GSA Data Repository 2015101

"Mid-latitude terrestrial climate of East Asia linked to global climate in the Late Cretaceous" (Gao et al.)

Cyclostratigraphy and Age Model of the Examined Section in SK-1

Age determination for each sample in the examined section is based on cyclostratigraphy combined with magnetostratigraphy (Gradstein et al., 2012; Deng et al., 2013; Wu et al., 2014). Thorium (Th) logging data was used as paleoenvironmental and paleoclimatic proxy to conduct cyclostratigraphy research on the Sifangtai and Mingshui formations of the SK-1 core. Power spectra, evolutionary fast Fourier transform and wavelet analysis results revealed significant meter- to decameter-scale sedimentary cycles. The ratios of the cycle periods in these stratigraphic units are ~20:5:2:1, which were interpreted as Milankovitch cycles of 405 kyr and 100 kyr eccentricity, 38.4 kyr obliquity and 20 kyr precession cycles, respectively (Wu et al., 2014). An astronomical time scale (ATS) is established by tuning the extracted 405 kyr eccentricity cycles to the target curve of the astronomical solution La2010d based on the magnetostratigraphic time framework of the SK-1 core (Laskar et al., 2011; Deng et al., 2013). This new ATS provides precise numerical ages for stratigraphic boundaries, biozones, geological and geophysical events, and can serve as a basis for correlation of strata and events between marine and terrestrial systems. The age of each sample was calibrated with the ATS in this study.

Methods of Stable Isotopic Analysis on Paleosol Carbonate

The paleosol carbonate nodules analyzed in this study were round to subround with a diameter of 0.1–3.5 cm. Micrite dominates microfabric in the carbonate nodules, and sparry calcite is constrained to the cracks, as also characteristic of the pedogenic carbonate analyzed by Huang et al. (2013). Carbonate nodules were powdered using mortar and pestle or drill. Stable carbon and oxygen isotope values of carbonates were obtained at the Stable Isotope Biogeochemistry Laboratory, Stanford University, using a Thermo Finnigan Gasbench and isotope ratios were measured by a Finnigan MAT Delta+ XL mass spectrometer via a Thermo Finnigan ConFlo III unit. Depending on the samples' carbonate content, 300 to 900 μg of sample powder was weighed into sealed vials that were flushed with He gas and reacted with ca. 0.25 ml of phosphoric acid (H_3PO_4) for 1 hour at 72°C. External precision (1σ) of oxygen and carbon isotope data is generally <0.1‰, based upon repeated measurements of two internal laboratory standards (calibrated against NBS 18, NBS 19, and LSVEC). Both $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to VPDB.

Soil Respiration Modeling

Pedogenic carbonate $\delta^{13}C$ is predominantly influenced by three factors: atmospheric pCO_2, the soil respiration flux and their respective isotopic compositions (Cerling, 1984; Cerling, 1999; Breecker, 2013). Here we briefly summarize the soil respiration modeling methods used in Caves et al. (2014) and improve upon them using a Monte Carlo routine to account for parameter uncertainty. To understand how soil respiration changed during the Late Cretaceous, we start with the CO_2 diffusion equation first defined by Cerling (1984).

$$C_s(z) = \frac{\theta}{D_s}\left(Lz - \frac{z^2}{2}\right) + C_{atm} \quad (1)$$

where C_s is the concentration of CO_2 in soil (g C/cm^3), L is the production depth of CO_2 (cm), θ is the soil CO_2 production rate (g C/cm^3/s), which we treat as constant with depth, C_{atm} is the concentration of CO_2 in the overlying atmosphere (g C/cm^3), D_s is the diffusion coefficient for CO_2 in soil (cm^2/s), and z is depth of the carbonate sampled in the soil (cm). In the case of constant θ with depth, soil respiration (SR) equals θ x L.

