Table 1

$\delta^{13}C_{PDB}$ (‰)	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{SMOW}$ (‰)	Δ_{47} (‰)	1se Δ_{47} analytical (‰)	1se Δ_{47} (‰)	summary
<u>*Imperial Formation (4-5 Ma)*</u>						
95-I-23 (Fish Creek area, 32 58.57N, 116 9.26W), deposited at sea level, oyster						*average Δ47: 0.588 ±0.004‰*
-1.8	-5.1	-0.3	0.593	0.0083	0.0131	*temperature: 38.9 ±1.7°C (1s.e.)*
-1.9	-5.1	-0.2	0.591	0.0081	0.0111	
-1.9	-5.2	0.4	0.577	0.0081	0.0049	
-1.8*	-7.1	-2.3	0.592	0.0035	0.0037	
95-I-24 (Fish Creek area, 32 58.57N, 116 9.26W), deposited at sea level, *anomia sp.*						*average Δ47: 0.589 ±0.007‰*
-1.0	-4.6	-0.2	0.602	0.0077	0.0139	*temperature: 38.8 ±2.1°C (1s.e.)*
-1.0	-4.5	0.6	0.586	0.0081	0.0118	
-1.0	-4.6	1.0	0.578	0.0075	0.0052	
<u>*Bouse Formation (4-9 Ma)*</u>						
96BS1 (Cibola area, AZ, 33 15.41N, 114 38.47W), elev 125 m, micrite						*average Δ47: 0.648 ±0.003‰*
0.6	-5.0	-2.6	0.644	0.0077	0.0147	*temperature: 24.7 ±1.1°C (1s.e.)*
0.5	-4.9	-2.8	0.651	0.0078	0.0148	
95BS8 (Cibola area, AZ, 33 15.41N, 114 38.47W), elev 110 m, micrite						*average Δ47: 0.660 ±0.018‰*
0.0	-6.6	-6.4	0.695	0.0074	0.0133	*temperature: 22.1 ±3.8°C (1s.e.)*
0.1	-6.5	-3.7	0.636	0.0087	0.0133	
0.1	-6.6	-4.3	0.648	0.0074	0.0050	
95BS10 (Cibola area, AZ, 33 15.41N, 114 38.47W), elev 100 m, calc siltstone						*average Δ47: 0.623 ±0.013‰*
0.5	-5.4	-1.4	0.610	0.0076	0.0144	*temperature: 30.5 ±3.0°C (1s.e.)*
0.5	-5.5	-2.6	0.635	0.0074	0.0054	
95BS17 (Milpitas Wash, CA, 33 15.54N, 114 43.73W), elev 88 m, barnacle						*average Δ47: 0.622 ±0.007‰*
1.6	-9.0	-5.9	0.629	0.0074	0.0127	*temperature: 30.8 ±1.8°C (1s.e.)*
1.7	-9.2	-5.3	0.614	0.0071	0.0108	
96BS24 (Silver Creek, AZ, 35 5.23N, 114 28.13W), elev 535 m, marl						*average Δ47: 0.629 ±0.008‰*
0.6	-5.1	-1.6	*0.621*	*0.0077*	*0.0105*	*temperature: 29.0 ±2.0°C (1s.e.)*
-2.0	-9.0	-6.2	*0.636*	*0.0079*	0.0043	
96BS25 (Silver Creek, AZ, 35 5.23N, 114 28.13W), elev 536 m, marl						*average Δ47: 0.623 ±0.001‰*
-5.5	-9.7	-6.3	0.623	0.0081	0.0123	*temperature: 30.4 ±0.9°C (1s.e.)*
-5.5	-9.5	-6.0	0.621	0.0077	0.0045	
-5.6	-9.6	-6.3	0.625	0.0076	0.0045	
<u>*Hualapai Limestone (~6 Ma)*</u>						
96HU2 (SW of Temple Bar, 35 58.48N, 114 24.84W), elev 646 m, limestone						*average Δ47: 0.616 ±0.016‰*
1.0	-11.6	-7.2	0.600	0.0089	0.0105	*temperature: 32.1 ±4.0°C (1s.e.)*
1.0	-11.5	-8.5	0.632	0.0090	0.0043	
96HU5 (SW of Temple Bar, 35 58.49N, 114 20.73W), elev 640 m, limestone						*average Δ47: 0.627 ±0.002‰*
1.6	-11.4	-8.3	0.629	0.0076	0.0104	*temperature: 29.6 ±1.1°C (1s.e.)*
1.6	-11.5	-8.1	0.624	0.0093	0.0044	
<u>*Bidahochi Formation, upper (younger than 6 Ma)*</u>						
98B11a (Eastern lake margin, 35 36.80N, 109 44.13W), elev 1870 m, lake edge tufa						*average Δ47: 0.647 ±0.003‰*
-5.4	-11.4	-8.9	*0.643*	*0.0072*	0.0100	*temperature: 24.9 ±1.0°C (1s.e.)*
-5.4	-11.3	-9.3	*0.653*	*0.0096*	0.0099	
-5.4	-11.4	-9.0	*0.645*	*0.0076*	0.0099	
98B11b (Eastern lake margin, 35 36.80N, 109 44.13W), elev 1870 m, lake edge tufa						*average Δ47: 0.652 ±0.008‰*
-5.1	-11.6	-9.8	0.658	0.0107	0.0099	*temperature: 23.7 ±2.0°C (1s.e.)*
-5.1	-11.5	-9.8	0.660	0.0077	0.0099	
-5.1	-11.5	-9.9	0.663	0.0086	0.0099	
-5.1	-11.5	-8.4	0.629	0.0085	0.0099	

