**Appendix A. Supplementary Material for**

**Heterogeneous sulfide reoxidationbuffered oxygen release in the Ediacaran Shuram ocean**

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**Timescale and rate of δ13Ccarb shift**

Calculations of linear sedimentation rate (LSR) require adequate age control. The duration of the SE event remains uncertain due to controversy regarding bio-, litho-, and chemostratigraphic correlations, combined with sparse radio-isotopic ages. However, recent radio-isotopic dates from an Ediacaran Shuram Excursion (SE) succession constrain the ages of key fossil assemblages and major carbonate carbon isotopic excursions to between 574.0±4.7 Ma and 567.3±3.0 Ma (Rooney et al., 2020) or ca. 565 Ma (Yang et al., 2021), as well as demonstrating their global synchronicity. The duration of the SE was thus ca. ~8 to 10 Myr. Here, we assume a uniform bulk sedimentation rate during the SE interval, despite facies and lithology changes in both the Jiulongwan section and the Miqrat-1 drillcore.

For each section, the age-equivalent beginning and ending tie-points were defined as follows: (1) for the beginning tie-point, we assigned a fixed position (with an age of 575 Ma) to the δ13Ccarb decrease from a stable background value (Miqrat-1: 3840 m, 3 ‰; Jiulongwan: 92 m, 5 ‰) (Fig. 9A and C); (2) for the end tie-point we assigned a fixed position (with an age of 565 Ma) to the δ13Ccarb increase back to ca. 0 ‰, typically accompanied by a significant facies change (Miqrat-1: 3360 m; Jiulongwan: 154 m) (Fig. 9A and C); and (3) for an internal tie-point, we assigned a fixed position where δ13Ccarb reached a nadir (Miqrat-1: 3740 m, –12.5 ‰; Jiulongwan: 115 m, –10 ‰), with its age determined by the total thickness and timescale of each section (Fig. 9A and C). At Jiulongwan, the total thickness of SE strata is 154 – 92 = 62 m, and the nadir of δ13Ccarb is at 115 m, so the age of the nadir is 575 Ma – (115 m – 92 m) / 62 m × 10 Myr = 571.25 Ma. At Miqrat-1, the total thickness of SE strata is 3840 – 3360 = 480 m, and the nadir of δ13Ccarb is at 3760 m, so the age of the nadir is 575 Ma – (3840 m – 3760 m) / 480 m × 10 Myr = 573.33 Ma. Based on these constraints, the rate of δ13Ccarb change can be calculated for each section as follows: (1) at Miqrat-1, it is –(3 ‰ + 12.5 ‰) / (575 Ma – 573.33 Ma) = –9.3 ‰/Myr (Fig. 9A); and (2) at Jiulongwan, it is –(5 ‰ + 10 ‰) / (575 Ma – 571.25 Ma) = –4 ‰/Myr (Fig. 9C), which is less than half of that of Miqrat-1.

**Burial flux of pyrite sulfur**

Table S2 shows the dataset for the burial flux of pyrite sulfur at Jiulongwan (South China) and Miqrat-1 (Oman).LSRs were calculated for a time-stratigraphic unit of interest based on its thickness at a given study site and its estimated duration based on recent radiometric dating studies. Bulk accumulation rates (BAR) were calculated as:

(1)

where LSR is in units of m Myr-1, is bulk sediment density in units of g cm-3, and thus BAR is in units of g m-2 Myr-1. Owing to lack of bulk sediment density data, a value of 2.5 g cm-3 was used in all BAR calculations (cf. Algeo and Twitchett, 2010). Burial fluxes of pyrite sulfur were calculated based on BAR and the concentration of pyrite sulfur (CpyS), which is expressed as follows:

(2)

where CpyS is in units of g/g %, thus the is also in units of g m-2 Myr-1. Figure 9 shows the comparison of between Miqrat-1 and Jiulongwan (CpyS data sources: Miqrat-1: Fike et al., 2006; Jiulongwan: Shi et al., 2018). In Stage I, the at Miqrat-1 range between 0.004 to 0.1 g m-2 Myr-1 with an average of 0.031 g m-2 Myr-1 (*n* = 20) (Fig. 9B); at Jiulongwan range between 0.0011 to 0.0035 g m-2 Myr-1 with an average of 0.0021 g m-2 Myr-1 (*n* = 11 with two outliers removed) (Fig. 9D). Thus, Miqrat-1 has a (0.031 g m-2 Myr-1) more than 10 times higher than that of Jiulongwan (0.0021 g m-2 Myr-1), as well as a significantly higher rate of δ13Ccarb change (–9.3 ‰/Myr versus –4.0 ‰/Myr).

**Steady-state mass balance of C-S cycles**

We estimated the surplus sulfate flux needed to sustain the Ediacaran SE via a standard isotope mass balance. At steady state, variations in the mass and isotopic composition of the atmospheric-oceanic carbon reservoir (A) over time respond to burial (B) and weathering (W) or metamorphic degassing (D), and are zero following these formulations:

(3)

(4)

where is the flux of DOC oxidation, δ with subscript ‘G’, ‘C’, or ‘DOC’ represents the isotopic composition of crustal organic carbon, crustal carbonate, or oceanic organic matter reservoirs, respectively, and Δ13C is the isotope fractionation during photosynthesis. Assuming an initial steady state before onset of the SE with δ13Ccarb = +3 ‰ and , adopting present-day parameter values (see Table S6), we solved for δ13Ccarb using a range of values for (Fig. S1A). We further assumed that DOC oxidation was driven solely by extra weathering sulfate, and set the flux of H2S produced via MSR as in moles. Figure S1A shows that δ13Ccarb decreases as increases, and a of around 22×1012 mol C yr–1 (Shields et al., 2019) could sustain a decrease in δ13Ccarb from +3 ‰ to ~–10 ‰ (full orange arrow). This gives the surplus sulfate input needed for this anomaly (~11×1012 mol S yr–1), based on the fixed stoichiometric relationship between reaction rates of DOC and sulfate during MSR (i.e., ).

A compilation of published sulfur isotopic compositions of Tonian-aged gypsum deposits (δ34Sgyp; from Crockford et al., 2019) and shale-hosted pyrite (δ34Spy; from Canfield and Farquhar, 2009) yields average values of ~15 ‰ and ~0 ‰, respectively. We denote as the fraction of the total sulfur weathering flux sourced from pyrite, which can range from 0 to 1. We inserted and a range of values into standard mass balance equations for the sulfur cycle as follows:

(5)

(6)

where and with subscript ‘S’, ‘GYP’ and ‘PYR’ represent the sulfur isotopic compositions of marine sulfur, crustal gypsum, and crustal pyrite reservoirs, respectively, and is the sulfur isotope fractionation during MSR; ‘GYP’ and ‘PYR’ with subscript ‘pulse’ represent the flux or its sulfur isotopic compositions of the additional gypsum and pyrite weathering pulse, respectively. Adopting present-day parameter values (Table S6), we solved for δ34SCAS using a range of values (Fig. S1B). Keeping the unchanged, δ34SSO4 decreases with increasing (Fig. S1B). When the is ~0.99, δ34SCAS decreases to the Shuram steady state of +12 ‰ (taking the Jiulongwan section as an example) (Fig. S1B), meaning that almost all (99%) of the weathering sulfate flux comes from pyrite. A pyrite weathering flux of 11×1012 mol S yr–1 is equal to ~24 times the present-day level (0.45×1012 mol S yr–1; Lenton et al., 2018).

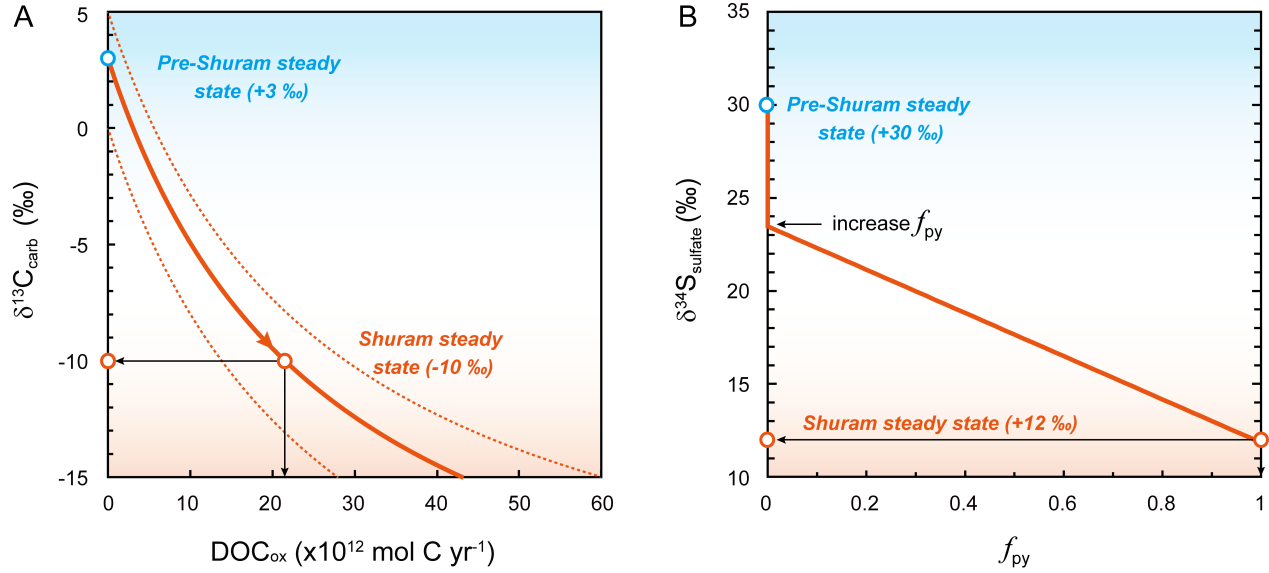
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Fig. S1. Mass balance results for a δ13Ccarb excursion driven by oxidation of a dissolved organic carbon (DOC) reservoir (A), and a negative δ34Ssulfate excursion due to increasing (B), using modern C-S cycle parameters (Table S6). In A, the solid line represents the δ13Ccarb decline from an initial steady-state value of +3 ‰, while the two dashed lines represent cases from initial values of +5 ‰ (upper) and 0 ‰ (lower). In B, the solid line represents the δ34Ssulfate decline from an initial steady-state value of +30 ‰ to the Shuram steady-state value of +12 ‰ with increasing , when the initial steady-state value of δ13Ccarb is +3 ‰. Modified from Shields et al. (2019).

