heating duration of 70000 years at a peak temperature of 270 °C, and a fixed heating-cooling rate (i.e., case 1 in *B*). In subfigures B and C, the "T-t fit" lines denote assumed heating T-time paths, while the "Modeled $T_{\Delta47}$" lines denote the corresponding $T_{\Delta47}$ evolution of the Doushantuo dolomites predicted by a solid-state reordering model. The shallow blue bands represent the range of measured $T_{\Delta47}$ values of well-preserved Doushantuo dolomites in this study. See main text for more modeling details.

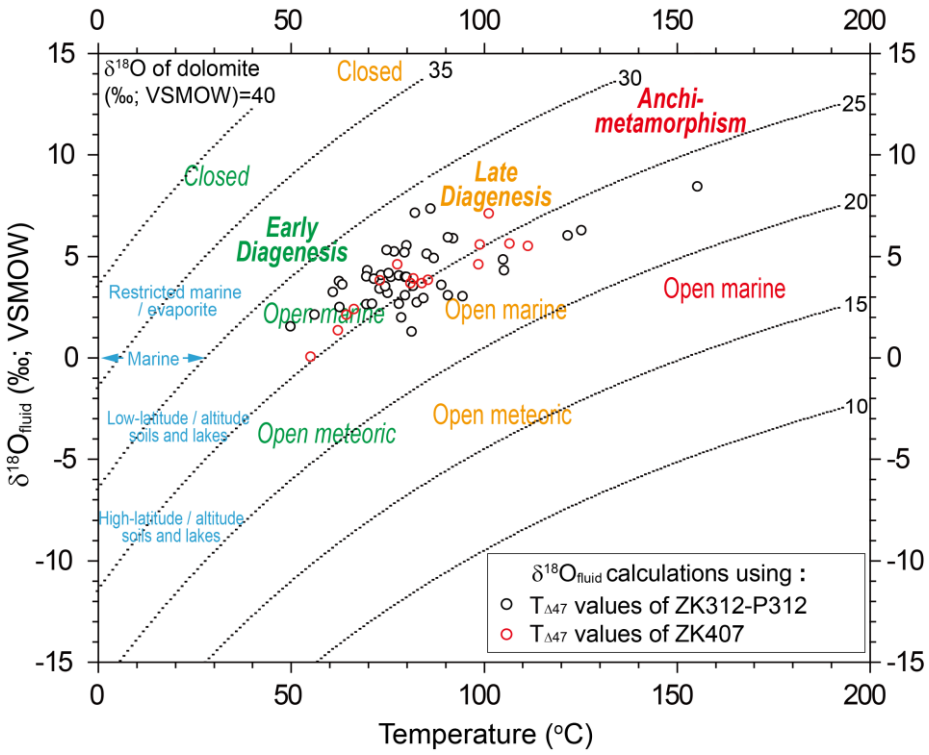


Fig. S9. Originally calculated $\delta^{18}O$ compositions of the diagenetic fluids ($\delta^{18}O_{fluid}$) versus paired $T_{\Delta47}$ data for Doushantuo dolomite. Recrystallization environments (colored text: early or late diagenetic or anchi-metamorphic) except for those modern environments (blue texts) are either closed (i.e., rock-buffered) or open (i.e., fluid-buffered). Reference isotopic compositions for carbonates and co-existing diagenetic fluids equilibrated over a range of geological conditions were adopted from ref. 10, but updated to the $\delta^{18}O$ compositions of dolomite. See Methods for further explanation of calculations and the text for detailed interpretations.

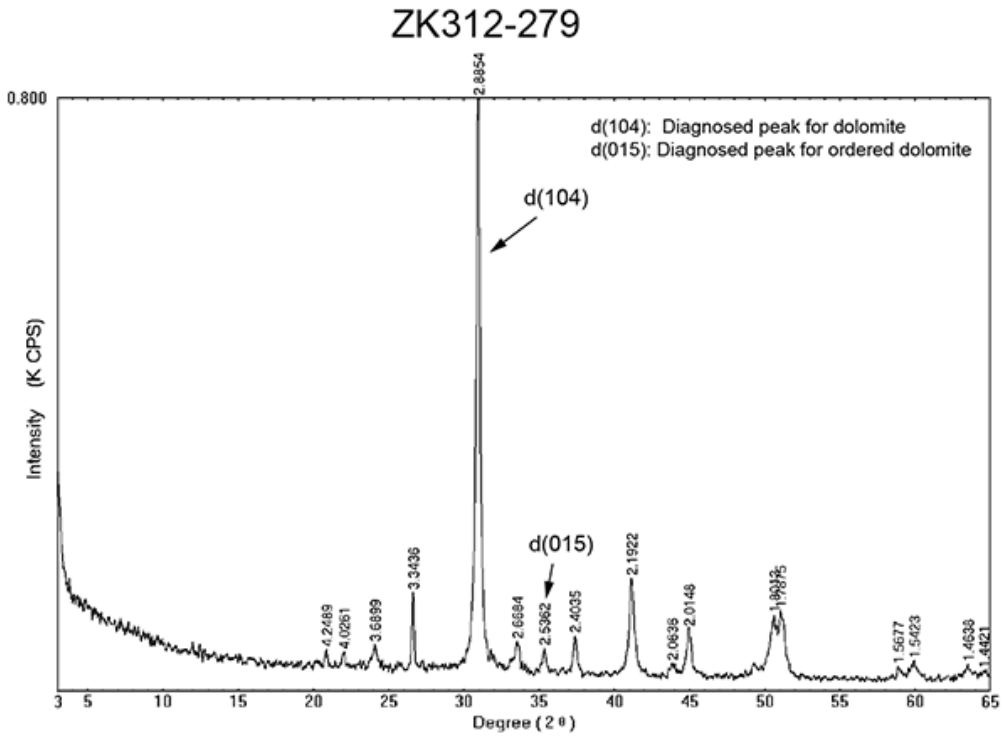


Fig. S10. Representative X-ray diffraction (XRD) spectrum for the Doushantuo Formation (sample ZK312-279). XRD spectra indicate that all study samples consist dominantly of ordered dolomite.

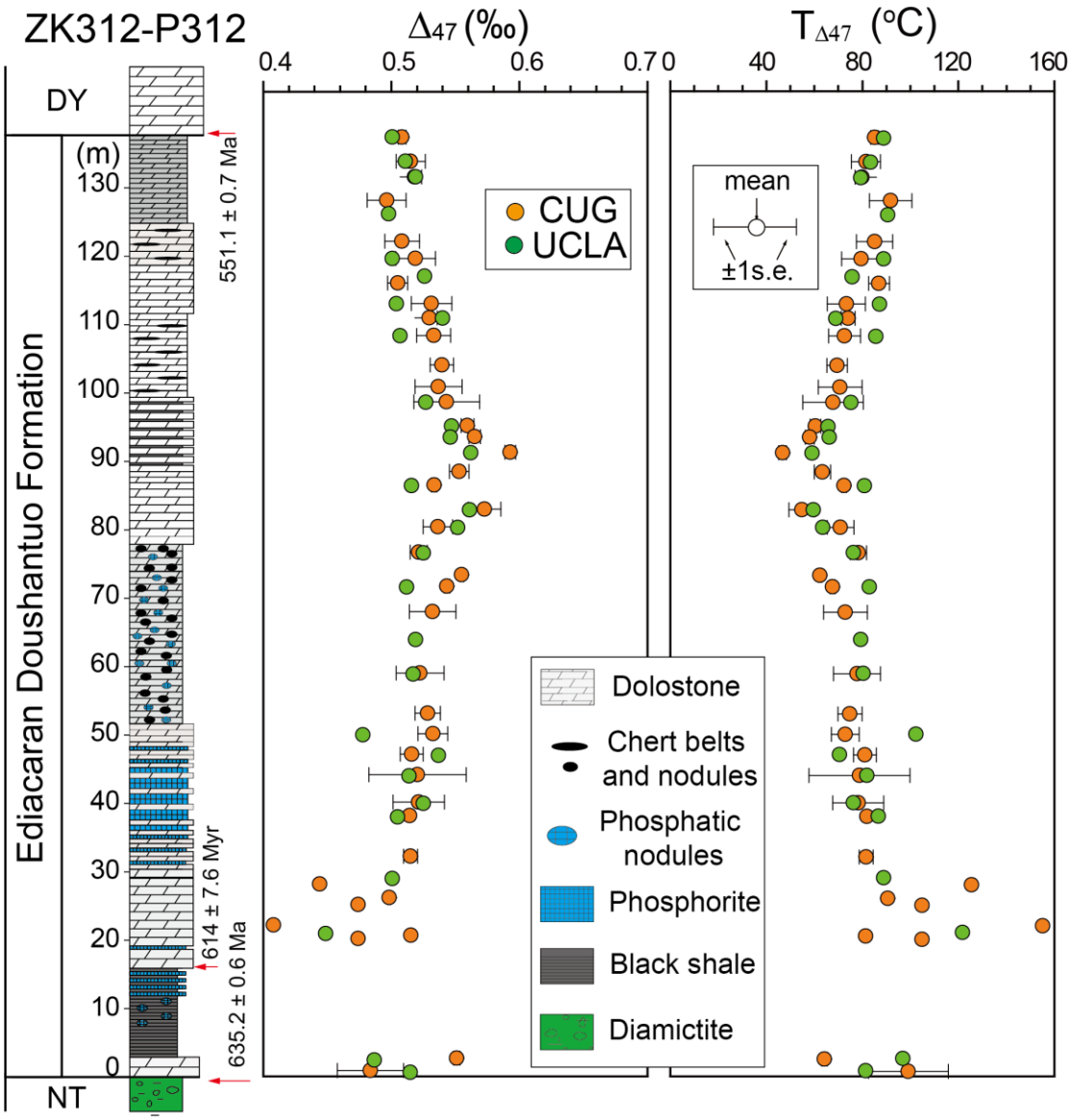


Fig. S11. Comparison of Δ_{47} and $T_{\Delta47}$ data measured at University of California-Los Angeles (UCLA) (green symbols) and at China University of Geosciences-Wuhan (CUG-W) (orange symbols). The two datasets show almost the same values and stratigraphic trends through the Doushantuo Formation, confirming the robustness of our Δ_{47} and $T_{\Delta47}$ data. NT = Nantuo Formation, DY = Dengying Formation.

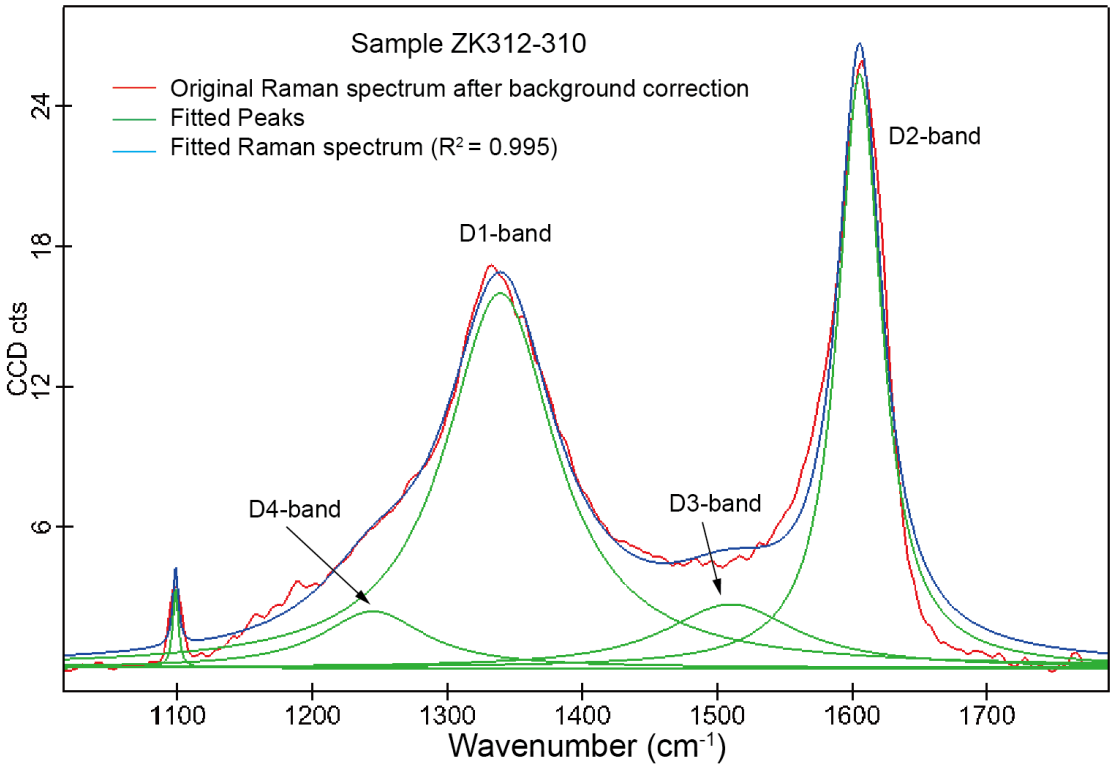


Fig. S12. Representative Raman spectra of organic matter (OM) of Doushantuo sample ZK312-310. Four discriminative bands (D1, D2, D3, and D4; green) are marked. The method of peak decomposition was adopted from ref. 11. The coefficient of variation ($R^2 = 0.995$) compares the original spectrum (red) with the fitted Raman spectrum (blue). CCD cts = charge-coupled device counts.

