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I am submitting herewith a dissertation written by Craig James Hardgrove entitled "Remote Sensing of Sediments and Volatiles on the Martian Surface and Terrestrial Analog Sites." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geology.

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**REMOTE SENSING OF SEDIMENTS AND VOLATILES ON THE MARTIAN SURFACE AND
TERRESTRIAL ANALOG SITES**

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Craig James Hardgrove

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Dedication

To Mom and Dad

Acknowledgements

Graduate school has been a truly memorable experience, and one that would not have been possible without my advisor, Jeff Moersch. Somewhere in the blackness of night, while I was strapped into the backseat of a Cessna Jeff was piloting at 10,000 feet above Death Valley, I remember having the realization that Jeff had the unique opportunity to both figuratively and literally hold my life in his hands. In a way, I was fortunate we were flying at night, so that it was a little bit harder to actually see my life flash before my eyes. If I could have seen it, however, it might have looked a little something like this... Before I started graduate school, I had never been west of Houston, TX. Now, because of my experiences under Jeff's advising at UT, I have visited a volcano and walked on a glacier in Iceland, drank at the pubs of Ireland, eaten fish and chips in London, seen Sadaam Hussein's decoy jets in Tunisia, eaten gnocchis in Sardinia, visited coral suppliers in Los Angeles, walked through a bear infested forest in Montana, spent weeks alone in the middle of Death Valley, and discovered the absolute joy of eating In n' Out burger in Las Vegas. While we certainly got plenty of research done on these trips, this section isn't the part to talk about that and honestly, a lot of those really memorable moments come during the time spent in between research. In those moments, where Jeff and I could stop being scientists and just be nerds, I found a very good friend. I'm almost certain Jeff and I ran across each other while BBSing in the late 80's-early 90's but didn't know it. In addition, as a mentor and scientist Jeff has taught me how to critically evaluate problems from start to finish, how to write up my results well, and perhaps most importantly, how to do it all in style!

I could not have completed any of my neutron spectroscopy work, either on instrumentation or modeling, without the help of Darrell Drake. Darrell is an experienced nuclear physicist, whose advise and guidance were essential for me to complete this dissertation. He is also a ham. One time he phoned while I was driving home to answer a question I asked him regarding my neutron work. He asked how I was doing and I mentioned I was driving, to which he responded, "What?! Well, get off the phone you a-hole." We both laughed. Also, without the help of Chris "Alpaca of Pain" Whisner, I probably would have been eaten by coyotes on my first trip to Death Valley. His experience in the field, geologic intuition and uncontrollable, high-pitched laughter were all invaluable resources.

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Abstract

The role of water and volatiles in the solar system is of critical interest in planetary science. Evidence for the past action of water or direct observation of water on a planetary body can indicate the potential to harbor life and is critical to human exploration of the solar system. We study two very different remote sensing techniques that address the issue of identifying water-related processes on the surface of other planetary bodies, and in particular, Mars. The first technique, combined thermal infrared and visible imaging, has been used extensively on Mars for determining the thermal inertia of surface materials. In the second part of this dissertation, we develop a technique that combines remote thermophysical and visible data sets with ground-based field investigations for the identification of sedimentary features at the surfaces of alluvial fans. Several methods for remotely identifying sedimentary features will be explored using thermal and visible images. We combine results from pre-existing ground-based studies with thermal images and ground-based field investigations to develop a robust technique to be used on a variety of alluvial fans. In the third part, we characterize the remote thermophysical and visible properties of specific classes of sedimentary features on alluvial fans using the technique developed in part two.

The second remote sensing technique, neutron spectroscopy, has been used on many planetary spacecraft missions for the identification of hydrogen on planetary surfaces. The Dynamic Albedo of Neutrons (DAN) instrument on the upcoming Mars Science Laboratory rover mission represents a new type of neutron detector for planetary spacecraft, with the neutron detectors mounted to a rover on the Martian surface (as opposed to in orbit around the planetary body) and neutron counts that are binned by time, energy, and location (as opposed to just by energy and location). In part four, we model expected neutron energies and arrival times for geologic settings where water has altered the chemistry of the near surface using available geochemical data from the Mars Exploration Rovers (MER). Particle transport models are used to determine the sensitivity of neutron detection techniques to the variations in hydrogen abundance, hydrogen layering and chemical composition measured by MER.

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Part 1

Introduction

1. Remote Sensing of Alluvial Fans

Many recent observations of Mars have shown a diverse range of sedimentary deposits. Malin and Edgett (2003) describe a fan-shaped apron of debris with meandering distributary channels in a crater seen in MOC and THEMIS images. Ponderelli *et al.* (2004) also describe morphological features in THEMIS visible images that they claim are indicative of a deltaic environment at the point where Uzboi Vallis debouches into Holden Crater. One of the fans described in the aforementioned abstract by Ponderelli *et al.* (2004) shows a constant dip in topographic profile, consistent with subaerial deposition. Moore and Howard (2005) describe several dozen large (10-40 km) alluvial fans using morphometric analyses from Mars Orbiter Laser Altimeter (MOLA) profiles and THEMIS daytime infrared images. Their comparison of these fans with a variety of terrestrial alluvial fans suggests the Martian examples formed via fluvial processes, as opposed to mud flows. Moore and Howard (2005) also present an analysis of one fan using a THEMIS nighttime infrared image. Ridges radiating from the apex across the surface of the fan are relatively warm, and therefore have a higher thermal inertia, indicative of a coarser or more indurated material than the immediate surroundings. Williams *et al.* (2008) have also identified sub-km fan features within Mojave Crater on Mars. These fans have branching tributary networks, distributary channels and inverted relief features that are common to terrestrial alluvial fans. Kraal *et al.* (2008) provide a catalog of large alluvial fan features within impact craters on Mars. Other Martian fan deposits have been described that are likely to be alluvial.

To date, no work has been done using thermophysical mapping to study terrestrial analogs for Martian sedimentary features. Kahle (1987) made a cursory examination of thermal inertia features in Death Valley's Middle Basin using the airborne Thermal Infrared Multispectral Scanner (TIMS), but her work was mostly focused on multispectral emissivity mapping of bedrock, a relatively unexplored technique at the time. Even earlier work using low quality (by today's standards) airborne and satellite thermal images established the feasibility of using thermal inertia to distinguish geologic features (see Abrams, *et al.*, 1984 and references reviewed therein). However, the emphasis in this work was on regional-scale mapping, rather than examining the similarities and differences in spatial-thermophysical properties of specific classes of sedimentary features.

In part two, we develop a technique for studying sedimentary features on alluvial fans by combining aerial thermal and visible imaging with ground-based field work (Hardgrove *et al.*, 2009). Several thermophysical methods for remotely identifying sedimentary features will be explored using thermal and visible images. We combine results from pre-existing ground-based studies with aerial thermal images and ground-based field investigations to develop a robust technique that can be used on a variety of alluvial fans. Thermophysical mapping is a useful tool for analysis of sedimentary features primarily because the thermal inertia of a surface is a function of the surface's particle size and degree of induration. Methods have been developed for calculations of "Apparent Thermal Inertias" (ATI) (Watson, 1975) which can be used to quantitatively and qualitatively compare thermophysical signatures between sedimentary features. In this investigation, we examine a variety of thermophysical techniques (i.e. ground-based diurnal temperature curve analysis, aerial temperature difference images, aerial ATI images) for assessing sedimentary features on the surfaces of alluvial fans. Using grain size measurements and geologic surface maps for a representative, well-studied alluvial fan, we develop a combined thermophysical and visible mapping technique that best reveals surface sedimentary features on alluvial fans in part two.

In part three, we apply the technique developed in part two to a suite of alluvial fans in the desert southwest (Hardgrove *et al.*, 2010). We choose fans that have a variety of surface sedimentary features, representative of different depositional environments and processes. This is accomplished through ground-based field investigations of alluvial fans, where we identify unique sedimentary features, acquire grain-size information and assess relationships between sedimentary features on the fans' surface. Once our suite of alluvial fans is established, we acquire high-resolution aerial thermal imaging of each alluvial fan. After data processing we identify, through ground-truth of our remotely acquired images, the sedimentary features on each alluvial fan. In part two, we produce a catalog of sedimentary features that can be identified using remote thermophysical and visible images. (e.g., Mars or remote places on Earth) and add to the available toolkit of remote techniques for studying these features in remote areas.

1.1 Addendum

The work presented in parts two and three of this dissertation was completed in early 2009. As the study of alluvial fans on Earth and Mars is an ongoing and active areas of research, the results of several, more recent publications are presented here. Haug et al., (2010) have recognized the importance of studying grain size within alluvial fan surface channels. Specifically, they show how the grain-size distribution of surface flows on alluvial fan channels are related to the precipitation rates in the Atacama desert in Chile (Haug et al., 2010). On Mars, in addition to the identification of sub-kilometer scale fans with incised channels, gullies and lobate materials by Williams et al., (2008), Williams et al., (2010) have identified a large alluvial fan with two distinct thermophysical surface units. These units correspond to topographically-raised, sinuous features of relatively higher thermal inertia and a friable, lobate, linear feature that extends from the apex to the distal regions of the fan. This lobate feature corresponds to a relatively thermal inertia unit. The inverted-relief sinuous features are overlain by the lobate, linear feature, indicating two distinct depositional periods in the fan's development. This represents one of the first studies to combine visible and thermal infrared data to study sedimentary features on Mars (Williams et al., 2010).

We also note that non-unit emissivities are not discussed in parts two and three. The FLIR thermal camera utilized in these studies is sensitive to a broadband (8-12 μm) wavelength region and assumes an emissivity of one for all surface materials. Geologic materials may not emit thermal radiation continuously across this wavelength region, which could result in erroneous temperatures reported by the thermal camera. The errors in reported temperatures can be related to uncertainties in emissivity by the Stefan-Boltzmann law, which states that the total radiance emitted by a surface in a given wavelength region is proportional to its emissivity times its temperature to the fourth power. A surface at 300 K, with an uncertainty of 10% in the broadband emissivity (the expected variability for common geologic materials) will have an uncertainty of approximately $\sim 2.6\%$ in temperature. The technique presented in parts two and three, however, utilizes temperature difference images where night-time temperature images have been subtracted from day-time temperature images. As temperature increases, the uncertainty in emissivity leads to larger uncertainties in the measured temperature (by the Stefan-Boltzmann law), however, for the range of temperatures presented in parts two and three, the uncertainty increases by less than 0.1%. By using

temperature difference images, uncertainties in emissivity are diminished as the total change in temperature for any surface geologic material will stay the same regardless of its emissivity.

2. Neutron Detection

Neutron detectors provide a means of estimating how much hydrogen is present in the near-surface of a planetary body. Neutrons have been used to measure the abundance of hydrogen at the lunar poles (Feldman et al., 1998, 2000a, 2001; Maurice et al., 2003; Lawrence et al., 2006) from the Lunar Prospector spacecraft, and globally on Mars (Feldman et al., 2002b; Mitrofanov et al., 2002; Feldman et al., 2004) from the Mars Odyssey (MO) spacecraft. In the context of planetary exploration, neutron detectors have, to date, only been used in orbital remote sensing applications. Several limitations are inherent to this measurement geometry, with the most critical being poor spatial resolution. One way to achieve higher spatial resolution is to lower the instrument's altitude so that less of the surface is within its field of view.

In part four, we characterize the expected neutron fluxes for a rover-based neutron detector. We use nuclear particle transport computational models to determine the expected neutron fluxes for a variety of Martian near-surface geochemistries using. These models are also used to determine the sensitivity of neutron detection techniques to variations in hydrogen abundance, layering and chemical composition. Whereas previous studies (Busch *et al.*, 2009 and Litvak *et al.*, 2008) modeled rover-based neutron detector response to variations in hydrogen abundance in the near-surface, here we will refine these results to incorporate the confounding effects of high neutron absorbing elements on the energy distributions of neutrons. On Mars, increased abundances of high neutron absorbing elements, like Cl and Fe, can represent chemical evidence for signal the interaction of water with the near-surface materials.

3. Summary

The combined thermophysical and visible technique developed in part two provides a useful tool for planetary scientists who wish to use thermophysical datasets to interpret the sedimentary history of the Martian surface. The

variety of sedimentary features identified using this technique on terrestrial alluvial fans in part three can be used as a guide to interpreting these types of data on other planetary surfaces and suggests the technique may also be useful in studying other sedimentary constructs that have characteristic grain size distributions. The results of part four show that high thermal neutron absorbing elements have a profound effect on the number of neutrons that will be detected by the DAN instrument. Modeled neutron die-away curves for MER Spirit and Opportunity compositions show that Martian rocks and soils which have undergone aqueous alteration in the past can influence neutron die-away measurements acquired by DAN.

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Part 2

Thermal Imaging of Alluvial Fans: A New Technique for Remote Classification of Sedimentary Features

This part is a reformatted version of a paper by the same name published in *Earth and Planetary Science Letters* in 2009 by Craig James Hardgrove, Jeffrey Moersch, and Stephen Whisner. All data analyses were performed by Craig Hardgrove.

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Abstract

We evaluate the utility of remote thermal image data for mapping geomorphic features and evidence of sedimentary processes on the surfaces of alluvial fans. Prior studies of alluvial fans have made extensive use of visible images and traditional field-based techniques. As a case study demonstration of this technique, we compare thermal images acquired from the ground and a light aircraft (altitude ~5000 ft) to a preexisting ground-based map of features on the Dolomite Fan in Owens Valley, California. Thermal images from the aircraft were acquired at several times of day to determine how the surface temperatures of the alluvial fan rise and fall throughout a diurnal cycle. We have also acquired thermal images from the ground at 5 minute intervals over the course of a diurnal cycle. The aerial thermal images (ground resolution ~2m/pixel) reveal evidence of a variety of sedimentary processes that have acted on the fan surface. These images show spatial-thermophysical patterns associated with clast-rich and clast-poor debris flows, debris-flow levees and the change in particle size at the toe of the fan. The locations of these features in the thermal images match the locations of the features previously mapped by others using traditional ground-based field sedimentology techniques. All debris flows that are exposed at the fan surface are evident in the aerial thermal images, including those that have been heavily weathered and are difficult to observe in visible images. This case study demonstrates that aerial thermal images can be used to provide reconnaissance of an alluvial fan, suggest what sedimentary processes have most recently acted on the surface of the fan, and to prioritize sites for detailed study on the ground.

1. Introduction

Alluvial fans form where high-gradient, confined, sediment-laden streams empty sub-aerially onto low-gradient, unconfined surfaces. The abrupt decrease in competence and capacity associated with the loss of stream energy at

the break in slope results in deposition of sediments that build the fan. Within this general depositional context, smaller-scale depositional and erosional processes act to distribute the sediment along the fan surface in patterns characteristic of the sedimentary process that transported them. Prior studies of alluvial fans have made extensive use of visible images and traditional field-based techniques to identify and map these surface features. The purpose of the present study is to demonstrate the utility of using thermal infrared images for remote mapping of these features. We will determine whether spatial-thermophysical patterns that are representative of sedimentary processes are observable at the surface of an example alluvial fan. This is accomplished through comparison of our remotely-acquired thermal images to a preexisting ground-based map of the Dolomite Fan in Owens Valley, California (Blair and McPherson, 1998).

In an arid climate with low vegetation cover, the temperature of a surface at any given time of day is a complex function of many parameters, including slope, azimuth, composition, degree of induration, and particle size. By analyzing the temperatures on the surface of an alluvial fan with comparable slopes, azimuth, and composition, we make estimates of the relative particle size or degree of induration. We utilize the fact that several sedimentary processes acting on the surface of alluvial fans sort particles by size. For example, both debris flow and channelized flow processes can form linear features of large and small clasts. Therefore, thermal images could be expected to reveal evidence of these processes at the surfaces of alluvial fans in the form of spatial patterns of thermophysical properties. Additionally, the use of remotely-acquired thermal data allows us to study sedimentary processes on alluvial fans where ground truth data are not available. This has the potential to be particularly useful in mapping sedimentary processes on Mars, where many alluvial fans have been proposed (*e.g.* Moore and Howard, 2003, Malin and Edgett, 2003, Kraal, E., 2008).

2. Background

2.1 Sedimentology of Fans

The type of particle size distribution found on alluvial fans is primarily related to both the sediment source and the sedimentary processes that have acted on the fan. Fan particle-size distributions are complicated, but there is a

nominal trend toward larger particles (sometimes called “fanglomerates”) in the upper fan, intermediate particle sizes in the midfan, and smaller particles in the distal fan, or fanbase (Boggs, 2001). Upper fan particle sizes can be as large as boulder-sized, and distal fan particle sizes can be sand-sized or smaller (Blissenbach, 1954). However, this conceptualization is oversimplified for most alluvial fans, as their surfaces are often reworked by overland water flow and winnowing of fines by aeolian processes. The alluvial fan is primarily composed of sediment from major, yet infrequent events that deposit the majority of fan sediments. Debris flows, incised channel floods, and sheetfloods are examples of processes that deposit large quantities of fan sediment. These large-scale deposits can then be reworked by decades of small-scale surface modification by rainfall or wind blown sand (Blair and McPherson, 1994). The surface particle size distribution will be representative of both the large-scale depositional processes and the reworking by smaller scale weathering processes.

Blair and McPherson (1994) studied the processes that operated on alluvial fans. They showed that sediments deposited by debris flows can be either clast-rich or clast-poor and will overlie pre-existing surface features. Clast-rich debris flows deposit a large percentage of the coarse component at the surface. They will also form debris flow levees, which are paired linear features that lie on opposite margins of the debris flow. Prolonged exposure to surface weathering processes will winnow away the finer components of the clast-rich debris flow and what remains will be the largest particle size component, forming an outline of the remnant debris flow. Clast-poor debris flows tend to form during the waning stage of a depositional event and leave a thin mantle of fines that drape over pre-existing deposits. Incised channel deposits tend to sort material within the channel into larger particle sizes near the center of the channel and smaller particle sizes along the margins of the channel. On many fans, repeated annual overland flow or aeolian activity will result in a sand skirt of fine material at the toe of the alluvial fan. Although the absolute particle sizes in these deposits can vary from fan to fan due to differences in source material, relative particle size patterns are consistent.

2.2 Thermophysical Remote Sensing

Thermal inertia, I , can be thought of as a surface’s ability conduct and store heat during the day and re-radiate it away at night in the thermal infrared portion of the spectrum. It is defined as $I = (k\rho C)^{1/2}$, where k is the thermal

conductivity, ρ is the bulk density, and C is the specific heat capacity of the surface (Kieffer, 1977). Thermal inertia has two primary effects on the shape of a surface's diurnal temperature curve. First, all other factors being equal, a low thermal inertia surface will experience higher peak temperatures and lower minimum temperatures than a high thermal inertia surface because the low thermal inertia surface heats and cools faster. Second, the time of day at which a low thermal inertia surface experiences its peak temperature will be close to local solar noon, whereas a high thermal inertia surface may not reach its peak until later in the afternoon. Surface slope and azimuth can also change diurnal temperature curves, as these variables affect the amount and timing of insolation the surface receives over a day-night cycle. A reasonable first order approximation to remove these geometric effects is to observe temperatures in the pre-dawn hours, when the effects of topography are muted. Another advantage of pre-dawn observations is that surfaces of different thermal inertias have cooled overnight at different rates, maximizing the variations in temperature between them (Watson, 1975; Watson, 1982; Colwell and Jakosky, 2002; Gupta, 2003).

For rocks and soils, bulk density (ρ) does not vary significantly. For a dry surface, the specific heat capacity (C) also does not vary significantly. Therefore, variations in thermal inertia are primarily due to variations in thermal conductivity (k) (e.g. Kieffer, 1977, Gupta, 2003). The primary controls on thermal conductivity of a dry surface are particle size and the degree of induration of the regolith (Kieffer, 1977). A surface composed primarily of bedrock or large ($> \sim 10$ cm) rocks has a very high thermal inertia, whereas a thermally-thick regolith of fine-grained dust has a very low thermal inertia. In very fine regolith, thermal inertia is controlled by the efficiency of thermal conduction in the pore spaces between grains (Jakosky, 1986). At larger particle sizes, thermal inertia is controlled by the size of the particle compared to the diurnal thermal skin depth (~ 10 cm for rock). At particle sizes above this scale, all rocks begin to look like bedrock in terms of their thermal inertia. A well-indurated (e.g., cemented) regolith of fine particles will have a thermal inertia more like solid rock than fines. In general, thermal inertia is sensitive to particle sizes ranging from dust size to cobble size.

It is important to note that diurnal temperature variations of geologic surfaces are not strongly influenced by the thermophysical properties of materials deeper than approximately one diurnal thermal skin depth (approximately 1 cm for sand and 10 cm for rocks, respectively). Therefore, thermal images are only useful for mapping sedimentary features at or near the surface. This means that the technique is not useful for characterizing the types of processes

that have volumetrically dominated the construction of the fan (e.g., identifying a fan as “debris flow dominated” or “fluvially dominated”). Typically, only the most recent processes that have overprinted the fan will be evident.

3. Methods

All thermal image data were acquired with a FLIR Systems ThermoCam S45 thermal infrared camera. The camera operates in the 7.5-13- μm telluric transmissivity window, and has an absolute temperature accuracy of 2K at ambient temperatures relevant for geologic studies. Relative pixel-to-pixel temperature accuracy is about 0.1K. The field of regard is $24^{\circ}\times 18^{\circ}$ across a 320x240 pixel array, giving the camera a pixel IFOV of 1.3 mrad. Images are captured at 60 Hz, which in practical terms means pixel blur from a light aircraft platform is not a problem at altitudes of about 3000' or greater above the terrain. The camera is able to auto-capture images at user-defined intervals, so that the camera need not be disturbed when taking time-sequences from a fixed location on the ground. We have written custom software that converts images from the manufacturer's digital image format into files for use in the Environment for Visualizing Images (ENVI) remote sensing software suite.

Thermal images are acquired in two different modes. For the first mode, time-lapse images are obtained by mounting the camera to a tripod on the ground at a position that allows the entire fan to fit within the camera's field of regard. Images in this mode are acquired at regular, short intervals (every few minutes) over the course of at least one diurnal cycle. Concurrent meteorological observations (air temperature, humidity, and barometric pressure) are made with a Nielson-Kellerman Kestrel 4000 pocket weather station. Images from the time-lapse sequence are stacked into a single data product called a hypertemporal image cube, in which two dimensions are the spatial dimensions of the scene and the third dimension is time of day. Temperature values extracted for a single spatial pixel along the time axis of this image cube comprise a diurnal thermal curve for that pixel's location.

The hypertemporal image cube of the target alluvial fan will display variations in diurnal temperature curves across its surface, as shown in Figure A1. The two example pixels in Figure A1 have significantly different diurnal temperature curves, representing two different thermal inertia surfaces. The higher thermal inertia (red) pixel displays a smaller day/night temperature change, is slower to rise in temperature after sunrise, and is slower to cool

after the time of peak temperature. The lower thermal inertia (blue) pixel displays a larger day/night temperature change, quickly rises in temperature after sunrise and rises drop in temperature at time of peak temperature. Figure A1 also shows that the greatest difference in temperature between the two pixels occurs in the pre-dawn hours and before local noon. These times of day provide the highest contrast thermal images for surfaces with different thermal inertias.

In the second mode of operation, individual images of the target alluvial fan are acquired at selected times of day and night from a light aircraft to give an overhead perspective similar to that seen from orbit, but at higher spatial resolution. As with ground-based data, pre-dawn arial images were found to be optimal for seeing contrasts in thermal inertia because topographic effects are muted at this time of day and surfaces with different thermal inertias have a relatively large spread in temperature (*e.g.* Gupta, 2003). Daytime thermal and visible images are also acquired during the same 24-hour period from the same airborne vantage points as the pre-dawn images by using an aviation GPS unit.

Sophisticated multivariable analytical models for the diurnal thermal behavior of terrestrial surfaces have been developed (*e.g.* Watson, 2000), but here we make the simplifying assumption that thermal inertia is inversely proportional to the change in surface temperature between pre-dawn and mid-day (ΔT). This assumption was necessary in acquisition of our aerial data because it was logistically impossible to acquire thermal images sampled frequently over the entire diurnal cycle. The ΔT approach affords us better separation between surfaces of different thermal inertias than would be available from a single temperature image because the temperatures of high vs. low thermal inertia surfaces trend in opposite directions in day vs. night images. Because the thermal radiance measured by the camera is non-linearly dependent on surface temperatures, mid-day thermal images are disproportionately sensitive to smaller grains that heat up quickly during the day and pre-dawn thermal images are particularly sensitive to larger grains that stay warmer at night. The ΔT image is therefore optimally sensitive to both larger and smaller grain sizes. The ΔT image also partially eliminates the effects of albedo on the diurnal temperature curve. Changes in albedo primarily shift the entire diurnal temperature curve up or down because of differences in how much insolation different albedo surfaces absorb (Figure A2 a). The primary effect on diurnal thermal curves of differences in thermal inertia, on the other hand, is to change the total daily temperature swing of the surface (Figure

A2 b). Therefore, by differencing the maximum and minimum temperature image, the ΔT image is sensitive primarily to the thermal inertia of the surface and not its albedo. Large-scale slope effects are reduced because the entire fan is generally oriented with surfaces facing to the west. As documented by Blair and McPherson, the fan has two discrete slope segments, where within those segments the slope is continuous. The overall average radial slope of the fan is 8.4 degrees (Blair and McPherson, 1998). Smaller-scale slope effects and shadows are not taken into account, however, as will be seen, these approximations are adequate for revealing surface thermophysical heterogeneities associated with differences in particle size and/or induration in the scene. We note, however, that the ΔT image only allows for derivation of relative thermal inertias, not absolute thermal inertia values. Because of this, we make no attempt to derive absolute grain sizes from our remote datasets – only relative grain sizes are discussed.

To choose our two times of day for acquisition of aerial data, we used our ground-based hypertemporal image cube acquired at 5 minute intervals. We selected times of day during which surfaces of different thermal inertias had the greatest separation in temperature - 3:30 to 5:00 AM local time for pre-dawn images and 11:00 to 12:30 AM local time for mid-day images. By co-registering and differencing the mid-day and pre-dawn aerial thermal images, we derive a new image in which pixel values approximate the diurnal change in temperature. Pixels with a high change in temperature contain relatively lower thermal inertia materials, and pixels with low temperature changes contain relatively higher thermal inertia materials. Because lower thermal inertias correspond to smaller particle sizes, this “delta-temperature” (ΔT) image shows the spatial distribution of relative particle sizes (or, in some areas of high thermal inertia, areas of induration). A 1st-order polynomial fit was used to warp the pre-dawn image to the mid-day image so that the image subtraction could be performed. The resulting error from the warping was +/- 8 meters/pixel, which represents the number of pixels that the pre-warped image deviates from the derived polynomial used for the warping.

4. Data

To test the methods described in Section 3, we have acquired data for the Dolomite Fan, which lies on the eastern side of Owens Valley in the arid southwestern United States Basin and Range extensional province (Figure A3).