To further evaluate the possibility of 99% of weathered sulfate in the additional weathering sulfate pulse coming from pyrite weathering, we modified the COPSE model in two regards as follows: (1) we set , which stops the H2S reoxidation process, and (2) we decreased the contribution of gypsum to the weathered sulfate flux to 1% during the while increasing the contribution of pyrite to 99%. As shown in Fig. S2, modeled δ34SSO4 variation (Fig. S2C) is not coupled with negative shifts of δ13Ccarb (Fig. S2B) and δ18OSO4 (Fig. S2D), while both atmospheric oxygen (Fig. S2E) and oceanic sulfate (Fig. S2F) are largely consumed. In this case, the oxygen consumption by pyrite weathering cannot be balanced by oxygen production via pyrite burial, which implies a net consumption of oxygen by the sulfur cycle, and would fall into the ‘Shuram oxidant paradox’ (see main text) (cf. Bristow and Kennedy, 2008 versus Shields et al., 2019).

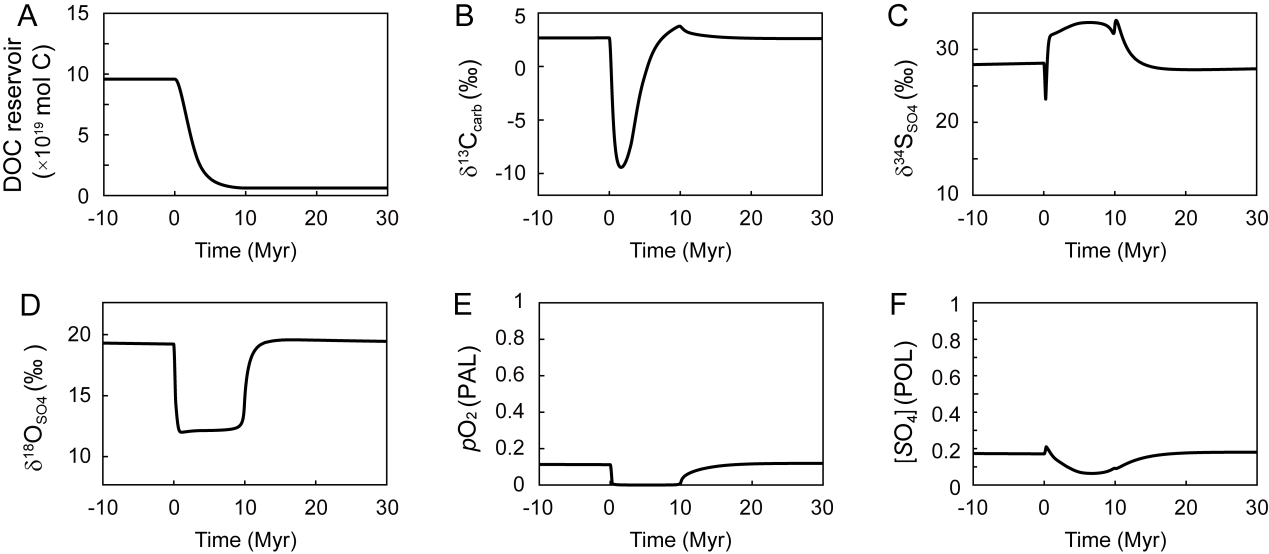


Fig. S2. COPSE model results for the scenario in which 99 % of weathered sulfate comes from pyrite during the Spulse. (A) Size of the dissolved organic carbon (DOC) reservoir in moles of carbon. (B) Seawater DIC δ13C. (C) Seawater sulfate δ34S. (D) Seawater sulfate δ18O. (E) Relative atmospheric oxygen concentration. (F) Relative oceanic sulfate concentration. DIC, dissolved inorganic carbon; PAL, present atmospheric level; POL, present oceanic level.

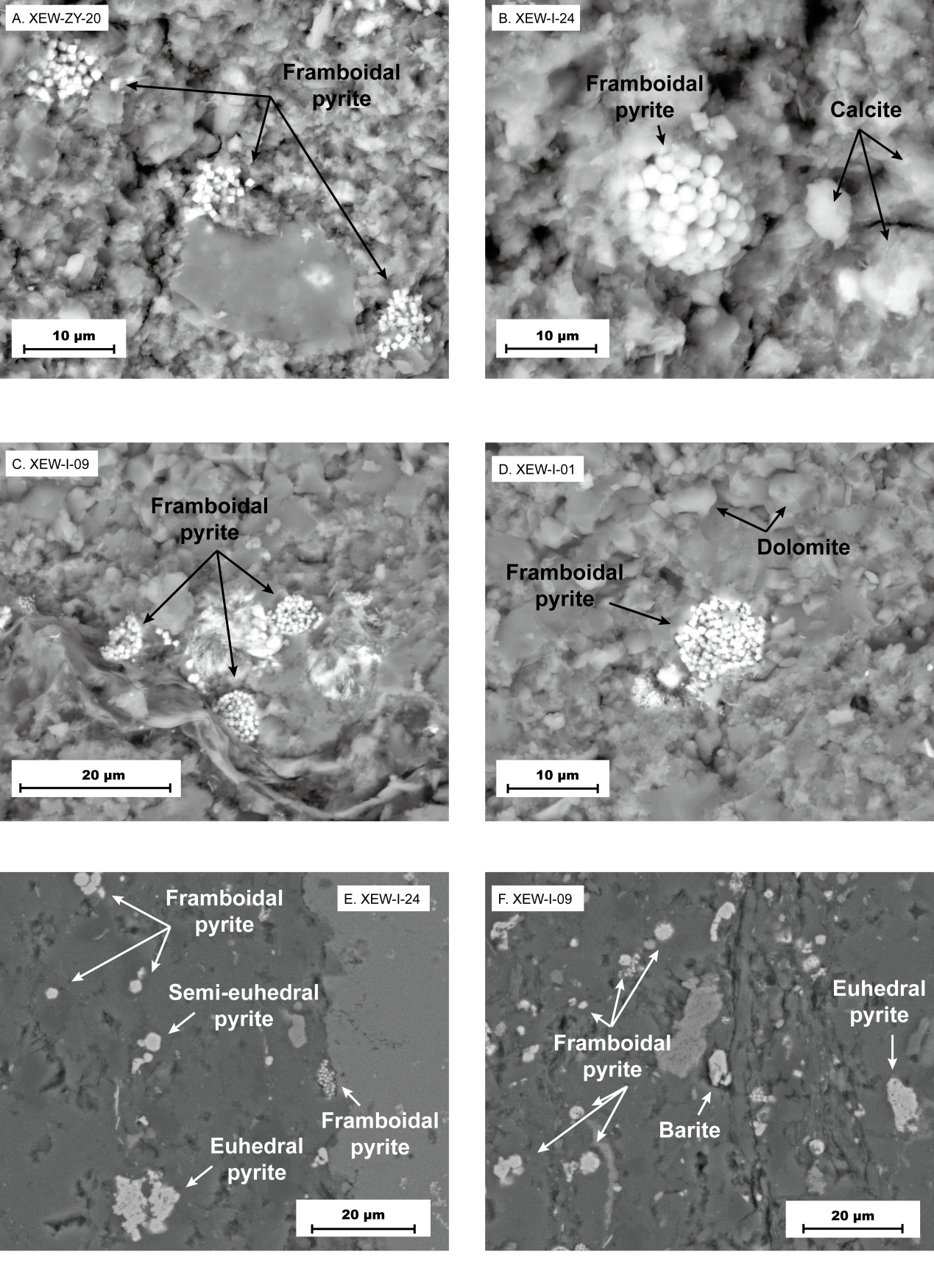


Fig. S3. Backscattered electron (BSE) images of pyrite framboids of 4 random samples from Xiang’erwan section.

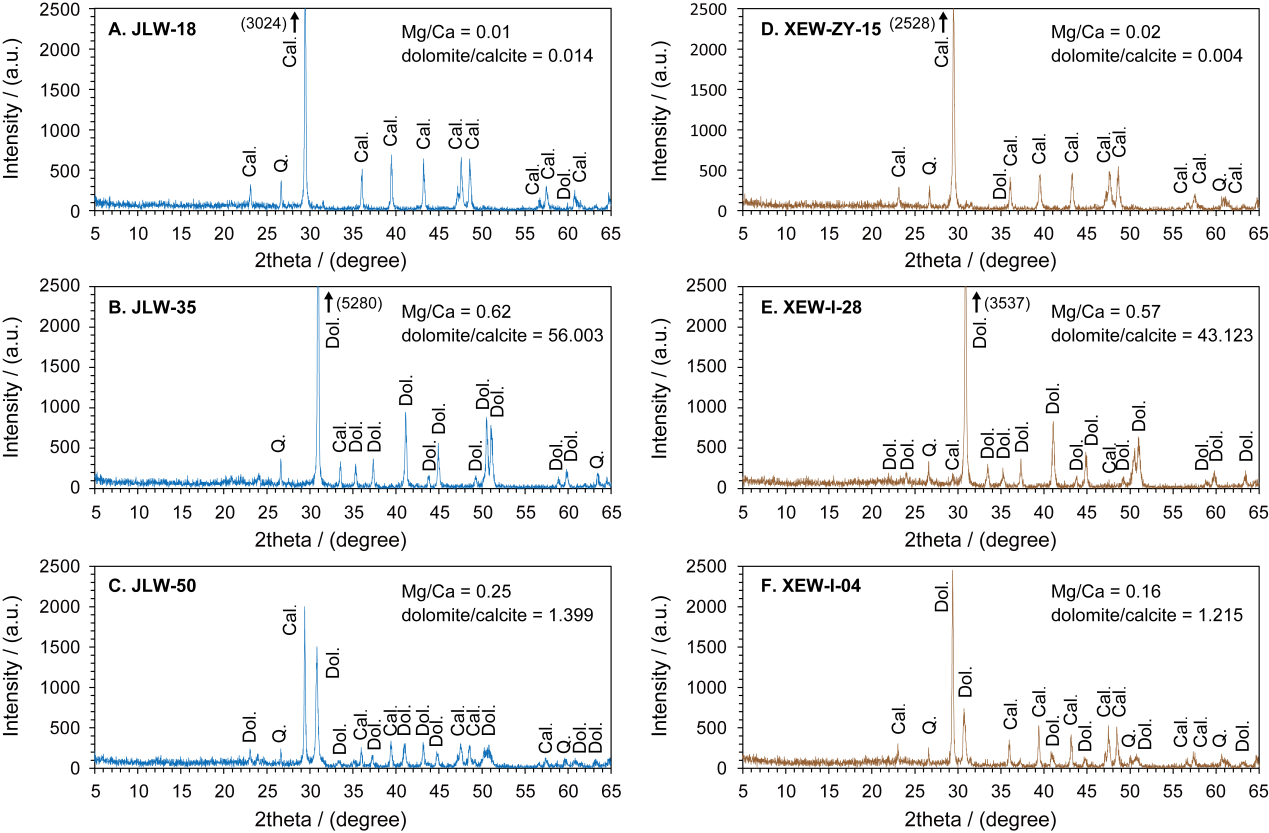


Fig. S4. XRD spectrum of 6 samples from Jiulongwan (A-C) and Xiang’erwan (D-F) sections. The diffraction peaks shown include those of dolomite (Dol.), calcite (Cal.) and quartz (Q). a.u. = arbitrary unit. The full dataset is given in Table S8.