Table 1 (continued)

$\delta^{13}C_{PDB}$ (‰)	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{SMOW}$ (‰)	Δ_{47} (‰)	1se Δ_{47} analytical (‰)	1se Δ_{47} full (‰)	summary
Bidahochi Formation, lower (~16 Ma)						
99B21 (Yellow Butte, AZ, 35 25.09N, 110 21.89W), elev 1898 m, marl						*average D47: 0.660 ±0.013‰*
-2.4	-8.5	-7.0	0.665	0.0132	0.0105	*temperature: 22.1 ±2.9°C (1s.e.)*
-2.4	-8.6	-6.5	0.652	0.0100	0.0043	
-2.4	-8.8	-5.0	0.615	0.0067	0.0105	
-2.4	-8.6	-8.0	0.685	0.0083	0.0043	
-2.4	-8.7	-7.9	0.681	0.0097	0.0086	
99B22 (Yellow Butte, AZ, 35 25.09N, 110 21.89W), elev 1898 m, marl						*average Δ47: 0.653 ±0.022‰*
-1.9	-4.4	-0.4	0.610	0.0080	0.0114	*temperature: 23.6 ±5.0°C (1s.e.)*
-1.9	-4.4	-3.0	0.668	0.0074	0.0051	
-1.8	-4.5	-3.7	0.680	0.0092	0.0102	
98B4 (Echo Spring Mt, AZ, 35 18.85N, 110 12.68W), 1806 m, marl						
-1.4	-6.0	-3.8	0.650	0.0075	0.0096	*temperature: 24.2 ±1.9°C (1s.e.)*
Rainbow Gardens Member, Horse Spring Formation (18-26 Ma)						
07KH12 (Tassai Wash, NV, 36 15.152N, 113 57.199W), elev 625 m, soil rip-up						*average Δ47: 0.610 ±0.0002‰*
-2.9	-11.9	-7.9	0.610	0.0071	0.0122	*temperature: 33.6 ±0.1°C (1s.e.)*
-3.0	-11.8	-7.8	0.610	0.0069	0.0045	
07KH14 (Tassai Wash, 36 15.152N, 113 57.199W), elev 628 m, micrite						
-1.8	-10.2	-6.0	0.606	0.0068	0.0108	*average Δ47: 0.620 ±0.015‰*
-2.0	-10.1	-7.3	0.635	0.0091	0.0043	*temperature: 31.0 ±3.8°C (1s.e.)*
Westwater Formation (45-55 Ma)						
07KH01 (Milkweed Canyon, AZ, 35 38.725N, 113 41.708W), elev 1269 m, limestone						
-4.5	-5.3	1.2	0.558	0.0075	0.0117	*temperature: 47.1 ±3.5°C (1s.e.)*
Rim Gravels (45-55 Ma),						
DB4-1 (Duff Brown Tank, 35 36.48N, 112 36.27W), elev 1780 m, sparry calcite cement						
-6.5	-14.5	-12.5	0.653	0.0102	0.0108	*temperature: 23.6 ±2.4°C (1s.e.)*
DB4-2 (Duff Brown Tank, 35 36.48N, 112 36.27W), elev 1780 m, matrix calcite						
-6.6	-14.4	-9.8	0.597	0.0067	0.0076	*temperature: 36.8 ±2.0°C (1s.e.)*
DB4-3 (Duff Brown Tank, 35 36.48N, 112 36.27W), elev 1780 m, calcified gastropod shell						
-9.2	-14.3	-3.7	0.477	0.0077	0.0165	*average Δ47: 0.482 ±0.0049‰*
-9.1	-14.3	-4.3	0.487	0.0080	0.0165	*temperature: 70.4 ±3.0°C (1s.e.)*