The first term on the right-hand side of Equation 1 is equivalent to the S(z) term used in the Cerling (1999) paleobarometer (see Equation 27 in Cerling (1999)). With the appropriate isotopic relations for $^{13}CO_2$, as derived by Davidson (1995) and Cerling (1999), the full paleobarometer equation is:

$$C_{atm} = \frac{\theta}{D_S}\left(Lz - \frac{z^2}{2}\right)\left(\frac{\delta_S - 1.0044\delta_\theta - 4.4}{\delta_{atm} - \delta_S}\right) \quad (2)$$

where δ_θ is the $\delta^{13}C$ of soil-respired CO_2; δ_{atm} is the $\delta^{13}C$ of atmospheric CO_2; δ_S is the $\delta^{13}C$ of soil CO_2. Because this S(z) term contains a production term (θ), our approach is to invert this equation and solve for θ, which presumes we know C_{atm}.

Thus, we first solve for θ, and, following Bowen and Beerling (2004) and Caves et al. (2014), correct for the fact that soil respired CO_2 (θ) is produced entirely in the pore space by multiplying by the inverse of porosity (ε). Finally, to convert to a soil respiration flux (SR), we multiply by the production depth (L):

$$SR = \frac{1}{\varepsilon}\left[\frac{D_S C_{atm}(\delta_{atm} - \delta_S)}{\left(Lz - z^2/2\right)\left(\delta_S - 1.0044\delta_\theta - 4.4\right)}\right]L \quad (3)$$

To calculate soil respiration through time in the Songliao Basin (Fig. 2G, main text), we use a Monte Carlo routine to account for uncertainties in the above parameters (e.g. Breecker, 2013) (see Table DR2 for a summary of parameter values and uncertainties). First, we use the measured depth of the sampled soil carbonate (Table DR1), and correct for compaction using the "decompaction" transfer function in Huang et al. (2013). We then calculate soil respiration for each sample using the $\delta^{13}C$ of the sampled soil carbonate (Table DR1). Second, we assign mean values and uncertainties to the remaining parameters in equation 3. We assume soil organic matter $\delta^{13}C$ is -25‰, similar to values found at the top of the underlying Nenjiang Formation (Song et al., 2013), with a normally distributed standard deviation of 1‰. To estimate C_{atm}, we use a compilation of paleo-atmospheric pCO_2 estimates from paleosols and stomata (Beerling et al., 2002; Nordt et al., 2002; Ekart et al., 1999; Nordt et al., 2003; Quan et al., 2009). We correct the paleosol-based pCO_2 estimates of Ekart et al., (1999) and Nordt et al., (2002, 2003) by using the lower estimated soil pCO_2 suggested by Breecker et al. (2010). This results in a lowering of estimated Late Cretaceous pCO_2. We kernel-smooth this pCO_2 data using a 0.25 Ma bandwidth and an Epanechnikov kernel. We linearly interpolate this kernel estimate to the age of the paleosol carbonate measurements. Due to large uncertainty in the pCO_2 data (Fig. 2B), we assume a constant, uniformly-distributed ± 150 ppm uncertainty on the kernel estimate. For Cretaceous δ_{atm}, we assume a constant value of -5‰ based upon Late Cretaceous estimates from Tipple et al. (2010). We do not assign an uncertainty to this value because the uncertainties for this estimate are unknown. To calculate soil CO_2 $\delta^{13}C$ (δ_s), we must also know the temperature of formation to estimate the carbon isotopic fractionation between CO_2 and calcite. For temperature, we use the recently published mid-latitude sea-surface temperature record (TEX_{86}^{L} proxy) of Linnert et al., (2014). This record comes from a paleo-latitude of ~35 °N, similar to the paleo-latitude of the SK-1 core. We use their published error of ± 4.0 °C and assume this error is normally distributed around the mean temperature. We then calculate δ_s assuming equilibrium fractionation between soil CO_2 and calcite using the fractionation factors compiled in Cerling (1999). Finally, using these estimates, we calculate soil respiration 2,000 times for each kernel estimate and plot the mean value for each sample as well as the error-weighted kernel estimate (thick black line) of the data in Fig. 2G (main text) with a 1σ errors (black dashed line).

