The Cryosphere

Supporting Information for

Evaporitic carbonates record surface melting in Antarctica

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Introduction

The supplemental information presented here includes additional descriptions of the methods for U-Th data collection in Text S1. Additional descriptions of the methods and equations for the surface melting radiative balance model are in Text S2. Figure S1 is a sample photo of PRR_33067 and Figure S2 is the isochron for PRR_33067 which uses multiple measurements to calculate an age. Figure S3 shows results of the surface melting radiative balance for the albedo and insolation values considered in this study. Table S1 summarizes the U-Th isotopic data.

Text S1. U-Th isotopic data methods

We used ^{234}U-^{230}Th methods to determine the time of formation for each carbonate. These ^{234}U-^{230}Th isotopic data are collected using methods modified from Piccione et al., (2022), for applications to these evaporitic carbonates. First, a fine bit Dremel is used to carefully isolate the carbonate coating from the host rock. Any host rock that is accidentally ground off is extracted with tweezers. The amount of powdered carbonate used for each measurement varies from 10mg to 200mg depending on carbonate abundance and uranium concentration. The calcite is dissolved in 7N nitric acid and spiked with a ^{236}U-^{229}Th tracer. Uranium and thorium are isolated using an AG-1X resin. Then, the uranium and thorium are loaded onto filaments and measured on the UCSC IsotopX X62 Thermal Ionization Mass Spectrometer (TIMS).

U-Th disequilibrium ages assume that parent ^{234}U is fractionated from intermediate daughter ^{230}Th due to the contrast in water solubilities (U soluble, Th insoluble). However, it is common for a pedogenic carbonate to exhibit elevated thorium concentrations, perhaps due to the weathering and evaporation of a thin film of water that forces the incorporation of this otherwise insoluble element. The degree to which initial (detrital) thorium is incorporated is determined by measuring ^{232}Th, as it is not a part of the ^{238}U decay chain. Because young samples have low ^{230}Th accumulation via radioactive decay of ^{234}U, a detrital ^{230}Th correction is crucial. We can correct for the detrital ^{230}Th by measuring the detrital ^{232}Th and using the naturally occurring relative abundances to correct for detrital ^{230}Th. Samples with abundant detrital thorium have low [$^{230}Th/^{232}Th$] (where brackets denote activity ratios) (data table 1, supplement). We use an isochron method (Osmond et al.; Rosholt; Vermeesch) to make this correction which requires more than one measurement of each sample. Generally, the amount of carbonate on each hand-sized clast host rock only permits two to three measurements. Using (ideally) three measurements of the same carbonate, we produce an isochron plot to determine an initial [$^{230}Th/^{232}Th$] value and an age that corrects for initial thorium. In one instance, limited material permitted only a 2-point isochron to be calculated, however, the dates from this location matched that of nearby samples. In most instances material permitted at least 3-point isochrons. However, some samples do not exhibit enough "spread" (difference) in uranium and thorium values across multiple measurements to produce a reliable isochron. For these samples we use the mean [$^{230}Th/^{232}Th$] initial value calculated by the isochrons of the other samples to make the correction. Toggling the mean [$^{230}Th/^{232}Th$] initial value (1.61) by one standard deviation (1.63) only changes the age by <0.5ka. For these samples we present the weighted mean value of their ages calculated using this mean [$^{230}Th/^{232}Th$] initial correction.

Text S2. Surface melting radiative balance

To illustrate how the local surface energy balance can lead to meltwater production under summer conditions, we use a simple model that assumes the energy budget is dominated by the combination of incoming shortwave solar radiation, outgoing infrared thermal radiation, and the latent heat of melting (when m > 0) or freezing (when m < 0 and sufficient liquid water is present):

$$S(1-\alpha) - \varepsilon\sigma T^4 - mL = 0 \qquad \text{Equation 1a}$$

where S is the solar irradiation per unit surface area (W/m^2), α is the surface albedo (ND), ε is the emissivity (assumed to be 0.97) (Aubry-Wake et al., 2015), σ is the Stefan-