Table 2

$\delta^{13}C_{PDB}$ (‰)	$\delta^{18}O_{PDB}$ (‰)	$\delta^{18}O_{SMOW}$ (‰)	Δ_{47} (‰)	1se Δ_{47} analytical (‰)	1se Δ_{47} full (‰)
ME: *Lake Mead, NV (36.30214N, 114.41845W), 372 m, lake edge precipitate*					
-8.7	-9.2	-7.3	0.655	0.0090	0.0105
-9.3	-9.0	-7.1	0.655	0.0073	0.0084
-8.7	-11.1	-9.4	0.661	0.0033	0.0037
		average Δ47:	*0.657*	*±0.002‰*	
		temperature:	*22.7*	*±0.7ºC (1s.e.)*	
MO: *Mono Lake, CA (37.94406N, 119.02741W), 1899 m, tufa*					
7.1	-1.8	-1.6	0.695	0.0069	0.0193
7.1	-2.2	-1.3	0.679	0.0075	0.0189
7.1	-3.9	-2.7	0.674	0.0036	0.0094
		average Δ47:	*0.682*	*±0.006‰*	
		temperature:	*17.3*	*±1.5ºC (1s.e.)*	
CR: *Lake Crowley, CA (37.58176N, 118.7392W), 2058 m, lake edge precipitate*					
-1.9	-16.9	-17.5	0.714	0.0078	0.0081
-0.4	-14.4	-12.7	0.661	0.0078	0.0113
-1.1	-15.6	-14.2	0.668	0.0080	0.0099
		average Δ47:	*0.681*	*±0.017‰*	
		temperature:	*17.7*	*±3.5ºC (1s.e.)*	
BE: *Blue (Eagle) Lake, CO(39.753265N, 106.764134W), 2552 m, core top sediment*					
-5.1	-16.2	-16.0	0.727	0.0078	0.0130
-3.3	-12.9	-12.0	0.697	0.0070	0.0097
-5.0	-14.6	-13.5	0.658	0.0069	0.0090
-4.0	-14.6	-13.0	0.724	0.0072	0.0086
		average Δ47:	*0.702*	*±0.016‰*	
		temperature:	*13.4*	*±3.2ºC (1s.e.)*	
EM: *Emerald Lake, UT (39.074272N, 111.497257W), 3093 m, core top sediment*					
-1.1	-13.6	-15.0	0.732	0.0073	0.0091
0.8	-10.2	-9.8	0.690	0.0064	0.0088
-0.1	-11.9	-12.6	0.716	0.0094	0.0086
-0.2	-11.5	-13.6	0.748	0.0077	0.0073
		average Δ47:	*0.721*	*±0.012‰*	
		temperature:	*9.6*	*±2.4ºC (1s.e.)*	
SG: *S. Grizzly Creek Lake, CO (39.690184N, 107.319730W), 3242 m, core top sediment*					
-3.0	-14.6	-16.3	0.739	0.0093	0.0105
-3.3	-15.0	-13.8	0.673	0.0075	0.0085
-2.9	-14.6	-16.4	0.742	0.0072	0.0082
		average Δ47:	*0.718*	*±0.023‰*	
		temperature:	*10.2*	*±4.4ºC (1s.e.)*	

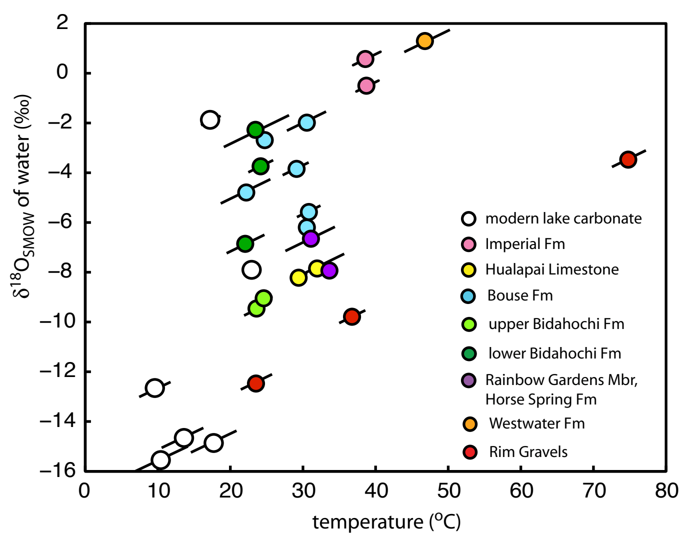

Figure 2. Temperature estimates from clumped isotope thermometry vs. δ18O of water in equilibrium with the carbonate, for modern and ancient samples listed in Tables 1 and 2. The δ18O of water was calculated from measured δ18O of carbonate and temperature from Δ47, using the carbonate-water fractionation factor of Kim and O'Neil (1997).