Other Isotopic Effects on δ^{18}O

Besides temperature and precipitation sources, some other factors can also change the pedogenic carbonate δ^{18}O values. The following is a discussion of these effects explaining why they contributed little to our δ^{18}O excursions.

Latitude and Surface Elevation: Precipitation usually has more depleted ^{18}O composition in regions with higher latitude (Craig, 1961; Rozanski et al., 1993) and higher elevation (Rowley and Garzione, 2007; Chamberlain et al., 2012). In the Late Cretaceous, the latitude of the Songliao Basin was similar to today, as revealed by previous paleomagnetic work (Fang et al., 1990), and mountains east of the Songliao Basin remained tectonic stable (Li et al., 2010). Furthermore, the timescale of our isotopic excursions (~ 1 Myr) is too brief to reflect tectonic shifts driving significant changes in latitude and topography (Brandon et al., 1998; Kent-Corson et al. 2006; Mix et al., 2011). Therefore, these two effects are unlikely to contribute to our isotopic excursions.

Continentality: The inland distance can affect isotopic composition of precipitation because an air mass will become progressively depleted as it rains out (Rozanski et al., 1993). To produce a δ^{18}O excursion in 1‰ magnitude, a change of 500 km (1.5 times the width of Songliao Basin) on the distance from SK-1 to the coast is necessary assuming a gradient of 0.002‰/km (Criss, 1999). Such a large change in distance on such a short-term timescale was unlikely to happen in the Songliao Basin in Late Cretaceous (Wang et al., 2013).

Evaporation: Evaporation of surface waters can have profound affects on the isotopic composition of lake and soil water (Gonfinatini, 1986). Previous studies show the Mg/Ca and Sr/Ca ratios of lacustrine ostracod shells in the same section are low (Chamberlain et al., 2012), which are indicative of a low paleosalinity (Chivas et al., 1993). Also, no typical evaporative minerals were found in middle Mingshui Formation (Gao et al., 2013; Huang et al., 2013). We thus consider evaporation to be a minor effect on our isotopic records.

Diagenesis: The isotope composition of pedogenic carbonates is also sensitive to diagenesis (Morrill and Koch, 2002). Several lines of evidence suggest that diagenetic effects were relatively minor in the samples we studied. First, samples were taken after detailed core observations devoid of obvious cementation or recrystallization. Second, petrographic analyses of carbonate nodules show micritic fabrics and little evidence for diagenetic alteration (Huang et al., 2013). Third, isotopic values of lacustrine ostracods in the same section revealed paleoenvironmental controls rather than diagenetic effects (Chamberlain et al., 2013).

Table DR1. Stable isotopic values, depths and modeled soil respiration of paleosol carbonate nodules in SK-1. ATS ages are from Wu et al. (2014). Dp – Depth to paleosol in core; z – uncompacted soil depth corrected for compaction using the “decompaction” transfer function of Huang et al. (2013). Soil production error is 1σ.