Table S1. Composite temperature- or diagenesis-related geochemical and petrographic data of dolomites from the Doushantuo Formation.

Sample ID	Height in ZK312-P312 (m)	Δ_{47} (‰) [a]	$T_{\Delta47}$ (°C) [b]	$T_{\Delta47}$ (°C) [c]	$T_{\Delta47}$ (°C) [d]	$T_{\Delta47}$ (°C) [e]	$T_{\Delta47}$ (°C) [f]	Initial $T_{\Delta47}$ (°C) by modeling [g]	Initial $T_{\Delta47}$ (°C) by modeling [h]	avg. $\delta^{13}C_{carb}$ (VPDB, ‰)	avg. $\delta^{18}O_{carb}$ (VPDB, ‰)	$\delta^{18}O_{fluid}$(VSMOW,‰) [i]	$\delta^{18}O_{fluid}$(VSMOW,‰) [j]	Grain size (μm)	Grain size 1 s.d. (μm)	Dolomite (wt %) [k]	Raman of OM FWHM-D1 (cm^{-1})	Raman of OM FWHM-D2 (cm^{-1})	Peak heating Temperature based on D1 (°C)	Peak heating temperature based on D2 (°C)	Average peak heating temperatures of D1 and D2 (°C)	$R_{o,mv}$ (%)	R_o (%)	Peak heating temperature based on R_o (°C)
ZK312-275	137.3	0.507	107	90	100	114	**86**	34	36	2.2	-2.0	7.4	-0.1			95								
ZK312-279	133.8	0.515	102	86	95	108	**82**	29	32	0.2	-1.7	7.2	-0.7	10	4	95	97.4	64.5	260	269	264			
ZK407-270	132.4	0.485	121	103	114	132	**99**	47	50	6.0	-5.1	5.6	-0.9	49	16									
ZK312-282	131.5	0.519	99	84	93	106	**80**	27	29	-0.4	-3.0	5.6	-2.5	17	8	91	86.5	66.2	265	292	279			
ZK312-286	128.1	0.497	113	96	106	122	**92**	40	43	0.5	-4.0	5.9	-1.1	10	4	91	93.4	65.1	253	277	265			
ZK312-288	126.1	0.499	112	95	105	121	**91**	38	41	0.3	-3.9	6.0	-1.1	8	3	93						3.5	2.58	275
ZK312-293	122.1	0.509	105	89	99	113	**85**	33	35	2.2	-4.0	5.2	-2.4	11	4	98	87.9	65.9	288	289	289			
ZK312-296	119.6	0.514	102	87	96	109	**82**	30	32	1.9	-6.0	2.8	-5.1	14	6	93	91.7	65.4	281	281	281			
ZK407-290	119.3	0.473	130	110	122	143	**106**	55	58	4.9	-5.8	5.6	-0.3	22	9									
ZK312-299	117.0	0.527	94	80	88	100	**76**	23	25	2.1	-4.0	4.0	-4.5	15	4	98	92.9	65.2	257	278	268			
ZK312-300	116.0	0.506	107	91	100	115	**87**	34	37	3.3	-4.4	5.0	-2.5	15	4	60								
ZK407-296	115.8	0.486	121	102	113	131	**98**	46	50	2.8	-6.0	4.6	-1.9											
ZK312-304	113.0	0.525	96	81	89	101	**77**	24	26	3.8	-2.9	5.3	-3.1	14	5	92	97.6	64.5	262	268	265	4.3	3.05	297
ZK312-307	110.9	0.532	91	78	86	97	**73**	20	22	5.4	-3.6	4.1	-4.6	19	6	99						3.0	2.26	258
ZK312-310	108.3	0.529	93	79	87	99	**75**	22	24	4.8	-2.6	5.4	-3.2	22	8	99	98.3	64.4	265	267	266			

ZK407-310	106.8	0.557	78	66	73	81	**62**	8	10	1.4	-4.8	1.3	-8.8	16	5								
ZK312-313	104.0	0.540	87	74	81	92	**69**	16	18	3.9	-4.5	2.7	-6.5			99	96.6	64.7	257	270	264		
ZK407-317	102.3	0.516	101	86	95	108	**81**	29	31	-0.3	-4.8	3.9	-4.1	16	5								
ZK312-317	100.8	0.537	89	75	83	93	**71**	18	20	4.1	-4.7	2.7	-6.3	8	3	93	101	64.0	283	261	272		
ZK407-320	100.1	0.547	83	71	78	87	**66**	13	15	-0.1	-4.4	2.4	-7.2	20	6								
ZK312-321	98.6	0.540	87	74	81	92	**69**	16	18	4.8	-2.9	4.3	-4.9	5	5	93	87.3	66.0	276	290	283		
ZK407-327	95.9	0.533	91	77	85	96	**73**	20	22	0.7	-3.9	3.8	-5.0	17	4								
ZK312-326	95.1	0.556	79	67	73	82	**62**	9	10	4.6	-2.4	3.8	-6.3	12	5	90	82.4	66.8	272	301	286		
ZK312-328	93.5	0.559	77	65	72	80	**61**	7	9	4.5	-2.7	3.3	-6.9	13	6	99							
ZK312-331	91.2	0.586	64	54	60	65	**50**	-4	-3	3.0	-2.7	1.6	-10.3	15	6	65	73.8	68.0	274	319	297		
ZK407-337	89.4	0.524	96	81	90	102	**77**	25	27	-0.4	-3.7	4.6	-3.8										
ZK312-335	88.4	0.554	80	67	74	83	**63**	10	11	3.1	-2.7	3.7	-6.3			90							
ZK312-339	86.4	0.528	94	80	88	99	**75**	22	25	4.0	-3.8	4.2	-4.3	13	4	91	80.4	67.1	261	305	283		
ZK312-346	82.9	0.570	72	61	67	74	**56**	3	4	2.5	-3.1	2.2	-8.7	18	7	90	74.9	67.9	271	317	294		
ZK407-351	81.2	0.481	124	105	117	136	**101**	50	53	-4.5	-3.9	7.1	0.8	15	4								
ZK312-351	80.3	0.540	87	74	81	92	**69**	16	18	1.0	-3.2	4.1	-5.1	14	4	90	79.8	67.1	270	306	288		
ZK312-356	76.6	0.523	97	82	91	103	**78**	25	27	4.0	-4.2	4.1	-4.2			30							
ZK407-360	73.8	0.509	105	89	99	113	**85**	33	35	0.8	-5.4	3.8	-3.8	22	9								
ZK312-361	73.3	0.556	79	67	73	82	**62**	9	10	3.8	-3.7	2.5	-7.6			60	90.6	65.5	251	283	267		
ZK312-364	71.6	0.536	89	76	83	94	**71**	18	20	2.9	-3.5	4.0	-5.0	22	8	35							
ZK312-368	67.9	0.533	91	77	85	96	**73**	20	22	2.9	-4.2	3.5	-5.4	22	8	75	91.6	65.4	262	281	272		
ZK312-376	63.9	0.520	98	83	92	105	**79**	27	29	3.4	-3.3	5.3	-2.9			25							
ZK312-384	58.9	0.522	97	82	91	103	**78**	26	28	3.6	-6.3	2.0	-6.2			70						2.7	2.07	247
ZK407-398	57.8	0.517	100	85	94	107	**81**	28	31	1.4	-5.0	3.7	-4.3	16	4								
P312-8	53.0	0.529	93	79	87	99	**75**	22	24	0.7	-4.7	3.2	-5.4	14	4	93							

ZK407-412p	50.4	0.512	103	88	97	111	**83**	31	33	0.6	-5.3	3.6	-4.1	15	5						
P312-14	50.0	0.520	98	83	92	105	**79**	27	29	0.3	-4.5	4.0	-4.1			97					
P312-20	47.0	0.519	99	84	93	106	**80**	27	29	-0.6	-4.5	4.0	-4.1			97					
ZK407-416	46.1	0.573	70	59	65	72	**55**	1	2	-1.2	-5.0	0.1	-11.0								
P312-26	44.0	0.520	98	83	92	105	**79**	27	29	-3.6	-5.3	3.1	-5.0			80					
P312-32	40.0	0.523	97	82	91	103	**78**	25	27	-0.8	-5.5	2.7	-5.6			93					
P312-37	38.0	0.511	104	88	97	111	**84**	32	34	0.1	-6.0	3.0	-4.7	60	23	93					
ZK407-424	35.4	0.552	81	68	75	84	**64**	11	12	-7.5	-4.4	2.1	-7.8	18	6						
P312-46	32.1	0.516	101	86	95	108	**81**	29	31	4.2	-5.1	3.6	-4.4	20	7	98					
ZK407-428	31.1	0.465	137	115	128	151	**111**	60	64	-1.3	-6.4	5.5	-0.1	33	11						
P312-53	29.0	0.502	110	93	103	118	**89**	37	39	4.8	-5.9	3.6	-3.6	86	26	98					
P312-55	28.0	0.445	154	129	144	172	**125**	75	79	4.0	-6.8	6.4	1.6								
P312-58	26.0	0.499	112	95	105	121	**91**	38	41	4.4	-6.6	3.1	-4.0								
P312-60	25.0	0.475	129	109	121	141	**105**	53	57	4.7	-6.4	4.9	-1.1			98					
P312-66	22.0	0.409	191	158	179	221	**155**	106	112	4.7	-7.0	8.5	5.1			98					
P312-67	21.0	0.450	149	125	140	167	**122**	71	75	4.8	-6.8	6.1	1.1			98					
P312-68	20.5	0.516	101	86	95	108	**81**	29	31	5.0	-7.3	1.4	-6.6								
P312-70	20.0	0.475	129	109	121	141	**105**	53	57	4.6	-6.9	4.3	-1.7			98					
P312-105	2.5	0.530	93	79	87	98	**74**	21	23	1.6	-4.3	3.6	-5.1			98	97.1	64.6	287	269	278
P312-114	0.7	0.492	116	99	109	126	**95**	43	46	-0.1	-7.1	3.1	-3.7			98	107	63.1	254	248	251

[a] We used Δ_{47} to replace the STF-$\Delta_{47ARF25}$. The STF-$\Delta_{47ARF25}$ value was calibrated by applying the Standards Transfer Function to average $\Delta_{47ARF25}$ value. The average $\Delta_{47ARF25}$ value was calculated using the repeated $\Delta_{47ARF25}$ values. The $\Delta_{47ARF25}$ value was calculated from Brand raw Δ_{47} value by applying it to the absolute reference frame (12) and then scaling it to a 25 °C phosphoric acid reaction by addition of a 0.082‰ temperature correction factor for 90 °C reactions (13). The Brand raw Δ_{47} value was calculated by converting our measured raw δ_{45}, raw δ_{46}, raw δ_{47}, raw δ_{48} and raw δ_{49} values into the Brand parameter frame (14, 15) (details see Table S3).

[b] The $T_{\Delta47}$ values were calculated using the calcite temperature calibration in ref. 16.

[c] The $T_{\Delta47}$ values were calculated using the calcite temperature calibration in ref. 17.

[d] The $T_{\Delta47}$ values were calculated using the dolomite temperature calibration in ref. 18.

[e] The $T_{\Delta47}$ value was calculated using the Brand parameter-based calcite temperature calibration in ref. 19.