This fan was chosen for our study because of extensive preexisting characterization using traditional field methods by Blair and McPherson (1998). The Owens Valley is a north-south oriented extensional basin. It is a classic graben system with a down-dropped block forming the valley floor and uplifted rocks forming the high mountains bounding it (Pakiser *et al.*, 1964). The eastern side of Owens Valley is bounded by the White-Inyo Mountains, which are composed of mixed lithologies as opposed to the primarily igneous lithology of the Sierra Nevada to the west (Bierman *et al.*, 1991). Owens Valley is a good choice to test this new technique because it lies within the rain shadow of the eastern Sierra Nevada and receives water mostly in the form of infrequent thunderstorms or from snowmelt. This aridity minimizes vegetation and the effects of moisture on the fans studied.

The Dolomite Fan has a typical conical fan shape, an apex elevation of 1,220 meters and a maximum relief of 80 meters. It is 515 meters wide at its maximum extent, extends radially for about 540 meters and covers an area of 0.26 km². The Dolomite Fan provides us with the opportunity to observe an alluvial fan that has undergone primary deposition in its recent history. This allows us to observe a relatively pristine alluvial fan surface, as it should appear with minimal reworking by secondary processes. In August, 1984, a multiphase debris flow was triggered by a thunderstorm in Owens Valley. The main deposition took place in two main debris flows on the northern and southern edges of the fan. The deposits vary in thickness from 10 to 300 cm and cover approximately 26% of the fan surface. The debris flow levees and lobes created by the flow generally consist of muddy, pebbly, and cobbly deposits, in varying proportions, leading to differences in average particle size. Debris flow levees, which are found around the margins of the flows, tend to be predominately clast-supported and contain a higher fraction of boulders, giving them a relatively high average particle size. The debris flows interior to the levees are also clast-rich but matrix supported, giving them a somewhat lower average particle size. The distal ends of the clast-rich lobes are overlain by off-fan wash materials which are rich in mud, giving them a lower average particle size (Blair and McPherson, 1998).

Using a traditional field sedimentological approach, Blair and McPherson (1998) produced a surface map of the features on the Dolomite Fan (Figure A4), which included the locations of both older and recent debris-flow lobes and levees, the off-fan wash and the break in slope near the toe of the fan. They performed particle size

measurements at 8 stations along the 1984 debris flows, which provide us with a means to verify our thermal image interpretations (Section 5).

We have acquired ground-based thermal images of the Dolomite Fan over the 24-hour period starting at 8AM local time on December 30th, 2007. Images were collected at 5 minute intervals over the full diurnal cycle, resulting in 288 images containing $\sim 2.3 \times 10^7$ individual temperature measurements. The stacked images were compiled into an 87 Mb hypertemporal image cube. Our aerial thermal images of the Dolomite Fan were acquired at 7:00 AM local time on March 29th, 2008 (just before sunrise) and 11:30 AM on the same day. Aerial visible images were acquired concurrently with the aerial mid-day thermal images. Figure A5 shows the mid-day and pre-dawn thermal images of the fan. Figure A6 shows the ΔT image, derived as described in Section 3. The corresponding visible image is shown in Figure A7.

5. Analysis and Interpretation

To evaluate the utility of our remote thermal imaging approach to mapping sedimentary processes on alluvial fans, we first validate the ability of the thermal data to distinguish different particle size distributions by quantitatively comparing ΔT values from our images to particle size measurements previously made on the ground using traditional sedimentological techniques. Then we qualitatively compare the spatial-thermophysical patterns seen in our thermal images with a surface feature map made on the ground.

The aforementioned particle size measurements made at eight stations on the Dolomite Fan by Blair and McPherson (1998) consist of fractional abundances for three broad particle size categories: gravel (greater than 2mm in diameter), sand (less than 2mm, greater than 0.06 mm in diameter), and mud (less than 0.06 mm in diameter) (Table 1). Figure A8 shows that there is a monotonic correlation between ΔT measurements from our images and the fractional abundance of mud (Figure A8 *top*). There is also a monotonic inverse correlation between ΔT measurements from our images and the fractional abundance of gravel (Figure A8 *bottom*). This demonstrates that our thermal difference images are sensitive to differences in particle size distributions, as expected. A comparison

of our ΔT measurements with Blair and McPherson's (1998) fractional abundances for sand (not shown) indicates that these parameters are not well-correlated. We speculate that the reason for this is that values in our ΔT image are largely determined by the extremes of the particle size distribution, not the intermediate particle sizes. The total radiance captured in a given pixel is dominated by the warmest sub-pixel component due to the highly non-linear dependence of the Planck function on temperature. In the pre-dawn hours, the largest particle size fraction (gravel) is warmest, contributing the most to the temperature reported in the thermal image. In the mid-day images, the smallest particle size fraction (mud) is warmest and dominates. When the mid-day and pre-dawn images are combined to form a ΔT image, the effects of the smallest and largest particle sizes are emphasized, leading to the strong correlations observed in Figure A8.

Qualitatively, there are many features in our ΔT image that correspond to the sedimentological features mapped on the ground by Blair and McPherson (1998) (Figure A4). The darkest pixels (largest average particle size) on the alluvial fan in the ΔT image correspond to the debris flows in the Blair and McPherson map (regardless of age). These regions are outlined blue (for 1984 debris flow) and maroon (for older debris flow) in the annotated ΔT image shown in Figure A9. Comparison of the thermal and visible images of the fan, Figures A6 and A7, shows that only the young debris flows are clearly identifiable in the visible image, whereas the thermal image unambiguously shows both the younger and older debris flows. Older, more weathered debris flows that have had their fine component removed are seen in the thermal data as lobate rims of high thermal inertia features (low ΔT values). The off-fan wash deposits near the terminus of the southern debris flows, having smaller average particle sizes, are evidenced in the thermal data as areas of larger ΔT values (brighter pixels). Several, relatively dark, linear features appear in the ΔT image on and around the debris flows in locations where Blair and McPherson (1998) have mapped debris flow levees. In Figure A9 we have only labeled levees where they appear in pairs. Several of the debris flow levees identified on the Blair and McPherson (1998) map are relatively small and may be unresolved in our thermal image. We note that the debris flow levees that are most easily distinguished in our ΔT image are those associated with older debris flows. We speculate that this is because the aforementioned winnowing process has, over time, removed the fine components from these levees, leading to a contrast in particle size distribution (and therefore ΔT) with the flows they surround. In order for thermal images to detect the levees there must be significant enough temperature contrast between the levee material and its surroundings. Modern debris flow levees that lie on the

margins of the 1984 debris flow lobes cannot be readily identified in our thermal images, presumably because there is not yet sufficient particle size contrast between these levees and the 1984 flow. The transition from clast-rich debris flow lobes to clast-poor debris flow lobes is clearly seen on the north and south sides of the fan. The lower thermal inertia (higher ΔT) clast-poor flows correspond to the “off-fan wash” materials mapped by Blair and McPherson (1998). Another spatial-thermophysical pattern displayed by the Dolomite Fan (Figure A6) is a general trend toward lower thermal inertia (larger ΔT) at the distal margin of the fan. This pattern follows the general sorting trend displayed by most alluvial fans of depositing the finest particle size fraction at the toe of the fan. Lastly, we note that there are several features revealed in the ΔT image that do not correspond to any features mapped by Blair and McPherson (1998). These spatial-thermophysical patterns may be evidence of debris flows and other sedimentary features too subtle to be mapped using traditional ground-based techniques with no *a priori* knowledge of their existence, or it is possible they represent remnant features due to mid-day and pre-dawn thermal image registration. Such features would be excellent candidates for follow up field work.

6. Conclusions

The significant agreement between the thermal images presented here and the ground-based measurements presented by Blair and McPherson for the Dolomite Fan show that remote thermal images offer a new way to perform initial reconnaissance of many sedimentary features on alluvial fans. Thermal images clearly show all debris flows that are exposed at the fan surface, even if the debris flows have been heavily weathered and are difficult to observe in visible images. Several other features can be identified, including the change in particle size at the toe of the fan, several thin clast-poor debris flows that extend beyond the clast-rich debris flows, and linear features that appear to be debris flow levees.

High spatial resolution thermal images may be especially useful on Mars, where ground truth is not available, and where evidence for surface water and overland flow would be a significant result. For regions on Earth with very little near-surface moisture content, where the primary controls on surface temperature are particle size and degree of surface induration, thermal images can be used to provide a quick reconnaissance of alluvial fans, suggest what processes have most recently acted on the surface of a fan, and to prioritize sites for detailed study on the ground.

Thermal images, when combined with ground measurements and visible images, are a useful tool for any geologist studying alluvial fans in an arid climate. Future work will expand our database of alluvial fans and the inventory of sedimentological features that can be identified with thermal images.

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Appendix A

Table A1: Grain Size Data and ΔT Data for Dolomite Fan

STATION	<i>DOL-02</i>	<i>DOL-03</i>	<i>DOL-04</i>	<i>DOL-05</i>	<i>DOL-06</i>	<i>DOL-07</i>	<i>DOL-08</i>	<i>DOL-09</i>
% Gravel	44	43	38	39	39	26	1	4
% Sand	26	27	27	28	26	30	41	30
% Mud	30	30	35	33	35	44	58	66
ΔT [K]	15.6	15.4	16.5	17.5	15.8	17.3	19.8	22.4

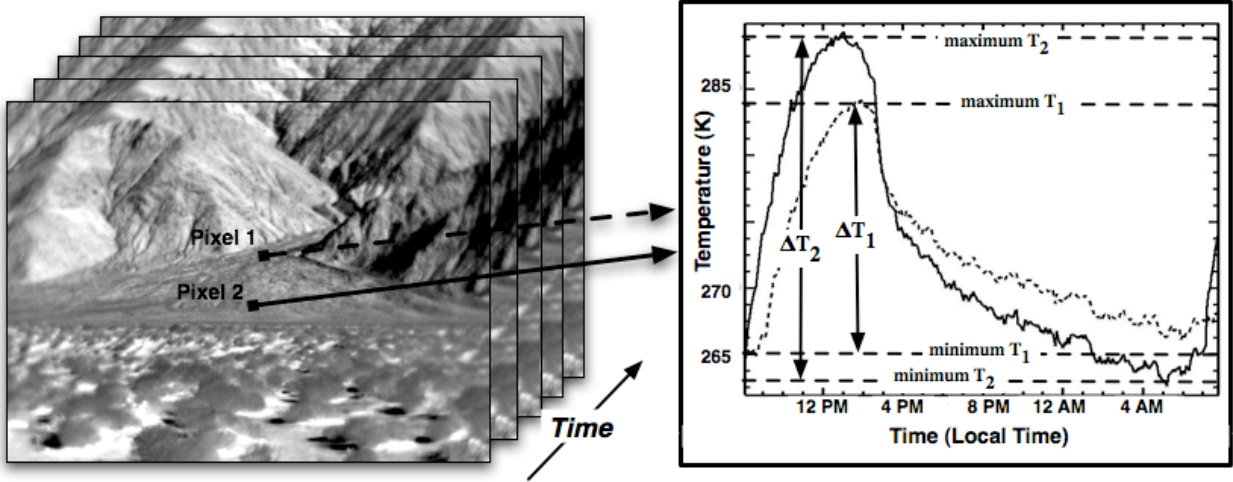
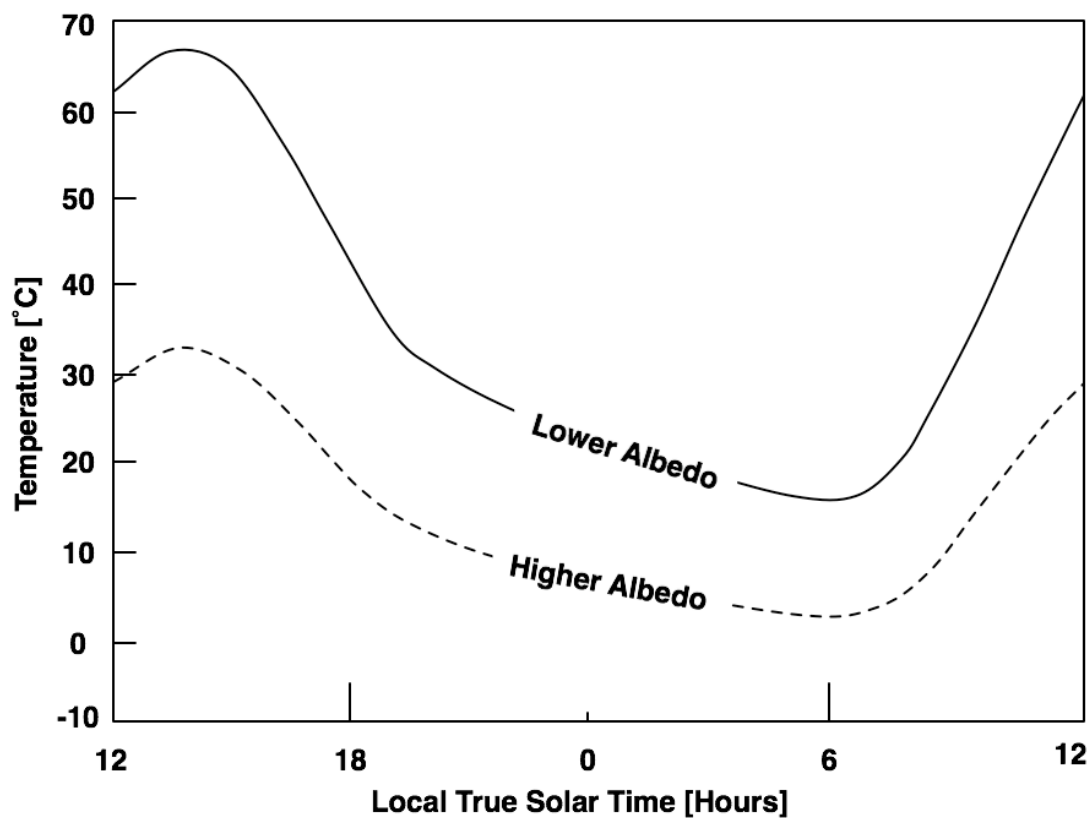


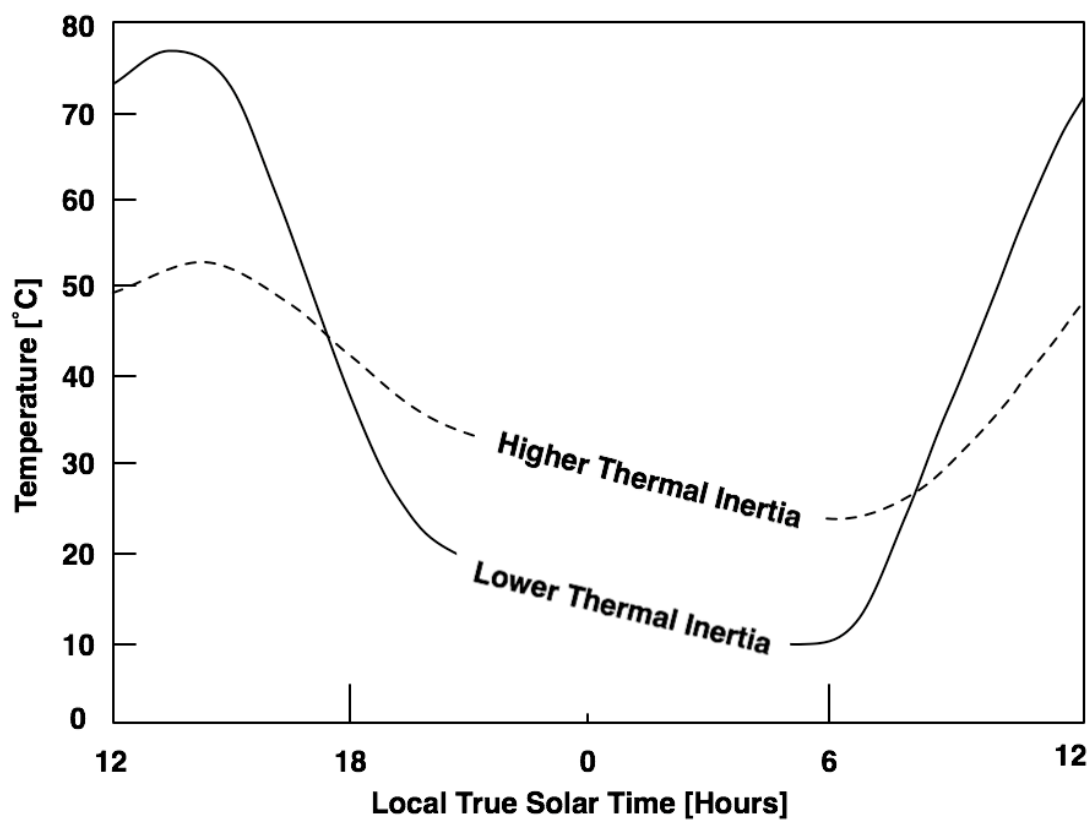
Figure A1: Representation of a hypertemporal image cube acquired from the ground over a 24-hour diurnal cycle. Two example diurnal temperature curves are extracted from the image cube in areas of high thermal inertia (pixel 1) and low thermal inertia (pixel 2).

Figure A2: Schematic diurnal temperature curves showing the effects of independently varying thermophysical properties (adapted from Watson, 1975). a) Diurnal temperature curves for two surfaces with the same thermal inertia, emissivity, insolation geometry and history, but with relatively low (solid curve) and high (dashed curve) albedos. b) Diurnal temperature curves for two surfaces with the same albedo, emissivity, insolation geometry and history, but with relatively low (solid curve) and high (dashed curve) thermal inertias.

a)



b)



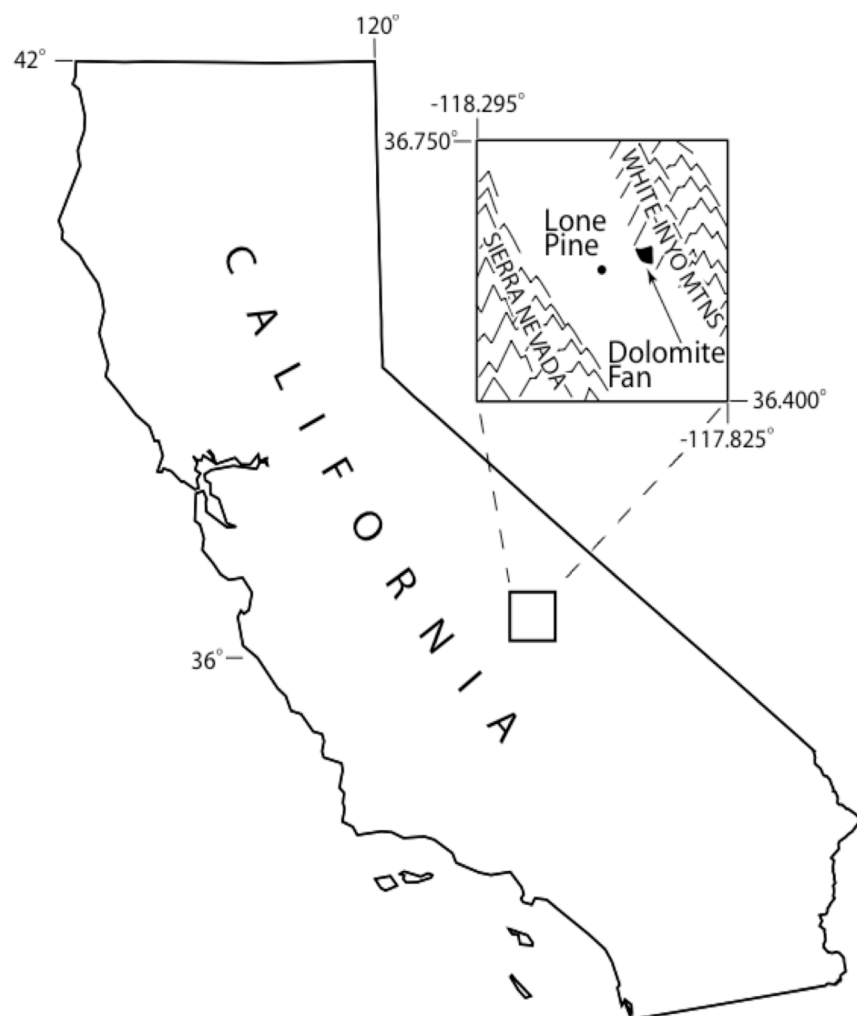


Figure A3: Location map for the Dolomite Fan in Owens Valley, CA. The Dolomite Fan is located at approximately 36.6° N, 117.9° W.

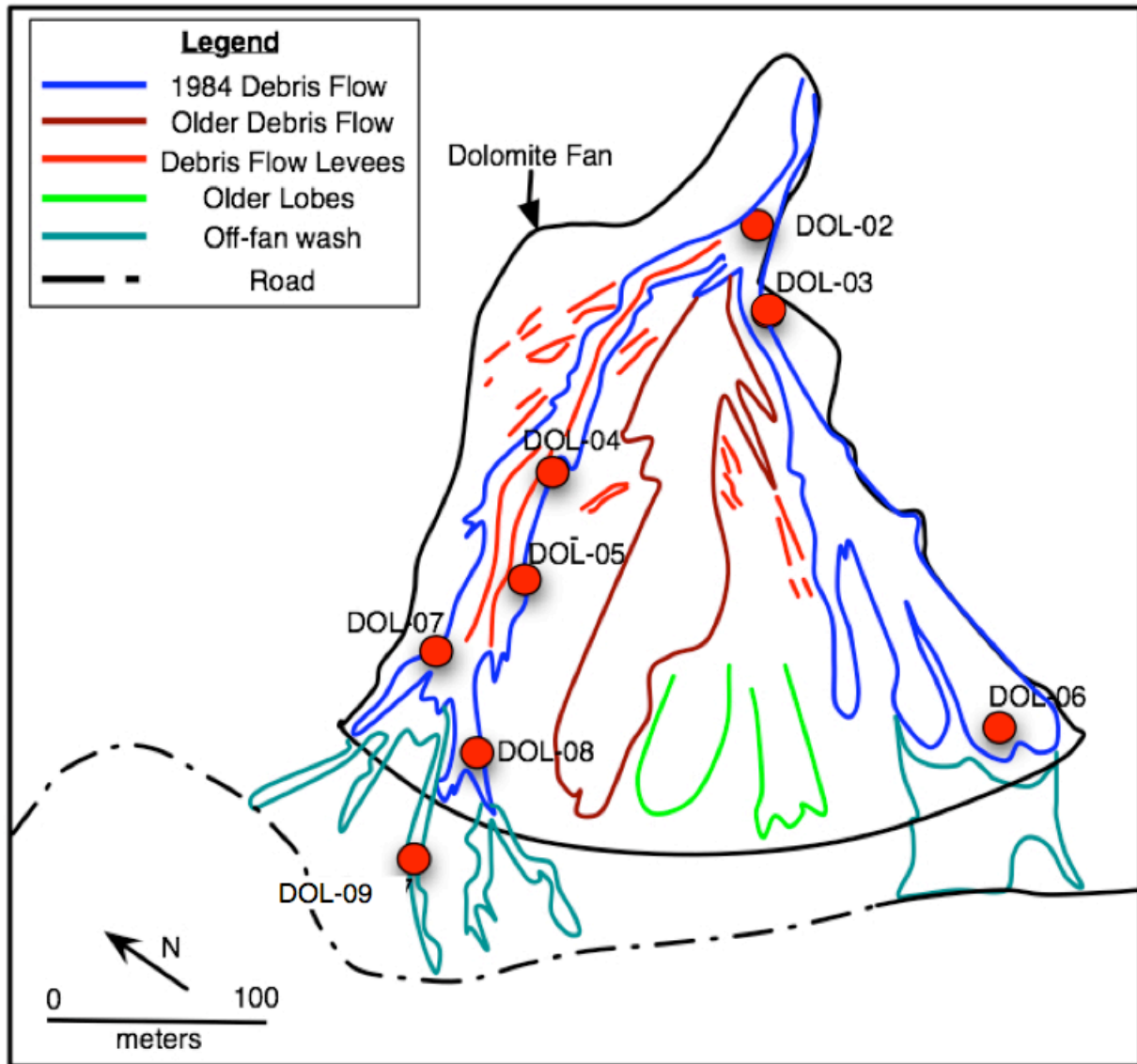


Figure A4: Surface map of Dolomite Fan, adapted from *Blair and McPherson (1998)* field investigation. Red dots indicate the locations of ground stations where grain size measurements, shown in Table 1, were acquired by Blair and McPherson. Solid blue lines represent the recent, 1984 clast-rich debris flows. Solid maroon lines represent older, continuous clast-rich debris flows. Solid red lines represent debris flow levees. Solid green lines represent older, discontinuous debris flow lobes that have been eroded by subsequent debris flows or weathering processes. Solid turquoise lines represent off-fan wash, which we found commonly corresponds to clast-poor debris flows near the toe of the fan. The dashed black line represents a dirt road near the Owenyo Lone Pine Road at the toe of the Dolomite Fan.

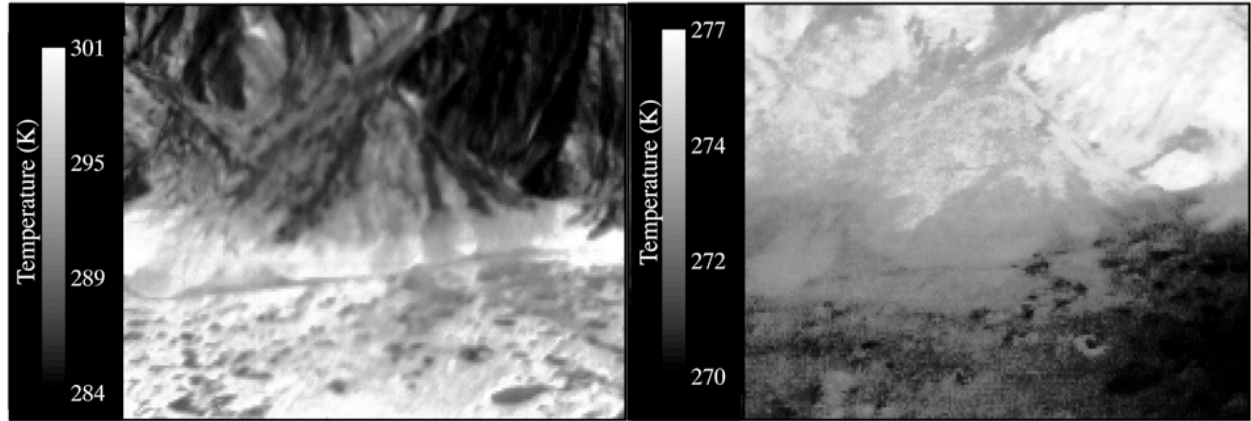


Figure A5: Oblique viewing angle aerial thermal images show mid-day (*left*) and pre-dawn (*right*) temperatures of Dolomite Fan. The night temperature image has been geometrically registered to the mid-day temperature image.