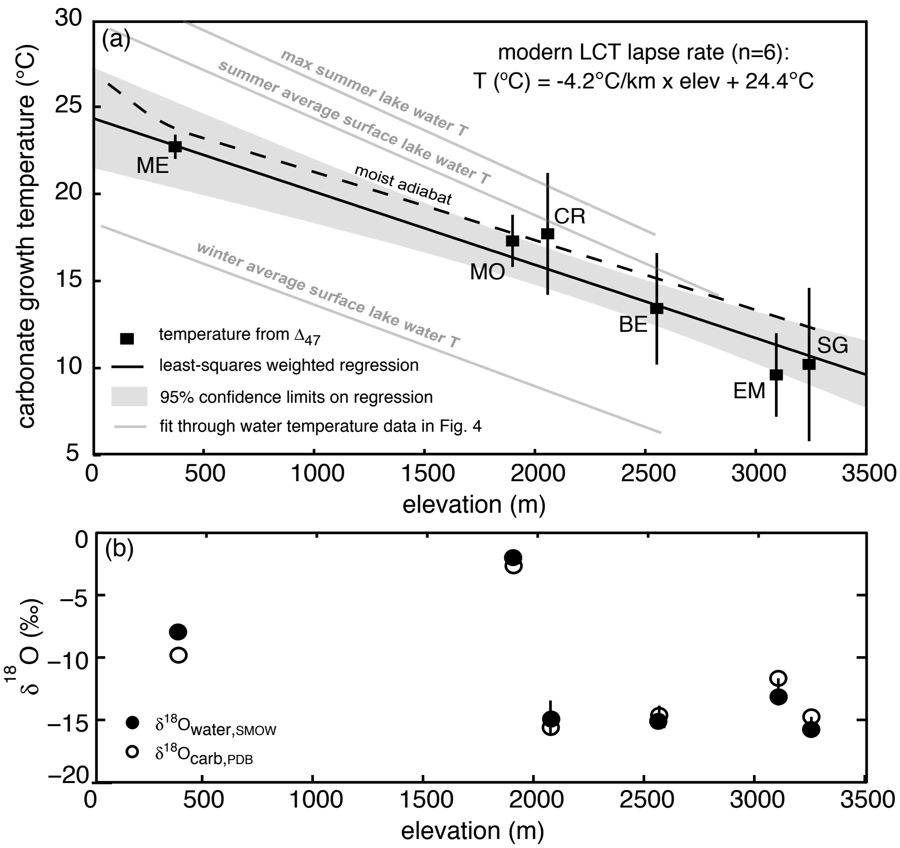

Figure 3. (a) Comparison of mid-latitude semi-arid lake surface water temperatures, modeled moist adiabat, and temperature estimates from modern carbonate sediments precipitated in lake waters as a function of elevation. Black squares represent clumped isotope thermometry results for modern lake carbonates listed in Table 2, with 1σ errors. Samples ME, BE, EM, and SG were collected within the modern Colorado River drainage. Solid line indicates best-fit York (1969) error-weighted linear least-squares regression through the temperature-elevation data. Best-fit water surface temperature curves (grey) are given by regressions through the data shown in Fig. 4. Dashed black line indicates modeled 'moist adiabat' lapse rate for 85% relative humidity (Schneider, 2007), for reference. (b) Open circles indicate δ18O of carbonate for the samples shown in (a) vs. elevation. Black circles indicate δ18O of the water in equilibrium with the carbonate vs. sample elevation.