**Sensitivity test for the necessity of a DOC reservoir.**

To further evaluate the necessity of the DOC reservoir, we conducted a sensitivity test that run our COPSE model with a pulsed weathering sulfate input but without a large organic carbon reservoir. As shown in the Fig. S5, the δ34Ssulfate and δ18Osulfate can decrease to +21 ‰ (Fig. S5C) and +15 ‰ (Fig. S5D), respectively, when Spulse is 7 and *f*reox is 1. However, the modelled δ13Ccarb increases from +3 ‰ to >+3.5 ‰ (Fig. S5B), which is inconsistent with the observed Shuram δ13Ccarb records. This sensitivity test suggests that an organic carbon reservoir is necessary to supply 12C and phosphorus for the observed Shuram δ13Ccarb, δ34Ssulfate and δ18Osulfate records. An organic carbon reservoir coupled with a pulsed weathering sulfate input with dynamic sulfide oxidation in basins would appear to provide the most concise solution to explain the paired C-S-O-U isotopic data during the Shuram Excursion.

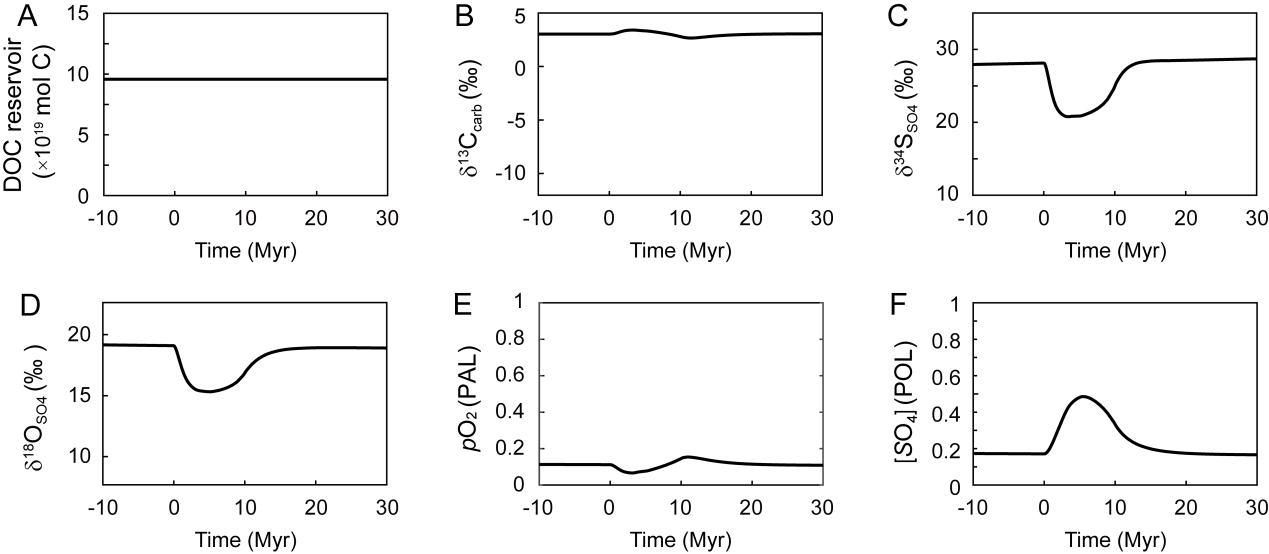


Fig. S5. COPSE model results for the scenario with Spulse = 7 and DOCox = 0. (A) Size of the DOC reservoir in moles of carbon. (B) Seawater DIC δ13C. (C) Seawater sulfate δ34S. (D) Seawater sulfate δ18O. (E) Relative atmospheric oxygen concentration. (F) Relative oceanic sulfate concentration. DOC， dissolved organic carbon; DIC, dissolved inorganic carbon; PAL, present atmospheric level; POL, present oceanic level.