[f] The $T_{\Delta47}$ values were calculated using the revised dolomite temperature calibration in this study.

[g] The initial $T_{\Delta47}$ value was derived from the modeling of the solid-state reordering effects by assuming a peak heating temperature of 270 °C for **2000** years based on the $T_{\Delta47}$ values in this study and the exchange-diffusion kinetic model from ref. 8 (see text for details).

[h] The initial $T_{\Delta47}$ value was derived from the modeling of the solid-state reordering effects by assuming a peak heating temperature of 270 °C for **4000** years based on the $T_{\Delta47}$ values in this study and the transient defect/equilibrium defect model in ref. 7 (see text for details).

[i] The $\delta^{18}O_{fluid}$ (VSMOW, ‰) value was calculated using the $T_{\Delta47}$ value which was calculated by using the revised dolomite temperature calibration in this study.

[j] The $\delta^{18}O_{fluid}$ (VSMOW, ‰) value was calculated using the initial $T_{\Delta47}$ value from modeling which is based on an exchange-diffusion kinetic solid-state reordering model in ref. 8 by assuming a hydrothermal event with a peak heating of 270°C for 2000 years (see text for details).

[k] Data were generated by XRD with an uncertainty of ca. ±5%.

Table S2. The summarized Δ_{47} values (CUG and UCLA) and $T_{\Delta47}$ values of dolomite samples from the Doushantuo Formation in this study.

Analysis #	Date	Laboratory	Sample ID	Height (m)	$\delta^{13}C$ (VPDB,‰)	$\delta^{18}O$ (VPDB,‰)	$\Delta_{47ARF25}$ (‰)	STF-$\Delta_{47ARF25}$ (‰) [a]	Average Δ_{47} (‰)	n	Average Δ_{47} 1 s.d. (‰) [b]	Average Δ_{47} 1 s.e. (‰) [c]	$T_{\Delta47}$ (°C)	$T_{\Delta47}$ 1 s.e. (°C)
ZK312-P312 section														
49355	150925-34	CUG	ZK312-275	137.3	2.11	-2.87	0.531	0.515	0.507	4	0.0054	0.003	86	2
49025	150908-22	CUG	ZK312-275		2.17	-2.61	0.523	0.507						
	201512	UCLA	ZK312-275		2.34	-0.01		0.502						
49035	150908-23	CUG	ZK312-275		2.28	-2.37	0.521	0.505						
49365	150925-35	CUG	ZK312-279	133.8	0.10	-1.78	0.537	0.521	0.515	4	0.0161	0.008	82	4
49055	150908-25	CUG	ZK312-279		0.06	-1.77	0.548	0.532						
	201512	UCLA	ZK312-279		0.31	-1.63		0.512						
49870	151011-34	CUG	ZK312-279		0.19	-1.65	0.510	0.494						
5255	20190215-2	CUG	ZK312-282	131.5	-0.24	-2.90	0.513	0.517	0.519	5	0.0099	0.004	80	2
5420	20190218-4	CUG	ZK312-282		-0.22	-2.94	0.506	0.504						
5610	20190222-4	CUG	ZK312-282		-0.22	-3.09	0.524	0.524						
	201512	UCLA	ZK312-282		-0.43	-2.85		0.520						
56808	160422-21	CUG	ZK312-282		-0.90	-3.16	0.534	0.530						
49105	150912-21	CUG	ZK312-286	128.1	0.47	-3.99	0.498	0.482	0.497	2	0.0210	0.015	92	8
49375	150925-36	CUG	ZK312-286		0.52	-4.10	0.528	0.512						
	201512	UCLA	ZK312-288	126.1	0.27	-3.86		0.499	0.499	1			91	
49115	150912-22	CUG	ZK312-293	122.1	2.30	-4.01	0.499	0.483	0.509	3	0.0236	0.014	85	7

49398	150927-31	CUG	ZK312-293		2.29	-4.26	0.531	0.515						
58898	160522-C12	CUG	ZK312-293		2.07	-3.78	0.532	0.529						
49413	150927-32	CUG	ZK312-296	119.6	1.96	-6.21	0.551	0.535	0.514	3	0.0185	0.011	83	6
	201512	UCLA	ZK312-296		2.10	-5.99		0.502						
59060	160528-E1	CUG	ZK312-296		1.70	-5.91	0.510	0.504						
	201512	UCLA	ZK312-299	117.0	2.12	-4.01		0.527	0.527	1			76	
49125	150912-23	CUG	ZK312-300	116.0	3.34	-4.63	0.537	0.521	0.506	3	0.0135	0.008	87	4
49423	150927-33	CUG	ZK312-300		3.41	-4.53	0.516	0.500						
60178	160614-G2	CUG	ZK312-300		3.09	-4.09	0.502	0.496						
49135	150912-24	CUG	ZK312-304	113.0	4.01	-3.45	0.517	0.501	0.525	4	0.0263	0.013	77	6
49433	150927-34	CUG	ZK312-304		3.77	-2.91	0.568	0.552						
	201512	UCLA	ZK312-304		3.83	-2.69		0.505						
59099	160528-E2	CUG	ZK312-304		3.56	-2.51	0.546	0.543						
49145	150912-25	CUG	ZK312-307	110.9	5.40	-3.60	0.538	0.522	0.532	6	0.0166	0.007	73	3
49443	150927-35	CUG	ZK312-307		5.36	-3.44	0.566	0.550						
56828	160422-23	CUG	ZK312-307		5.09	-3.32	0.525	0.521						
	201512	UCLA	ZK312-307		5.45	-3.09		0.541						
59268	160601-F1	CUG	ZK312-307		5.06	-3.42	0.541	0.538						
49888	151011-35	CUG	ZK312-307		5.44	-3.15	0.537	0.521						
5370	20190217-4	CUG	ZK312-310	108.3	4.83	-2.58	0.500	0.497	0.529	6	0.0188	0.008	75	4
5430	20190218-5	CUG	ZK312-310		4.79	-2.50	0.513	0.512						
5660	20190223-4	CUG	ZK312-310		4.91	-2.47	0.534	0.534						
56908	160422-25	CUG	ZK312-310		4.31	-2.53	0.561	0.560						
	201512	UCLA	ZK312-310		4.87	-2.07		0.508						
59157	160528-E3	CUG	ZK312-310		4.35	-1.97	0.566	0.565						

49155	150912-26	CUG	ZK312-313	104.0	3.95	-4.90	0.566	0.549	0.540	2	0.0130	0.009	69	4
49476	150929-31	CUG	ZK312-313		3.88	-4.08	0.547	0.531						
49486	150929-32	CUG	ZK312-317	100.8	4.15	-4.93	0.536	0.520	0.537	3	0.0317	0.018	71	8
57206	160503-33	CUG	ZK312-317		4.20	-4.60	0.573	0.574						
59167	160528-E4	CUG	ZK312-317		3.92	-4.46	0.522	0.518						
49165	150914-31	CUG	ZK312-321	98.6	4.84	-3.24	0.534	0.518	0.540	4	0.0375	0.019	70	9
49496	150929-33	CUG	ZK312-321		4.85	-2.98	0.534	0.518						
	201512	UCLA	ZK312-321		4.89	-2.90		0.528						
60193	160614-G3	CUG	ZK312-321		4.56	-2.56	0.593	0.595						
57273	160503-35	CUG	ZK312-326	95.1	4.46	-2.71	0.556	0.555	0.556	3	0.0083	0.005	62	2
	201512	UCLA	ZK312-326		4.91	-2.35		0.548						
58459	160520-C1	CUG	ZK312-326		4.45	-2.24	0.565	0.565						
49513	150929-34	CUG	ZK312-328	93.5	4.46	-3.03	0.587	0.570	0.559	3	0.0118	0.007	61	3
	201512	UCLA	ZK312-328		4.76	-2.54		0.547						
59177	160528-E5	CUG	ZK312-328		4.20	-2.59	0.562	0.561						
49523	150929-35	CUG	ZK312-331	91.2	3.14	-3.01	0.601	0.585	0.586	4	0.0163	0.008	50	3
58908	160522-D1	CUG	ZK312-331		2.81	-2.45	0.595	0.597						
	201512	UCLA	ZK312-331		3.29	-2.70		0.563						
58928	160522-D2	CUG	ZK312-331		2.80	-2.76	0.596	0.598						
49185	150914-33	CUG	ZK312-335	88.4	3.02	-3.03	0.577	0.561	0.554	2	0.0102	0.007	63	3
49537	150930-36	CUG	ZK312-335		3.16	-2.41	0.563	0.546						
49195	150914-34	CUG	ZK312-339	86.4	4.08	-4.50	0.552	0.536	0.528	3	0.0104	0.006	75	3
	201512	UCLA	ZK312-339		4.04	-3.29		0.517						
49547	151001-31	CUG	ZK312-339		3.90	-3.46	0.548	0.532						
59317	160602-F3	CUG	ZK312-346	82.9	2.12	-2.94	0.584	0.585	0.570	4	0.0189	0.009	56	4

5305	20190216-3	CUG	ZK312-346		2.64	-3.44	0.577	0.587						
	201512	UCLA	ZK312-346		2.54	-3.06		0.562						
5410	20190218-3	CUG	ZK312-346		2.82	-3.04	0.546	0.548						
49205	150914-35	CUG	ZK312-351	80.3	0.97	-3.32	0.536	0.520	0.540	5	0.0209	0.009	69	4
49557	151001-32	CUG	ZK312-351		1.06	-3.22	0.586	0.570						
59327	160602-F4	CUG	ZK312-351		0.82	-3.47	0.537	0.534						
	201512	UCLA	ZK312-351		1.15	-2.71		0.553						
49908	151012-31	CUG	ZK312-351		1.14	-3.08	0.540	0.524						
49572	151001-33	CUG	ZK312-356	76.6	3.57	-4.62	0.551	0.535	0.523	5	0.0117	0.005	78	3
5390	20190218-1	CUG	ZK312-356		4.05	-4.12	0.516	0.515						
	201512	UCLA	ZK312-356		3.90	-3.99		0.526						
5460	20190219-3	CUG	ZK312-356		4.03	-4.37	0.531	0.531						
5720	20190225-1	CUG	ZK312-356		4.24	-3.91	0.509	0.507						
49215	150914-36	CUG	ZK312-361	73.3	3.24	-3.79	0.570	0.554	0.556	2	0.0018	0.001	62	1
49580	151001-34	CUG	ZK312-361		4.33	-3.58	0.573	0.557						
49590	151001-35	CUG	ZK312-364	71.6	3.20	-4.44	0.561	0.545	0.536	4	0.0157	0.008	71	4
58938	160522-D3	CUG	ZK312-364		2.56	-3.50	0.549	0.547						
	201512	UCLA	ZK312-364		3.13	-3.73		0.513						
59187	160528-E7	CUG	ZK312-364		2.83	-2.48	0.542	0.540						
49278	150916-32	CUG	ZK312-368	67.9	2.82	-4.71	0.581	0.565	0.533	4	0.0361	0.018	73	8
49598	151001-36	CUG	ZK312-368		2.93	-3.95	0.577	0.561						
60243	160614-G5	CUG	ZK312-368		2.94	-3.87	0.519	0.514						
49918	151012-32	CUG	ZK312-368		2.97	-4.29	0.507	0.491						
	201512	UCLA	ZK312-376	63.9	3.36	-3.26		0.520	0.520	1			79	
49225	150916-22	CUG	ZK312-384	58.9	3.58	-6.15	0.573	0.557	0.522	4	0.0262	0.013	78	7