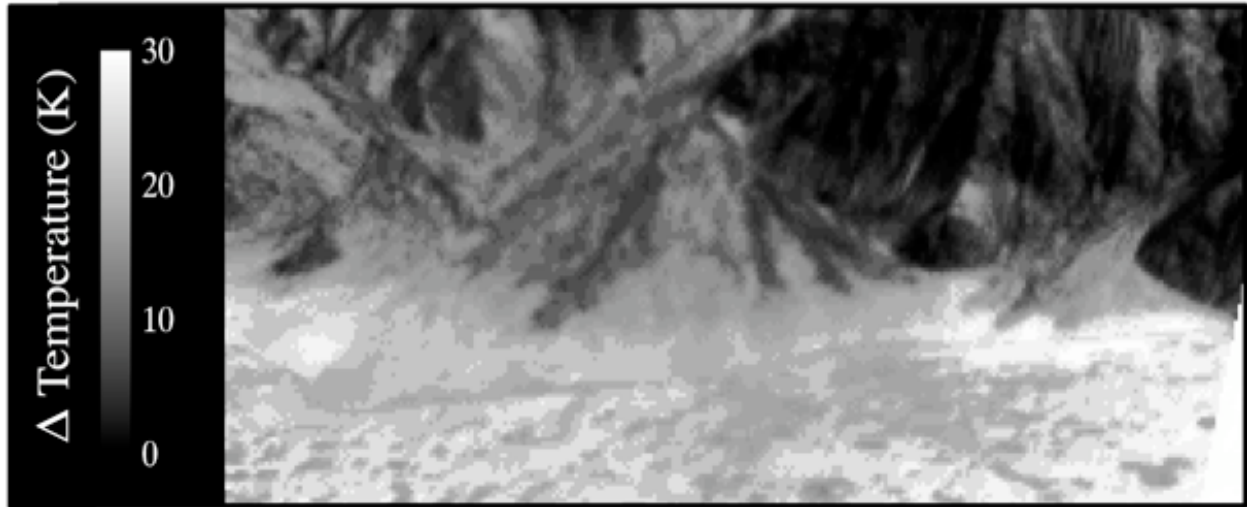
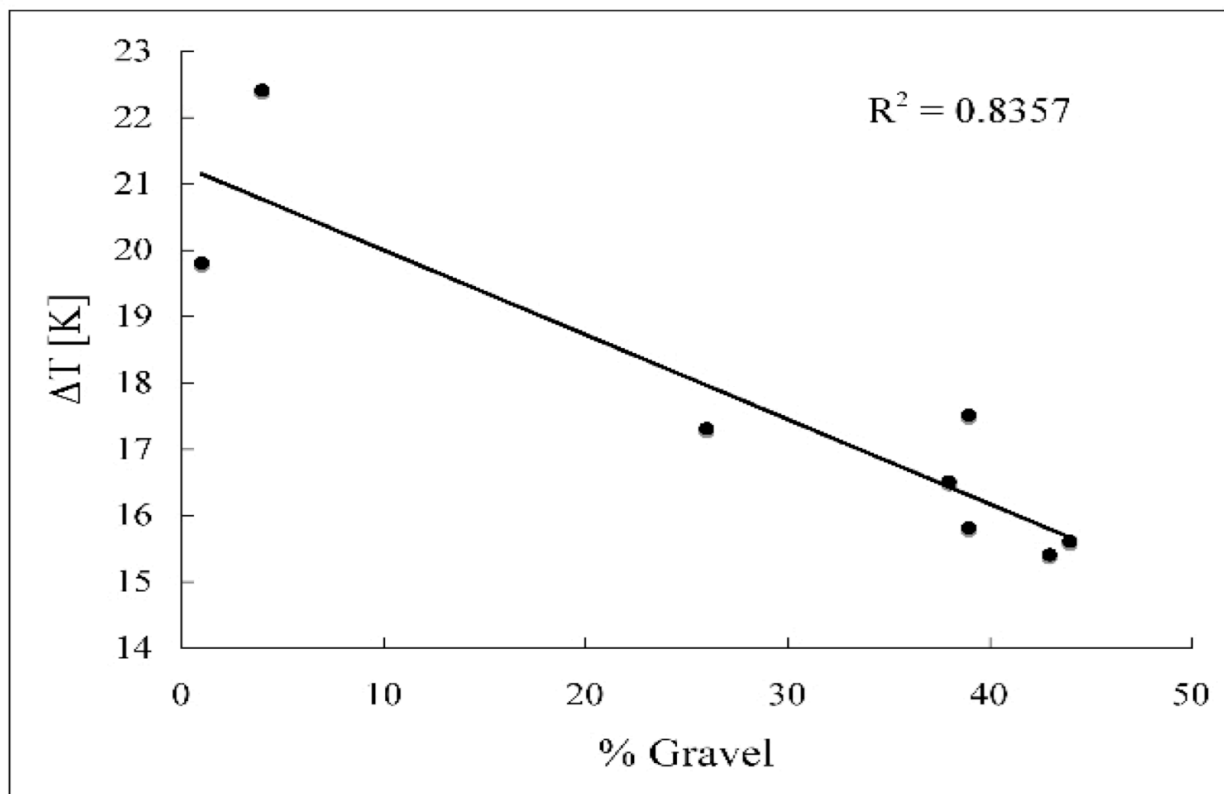
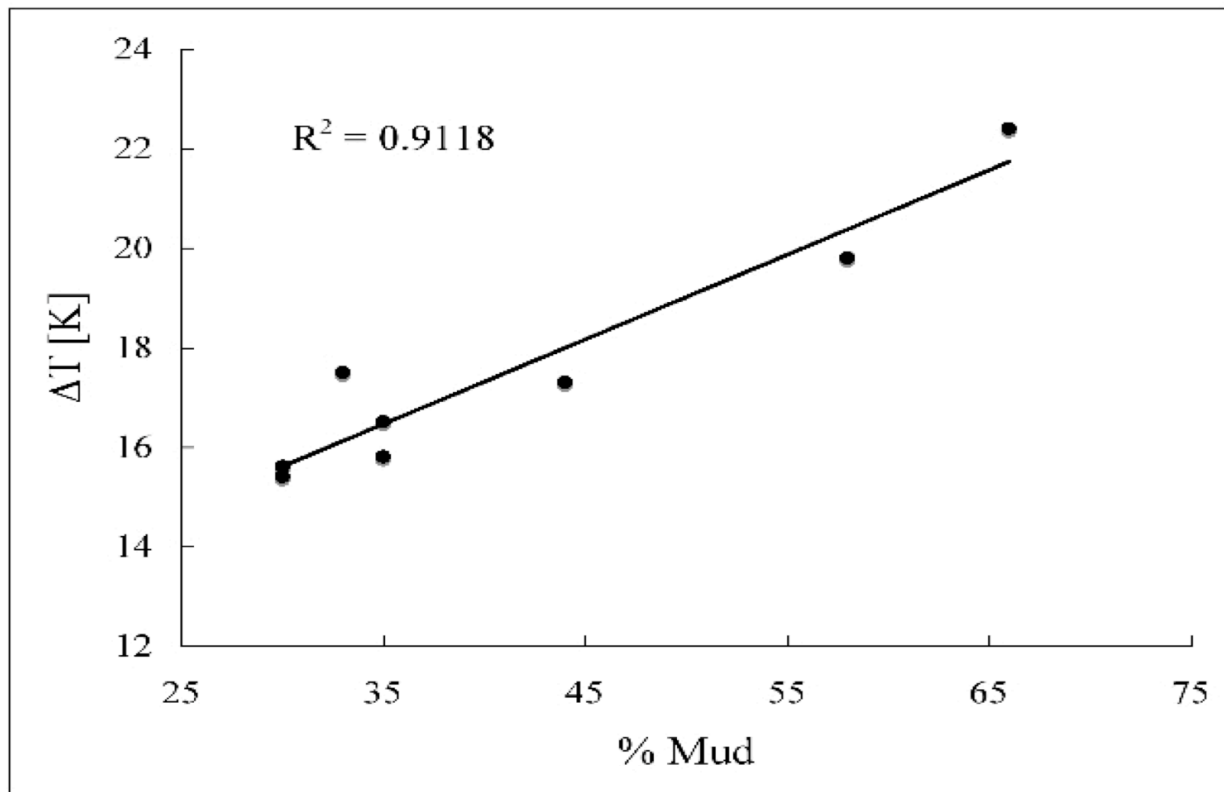


Figure A6: ΔT image of Dolomite Fan calculated by differencing the pre-dawn and mid-day images in previous figure. In this image pixel values approximate the diurnal change in temperature. Pixels with a high change in temperature contain relatively lower thermal inertia materials, and pixels with low temperature changes contain relatively higher thermal inertia materials. Because lower thermal inertias correspond to smaller particle sizes, this “delta-temperature” (ΔT) image shows the spatial distribution of relative particle sizes (or, in some areas of high thermal inertia, areas of induration).



Figure A7: Oblique viewing angle aerial visible image of Dolomite Fan, taken from the same vantage point as the thermal images in previous figures. The light-toned features on the east and west margins of the fan are the 1984 clast-rich debris flows. The dark-toned feature in the mid-fan is an older debris flow. Other features, such as the clast-poor debris flows, remnant debris flows and levees are difficult to discern in this image while they represent prominent features in the thermal image.

Figure A8: Correlation between ΔT and fractional abundance of mud (*top*) and gravel (*bottom*) at 8 ground stations analyzed by Blair and McPherson (1998). Line is a calculated least squares regression through the data.



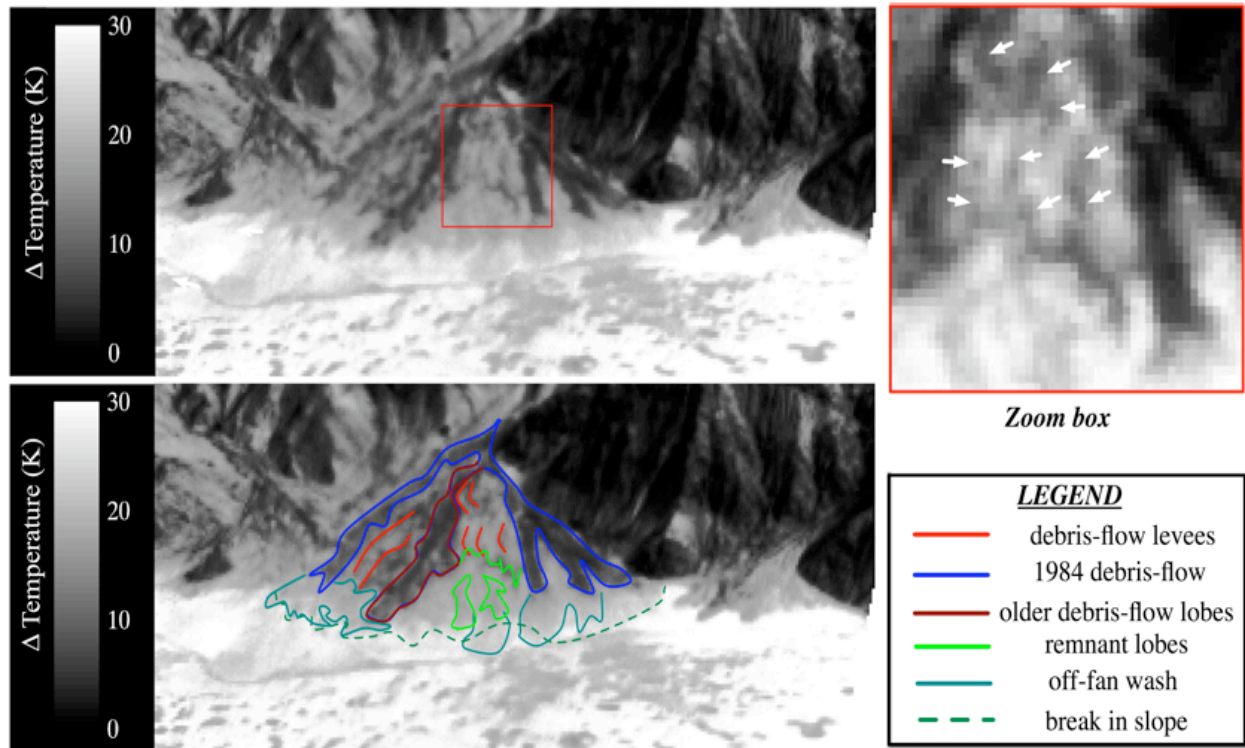


Figure 8, C. Hardgrove, .tiff

Figure A9: ΔT image of Dolomite Fan with (bottom-left) and without (top-left) sedimentary features labeled. The zoom box (upper-right) shows the central debris flow (outlined in red in the top left panel) as well as linear features that represent levees from remnant debris flows (white arrows).

Part 3

Thermal Imaging of Sedimentary Features on Alluvial Fans

This part is a reformatted version of a paper by the same name published in Planetary and Space Science in 2010 by Craig James Hardgrove, Jeffrey Moersch, and Stephen Whisner. All data analyses were performed by Craig Hardgrove.

Hardgrove, C., Moersch, J., Whisner S.C., Thermal Imaging of Sedimentary Features on Alluvial Fans, *Planetary and Space Science*, 2010., 58, 482-508.

Abstract

Aerial thermal imaging is used to study grain size distributions and induration on a wide variety of alluvial fans in the desert southwest of the United States. High resolution aerial thermal images reveal evidence of sedimentary processes that rework and build alluvial fans, as preserved in the grain size distributions and surface induration those processes leave behind. A catalog of constituent sedimentary features that can be identified using aerial thermal and visible imaging is provided. These features include clast-rich and clast-poor debris flows, incised channel deposits, headward-eroding gullies, sheetflood, lag surfaces, active/inactive lobes, distal sand skirts, and basin-related salt pans. Ground-based field observations of surface grain size distribution, as well as morphologic, cross-cutting, and topographic relationships were used to confirm the identifications of these feature types in remotely acquired thermal and visible images. Thermal images can also reveal trends in grain sizes between neighboring alluvial fans on a regional scale. Although inferences can be made using thermal images alone, the results from this study demonstrate that a more thorough geological interpretation of sedimentary features on an alluvial fan can be made using a combination of thermal and visible images. The results of this study have potential applications for Mars, where orbital thermal imaging might be used as a tool for evaluating constituent sedimentary processes on proposed alluvial fans.

1. Introduction

Alluvial fans are common features in arid, desert environments on Earth. Their characteristic apron shape is the result of channelized, sediment-laden fluids from the source (catchment) area being deposited as the mixture travels downslope, expands into the basin and loses carrying capacity. The relative amounts of fluid and sediment, as well as the proportions of coarse-grained versus fine-grained sediment, influences the types of sedimentary processes that operate on the surface of the alluvial fan (Blair and McPherson, 1994). We investigate the use of thermal images for

the detection of a wide variety of constituent sedimentary features on alluvial fans within several geologic settings. Hardgrove *et al.* (2009) showed that day/night temperature variations observed in aerial thermal images of an alluvial fan are quantitatively correlated with differences in particle size distributions measured on the ground. This previous work also qualitatively demonstrated the utility of remote thermal images in identifying regions where grain sizes have been sorted or indurated by the limited set of sedimentary processes that operated on the particular fan used as a test case for developing the technique. In the present work, we show that the technique may be used to identify a much wider variety of sedimentary features found on a diverse suite of alluvial fans that have been formed and modified by a range of sedimentary processes. We have chosen to use fans from Owens Valley and Death Valley, CA because they display a wide variety of sedimentary features common to arid regions everywhere. The fans of Death Valley, in particular, are considered to be some of the best examples of alluvial fans in the world, and are among the most studied (*e.g.*, Denny, 1965; Hunt and Mabey, 1966; Denny, 1967).

Here we provide a catalog of common sedimentary features on alluvial fans that can be inferred from aerial, high spatial resolution ($\sim 2\text{m/pixel}$) thermal imaging used in conjunction with high resolution ($\sim 1\text{m/pixel}$) visible images. These sedimentary features include clast-rich and clast-poor debris flows, incised channel deposits, headward-eroding gullies, sheetflood, lag surfaces, active/inactive lobes, distal sand skirts, and basin-related salt pans. Although some inferences about these sedimentary features may be made using aerial thermal images alone, the addition of high resolution visible images ($\sim 1\text{ m/pixel}$) provides an albedo and morphologic context for interpretation of the thermal data. Our work in using high spatial resolution thermal image data to study relatively small-scale constituent sedimentary features on alluvial fans builds on previous work at moderate spatial resolution ($\sim 50\text{ m/pixel}$) that characterized variations in grain size distributions at regional scales (*e.g.*, Kahle, 1987; Applegarth, 2006). These results have potential applications for Mars, where orbital thermal imaging might be used as a tool for evaluating constituent sedimentary processes on proposed alluvial fans (Moore and Howard, 2003; Malin and Edgett, 2003; Kraal *et al.*, 2008, Williams and Malin, 2008). Recently, temperature images from the Thermal Emission Imaging System (THEMIS) on the Mars Odyssey spacecraft have been used to derive thermal inertias for various areas of geologic interest on Mars (Michalski and Fergason, 2009; Fergason and Christensen, 2008; Bandfield and Feldman, 2008; Cushing and Titus, 2008).

2. Sedimentology of Alluvial Fans

Blair and McPherson (1994) performed a detailed, survey study of sedimentary processes on alluvial fans. Except where noted, the discussion below follows from their work. Unless otherwise noted, the details of Section 2 can be attributed to Blair and McPherson's work.

2.1 Primary and Secondary Deposits

Variations in grain sizes on alluvial fans are primarily related to both the sediment source and the sedimentary processes that have acted on the fan. Nominally, there is a trend towards larger grain sizes (sometimes called “fanglomerates”) in the upper-fan, intermediate grain sizes in the mid-fan and smaller grain sizes in the distal fan, or toe (Boggs, 2001). Upper fan grain sizes can be as large as boulder-sized, and distal fan grain sizes can be sand-sized or smaller (Blissenbach, 1954). Volumetrically, alluvial fans are primarily composed of deposits that are initiated by major, yet infrequent, storm events. These deposits can be the result of either debris flow processes (*e.g.*, clast-rich or clast-poor) or fluvial processes (*e.g.*, incised channel floods and sheetfloods). However, this generalized conceptualization is oversimplified for most alluvial fans, as their surfaces are often reworked by processes that modify surface grain size distributions. Overprinting of the primary deposits by secondary aeolian and fluvial processes can influence the final grain size distribution on the surface of the fan. Thus, the spatial pattern of surface grain size distributions is representative of both the primary, large-scale depositional processes and these smaller-scale secondary processes. Although the absolute grain sizes in these deposits can vary from fan to fan due to differences in source material, relative grain size patterns are observed to be consistent.

2.1.1 Primary deposits from debris flow processes

Debris flow is the most significant sediment-gravity process in terms of the volume of material deposited directly on alluvial fans. Blair and McPherson (1994) characterized debris flows as “a mixture of granular solids (gravel, sand, clay, tree limbs, etc.) and small amounts of entrained water and air that move downslope under the force of gravity.”

They distinguish three classes of debris flows: 1) clast-rich, which consist primarily of gravel and clay, 2) clast-poor, which are commonly called mudflows, and 3) non-cohesive, which is a clast-rich, clay-poor flow. The lack of clay reduces the cohesiveness of the flow, thus reducing the run-out distance when compared to cohesive clast-rich flows. We did not observe non-cohesive debris flows in our study area, therefore, we restrict our discussion to clast-rich and clast-poor debris flows. In clast-rich debris flows, gravel-rich deposits are lobate and tend to overlie pre-existing surface features. Often, the largest particle size component moves towards the front and sides of the flow (Middleton, 1970, Fisher 1971). Subsequent winnowing and fluvial processes remove fine-grained material around their margins, leaving a lobate outline primarily of large clasts.

Clast-poor debris flows have a high fraction of clay and can either form in association with clast-rich debris flows or independently. Whether clast-poor debris flows form independently of clast-rich debris flows depends on many factors including catchment lithology and amount of fluid influx to the catchment. Clast-poor debris flows are found in association with clast-rich debris flows when the clast-rich debris flow contains a mixture of large and small particle sizes. In some cases, as the flow moves down the fan, the large clasts are deposited and the clast-poor portion of the flow continues down the fan. This leaves a lobate rim of clast-poor material at the toe of the clast-rich deposit. Both types of clast-poor debris flows will mantle or flow around pre-existing fan material.

Incised channels also will accommodate the passage of debris flows (high sediment to water ratio), both clast-rich and clast-poor. If debris flows have passed through the channel, larger grain sizes from clast-rich debris flows, indurated material from clast-poor debris flows, or both may be found within the channel. Aeolian and/or fluvial winnowing of fines from the deposits left by the passage of these flows may leave a flat bed of cobbles and boulders.

We have further subdivided the clast-rich/clast-poor classifications of Blair and McPherson because our technique (described in Section 4) allows us to discern other characteristic features of these flows that are related to their formation. Both classes of debris flow deposits may be subdivided based on their degree of confinement (or lack thereof) and clast-poor debris flow deposits may be subdivided by their degree of induration.

2.1.2 Primary deposits from fluvial processes

Fluvial processes are distinguished from debris flow processes by having a smaller proportion of sediment to fluid. The most prevalent fluvial processes on alluvial fans are sheetflood and incised channel flows. Sheetfloods are unchannelized or unconfined flows that occur when the amount of water is sufficient to overflow the banks of any pre-existing channels and form a thin layer moving as a sheet overlying the alluvial fan. Seen from overhead, sheetflood deposits are relatively featureless, unconfined, and form a thin veneer over pre-existing topography. Viewed in cross-section (in erosional exposures such as incised channels) sheetflood deposits appear as planar bedded sand-skirts and coupled gravel-pebble stacked deposits. Coupled deposits are typically tens of centimeters thick and are oriented at an angle sub-parallel to the local slope (Blair, 2000).

The other common transport mechanism for fluvial processes on alluvial fans are incised channel flows. On the upper-fan, incised channels confine the flow and can facilitate the delivery of sediment to lower parts of the fan. When the ratio of sediment to water is low (normal fluvial flow), deposits within incised channels contain the coarsest sediment fraction due to higher flow competence created by the confinement. Finer-grained sediment may accumulate on the margins of these coarse-grained deposits during the waning flood stage or less energetic events.

2.2 Effects of Secondary Processes

Secondary processes tend to produce characteristic grain-size distributions and can provide critical insight into the environment and climate conditions experienced by alluvial fans in the period after deposition. Secondary processes such as overland flow, aeolian weathering, induration or formation of salt crusts act to sort sediment by size or cement grains.

The secondary processes that dominate the surface features of alluvial fans are winnowing of fines and overland flow. Aeolian or fluvial winnowing of fines within debris flow deposits leads to the preferential preservation of larger clasts within clast-rich debris flows as well as erosion of clast-poor debris flows entirely. Erosive overland

flow can also produce gullies, which erode headward toward the fan apex. Often these depressions are filled with fine-grained sediment that is presumably carried during low energy flow events, not the high-energy flow events characteristic of primary processes. The gullies erode radially up the surface of the fan, therefore they tend to converge in V-shaped intesections pointed toward the fan apex. On many fans, repeated annual overland flow or aeolian activity will result in a sandskirt of fine material at the toe of the alluvial fan. In addition to the winnowing of channel fill described above, aeolian secondary processes can result in the development of desert pavement or other types of lag surfaces. Aeolian secondary processes can also lead to deposition of blown sand around vegetation or irregular topography unrelated to primary deposits on the fan.

3. Thermophysical Remote Sensing

A detailed description of the principles of thermophysical remote sensing relevant to this study is covered in Hardgrove et. al (2009). In brief, the temperature of a surface is governed by both its albedo and its thermal inertia (Kieffer et. al, 1977). Albedo is simply the broadband reflectance of a surface. Thermal inertia can be thought of as the resistance of a material to changing temperature when incident sunlight is added or removed. Very fine-grained surfaces have relatively low thermal inertias and coarse-grained surfaces or highly indurated surfaces have high thermal inertias. Sophisticated multivariable analytical models are required to quantify the thermal inertia of a surface from diurnal temperature measurements. Although such models have been developed (*e.g.*, Watson, 2000), we make the simplifying assumption that thermal inertia is inversely proportional to the change in surface temperature (ΔT) between pre-dawn and mid-day. Using an image composed of ΔT values as a proxy for a thermal inertia map affords us better separation between surfaces of different thermal inertias than using a single pre-dawn temperature image because the temperatures of high versus low thermal inertia surfaces trend in opposite directions in day versus night images. The ΔT image also partially eliminates the effects of albedo on the diurnal temperature curve. Changes in albedo primarily shift the entire diurnal temperature curve for a given image pixel up or down in temperature (Figure B1A). Because the ΔT image is only sensitive to the diurnal temperature spread, variations in absolute temperature due to albedo differences are minimized. Slope and azimuthal orientation of slopes can also affect diurnal thermal behavior of geologic surfaces (Cushing et al, 2009). The first-order effects of slope and slope orientation are phase shifting and mean value shifting of the diurnal thermal curve compared to a horizontal surface.

If significant slope orientation effects were present in temperature images, they would appear as smoothly varying effects across the surface of the fans because the slope azimuths themselves are smoothly varying. We do not observe this effect in our mid-day or pre-dawn temperature images, in fact, most of our analyses focus on relatively discrete, well-defined thermophysical features. In addition, the mean slopes of the alluvial fans studied do not vary significantly, approximately 2 to 9 degrees, with the highest slopes near the fan apex and the lowest slopes near the toe. To determine the effects of decreasing slopes on ΔT values, we conducted a control experiment on well-characterized quartz sand grains (50 wt. % 200-500 micron diameter, 40 wt. % 500-800 micron diameter) at two different slope angles (0 and 30 degrees) and orientations. Diurnal temperature curves were acquired for flat-lying sand and a westward-facing slope dipping at 30 degrees under clear sky conditions (Figure B1B). We have chosen to highlight westward-facing slopes because they are most similar to the slope orientations of the fans studied in Death Valley and Owens Valley. Gently sloped, westward-facing surfaces of equivalent grain size have lower ΔT values, which is opposite to the observed trends in our data where we see higher ΔT near the toes of the fans (Section 6). As will be seen, the trend of higher ΔT values towards the toe of the fan is also verified by our ground observations of smaller grain-sizes near the toes of many fans. We are confident, therefore, that the effects of grain-size are dominant in our ΔT images, even across areas of changing slope. Smaller-scale slope effects and shadows are not taken into account, however, as will be seen, these approximations are adequate for revealing surface thermophysical heterogeneities associated with differences in particle size and/or induration in the scene. We note, however, that the ΔT image is only a proxy for in-scene relative thermal inertias, not absolute thermal inertia values. Because of this, it is only proper to interpret ΔT images in terms of relative differences in grain sizes (or degree of induration) on the ground, not absolute grain size values.

4. Methods and Data Sets

Two broad approaches were used to characterize the sedimentary features found on a suite of alluvial fans in this study. Remotely acquired thermal and visible images were used to map thermophysical, albedo and morphologic patterns on the alluvial fans, which were then interpreted in terms of different sedimentary processes that could have produced these features. Ground-based field observations were then used to validate or, in some cases, refine these interpretations. This resulted in a catalog of different types of sedimentary features, as observed across the suite of

alluvial fans. Examples of each type of feature were examined for common traits in order to synthesize a method for identifying these features from remote visible and thermal observations when no ground truth is available (*e.g.*, Martian alluvial fans).