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**Supplementary Tables**

Table S1: Carbon-sulfur geochemical data of the study sections.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Jiulongwan (Three Gorges, South China) | | | | | | | | | | | | | | |
| Sample | †Depth | Relative  stratigraphic  position | \*δ13Ccarb | \*δ18Ocarb | δ18OCAS | \*δ34SCAS | Mg | Ca | P | P/(Ca+Mg) | Mg/Ca | \* **[CAS]** |  |  |
| (m) | (‰ VPDB) | (‰ VPDB) | (‰ VSMOW) | (‰ VCDT) | (%) | (%) | (ppm) | (ppm/wt %) | (% / %) | (ppm in  carbonate) |  |  |
| JLW-01 | 142 | 0.81 | -7.8 | -0.2 | 8.6 |  |  |  |  |  |  | 422.2 |  |  |
| JLW-03 | 140.6 | 0.78 | -7.7 | -3.6 |  | 25.2 |  |  |  |  |  | 586.4 |  |  |
| JLW-04 | 140.3 | 0.78 | -7.5 | -3 |  | 25.7 |  |  |  |  |  | 942.9 |  |  |
| JLW-05 | 139.9 | 0.77 | -7.9 | -4.2 |  |  | 8.35 | 21.29 | 661.05 | 22.3 | 0.39 |  |  |  |
| JLW-06 | 139 | 0.76 | -8 | -5.2 | 14.35 | 19.7 | 6.18 | 28.91 | 350.62 | 9.99 | 0.21 | 1127.2 |  |  |
| JLW-07 | 138.2 | 0.75 | -8.5 | -7.3 |  |  | 0.82 | 36.07 | 509.03 | 13.8 | 0.02 |  |  |  |
| JLW-08 | 137.1 | 0.73 | -8.4 | -7.3 | 11.97 | 13.9 | 0.44 | 35.86 | 330.51 | 9.1 | 0.01 | 731.8 |  |  |
| JLW-09 | 136 | 0.71 | -8.3 | -7 |  |  | 0.33 | 37.86 | 308.73 | 8.08 | 0.01 |  |  |  |
| JLW-10 | 135 | 0.69 | -8.4 | -7.4 | 11.3 | 13.5 | 0.42 | 37.10 | 298.90 | 7.97 | 0.01 |  |  |  |
| JLW-11 | 134.2 | 0.68 | -8.4 | -7.7 |  |  | 2.42 | 32.24 | 481.67 | 13.9 | 0.07 |  |  |  |
| JLW-12 | 133.6 | 0.67 | -8.4 | -7.9 | 13.28 |  | 1.21 | 34.64 | 339.34 | 9.47 | 0.03 | 283.3 |  |  |
| JLW-13 | 132.7 | 0.66 | -8.5 | -8.3 |  |  | 0.58 | 36.17 | 202.04 | 5.5 | 0.02 |  |  |  |
| JLW-14 | 132 | 0.65 | -8.5 | -8.4 |  | 15.8 | 0.35 | 36.73 | 228.47 | 6.16 | 0.01 | 264.6 |  |  |
| JLW-15 | 131 | 0.63 | -8.5 | -8.4 |  |  | 0.46 | 35.98 | 260.57 | 7.15 | 0.01 |  |  |  |
| JLW-16 | 130 | 0.61 | -8.6 | -8.6 | 13.94 | 18.5 | 0.70 | 37.28 | 261.93 | 6.9 | 0.02 | 879.2 |  |  |
| JLW-17 | 129 | 0.6 | -8.7 | -8.9 |  |  | 0.37 | 37.54 | 175.96 | 4.64 | 0.01 |  |  |  |
| JLW-18 | 128.3 | 0.59 | -8.8 | -9 | 12.22 | 18.4 | 0.37 | 36.58 | 176.03 | 4.76 | 0.01 | 844.7 |  |  |
| JLW-19 | 127 | 0.56 | -8.8 | -8.9 |  |  | 0.84 | 31.70 | 223.54 | 6.87 | 0.03 |  |  |  |
| JLW-20 | 126.2 | 0.55 | -8.9 | -9.1 |  |  | 0.41 | 37.13 | 163.43 | 4.35 | 0.01 |  |  |  |
| JLW-21 | 125.2 | 0.54 | -8.9 | -9 | 11.15 | 18.4 | 1.33 | 34.06 | 176.39 | 4.98 | 0.04 | 816.2 |  |  |
| JLW-22 | 124.2 | 0.52 | -8.7 | -9.7 |  |  | 1.56 | 34.06 | 289.03 | 8.12 | 0.05 |  |  |  |
| JLW-23 | 123.2 | 0.5 | -9 | -9.8 | 10.05 | 15.5 | 0.52 | 35.52 | 157.63 | 4.37 | 0.01 | 323.1 |  |  |
| JLW-24 | 122 | 0.48 | -9 | -9.7 |  |  | 0.60 | 35.34 | 178.10 | 4.96 | 0.02 |  |  |  |
| JLW-25 | 121.2 | 0.47 | -9 | -9.8 | 11.58 | 20.2 | 0.51 | 35.19 | 170.52 | 4.78 | 0.01 | 409.5 |  |  |
| JLW-26 | 120 | 0.45 | -9.1 | -10 | 9.83 |  | 0.71 | 30.47 | 128.04 | 4.11 | 0.02 | 701.5 |  |  |
| JLW-27 | 119.4 | 0.44 | -9.1 | -9.9 |  |  | 1.71 | 32.83 | 172.84 | 5 | 0.05 |  |  |  |
| JLW-28 | 118.6 | 0.43 | -9.1 | -9.9 |  |  | 2.24 | 30.32 | 227.13 | 6.97 | 0.07 |  |  |  |
| JLW-29 | 118 | 0.42 | -9 | -10.5 | 8.74 | 14.6 |  |  |  |  |  | 602.9 |  |  |
| JLW-30 | 117 | 0.4 | -8.9 | -7.1 |  |  | 11.08 | 18.35 | 276.46 | 9.39 | 0.60 |  |  |  |
| JLW-31 | 116 | 0.39 |  |  |  |  | 11.36 | 20.82 | 195.98 | 6.09 | 0.55 |  |  |  |
| JLW-32 | 115 | 0.37 | -8.7 | -6.4 | 12.91 | 21.3 | 11.27 | 19.52 | 375.78 | 12.2 | 0.58 | 969.1 |  |  |
| JLW-33 | 114 | 0.35 | -7.8 | -5.7 |  | 28.3 | 10.69 | 18.07 | 460.95 | 16.03 | 0.59 | 923.8 |  |  |
| JLW-34 | 113 | 0.34 | -6.3 | -2.6 |  |  | 11.43 | 18.64 | 243.87 | 8.11 | 0.61 |  |  |  |
| JLW-35 | 112 | 0.32 | -5.4 | -4 | 12.89 | 17.2 | 12.44 | 19.98 | 470.16 | 14.5 | 0.62 | 304.9 |  |  |
| JLW-36 | 111 | 0.31 |  |  |  |  | 11.14 | 18.99 | 244.49 | 8.11 | 0.59 |  |  |  |
| JLW-37 | 110.7 | 0.3 | -6.1 | -4.3 | 15.55 |  | 10.35 | 17.18 | 384.12 | 13.95 | 0.60 |  |  |  |
| JLW-39 | 108.6 | 0.27 |  |  |  |  | 3.12 | 7.23 | 76.40 | 7.38 | 0.43 |  |  |  |
| JLW-41 | 106.6 | 0.24 | -1.8 | -3.7 |  |  | 13.05 | 21.06 | 269.58 | 7.9 | 0.62 |  |  |  |
| JLW-42 | 105.6 | 0.22 |  |  |  |  | 12.90 | 21.36 | 380.82 | 11.12 | 0.60 |  |  |  |
| JLW-43 | 104.6 | 0.2 | -0.8 | -4.1 |  | 28.3 | 13.23 | 21.35 | 137.35 | 3.97 | 0.62 |  |  |  |
| JLW-44 | 101.6 | 0.15 |  |  |  |  | 12.02 | 20.16 | 250.62 | 7.79 | 0.60 |  |  |  |
| JLW-45 | 102.7 | 0.17 | -0.1 | -4.3 |  |  | 12.94 | 20.95 | 263.88 | 7.79 | 0.62 |  |  |  |
| JLW-46 | 101.7 | 0.16 | 2.7 | -4.8 | 19.28 |  | 10.98 | 18.29 | 615.28 | 21.02 | 0.60 | 615.1 |  |  |
| JLW-47 | 100.8 | 0.14 | 2.9 | -6.1 | 18.31 |  | 12.03 | 20.32 | 316.68 | 9.79 | 0.59 |  |  |  |
| JLW-48 | 99.8 | 0.13 | 2.9 | -6.4 | 17.03 | 29.9 | 12.47 | 21.66 | 159.50 | 4.67 | 0.58 |  |  |  |
| JLW-49 | 98.8 | 0.11 | 3.5 | -3.6 |  |  | 10.43 | 19.50 | 322.66 | 10.78 | 0.53 |  |  |  |
| JLW-50 | 97.8 | 0.09 | 2.6 | -7.8 | 20 | 33.3 | 7.21 | 29.11 | 200.02 | 5.51 | 0.25 | 528.9 |  |  |
| JLW-51 | 96.8 | 0.08 | 3.2 | -6.7 | 19.29 |  | 7.39 | 26.32 | 417.33 | 12.38 | 0.28 |  |  |  |
| JLW-52 | 95.8 | 0.06 | 4 | -4.4 | 21.58 |  | 9.91 | 18.64 | 682.90 | 23.92 | 0.53 |  |  |  |
| JLW-53 | 94.8 | 0.05 | 4.3 | -6.5 | 23.5 |  | 7.43 | 27.64 | 239.05 | 6.82 | 0.27 |  |  |  |
| JLW-54 | 93.8 | 0.03 | 4.5 | -9.1 | 20.64 | 36.4 | 3.53 | 26.24 | 174.75 | 5.87 | 0.13 | 422.1 |  |  |
| JLW-55 | 92.8 | 0.01 | 4.8 | -9 |  |  | 0.71 | 37.85 | 84.97 | 2.2 | 0.02 |  |  |  |
| JLW-56 | 91.6 | -0.01 | 4.4 | -4.3 | 19.29 | 29.7 | 10.58 | 18.55 | 138.15 | 4.74 | 0.57 | 73.7 |  |  |
| Xiang'erwan (Three Gorges, South China) | | | | | | | | | | | | | | |
| Sample | ††Depth | Relative  stratigraphic  position | δ13Ccarb | δ18Ocarb | δ18OCAS | δ34SCAS | Mg | Ca | P | P/(Ca+Mg) | Mg/Ca | Mn | Sr | Mn/Sr |
| (m) | (‰ VPDB) | (‰ VPDB) | (‰ VSMOW) | (‰ VCDT) | (%) | (%) | (ppm) | (ppm/wt %) | (% / %) | (ppm) | (ppm) |
| XEW-ZY-12 | 73 | 0.91 | -4.06 | -3.14 |  |  | 12.16 | 19.79 | 447.3 | 14.00 | 0.61 | 119.54 | 38.37 | 3.12 |
| XEW-ZY-13 | 70.8 | 0.89 | -4.68 | -5.61 |  |  | 12.33 | 20.21 | 365.38 | 11.23 | 0.61 | 170.85 | 46.31 | 3.69 |
| XEW-ZY-15 | 66.4 | 0.83 | -7.31 | -10.93 |  | 16.27 | 0.64 | 36.65 | 458.44 | 12.29 | 0.02 | 87.53 | 77.54 | 1.13 |
| XEW-ZY-16 | 64.2 | 0.80 | -7.04 | -9.45 |  | 19.03 | 3.56 | 32.30 | 310.36 | 8.65 | 0.11 | 129.45 | 59.18 | 2.19 |
| XEW-ZY-17 | 62 | 0.78 | -7.52 | -9.96 |  |  | 0.67 | 36.64 | 269.4 | 7.22 | 0.02 | 77.64 | 67.36 | 1.15 |
| XEW-ZY-19 | 57.6 | 0.72 | -7.61 | -10.18 |  | 16.7 | 0.56 | 36.74 | 201.08 | 5.39 | 0.02 | 100.21 | 193.56 | 0.52 |
| XEW-ZY-20 | 55.4 | 0.69 | -8.15 | -8.99 | 13.84 | 18.07 | 0.32 | 37.38 | 167.04 | 4.43 | 0.01 | 56.85 | 155.24 | 0.37 |