49618	151004-32	CUG	ZK312-384		3.43	-6.78	0.509	0.493						
	201512	UCLA	ZK312-384		3.69	-6.03		0.518						
49938	151012-33	CUG	ZK312-384		3.55	-6.12	0.535	0.519						
49235	150916-23	CUG	P312-8	53.0	1.32	-4.41	0.555	0.539	0.529	2	0.0139	0.010	75	5
49645	151004-35	CUG	P312-8		0.09	-4.95	0.535	0.519						
49655	151004-36	CUG	P312-14	50.0	0.34	-4.87	0.541	0.525	0.520	4	0.0317	0.016	80	8
59050	160522-D7	CUG	P312-14		0.30	-3.98	0.557	0.556						
59379	160602-F6	CUG	P312-14		0.18	-4.11	0.523	0.518						
	201512	UCLA	P312-14		0.42	-4.90		0.479						
49665	151005-31	CUG	P312-20	47.0	-0.44	-4.61	0.587	0.571	0.519	9	0.0246	0.008	80	4
49810	151009-34	CUG	P312-20		-0.45	-4.53	0.514	0.498						
58479	160520-C3	CUG	P312-20		-0.68	-4.40	0.515	0.510						
59237	160528-E8	CUG	P312-20		-0.74	-4.55	0.509	0.504						
59337	160602-F5	CUG	P312-20		-0.73	-4.33	0.525	0.521						
49948	151012-34	CUG	P312-20		-0.50	-4.53	0.547	0.531						
59247	160528-E9	CUG	P312-20		-0.83	-4.82	0.511	0.505						
49965	151012-35	CUG	P312-20		-0.46	-4.37	0.509	0.493						
	201512	UCLA	P312-20		-0.38	-4.34		0.538						
49683	151005-32	CUG	P312-26	44.0	-4.69	-5.27	0.527	0.511	0.520	4	0.0537	0.027	80	13
60253	160614-G6	CUG	P312-26		-0.08	-4.80	0.470	0.461						
60352	160616-A1	CUG	P312-26		-5.11	-6.09	0.590	0.591						
	201512	UCLA	P312-26		-4.58	-5.20		0.515						
49248	150916-24	CUG	P312-32	40.0	-0.69	-5.78	0.521	0.505	0.523	4	0.0285	0.014	78	7
49693	151005-33	CUG	P312-32		-0.76	-5.56	0.515	0.499						
59257	160528-E10	CUG	P312-32		-0.98	-5.38	0.563	0.562						

	201512	UCLA	P312-32		-0.71	-5.44		0.526						
49703	151005-34	CUG	P312-37	38.0	0.04	-6.11	0.531	0.515	0.511	2	0.0065	0.005	84	2
	201512	UCLA	P312-37		0.19	-5.95		0.506						
49258	150916-25	CUG	P312-46	32.1	4.08	-5.67	0.528	0.512	0.516	5	0.0123	0.005	82	3
49713	151005-35	CUG	P312-46		4.48	-4.55	0.532	0.516						
58968	160522-D5	CUG	P312-46		4.16	-4.30	0.505	0.499						
59040	160522-D6	CUG	P312-46		4.09	-5.61	0.536	0.533						
60233	160614-G4	CUG	P312-46		4.05	-5.54	0.523	0.518						
	201512	UCLA	P312-53	29.0	4.76	-5.94		0.502	0.502	1			89	
49730	151005-36	CUG	P312-55	28.0	4.00	-6.84	0.461	0.445	0.445	1			125	
49820	151009-35	CUG	P312-58	26.0	4.45	-6.64	0.515	0.498	0.499	2	0.0008	0.001	91	0
49975	151012-36	CUG	P312-58		4.33	-6.57	0.516	0.500						
49740	151007-31	CUG	P312-60	25.0	4.68	-6.39	0.491	0.475	0.475	1			105	
49750	151007-32	CUG	P312-66	22.0	4.72	-7.00	0.425	0.409	0.409	1			155	
	201512	UCLA	P312-67	21.0	4.78	-6.79		0.450	0.450	1			122	
49268	150916-26	CUG	P312-68	20.5	4.97	-7.28	0.533	0.516	0.516	1			81	
49765	151007-33	CUG	P312-70	20.0	4.63	-6.94	0.491	0.475	0.475	1			105	
49785	151009-32	CUG	P312-105	2.5	1.93	-4.04	0.565	0.549	0.530	3	0.0369	0.021	74	10
7894	170325-5	UCLA	P312-105		1.27	-4.65	0.504	0.488						
49830	151009-36	CUG	P312-105		1.47	-4.08	0.570	0.554						
49288	150916-31	CUG	P312-114	0.7	0.02	-7.06	0.523	0.507	0.492	4	0.0395	0.020	94	11
49800	151009-33	CUG	P312-114		-0.13	-6.94	0.529	0.513						
7707	170321-4	CUG	P312-114		-0.63	-7.55	0.452	0.433						
	201512	UCLA	P312-114		0.18	-6.73		0.516						
ZK407 section														

9244	170418-3	CUG	ZK407-270	132.4	6.14	-4.80	0.497	0.480	0.485	3	0.0243	0.014	99	8
9504	170422-6	CUG	ZK407-270		6.03	-5.12	0.481	0.463						
9524	170423-2	CUG	ZK407-270		5.89	-5.42	0.526	0.511						
9294	170419-6	CUG	ZK407-290	119.3	4.88	-5.70	0.466	0.448	0.473	4	0.0520	0.026	106	16
9494	170422-5	CUG	ZK407-290		4.80	-6.06	0.452	0.433						
11232	170601-4	CUG	ZK407-290		4.88	-5.64	0.561	0.549						
11302	170603-2	CUG	ZK407-290		5.02	-5.96	0.479	0.461						
10872	170525-2	CUG	ZK407-296	115.8	1.72	-6.19	0.510	0.495	0.486	3	0.0233	0.013	98	8
10962	170526-5	CUG	ZK407-296		3.26	-6.08	0.477	0.459						
11122	170529-3	CUG	ZK407-296		3.32	-5.79	0.518	0.503						
10882	170525-3	CUG	ZK407-310	106.8	0.93	-4.80	0.607	0.597	0.557	4	0.0294	0.015	62	6
10972	170527-1	CUG	ZK407-310		1.57	-4.64	0.559	0.546						
11132	170529-4	CUG	ZK407-310		1.54	-4.71	0.542	0.528						
11212	170601-2	CUG	ZK407-310		1.45	-4.98	0.569	0.556						
9224	170418-1	CUG	ZK407-317	102.3	-0.49	-5.15	0.562	0.549	0.516	4	0.0446	0.022	82	11
9484	170422-4	CUG	ZK407-317		-0.33	-4.97	0.504	0.488						
9594	170424-6	CUG	ZK407-317		-0.09	-4.23	0.485	0.468						
11192	170530-5	CUG	ZK407-317		-0.26	-5.02	0.570	0.558						
10902	170525-5	CUG	ZK407-320	100.1	-0.07	-4.38	0.511	0.496	0.547	4	0.0373	0.019	66	8
10982	170527-2	CUG	ZK407-320		-0.02	-4.42	0.559	0.547						
11152	170530-1	CUG	ZK407-320		-0.09	-4.42	0.593	0.582						
11242	170601-5	CUG	ZK407-320		-0.07	-4.22	0.577	0.565						
9234	170418-2	CUG	ZK407-327	95.9	0.75	-3.58	0.516	0.500	0.533	4	0.0254	0.013	73	6
9474	170422-3	CUG	ZK407-327		0.65	-4.00	0.545	0.531						
9544	170424-1	CUG	ZK407-327		0.74	-4.03	0.553	0.540						

11222	170601-3	CUG	ZK407-327		0.78	-3.85	0.574	0.562					
7055	20180303-2	CUG	ZK407-337	89.4	-0.49	-3.75	0.479	0.487	0.524	4	0.0251	0.013	77	6
8465	20180401-5	CUG	ZK407-337		-0.32	-3.50	0.526	0.533						
9698	20180428-3	CUG	ZK407-337		-0.39	-3.71	0.537	0.544						
9848	20180501-4	CUG	ZK407-337		-0.41	-3.74	0.524	0.532						
9254	170419-2	CUG	ZK407-351	81.2	-4.46	-3.62	0.497	0.481	0.481	2	0.0143	0.010	101	6
9454	170422-1	CUG	ZK407-351		-4.63	-4.13	0.498	0.482						
9284	170419-5	CUG	ZK407-360	73.8	0.88	-5.06	0.521	0.506	0.509	2	0.0244	0.017	85	9
9444	170421-6	CUG	ZK407-360		0.69	-5.64	0.526	0.511						
9274	170419-4	CUG	ZK407-398	57.8	1.51	-4.70	0.563	0.551	0.517	3	0.0290	0.017	81	8
9434	170421-5	CUG	ZK407-398		1.39	-5.06	0.514	0.498						
9554	170424-2	CUG	ZK407-398		1.43	-5.15	0.518	0.503						
9304	170419-7	CUG	ZK407-412P	50.4	0.70	-4.87	0.500	0.484	0.512	3	0.0247	0.014	84	7
9424	170421-4	CUG	ZK407-412P		0.58	-5.42	0.544	0.530						
9564	170424-3	CUG	ZK407-412p		0.51	-5.68	0.535	0.521						
10912	170525-6	CUG	ZK407-416	46.1	-1.20	-5.22	0.604	0.593	0.573	4	0.0213	0.011	55	4
11082	170528-4	CUG	ZK407-416		-1.22	-4.98	0.581	0.569						
11162	170530-2	CUG	ZK407-416		-1.22	-5.16	0.558	0.545						
11272	170602-3	CUG	ZK407-416		-1.16	-4.75	0.596	0.585						
10922	170526-1	CUG	ZK407-424	35.4	-7.48	-4.33	0.533	0.518	0.552	4	0.0289	0.014	64	6
11102	170529-1	CUG	ZK407-424		-7.44	-4.52	0.556	0.543						
11172	170530-3	CUG	ZK407-424		-7.57	-4.26	0.598	0.587						
11252	170602-1	CUG	ZK407-424		-7.61	-4.31	0.571	0.558						
10932	170526-2	CUG	ZK407-428	31.1	-1.23	-6.28	0.449	0.430	0.465	3	0.0307	0.018	111	11
11112	170529-2	CUG	ZK407-428		-1.31	-6.49	0.498	0.482						

11182	170530-4	CUG	ZK407-428	-1.22	-6.46	0.500	0.484

[a] In order to simplify the description, we use Δ_{47} to replace the STF-$\Delta_{47ARF25}$ (more details see Table S3).

[b] Standard deviations (s.d.) correspond to duplicate analyses.

[c] Standard error (s.e.) was given by s.d./($n^{0.5}$).

Table S3. Raw data, Δ_{47} values and other related values of absolute reference frame (ARF) and the standards in this study.

Analysis-#	Date	Sample ID	raw δ_{45} (‰,WG[a])	raw δ_{46} (‰,WG[a])	raw δ_{47} (‰,WG[a])	raw δ_{48} (‰,WG[a])	raw δ_{49} (‰,WG[a])	Brand raw Δ_{47} (‰)[b]	Brand raw Δ_{48} (‰)[b]	Brand raw Δ_{49} (‰)[b]	$Slope_{EGL}$ [c]	$Slope_{ETF}$ [d]	$Intercept_{ETF}$ [d]	$\Delta_{47ARF25}$ (‰) [e]	Average $\Delta_{47ARF25}$ (‰)	Expected $\Delta_{47ARF25}$ (‰) [f]	Δ_{47} (STF-$\Delta_{47ARF25}$) (‰) [g]
48910	150830-32	Equilibrated CO_2 at 10 ºC	-0.447	-12.074	-12.318	-27.740	6.083	0.009	-3.829	30.877	0.003	1.139	0.915				
48900	150830-31	Equilibrated CO_2 at 10 ºC	-0.351	-12.165	-12.288	-27.801	4.995	0.030	-3.709	29.842	0.003	1.139	0.915				
48920	150830-33	Equilibrated CO_2 at 10 ºC	0.186	4.244	4.434	9.801	4.853	0.068	1.283	-3.672	0.003	1.139	0.915				
48732	150824-31	Equilibrated CO_2 at 10 ºC	17.851	-12.349	6.152	-27.864	2.724	0.100	-3.401	8.325	0.003	1.139	0.915				
48442	150815-31	Equilibrated CO_2 at 10 ºC	17.795	-11.804	6.617	-26.568	4.692	0.075	-3.173	9.267	0.003	1.139	0.915				
48452	150815-32	Equilibrated CO_2 at 10 ºC	18.137	-3.267	15.504	-7.252	4.265	0.060	-0.733	-8.431	0.003	1.139	0.915				
48742	150824-32	Equilibrated CO_2 at 10 ºC	18.175	-3.211	15.674	-7.097	3.226	0.133	-0.690	-9.606	0.003	1.139	0.915				
48467	150815-33	Equilibrated CO_2 at 10 ºC	18.126	-1.182	17.658	-2.043	2.611	0.135	0.321	-14.109	0.003	1.139	0.915				
48755	150824-33	Equilibrated CO_2 at 10 ºC	18.271	-0.717	18.222	-1.426	2.862	0.085	0.008	-14.914	0.003	1.139	0.915				