4.1 Remote Thermal and Visible Image Acquisition and Processing

All thermal image data were acquired from a light aircraft, using a FLIR Systems ThermaCam S45 thermal infrared camera. The camera operates in the 7.5-13- μm telluric transmissivity window, and has an absolute temperature accuracy of 2K at ambient temperatures relevant for geologic studies. Relative pixel-to-pixel temperature accuracy is about 0.1K, which is much smaller than the kinetic temperature differences typically found on the ground at the relevant spatial scale. The field of regard is $24^\circ \times 18^\circ$ across a 320x240 pixel array, giving the camera a pixel IFOV of 1.3 mrad. Images are captured at 60 Hz, which in practical terms means pixel blur from the light aircraft platform is not a problem at altitudes of about 900 m or greater above the terrain. We have written custom software that converts images from the manufacturer's digital image format into files for use in the Environment for Visualizing Images (ENVI) remote sensing software suite.

Over 100 aerial thermal images were acquired from a suite of 24 alluvial fans in Owens Valley and Death Valley, CA (Section 5). A subset of 16 alluvial fans were chosen for use in this study; images of the remaining 8 fans were discarded because of image blur (resulting from bumps due to air turbulence in flight) and other data acquisition problems. These data were acquired in March, 2008, under clear sky weather conditions. Individual thermal images of the target alluvial fans were acquired from an altitude of $\sim 1,500$ m to give an overhead perspective similar to that seen from orbit, but at higher spatial resolution (~ 2 m/pixel). Images were acquired at pre-dawn and mid-day times during the same 24-hour period from the same airborne vantage points by using an aviation GPS unit. Table B1 shows the day and night acquisition dates and times for the 16 alluvial fans studied.

By co-registering and differencing the pre-dawn and mid-day aerial thermal image pairs, we derive a new image in which pixel values approximate the diurnal change in temperature (ΔT). As described in Section 3, pixels with a high change in temperature contain lower relative thermal inertia materials, and pixels with low temperature changes

contain higher relative thermal inertia materials. Because lower relative thermal inertias correspond to smaller particle sizes, this ΔT image shows the spatial distribution of relative particle sizes (or, in some areas of high relative thermal inertia, areas of induration). The ΔT image was then warped using a second order polynomial function to a georeferenced USGS orthophotoquadrangle. The resulting georectified ΔT image was then loaded onto a handheld DeLorme PN-20 GPS unit for ground-truthing of sedimentary features.

Visible wavelength images with a spatial resolution of 1 m/pixel were extracted from a database sold by the DeLorme corporation (© 2008 DeLorme www.delorme.com; © 2001 CNES Licensed by SPOT Image Corp) for mapping color albedo and morphologic features on the alluvial fans. These images were also loaded onto the PN-20 GPS unit for subsequent field work.

4.2 Field Work

Of the 16 fans for which we have acquired aerial data, 12 were selected for detailed ground-based field study over the course of two field trips in November and December, 2008. An initial reconnaissance of each alluvial fan was made so that the ΔT values from our aerial data at specific locations could be understood in the context of the fan's overall grain size distribution. For each fan visited on the ground, we selected specific locations of high or low ΔT or regions that showed distinctive spatial patterns of ΔT values. By examining the particle sizes and morphologic, cross-cutting, and topographic relationships between the various surface materials at each location, we were able to evaluate the sedimentary features that comprised the fan and how they were related to features on our ΔT image. The degree of reddening (seen in visible wavelength images), due to prolonged oxidation alteration of fan surface materials in arid environments, was used to identify inactive regions of the alluvial fans or remnant surface materials (White and Walden, 1994). At each study site, the particle size distribution and sedimentary features were documented with digital photographs. We qualitatively assessed the relative abundances of various particle sizes at each location as well as feature morphologies and spatial relationships. Included in many of the digital photographs is a field notebook 19.5 cm long by 12.5 cm wide for scale.

5. Geologic Setting

Death Valley and Owens Valley, CA lie within the Basin and Range extensional province of the arid southwestern United States. Sediment eroded from the high-relief bounding mountain ranges has formed extensive alluvial fan aprons in both north-south oriented valleys.

Death Valley is bounded by two large, rotated blocks of mixed lithologies that dip generally to the east (Burchfiel and Stewart, 1966; Hunt and Mabey, 1966). These rotated blocks form two mountain ranges, the Black Mountains to the east and the Panamint Mountains to the west. Faulting and rotation create generally steep scarp slopes on the eastern sides of the valley and gently dipping slopes on the western side. Larger fans form on the generally gentler western side of the valley, and smaller fans form below the steep eastern slope.

Owens Valley is a classic graben system with a down-dropped block forming the valley floor and uplifted rocks forming the high mountains bounding it (Pakiser, 1964). The eastern side of Owens Valley is bounded by the White-Inyo Mountains, which are composed of mixed lithologies. In contrast, the Sierra Nevada Mountains to the west are composed of primarily igneous lithologies (Bierman, 1991). Owens Valley alluvial fans form on both sides of the valley, with western fans being an order of magnitude larger than the eastern fans. Only the Eastern Owens Valley fans were studied in the present work because meltwater runoff from snowpack in the Sierras gives the Western fans much greater soil moisture and vegetative cover, which obscures the geology of the fans from remote sensing observations. The valley varies in width from 15 to 25 km, and extends for 150 km in a north-northwest trend.

The fans studied in both valleys were chosen because they lie within the rain shadow of the eastern Sierra Nevada and receive water mostly in the form of infrequent thunderstorms. This aridity minimizes the influence of vegetation and water on these fans. Also, these valleys allowed relatively easy access to a large number of fans with a wide variety of source areas, sediment supply, basin locations, and depositional processes. A contextual map showing the locations of all alluvial fans for which aerial thermal images were acquired is presented in Figure B2.

6. Results

Figure B3 shows ΔT images of all the alluvial fans for which we have acquired useable aerial thermal imaging data. Figure B4 shows the corresponding visible images. Note that the ΔT images in Figure B3 reveal the details of significant spatial features which are not apparent in the visible images in Figure B4, even though the latter has higher spatial resolution. Below, we discuss both regional-scale trends in grain sizes and the appearance of different classes of sedimentary features in remote data sets.

6.1 Valley-wide aerial thermal images of alluvial fans in eastern Death Valley, CA

Although the overall focus of this study is on the constituent sedimentary features of alluvial fans, we note that the inter-fan trends for neighboring fans can also be studied using thermal images. A ΔT map for alluvial fans on the eastern side of Death Valley south of Badwater is presented in Figure B5. Figure B5 has the same contrast enhancement applied across to all the constituent alluvial fans, emphasizing the differences in grain size across multiple fans in the valley. There is a general trend toward increasing ΔT values on the fans from north to south, consistent with the general decrease in average particle size to the south. Ground-based field observations of these fans verified this trend in average particle size, from boulder sized clasts on the Badwater Fan (BWF) to cobble and mud sized clasts on the Coffin Canyon Fan (CCF). There is a corresponding decrease in fan slopes from the northern fans, ~ 6 degrees at the Badwater Fan (BWF), to the southern fans, ~ 2 degrees at the Coffin Canyon Fan (CCF). As shown in Figure B1B, for westward-facing surfaces, the effects of decreasing slope (lower ΔT values on lower slopes) are opposite to those observed in our ΔT images (higher ΔT values on lower slopes). Blair and McPherson (1994) suggest that the two main factors that determine the radial topographic profile of an alluvial fan are the dominant sedimentary processes and the sediment size available for fan construction. Larger particle sizes, which are associated with clast-rich debris flow deposits lead to steeper sloped fans while finer-grained sheetfloods and clast-poor debris flows lead to alluvial fans with more gentle slopes. The regional trends observed in ΔT seen in Figure B5 are consistent with this model. Our field observations indicate that reworked debris flows tend to dominate the surfaces of fans to the north, while fluvial processes tend to dominate the fan surfaces to the south. This is best evidenced by a large incised channel filled with clast-poor debris flow material in the southernmost

Coffin Canyon Fan. Another possible explanation for the regional trend in particle size is the influence of changing source lithology. The Coffin Canyon Fan shares some second and third-order feeder channels with the Copper Canyon Fan, further to the south, which is composed of soft Miocene and Pliocene sedimentary rocks, which may account for the increase in finer-grained surface deposits (Blair and McPherson, 1994).

6.2 Identifiable Sedimentary Features

6.2.1 Clast-rich, unconfined debris flows

We present 4 examples of clast-rich debris flows that were identified from our suite of 16 study fans. Clast-rich unconfined debris flows were identified using aerial thermal and visible imaging and confirmed with field observations (Figures B6, B7, B8). In selecting these examples, we looked relatively low ΔT features having a lobate morphology that were not confined to an incised channel, as identified using corresponding visible images. The best examples of these features were found on the Dolomite Fan (DF), Fossil Hill Fan (FHF), French Spring Fan (FSF), and Talc Canyon Fan (TAC). Clast-rich debris flows were found as high or low albedo features, depending upon their relative age.

Dolomite Fan (Figure B6):

According to first-hand accounts, the thunderstorm that triggered the debris flows on the Dolomite Fan in 1984 also initiated debris flows on at least two other alluvial fans on the east side of Owens valley (Blair and McPherson, 2000). Here we present the results of our traverse across several of the clast-rich debris flows on the Dolomite Fan. Lobate, low ΔT features that were identified on the ground as clast-rich debris flows are draped over existing topography, and are composed of significantly larger grain sizes (commonly cobbles to boulders) than the surrounding material. We traversed across the older, low albedo debris flow near the center of the Dolomite Fan (Figure B6B, B6C) and documented several abrupt changes in grain size that represented the presence of clast-rich debris flows (Figure B6D, B6E, B6F, B6G, B6H, B6I, B6M, B6N, B6O) and inter-debris flow material (Figure B6J,

B6K, B6L) as we traversed south. Figure B6J, B6K, and B6L show the finer-grained material surrounding the clast-rich debris flows. Figure B6L also shows evidence of a partially buried, remnant debris flow, which is composed of cobble to boulder-sized clasts that are buried under unconsolidated sand to pebble sized grains. In the thermal image (Figure B6C - arrows) the remnant debris flow appears as a lobate rim of lower ΔT . The southern clast-rich debris flow at DF 7 shows a significantly higher albedo (Figure B6B), indicating it is more recent than the debris flow in the center of the Dolomite Fan. We also note the presence of debris flow levees near DF 7 (marked with arrows in Figure B6O) that are below the resolution of the aerial ΔT image. Both the high and low albedo clast-rich debris flows, however, are some of the lowest ΔT features on the Dolomite Fan.

Fossil Hill Fan (Figure B7):

On the Fossil Hill Fan, the clast-rich portion of the debris flow extends from the fan apex to the toe. The lack of a significant clay component within the flow as well as the degree of reddening (lower albedo) on many of the surface debris flow materials indicates these features are older than the debris flow initiated in 1984 on the Dolomite Fan to the south (Figure B6A, Figure B7A). We traversed a path across the Fossil Hill Fan, observing changes in grain size, morphology and albedo (Figure B7B, B7C). We identified two main clast-rich debris flows at FHF 7 and FHF 9, corresponding to lobate, low ΔT features in our thermal image, with regions of finer-grained surface material in-between at FHF 8 and FHF 10 (Figure B7F, B7G, B7J, B7K). The thermal images of these fans shows that regardless of age, the clast-rich, larger grain size portion of debris flows allows these features to resist large changes in temperature over a diurnal cycle, therefore, a continuous, lobate, low ΔT feature is highly suggestive of a clast-rich debris flow, especially when coupled with a rim of higher ΔT material (unconsolidated clast-poor debris flow, see Section 6.2.2) surrounding it at the toe.

Talc Canyon Fan (Figure B8):

We are not aware of any specific studies of the Talc Canyon Fan, however, Blair (1999) studied the dominance of debris flow vs. sheetflood processes on many of the alluvial fans on the western side of Death Valley. He concluded that alluvial fans to the south of the Anvil Springs Fan, which includes the Talc Canyon Fan, are sheetflood-

dominated by studying catchment size, lithology and the deposits exposed within cut-banks on the Anvil Spring Fan (Blair, 1999). We did not observe any sheetflood deposits exposed at the surface, although this is expected due to prolonged surface weathering in between sheetflood events. The surface of the Talc Canyon Fan was predominantly covered with boulder-sized clasts of granitic composition that were heavily weathered. During our field study, several prominent, lobate features composed of very large grain size were identified at TAF 5 (Figure B8E, B8F, B8G). Arrows in Figure B8C and B8E mark the boundary of the lobate, clast-rich debris flow at TAF 5 with the surrounding finer-grained granitic sand. These features corresponded to lobate, low ΔT features in our thermal image (Figure B8B). Although this fan was constructed by sheetflood deposits, the surface is dominated by sediment-gravity driven debris flows, demonstrating the difficulty in using surface features for classification of alluvial fans by sediment-gravity or fluvial sedimentary processes.

6.2.2 Unconsolidated clast-poor, unconfined debris flows

On several fans, clast-poor debris flows were identified first by using the thermal image to identify lobate rims surrounding the terminus of clast-rich debris flows. On the ground, clast-poor debris flows are identified by their smaller grain size distribution and emplacement around the toe of clast-rich debris flows. These unconsolidated mixtures of clay to sand-sized grains have a higher ΔT than the clast-rich debris flows they surround. These features were identified on several Owens Valley fans, with the best examples on Dolomite and French Spring Fan (Figure B9). Unconsolidated clast-poor, unconfined debris flows were identified as unique features due to their spatial relationships with clast-rich debris flows, as they tend to surround clast-rich debris flows near the toe of the alluvial fan, are unchannelized, and are composed of a nearly uniform clay-rich grain size distribution.

Dolomite Fan and French Spring Fan (Figure B9):

On the Dolomite Fan, the clast-poor debris flow can be seen lining the toe of the clast-rich debris flow at DF 28 in Figure B9C. Figure B9D shows the relatively fine-grained and loosely packed nature of the unconsolidated mudflow, while Figure B9E shows the toe of the clast-rich debris flow (to the left) lined by the clast-poor mudflow. On the French Spring Fan (overview in Figure B9F-H), two clast-poor unconfined debris flows were identified at

FSF 27 and FSF 29. These features were also found near the toe of the fan, are relatively unconsolidated (Figure B9I) and line the toe of clast-rich debris flows (Figure B9H, B9J). Arrows in Figure B9J mark the boundary of the unconsolidated clast-poor, unconfined debris flow at FSF 29 with the clast-rich debris flow that it surrounds. Unconsolidated mudflows tend to be higher albedo features, presumably due to the ease with which finer-grained surfaces are eroded.

6.2.3 Indurated clast-poor, unconfined debris flows

In thermal images, indurated clast-poor debris flows tend to be associated with clast-rich debris flows, appearing as linear features that branch off the main clast-rich debris flow (Figure B10C, B10J). The clast-rich debris flows can be seen in the upper regions of Figure B10C and B10J as more spatially expansive, low ΔT features, while the indurated clast-poor debris flows are relatively small, branching features that have a slightly higher ΔT than the clast-rich debris flows they surround. Indurated clast-poor, unconfined debris flows were identified as unique features as they tend to branch from clast-rich debris flows in the mid-fan region, are unchannelized and are composed of a nearly uniform clay-rich grain size distribution.

French Spring Fan (Figure B10):

We have identified a clast-poor debris flow in the mid-fan region of the French Spring alluvial fan. The indurated, unconfined mudflow is represented by a generally lobate, low ΔT feature branches out from a clast-rich debris flow in the mid-fan region. The mudflow on the French Spring Fan was also relatively high albedo, without significant desert varnish, suggesting it is younger than the surrounding deposits at FSF 20, FSF 21, and FSF 25 (Figure B10). The mid-fan region is more likely to prevent mudflow desiccation, as deposits there are more likely to receive periodic infiltration of ground water or snowmelt. At FSF 21, the mudflow also appears to drape over and move around the larger clasts (Figure B10F, B10G - arrows), indicating the flow itself did not have sufficient carrying capacity to transport the larger clasts down the fan. The darker toned gravel (Figure B10D, B10E, B10F, B10G) that lies atop the indurated mudflow appears to be a surface lag from subsequent overland flow events that are not associated with the mudflow itself, as the gravel is not entrained in the flow.

6.2.4 Incised channel deposits

Some alluvial fans have a prominent, well developed, incised channel that extends from the apex to the toe. Debris flows will often utilize these channels, depositing mixtures of coarse-grained and indurated fine-grained material from repeated periods of activity. Both the Gower Gulch Fan (GGF) and Coffin Canyon Fans (CCF) in our study have prominent incised channels (Figures B11, B12). On these fans, the banks of the incised channel are composed of relatively fine-grained sand with scattered coarse-grained material, while the interior of the channel is filled with a mixture of relatively coarse-grained cobbles and indurated mudflows, representing a combination of both clast-rich and clast-poor deposits. We show examples of incised channel deposits can contain a mixture of clast-rich and clast-poor debris flow materials (Figure B11, Figure B12A - B12G) as well as those that are dominated by fluvial processes (Figure B12H - B12P).

Gower Gulch Fan (Figure B11):

The Gower Gulch Fan has an overall gentler downfan slope (less than ~ 2 degrees) than the Badwater fans to the south. The primary features of the Gower Gulch Fan are two main incised channels. The main channel varies from approximately 10 - 20 meters wide, ~ 3 meters deep that starts at the mouth of the fan and trends east-northeast down the fan (Figure B11B, B11C, B11E). The secondary channel is smaller (~ 2 meters wide), has shallower banks and trends west-southwest. The main channel fill material is composed of a basement of indurated, dry hard-pan mud overlain in places by a loose cobbly deposit (Figure B11F, B11G, B11H). The main channel fill deposits are the lowest ΔT values in the scene, presumably due to the indurated mudflow, combined with overlapping and entrained coarse-grained lag and clast-rich debris flows (Figure B11F, B11G, B11H). The clast-rich and clast-poor deposits in the interior channel at GGF 2 are higher albedo than the surrounding material atop the channel walls at GGF 1, indicating they are relatively recent features. Atop the channel walls, at GGF 1, is a less cemented mixture of fines and pebbles with rare and scattered boulders (Figure B11D). This material represents some of the higher ΔT values in the image, and therefore lower relative thermal inertia materials, on the fan.

Coffin Canyon Fan (Figure B12):

The Coffin Canyon Fan has two main channels that cut through the central and southern portions of the fan. The larger of the two incised channels cuts through the southern side of the fan and is characterized in the ΔT (Figure B12C) image by higher relative thermal inertia (lower ΔT) within the channel and a lower relative thermal inertia (higher ΔT) on the top of the channel walls. In the visible image (Figure B12B), these two surfaces have similar albedo and are not easily distinguishable. Our field study revealed that the interior channel fill at CCF 57 is composed of cobbly to pebbly material, with a layer of indurated muddy material beneath (Figure B12F, B12G). Atop the channel wall at CCF 61 the surface is primarily finer-grained material with a few scattered boulders (Figure B12D, B12E). The presence of wide expanses of finer grains presumably made it easier for the channel in the southern portion of the fan to become incised. These finer grained deposits on either side of the incised channel show a lobate pattern, with braided stream features at their surfaces, indicating this may have once been a continuous sheetflood deposit. This is consistent with their appearance in the ΔT image (Figure B12C) as a lobate, high ΔT features in the mid to upper-fan region. Subsequent clast-rich and clast-poor debris flows have utilized the incised channel and deposited a mixture of coarse-grained material and indurated mud (Figure B12F, B12G).

The incised channel in the central region (Figure B12H, B12I) of the Coffin Canyon Fan has a significantly different grain-size distribution than the southern channel. Within the channel itself, the thermal image shows the presence of low ΔT material in the central region of the channel with higher ΔT material surrounding it. During a fluid-driven stream flow, the finer-grain sizes will be deposited near the channel margins, as the channel walls act to reduce the flow velocity. Near the interior of the flow, where flow velocities are highest, larger grain sizes will be deposited. This was verified with ground observations of the surface particle size distribution. We traversed across the central channel stopping at locations CCF 21, CCF 19 and CCF 24 to document the changes in surface particle size distribution. Atop the channel walls of the central incised channel, we found larger grain-sizes, presumed to be remnant debris flow material. Within the channel, near its northern margin at CCF 21, we note the presence of braided stream patterns on the surface (Figure B12K, B12L). Near the central region of the channel at CCF 19, there is a marked increase in grain size distribution (Figure B12M, B12N), which is mirrored by lower ΔT values in our thermal image (Figure B12J). Finally, at CCF 24, we observe a change to lower grain sizes at a small cut bank

(Figure B12O) with finer-grain sizes and braided stream patterns continuing to the southern wall of the main channel (Figure B12P). We believe this is representative of a fluvial deposit within the central incised channel, as there was no evidence of either clast-rich debris flows or indurated mudflows from ground-based observations or from the ΔT image (Figure B12).

6.2.5 Sheetflood and upper-fan features

Badwater Fan 1, Badwater Fan 2, Badwater Fan 3 (Figure B12):

In addition to the sheetflood on the banks of the incised channel on the Coffin Canyon Fan (Figure B12C), we identified surfaces of expansive fine-grained material that resemble sheetflood deposits on several Badwater fans. The sheetflood results from the relatively confined flow expanding as it reaches the fan apex and retaining significant energy to strip the surface of any significant topographic features. The sheetflood is composed of a relatively fine-grained (pebble to cobble) flat surface. These deposits show braided patterns common to fluid flow and tend to fill the entire upper-fan region (Figure B13). These features tend to be represented as lobate high ΔT material in the upper-fan region, and can be either high or low albedo, depending upon their relative age. We identified sheetflood deposits on Badwater Fan 1 at BF1 N (Figure B13A-D), Badwater Fan 2 at BF2 5 (Figure B13E-H) and Badwater Fan 3 at BF3 3 (Figure B13I-L).

Badwater Fan 1, Badwater Fan 2, Badwater Fan 3 (Figure B14):

The other primary features in the upper fan region are isolated areas of large boulders either deposited with the sheetflood or by rockfall from the adjacent mountain range as well as remnant incised channel wall mesa features. The boulders can be isolated (Figure B14D), or can form lines that radiate out from the fan apex. They do not appear to be associated with other surface features. Boulders in the upper-fan region appear as low ΔT features (Figure B14C) that can appear to radiate from the apex when several boulders are aligned. The incised channel wall mesa features consist of a coarse-grained lag and the channel wall material below is commonly indurated (Figure B14E, B13I). These features are presumably the partially buried remains of incised channels that were on the active

depositional region of the alluvial fan, as mesas tend to grade into the mid-fan surface features. Mesa features are prominent near the apex of Badwater Fan 1 (BF1), Badwater Fan 2 (BF2) and Badwater Fan 3 (BF3). These features tend to be lower ΔT , and form a V-shape near the apex of the fan (Figure B14C, B14H). These are commonly older features and are, therefore, lower albedo due to surface reddening from oxidation.

6.2.6 Deposits by Secondary Processes

6.2.6.1 Headward-eroding gullies

Persistent overland flow can produce rills and gullies that coalesce in the mid-fan regions. Continued flow can further erode these gullies, creating channel walls up to a meter high and extending the gullies towards the fan apex (Blair and McPherson, 1994). We identified these features on several of the Badwater fans (Badwater Fans 1, 2, and 3 in Figure B15). They consist of shallow to deep (~ 0.1 to 1 meter) channels that have cut into preexisting cobble and boulder-rich fan materials (Figure B15F, B15L, B15P, B15Q, B15R). Because of the relatively large particle size of the channel bank material (Figure B15E, B15K), these features are represented by some of the lowest ΔT s on the fans on which they are present.

Badwater Fan 1, Badwater Fan 2, Badwater Fan 3 (Figure B15):

On the Badwater fans surfaces are dominated by headward-eroding gullies that cut into pre-existing debris flow deposits. They are observed on the ground as cobble- to boulder-covered on their banks with finer-grained material within the channels. They are seen as linear, radial, low ΔT and low albedo features. They typically radiate outward, come to a 'V' toward the fan apex, are confined to the mid-fan regions and do not extend the full radius of the fan (Figure B15I, B15O). The channel fill material consists of more flat and broad expanses of finer-grained pebble-sized material ($\sim 1/2$ to 1 cm sized) that forms a braided stream pattern (Figure B15D, B15J). These features are represented by relatively higher ΔT and albedo. They fill the channels between the older, low ΔT , lower albedo cobble and boulder-rich fan material.

6.2.6.2 Sand-skirt

Repeated annual overland flow or aeolian activity will result in a sand skirt of fine material at the toe of the alluvial fan. We note that several fans have expansive high ΔT features beyond the toe of the fan, including many in Owens Valley. Although these deposits could be related to weathering of fan surface materials, it is also possible that these are lake sediments from the dry lake bed. On the ground, we found that these features are all present within large areas with significant amounts of vegetation cover. The vegetation obscures much of the surface material from view overhead, therefore, we did not include these features in our field study. The Talc Canyon Fan, however, is separated from Death Valley basin by foothills formed from regional folding and extensional faulting (Butler *et al.*, 1988). These foothills isolate the lower fan materials from the inner Death Valley basin. Therefore, we are confident that the sand skirt observed on the Talc Canyon Fan is the result of weathering of the fan surface materials themselves and has no connection to Lake Manly deposits.

Talc Canyon Fan (Figure B16):

We observed significant weathering of the granite debris flows on the Talc Canyon Fan (Figure B16E), and identified an extensive deposit of fine-grained loosely consolidated sand to pebble-sized deposits of granitic composition at TAF 1 near the toe of the fan (Figure B16D, B16F). This expansive, high ΔT surface is the product of aeolian and/or fluvial winnowing of these weathering products towards the toe of the fan. Figure B16A-C shows the extensive weathering of the granitic surface materials and the resulting sand skirt deposit, as well as the large, high ΔT region in the thermal image at the toe of the fan.

6.2.7 Lag surfaces

For the east Badwater fans, the sedimentary features near the toe of the fans include muted channels (Figure B17F, B16G) with higher topography lag surfaces in the interfluvies (Figure B17D, B17E). The muted channels have smooth banks and have a relatively higher ΔT , implying a lower relative thermal inertia. The material fills areas of low topographic relief, has an abundance of fine-grained (less than 1 cm in diameter), lightly cemented material at

the surface (Figure B17F, B17G). Directly below the surface is a fine-grained dirt mixture with some moisture from the nearby basin. The lag deposits in the bottom fan are generally tear-dropped shaped and consist of non-indurated ~1 cm diameter pebbles and cobbles atop fine-grained dirt. Because of the higher abundance of cobbles and lower proportions of exposed fine-grained material, these deposits have a relatively lower ΔT than the channel deposits, and therefore a higher relative thermal inertia.

Badwater Fan 1 (Figure B17):

The lag deposit on Badwater Fan 1 was verified by observing rocks on pedestals of fine-grained material (Figure B17E). Figure B17H shows a representative lag surface on Badwater Fan 1, with the surrounding muted channel denoted by arrows. Lag surfaces in the lower fan were found to be both higher and lower albedo than the surrounding, channelized material. This appears to be due to the presence or absence of basin-related salts in the surrounding, topographically lower, material.