Depth (m)	ATS Age (Ma)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Data Source	Dp (cm)	z (cm)	Soil Respiration ($gC/m^2/year$)		
268.55	65.515	-9.22	-7.6	This study	40	41.1	547	±	406
268.85	65.519	-9.1	-8.06	This study	70	71.9	376	±	285
269	65.521	-9.02	-8.21	Huang et al., 2013	60	61.6	376	±	282
269.25	65.523	-8.79	-7.91	This study	20	20.5	753	±	459
269.35	65.525	-9.31	-7.57	This study	30	30.8	672	±	451
269.85	65.53	-9.78	-8.46	This study	80	82.2	524	±	429
270	65.531	-8.86	-7.36	Huang et al., 2013	35	36.0	498	±	330
271.05	65.542	-8.7	-7.2	This study	70	71.9	294	±	211
271.05	65.542	-11.29	-8.72	This study	70	71.9	968	±	641
287.11	65.688	-9.28	-8.83	This study	45	46.3	490	±	351
289.66	65.71	-9.85	-9.3	This study	50	51.5	621	±	491
289.96	65.713	-9.93	-9.31	This study	80	82.4	535	±	445
292.06	65.731	-9.36	-10.58	This study	70	72.1	399	±	334
292.36	65.735	-7.76	-10.22	This study	100	103.0	174	±	105
292.85	65.739	-8	-10.04	This study	50	51.5	251	±	161
293.49	65.744	-8.99	-9.17	This study	60	61.8	354	±	273
293.89	65.748	-9.36	-9.37	This study	40	41.2	554	±	392
294.69	65.754	-9.46	-9.74	This study	60	61.8	463	±	386
296.94	65.778	-9.34	-8.54	This study	40	41.2	601	±	394
297	65.778	-9.11	-7.7	Huang et al., 2013	30	30.9	567	±	397
297.14	65.779	-8.96	-8.6	This study	20	20.6	768	±	469
297.59	65.784	-10.75	-7.63	This study	65	67.0	831	±	604
298.94	65.799	-8.77	-8.99	This study	75	77.3	399	±	314
299	65.799	-8.93	-8.7	Huang et al., 2013	50	51.5	289	±	211
300	65.809	-8.35	-7.71	Huang et al., 2013	10	10.3	1079	±	549
300.58	65.815	-8.27	-8.43	This study	30	30.9	421	±	253
301	65.819	-8.05	-8.61	Huang et al., 2013	40	41.2	311	±	199
301	65.819	-8	-8.72	Huang et al., 2013	40	41.2	306	±	180
307	65.882	-9.22	-8.03	Huang et al., 2013	40	41.2	553	±	378
307.05	65.882	-9.41	-9.24	This study	45	46.4	563	±	403
308.85	65.891	-8.83	-8.79	This study	25	25.8	658	±	401
309.76	65.91	-7.95	-9.33	This study	70	72.2	220	±	128
310.51	65.918	-7.75	-8.6	This study	40	41.3	289	±	156

