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Supplemental Material

Figure S1. Time series analysis of the Moscovian interval. 3pi multiple tapers power spectrum (a), harmonic amplitude (b), and F-test significance of the SMF record (c). Spatial frequencies with F-test significance exceeding 90% are labeled with vertical dotted lines. ASM (d) and null hypothesis testing indicate an optimum sedimentation rate of 4.817 cm/kyr indicated by the vertical dashed red line (e) and frequency alignment with six astronomical frequencies (f & g). The SMF significant spatial frequencies converted to temporal frequencies (dotted vertical lines) aligned with the astronomical target frequencies (red vertical lines) are depicted in Panel g.

Figure S2. Time series analysis of the Asselian interval. 3pi multiple tapers power spectrum (a), harmonic amplitude (b), and F-test of the SMF record (c). Spatial frequencies with F-test significance exceeding 90% are labeled with vertical dotted lines. ASM (d) and null hypothesis testing indicate an optimum sedimentation rate of 6.337 cm/kyr indicated by the vertical dashed red line (e) and frequency alignment with six astronomical frequencies (f & g). The dust significant spatial frequencies converted to temporal frequencies (dotted vertical lines) aligned with the astronomical target frequencies (red vertical lines) are depicted in Panel g.

Figure S3. The relationship between weight percent of silicate mineral fractions (SMF) and facies are illustrated. Facies code follows as 1: Fenestrate bryozoan – Tubiphytes boundstone, 2: Phylloid algal packstone, 3: Small foraminiferal packstone-grainstone, 4: calcareous siltstone, 5: Brachiopod – bryozoan packstone, 6: Bioclastic packstone – grainstone, 7: Oolitic grainstone – packstone, 8: Oncolitic packstone, 9: Calcareous mudstone – wackestone, 10: Sandstone – siltstone. As illustrated, there is no significance relationship between the %SMF content in carbonate facies (1,2,3,5,6,7,8), except those facies are associated either with cycle boundaries or enriched in siliciclastic material as to constitute clastic (siltstone or fine-grained sandstone) facies.

Figure S4. Principal component analysis (PCA) of potential sources for dust particles in the studied sections.

Figure S5. Principal component analysis (PCA) of potential sources for dust particles in the studied sections.

Figure S6. The relationship between $^{87}\text{Sr}/^{86}\text{Sr}$ values, grain size and dust flux values.

Figure S7. $^{87}\text{Sr}/^{86}\text{Sr}$ decreases with increasing dust flux. Negative binomial trend
Residual standard error: 0.002343 on 5 degrees of freedom
Multiple R-squared: 0.7631, Adjusted R-squared: 0.6683
F-statistic: 8.053 on 2 and 5 DF, p-value: 0.02731

Figure S8. Annual and zonal mean of the zonal wind on the 850 hPa pressure level (~500 m above the surface) over land and ocean grid points for the reference interglacial simulation.

Figure S9. Annual and zonal mean of the zonal wind on the 850 hPa pressure level (~500 m above the surface) over land and ocean grid points for the reference glacial simulation.
SP9-10 suggest that zonal winds in the baseline climate simulations are twice as strong at 45 S in our glacial case than our interglacial case. The subtropics are transitional between easterlies and westerlies, where change is minimal. However, dust emission is strongly biased to the tail of the wind distribution, which the average may not capture.

Figure S10. Differences in the seasonal mean wind magnitude (i.e., the average windspeed whatever the direction) ~ 500 m above the surface between our “glacial” and “interglacial” case. This figure shows that winds are usually similar or slightly weaker over the putative source region in the reference glacial simulation than in the reference interglacial simulation.

Table S1. Loadings for the first 2 principal components of the set of 16 measurements for the 10 elements listed at the left.

Table S2. ANOVA table for RDA of elemental composition. F distributions are based on 999 permutations.

Marshall et al. (2016) used two simulations (referred to as interglacial and glacial) with the Community Climate System Model version 3 (CCSM3) of dust emission, transport, and sedimentation with radiatively inactive dust and tuned them to one observation: a reconstructed dust deposition rate of $32 \text{ g/m}^2/\text{yr}^-$ ($3.2 \text{ g/cm}^2/\text{kyr}$) in Middle Permian western Brazil. Each simulation used by Marshall et al. (2016) was initialized from a modified version of a baseline simulation of late Paleozoic climate described in Heavens et al. (2015).