6.2.8 Active vs. Inactive Lobes

On alluvial fans, material is often deposited on what is called the “active lobe” (Blair and McPherson, 1994). The active lobe migrates across the fan surfaces over time and represents a large area of the fan where primary processes are most likely to deposit material. Large, expansive regions of desert varnished material are common on inactive fan lobes, where material has not been deposited for long periods of time. We found the surfaces of active fan lobe commonly have headward-eroding gullies and are characterized by an overall lower ΔT than the inactive fan lobe.

Hells Gate Fan (Figure B18):

Blair (2000) identified Hells Gate (HGF) as a sheetflood-dominated fan. The sheetflood deposits themselves, however, are only exposed in cross-sections within deeply cut channels and are not exposed at the surface. Therefore, thermal imaging can only reveal the resulting grain-size distribution due to secondary processes. The thermal image trends toward higher ΔT at the toe of the fan with one large expanse of high ΔT on the northern side

at HGF 10 (Figure B18C). This high ΔT deposit represents an inactive region of the fan, as documented by Blair (2000). The high ΔT deposit extends for hundreds of meters, is desert varnished, and is topographically elevated (Figure B18D). In the upper portions of the deposit, it is a relatively fine-grained mixture of cobbles and pebbles, with few fines at the surface. Near the margins of this inactive high ΔT area, low relief fine-grained channels become abundant with younger, fine-grained material filling channels that flow around the inactive region. The southern side of the fan, near HGF 4, has lower ΔT features that represent the channels and associated interfluvial typical of headward-eroding gullies (Figure B18F, B18G, B18H). The channel walls are typically low relief (Figure B18G), with the interfluvial generally having larger grain sizes (Figure B18F), and the channel fill having a higher percentage of fine-grained sediment (Figure B18H).

Titus Canyon Fan (Figure B19):

The Titus Canyon Fan (TCF) shows similar thermal patterns to the Hell's Gate Fan. We observed many headward-eroding gullies in the southern portion of the fan near TCF 1 (Figure B19D, B19E, B19F), while the northern portion of the fan near TCF 4 and TCF 5 includes shallow channels, but more wide expanses of elevated, desert varnished fan regions (Figure B19H, B19J). The northern fan region also contains wide expanses of finer-grained, topographically raised lag surfaces near TCF 4 and TCF 5 (Figure B19G, B19H, B19I, B19J). These older surfaces tend to be lower albedo, while the younger deposits to the south are higher albedo. The sharp boundary of low to high ΔT in the thermal image represents the transition from active to inactive depositional lobe (Figure B19C).

6.2.9 Salt Pan

Badwater Fan 1 (Figure B20):

In the distal regions of alluvial fans in the Badwater region, seasonal influxes of groundwater can form a hard mixture of salt and mud. The salt pan is readily identifiable remotely by its higher albedo (in contrast to the surrounding lower fan materials), low ΔT , and orientation parallel to the basin margin, while in the field it is identified by the presence of salt crystals, polygons and a mottled surface texture (Figure B20D). We have found it

to have a very low ΔT , presumably due to the indurated nature of the deposits and the presence of water. Although not part of the fan formation process, the presence of a rim of high albedo, low ΔT material surrounding the toe of an alluvial fan (Figure B20B, B20C) would suggest the formation of salts due to the infiltration of seasonal ground water to the basin. This would be an important result for proposed Martian alluvial fans (Osterloo *et al.*, 2008). Although this study focuses on constituent sedimentary features of alluvial fans, the identification of basin-related deposits such as salt pans and evaporite minerals using thermal imaging will be explored in future work. We show the contact of the salt-rich basin material with the lower fan surface of Badwater Fan 1 near BW3 24 in Figure B20D.

7. Discussion and Summary

We have shown that many constituent sedimentary features on alluvial fans may be identified using aerial thermal images augmented with high resolution visible images. This was demonstrated by comparing the thermal, albedo, and morphologic patterns seen in these remotely-acquired images with direct observations made on the ground. Feature types that may be identified in remote thermal and visible images are: clast-rich and clast-poor debris flows, incised channel deposits, headward-eroding gullies, sheetflood, lag surfaces, active/inactive lobes, distal sand skirts and basin-related salt pans. To aid future workers in using the techniques described in this study, we have distilled the remote sensing properties discussed in Section 6 into a summary table (Table B2). We anticipate this table will be useful in situations where only remote data are available for initial reconnaissance of alluvial fans. It is important to note that using albedo variations to determine relative age worked well for terrestrial alluvial fans in the environments we studied, however, on Mars changes in albedo (*e.g.*, addition or removal of dust), may not be related to the relative surface age. We have also shown that thermal images can reveal trends in grain sizes between neighboring alluvial fans on a regional scale.

Optimally, thermal imaging should not be used in isolation for identifying the sedimentary features present on an alluvial fan surface. Rather, our results show that ΔT images (Section 3) are most useful when combined with corresponding visible images because many sedimentary features cannot be uniquely identified using a ΔT image alone. For example, on several fans in Owens Valley, we have identified lobate, low ΔT features that extend from

the apex to the toe of the fan. In the absence of accompanying visible images, these features could be interpreted as either clast-rich debris flows or indurated clast-poor debris flows. Corresponding visible images can identify clast-poor debris flows, as they tend to appear as higher albedo features. These mudflows erode away quickly and, therefore, do not have time to develop a varnish or redden due to oxidation. In Death Valley, incised channels like those found on the Coffin Canyon and Gower Gulch Fans can be readily identified using visible images. However, the nature of the deposits within the channels is often difficult to discern if grain sizes are smaller than the visible camera's resolution (which is usually the case). ΔT images for both of these fans (Figure B11C and B12C) shows a remarkable difference in the nature of the deposits within these channels. On the Gower Gulch Fan, the interior of the channel is found to be blanketed from apex to toe in low ΔT material, which was found through our field work to be an indurated mudflow, while on the Coffin Canyon Fan, the interior of the channels shows a mixture of high and low ΔT values as described in Section 6.2.3, which our field work determined was related to fluvial deposition and modification. In these cases, field work is required to positively identify the sedimentary feature from a short list of options that are consistent with the remote data.

Other types of features are relatively easy to uniquely identify from their appearance in remote thermal data alone. We were able to identify patterns in morphology and ΔT across multiple fans that gave us confidence in making more definitive interpretations. For example, lower ΔT materials that are confined to the upper fan tend to be associated with boulders and mesas related to now-buried incised channels. Lower ΔT materials confined to the mid-fan region are predominantly related to headward-eroding gullies, especially if they are found to have a V shape at their apex and are surrounded by higher ΔT materials. As described in Section 6.2.5, we found that these features correspond to cobble-rich materials on the gully banks, with finer-grained materials filling the channels between the gully walls. Lower ΔT surfaces that line the toe of the fan are predominately basin-related salt deposits. In the mid to upper-fan, if an incised channel is present, our field work shows that it is more common to find a mixture of clast-rich and indurated clast-poor deposits within the incised channel than to find clast-rich debris flows alone. This is presumably because clast-rich flows will ignore existing topography, while fluvial deposits tend to follow topographic lows.

Other examples of features that can be readily identified by their appearance in the thermal data include sheetflood

deposits, which are lobate, high ΔT surfaces in the upper to mid-fan regions. Linear, channelized, high ΔT surfaces in the mid-fan region tended to correspond to finer-grained gully fill. In the lower fan regions, several higher ΔT deposits were identified. If the high ΔT material is tear-dropped in plan view, it may correspond to a lag surfaces, as is the case for Badwater Fan 1. As seen on fans in Owens Valley, high ΔT surfaces near the toe of the fan are unconsolidated clast-poor debris flows which are lobate and form rims around clast-rich, lower ΔT , debris flows. On other fans like Talc Canyon Fan in Death Valley, we find an expansive, homogeneously high ΔT feature lining the toe of the fan that corresponds to a sand skirt. Our field work found that the sand skirt is forming from weathering and erosion of the granitic clast-rich debris flow material that extends to the toe of the fan.

On the Coffin Canyon Fan, lobate, high ΔT (lower relative thermal inertia) features are found in the mid-fan region on either side of an incised channel that contains lower ΔT (higher relative thermal inertia) material, showing that thermal images can be used to identify cross-cutting relationships on the fan's surface. Having verified the cross-cutting sedimentary deposits on the ground, we are confident these types of relationships can be made using remote visible and thermal images alone. Visible images can be used to readily identify a large incised channel, while corresponding thermal images can be used to identify lobate, higher ΔT surfaces bounding lower ΔT surfaces within the channel itself. We are able to use this information to extract a crude geologic history, namely that the fan experienced a large fine-grained sheetflood deposit which later became incised and subsequently filled with clast-rich and clast-poor debris flows.

High spatial resolution thermal images may be especially useful on Mars, where ground truth is not available, and where evidence for surface water and overland flow would be a significant result. On Earth, thermal images can be used to provide a quick reconnaissance of alluvial fans in arid desert environments, suggest what processes have most recently acted on the surface of a fan, and to prioritize sites for detailed study on the ground. This study also provides a means for hazard and land use management organizations to suggest the relative grain size distribution or degree of induration of surface materials in order to make a quick risk assessment of individual alluvial fans. Aerial thermal images, augmented by high resolution visible images, are a useful new tool for any geologist studying alluvial fans in an arid climate.

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Appendix B

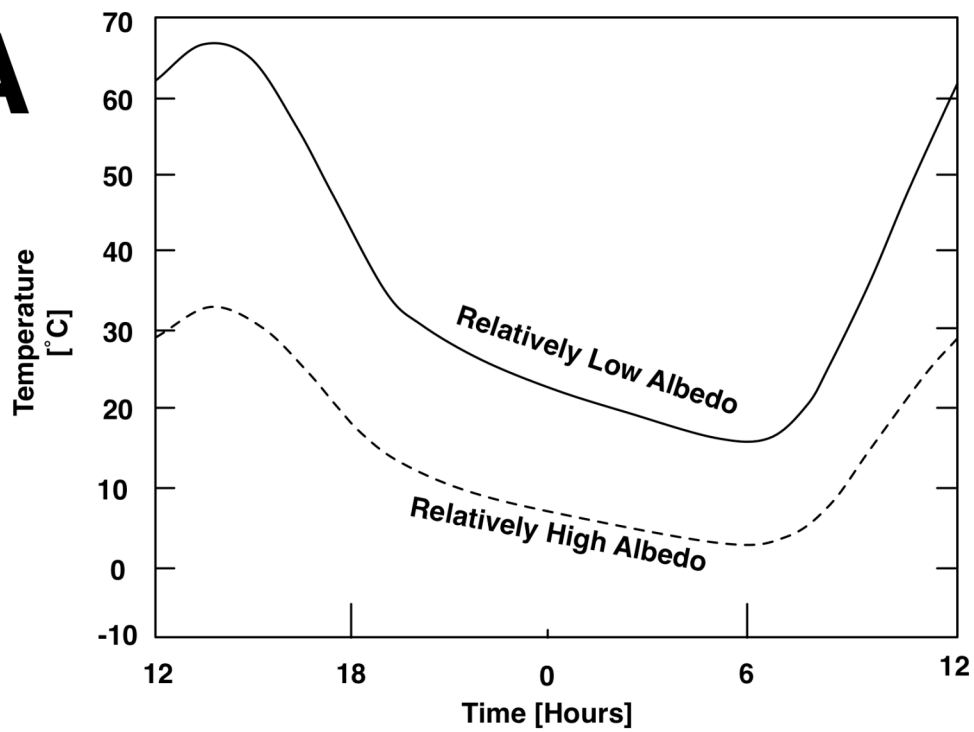
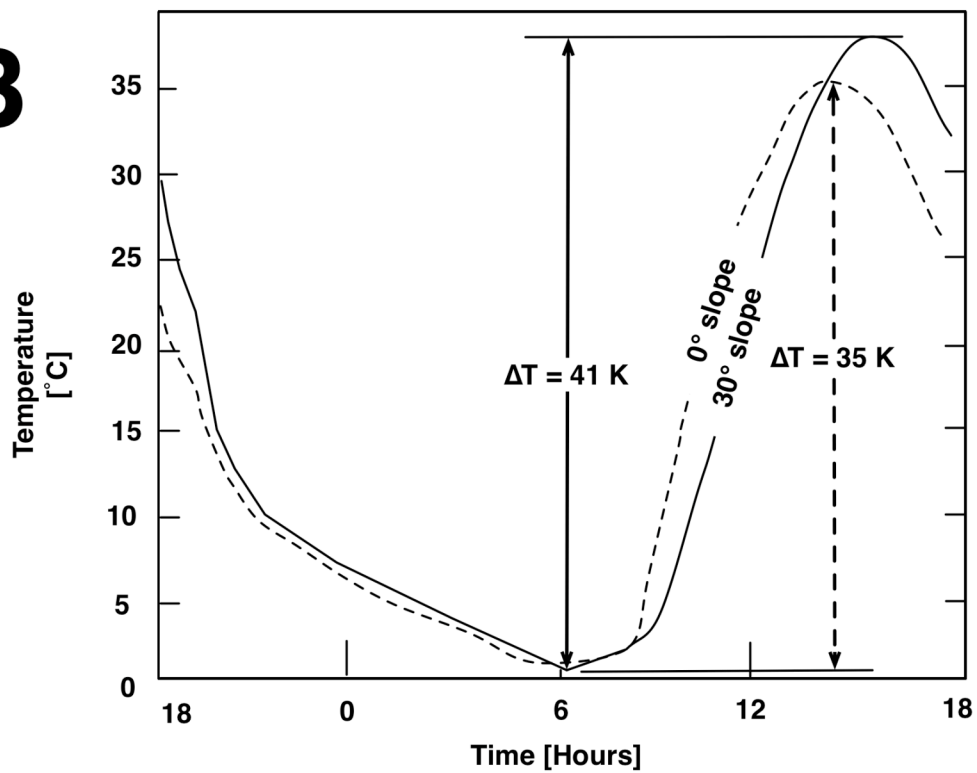
Table B1: Thermal Image Acquisition Dates and Times for Alluvial Fans

Alluvial Fan	Image Acquisition Times	
	Day	Night
BF	3/20/09 12:35	3/21/09 6:25
BF1	3/20/09 12:35	3/21/09 6:26
BF2	3/20/09 12:36	3/21/09 6:26
BF3	3/20/09 12:36	3/21/09 6:26
CCF	3/20/09 12:37	3/21/09 6:27
GGF	3/20/09 12:28	3/21/09 6:19
HGF	3/20/09 12:19	3/21/09 6:09
TCF	3/20/09 12:10	3/21/09 6:00
TAF	3/20/09 11:24	3/21/09 5:15
TF	3/20/09 11:40	3/21/09 5:30
WSF	3/20/09 11:29	3/21/09 5:20
FHF	3/21/09 10:50	3/22/09 6:24
UWF	3/22/09 12:28	3/22/09 6:25
FSF	3/21/09 10:53	3/22/09 6:26
GSF	3/21/09 10:54	3/22/09 6:27
DF	3/21/09 10:56	3/22/09 6:29

Table B2: Interpretation of Sedimentary Features Using Relative Albedo, ΔT , and Morphology

RELATIVE ALBEDO	RELATIVE ΔT	MORPHOLOGY	INTERPRETATION	EXAMPLES
High/Low	High	Channelized (mid-fan with lower ΔT "V-shapes" surrounding)	Fluvial channel fill	Figures 15D, F, J, L, P
		Lobate, unconfined	(lower-fan) Unconsolidated clast-poor debris flow	Figures 9B - 9E, 9G - 9J
			(upper- and mid- fan) Sheetflood deposit	(upper-fan) Figure 13, (mid-fan) Figure 12C, 12D, 12E
		Uniform, large lower fan deposit	Sand-skirt	Figures 16A - 16C, 16D, 16F
High	Low	Channelized	Recent clast-rich debris flow using pre-existing channel	Figure 11B, 11C, 11E, 11G, Figure 12B, 12C, 12G
			Recent, indurated clast-poor debris flow using pre-existing channel"	Figure 11B, 11C, 11E, 11F, Figure 12B, 12C, 12F"
		Lobate, unconfined	Recent clast-rich debris flow	Figures 6B, 6C, 6M, 6N
			Recent, indurated clast-poor debris flow	Figure 10
High/Low	Low	Linear	(upper-fan) Recent debris flow levees	Figure 6O
		Radial, "V-shaped" (mid-fan with surrounding higher ΔT channel fill)	Headward eroding gullies	Figures 15B, 15C, 15E, 15F, Figure 15H, 15I, 15K, 15L, Figure 15N, 15O, 15Q, 15R
		Isolated	(upper-fan) Boulders	Figures 14B, 14C, 14D
		Lining toe of fan	Salt-pan	Figure 20
Low	Low	Tear-dropped	(lower-fan) Lag surface	Figure 17
		Lobate, unconfined	Remnant clast-rich debris flow	Figures 6B - 6I, Figures 7B - 7E, Figures 7H, 7I, Figure 8
		Radial, "V-shaped"	(upper-fan) Mesas	Figure 14

Figure B1: (A) Schematic diurnal temperature curves for two surfaces with the same thermal inertia, emissivity, insolation geometry and history, but with relatively low (solid curve) and high (dashed curve) albedos (adapted from Watson, 1975). The effect of varying albedo does not significantly change the overall ΔT . (B) Diurnal temperature data for sand (50 wt. % of 200-500 microns, 40 wt. of % 500-800 microns) sloping at 0 degrees (dashed curve) and a westward-oriented face sloping at 30 degrees (solid curve) showing the effect of decreasing slope on ΔT . For westward-facing surfaces of equivalent composition and grain size, decreasing slopes tend toward lower ΔT , opposite to the trends seen in our ΔT images which consistently show higher ΔT values toward the lower slopes at the toe of the alluvial fans. These results, combined with our ground observations of smaller grain sizes near the toes of the fans, indicates that ΔT images are dominated by changes in grain-size.

A**B**

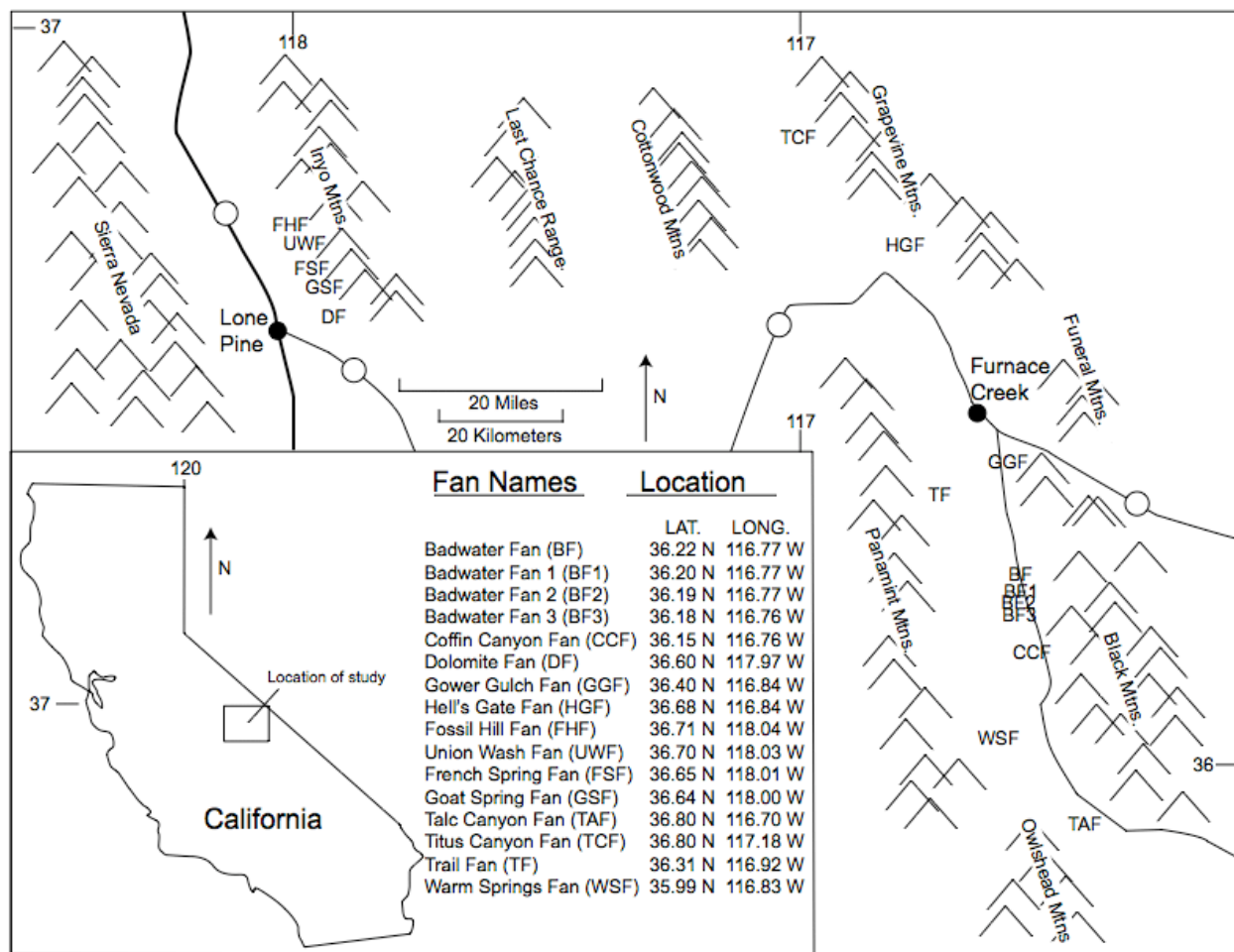


Figure B2: Context map showing the locations of alluvial fans within Owens Valley and Death Valley that are included in our study. The inset includes the abbreviations that will be used to reference individual alluvial fans in subsequent sections as well as the latitudes and longitudes for each of fan studied.

Figure B3: Mosaic of all ΔT images for alluvial fans in Owens Valley and Death Valley. Each fan is labeled with its associated abbreviation from Figure B1. Warmer colors (reds) correspond to lower ΔT values or high relative thermal inertias. Cooler colors (blues) correspond to higher ΔT values or low relative thermal inertias. Each ΔT image has been independently contrast enhanced to accentuate the differences in ΔT on each alluvial fan. Full names and ΔT ranges (in $^{\circ}\text{C}$) for each fan are as follows: Badwater Fan, BF (7.7 - 25.3); Badwater Fan 1, BF1 (15.0 - 26.7); Badwater Fan 2, BF2 (17.8 - 27.2); Badwater Fan 3, BF3 (14.4 - 27.0); Coffin Canyon Fan, CCF (15.0 - 30.0); Gower Gulch Fan, GGF (14.5 - 27.2); Hells Gate Fan, HGF (12.5 - 22.9); Titus Canyon Fan, TCF (10.1 - 20.0); Talc Canyon Fan, TAF (4.2 - 14.0); Trail Fan, TF (9.2 - 21.7); Warm Springs Fan (9.2 - 21.7), WSF; Fossil Hill Fan, FHF (18.0 - 25.0); Union Wash Fan, UWF (21.5 - 33.2); French Spring Fan, FSF (9.9 - 26.2); Goat Spring Fan, GSF (18.0 - 28.0); Dolomite Fan, DF (14.6 - 27.8).

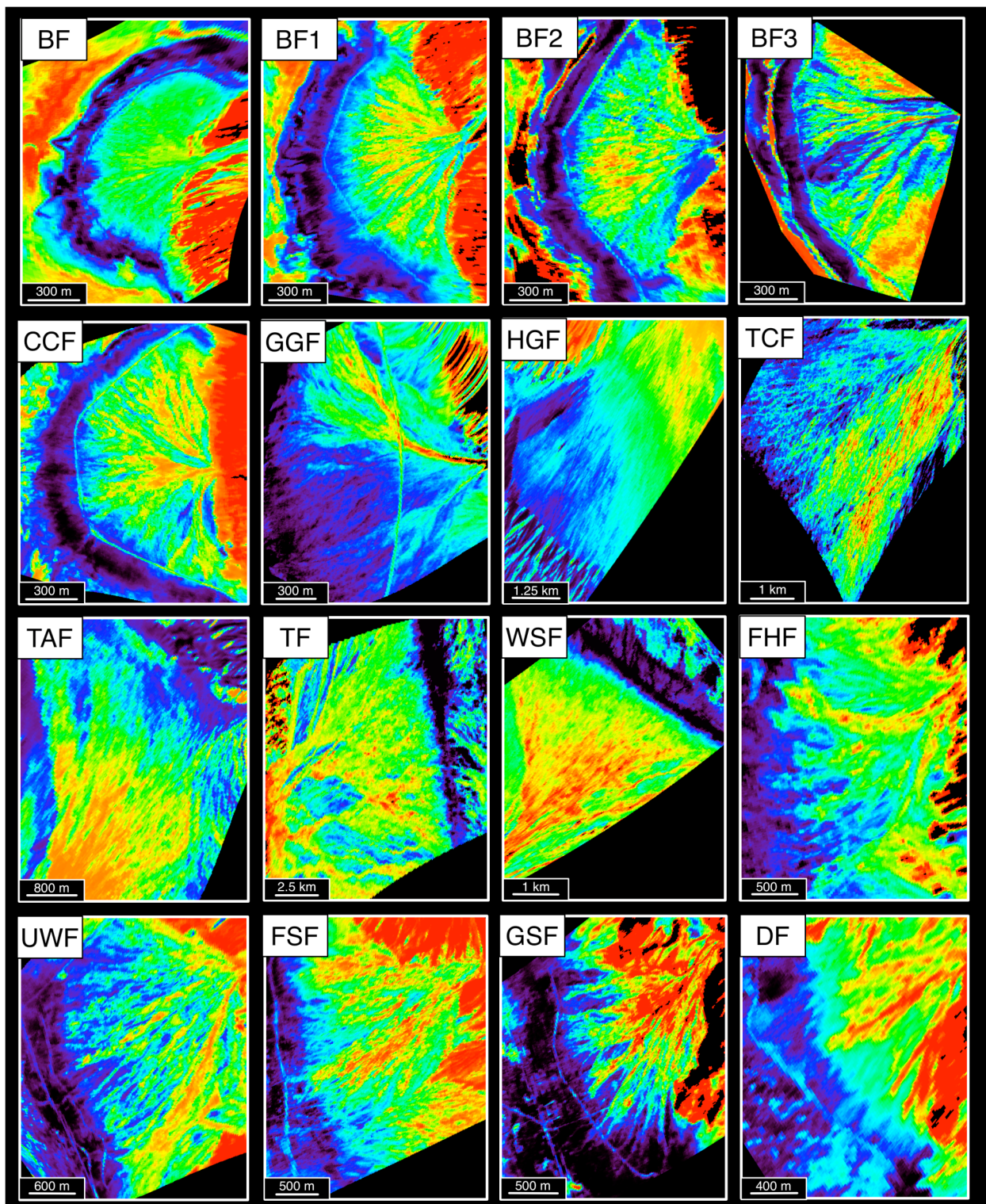


Figure B4: High-resolution visible images (© 2008 DeLorme www.delorme.com; Licensed by SPOT Image Corp) for each alluvial fan studied. Spectral bands are at 0.45-0.52 microns (blue), 0.52-0.60 microns (green) and 0.63-0.69 microns (red). See Figure B2 for the corresponding ΔT image for each fan. Beneath the north arrow (represented by a star) on all DeLorme figure legends MN stands for magnetic north, with the magnetic declination listed in decimal degrees to the right.