| XEW-ZY-21 | 53.2 | 0.67 | -8.23 | -8.82 |  | 17.5 | 0.41 | 37.19 | 316 | 8.41 | 0.01 | 151.44 | 280.45 | 0.54 |
| XEW-ZY-23 | 51 | 0.64 | -8.61 | -8.85 |  | 16.76 | 0.61 | 36.35 | 177.46 | 4.80 | 0.02 | 56.73 | 193.54 | 0.29 |
| XEW-I-37 | 48.8 | 0.61 | -8.75 | -9.93 |  | 17.02 | 0.56 | 36.67 | 215.12 | 5.78 | 0.02 | 46.52 | 174.67 | 0.27 |
| XEW-I-36 | 48.4 | 0.61 | -8.73 | -11.2 |  | 17.82 | 1.43 | 33.13 | 264.58 | 7.66 | 0.04 | 77.53 | 218.65 | 0.35 |
| XEW-I-35 | 47.6 | 0.60 |  |  |  | 20.92 | 10.61 | 21.02 | 126.04 | 3.98 | 0.50 | 1197.56 | 195.00 | 6.14 |
| XEW-I-31 | 44.4 | 0.56 | -8.55 | -7.73 |  | 14.44 | 11.26 | 18.84 | 172.58 | 5.74 | 0.60 | 310.27 | 787.00 | 0.39 |
| XEW-I-30 | 43.5 | 0.54 | -8.36 | -7.59 |  | 18.49 | 10.76 | 18.70 | 261.76 | 8.89 | 0.58 | 294.37 | 421.68 | 0.7 |
| XEW-I-29 | 41.5 | 0.52 | -8.68 | -7.41 |  | 17.86 | 11.88 | 20.04 | 181.56 | 5.69 | 0.59 | 367.34 | 591.24 | 0.62 |
| XEW-I-28 | 40.6 | 0.51 | -8.31 | -7 |  | 18.79 | 11.47 | 20.01 | 173.84 | 5.52 | 0.57 | 328.52 | 624.38 | 0.53 |
| XEW-I-27 | 37.7 | 0.47 | -6.79 | -5.22 |  | 21.99 | 11.84 | 19.45 | 205.38 | 6.56 | 0.61 | 183.27 | 292.54 | 0.63 |
| XEW-I-24 | 33.6 | 0.42 | -5.41 | -5.62 |  | 23.95 | 11.13 | 18.81 | 278.12 | 9.29 | 0.59 | 254.22 | 282.10 | 0.9 |
| XEW-I-23 | 22.6 | 0.28 | 1.22 | -3.52 |  |  | 12.54 | 20.30 | 451.3 | 13.74 | 0.62 | 417.28 | 59.34 | 7.03 |
| XEW-I-22 | 19.6 | 0.25 | 1.82 | -4.38 |  | 29.05 | 12.26 | 19.95 | 305.22 | 9.48 | 0.61 | 194.51 | 42.87 | 4.54 |
| XEW-I-21 | 18.3 | 0.23 | 1.41 | -3.99 |  |  | 12.61 | 19.70 | 190.58 | 5.90 | 0.64 | 217.57 | 45.84 | 4.75 |
| XEW-I-19 | 16.1 | 0.20 | 3.15 | -4.6 |  | 25.85 | 11.64 | 18.90 | 518.6 | 16.98 | 0.62 | 201.41 | 47.83 | 4.21 |
| XEW-I-17 | 14.5 | 0.18 | 3.48 | -4.75 |  | 32.51 | 11.93 | 19.87 | 317.34 | 9.98 | 0.60 | 180.45 | 41.21 | 4.38 |
| XEW-I-16 | 13.7 | 0.17 | 4.32 | -4.72 | 22.5 | 32.49 | 10.85 | 19.56 | 111.14 | 3.66 | 0.55 | 127.80 | 28.32 | 4.51 |
| XEW-I-13 | 10.5 | 0.13 | 6.32 | -8.28 | 20.23 | 31.42 | 3.32 | 32.20 | 436.08 | 12.28 | 0.10 | 121.43 | 23.27 | 5.22 |
| XEW-I-12 | 9.5 | 0.12 | 5.07 | -8.84 | 20.97 | 31.39 | 4.35 | 32.26 | 283.4 | 7.74 | 0.13 | 185.60 | 37.46 | 4.95 |
| XEW-I-09 | 7.1 | 0.09 | 3.74 | -5.42 | 20.84 | 30.69 | 10.69 | 21.02 | 150.26 | 4.74 | 0.51 | 194.27 | 38.35 | 5.07 |
| XEW-I-08 | 6.2 | 0.08 | 3.89 | -4.41 | 22.23 | 33.65 | 10.04 | 21.62 | 269.2 | 8.50 | 0.46 | 88.53 | 19.35 | 4.58 |
| XEW-I-05 | 3.8 | 0.05 | 6.67 | -7.57 | 23.41 |  | 3.24 | 33.98 | 200.86 | 5.40 | 0.10 | 70.14 | 47.89 | 1.46 |
| XEW-I-04 | 3.2 | 0.04 | 5.55 | -7.17 | 20.82 | 30.84 | 4.91 | 30.99 | 180.78 | 5.04 | 0.16 | 59.86 | 46.84 | 1.28 |
| XEW-I-01 | 1.1 | 0.01 | 5.68 | -6.41 | 23.8 | 33.2 | 6.39 | 28.84 | 166.64 | 4.73 | 0.22 | 34.95 | 31.97 | 1.09 |
| Parachilna Gorge (South Australia) | | | | | | | | | | | | | | |
| Sample | Depth | δ13Ccarb | δ18Ocarb | δ34SCAS | δ18OCAS |  |  |  |  |  |  |  |  |  |
| (m) | (‰ VPDB) | (‰ VPDB) | (‰ VCDT) | (‰ VSMOW) |  |  |  |  |  |  |  |  |  |
| PG3-590 | 590 | -4.01 | -11.16 | 21.66 | 12.82 |  |  |  |  |  |  |  |  |  |
| PG3-540 | 540 | -5.78 | -10.51 | 24.51 |  |  |  |  |  |  |  |  |  |  |
| PG3-501 | 501 | -6.31 | -10.77 | 22.17 |  |  |  |  |  |  |  |  |  |  |
| PG3-490 | 490 | -6.37 | -11.4 | 16 | 13.25 |  |  |  |  |  |  |  |  |  |
| PG3-460 | 460 | -7.18 | -12.82 | 26.22 |  |  |  |  |  |  |  |  |  |  |
| PG3-450 | 450 | -7.32 | -13.38 | 19.68 |  |  |  |  |  |  |  |  |  |  |
| PG3-330 | 330 | -7.4 | -13.01 | 18.06 | 12.21 |  |  |  |  |  |  |  |  |  |
| PG3-312 | 312 | -7.45 | -12.79 | 18.4 |  |  |  |  |  |  |  |  |  |  |
| PG3-290 | 290 | -7.37 | -12.55 | 19.16 |  |  |  |  |  |  |  |  |  |  |
| PG3-280 | 280 | -7.58 | -12.93 | 19.38 |  |  |  |  |  |  |  |  |  |  |
| PG3-260 | 260 | -7.15 | -12.43 | 18.69 |  |  |  |  |  |  |  |  |  |  |
| PG3-240 | 240 |  |  | 18.17 | 12.38 |  |  |  |  |  |  |  |  |  |
| PG3-210 | 210 | -7.91 | -13.54 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-195 | 195 | -7.97 | -13.79 | 19.1 | 11.59 |  |  |  |  |  |  |  |  |  |
| PG3-188 | 188 | -7.7 | -13.69 | 18.75 |  |  |  |  |  |  |  |  |  |  |
| PG3-188 | 188 | -7.86 | -13.8 | 18.93 | 12.25 |  |  |  |  |  |  |  |  |  |
| PG3-188 | 188 |  |  | 19.02 |  |  |  |  |  |  |  |  |  |  |
| PG3-174 | 174 | -7.76 | -13.68 | 18.37 | 13.45 |  |  |  |  |  |  |  |  |  |
| PG3-169 | 169 | -8.12 | -14.14 | 19.34 | 12.42 |  |  |  |  |  |  |  |  |  |
| PG3-165 | 165 | -7.64 | -13.78 | 18.77 | 11.87 |  |  |  |  |  |  |  |  |  |
| PG3-165 | 165 | -7.81 | -13.92 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-150 | 150 | -7.86 | -14.36 | 18.95 | 13.59 |  |  |  |  |  |  |  |  |  |
| PG3-146 | 146 | -7.74 | -13.95 | 18.03 |  |  |  |  |  |  |  |  |  |  |
| PG3-146 | 146 | -7.76 | -14.21 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-135 | 135 |  |  | 17.79 | 13.02 |  |  |  |  |  |  |  |  |  |
| PG3-117 | 117 | -8.48 | -14.4 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-117 | 117 | -8.5 | -14.43 | 17.89 |  |  |  |  |  |  |  |  |  |  |
| PG3-109 | 109 | -8.69 | -14.49 | 18.58 |  |  |  |  |  |  |  |  |  |  |
| PG3-109 | 109 | -8.67 | -14.35 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-96 | 96 | -8.94 | -14.3 | 19.19 | 12.36 |  |  |  |  |  |  |  |  |  |
| PG3-94 | 94 | -8.65 | -14.35 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-94 | 94 | -8.97 | -14.26 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-92 | 92 | -9.37 | -14.44 | 19.34 | 13.59 |  |  |  |  |  |  |  |  |  |
| PG3-79.5 | 79.5 | -8.47 | -12.53 | 17.03 |  |  |  |  |  |  |  |  |  |  |
| PG3-79.5 | 79.5 | -8.6 | -12.88 |  | 16.54 |  |  |  |  |  |  |  |  |  |
| PG3-75 | 75 | -10.11 | -14.58 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-70 | 70 | -8.13 | -11.48 | 17.43 |  |  |  |  |  |  |  |  |  |  |
| PG3-60 | 60 | -8.49 | -8.22 | 22.16 |  |  |  |  |  |  |  |  |  |  |
| PG3-57 | 57 | -10.2 | -8.85 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-45 | 45 | -7.75 | -13.89 | 17.03 | 11.84 |  |  |  |  |  |  |  |  |  |
| PG3-45 | 45 | -7.76 | -13.49 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-41 | 41 | -8 | -9.29 |  | 14.42 |  |  |  |  |  |  |  |  |  |
| PG3-41 | 41 | -8 | -9.33 | 21.36 |  |  |  |  |  |  |  |  |  |  |
| PG3-36 | 36 | -5.39 | -11.36 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-35 | 35 | -3.43 | -8.2 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-30 | 30 | -4.78 | -8.71 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-21 | 21 | -3.41 | -9.05 |  |  |  |  |  |  |  |  |  |  |  |
| PG3-15 | 15 | -2.22 | -7.56 | 19 | 15.19 |  |  |  |  |  |  |  |  |  |
| PG3-10 | 10 | -2.67 | -8.07 | 25.29 | 16.17 |  |  |  |  |  |  |  |  |  |
| PG3-6 | 6 | -2.3 | -5.74 | 26.63 |  |  |  |  |  |  |  |  |  |  |
| PG3-0 | 0 | -3.41 | -5.94 | 30.87 | 19.84 |  |  |  |  |  |  |  |  |  |