Boltzmann constant (ca. 5.67E-8 W/(m^2 K^4)), T is the surface temperature in Kelvin, m is the melting(+) or freezing(-) rate (m/s), and L is the volumetric latent heat of ice fusion (3.06E8 J/m^3). When solved for the melting/freezing rate, this equation becomes:

$$m = \frac{S(1-\alpha)-\sigma T^4}{L} \qquad \text{Equation 1b}$$

For simplicity, our treatment omits turbulent heat fluxes. (Van Den Broeke et al., 2006) measured summer turbulent heat fluxes at a high-altitude weather station in Antarctica (their AWS9) and showed that the radiative budget dominates the surface energy balance, especially on summer days when surface melting is most likely. We justify the simplifications underlying our model by the fact that we are not trying to reproduce specific climatic conditions at a specific location, but rather to illustrate the plausibility of summer surface melting at the ice-marginal locations where our samples were found.

Figure S1. Photo of PRR_33067. The host rock is basalt and the red outline shows one of the sampling locations.

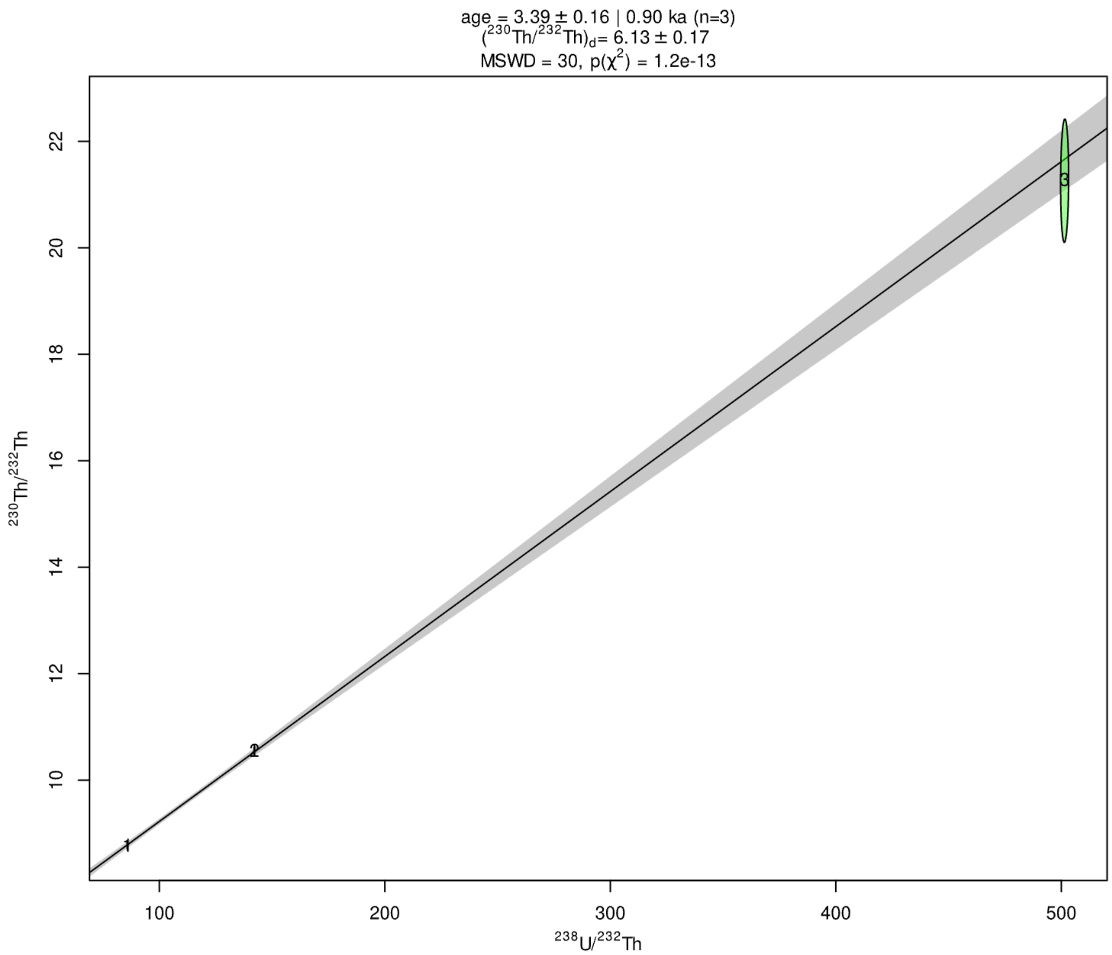

Figure S2. Rosholt A Isochron with three measurements for PRR_33067. Age: 3.39 ± 0.16 ka. Age uncertainty: 4.7%.

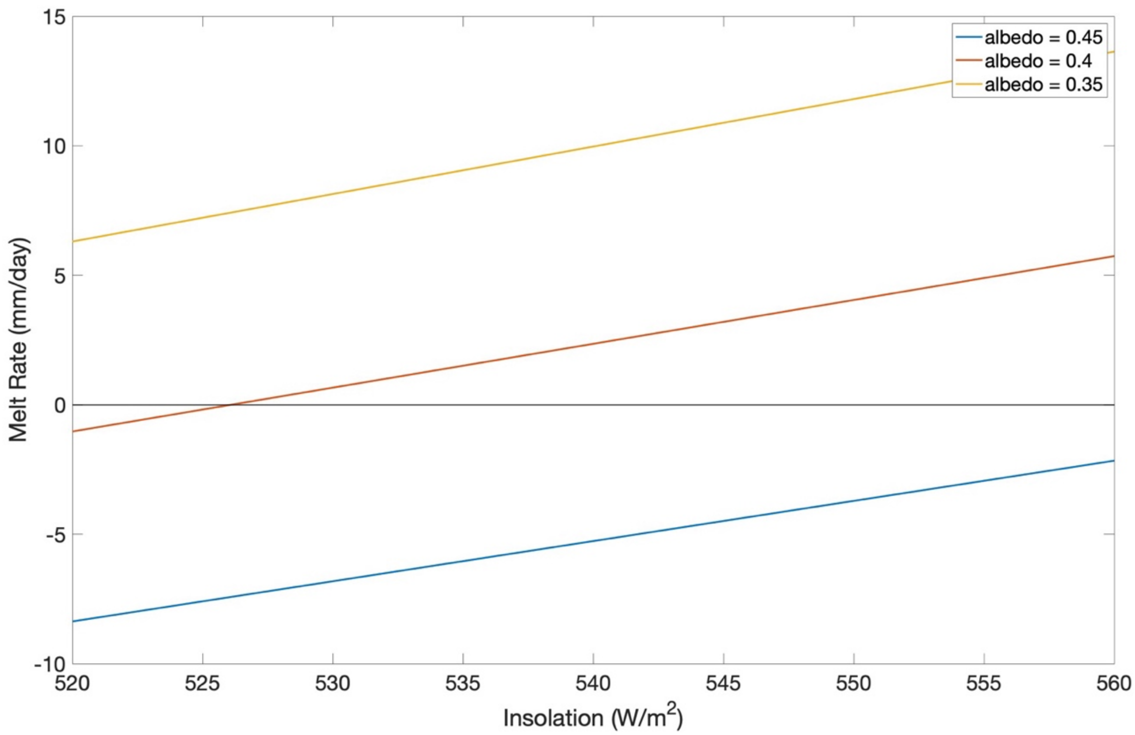

Figure S3. Model results showing insolation versus melt rate for three different albedos. Positive melt rates indicate melting while negative melt rates indicate freezing.