48477	150815-34	Equilibrated CO_2 at 10 ºC	18.440	4.198	23.358	9.808	3.588	0.121	1.383	-23.834	0.003	1.139	0.915
48765	150824-34	Equilibrated CO_2 at 10 ºC	18.540	4.606	23.905	10.864	3.420	0.153	1.615	-24.880	0.003	1.139	0.915
48193	150802-11	Equilibrated CO_2 at 25 ºC	-0.552	-14.900	-15.255	-33.317	5.683	-0.045	-3.852	36.400	0.003	1.139	0.915
48203	150802-12	Equilibrated CO_2 at 25 ºC	-0.491	-14.561	-14.862	-32.432	6.104	-0.047	-3.626	36.066	0.003	1.139	0.915
48213	150802-13	Equilibrated CO_2 at 25 ºC	-0.481	-14.741	-15.022	-32.762	6.581	-0.040	-3.602	36.918	0.003	1.139	0.915
48222	150802-14	Equilibrated CO_2 at 25 ºC	-0.181	-5.588	-5.697	-12.198	1.065	-0.018	-1.064	12.343	0.003	1.139	0.915
48232	150802-15	Equilibrated CO_2 at 25 ºC	-0.116	-5.520	-5.597	-12.267	3.868	-0.051	-1.271	14.972	0.003	1.139	0.915
48242	150802-16	Equilibrated CO_2 at 25 ºC	-0.224	-5.604	-5.763	-12.384	6.145	-0.024	-1.221	17.559	0.003	1.139	0.915
48252	150806-21	Equilibrated CO_2 at 25 ºC	-0.053	-2.819	-2.837	-6.300	-0.581	-0.011	-0.673	5.035	0.003	1.139	0.915
48262	150806-24	Equilibrated CO_2 at 25 ºC	0.180	1.934	2.085	4.436	4.239	-0.002	0.562	0.242	0.003	1.139	0.915
48327	150811-31	Equilibrated CO_2 at 25 ºC	17.650	-15.108	3.107	-33.851	2.854	0.024	-3.982	14.229	0.003	1.139	0.915
48337	150811-32	Equilibrated CO_2 at 25 ºC	18.048	-5.671	12.997	-12.891	4.065	0.053	-1.600	-3.819	0.003	1.139	0.915
48347	150811-33	Equilibrated CO_2	18.197	-2.890	15.891	-6.303	2.957	0.008	-0.533	-10.519	0.003	1.139	0.915

		at 25 ºC											
48357	150811-34	Equilibrated CO_2 at 25 ºC	18.340	1.736	20.752	4.087	3.582	0.085	0.609	-19.018	0.003	1.139	0.915
48586	150819-31	Equilibrated CO_2 at 25 ºC	17.685	-14.792	3.456	-33.435	4.116	0.021	-4.192	14.829	0.003	1.139	0.915
48596	150819-32	Equilibrated CO_2 at 25 ºC	18.020	-5.717	12.920	-13.111	5.119	0.051	-1.728	-2.653	0.003	1.139	0.915
48616	150819-33	Equilibrated CO_2 at 25 ºC	18.114	-3.031	15.711	-6.855	4.814	0.055	-0.806	-8.325	0.003	1.139	0.915
48606	150819-34	Equilibrated CO_2 at 25 ºC	18.358	1.822	20.849	4.390	4.168	0.078	0.740	-18.629	0.003	1.139	0.915
48712	150824-14	Equilibrated CO_2 at 50 ºC	29.853	-13.593	17.028	-30.887	5.283	0.006	-3.994	0.843	0.003	1.139	0.915
48407	150814-12	Equilibrated CO_2 at 50 ºC	17.696	-16.651	1.536	-37.691	3.641	-0.048	-4.824	18.110	0.003	1.139	0.915
48417	150814-13	Equilibrated CO_2 at 50 ºC	17.675	-15.663	2.501	-35.207	5.169	-0.051	-4.258	17.671	0.003	1.139	0.915
48427	150814-14	Equilibrated CO_2 at 50 ºC	17.818	-12.756	5.566	-28.832	5.451	-0.044	-3.573	11.921	0.003	1.139	0.915
48541	150819-11	Equilibrated CO_2 at 50 ºC	17.247	-28.181	-10.479	-63.150	3.414	-0.062	-8.028	42.245	0.003	1.139	0.915
48551	150819-12	Equilibrated CO_2 at 50 ºC	17.648	-16.551	1.584	-37.410	6.814	-0.051	-4.738	21.174	0.003	1.139	0.915
48561	150819-13	Equilibrated CO_2 at 50 ºC	17.740	-13.150	5.091	-29.692	7.289	-0.045	-3.661	14.649	0.003	1.139	0.915

48571	150819-14	Equilibrated CO_2 at 50 ºC	17.826	-13.069	5.251	-29.638	7.153	-0.054	-3.769	14.256	0.003	1.139	0.915
48692	150824-11	Equilibrated CO_2 at 50 ºC	17.249	-28.888	-11.213	-64.974	4.703	-0.090	-8.517	45.077	0.003	1.139	0.915
48702	150824-13	Equilibrated CO_2 at 50 ºC	29.937	-12.632	18.061	-28.561	3.945	-0.020	-3.545	-2.487	0.003	1.139	0.915
48722	150824-13	Equilibrated CO_2 at 50 ºC	17.244	-28.148	-10.461	-63.591	6.748	-0.073	-8.562	45.643	0.003	1.139	0.915
48833	150830-11	Equilibrated CO_2 at 50 ºC	-1.100	-28.028	-28.824	-63.470	5.704	-0.163	-8.679	64.732	0.003	1.139	0.915
48843	150830-12	Equilibrated CO_2 at 50 ºC	-1.071	-26.644	-27.422	-60.504	6.770	-0.150	-8.366	62.850	0.003	1.139	0.915
48853	150830-13	Equilibrated CO_2 at 50 ºC	-0.392	-8.765	-9.085	-20.096	5.924	-0.067	-2.689	23.904	0.003	1.139	0.915
48866	150830-14	Equilibrated CO_2 at 50 ºC	-0.386	-10.541	-10.874	-24.079	5.476	-0.118	-3.174	27.054	0.003	1.139	0.915
48083	150801-11	Heated CO_2 at 1000 ºC	18.124	-4.719	13.181	-10.182	0.543	-0.784	-0.774	-9.258	0.003	1.139	0.915
48093	150801-12	Heated CO_2 at 1000 ºC	18.139	-4.557	13.418	-10.312	2.626	-0.725	-1.229	-7.528	0.003	1.139	0.915
48118	150801-14	Heated CO_2 at 1000 ºC	18.093	-4.540	13.364	-10.053	1.013	-0.748	-1.003	-9.110	0.003	1.139	0.915
48103	150801-13	Heated CO_2 at 1000 ºC	22.000	-19.490	2.332	-42.678	2.450	-0.760	-4.241	18.116	0.003	1.139	0.915
48128	150801-15	Heated CO_2 at	22.113	-18.964	2.969	-41.742	3.746	-0.767	-4.336	18.236	0.003	1.139	0.915

		1000 ºC											
48146	150801-16	Heated CO_2 at 1000 ºC	21.994	-19.352	2.475	-42.679	1.453	-0.751	-4.524	16.826	0.003	1.139	0.915
48156	150801-17	Heated CO_2 at 1000 ºC	-0.103	-1.669	-2.575	-3.727	4.862	-0.829	-0.392	8.277	0.003	1.139	0.915
48166	150801-18	Heated CO_2 at 1000 ºC	-0.086	-1.724	-2.563	-4.151	5.046	-0.781	-0.707	8.552	0.003	1.139	0.915
48276	150802-11-R	Heated CO_2 at 1000 ºC	-0.681	-15.911	-17.156	-35.826	5.492	-0.834	-4.396	38.438	0.003	1.139	0.915
48286	150802-15-R	Heated CO_2 at 1000 ºC	-0.310	-8.140	-9.143	-18.423	4.999	-0.831	-2.246	21.606	0.003	1.139	0.915
48301	150802-23-R	Heated CO_2 at 1000 ºC	-0.211	-7.034	-7.924	-16.208	5.356	-0.798	-2.221	19.626	0.003	1.139	0.915
48311	150802-26-R	Heated CO_2 at 1000 ºC	-0.010	-5.898	-6.628	-13.528	5.466	-0.824	-1.789	17.231	0.003	1.139	0.915
48392	150811-33-R	Heated CO_2 at 1000 ºC	17.963	-5.644	12.107	-13.075	4.802	-0.766	-1.839	-3.052	0.003	1.139	0.915
48511	150814-14-R	Heated CO_2 at 1000 ºC	17.652	-14.474	2.941	-33.061	5.999	-0.776	-4.450	16.122	0.003	1.139	0.915
48521	150815-31-R	Heated CO_2 at 1000 ºC	17.630	-14.258	3.141	-32.340	4.686	-0.770	-4.143	14.382	0.003	1.139	0.915
48531	150815-33-R	Heated CO_2 at 1000 ºC	17.893	-5.435	12.255	-12.499	4.233	-0.756	-1.675	-3.955	0.003	1.139	0.915
48639	150819-11-R	Heated CO_2 at 1000 ºC	17.192	-27.313	-10.420	-62.045	5.985	-0.825	-8.630	43.142	0.003	1.139	0.915

48649	150819-14-R	Heated CO_2 at 1000 ºC	17.557	-14.955	2.389	-33.823	4.975	-0.751	-4.262	16.163	0.003	1.139	0.915				
48778	150824-11-R	Heated CO_2 at 1000 ºC	17.127	-28.593	-11.775	-64.549	5.359	-0.833	-8.669	45.268	0.003	1.139	0.915				
48788	150824-14-R	Heated CO_2 at 1000 ºC	29.620	-15.014	14.614	-34.632	4.678	-0.719	-4.977	3.321	0.003	1.139	0.915				
48798	150824-13-R	Heated CO_2 at 1000 ºC	29.318	-13.848	15.469	-31.373	3.956	-0.738	-3.978	0.583	0.003	1.139	0.915				
48811	150824-31-R	Heated CO_2 at 1000 ºC	17.513	-14.544	2.744	-33.414	5.116	-0.763	-4.672	15.518	0.003	1.139	0.915				
48821	150824-34-R	Heated CO_2 at 1000 ºC	18.220	-0.920	17.132	-2.285	4.274	-0.735	-0.447	-13.081	0.003	1.139	0.915				
48975	150830-11-R	Heated CO_2 at 1000 ºC	-1.266	-27.908	-29.547	-63.490	6.840	-0.857	-8.946	65.864	0.003	1.139	0.915				
48985	150830-12-R	Heated CO_2 at 1000 ºC	-1.012	-25.936	-27.376	-59.009	7.121	-0.877	-8.231	61.636	0.003	1.139	0.915				
49065	150910-31	NBS-19	30.438	2.807	33.831	6.633	2.743	-0.412	1.005	-34.114	0.003	1.139	0.915	0.407	0.394	0.378	0.391
49085	150910-32	NBS-19	30.512	3.010	34.131	7.155	2.835	-0.394	1.120	-34.483	0.003	1.139	0.915	0.426			0.410
49318	150925-31	NBS-19	30.565	3.058	34.224	7.661	-2.765	-0.405	1.525	-40.018	0.003	1.139	0.915	0.413			0.397
49328	150925-32	NBS-19	30.669	3.370	34.612	8.372	0.658	-0.440	1.609	-37.415	0.003	1.139	0.915	0.372			0.356
49850	151011-31	NBS-19	30.640	3.292	34.480	7.557	4.452	-0.461	0.957	-33.588	0.003	1.139	0.915	0.348			0.332
49985	151014-31	NBS-19	30.635	3.394	34.588	7.622	4.111	-0.453	0.817	-34.106	0.003	1.139	0.915	0.357			0.341
50003	151014-32	NBS-19	30.491	2.953	34.064	6.700	3.172	-0.382	0.782	-34.030	0.003	1.139	0.915	0.439			0.423
50013	151014-33	NBS-19	30.515	2.978	34.076	6.748	3.829	-0.419	0.777	-33.469	0.003	1.139	0.915	0.397			0.381
50023	151014-34	NBS-19	30.703	3.514	34.814	10.120	2.045	-0.419	3.058	-36.387	0.003	1.139	0.915	0.395			0.378