Western Brazil was both a strong source of dust and site of high dust deposition in both the interglacial and glacial simulations. Thus, tuning to the same deposition rate for both simulations enabled better identification of sources that differed between the simulations. (In addition, it was necessary, because Marshall et al. (2016) did not attempt to attribute dust deposition in coals to glacial or interglacial intervals.) For better comparison with the paleogeography in which the reconstructions of dust deposition took place, the simulations were shifted 30° in longitude to the east. Yet while Marshall et al. (2016) considered the entirety of Permian time, the paleogeography used in the simulations was Asselian-Sakmarian (Early Permian) (Heavens et al., 2015) and so is appropriate for this study.

The interglacial and glacial baseline climate simulations contrasted in two major ways. First, the interglacial simulation had an atmospheric CO_2 level of 2500 ppmv, as opposed to 250 ppmv in the glacial simulation. Second, in the glacial simulation, a large ice sheet was imposed over the high latitudes of Gondwana and a small one was imposed over Angara. These ice sheets are absent from the interglacial simulation. These simulations differ as well in vegetation distribution and sea level, consistent with their contrasts in greenhouse gas levels and extent of glaciation. Note that the contrasting forcings of these simulations likely exceeds the contrast in equivalent forcings between glacial and interglacial intervals in the late Cenozoic, because the baseline simulations were designed to capture the variability in greenhouse gas levels reported for the Asselian and Sakmarian stages by Montañez et al. (2007).

The CCSM3 dust emission parameterization reduces emission over vegetated areas, so the vegetation input to the dust emission parameterization used in the simulations of dust emission, transport, and sedimentation was based on the output of an equilibrium vegetation model forced by the baseline climate simulations, though the vegetation that forced the climate aspects of the simulation (such as surface albedo) was left unmodified (See Soreghan et al. (2015) for further details.). Because averaged output from all of these simulations is publicly archived, Table 2 provides the names of these simulations in published papers and archives.

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Figure S2: Time series analysis of the Asselian interval. 3pi multiple tapers power spectrum (a), harmonic amplitude (b), and F-test of the SMF record (c). Spatial frequencies with F-test significance exceeding 90% are labeled with vertical dotted lines. ASM (d) and null hypothesis testing indicate an optimum sedimentation rate of 6.337 cm/kyr indicated by the vertical dashed red line (e) and frequency alignment with six astronomical frequencies (f and g). The dust significant spatial frequencies converted to temporal frequencies (dotted vertical lines) aligned with the astronomical target frequencies (red vertical lines) are depicted in Panel g.

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Table S1: Loadings for the first 2 principal components of the set of 16 measurements for the 10 elements listed at the left.

	PC1	PC2
Al	0.916	0.181
As	0.371	0.062
Ca	-0.927	0.244
Co	0.817	-0.156
Cr	0.852	-0.219
Fe	0.68	-0.217
K	0.776	0.266
Mg	0.069	-0.883
Mn	0.423	0.11
Na	0.847	-0.3
Nb	0.685	0.174
Ni	0.382	-0.292
Pb	0.554	0.061
Rb	0.642	0.278
S	0.609	0.021
Sb	-0.372	0.481
Si	0.918	0.128
SMF	0.879	0.114
Sn	-0.389	0.489
Sr	-0.36	0.552
Th	0.768	0.293
Ti	0.709	0.239
U	-0.182	0.146
V	-0.19	-0.759
Y	0.628	0.071
Zn	-0.057	0.763
Zr	0.801	0.242
RB.10.	-0.387	0.074

Table S2: ANOVA table for RDA of elemental composition. F distributions are based on 999 permutations.

Driver variable	Df	Variance	F	P
Interval	1	0.83	13	<0.001
Cycle boundary	1	4.38	68.5	<0.001
% Dust	1	2.25	35.2	<0.001
Dust volume % >20µm	1	0.25	3.9	0.006
Residual	208	13.3		

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