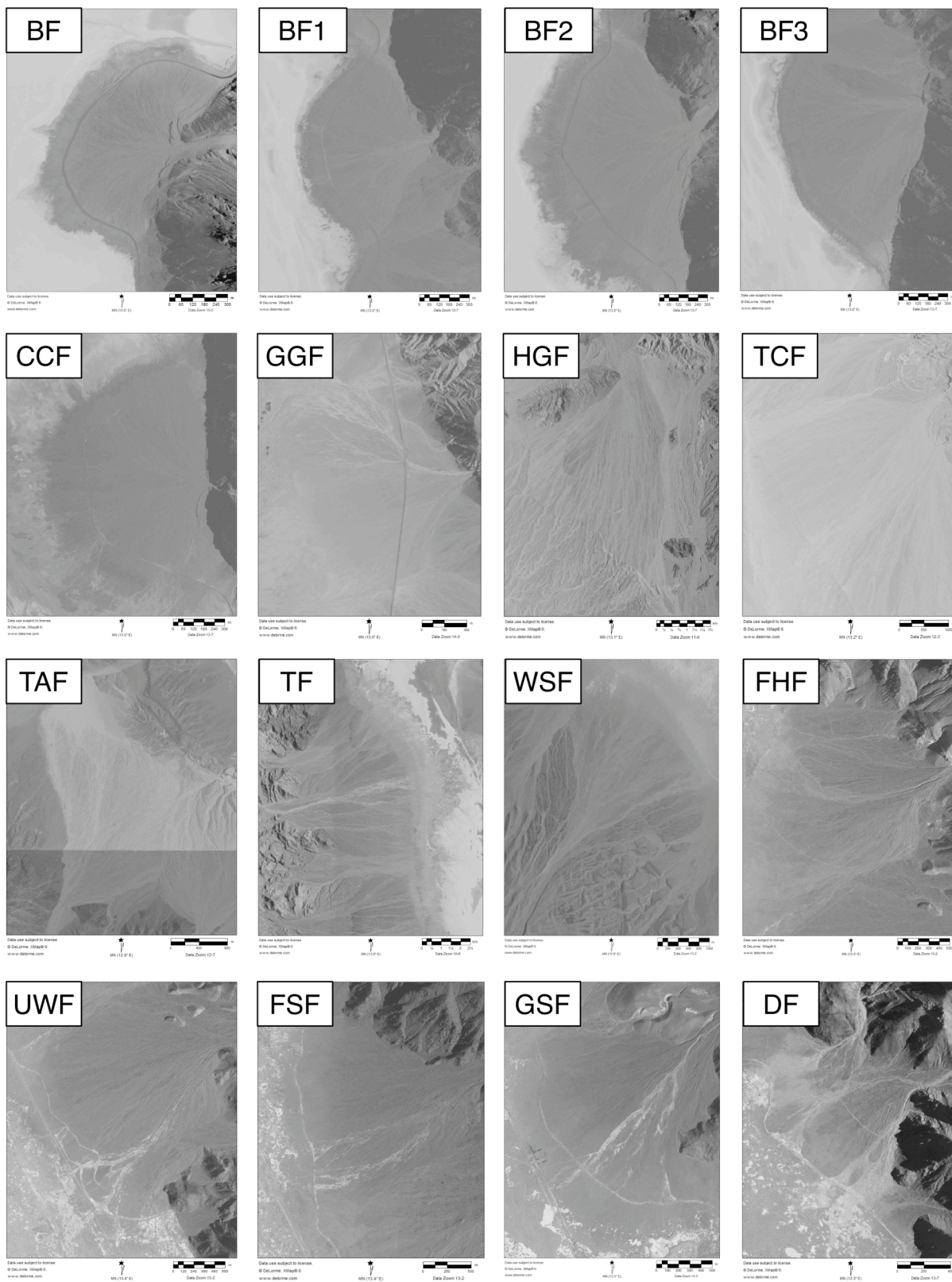


Figure B5: Mosaic of ΔT images for the eastern Badwater fans in Death Valley, CA using a single contrast enhancement for all images. Warmer (reds) colors correspond to smaller values of ΔT . Cooler colors (blues) corresponds to larger values of ΔT . Note the overall increase in ΔT for fan surfaces from north to south.

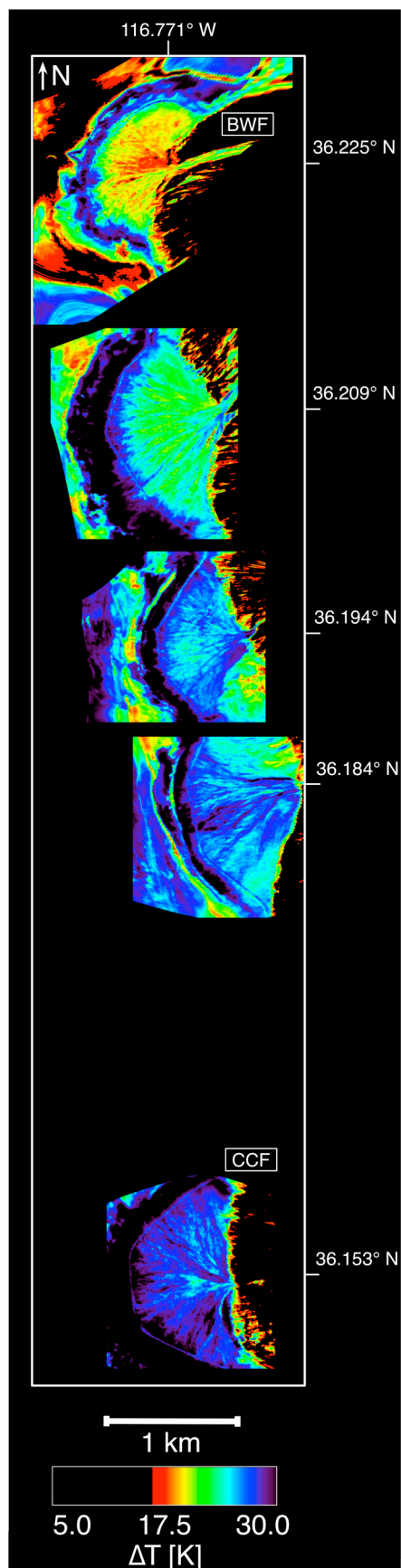


Figure B6: (A) High resolution visible image of the Dolomite Fan in Owens Valley with zoom box showing location of Figure 6B - 6O. (B) Visible context image showing the locations of clast-rich debris flows 'DF 3', 'DF 4', 'DF 7' and finer-grained surfaces at 'DF 6'. (C) ΔT context image shows the locations and relative ΔT values for clast-rich debris flows 'DF 3', 'DF 4', 'DF 7' and finer-grained surfaces between clast-rich debris flows 'DF 6'. (D, E, F) Ground photos showing the surface grain sizes at 'DF 3'. The surface materials are composed of cobble to boulder-sized material that makes up the central clast-rich debris flow lobe. (G, H, I) Ground photos shows the surface grain sizes at 'DF 4'. The surface materials are similar in grain size to those at 'DF 3', indicating this is a breakout section of the central debris flow. (J, K) Ground photos shows the sand to pebble grain-size distribution in-between the central and southern debris flows at 'DF 6'. (L) The boulder sized components (marked with arrows) at 'DF 4' are remnant, partially buried, clast-rich debris flows that appear as rims of lower ΔT material in the thermal image. (M, N) Ground photos shows the surface grain sizes at 'DF 7'. The surface materials for this clast-rich debris flow are of cobble to boulder grain size distribution. (O) We note the presence of debris flow levees less than 2 meters wide present at 'DF 7' (marked with arrows), however, they are too small to be seen with our aerial thermal imaging.

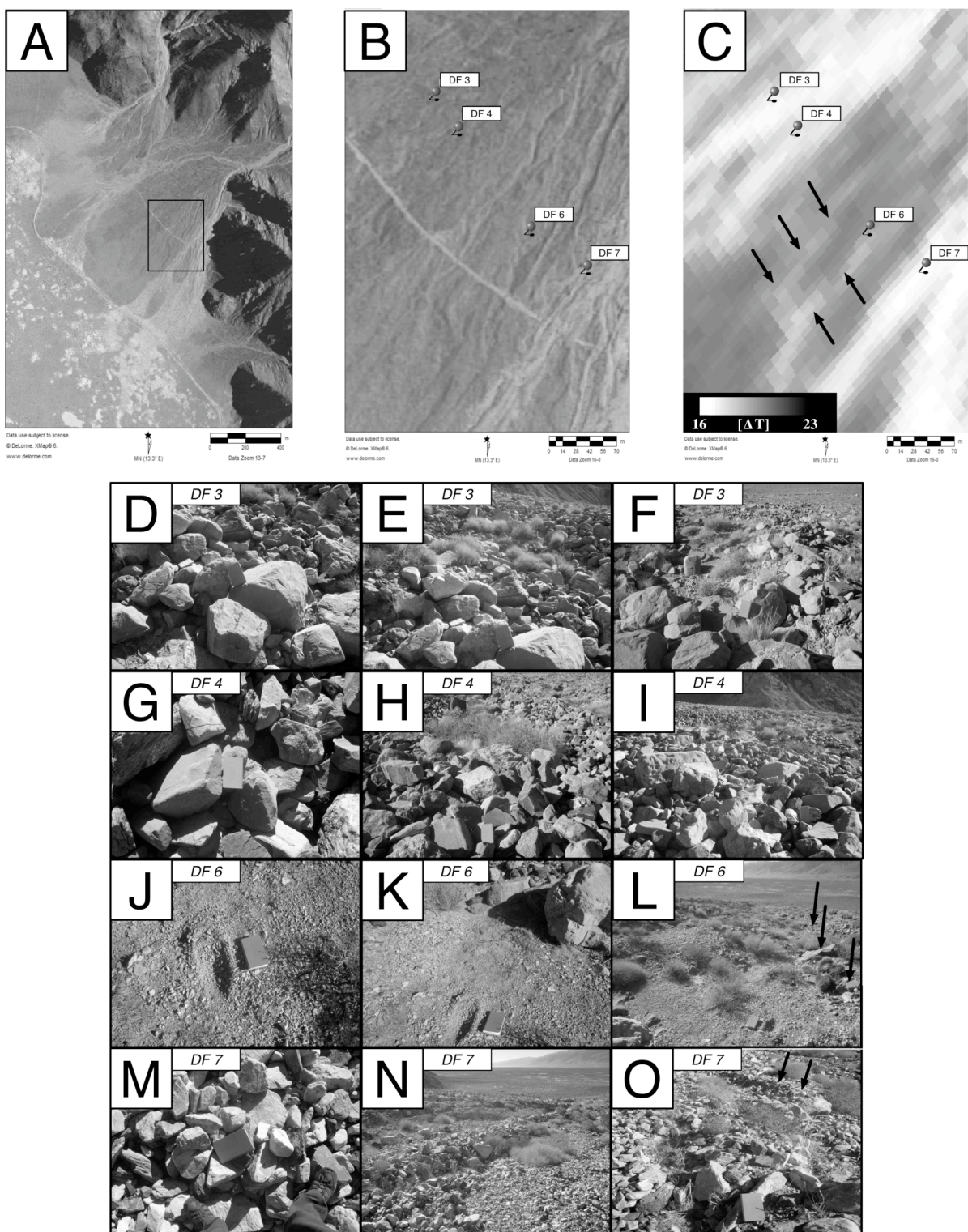


Figure B7: (A) High resolution visible image of Fossil Hill Fan (FHF) in Owens Valley with zoom box showing location of Figure 7B - 7K. (B) Visible context image shows the locations of clast-rich debris flows (FHF 7, FHF 9) and inactive, varnished regions (FHF 8, FHF 10). (C) ΔT context image showing the locations and relative ΔT values for clast-rich debris flows (FHF 7, FHF 10) and inactive, varnished regions (FHF 8, FHF 10). (D) Ground photo showing the surface grain sizes at 'FHF 7'. The clast-rich debris flows are composed primarily of pebble to boulder-sized grains. (E) Context image shows the boundaries (marked with arrows) of the debris flow at 'FHF 7' with the surrounding, inactive and varnished surface. (F) Ground photo showing the surface grain sizes at 'FHF 8'. The fine-grained mixture of sand to small pebbles fills the regions between the clast-rich debris flows. (G) Context image of the expansive, finer-grained, varnished surface at 'FHF 8'. (H) Ground photo showing the surface grain sizes at 'FHF 9'. The clast-rich debris flows are composed primarily of pebble to boulder-sized grains. (I) Context image shows the boundaries (marked with arrows) of the debris flow at 'FHF 9' with the surrounding, inactive and varnished surface. (J) Ground photo showing the surface grain sizes at 'FHF 10'. The fine-grained mixture of sand to small pebbles fills the regions between the clast-rich debris flows. (K) Context image of the expansive, finer-grained, varnished surface at 'FHF 10'.

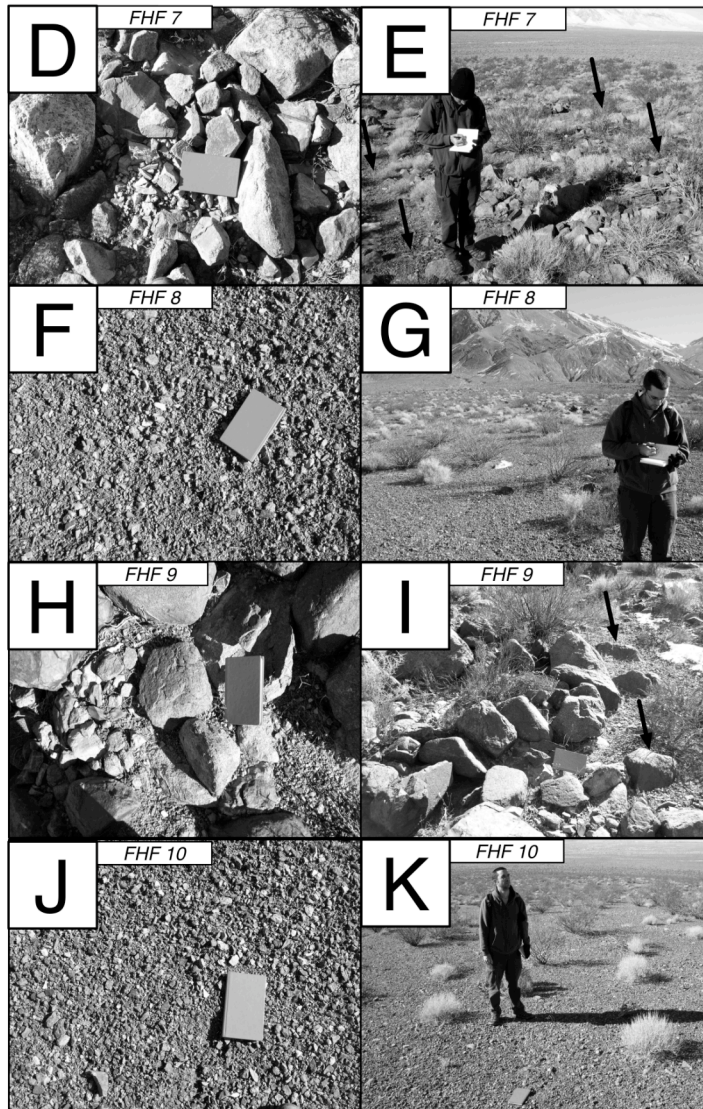
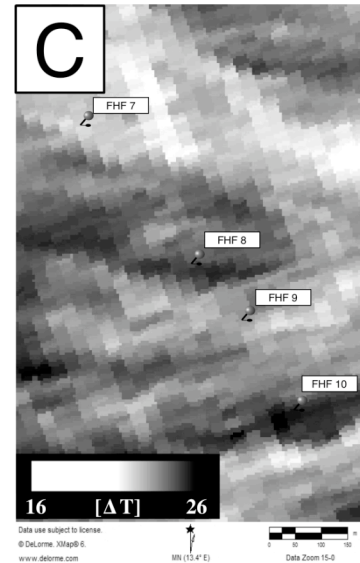
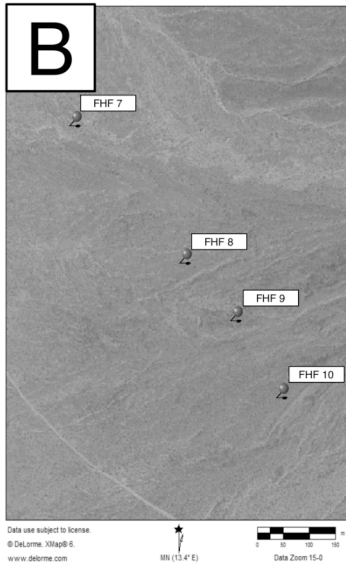
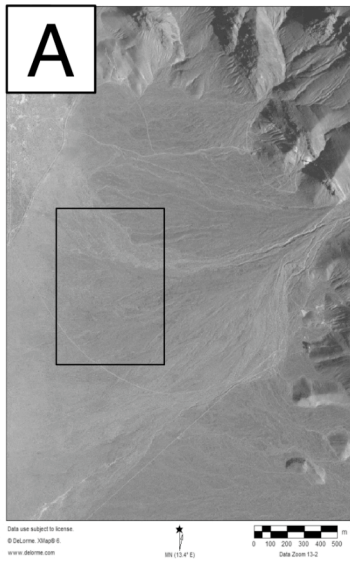


Figure B8: (A) High resolution visible image of Talc Canyon Fan (TAF) in Death Valley showing the location of the toe of a clast-rich debris flow (TAF 2) and the main body of the clast-rich debris flow (TAF 5). (B) ΔT context image showing the locations of the toe of a clast-rich debris flow (TAF 2) and the main body of the clast-rich debris flow at TAF 5 (marked with dashed line). (C) Ground photo shows the lobate form of a debris flow at ‘TAF 2’ at the toe of the fan. The lobate form and relatively large grain size of this feature indicate it is a clast-rich debris flow. We did not identify significant clast-poor debris flow components to this flow. However, due to the extensive granitic weathering and prevalence of granitic sands at the toe, we interpret that this debris flow represents one of the older surfaces on the fan. (D) Ground photo at ‘TAF 5’ shows the granitic boulders that composed this clast-rich debris flow. (E) Ground photo shows the margins of the debris flow (denoted with arrows) with the surrounding finer-grained surface materials near ‘TAF 5’ (F) Ground photo shows the main body of the clast-rich debris flow at ‘TAF 5’.

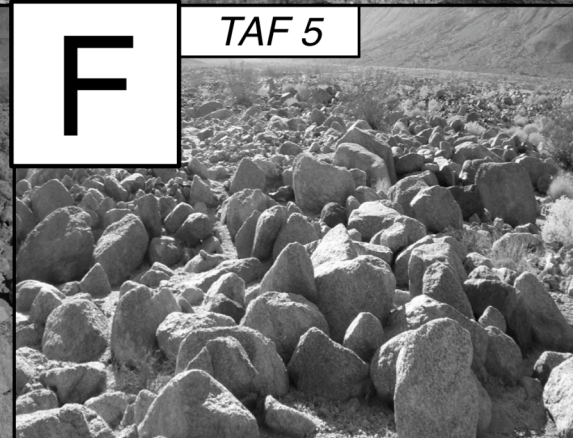
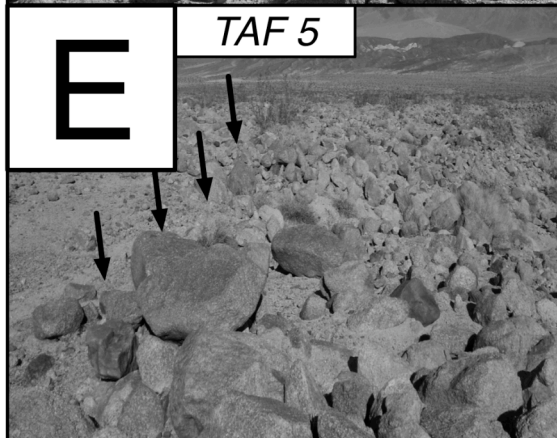
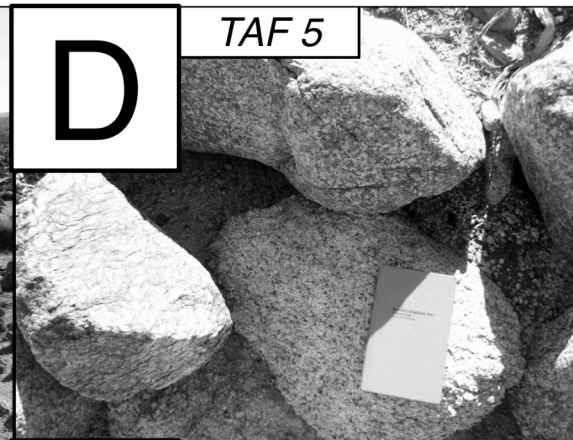
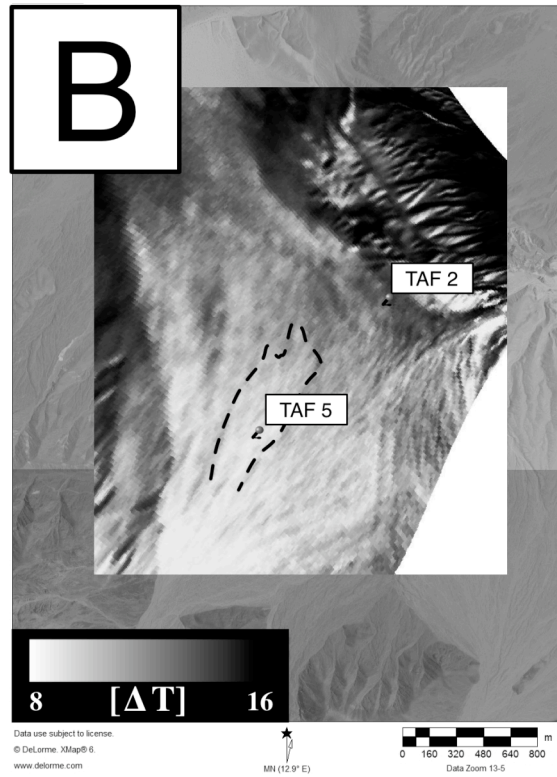
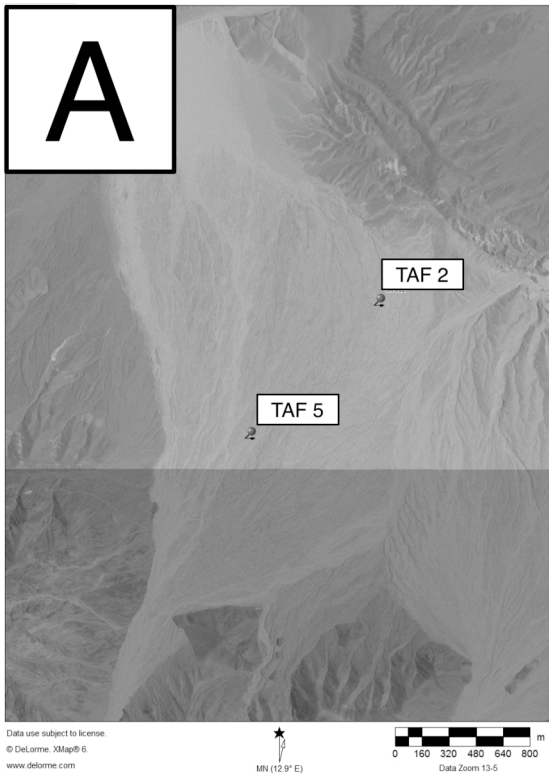


Figure B9: (A) High resolution visible image of Dolomite Fan (DF) in Owens Valley with zoom box showing the location of Figure 9B - 9E. (B) Visible context image showing the location of the unconsolidated clast-poor debris flow (DF 28). (C) ΔT context image showing the location of the unconsolidated clast-poor debris flow (DF 28). (D) Ground photo at 'DF 28' shows a close up image of the unconsolidated clast-poor debris flow. Although the surface appears to be indurated, the clay mixture is not well consolidated and was easily disturbed as evidenced by the nearby trench. (E) Ground photo at 'DF 28' shows the unconsolidated mudflow surrounding the sand and pebble-rich toe of the southern clast-rich debris flow (arrows denote the boundary) (trench is same as in Figure 9D). (F) High resolution visible image of French Spring Fan (FSF) in Owens Valley with zoom box showing the location of Figure 9G - 9J. (G) Visible context image showing the locations of the unconsolidated mudflows at 'FSF 27' and 'FSF 29'. (H) ΔT context image showing the locations of the unconsolidated mudflows at 'FSF 27' and 'FSF 29'. (I) Ground photo at 'FSF 27' shows the uniform grain-size distribution of the mudflow as well as the unconsolidated nature, similar to the unconsolidated mudflow identified on the Dolomite Fan at DF 28. (J) Ground photo at 'FSF 2' shows the boundary (marked with arrows) between the clast-rich and unconsolidated mudflow at the toe of the fan. Unconsolidated mudflows were identified as unique features due to their spatial relationships with clast-rich debris flows, as they tend to surround clast-rich debris flows near the toe of the alluvial fan and are composed of a nearly uniform clay-rich grain size distribution.