Note: (1) \*Data source: Li et al. (2017) and Shi et al. (2018). (2) †Meters above the boundary between Doushantuo Formation and Nantuo Formation; †† Meters above the boundary between Doushantuo Member II and III.

Table S2: Burial flux of pyrite sulfur of Jiulongwan Section (Three Gorges, South China; Data source-Li et al., 2017; Shi et al., 2018) and Miqrat-1 Drillcore (Oman; Data source-Fike et al., 2006).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Jiulongwan (Three Gorges) | | | | Miqrat-1 (Oman) | | | |
| Depth | δ13Ccarb | Spy | Flux of Spy | **Depth** | δ13Ccarb | Spy | Flux of Spy |
| (m) | (‰ VPDB) | (wt. %) | (g m-2 Myr-1) | **(m)** | (‰ VPDB) | (wt. %) | (g m-2 Myr-1) |
| 154.0 | -5.3 | 2.279 | 0.365 | **3376** | -0.7 | 0.183 | 0.156 |
| 152.0 | -4.4 | 1.207 | 0.193 | **3400** | -3.5 | 0.038 | 0.032 |
| 149.0 | -6.4 | 1.145 | 0.183 | **3426** | -4.6 | 0.093 | 0.079 |
| 146.0 | -7.9 | 1.640 | 0.262 | **3450** | -3.7 | 0.212 | 0.181 |
| 144.0 | -7.8 | 1.196 | 0.191 | **3476** | -5.6 | 0.169 | 0.144 |
| 144.0 | -8.3 | 2.304 | 0.369 | **3500** | -6.1 | 0.111 | 0.094 |
| 143.0 | -7.8 | 2.512 | 0.402 | **3560** | -7.1 | 0.063 | 0.054 |
| 142.2 | -6.4 | 2.475 | 0.396 | **3600** | -8.5 | 0.029 | 0.025 |
| 142.0 | -7.8 | 0.320 | 0.051 | **3620** | -8.4 | 0.053 | 0.045 |
| 141.5 | -8.6 | 0.434 | 0.069 | **3630** | -9.5 | 0.039 | 0.033 |
| 140.9 | -8.7 | 0.353 | 0.056 | **3650** | -8.5 | 0.029 | 0.025 |
| 140.6 | -7.7 | 1.014 | 0.162 | **3680** | -8.8 | 0.043 | 0.037 |
| 140.3 | -7.5 | 0.859 | 0.137 | **3682** | -7.7 | 0.085 | 0.072 |
| 140.0 | -7.8 | 0.274 | 0.044 | **3686** | -7.6 | 0.092 | 0.079 |
| 139.0 | -8.0 | 0.403 | 0.064 | **3690** | -8.1 | 0.078 | 0.067 |
| 138.5 | -8.2 | 0.362 | 0.058 | **3692** | -8.5 | 0.067 | 0.057 |
| 137.1 | -8.4 | 0.419 | 0.067 | **3700** | -9.2 | 0.034 | 0.029 |
| 135.0 | -8.4 | 0.264 | 0.042 | **3702** | -8.9 | 0.030 | 0.026 |
| 133.6 | -8.4 | 0.307 | 0.049 | **3706** | -7.2 | 0.101 | 0.086 |
| 132.0 | -8.5 | 0.094 | 0.015 | **3712** | -7.7 | 0.071 | 0.061 |
| 130.0 | -8.6 | 0.042 | 0.007 | **3716** | -7.9 | 0.033 | 0.028 |
| 128.3 | -8.8 | 0.133 | 0.021 | **3720** | -8.5 | 0.039 | 0.033 |
| 125.2 | -8.9 | 0.180 | 0.029 | **3722** | -8.5 | 0.043 | 0.037 |
| 124.2 | -8.7 | 0.267 | 0.043 | **3726** | -8.9 | 0.035 | 0.030 |
| 121.2 | -9.0 | 0.253 | 0.040 | **3730** | -10.7 | 0.037 | 0.032 |
| 120.0 | -9.1 | 0.359 | 0.057 | **3732** | -10.8 | 0.016 | 0.014 |
| 118.0 | -9.0 | 0.322 | 0.051 | **3736** | -11.0 | 0.014 | 0.012 |
| 116.0 | -9.1 | 0.008 | 0.001 | **3740** | -11.7 | 0.037 | 0.032 |
| 114.0 | -7.8 | 0.338 | 0.054 | **3742** | -11.9 | 0.037 | 0.031 |
| 113.3 | -9.1 | 0.016 | 0.003 | **3746** | -11.8 | 0.011 | 0.010 |
| 112.0 | -5.4 | 0.007 | 0.001 | **3750** | -12.0 | 0.031 | 0.026 |
| 109.6 | -5.1 | 0.015 | 0.002 | **3752** | -10.7 | 0.010 | 0.009 |
| 107.7 | -2.7 | 0.012 | 0.002 | **3756** | -10.5 | 0.005 | 0.004 |
| 105.0 | -8.1 | 0.632 | 0.101 | **3760** | -10.5 | 0.035 | 0.030 |
| 103.7 | -0.2 | 0.013 | 0.002 | **3762** | -9.1 | 0.008 | 0.007 |
| 99.8 | 2.9 | 0.010 | 0.002 | **3770** | -9.8 | 0.035 | 0.030 |
| 98.0 | -2.7 | 0.022 | 0.003 | **3780** | -7.8 | 0.042 | 0.036 |
| 97.8 | 2.6 | 0.016 | 0.003 | **3790** | -8.9 | 0.029 | 0.025 |
| 93.8 | 4.5 | 0.010 | 0.002 | **3796** | -8.0 | 0.039 | 0.034 |
| 92.8 | 4.8 | 0.012 | 0.002 | **3800** | -8.1 | 0.034 | 0.029 |
|  |  |  |  | **3806** | -5.4 | 0.036 | 0.030 |
|  |  |  |  | **3810** | -3.5 | 0.046 | 0.039 |
|  |  |  |  | **3830** | 0.0 | 0.115 | 0.098 |
|  |  |  |  | **3840** | 2.6 | 0.118 | 0.100 |

Table S3: Equations for core reservoirs of COPSE model (Lenton et al., 2018; Tostevin and Mills, 2020).

|  |  |  |
| --- | --- | --- |
| \*Reservoir | Label | Equation |
| Atmosphere-ocean CO2 | *A* |  |
| Ocean (sulfate) sulfur | *S* |  |
| Atmosphere-ocean O2 | *O* |  |
| Ocean reactive phosphorus | *P* |  |
| Rock organic carbon | *G* |  |
| Rock carbonate carbon | *C* |  |
| Rock pyrite sulfur | *PYR* |  |
| Rock gypsum sulfur | *GYP* |  |
| Ocean reactive nitrogen | *N* |  |
| Deep ocean DOC/ DOM | *DOC* |  |
| Ocean uranium | *U* |  |

Note: \*Units of reservoirs are ×1018 mol while units of fluxes are ×1012 mol yr–1.

Table S4: Equations for isotope calculations of COPSE model (Lenton et al., 2018; Tostevin and Mills, 2020).

|  |  |  |
| --- | --- | --- |
| \*Isotope composition | Label | Equation |
| Atmosphere-ocean carbon (δ13Ccarb) | *δA* |  |
| Ocean sulfate sulfur (δ34Ssulfate) | *δS* |  |
| Ocean uranium (δ238Ucarb) | *δU* |  |
| Ocean sulfate oxygen (δ18Osulfate) | *δO* |  |

Note: \*Units of isotopic reservoirs are ‰ while units of fluxes are ×1012 mol yr–1.

Table S5: Equations for flux calculations of COPSE model (Lenton et al., 2018; Tostevin and Mills, 2020).

|  |  |  |
| --- | --- | --- |
| Process | Label | Equation |
| Marine organic C burial | *mocb* |  |
| Marine pyrite S burial | *mpsb* |  |
| Oxidative weathering | *oxidw* |  |
| Carbonate weathering | *carbw* |  |
| Pyrite weathering | *pyrw* |  |
| Gypsum weathering | *gypw* |  |
| Marine carbonate C burial | *mccb* |  |
| Marine gypsum S burial | *mgsb* |  |
| Organic C degassing | *ocdeg* |  |
| Carbonate C degassing | *ccdeg* |  |
| Pyrite degassing | *pyrdeg* |  |
| Gypsum degassing | *gypdeg* |  |
| Reactive P weathering | *phosw* |  |
| Terrestrial organic P burial | *pland* |  |
| Terrestrial organic C burial | *locb* |  |
| Reactive P to ocean | *psea* |  |
| Marine organic P burial | *mopb* |  |
| Ca-bound burial | *capb* |  |
| Fraction of anoxia | *f*(anox) |  |
| New primary productivity | *newp* |  |
| Degree of anoxia | *ANOX* |  |
| Denitrification | *denit* |  |
| Nitrogen fixation | *nfix* | for , else 0 |
| Marine organic N burial | *monb* |  |
| Oxidation of DOC | *DOC\_ox* |  |
| MSR-derived H2S | *H2SMSR* |  |
| Reoxidation of H2S | *reox* |  |
| Seafloor weathering | *sfw* |  |
| Temperature dependence of basalt weathering | *ƒTbas* |  |
| Temperature dependence of granite weathering | *ƒTgran* |  |
| Temperature dependence of carbonate weathering | *gT* |  |
| Pre-plant silicate weathering | *ƒpreplant* |  |
| Pre-plant carbonate weathering | *gpreplant* |  |
| Vegetation feedback | *VEG* |  |
| Climate forcing for silicates | *ƒCO2* |  |
| Climate forcing for carbonates | *gCO2* |  |
| CO2 dependence of basalt weathering | *ƒCO2bas* |  |
| CO2 dependence of granite weathering | *ƒCO2gran* |  |
| CO2 dependence of carbonate weathering | *gCO2* |  |
| Basalt weathering | *basw* |  |
| Granite weathering | *granw* |  |
| Silicate weathering | *silw* |  |
| Relative atmospheric O2 | *RO2* |  |
| Solar forcing | *SOL* |  |
| Albedo | *ALB* |  |
| Temperature | *TEMP* |  |
| Carbon isotope fractionation | *ΔC* |  |
| Uranium river input | *uriv* |  |
| Uranium hydrothermal sink | *uhyd* |  |
| Uranium anoxic sink | *uanox* |  |
| Uranium other sink (carbonate, suboxic, and oxic metals) | *uother* |  |

Table S6: Parameters of COPSE model (Lenton et al., 2018; Tostevin and Mills, 2020).