Sample Run/ID	[Th] (ppm)	[U] (ppm)	[232Th / 238U]	+/-2s (%)	[230Th / 232Th]*	+/-2s (%)	[230Th / 238U]	+/-2s (%)	[234U / 238U]	+/-2s (%)	U-Th age (ka)	+/-2s (ka)	U-Th age (Th corr.) (ka)**	+/-2s (ka)	[234U / 238U]i	+/-2s
SC_B7_1_1	10.87	63.97	0.0554	1.81	1.63	10.17	0.0904	10.33	1.0602	0.60	9.72	1.05	4.93	2.60	1.062	0.0065
SC_B7_3_1	11.01	56.25	0.0639	0.26	1.35	2.48	0.0865	2.49	1.1359	0.13	8.62	0.22	3.48	2.57	1.139	0.0015
SC_B7_4_1	11.39	39.96	0.0930	0.22	1.25	1.20	0.1164	1.22	1.0699	0.21	12.55	0.16	2.63	3.52	1.072	0.0023
SC_C4_1	2.60	281.56	0.0030	0.87	22.09	1.39	0.0665	1.64	1.0468	0.12	7.16	0.12	6.90	0.17	1.048	0.0013
SC_C4_2	1.80	302.30	0.0019	0.34	21.53	1.35	0.0417	1.39	1.0196	0.13	4.55	0.06	4.38	0.11	1.020	0.0014
SC_E3_1	32.68	88.88	0.1199	0.44	1.07	2.38	0.1283	2.42	1.2196	0.81	12.08	0.33	2.93	4.68	1.227	0.0102
SC_E3_2	12.65	34.76	0.1187	0.09	1.13	1.83	0.1336	1.83	1.2892	0.24	11.89	0.23	3.34	4.33	1.299	0.0032
SC_E3_3_1	10.94	36.21	0.0986	0.14	1.15	3.16	0.1130	3.16	1.2441	0.13	10.35	0.34	3.04	3.70	1.251	0.0016
PRR_33067_3_1	4.90	137.25	0.0116	0.09	8.77	0.74	0.1022	0.75	0.9999	0.14	11.76	0.09	7.88	0.20	1.000	0.0014
PRR_33067_5_1	3.33	154.27	0.0070	0.08	10.55	0.80	0.0743	0.80	0.9965	0.21	8.44	0.07	7.67	0.17	0.996	0.0022
PRR_33067_5_2	1.55	253.24	0.0020	0.29	21.26	4.37	0.0424	4.38	1.0114	0.13	4.67	0.21	4.45	0.21	1.012	0.0013
PRR56408_1_2	0.28	2.34	0.0391	0.25	2.38	10.45	0.0931	10.45	1.4013	5.25	7.48	0.91	4.97	1.51	1.410	0.0747
PRR_56408_5_1	0.29	3.31	0.0287	0.09	2.64	4.58	0.0758	4.59	1.3457	0.19	6.31	0.30	3.96	0.56	1.352	0.0026
PRR58295_1	0.25	2.85	0.0282	0.40	2.51	5.03	0.0708	5.05	1.1068	2.50	7.21	0.42	4.90	1.20	1.109	0.0282
PRR_58295_3_1	0.20	3.12	0.0212	0.10	2.98	8.15	0.0631	8.15	1.0902	0.25	6.50	0.54	4.75	1.02	1.092	0.0028
PRR_58295_5_1	0.33	3.04	0.0357	0.21	2.01	12.29	0.0718	12.29	1.0823	0.37	7.48	0.95	3.83	1.21	1.084	0.0041
PRR4622_1	0.73	15.27	0.0156	0.29	3.71	5.88	0.0580	5.89	1.1043	0.36	5.88	0.36	4.60	0.72	1.106	0.0040
PRR4622_2	0.04	1.35	0.0086	0.17	7.25	1.77	0.0627	1.78	1.0977	0.11	6.41	0.12	5.70	0.37	1.099	0.0012
PRR4624_1	0.90	22.77	0.0128	0.12	3.43	1.57	0.0440	1.57	1.1055	0.38	4.43	0.07	3.38	0.52	1.107	0.0042
PRR4624_2	1.17	17.94	0.0214	0.27	2.46	3.64	0.0526	3.65	1.1089	0.26	5.30	0.20	3.56	0.87	1.111	0.0029