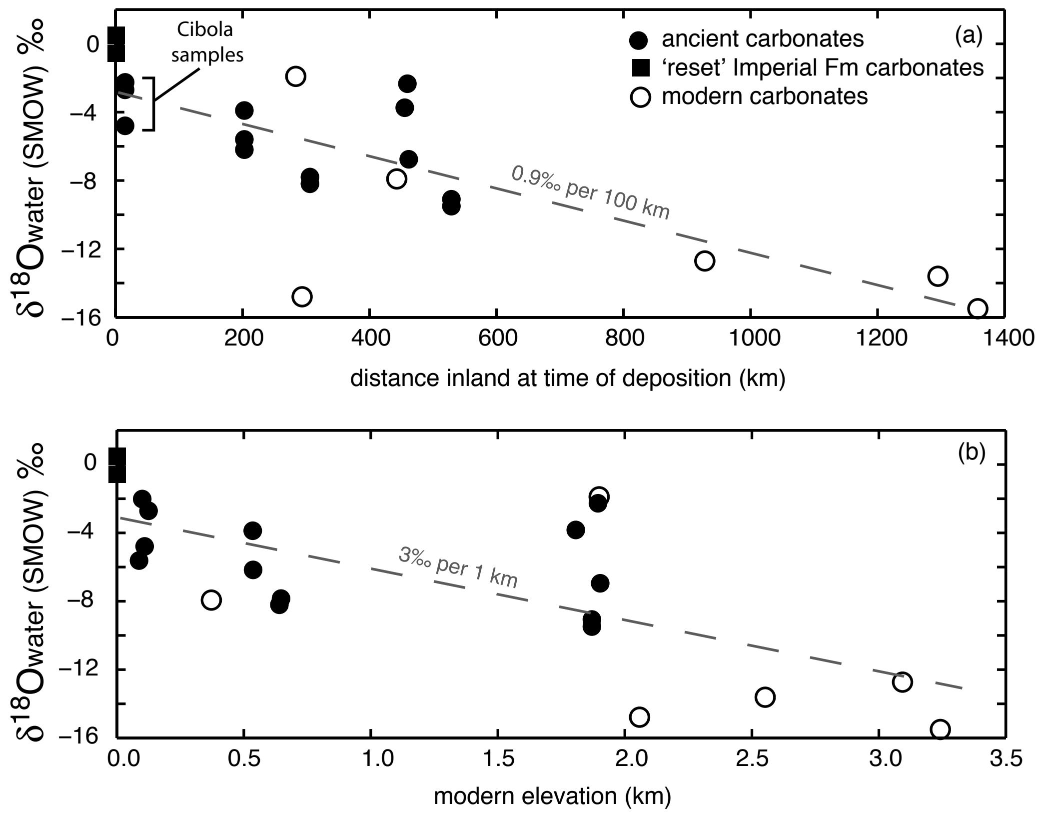

Figure 4. O isotope results for modern and ancient carbonates vs. elevation and inland distance. (a) δ18O of the water in equilibrium with the carbonate vs. distance inland at the time of deposition. Closest linear distance inland is plotted for modern samples. For the ancient carbonates, the Cibola samples were taken to be 15 km from the coast at the time of deposition. Distance inland for the other ancient carbonates was measured relative to the Cibola samples. Marine water plots at 0‰. (b) δ18O of the water in equilibrium with the carbonate vs. modern elevation above sea level of the deposit. Modern carbonate data are also plotted in Fig. 3b. In (a) and (b), the dashed lines indicate the simple best-fit linear regression through the modern and ancient data. The Imperial Formation samples are plotted for reference.