49075	150910-33	NBS-19	30.562	3.338	34.477	7.738	3.263	-0.432	1.044	-34.743	0.003	1.139	0.915	0.381			0.364
49095	150910-34	NBS-19	30.551	3.265	34.410	7.555	3.667	-0.414	1.007	-34.205	0.003	1.139	0.915	0.402			0.386

Analysis-#	Date	Sample ID	raw δ_{45} (‰,WG [a])	raw δ_{46} (‰,WG [a])	raw δ_{47} (‰,WG [a])	raw δ_{48} (‰,WG [a])	raw δ_{49} (‰,WG [a])	Brand raw Δ_{47}(‰) [b]	Brand raw Δ_{48}(‰) [b]	Brand raw Δ_{49}(‰) [b]	$Slope_{EGL}$ [c]	$Slope_{ETF}$ [d]	$Intercept_{ETF}$ [d]	$\Delta_{47ARF25}$ (‰) [e]	Mean $\Delta_{47ARF25}$ (‰)	Expected $\Delta_{47ARF25}$ (‰) [f]	Δ_{47} (STF-$\Delta_{47ARF25}$) (‰) [g]
56662	160415-32	Equilibrated CO_2 at 50 ºC	-0.755	-22.415	-22.913	-50.110	6.387	-0.113	-6.050	53.079	0.001	1.124	0.908				
56682	160415-34	Equilibrated CO_2 at 50 ºC	17.839	-5.662	12.651	-12.965	8.223	-0.086	-1.691	0.508	0.001	1.124	0.908				
56891	160415-31	Equilibrated CO_2 at 50 ºC	-1.153	-26.983	-27.821	-61.244	12.546	-0.132	-8.456	69.775	0.001	1.124	0.908				
56948	160415-32	Equilibrated CO_2 at 50 ºC	28.457	-22.071	6.928	-50.693	8.109	-0.084	-7.359	22.312	0.001	1.124	0.908				
56968	160421-34	Equilibrated CO_2 at 50 ºC	29.184	-7.257	22.707	-16.490	-5.606	-0.053	-2.058	-21.705	0.001	1.124	0.908				
56978	160415-32	Heated CO_2 at 1000 ºC	-0.775	-22.555	-23.751	-52.095	9.928	-0.809	-7.843	57.104	0.001	1.124	0.908				
56988	160415-24	Heated CO_2 at 1000 ºC	30.119	-0.040	30.275	-0.671	5.729	-0.741	-0.590	-25.487	0.001	1.124	0.908				
56998	160422-26	Heated CO_2 at 1000 ºC	18.040	-4.947	12.848	-12.002	9.043	-0.801	-2.153	-0.302	0.001	1.124	0.908				
57008	160415-31	Heated CO_2 at 1000 ºC	-1.009	-26.204	-27.581	-60.311	11.231	-0.821	-9.058	66.543	0.001	1.124	0.908				

57088	160421-32	Heated CO_2 at 1000 ºC	28.408	-22.154	6.101	-51.661	8.692	-0.774	-8.204	23.125	0.001	1.124	0.908				
57098	160421-34	Heated CO_2 at 1000 ºC	29.040	-8.815	20.286	-20.948	7.114	-0.735	-3.456	-5.980	0.001	1.124	0.908				
57166	160503-31	ISTB-1	18.140	-3.109	15.326	-7.561	6.323	-0.275	-1.361	-6.712	0.001	1.124	0.908	0.659	0.713	0.726	0.667
57392	160506-16	ISTB-1	18.164	-3.088	15.412	-7.534	5.816	-0.234	-1.375	-7.277	0.001	1.124	0.908	0.704			0.716
57607	160509-46	ISTB-1	18.144	-3.044	15.438	-7.558	5.871	-0.232	-1.487	-7.288	0.001	1.124	0.908	0.706			0.719
58028	160514-02	ISTB-1	17.976	-3.663	14.642	-8.966	2.920	-0.236	-1.666	-8.819	0.001	1.124	0.908	0.703			0.715
58038	160515-A1	ISTB-1	17.977	-3.733	14.571	-9.313	4.468	-0.238	-1.875	-7.153	0.001	1.124	0.908	0.701			0.713
58133	160516-B1	ISTB-1	18.244	-3.173	15.418	-7.796	3.970	-0.225	-1.469	-9.016	0.001	1.124	0.908	0.714			0.727
58527	160520-B1	ISTB-1	18.081	-3.410	15.012	-8.220	3.219	-0.228	-1.422	-9.127	0.001	1.124	0.908	0.712			0.724
58918	160522-B1	ISTB-1	18.117	-3.520	14.923	-8.545	4.141	-0.243	-1.528	-8.039	0.001	1.124	0.908	0.695			0.706
59022	160522-B3	ISTB-1	18.135	-3.282	15.193	-7.712	0.957	-0.230	-1.167	-11.667	0.001	1.124	0.908	0.709			0.721
59197	160522-B4	ISTB-1	17.975	-3.914	14.390	-9.601	4.074	-0.235	-1.801	-7.184	0.001	1.124	0.908	0.705			0.717
59553	160605-B8	ISTB-1	18.054	-3.599	14.830	-8.900	4.699	-0.192	-1.727	-7.265	0.001	1.124	0.908	0.753			0.769
59603	160606-B1	ISTB-1	18.199	-3.248	15.306	-8.006	2.588	-0.217	-1.530	-10.188	0.001	1.124	0.908	0.724			0.737
59749	160608-E8	ISTB-1	18.010	-3.732	14.586	-9.147	4.318	-0.256	-1.709	-7.337	0.001	1.124	0.908	0.681			0.690
59944	160610-E10	ISTB-1	16.092	-8.306	8.171	-18.621	-3.059	-0.130	-2.113	-3.677	0.001	1.124	0.908	0.831			0.855
59964	160611-F6	ISTB-1	18.277	-3.423	15.197	-8.300	4.650	-0.230	-1.476	-7.890	0.001	1.124	0.908	0.709			0.721
60158	160614-B3	ISTB-1	18.133	-3.359	15.070	-8.220	4.176	-0.273	-1.523	-8.334	0.001	1.124	0.908	0.661			0.669
56724	160415-23	ISTB-1	18.104	-2.987	15.491	-7.150	8.296	-0.196	-1.192	-4.966	0.001	1.124	0.908	0.746			0.762
56734	160415-24	ISTB-1	18.136	-3.025	15.462	-7.321	11.423	-0.220	-1.288	-1.839	0.001	1.124	0.908	0.720			0.734
56881	160422-26	NBS-19	30.264	3.060	33.830	6.512	5.677	-0.487	0.381	-31.594	0.001	1.124	0.908	0.394	0.394	0.378	0.378
57243	160503-36	NBS-19	30.040	2.579	33.129	5.668	5.906	-0.469	0.500	-30.237	0.001	1.124	0.908	0.414			0.400
57303	160504-26	NBS-19	30.413	3.293	34.221	7.239	5.060	-0.486	0.639	-32.779	0.001	1.124	0.908	0.394			0.378

57527	160507-46	NBS-19	30.156	2.773	33.411	6.121	5.112	-0.502	0.565	-31.486	0.001	1.124	0.908	0.376	0.359
57887	160512-46	NBS-19	30.284	3.039	33.823	6.781	4.370	-0.492	0.691	-32.831	0.001	1.124	0.908	0.387	0.371
58048	160515-A3	NBS-19	30.170	2.597	33.244	5.559	4.756	-0.505	0.357	-31.508	0.001	1.124	0.908	0.374	0.356
58262	160514-16	NBS-19	30.410	3.212	34.182	7.246	2.706	-0.442	0.806	-34.889	0.001	1.124	0.908	0.443	0.432
58331	160516-A1	NBS-19	30.130	2.706	33.344	6.277	2.054	-0.476	0.853	-34.280	0.001	1.124	0.908	0.406	0.392
58419	160520-A2	NBS-19	30.275	2.705	33.470	6.239	3.453	-0.498	0.818	-33.075	0.001	1.124	0.908	0.381	0.365
58606	160522-A1	NBS-19	30.363	2.956	33.844	6.850	4.275	-0.470	0.924	-32.846	0.001	1.124	0.908	0.413	0.398
58948	160522-A3	NBS-19	30.264	2.813	33.532	6.500	3.006	-0.534	0.861	-33.699	0.001	1.124	0.908	0.341	0.321
59110	160522-A4	NBS-19	30.291	2.802	33.590	6.359	3.792	-0.492	0.743	-32.947	0.001	1.124	0.908	0.388	0.371
59419	160603-A7	NBS-19	30.345	2.936	33.799	6.777	4.208	-0.475	0.892	-32.854	0.001	1.124	0.908	0.406	0.392
59613	160606-A1	NBS-19	30.437	3.121	34.101	7.242	0.891	-0.457	0.984	-36.490	0.001	1.124	0.908	0.426	0.413
59663	160607-C9	NBS-19	30.304	2.821	33.618	6.435	3.376	-0.498	0.780	-33.397	0.001	1.124	0.908	0.382	0.365
59829	160609-E7	NBS-19	30.364	2.940	33.836	6.752	3.270	-0.463	0.858	-33.785	0.001	1.124	0.908	0.420	0.406
59879	160610-E9	NBS-19	30.292	2.824	33.630	6.675	3.434	-0.477	1.013	-33.335	0.001	1.124	0.908	0.405	0.390
60024	160612-F5	NBS-19	30.278	2.691	33.419	6.303	3.318	-0.536	0.910	-33.180	0.001	1.124	0.908	0.339	0.318
60044	160612-F7	NBS-19	30.152	2.303	32.915	5.282	5.098	-0.517	0.669	-30.601	0.001	1.124	0.908	0.361	0.342
60088	160613-A1	NBS-19	30.367	2.949	33.835	6.897	3.716	-0.476	0.984	-33.375	0.001	1.124	0.908	0.405	0.391
56744	160415-25	NBS-19	30.336	3.282	34.158	6.849	8.757	-0.459	0.273	-29.122	0.001	1.124	0.908	0.424	0.411
56754	160415-26	NBS-19	30.217	3.075	33.788	6.510	9.707	-0.495	0.348	-27.695	0.001	1.124	0.908	0.384	0.368

[a] WG: working gas. These are raw values relative to a reference gas with $\delta^{13}C$ = -29.85‰ (VPDB) and $\delta^{18}O$ = -5.31‰ (VPDB).

[b] The Brand raw Δ_{47}, raw Δ_{48} and raw Δ_{49} values were calculated by converting our measured raw δ_{45}, raw δ_{46}, raw δ_{47}, raw δ_{48} and raw δ_{49} values within the Brand parameter frame (14-15).

[c] $Slope_{EGL}$: the slope of Equilibrated Gas Line (EGL) of our laboratory following the method of ref. 12.

[d] $Slope_{ETF}$ and $Intercept_{ETF}$: the slope and intercept of Empirical Transfer Function (ETF) of our laboratory following the method of ref. 12.

[e] $\Delta_{47ARF25}$ was calculated from Brand raw Δ_{47} value by applying it to the Absolute Reference Frame (ARF, which includes the values of $Slope_{EGL}$, $Slope_{ETF}$ and $Intercept_{ETF}$) of our laboratory following the method of ref. 12 and then scaling to a 25 °C phosphoric acid reaction by addition of a 0.082‰ temperature correction factor for 90 °C reactions (ref. 13).

[f] The expected $\Delta_{47ARF25}$ value was the long-term observed value or the reported value based on the four ETH standards (ETH-1: 0.258 ‰, ETH-2: 0.256 ‰, EHT-3: 0.693 ‰ and ETH-4: 0.507 ‰) in ref. 17. In this study, two standards were used, one is international standard (NBS-19) and another is in-house standard (ISTB-1), and their expected values are 0.378 ‰ and 0.726 ‰, respectively.

[g] The STF-$\Delta_{47ARF25}$ value was calibrated by applying the Standards Transfer Function (STF) to its average $\Delta_{47ARF25}$ value. The STF was built by comparing the observed average $\Delta_{47ARF25}$ values to their expected $\Delta_{47ARF25}$ values. In order to simplify the description, here we use Δ_{47} to replace the STF-$\Delta_{47ARF25}$ and also in the paper.

