**The Atacama Desert Cave Shredder: A Case for Conduction Thermodynamics.** T. N. Titus[1], J. J. Wynne[2], D. Ruby[3], and N. Cabrol[4]. [1]U.S. Geological Survey, Flagstaff, AZ 86001, [2]Merriam-Powell Center for Environmental Research, Dept. of Biological Sciences, Northern Arizona University, Flagstaff, AZ 86011, [3]Fleischmann Planetarium and Science Center, University of Nevada-Reno, Reno, NV, [4]NASA Ames Research Center, Space Science Division, MS 245-3, Moffett Field, CA 94035

**Introduction:** The interior temperature of a cave is controlled by heat transport through conduction, air convection, and water flow. Heat conduction occurs from above (surface temperatures) and from below (geothermal). Near entrances, especially skylights, temperatures can also be affected by solar insolation. The presence of water (which has a very high heat capacity) can affect cave temperatures through a variety of processes, including flowing underground rivers and ground seepage. In the high desert of the Atacama (northern Chile), where the rain fall is measured in mm/yr, caves are quite dry and near the surface [1-7]. In such a cave, if one is able to discount the effects of air flow, the rock temperature should be a function of only the thermal conduction through the rock, which is driven by the temperature changes at the surface [7-9]. We were able to use the principles of thermal conduction to accurately estimate the thickness of a cave roof (overburden) by simultaneously measuring the surface temperature and the dark zone temperature over a period of 10 months.

**Study Area:** We selected caves in the Atacama Desert of northern Chile due to the region's hyperaridity, which makes this area an ideal analog for Mars. Recent studies suggest that conditions there have been arid for 90 Ma [10-11] and regions within the desert have been hyper-arid for 10-15 Ma [12-14]. The level of rain in the hyper-arid core is virtually indistinguishable from zero; however, this region may once have been a much wetter place - much like Mars [2-3,5-6,15]. For this paper, we present the analysis of the thermal data from one of the caves – a cave referred to as "Shredder."

**The Theory**: If we assume that the temperature inside a cave is strictly determined by the heat conducted from the surface, then the interior temperature is determined by solving for thermal diffusion [1,7,9].

**Thermal Diffusion Equation:**

$$\frac{k}{\rho c}\frac{\partial^2 T}{\partial x^2}+\frac{dT}{dt}=0$$

, where k is the thermal conductivity, ρ is the density, c is the heat capacity, and T is the temperature.

Annual temperature behavior acquired deeper in the cave should have a longer phase lag and a greater attenuation of the thermal wave than temperatures closer to the surface. By solving the thermal diffusion equation, the depth of the cave ceiling can be solved either as a function of the phase lag or the attenuation of the annual temperature cycle.

**Resulting equation for phase lag:**

$$\Delta x_\ell = \sqrt{\frac{4\pi}{\tau}}\sqrt{\frac{k}{\rho c}}\Delta t$$

, where τ is the number of seconds in a year, Δt is the phase lag in number of seconds, and $\Delta x_\varphi$ is the estimated thickness.

**Resulting equation for attenuation:**

$$\Delta x_A = \sqrt{\frac{\tau}{\pi}}\sqrt{\frac{k}{\rho c}}\ln\left(\frac{A_0}{A_1}\right)$$

, $A_0$ and $A_1$ are the amplitudes of the annual thermal cycle of the surface and the dark zone, respectively.

The interior of Shredder cave was mapped using simple survey techniques that recorded distance, azimuth, and inclination. These data were compiled in an excel spreadsheet and converted to GPS coordinates. A GPS was then used to walk the surface and note elevation changes on the surface along the cave route. While not as accurate as needed for a comprehensive study, this method was sufficient to estimate the cave roof (surface overburden) thickness at the dark zone. A comparison between the cave profile and the surface elevations suggest that the roof overburden (or thickness) is 7.2 (±1.2) meters. This is a crude first-order estimate; more accurate surface survey methods (e.g. the use of a base station and roving stations to do differential GPS) are needed to further test our hypothesis that the Atacama cave dark zones are thermally well-behaved and can be used to accurately estimate cave roof thickness.

**Results:**

*Phase lag* – The phase lag between the surface temperature and the dark zone temperature is 102 days. If the phase lag is only due to thermal conduction, then the corresponding roof thickness is 5.6 meters. This is mostly a lower estimate of roof thickness as the measured phase lag may be influenced by convection within the cave, thus reducing the phase lag.

*Attenuation* – The attenuation of the amplitude of the annual thermal cycle from the surface to the dark zone corresponds to the roof thickness of 6.5 meters. Because the surface temperatures were measured under a cairn, the surface temperature amplitude is less than the expected amplitude if the sensor had been in direct sunlight. Once again, this would suggest that 6.5 meters is a lower limit to the cave roof thickness.

*Estimated Roof Thickness*. – We used cave map profiles, combined with GPS measurements to estimate that the cave roof thickness above the placement of the dark zone sensor was 7.2(±1.2) meters. This estimate is consistent with the lower-bound estimates, assuming that the dark zone temperatures are strictly due to conduction of heat from the surface.

**Figure 1: Surface above Shredder Cave, Valley of the Moon, Atacama Desert, Chile. Co-author and expedition lead is seen in the foreground.**

**Conclusions:** Over the past year, significant progress has been made in understanding the thermal behavior of caves in the Atacama. In regions with negligible water flow and geothermal activity, the rock temperature of cave walls can be predicted based on the surface temperature profile and the roof thickness/composition.

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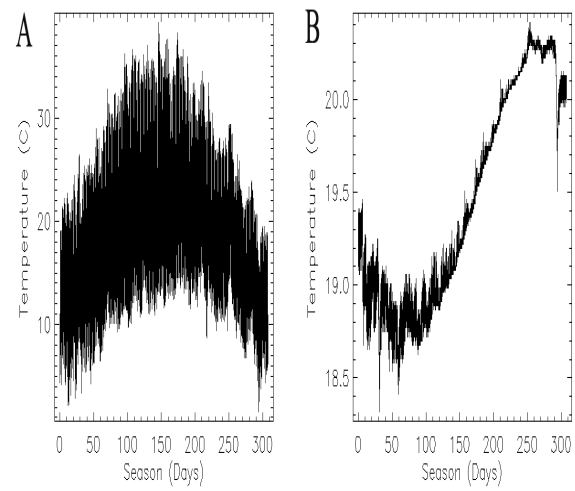


**Figure 2: Surface and dark zone temperatures from Shredder cave. (A) Surface Temperatures. (B) Dark zone temperatures. Comparison of these figures demonstrates both a phase lag and attenuation of the temperature curves.**

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