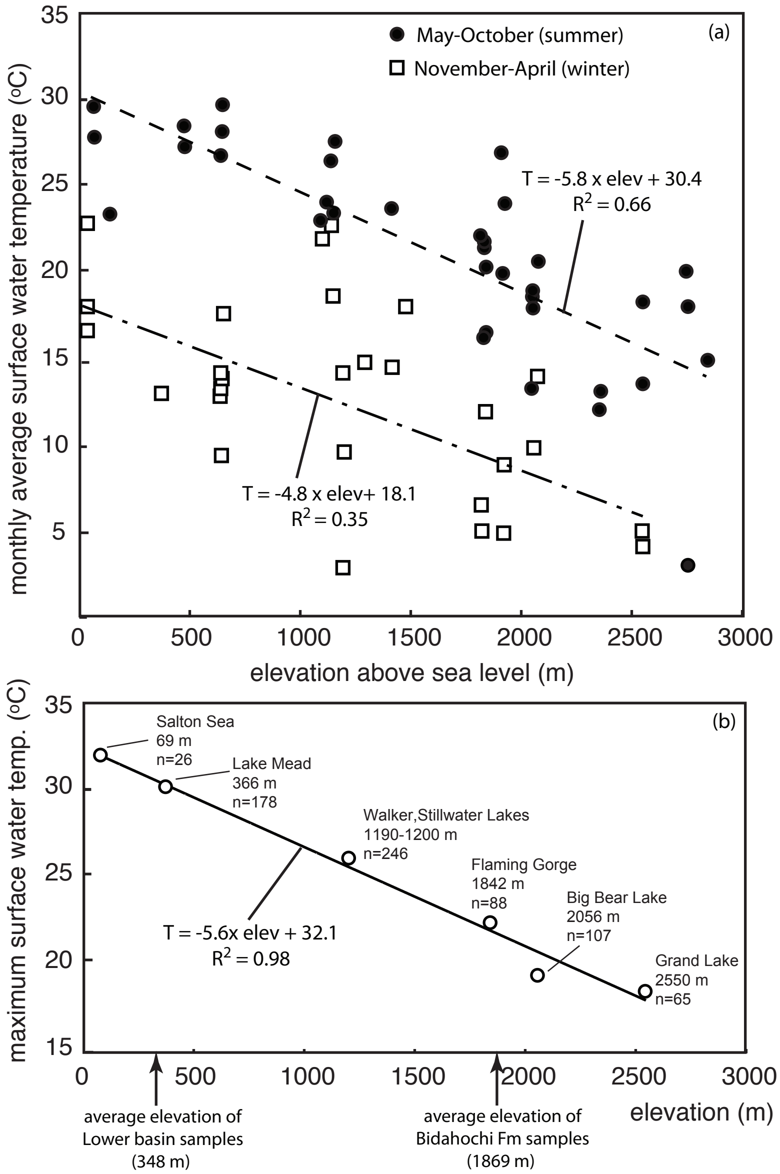

Figure 5. Lake surface water temperature (LST) measurements made between 1979 and 2007 for Colorado plateau area surface waters compiled from US Geological Survey Water Resources Data (http://waterdata.usgs.gov) (a) Surface water temperature measurements for lakes, ponds, and reservoirs in Arizona vs. elevation above sea level, binned according to season in which measurement was made (summer months: black circles; winter months: open squares). Dashed and dash-dot lines indicate LST lapse rates based on simple linear regression through data for summer and winter months, respectively. (b) Maximum surface water temperature observed between 1979 and 2007 for well-monitored water bodies in the Colorado plateau region, where n indicates the number of temperature observations for each water body.

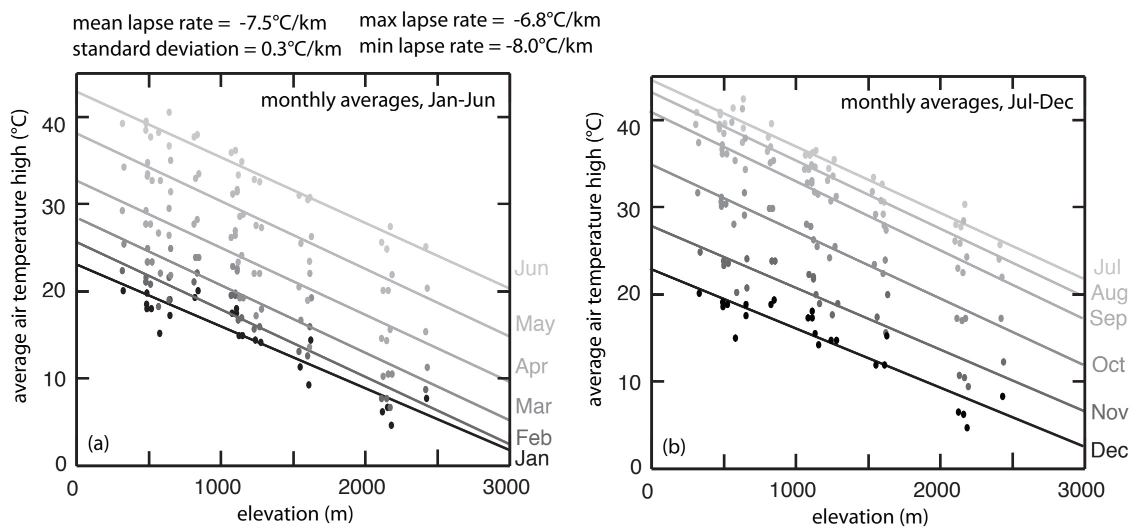

Figure 6. Air temperature lapse rates based on average of monthly air temperature highs recorded at 24 Arizona weather stations from 341 to 2441 m elevation above sea level between 1971 and 2000, compiled from the Desert Research Institute's Western Regional Climate Center data (http://www.wrcc.dri.edu) (a) Monthly average temperatures for January through June, with simple best-fit linear regression. (b) Monthly average temperatures for July through December, with simple best-fit linear regression.