|  |  |  |
| --- | --- | --- |
| Reservoirs | Label | Value |
| Atmosphere-ocean CO2 | *A0* |  |
| Ocean (sulfate) sulfur | *S0* |  |
| Atmosphere-ocean O2 | *O0* |  |
| Rock organic carbon | *G0* |  |
| Rock carbonate carbon | *C0* |  |
| Ocean phosphorus | *P0* |  |
| Ocean nitrogen | *N0* |  |
| Rock pyrite sulfur | *PYR0* |  |
| Rock gypsum sulfur | *GYP0* |  |
| Dissolved organic carbon | *DOC0* |  |
| Ocean uranium | *U0* |  |
| Isotopic composition of rock organic carbon | *δG0* |  |
| Isotopic composition of rock carbonate carbon | *δC0* |  |
| Isotopic composition of rock pyrite sulfur | *δPYR0* |  |
| Isotopic composition of rock gypsum sulfur | *δGYP0* |  |
| Isotopic composition of rock gypsum oxygen | *δGYPO* | *δGYPO = 20 ‰* |
| Isotopic composition of water oxygen | *δOH2O* | *δOH2O = 0 ‰* |
| Isotopic composition of additional pyrite sulfur | *δPYRaddi* |  |
| Isotopic composition of additional gypsum sulfur | *δGYPaddi* |  |
| Isotopic composition of additional gypsum oxygen | *δGYPO\_addi* | *δGYPO\_addi = 20 ‰* |
| Isotopic composition of dissolved organic carbon | *δDOC* | *δDOC = 30 ‰* |
| Oxidative C weathering | *koxidw* |  |
| Carbonate C weathering | *kcarbw* |  |
| Seafloor C weathering | *ksfw* |  |
| Carbonate C degassing | *kccdeg* |  |
| Organic C degassing | *kocdeg* |  |
| Organic C burial | *kmocb* |  |
| Carbonate C burial | *kmccb* |  |
| Sulfur isotope fractionation during MSR | *ΔS* | *35 ‰* |
| Oxygen isotope fractionation during MSR | *ΔOMSR* | *12 ‰* |
| Oxygen isotope fractionation during H2S reoxidation | *ΔOreox* | *5 ‰* |
| Pyrite S weathering | *kpyrw* |  |
| Gypsum S weathering | *kgypw* |  |
| Gypsum S degassing | *kgypdeg* |  |
| Pyrite S degassing | *kpyrdeg* |  |
| Pyrite S burial | *kmpsb* |  |
| Gypsum S burial | *kmgsb* |  |
| Silicate weathering |  |  |
| Present oceanic oxic fraction |  | 0.997527 |
| Pre-plant weathering |  | 0.15 |
| Climate sensitivity control |  | 4.328 ℃ |
| Luminosity sensitivity control |  | 7.4 ℃ |
| Temperature sensitivity of seafloor weathering |  | 0.0608 |
| Temperature sensitivity of granite weathering |  | 0.0724 |
| Temperature sensitivity of basalt weathering |  | 0.0608 |
| Silicate fraction of P weathering |  | 0.80 |
| Carbonate fraction of P weathering |  | 0.14 |
| Oxidation fraction of P weathering |  | 0.06 |
| Terrestrial organic matter burial fraction in aquatic setting |  | 0.80 |
| Nutrient utilization efficiency |  | 0.4 |
| Sharpness of oxic-anoxic transition |  | 10 |
| Reactive P weathering | *k10* |  |
| Terrestrial organic | *k10k11* |  |
| Reactive P to ocean | (1 - *k11*) *k10* |  |
| Marine organic P burial | *k2/CPsea* |  |
| Iron-sorbed burial | *k6* |  |
| Ca-bound burial | *k7* |  |
| Nitrogen fixation | *k3* |  |
| Denitrification | *2\*k4* |  |
| Marine organic N burial | *k2/CNsea* |  |
| Uranium river input | *kuriv* |  |
| Uranium hydrothermal sink | *kuhyd* |  |
| Uranium anoxic sink | *kuanox* |  |
| Uranium other sink (carbonate, suboxic, and oxic metals) | *kuother* |  |
| Fractionation of uranium hydrothermal sink |  | 0.2 ‰ |
| Fractionation of uranium anoxic sink |  | 0.6 ‰ |
| Fractionation of uranium other sink |  | 0.0156 ‰ |
| Isotopic composition of riverine uranium |  | –0.29 ‰ |

Table S7: Present-day values of background forcings of COPSE model (Lenton et al., 2018; Tostevin and Mills, 2020).

|  |  |  |
| --- | --- | --- |
| Forcing | Label | Present day |
| Relative global CO2 degassing | *D* | 1 |
| Relative uplift rate | *U* | 1 |
| Paleogeographic river runoff effect | *PG* | 1 |
| Weathering effect of plant evolution | *W* | 1 |
| Carbonate burial depth | *B* | 1 |
| Relative basalt area | *BA* | 1 |
| Relative granite area | *GA* |  |
| Relative carbonate area | *CA* | 1 |
| Relative organic area | *OA* | 1 |
| Relative total area | *TA* | 1 |