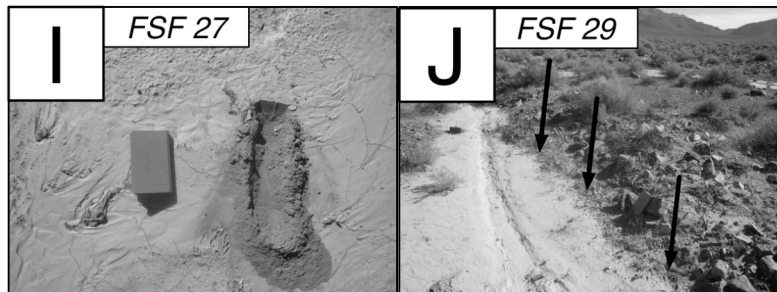
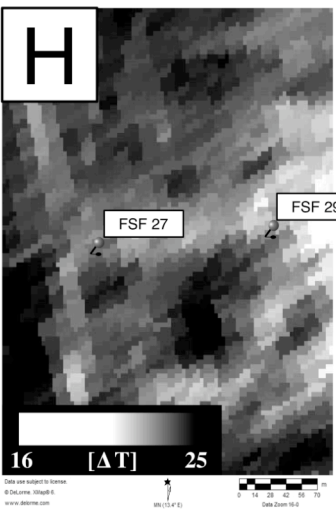
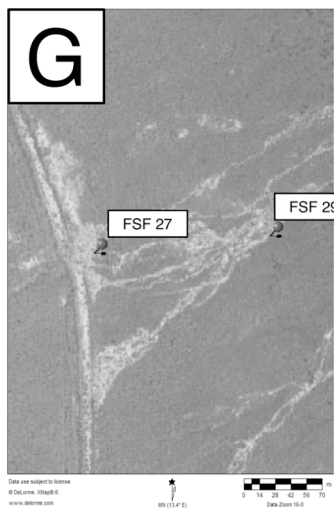
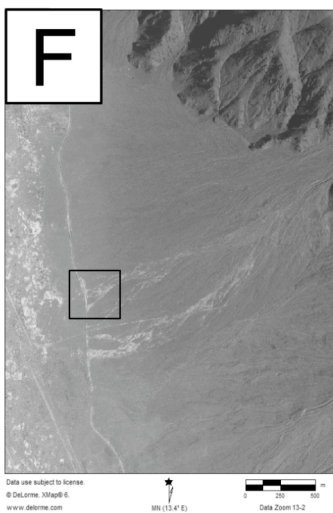
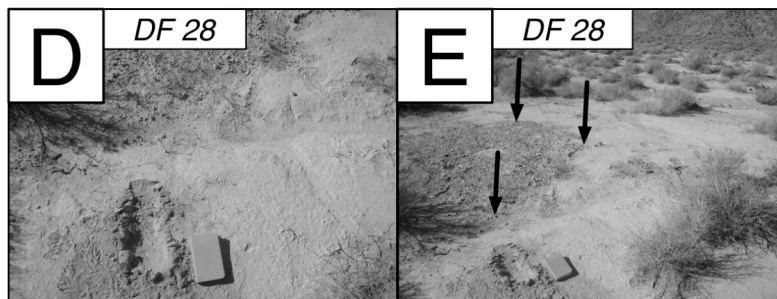
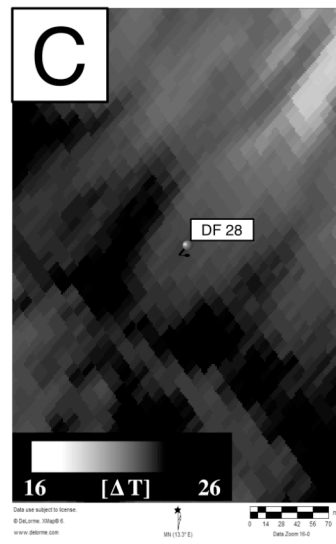
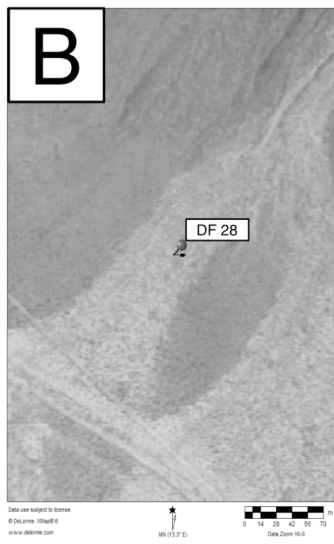
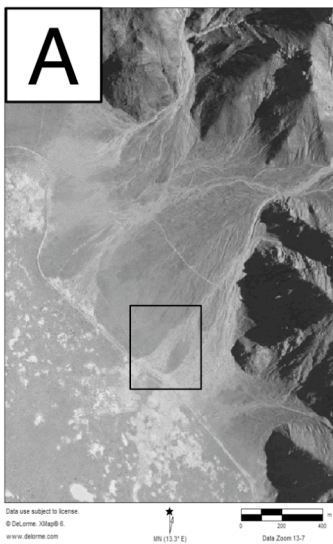
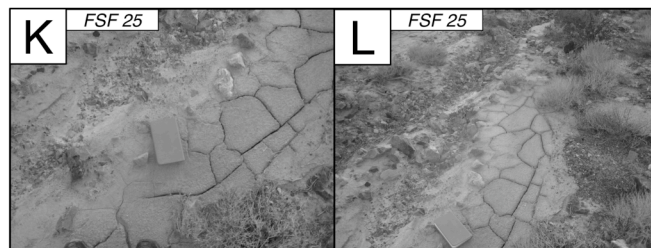
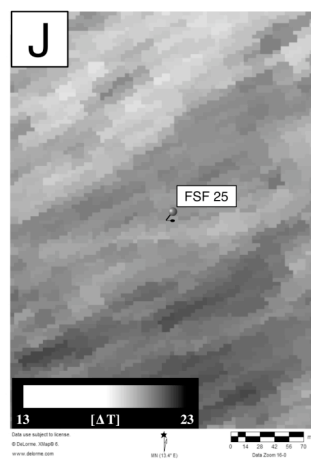
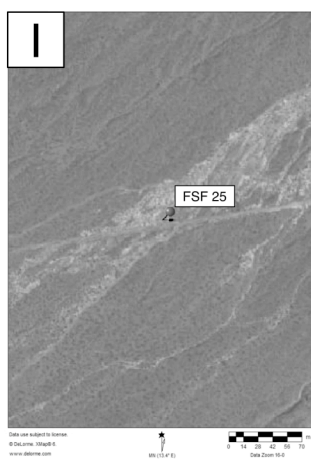
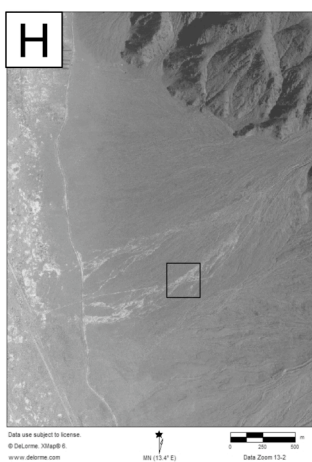
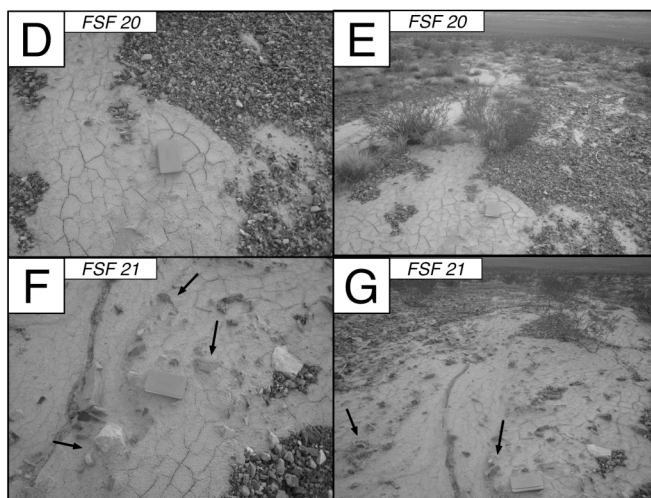
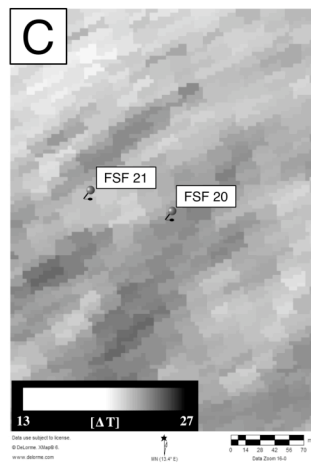
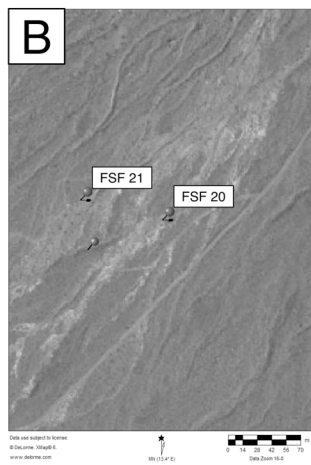
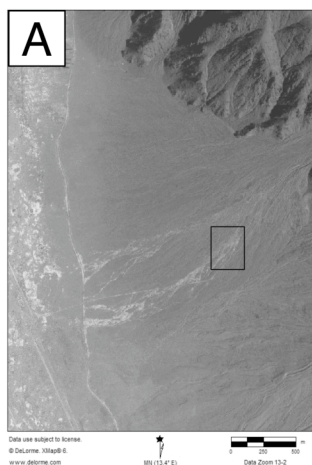


Figure B10: (A) High resolution visible image of French Spring Fan (FSF) in Owens Valley with zoom box showing the location of Figures 10B - 10G. (B) Visible context image showing the locations of indurated clast-poor debris flows at 'FSF 20' and 'FSF 21'. (C) ΔT context image showing the location of the indurated clast-poor debris flows at 'FSF 20' and 'FSF 21'. Note the waypoint locations are near the margins of the flow and that the relative ΔT values are slightly lower in this region (~ 13 K) than in the clast-rich debris flows to the north (~ 16 K) (see Figure 7). (D, E) Ground photos at 'FSF 20' show the indurated mudflow with a scattered surface lag of gravel that appears to be unrelated to the mudflow itself. (F, G) Ground photos at 'FSF 21' shows several larger clasts that the mudflow appears to have moved around or overlapped (marked with arrows), indicating these clasts were not part of the mudflow. The surface gravel lag is lying atop the mudflow, and is presumably the result of subsequent overland flow carrying gravel sized material down the fan. (H) High resolution visible image of French Spring Fan (FSF) in Owens Valley with zoom box showing the location of Figures 10I - 10L. (I) Visible context image showing the location of the indurated clast-poor debris flow at 'FSF 25'. (J) ΔT context image showing the location of the indurated clast-poor debris flow at 'FSF 25'. (K, L) Ground photos at 'FSF 25' showing continuation of the clast-poor debris flow at 'FSF 21' at a location further down the fan. The mudflow is beginning to thin and grade into the surrounding gravel lags, which significantly reduces its expression in the ΔT image. The surface temperature at 'FSF 25' is more dominated by the finer-grained gravel lag than at 'FSF 21', where the surface is primarily indurated mudflow, thus elevating the ΔT at 'FSF 25'.



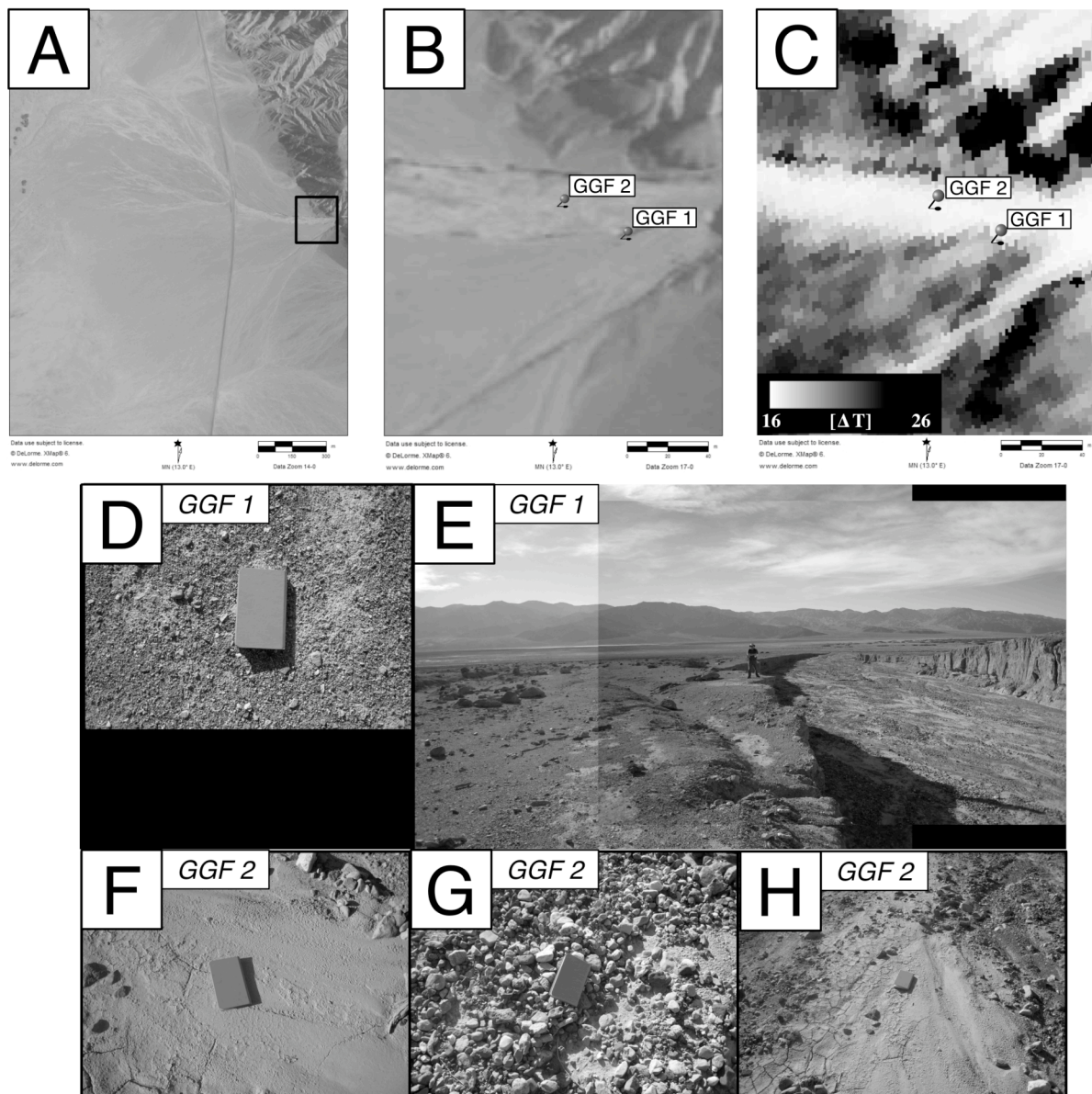


Figure B11: (A) High resolution visible image of the Gower Gulch Fan (GGF) in Death Valley with zoom box showing the location of Figures 11B - 11H. (B) Visible context image showing the locations of 'GGF 1' and 'GGF 2'. (C) ΔT context image showing the locations of 'GGF 1' and 'GGF 2'. (D) Ground photo at 'GGF 1' shows the loosely consolidated sand to pebble grain-size distribution of the material outside the channel. (E) Mosaic at 'GGF 1' shows the outer and inner channel materials. (F, G, H) Ground photos at 'GGF 2' of the inner channel material, which is filled with a mixture of indurated mudflow (Figure 11F) and clast-rich debris flow material (Figure 11G, 11H).

Figure B12: (A) High resolution visible image of Coffin Canyon Fan (CCF) in Death Valley with zoom box showing the location of Figures 12B - 12G. (B) Visible context image showing the locations of ‘CCF 57’ and ‘CCF 61’. (C) ΔT context image showing the locations of ‘CCF 57’ and ‘CCF 61’. (D) Ground photo at ‘CCF 61’ shows the sand to pebble grain-size distribution outside the channel walls. (E) Ground photo at ‘CCF 61’ shows the expansive, sand to pebble grain-size distribution outside the channel walls. The identification of these finer-grain sizes, along with the lobate shape of this deposit (see high ΔT lobes on channel margin in Figure 12C) indicates this is a sheetflood deposit that has been incised by the channel. (F, G) Ground photos at ‘CCF 57’ show the mixture of indurated mudflow and clast-rich debris flow that make up the interior of the channel, represented by lower ΔT values in the thermal image. (H) High resolution visible image Coffin Canyon Fan (CCF) in Death Valley with zoom box showing the location of Figure 12I - 12P. (I) Visible context image showing the locations of ‘CCF 19’, ‘CCF 21’ and ‘CCF 24’. (J) ΔT context image showing the locations of ‘CCF 19’, ‘CCF 21’ and ‘CCF 24’ within the central incised channel. (K-P) The central incised channel shows grain-size sorting that is characteristic of fluid flow, with finer grain sizes deposited on the flow margins (K, L), and coarser grains deposited near the channel interior (M, N). (O) Ground photo just north of ‘CCF 24’ shows a cut bank that forms the boundary between the coarse (*left*) and fine-grained (*right*) inner-channel material. (P) Ground photo at ‘CCF 24’ shows the boundary between the finer-grained inner-channel fill (*left*) and the coarse-grained outer-channel wall material (*right*).

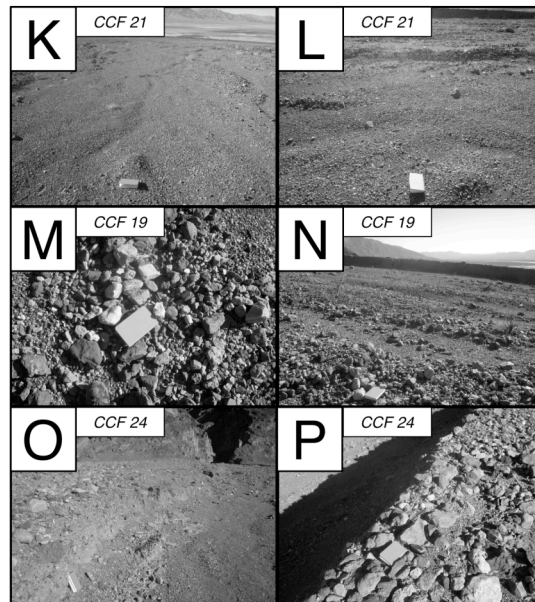
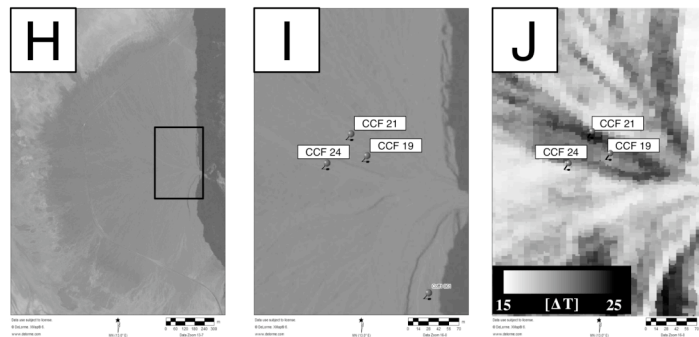
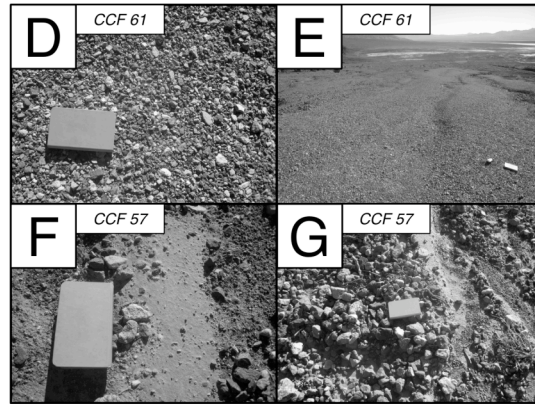
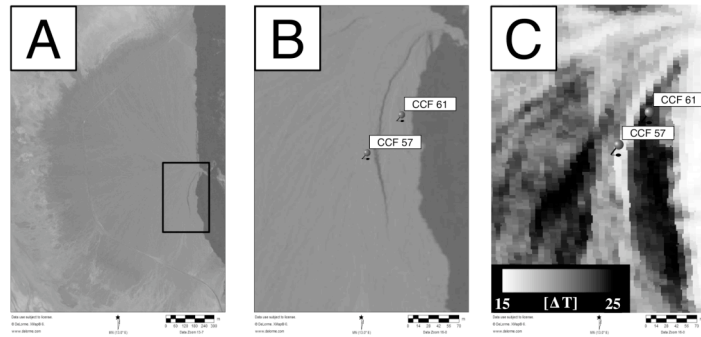


Figure B13: (A) High resolution visible image of Badwater Fan 1 (BF1) in Death Valley with zoom box showing the location of Figures 13B - 13D. (B) Visible context image showing the location of 'BF1 N' in the upper-fan. (C) ΔT context image showing the location of 'BF1 N' in the upper-fan, and the lobate, high ΔT (marked with oval) sheetflood feature to the south. (D) Ground mosaic, looking south from 'BF1 N', of the upper-fan sheetflood deposit, showing the expansive, relatively flat, fine-grained sand to pebble sized surface. (E) High resolution visible image of Badwater Fan 2 (BF2) in Death Valley with zoom box showing the location of Figures 13F - 13H. (F) Visible context image showing the location of 'BF2 5' in the upper-fan. (G) ΔT context image showing the locations of 'BF2 5' in the upper-fan and the lobate, low ΔT (marked with oval) sheetflood feature to the south. (H) Ground mosaic, looking south from 'BF2 5', of the upper-fan sheetflood deposit, showing the relatively flat, fine-grained sand to pebble sized surface and braided stream patterns at the surface. (I) High resolution visible image of Badwater Fan 3 (BF3) in Death Valley with zoom box showing the location of Figures 13J - 13L. (J) Visible context image showing the location of 'BF3 3' in the upper-fan. (K) ΔT context image showing the locations of 'BF3 3' in the upper-fan and the lobate, low ΔT (marked with oval) sheetflood feature to the south. (L) Ground mosaic, looking south from 'BF3 3', of the upper-fan sheetflood deposit, showing the relatively flat, fine-grained sand to pebble sized surface.

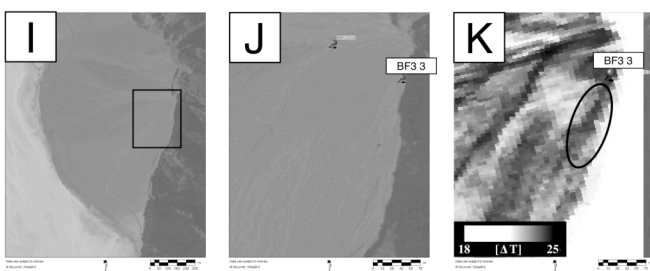
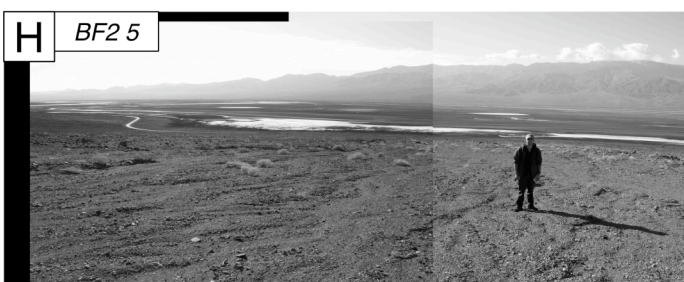
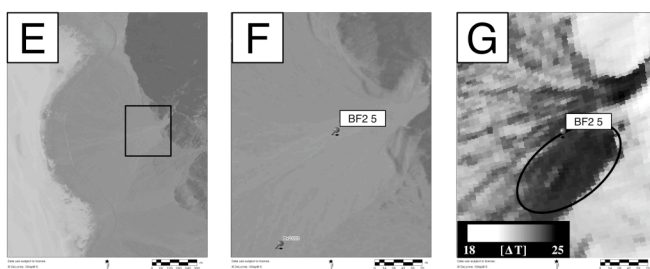
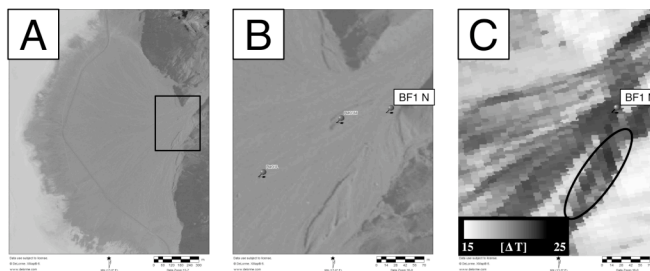


Figure B14: (A) High resolution visible image of Badwater Fan 1 (BF1) in Death Valley with zoom box showing the location of Figures 14B - 14L. (B) Visible context image showing the location of 'BW1M' and 'BW1 L' in the upper-fan. (C) ΔT context image showing the locations of 'BW1 M' in the upper-fan, which marks the location of a relatively isolated, low ΔT boulder feature (marked with oval) and 'BW1 L', which marks the locations of a V-shaped, low ΔT mesa feature (marked with oval). (D) Ground photo taken at 'BW1 M' of a boulder, several meters in diameter, in the upper-fan region. (E) Ground photo taken at 'BW1 L' from atop the mesa feature looking southwest. The coarse-grained mesa material is surrounded by fine-grained sheetflood deposits. (F) High resolution visible image of Badwater Fan 3 (BF3) in Death Valley with zoom box showing the location of Figures 14G - 14I. (G) Visible context image showing the location of 'BW3 4' in the upper-fan. (H) ΔT context image showing the location of 'BW3 4' in the upper fan, and the V-shaped low ΔT feature (marked with oval). (I) Ground photo taken at 'BW3 4', looking down the fan at the V-shaped mesa feature which is approximately 1 meter high. The mesa surface is coarse-grained and the walls are composed of indurated material. This results in a low ΔT , low albedo surface feature.

Figure B15: (A) High resolution visible image of Badwater Fan 1 (BF1) in Death Valley with zoom box showing the locations of Figures 15B - 15F. (B) Visible context image showing the location of 'BW1 G' in the mid-fan. (C) ΔT context image showing the locations of 'BW1 G' in the mid-fan, which marks the location of a cut-bank formed by a gully. (D) Ground photo at 'BW1 G' shows fine-grained sand to cobbles within the channel. (E) Ground photo at 'BW1 G' shows the coarser-grained fan materials that were eroded to form the cut bank. (F) Ground photo at 'BW1 G' shows a context image of the cut bank and related fine-grained channel fill materials. (G) High resolution visible image of Badwater Fan 2 (BF2) in Death Valley with zoom box showing the location of Figures 15H - 15L. (H) Visible context image showing the location of 'BW2 3' at a small-scale gully in the mid-fan. (I) ΔT context image showing the location of 'BW2 3'. (J) Ground photo at 'BW2 3' shows fine-grained sand to cobbles within the fine-grained channel. (K) Ground photo at 'BW2 3' shows the coarser-grained fan materials that were eroded to form the small cut bank (maximum height ~5 cm). (L) Ground photo at 'BW2 3' shows a context image of the small cut bank, with fine-grained channel fill and coarser-grained older fan materials. (M) High resolution visible image of Badwater Fan 3 (BF3) in Death Valley with zoom box showing the location of Figures 15N - 15R. (N) Visible context image showing the locations of gullies at 'BW3 15', 'BW3 16', and 'BW3 17' in the mid-fan. (O) ΔT context image showing the locations of gullies at 'BW3 15', 'BW3 16', and 'BW3 17' in the mid-fan. The ΔT image clearly shows the gullies merging toward the fan apex to form V-shape. (P, Q, R) Ground photos at 'BW3 15', 'BW3 16', and 'BW3 17' show ~0.2 meter high cut banks at each of the waypoints shown above, respectively.