310.51	65.918	-8.21	-8.3	This study	40	41.3	350	±	220
311	65.923	-8.27	-7.58	Huang et al., 2013	40	41.3	364	±	227
312	65.934	-8.48	-8.56	Huang et al., 2013	60	61.9	304	±	184
314	65.955	-8.38	-8.02	Huang et al., 2013	16	16.5	826	±	440
314.68	65.961	-6.66	-8.06	This study	20	20.6	372	±	168
315	65.965	-7.14	-7.3	Huang et al., 2013	20	20.6	438	±	205
315	65.965	-8.41	-7.41	Huang et al., 2013	20	20.6	710	±	387
315	65.965	-8.06	-7.13	Huang et al., 2013	20	20.6	618	±	320
315.93	65.975	-6.44	-8.72	This study	23	23.7	318	±	137
316	65.977	-7.57	-8.59	Huang et al., 2013	30	31.0	363	±	169
316	65.977	-8.12	-7.6	Huang et al., 2013	30	31.0	456	±	253
321	66.037	-7.56	-8.6	Huang et al., 2013	30	31.0	393	±	200
335.97	66.22	-8.46	-9.96	This study	40	41.4	561	±	330
336.77	66.229	-8.34	-8.77	This study	30	31.0	653	±	338
339.3	66.261	-8.28	-9.46	This study	50	51.7	459	±	266
342.87	66.307	-8.43	-11.39	This study	30	31.0	748	±	394
344.07	66.323	-7.19	-11.84	This study	15	15.5	829	±	349
349.48	66.391	-6.82	-10.04	This study	45	46.6	309	±	114
366	66.598	-6.95	-9	Huang et al., 2013	60	62.2	318	±	135
387.13	66.919	-7.46	-11.06	This study	20	20.8	919	±	357
403.05	67.243	-8.59	-8.03	This study	30	31.2	837	±	440
406.05	67.3	-8.09	-9.63	This study	40	41.6	528	±	286
408.21	67.343	-6.51	-10.43	This study	30	31.2	351	±	141
416.61	67.475	-7.09	-10.13	This study	20	20.8	530	±	240
430.14	67.695	-6.23	-9.93	This study	40	41.7	189	±	87
442.25	67.938	-6.7	-11.12	This study	30	31.3	221	±	125
445.21	68.001	-6.65	-8.67	This study	15	15.7	369	±	209
450.31	68.108	-6.92	-8.14	This study	40	41.8	187	±	114
462.74	68.395	-6.25	-12.7	This study	35	36.6	185	±	92
463.74	68.413	-6.22	-8.6	This study	25	26.2	240	±	112
466.32	68.449	-6.86	-8.39	This study	40	41.9	201	±	102
470.52	68.504	-8.17	-8.5	This study	40	41.9	361	±	223
470.52	68.504	-7.37	-8.61	This study	40	41.9	259	±	136
473.63	68.546	-6.82	-9.85	This study	30	31.4	267	±	128
476.42	68.584	-8.04	-8.75	This study	50	52.4	308	±	193
476.78	68.589	-7.67	-9.45	This study	60	62.9	238	±	138
477	68.592	-7.51	-9.52	Huang et al., 2013	30	31.4	353	±	173
477.38	68.597	-8.93	-9.4	This study	45	47.1	506	±	356
477.78	68.602	-9.11	-8.83	This study	85	89.1	409	±	313
478	68.606	-7.07	-9.13	Huang et al., 2013	20	21.0	444	±	221

478.82	68.617	-9.27	-9.82	This study	75	78.6	468	±	362
479	68.619	-7.33	-9.31	Huang et al., 2013	35	36.7	297	±	139
479	68.619	-7.38	-8.41	Huang et al., 2013	40	41.9	279	±	137
479.3	68.622	-7.15	-9.1	This study	35	36.7	283	±	139
480	68.632	-7.17	-8.69	Huang et al., 2013	26	27.2	360	±	177
480.31	68.637	-6.72	-9.76	This study	20	21.0	398	±	186
483.8	68.682	-6.91	-9.26	This study	30	31.5	302	±	139
484.19	68.688	-8.9	-10.17	This study	55	57.7	469	±	345
485.89	68.71	-7.15	-7.78	This study	60	62.9	206	±	105
497.78	68.865	-6.27	-12.9	This study	30	31.5	274	±	111
499.8	68.891	-6.8	-8.71	This study	45	47.2	239	±	98
500.9	68.906	-6.64	-8.01	This study	30	31.5	313	±	127
503.1	68.935	-7.51	-9.28	This study	55	57.8	288	±	152
503.1	68.936	-7.09	-7.06	This study	55	57.8	242	±	108
506.2	68.975	-6.86	-9.23	This study	70	73.5	202	±	83
507.7	68.994	-9.92	-11.27	This study	30	31.5	1209	±	615
508.2	69.001	-8.03	-10.91	This study	80	84.1	311	±	162
522.61	69.179	-6.17	-10.68	This study	70	73.6	191	±	72
535.71	69.347	-8.25	-11.65	This study	20	21.1	935	±	413
537.91	69.374	-8.57	-11.77	This study	75	79.0	456	±	283
539.1	69.39	-7.88	-11	This study	70	73.8	344	±	172
557.96	69.637	-6.47	-10.24	This study	30	31.7	306	±	125
576.34	69.879	-6.45	-13.23	This study	20	21.1	362	±	165
592.8	70.073	-6.38	-14.19	This study	55	58.2	146	±	72
593.7	70.083	-6.48	-13.36	This study	30	31.8	232	±	116
616.09	70.298	-6.31	-13.27	This study	15	15.9	476	±	200
626.1	70.395	-7.08	-12.7	This study	35	37.2	314	±	147
626.5	70.399	-7.66	-15.05	This study	30	31.9	435	±	225
699.49	71.439	-7.48	-11.9	This study	50	53.4	519	±	225
700.44	71.451	-6.32	-12.14	This study	30	32.1	510	±	181
703.39	71.486	-7.23	-9.01	This study	20	21.4	981	±	369
755.79	72.142	-5.5	-11.55	This study	15	16.1	829	±	230
762.49	72.236	-6.64	-11.27	This study	25	26.9	730	±	252
764.89	72.273	-8.81	-10.17	This study	45	48.4	1065	±	497
770.8	72.363	-8.04	-13.12	This study	20	21.5	1410	±	483
771.33	72.372	-6.63	-11.81	This study	40	43.0	503	±	160
783.94	72.557	-5	-13.12	This study	10	10.8	1035	±	266
812.77	72.953	-7.09	-11.31	This study	50	54.0	516	±	194
868.5	73.947	-6.62	-13.05	This study	30	32.5	684	±	222
887.58	74.236	-5.05	-13.39	This study	15	16.3	823	±	211