Table S4. The total organic carbon (TOC), major and trace elements data of whole rocks from the Doushantuo Formation, and rare earth elements + Yttrium (REE+Y) concentration data of the whole rock and the carbonate fraction.

Height in ZK312-P312（m）	Sample ID	TOC (%)[a]	Major element (ppm)		Trace element (ppm)	REE+Y of the whole rock (ppm)														
			Mn	Sr	Th	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Ho	Er	Tm	Yb	Lu
137.3	ZK312-275	0.36	39	49	0.16	1.31	2.00	0.32	1.37	0.26	0.07	0.30	0.05	0.27	2.29	0.05	0.17	0.02	0.13	0.02
133.8	ZK312-279	0.28	34	75	0.19	2.45	3.30	0.50	2.36	0.51	0.10	0.52	0.07	0.42	4.00	0.09	0.30	0.03	0.22	0.03
131.5	ZK312-282		87	121	0.36	3.04	4.98	0.81	3.42	0.70	0.17	0.72	0.10	0.60	5.04	0.12	0.33	0.05	0.26	0.04
128.1	ZK312-286	0.37	46	82	0.18	2.25	2.71	0.50	2.20	0.39	0.09	0.34	0.05	0.32	2.84	0.06	0.19	0.03	0.17	0.02
126.1	ZK312-288	0.55	57	85	0.56	2.85	4.28	0.64	2.71	0.56	0.13	0.52	0.07	0.45	3.60	0.10	0.30	0.04	0.27	0.03
122.1	ZK312-293	0.04	56	47	0.17	1.80	3.16	0.48	2.04	0.40	0.10	0.43	0.06	0.36	2.95	0.07	0.19	0.03	0.15	0.02
119.6	ZK312-296		70	90	0.30	2.32	4.46	0.63	2.59	0.60	0.12	0.54	0.09	0.52	3.84	0.11	0.31	0.05	0.31	0.05
116.9	ZK312-299	0.13	62	92	0.46	3.96	6.84	1.00	4.22	0.85	0.19	0.95	0.13	0.77	6.22	0.14	0.40	0.07	0.36	0.04
116.0	ZK312-300	0.11	40	56	0.51	3.27	5.67	0.86	3.91	0.83	0.20	0.79	0.13	0.79	6.48	0.15	0.45	0.07	0.37	0.05
113.0	ZK312-304	1.02	51	101	1.32	8.71	14.10	2.02	8.86	1.87	0.40	1.93	0.28	1.76	14.75	0.34	0.99	0.14	0.90	0.12
110.9	ZK312-307	0.69	24	93	0.53	5.58	7.60	1.09	4.66	0.87	0.19	0.96	0.15	0.91	9.51	0.19	0.59	0.08	0.45	0.05
108.3	ZK312-310		24	93	0.11	2.64	4.27	0.67	3.01	0.67	0.15	0.73	0.12	0.71	7.31	0.16	0.39	0.06	0.24	0.04
104.0	ZK312-313	0.11	48	54	0.33	2.11	2.98	0.50	2.20	0.44	0.08	0.43	0.06	0.37	2.99	0.08	0.23	0.03	0.20	0.03
100.8	ZK312-317	0.02	68	38	0.12	1.71	2.65	0.42	1.75	0.35	0.09	0.36	0.05	0.30	2.03	0.06	0.16	0.02	0.13	0.02
98.6	ZK312-321	0.03	96	52	0.16	2.61	3.71	0.70	3.11	0.59	0.13	0.60	0.08	0.45	3.15	0.08	0.21	0.03	0.15	0.02
95.1	ZK312-326		81	48	0.14	1.88	2.48	0.47	2.00	0.42	0.10	0.40	0.07	0.36	2.51	0.07	0.17	0.03	0.15	0.02
93.0	ZK312-328		89	51	0.19	1.84	3.15	0.53	2.17	0.45	0.12	0.47	0.08	0.46	3.17	0.08	0.24	0.03	0.17	0.02
91.2	ZK312-331	0.13	79	59	0.13	1.04	1.72	0.30	1.41	0.37	0.07	0.39	0.06	0.34	2.72	0.07	0.20	0.02	0.14	0.02

88.5	ZK312-335	0.25	111	118	0.75	4.28	7.52	1.26	5.77	1.34	0.31	1.33	0.20	1.21	7.87	0.22	0.61	0.09	0.48	0.07
86.5	ZK312-339	0.23	101	48	0.19	1.31	2.38	0.34	1.50	0.33	0.09	0.37	0.05	0.31	2.36	0.06	0.17	0.02	0.15	0.02
83.0	ZK312-346		132	74	0.11	0.93	1.78	0.28	1.08	0.29	0.06	0.30	0.05	0.38	3.21	0.08	0.23	0.03	0.20	0.03
80.3	ZK312-351	0.1	85	125	0.52	3.21	5.27	0.96	4.04	0.96	0.22	0.97	0.15	0.89	6.83	0.19	0.50	0.07	0.38	0.05
76.6	ZK312-356	1.38	122	540	1.39	12.44	21.03	3.34	14.79	3.06	0.77	3.24	0.48	2.87	20.95	0.56	1.52	0.21	1.18	0.16
73.3	ZK312-361	0.9	128	680	0.93	8.95	14.41	2.37	10.23	2.21	0.56	2.41	0.35	2.12	16.52	0.42	1.17	0.15	0.89	0.13
71.6	ZK312-364	1.32	125	595	1.39	10.80	18.47	2.95	13.40	2.93	0.67	3.02	0.47	2.84	21.20	0.53	1.57	0.22	1.20	0.17
67.9	ZK312-368	0.34	87	367	0.09	0.80	1.58	0.27	1.35	0.32	0.07	0.30	0.04	0.27	2.35	0.06	0.17	0.03	0.16	0.02
64.0	ZK312-376	0.3	51	381	0.13	1.05	1.85	0.34	1.52	0.37	0.07	0.35	0.05	0.30	2.48	0.06	0.18	0.03	0.15	0.02
59.0	ZK312-384	1.7	108	256	0.43	6.22	10.45	1.85	8.84	1.99	0.47	2.05	0.30	1.82	16.88	0.38	1.05	0.15	0.74	0.09
53.0	P312-8	0.13	229	50	2.00	4.56	8.68	1.46	6.47	1.55	0.30	1.38	0.25	1.59	10.14	0.34	1.01	0.16	1.00	0.15
50.0	P312-14		311	143	0.03	0.71	0.98	0.18	0.90	0.20	0.05	0.20	0.03	0.22	1.80	0.04	0.13	0.02	0.09	0.01
47.0	P312-20	0.02	419	109	0.14	1.55	2.95	0.42	2.05	0.50	0.11	0.56	0.08	0.52	4.26	0.10	0.27	0.04	0.22	0.03
44.0	P312-26		228	367	0.56	20.70	24.02	5.55	25.92	6.28	1.40	6.98	1.01	6.13	53.81	1.19	3.15	0.40	1.90	0.25
40.0	P312-32	0.12	383	91	0.21	4.95	7.00	1.45	7.29	1.74	0.41	2.15	0.31	1.90	15.85	0.39	1.00	0.14	0.70	0.10
38.5	P312-37		290	126	0.84	15.16	17.82	4.60	22.15	5.08	1.11	5.33	0.74	4.29	31.62	0.82	2.05	0.24	1.30	0.17
32.1	P312-46		840	59	0.07	0.36	4.27	0.07	0.29	0.05	0.02	0.07	0.01	0.05	0.46	0.01	0.04	0.01	0.04	0.01
28.0	P312-53		676	40	0.13	0.45	3.29	0.15	0.61	0.15	0.03	0.14	0.02	0.13	0.76	0.03	0.08	0.01	0.08	0.01
27.0	P312-55		609	31	0.11	0.45	0.86	0.15	0.72	0.17	0.03	0.15	0.02	0.12	0.87	0.02	0.08	0.01	0.05	0.01
25.0	P312-60	0.01	614	36	0.12	0.39	0.72	0.13	0.56	0.12	0.02	0.09	0.01	0.11	0.64	0.02	0.05	0.01	0.05	0.01
22.0	P312-66		320	43	0.10	0.33	0.48	0.08	0.33	0.08	0.02	0.06	0.01	0.07	0.41	0.02	0.05	0.01	0.05	0.01
21.0	P312-68	0.02	265	51	0.55	0.88	1.94	0.32	1.42	0.35	0.05	0.35	0.05	0.32	1.86	0.05	0.21	0.03	0.15	0.03
20.0	P312-70		335	51	0.14	0.50	0.92	0.13	0.49	0.13	0.02	0.09	0.02	0.12	0.58	0.02	0.06	0.01	0.06	0.01
2.5	P312-105	0.02	1844	72	0.59	1.43	3.77	0.34	1.28	0.31	0.07	0.31	0.04	0.27	2.08	0.06	0.18	0.03	0.16	0.03
0.7	P312-114	0.02	808	54	2.17	6.84	11.96	1.32	4.82	1.05	0.23	1.06	0.17	1.13	7.32	0.23	0.70	0.11	0.67	0.10

Height in ZK312-P312 (m)	Sample ID	Major element (ppm)		Trace element (ppm)	REE+Y of the carbonate fraction [b] (ppm)														
		Mn	Sr	Th	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Ho	Er	Tm	Yb	Lu
137.3	ZK312-275	39	49	0.16	1.30	1.97	0.31	1.35	0.25	0.07	0.29	0.05	0.27	2.26	0.05	0.17	0.02	0.13	0.02
133.8	ZK312-279	34	75	0.19	2.42	3.26	0.50	2.33	0.50	0.10	0.52	0.07	0.41	3.95	0.08	0.29	0.03	0.22	0.03
131.5	ZK312-282	87	121	0.36	2.96	4.86	0.79	3.33	0.68	0.16	0.70	0.10	0.58	4.92	0.12	0.33	0.05	0.26	0.03
128.1	ZK312-286	46	82	0.18	2.22	2.67	0.49	2.17	0.38	0.08	0.34	0.05	0.31	2.81	0.06	0.19	0.03	0.16	0.02
126.1	ZK312-288	57	85	0.56	2.75	4.12	0.62	2.60	0.54	0.12	0.50	0.07	0.44	3.46	0.09	0.29	0.04	0.26	0.03
122.1	ZK312-293	56	47	0.17	1.78	3.12	0.48	2.01	0.40	0.10	0.42	0.06	0.36	2.92	0.07	0.19	0.03	0.15	0.02
119.6	ZK312-296	70	90	0.30	2.27	4.36	0.62	2.53	0.58	0.12	0.53	0.09	0.51	3.76	0.11	0.30	0.05	0.30	0.05
116.9	ZK312-299	62	92	0.46	3.84	6.63	0.97	4.09	0.82	0.19	0.92	0.13	0.74	6.02	0.14	0.39	0.06	0.35	0.04
116.0	ZK312-300	40	56	0.51	3.16	5.47	0.83	3.77	0.80	0.19	0.77	0.13	0.76	6.26	0.14	0.43	0.06	0.35	0.05
113.0	ZK312-304	51	101	1.32	7.92	12.82	1.84	8.06	1.70	0.36	1.76	0.25	1.60	13.41	0.31	0.90	0.13	0.82	0.11
110.9	ZK312-307	24	93	0.53	5.38	7.32	1.05	4.49	0.84	0.19	0.93	0.15	0.87	9.16	0.18	0.57	0.08	0.44	0.05
108.3	ZK312-310	24	93	0.11	2.62	4.24	0.67	2.99	0.66	0.15	0.73	0.12	0.70	7.25	0.16	0.39	0.06	0.24	0.04
104.0	ZK312-313	48	54	0.33	2.06	2.91	0.49	2.15	0.43	0.08	0.42	0.06	0.36	2.93	0.08	0.22	0.03	0.20	0.03
100.8	ZK312-317	68	38	0.12	1.70	2.63	0.42	1.74	0.35	0.09	0.36	0.05	0.30	2.01	0.06	0.16	0.02	0.13	0.02
98.6	ZK312-321	96	52	0.16	2.58	3.67	0.69	3.08	0.58	0.13	0.59	0.08	0.44	3.11	0.08	0.21	0.03	0.15	0.02
95.1	ZK312-326	81	48	0.14	1.86	2.46	0.46	1.98	0.42	0.09	0.40	0.06	0.36	2.48	0.07	0.17	0.03	0.15	0.02
93.0	ZK312-328	89	51	0.19	1.81	3.11	0.53	2.15	0.45	0.12	0.46	0.08	0.45	3.13	0.08	0.24	0.03	0.17	0.02
91.2	ZK312-331	79	59	0.13	1.03	1.71	0.30	1.40	0.36	0.07	0.39	0.06	0.33	2.70	0.07	0.20	0.02	0.14	0.02
88.5	ZK312-335	111	118	0.75	4.06	7.14	1.20	5.47	1.27	0.29	1.26	0.19	1.15	7.46	0.21	0.57	0.09	0.46	0.07
86.5	ZK312-339	101	48	0.19	1.29	2.34	0.33	1.48	0.33	0.09	0.36	0.05	0.31	2.33	0.06	0.17	0.02	0.15	0.02