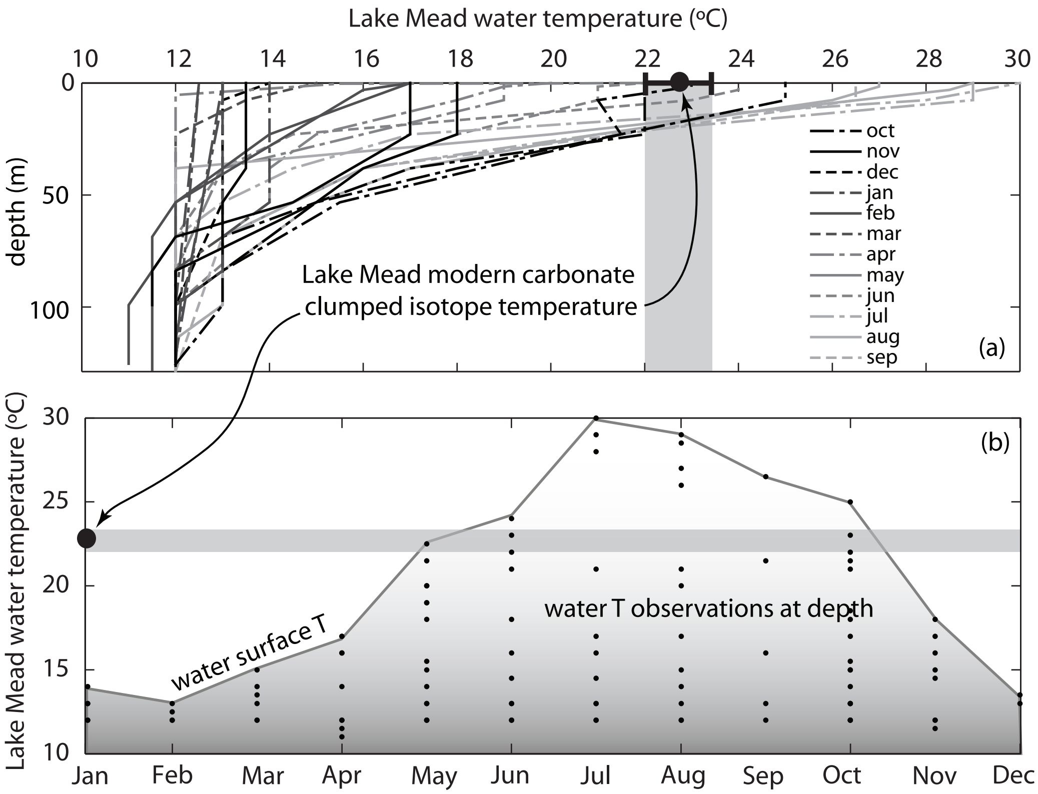

Figure 7. Lake Mead water temperature data compiled from US Geological Survey Water Resources Data (http://waterdata.usgs.gov). (a) Water temperature vs. depth profiles indicated by month during which observations were made. (b) Water temperature vs. month during which observations were made. The measured clumped isotope temperature of modern carbonate precipitated from Lake Mead (ME, Table 2) indicated on the figure is consistent with carbonate precipitation during spring/summer months (May to October), from near-surface lake waters.