896.63	74.363	-5.31	-14.38	This study	30	32.6	496	±	129
901	74.424	-6.49	-10.93	This study	25	27.2	812	±	260
901.2	74.427	-6.26	-10.27	This study	45	48.9	479	±	147
902	74.438	-6.18	-13.7	This study	30	32.6	637	±	199
902	74.438	-6.12	-11.61	This study	30	32.6	625	±	191
963.22	75.307	-5.5	-11.48	This study	30	32.8	649	±	146
982.45	75.52	-6.93	-14.3	This study	15	16.4	1761	±	410
985.62	75.56	-6.05	-13.28	This study	40	43.8	609	±	156
996.28	75.7	-6.04	-14.57	This study	20	21.9	1016	±	239
1000.4	75.761	-6.35	-11.47	This study	25	27.4	901	±	236
1000.8	75.767	-6.63	-11.43	This study	20	21.9	1177	±	310
1001.1	75.773	-6.95	-11.31	This study	50	54.8	651	±	202
1005.5	75.838	-6.49	-11.79	This study	15	16.4	1433	±	368
1008.13	75.878	-6.54	-13.18	This study	30	32.9	795	±	219
1009.13	75.893	-5.97	-12.11	This study	15	16.4	1217	±	305
1009.53	75.899	-5.71	-13.02	This study	30	32.9	621	±	157
1009.83	75.905	-6.19	-14.29	This study	20	21.9	998	±	265
1010.33	75.913	-5.86	-13.02	This study	30	32.9	644	±	161

Table DR2. Parameter values and uncertainties used in calculating soil respiration (Eq. 1 and 2)

Parameter	**Value**	**Uncertainty**
Porosity (ε)	0.45	± 0.05[1]
Tortuosity (ρ)	0.6	± 0.05[1]
Diffusion of CO_2 in air (D_{air})	0.14 cm^2/s	--
Diffusion of CO_2 in soil	$\rho \times \varepsilon \times D_{air} = 0.0378\ cm^2/s$	--
Production Depth (L)	100 cm	--
Depth of Sampling (z)	Measured in SK-1 core (Table DR1)	--
Atmospheric CO_2 $\delta^{13}C$	-5 ‰	--
Soil organic matter $\delta^{13}C$	-26 ‰	± 1‰[1]
Atmospheric CO_2 (C_{atm})	From compilation (see text)	± 150 ppm[2]
Temperature	From Linnert et al. (2014)	± 4.0 °C[1]

[1] Uncertainties assumed to be normally-distributed absolute 1σ.
[2] pCO_2 uncertainty is assumed to be uniformly-distributed.

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