83.0	ZK312-346	132	74	0.11	0.92	1.77	0.28	1.08	0.29	0.06	0.30	0.05	0.37	3.19	0.08	0.23	0.03	0.19	0.03
80.3	ZK312-351	85	125	0.52	3.10	5.08	0.93	3.90	0.92	0.21	0.94	0.15	0.86	6.59	0.18	0.48	0.06	0.37	0.05
76.6	ZK312-356	122	540	1.39	11.26	19.03	3.02	13.39	2.77	0.70	2.93	0.43	2.60	18.96	0.51	1.38	0.19	1.07	0.14
73.3	ZK312-361	128	680	0.93	8.38	13.49	2.22	9.58	2.07	0.52	2.26	0.32	1.98	15.47	0.39	1.09	0.14	0.83	0.12
71.6	ZK312-364	125	595	1.39	9.77	16.72	2.67	12.13	2.65	0.61	2.74	0.42	2.57	19.19	0.48	1.42	0.20	1.09	0.15
67.9	ZK312-368	87	367	0.09	0.79	1.57	0.27	1.35	0.32	0.07	0.30	0.04	0.27	2.34	0.06	0.17	0.03	0.16	0.02
64.0	ZK312-376	51	381	0.13	1.04	1.84	0.34	1.51	0.36	0.07	0.35	0.05	0.30	2.45	0.06	0.18	0.02	0.15	0.02
59.0	ZK312-384	108	256	0.43	6.04	10.14	1.80	8.57	1.93	0.46	1.99	0.29	1.77	16.38	0.37	1.02	0.14	0.72	0.09
53.0	P312-8	229	50	2.00	3.93	7.49	1.26	5.58	1.34	0.26	1.19	0.21	1.38	8.75	0.29	0.87	0.14	0.86	0.13
50.0	P312-14	311	143	0.03	0.71	0.98	0.18	0.90	0.20	0.05	0.20	0.03	0.22	1.80	0.04	0.13	0.02	0.09	0.01
47.0	P312-20	419	109	0.14	1.53	2.92	0.41	2.03	0.50	0.11	0.55	0.08	0.51	4.22	0.10	0.27	0.04	0.21	0.03
44.0	P312-26	228	367	0.56	19.91	23.10	5.34	24.92	6.03	1.35	6.71	0.97	5.90	51.73	1.14	3.03	0.39	1.83	0.24
40.0	P312-32	383	91	0.21	4.88	6.90	1.43	7.18	1.71	0.40	2.12	0.31	1.87	15.62	0.38	0.99	0.14	0.69	0.10
38.5	P312-37	290	126	0.84	14.29	16.80	4.34	20.88	4.79	1.05	5.02	0.70	4.05	29.81	0.77	1.93	0.23	1.22	0.16
32.1	P312-46	840	59	0.07	0.36	4.25	0.07	0.29	0.05	0.02	0.07	0.01	0.05	0.45	0.01	0.04	0.01	0.04	0.01
28.0	P312-53	676	40	0.13	0.45	3.26	0.15	0.60	0.15	0.03	0.14	0.02	0.12	0.75	0.03	0.08	0.01	0.08	0.01
27.0	P312-55	609	31	0.11	0.45	0.86	0.15	0.72	0.16	0.03	0.15	0.02	0.12	0.87	0.02	0.08	0.01	0.05	0.01
25.0	P312-60	614	36	0.12	0.39	0.71	0.13	0.56	0.12	0.02	0.09	0.01	0.11	0.64	0.02	0.05	0.01	0.05	0.01
22.0	P312-66	320	43	0.10	0.33	0.48	0.08	0.32	0.08	0.02	0.06	0.01	0.07	0.41	0.02	0.05	0.01	0.05	0.01
21.0	P312-68	265	51	0.55	0.84	1.86	0.30	1.36	0.34	0.05	0.34	0.05	0.31	1.79	0.05	0.20	0.03	0.15	0.03
20.0	P312-70	335	51	0.14	0.50	0.91	0.13	0.49	0.13	0.02	0.09	0.02	0.12	0.57	0.02	0.06	0.01	0.06	0.01
2.5	P312-105	1844	72	0.59	1.38	3.62	0.33	1.23	0.29	0.06	0.29	0.04	0.26	2.00	0.06	0.17	0.03	0.16	0.02
0.7	P312-114	808	54	2.17	5.83	10.18	1.12	4.10	0.89	0.20	0.91	0.15	0.97	6.23	0.19	0.60	0.09	0.57	0.08

[a] TOC data are from ref. 20. [b] REE concentration in carbonate fraction was calculated through the equation $X_{Sample} \times (1-Th_{Sample}/Th_{PAAS})$, where X represents the concentration of interested element.

Table S5. Geochemical and petrographic data for samples with different carbonate textures as observed in the sample slab and under microscopy.

Sample ID	Formation	Carbonate texture	Average Δ_{47} [a] (‰)	$\delta^{18}O$ (VPDB,‰)	Grain size (μm)	1 s.d. of grain size [b] (μm)	$T_{\Delta47}$ (°C)	1 s.e. of $T_{\Delta47}$ [c] (°C)
ZK312-29	Dengying	Microcrystalline dolomite	0.512	-4.86	10	4	83	7
ZK312-29	Dengying	Carbonate vein	0.431	-7.72	61	10	137	4
ZK312-282	Doushantuo	Microcrystalline dolomite	0.519	-3.15	17	8	80	3
ZK312-282	Doushantuo	Carbonate vein	0.420	-11.62	182	55	146	
ZK312-293	Doushantuo	Microcrystalline dolomite	0.509	-2.92	11	4	85	7
ZK312-293	Doushantuo	Coarse-crystalline dolomite	0.488	-3.93	59	36	97	14
ZK312-307	Doushantuo	Microcrystalline dolomite	0.531	-2.37	19	6	74	3
ZK312-307	Doushantuo	Coarse-crystalline dolomite	0.501	-2.71	68	5	90	4
ZK312-310	Doushantuo	Microcrystalline dolomite	0.532	-2.29	22	8	73	6
ZK312-310	Doushantuo	Coarse-crystalline dolomite	0.528	-2.84	56	20	75	4
ZK312-317	Doushantuo	Microcrystalline dolomite	0.546	-4.31	8	3	67	12
ZK312-317	Doushantuo	Carbonate vein	0.520	-8.20	247	15	79	11
ZK312-326	Doushantuo	Microcrystalline dolomite	0.560	-2.19	12	5	61	2
ZK312-326	Doushantuo	Carbonate vein	0.484	-9.42	232	15	100	
P312-20	Doushantuo	Microcrystalline dolomite	0.513	-4.33	26	8	83	3
P312-20	Doushantuo	Coarse-crystalline dolomite	0.499	-4.48	26	8	91	4
P312-46	Doushantuo	Microcrystalline dolomite	0.509	-3.75	20	7	85	3
P312-46	Doushantuo	Coarse-crystalline dolomite	0.526	-5.38	111	28	76	4

[a] For simplification, we used Δ_{47} to replace the STF-$\Delta_{47ARF25}$ here (more details see Table S3).

[b] Standard deviation (s.d.) was derived from duplicate analyses.

[c] Standard error (s.e.) was given as 1 s.d./($n^{0.5}$).

References

1. Zhang S, et al. (2015) New paleomagnetic results from the Ediacaran Doushantuo Formation in South China and their paleogeographic implications. *Precamb. Res.* 259:130–142.

2. Loyd SJ, et al. (2015) Evolution of Neoproterozoic Wonoka–Shuram Anomaly-aged carbonates: Evidence from clumped isotope paleothermometry. *Precamb. Res.* 264:179–191.

3. Bristow TF, Bonifacie M, Derkowski A., Eiler JM, Grotzinger JP (2011) A hydrothermal origin for isotopically anomalous cap dolostone cements from south China. *Nature* 474:68–71.

4. Zhang S, et al. (2013) Paleomagnetism of the late Cryogenian Nantuo Formation and paleogeographic implications for the South China Block. *J. Asian Earth Sci.* 72:164–177.

5. Jiang G, Shi X, Zhang S, Wang Y, Xiao S (2011) Stratigraphy and paleogeography of the Ediacaran Doushantuo Formation (ca. 635–551Ma) in South China. *Gondwana Res.* 19(4):831–849.

6. An Z, et al. (2015) Stratigraphic position of the Ediacaran Miaohe biota and its constrains on the age of the upper Doushantuo $\delta^{13}C$ anomaly in the Yangtze Gorges area, South China. *Precamb. Res.* 271:243–253.

7. Henkes GA, et al. (2014) Temperature limits for preservation of primary calcite clumped isotope paleotemperatures. Geochimica et Cosmochimica Acta 139:362-382.

8. Lloyd MK, Ryb U, & Eiler JM (2018) Experimental calibration of clumped isotope reordering in dolomite. *Geochimica et Cosmochimica Acta* 242:1-20.

9. Passey BH & Henkes GA (2012) Carbonate clumped isotope bond reordering and geospeedometry. *Earth and Planetary Science Letters* 351-352:223-236.

10. Eiler JM (2011) Paleoclimate reconstruction using carbonate clumped isotope thermometry. *Quaternary Science Reviews* 30: 3575-3588.

11. Kouketsu Y, et al. (2014) A new approach to develop the Raman carbonaceous material geothermometer for low-grade metamorphism using peak width. *Island Arc* 23:33–50.

12. Dennis KJ, Affek HP, Passey BH, Schrag DP, Eiler JM (2011) Defining an absolute reference frame for 'clumped' isotope studies of CO_2. *Geochim. Cosmochim. Acta* 75:7117–7131.

13. Defliese WF, Hren MT, Lohmann KC (2015) Compositional and temperature effects of phosphoric acid fractionation on Δ_{47} analysis and implications for discrepant calibrations. *Chem. Geol.* 396:51–60.

14. Daëron M, Blamart D, Peral M, Affek HP et al. (2016) Absolute isotopic abundance ratios and the accuracy of Δ_{47} measurements. *Chem. Geol.* 441:83–96.

15. Brand WA, Assonov SS, Coplen TB (2010) Correction for the ^{17}O interference in $\delta^{13}C$ measurements when analyzing CO_2 with stable isotope mass spectrometry (IUPAC Technical Report). *Pure Appl. Chem.* 82:1719-1733.

16. Müller IA, et al. (2019) Calibration of the oxygen and clumped isotope thermometers for (proto-)dolomite based on synthetic and natural carbonates. *Chemical Geology* 525:1-17.

17. Bernasconi SM, et al. (2018) Reducing uncertainties in carbonate clumped isotope analysis through consistent carbonate-based standardization. *Geochem. Geophys. Geosyst.* 19:2895–2914.

18. Bonifacie M, et al. (2017) Calibration of the dolomite clumped isotope thermometer from 25 to 350 °C, and implications for a universal calibration for all (Ca, Mg, Fe)CO_3 carbonates. *Geochim. Cosmochim. Acta* 200:255–279.

19. Petersen SV, et al. (2019) Effects of Improved ^{17}O Correction on Interlaboratory Agreement in Clumped Isotope Calibrations, Estimates of Mineral‐Specific Offsets, and Temperature Dependence of Acid Digestion Fractionation. *Geochemistry, Geophysics, Geosystems* 20:1-25.

20. Li C, et al. (2017) Uncovering the spatial heterogeneity of Ediacaran carbon cycling. *Geobiology* 15:211-224.