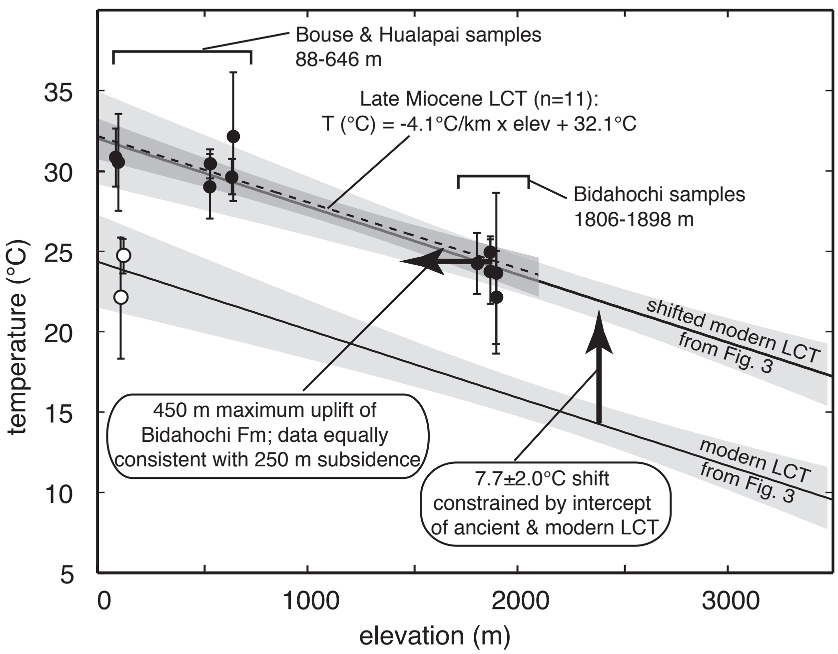

Figure 8. Carbonate clumped isotope thermometry temperature estimates vs. modern elevation for samples collected in the Colorado River basin. Data points marked by unfilled circles are interpreted to reflect cooling of lake surface temperatures by a marine climate; horizontal arrow indicates magnitude of post-6 Ma uplift of Bidahochi samples assuming minimal zero-elevation intercept of the LCT trend.

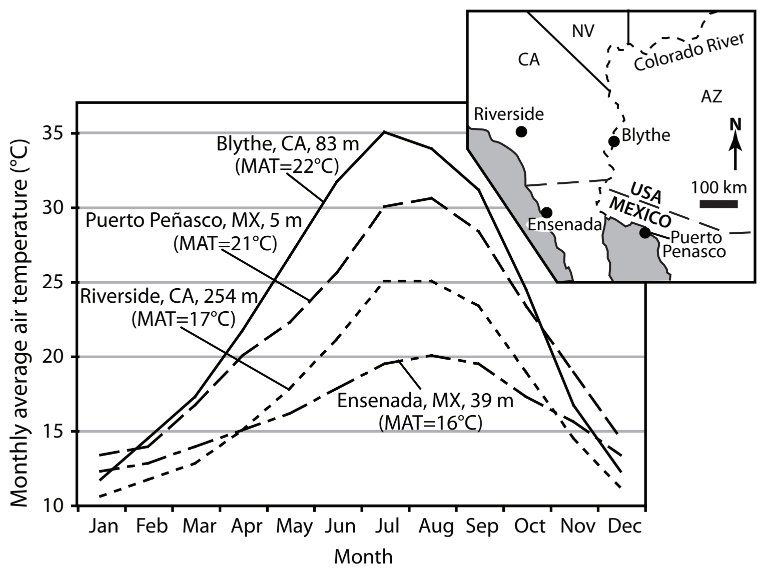

Figure 9. Mean monthly temperature curves for four cities in southwestern North America from the National Climatic Data Center (WeatherbaseSM), showing the climatic influence of proximity to the marine waters of the Gulf of California (Puerto Peñasco) and Pacific Ocean (Riverside and Ensenada).

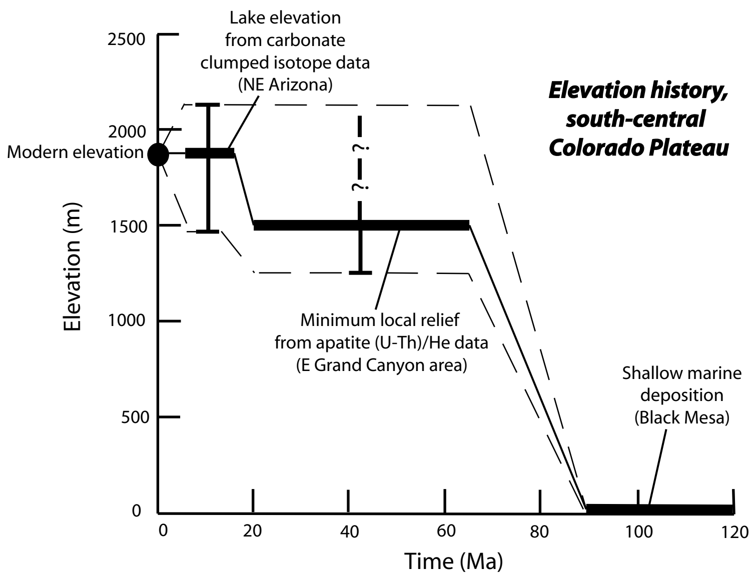

Figure 10. Plot showing elevation history of the southern interior of the Colorado Plateau based on the age of marine deposition (Nations, 1989), local relief inferred from (U-Th)/He dating (Flowers et al., 2008), and lake elevation of the Bidahochi Formation (this study).