PRR_4624_3_1	0.98	16.95	0.0188	0.10	2.43	4.89	0.0456	4.89	1.1108	0.59	4.57	0.23	3.05	0.78	1.112	0.0066
PRR_4601_6_1	14.42	9.81	0.4799	0.36	0.95	2.25	0.4566	2.28	1.0507	0.15	61.85	1.89	10.83	28.41	1.060	0.0018
PRR_4601_6_2	3.19	12.62	0.0824	0.22	1.36	2.29	0.1120	2.30	1.1163	4.19	11.51	0.59	4.71	3.45	1.120	0.0482
PRR4601_1_1	1.42	7.47	0.0619	0.55	1.52	8.42	0.0938	8.44	1.1114	0.12	9.60	0.84	4.51	2.69	1.114	0.0014
PRR_36401_6_1	0.21	1.15	0.0610	0.10	8.38	0.92	0.5107	0.93	0.8886	0.48	95.61	1.69	89.03	3.69	0.854	0.0060
PRR_36401_6_2	0.71	9.23	0.0252	0.06	21.92	0.92	0.5521	0.92	0.9392	0.16	97.97	1.51	95.48	2.98	0.920	0.0021
PRR_12678_6_1	6.07	1.26	1.5700	0.74	0.52	18.66	0.8177	18.67	1.5544	0.35	77.62	20.15	11.42	99.63	1.690	0.0399
PRR12678_2	0.50	0.35	0.4669	0.97	1.22	1.87	0.5688	2.11	1.5802	0.38	47.25	1.23	17.79	16.81	1.663	0.0067
PRR12678_3	0.36	0.10	1.1328	1.80	0.55	5.66	0.6284	5.94	1.5782	0.67	53.53	4.00	-8.50	15.07	1.672	0.0136
PRR36574_1_1	0.18	1.20	0.0502	2.63	14.90	1.74	0.7476	3.15	1.1469	2.88	111.56	8.56	107.73	8.72	1.201	0.0420
PRR36574_1_2	0.21	1.28	0.0531	0.42	15.08	1.48	0.8016	1.54	1.1641	0.73	122.13	3.81	118.20	4.27	1.232	0.0111
PRR36574_1_3	0.17	0.87	0.0649	0.60	12.48	0.76	0.8106	0.97	1.1392	0.68	130.35	3.03	125.40	3.90	1.201	0.0102
PRR36574_1_4	0.72	1.17	0.2022	2.56	5.14	1.51	1.0385	2.97	1.1583	2.49	220.74	28.49	205.60	29.43	1.295	0.0404
PRR36714_1_1	0.95	2.35	0.1318	0.18	3.04	2.24	0.4014	2.25	1.0728	0.23	50.80	1.45	39.28	6.08	1.084	0.0028
PRR36714_1_2	1.08	2.57	0.1375	1.47	2.86	1.86	0.3930	2.37	1.1373	3.95	45.84	2.71	34.57	6.24	1.156	0.0500
PRR36714_1_3	1.06	1.78	0.1942	0.49	2.84	2.33	0.5523	2.38	1.0782	0.26	77.45	2.67	60.21	9.49	1.097	0.0034
PRR37868_1_1	0.31	1.95	0.0518	6.34	2.34	17.52	0.1209	18.63	1.6917	1.16	8.05	1.55	5.30	2.08	1.708	0.0202
PRR37868_1_2	0.34	1.95	0.0574	1.10	1.77	2.65	0.1013	2.87	1.7354	0.71	6.53	0.20	3.55	1.49	1.749	0.0125
PRR37868_1_4	0.96	2.08	0.1503	0.76	1.41	5.90	0.2115	5.95	1.6975	0.25	14.39	0.91	6.25	4.24	1.726	0.0047

Table S1. Summary of U-Th isotopic data. * For samples with a $^{230}Th/^{232}Th$ > 20, the detrital thorium quantity is low enough that we did not need to do an isochron. ** For samples that did not need an isochron, an average of the values in the "U-Th age (Th corr.) (ka)" column are used as ages for this study.