Table S8: XRD analysis results of 6 samples from Jiulongwan and Xiang’erwan sections.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| JLW-18 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 10.617 | 8.3254 | 51 | 30 | 1.2 | 288 | 0.9 | 0.163 | calcite |
| 20.92 | 4.2429 | 52 | 43 | 1.8 | 965 | 2.9 | 0.382 | quartz |
| 23.1 | 3.8472 | 55 | 187 | 7.7 | 2919 | 8.9 | 0.265 | calcite |
| 25.759 | 3.4558 | 38 | 30 | 1.2 | 1026 | 3.1 | 0.581 | calcite |
| 26.66 | 3.3409 | 33 | 233 | 9.6 | 3159 | 9.6 | 0.23 | quartz |
| 27.52 | 3.2384 | 39 | 34 | 1.4 | 507 | 1.5 | 0.254 | calcite |
| 29.46 | 3.0294 | 51 | 2428 | 100 | 32787 | 100 | 0.23 | calcite |
| 31.521 | 2.8359 | 33 | 54 | 2.2 | 544 | 1.7 | 0.171 | calcite |
| 36.04 | 2.49 | 26 | 368 | 15.2 | 5328 | 16.3 | 0.246 | calcite |
| 39.48 | 2.2806 | 19 | 515 | 21.2 | 7757 | 23.7 | 0.256 | calcite |
| 43.24 | 2.0906 | 19 | 451 | 18.6 | 7324 | 22.3 | 0.276 | calcite |
| 47.18 | 1.9248 | 21 | 184 | 7.6 | 4643 | 14.2 | 0.429 | calcite |
| 47.6 | 1.9088 | 29 | 509 | 21 | 11628 | 35.5 | 0.388 | calcite |
| 48.6 | 1.8718 | 16 | 505 | 20.8 | 8646 | 26.4 | 0.291 | calcite |
| 50.239 | 1.8145 | 16 | 24 | 1 | 678 | 2.1 | 0.48 | quartz |
| 56.64 | 1.6237 | 17 | 80 | 3.3 | 1632 | 5 | 0.347 | calcite |
| 57.5 | 1.6015 | 33 | 214 | 8.8 | 3984 | 12.2 | 0.316 | calcite |
| 59.919 | 1.5424 | 17 | 31 | 1.3 | 362 | 1.1 | 0.199 | dolomite |
| 60.76 | 1.5231 | 14 | 164 | 6.8 | 5382 | 16.4 | 0.558 | calcite |
| 61.48 | 1.507 | 14 | 66 | 2.7 | 2856 | 8.7 | 0.736 | calcite |
| 63.261 | 1.4688 | 13 | 36 | 1.5 | 1024 | 3.1 | 0.484 | dolomite |
| JLW-35 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 5.001 | 17.6565 | 115 | 39 | 0.9 | 810 | 1.6 | 0.353 | quartz |
| 15.819 | 5.5977 | 48 | 32 | 0.8 | 684 | 1.3 | 0.363 | dolomite |
| 17.301 | 5.1213 | 50 | 28 | 0.7 | 602 | 1.2 | 0.366 | dolomite |
| 20.9 | 4.2468 | 77 | 51 | 1.2 | 687 | 1.3 | 0.229 | quartz |
| 21.98 | 4.0406 | 68 | 52 | 1.2 | 1149 | 2.2 | 0.376 | dolomite |
| 23.639 | 3.7605 | 57 | 37 | 0.9 | 1278 | 2.5 | 0.587 | dolomite |
| 24.06 | 3.6957 | 58 | 101 | 2.4 | 1974 | 3.8 | 0.332 | dolomite |
| 26.62 | 3.3458 | 47 | 209 | 4.9 | 2720 | 5.2 | 0.221 | quartz |
| 27.52 | 3.2384 | 45 | 45 | 1.1 | 783 | 1.5 | 0.296 | calcite |
| 30.959 | 2.8861 | 54 | 4226 | 100 | 52043 | 100 | 0.209 | dolomite |
| 33.06 | 2.7073 | 25 | 29 | 0.7 | 689 | 1.3 | 0.404 | calcite |
| 33.559 | 2.6682 | 27 | 234 | 5.5 | 3325 | 6.4 | 0.242 | dolomite |
| 35.32 | 2.5391 | 30 | 211 | 5 | 3023 | 5.8 | 0.244 | dolomite |
| 37.36 | 2.405 | 13 | 275 | 6.5 | 4493 | 8.6 | 0.278 | dolomite |
| 41.14 | 2.1923 | 26 | 788 | 18.6 | 12038 | 23.1 | 0.26 | dolomite |
| 43.8 | 2.0652 | 21 | 120 | 2.8 | 1758 | 3.4 | 0.249 | dolomite |
| 44.94 | 2.0154 | 27 | 390 | 9.2 | 5643 | 10.8 | 0.246 | dolomite |
| 49.28 | 1.8476 | 35 | 100 | 2.4 | 1411 | 2.7 | 0.24 | dolomite |
| 50.56 | 1.8038 | 42 | 726 | 17.2 | 13910 | 26.7 | 0.326 | dolomite |
| 51.08 | 1.7866 | 28 | 658 | 15.6 | 12928 | 24.8 | 0.334 | dolomite |
| 58.88 | 1.5672 | 25 | 80 | 1.9 | 1226 | 2.4 | 0.261 | dolomite |
| 59.84 | 1.5443 | 16 | 172 | 4.1 | 3569 | 6.9 | 0.353 | dolomite |
| 61.979 | 1.496 | 17 | 31 | 0.7 | 706 | 1.4 | 0.387 | calcite |
| 63.459 | 1.4647 | 24 | 143 | 3.4 | 2788 | 5.4 | 0.331 | quartz |
| 64.52 | 1.4431 | 34 | 64 | 1.5 | 920 | 1.8 | 0.244 | dolomite |
| JLW-50 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 9.301 | 9.5005 | 61 | 32 | 2.4 | 278 | 1.3 | 0.148 | illite |
| 12.241 | 7.2246 | 61 | 38 | 2.9 | 1694 | 7.8 | 0.758 | smectite |
| 12.72 | 6.9537 | 65 | 37 | 2.8 | 1025 | 4.7 | 0.471 | smectite |
| 23.101 | 3.847 | 62 | 109 | 8.3 | 1929 | 8.8 | 0.301 | calcite |
| 23.981 | 3.7078 | 62 | 78 | 6 | 1519 | 7 | 0.331 | dolomite |
| 24.541 | 3.6244 | 55 | 39 | 3 | 1227 | 5.6 | 0.535 | dolomite |
| 26.699 | 3.3361 | 49 | 91 | 6.9 | 1693 | 7.8 | 0.316 | quartz |
| 29.46 | 3.0294 | 77 | 1310 | 100 | 17776 | 81.4 | 0.231 | calcite |
| 30.88 | 2.8933 | 72 | 1206 | 92.1 | 21835 | 100 | 0.308 | dolomite |
| 33.419 | 2.679 | 24 | 59 | 4.5 | 1629 | 7.5 | 0.469 | dolomite |
| 35.16 | 2.5503 | 35 | 42 | 3.2 | 911 | 4.2 | 0.369 | dolomite |
| 36.04 | 2.49 | 40 | 143 | 10.9 | 1842 | 8.4 | 0.219 | calcite |
| 37.32 | 2.4075 | 29 | 107 | 8.2 | 1723 | 7.9 | 0.274 | dolomite |
| 39.5 | 2.2795 | 23 | 248 | 18.9 | 4196 | 19.2 | 0.288 | calcite |
| 41.06 | 2.1964 | 25 | 247 | 18.9 | 5463 | 25 | 0.376 | dolomite |
| 43.24 | 2.0906 | 23 | 217 | 16.6 | 4426 | 20.3 | 0.347 | calcite |
| 43.799 | 2.0652 | 26 | 34 | 2.6 | 1475 | 6.8 | 0.738 | dolomite |
| 44.86 | 2.0188 | 22 | 157 | 12 | 3040 | 13.9 | 0.329 | dolomite |
| 47.6 | 1.9088 | 18 | 242 | 18.5 | 6824 | 31.3 | 0.479 | calcite |
| 48.6 | 1.8718 | 48 | 203 | 15.5 | 4168 | 19.1 | 0.349 | calcite |
| 49.221 | 1.8496 | 43 | 39 | 3 | 1132 | 5.2 | 0.493 | dolomite |
| 50.32 | 1.8118 | 39 | 147 | 11.2 | 8430 | 38.6 | 0.975 | dolomite |
| 50.86 | 1.7938 | 37 | 175 | 13.4 | 8631 | 39.5 | 0.838 | dolomite |
| 56.661 | 1.6232 | 20 | 38 | 2.9 | 577 | 2.6 | 0.258 | calcite |
| 57.46 | 1.6025 | 21 | 77 | 5.9 | 1744 | 8 | 0.385 | calcite |
| 58.801 | 1.5691 | 20 | 33 | 2.5 | 608 | 2.8 | 0.313 | dolomite |
| 59.84 | 1.5443 | 27 | 57 | 4.4 | 1352 | 6.2 | 0.403 | quartz |
| 60.779 | 1.5227 | 31 | 52 | 4 | 1773 | 8.1 | 0.58 | dolomite |
| 63.399 | 1.4659 | 23 | 51 | 3.9 | 1429 | 6.5 | 0.476 | dolomite |
| XEW-ZY-15 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 23.126 | 3.8428 | 16 | 184 | 9.2 | 1090 | 4.9 | 0.101 | calcite |
| 29.462 | 3.0292 | 10 | 2001 | 100 | 22252 | 100 | 0.189 | calcite |
| 31.512 | 2.8367 | 14 | 58 | 2.9 | 233 | 1 | 0.068 | calcite |
| 35.722 | 2.5114 | 6 | 50 | 2.5 | 176 | 0.8 | 0.06 | dolomite |
| 36.057 | 2.4889 | 12 | 289 | 14.4 | 2417 | 10.9 | 0.142 | calcite |
| 39.461 | 2.2816 | 9 | 325 | 16.2 | 3522 | 15.8 | 0.184 | calcite |
| 43.223 | 2.0914 | 8 | 342 | 17.1 | 3875 | 17.4 | 0.193 | calcite |
| 47.232 | 1.9228 | 11 | 169 | 8.4 | 891 | 4 | 0.09 | calcite |
| 47.567 | 1.91 | 19 | 375 | 18.7 | 4556 | 20.5 | 0.207 | calcite |
| 48.086 | 1.8906 | 20 | 72 | 3.6 | 288 | 1.3 | 0.068 | calcite |
| 48.633 | 1.8706 | 14 | 372 | 18.6 | 4526 | 20.3 | 0.207 | calcite |
| 56.681 | 1.6226 | 18 | 63 | 3.1 | 521 | 2.3 | 0.141 | calcite |
| 57.54 | 1.6004 | 24 | 129 | 6.4 | 2049 | 9.2 | 0.27 | calcite |
| 60.841 | 1.5213 | 16 | 99 | 4.9 | 566 | 2.5 | 0.097 | quartz |
| 61.08 | 1.5159 | 12 | 127 | 6.3 | 488 | 2.2 | 0.065 | calcite |
| 61.464 | 1.5073 | 16 | 65 | 3.2 | 227 | 1 | 0.059 | calcite |
| XEW-I-28 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 8.56 | 10.3208 | 63 | 32 | 1.2 | 998 | 2.3 | 0.53 | illite |
| 15.58 | 5.6829 | 53 | 33 | 1.2 | 693 | 1.6 | 0.357 | dolomite |
| 21.961 | 4.044 | 77 | 43 | 1.6 | 624 | 1.4 | 0.247 | dolomite |
| 23.98 | 3.7079 | 65 | 109 | 4.1 | 2570 | 6 | 0.401 | dolomite |
| 25.54 | 3.4848 | 60 | 30 | 1.1 | 945 | 2.2 | 0.535 | calcite |
| 26.6 | 3.3483 | 60 | 152 | 5.7 | 2715 | 6.3 | 0.304 | quartz |
| 29.38 | 3.0375 | 69 | 67 | 2.5 | 995 | 2.3 | 0.252 | calcite |
| 30.88 | 2.8933 | 66 | 2679 | 100 | 43044 | 100 | 0.273 | dolomite |
| 33.46 | 2.6758 | 33 | 191 | 7.1 | 3156 | 7.3 | 0.281 | dolomite |
| 35.261 | 2.5432 | 32 | 133 | 5 | 2851 | 6.6 | 0.364 | dolomite |
| 37.32 | 2.4075 | 22 | 232 | 8.7 | 4201 | 9.8 | 0.308 | dolomite |
| 39.421 | 2.2839 | 27 | 25 | 0.9 | 312 | 0.7 | 0.212 | calcite |
| 41.08 | 2.1954 | 30 | 650 | 24.3 | 11795 | 27.4 | 0.308 | dolomite |
| 42.401 | 2.13 | 24 | 24 | 0.9 | 289 | 0.7 | 0.205 | quartz |
| 43.78 | 2.0661 | 26 | 96 | 3.6 | 1688 | 3.9 | 0.299 | dolomite |
| 44.88 | 2.0179 | 23 | 338 | 12.6 | 6218 | 14.4 | 0.313 | dolomite |
| 47.54 | 1.9111 | 23 | 28 | 1 | 315 | 0.7 | 0.191 | calcite |
| 49.2 | 1.8504 | 36 | 79 | 2.9 | 1384 | 3.2 | 0.298 | dolomite |
| 50.5 | 1.8058 | 47 | 349 | 13 | 11084 | 25.8 | 0.54 | dolomite |
| 51 | 1.7892 | 23 | 502 | 18.7 | 14545 | 33.8 | 0.493 | dolomite |
| 58.801 | 1.5691 | 28 | 48 | 1.8 | 1049 | 2.4 | 0.372 | dolomite |
| 59.8 | 1.5452 | 31 | 129 | 4.8 | 2578 | 6 | 0.34 | dolomite |
| 63.4 | 1.4659 | 30 | 96 | 3.6 | 2382 | 5.5 | 0.422 | dolomite |
| 64.5 | 1.4435 | 38 | 43 | 1.6 | 836 | 1.9 | 0.331 | dolomite |
| XEW-I-04 | | | | | | | | |
| 2-Theta | **d(A)** | **BG** | **Height** | **I%** | **Area** | **I%** | **FWHM** | **Mineral** |
| 21.881 | 4.0587 | 70 | 46 | 2.5 | 544 | 2.2 | 0.201 | dolomite |
| 23.039 | 3.8571 | 76 | 121 | 6.6 | 1916 | 7.9 | 0.269 | calcite |
| 25.781 | 3.4529 | 53 | 32 | 1.7 | 549 | 2.3 | 0.292 | calcite |
| 26.6 | 3.3484 | 56 | 92 | 5 | 1248 | 5.2 | 0.231 | quartz |
| 29.4 | 3.0355 | 71 | 1834 | 100 | 24219 | 100 | 0.224 | dolomite |
| 30.72 | 2.908 | 59 | 575 | 31.4 | 12061 | 49.8 | 0.357 | dolomite |
| 31.44 | 2.8431 | 34 | 83 | 4.5 | 1550 | 6.4 | 0.317 | calcite |
| 34.138 | 2.6243 | 26 | 25 | 1.4 | 443 | 1.8 | 0.301 | dolomite |
| 35.96 | 2.4954 | 32 | 236 | 12.9 | 3706 | 15.3 | 0.267 | calcite |
| 37.221 | 2.4137 | 24 | 62 | 3.4 | 1245 | 5.1 | 0.341 | dolomite |
| 39.4 | 2.285 | 27 | 385 | 21 | 5703 | 23.5 | 0.252 | calcite |
| 40.88 | 2.2057 | 27 | 129 | 7 | 2853 | 11.8 | 0.376 | dolomite |
| 43.16 | 2.0943 | 23 | 299 | 16.3 | 5066 | 20.9 | 0.288 | calcite |
| 44.8 | 2.0214 | 21 | 90 | 4.9 | 2021 | 8.3 | 0.382 | dolomite |
| 47.121 | 1.9271 | 14 | 145 | 7.9 | 3341 | 13.8 | 0.392 | calcite |
| 47.5 | 1.9126 | 23 | 355 | 19.4 | 8153 | 33.7 | 0.39 | calcite |
| 48.5 | 1.8755 | 46 | 350 | 19.1 | 5860 | 24.2 | 0.285 | calcite |
| 50.039 | 1.8213 | 62 | 47 | 2.6 | 261 | 1.1 | 0.094 | quartz |
| 50.72 | 1.7984 | 34 | 92 | 5 | 3810 | 15.7 | 0.704 | dolomite |
| 56.6 | 1.6248 | 14 | 60 | 3.3 | 1669 | 6.9 | 0.473 | calcite |
| 57.38 | 1.6045 | 28 | 109 | 5.9 | 2296 | 9.5 | 0.358 | calcite |
| 60.66 | 1.5254 | 32 | 96 | 5.2 | 2784 | 11.5 | 0.493 | quartz |
| 63.14 | 1.4713 | 21 | 45 | 2.5 | 1180 | 4.9 | 0.446 | dolomite |