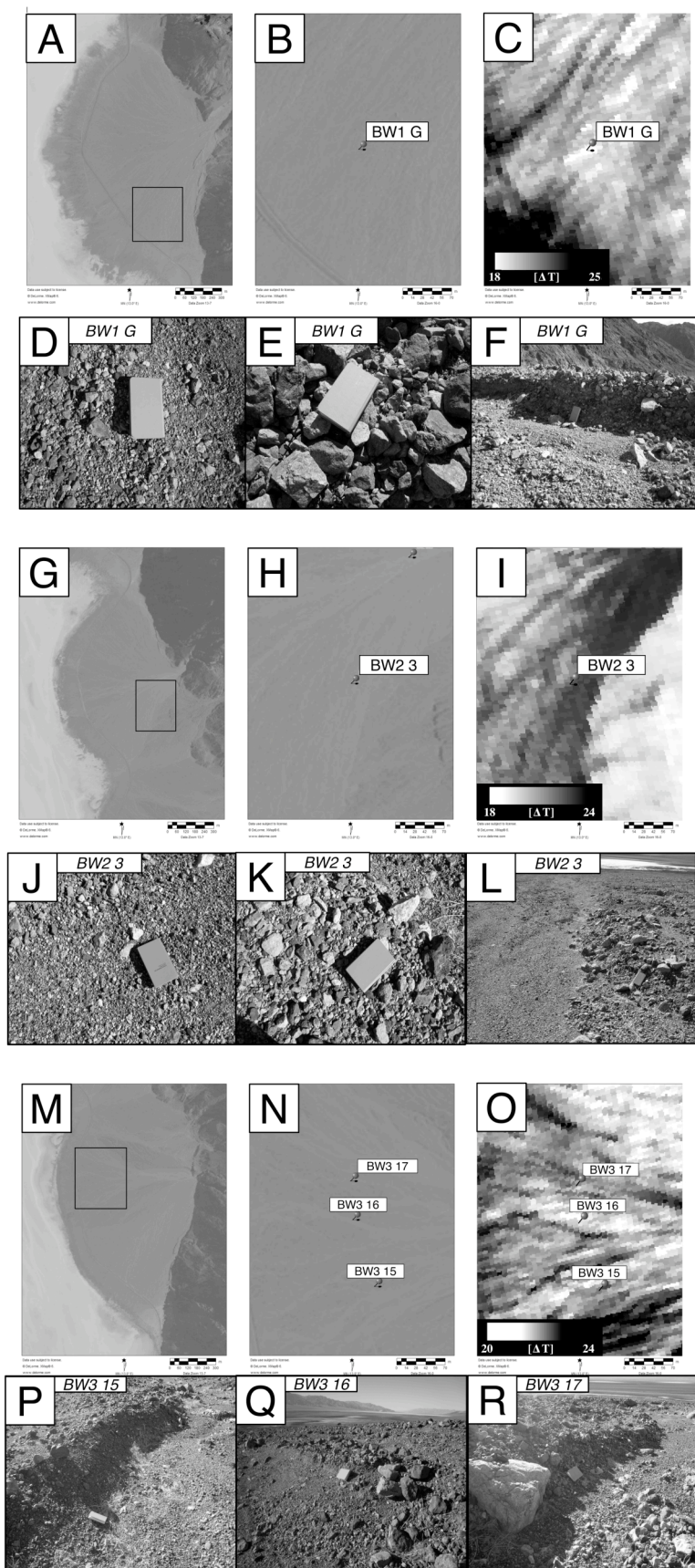


Figure B16: (A) High resolution visible image of Talc Canyon Fan (TAF) in Death Valley with zoom box showing the location of the sand-skirt on the lower-fan. (B) Visible context image showing the location of 'TAF 1' on the lower-fan. (C) ΔT context image showing the location of 'TAF 1' in the lower-fan, which marks an expansive, high ΔT deposit. (D) Ground photo at 'TAF 1' shows the fine-grained granitic sand comprising the sand-skirt. (E) Ground photo taken at 'TAF 2', just south of the sand-skirt at 'TAF 1', at the toe of the debris flows identified in Figure 8. The photo documents the weathering of the granitic boulders to form the fine-grained sand that makes up the sand-skirt. (F) Ground mosaic taken at 'TAF 1', looking north, at the distal sand-skirt showing the wide expanse of fine-grained sand at the toe of the fan.

Figure B17: (A) High resolution visible image of Badwater Fan 1 (BF1) in Death Valley with zoom box showing the location of Figures 17B - 17H. (B) Visible context image showing the location of 'BW1 B' on the lower-fan. (C) ΔT context image showing the location of 'BW1 B' in the lower-fan, which marks the location of a tear-dropped shaped, relatively high ΔT feature. (D, E) Ground photos show the lag surface at 'BW1 B', showing material composed of primarily sand-sized grains with some pebbles, as well as a pedestal rock in Figure 17E. (F, G) Ground photos show the channel material, which is lightly cemented at the top surface but is extremely fine-grained just below the surface. (H) Ground context photo taken looking East from the salt flat, toward the tear-drop shaped feature. The arrows mark the location of the surrounding channel material (Figure 17F, 17G), while the field assistant is standing in the middle of the tear-drop shaped lag surface (Figure 17D, 17E).

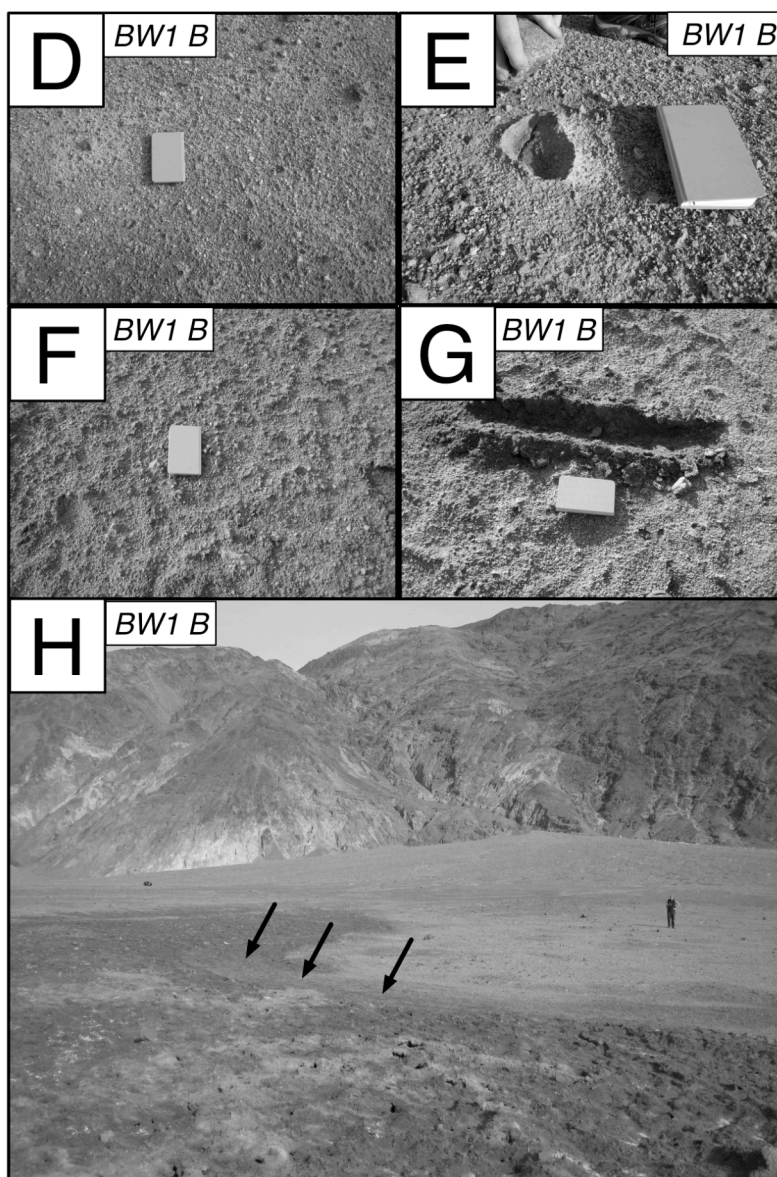
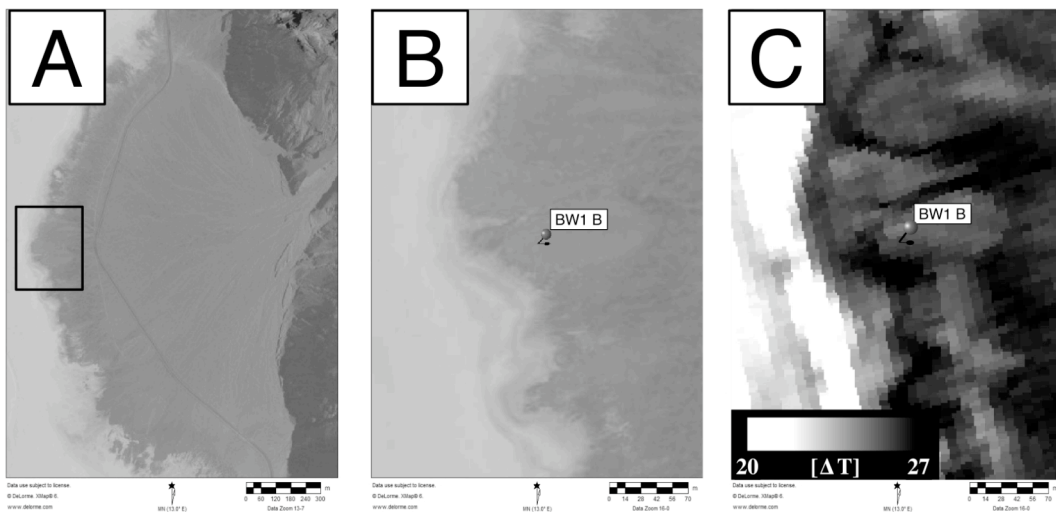


Figure B18: (A) High resolution visible image of the Hells Gate Fan (HGF) in Death Valley with zoom box showing the general locations of Figures 18B - 18H. (B) Visible context image showing the locations of 'HGF 4' and 'HGF 10'. (C) ΔT context image showing the locations of 'HGF 4' and 'HGF 10', which mark the locations of active and inactive regions of the fan, respectively. (D) Ground mosaic taken from 'HGF 10' of the expansive, low ΔT lag surface in the mid-fan region. This low albedo and elevated surface indicate is an old region of the fan that has not experienced deposition recently. (E) Ground photo at 'HGF 10' shows the fine pebble to cobble grain-size distribution of the lag surface. (F) Ground photo at 'HGF 4' shows a close-up of the larger pebble to cobble grain-size distribution within the channels. (G) Ground photo at 'HGF 4' show the inner channel, braided stream material, (H) Ground photo at 'HGF 4' shows the cut banks formed by headward-eroding gullies in this, more active depositional lobe.

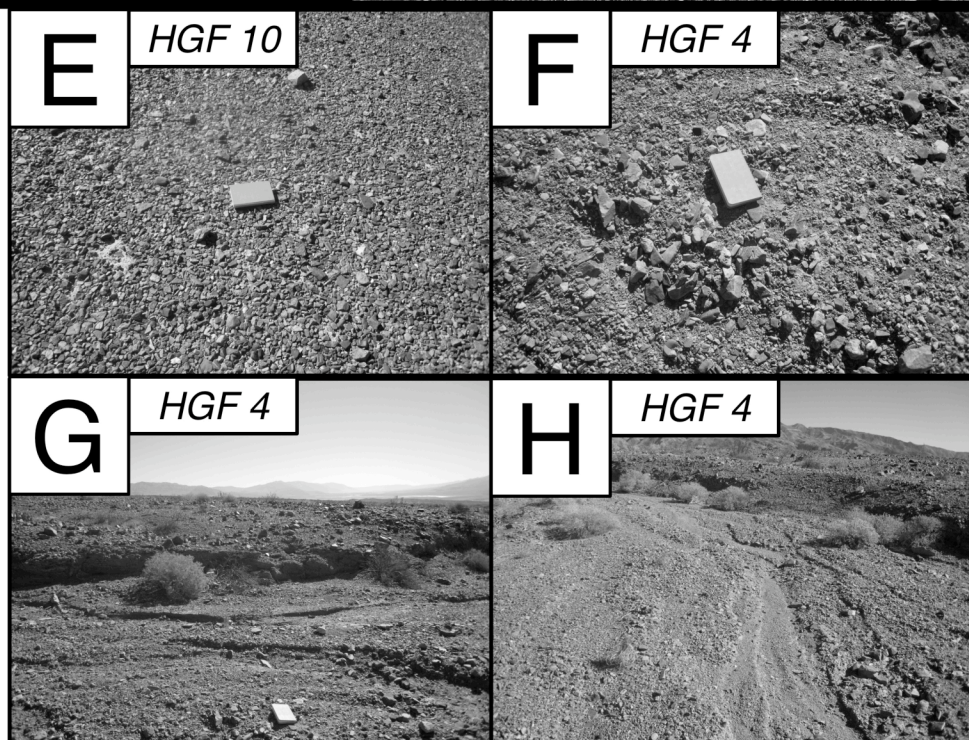
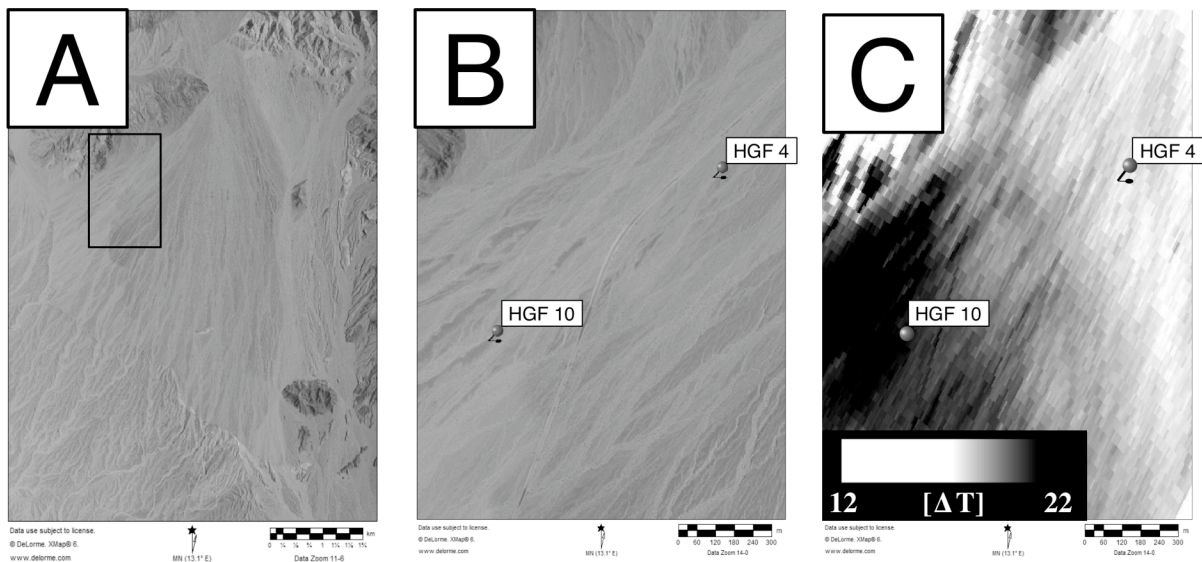


Figure B19: (A) High resolution visible image of the Titus Canyon Fan (TCF) in Death Valley with zoom box showing the location of Figures 19B - 19J. (B) Visible context image showing the locations of 'TCF 1', 'TCF 4' and 'TCF 5' on the Titus Canyon Fan. (C) ΔT context image showing the locations of 'TCF 1' on the active depositional lobe (lower ΔT) and 'TCF 4' and 'TCF 5', on the inactive fan lobe (higher ΔT). (D) Ground photo at 'TCF 1' shows coarse-grained material atop the channel walls associated with headward-eroding gullies in this region of the fan. (E) Ground photo at 'TCF 1' shows a context image of a ~6 meter high cut bank and surrounding coarse-grained material. (F) Ground photo at 'TCF 1' shows several cut banks with coarse-grained material atop the channel walls. Field assistant is standing within a small scale (~ 1 meter wide) gully filled with finer-grained material. (G) Ground photo at 'TCF 4' shows the sand to cobble sized lag deposit typical of the northern region of the Titus Canyon Fan. (H, I, J) Ground photos at 'TCF 4' are context images to show the lack of significant cut banks, and wide expanses of fine-grained lag surfaces.

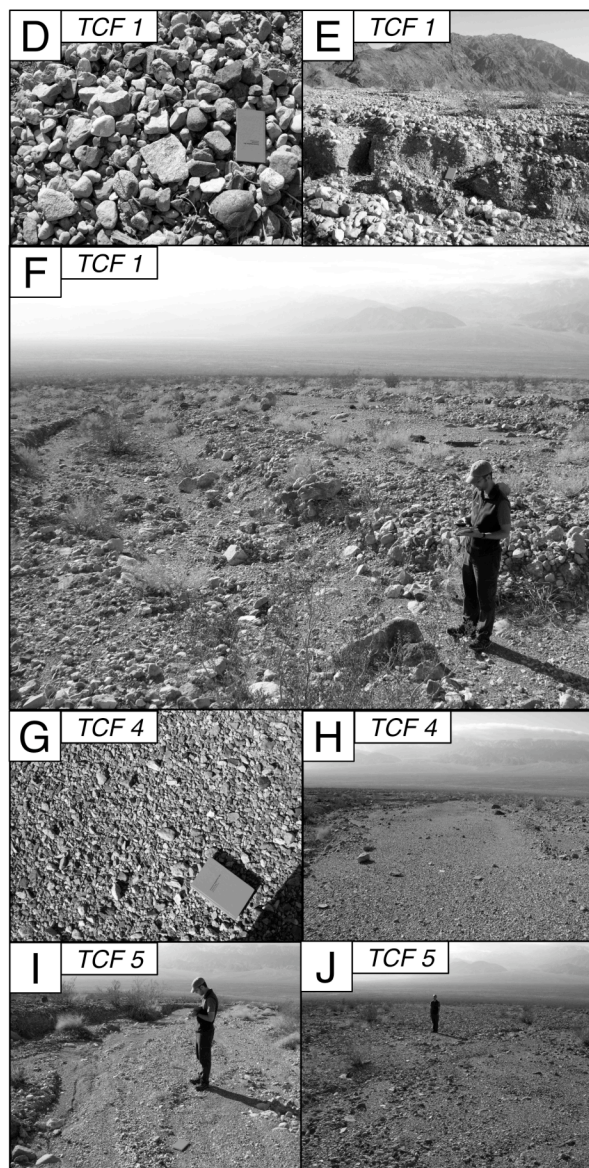
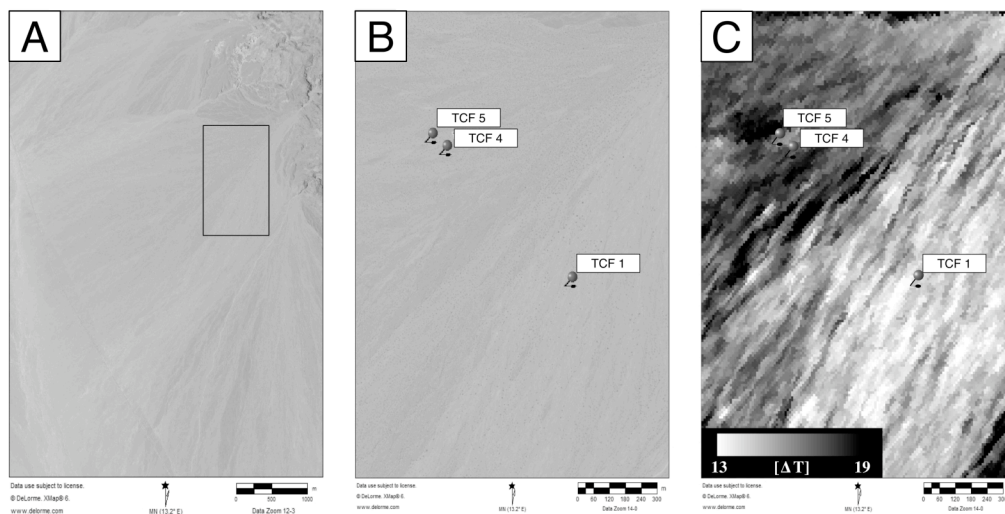
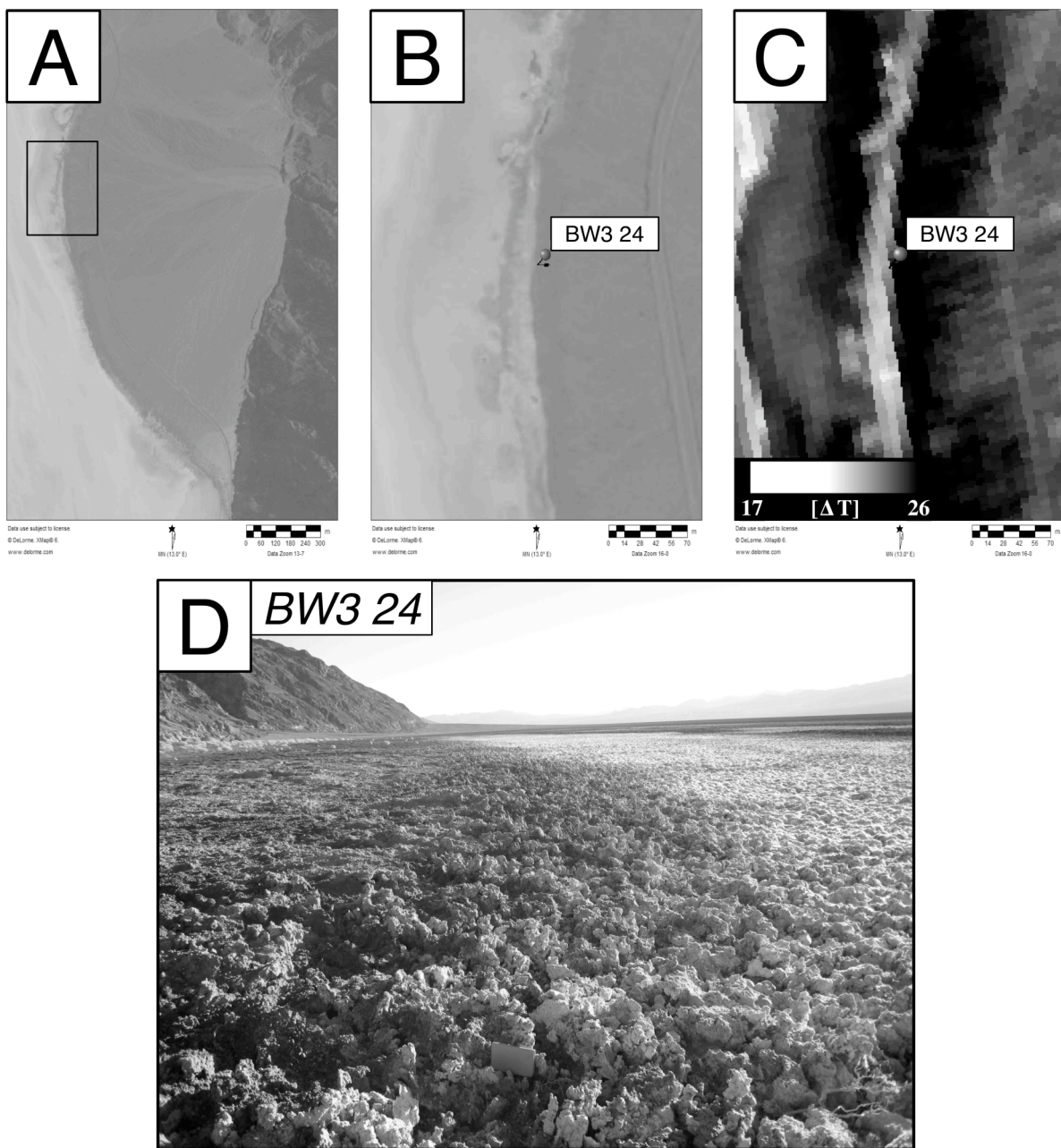


Figure B20: (A) High resolution visible image of Badwater Fan 3 (BF3) in Death Valley with zoom box showing the location of Figure 20B - 20D. (B) Visible context image showing the location of the salt pan and identifying it as a significantly high albedo surface. (C) ΔT context image showing the location of the salt pan, represented as a low ΔT feature lining the toe of the fan. (D) Ground mosaic taken at 'BW3 24', looking South, showing the margin of the salt-pan and the corresponding change in surface albedo as well as the gradual change in surface texture from relatively smooth to the east (toward the fan) to polygons, a mottled surface texture and the presence of salt crystals to the west (towards the basin).



Part 4

Effects of Chlorine on Neutron Die-Away: Implications for Mars Science Laboratory's Dynamic Albedo of Neutrons Instrument

This part is a reformatted version of a paper in preparation for submission to Nuclear Instruments and Methods in Physics Research A by Craig James Hardgrove, Jeffrey Moersch, and Darrell Drake. All data analyses, except simulations of background counting rates due to galactic cosmic background radiation, were performed by Craig Hardgrove.

Hardgrove, C., Moersch, J., Drake, D., Effects of Chlorine on Neutron Die-Away: Implications for Mars Science Laboratory's Dynamic Albedo of Neutrons Instrument, *Nuclear Instruments and Methods in Physics Research A*, in prep.

Abstract

The Dynamic Albedo of Neutrons (DAN) instrument on-board the Mars Science Laboratory (MSL) rover has the ability to assess both hydrogen abundance and burial depth as it traverses the Martian surface. DAN uses a new method of neutron detection for planetary spacecraft, neutron die-away that requires the use of a pulsed neutron generator as a supplementary neutron source as opposed to relying solely on spallation of neutrons in the subsurface by the cosmic ray background (as has been the case with all previous other planetary neutron detection experiments). It is well established in orbital neutron remote sensing that low energy (thermal) neutrons are sensitive not only to hydrogen content, but also to the macroscopic absorption cross section of the near surface materials. We model the effects of varying abundances of high absorption cross section elements that are likely to be found on the Martian surface (Cl, Fe). Mars Exploration Rovers (MER) Spirit and Opportunity found that higher abundances of these elements are commonly associated with locales that have experienced aqueous activity in the past, but where hydrogen-rich materials are not necessarily still present. By modeling a suite of H and Cl compositions, we show how Cl can strongly affect thermal neutron die-away curves. Additionally, we show how the timing of thermal neutron arrival at the detector can be used to discriminate between changes in hydrogen content or changes in the abundance of high macroscopic absorption cross section elements. If epithermal neutron die-away curves are acquired, they too may be used to discriminate between these changes. By modeling specific “real world” (for Mars) geochemical compositions based on measurements made by the MER Alpha Proton X-Ray Spectrometer (APXS) at localities on Mars with high and low abundances of Cl and Fe. These MER targets are named “Eileen Dean” (a Cl-rich soil), “Jack Russell” (a hematite-rich observation of Berry Bowl “blueberries,”) and “Kenosha Comets” (a Si-rich soil). Using these examples we demonstrate how DAN can be used not only to assess the amount of hydrogen in the near-surface but also to identify other locations that may be relevant to the aqueous geologic history of Mars.

1. Introduction

The Mars Science Laboratory (MSL) mission, currently scheduled to launch in 2011, will carry the Dynamic Albedo of Neutrons (DAN) instrument to the surface of Mars onboard the rover “Curiosity” (Litvak et al., 2009). DAN will measure the spatial variability in the energy distributions of neutrons emitted from the Martian surface. DAN measurements of neutron energies will be used to provide estimates of, or constraints on, total subsurface hydrogen content, stratigraphy, and composition in the top ~50 cm of the Martian surface as it traverses. The landing site for MSL (not yet determined) will be in the equatorial regions of Mars where the near-surface hydrogen content varies between 2 and 10 wt. % water-equivalent hydrogen (Golomek et al., 2010; Feldman et al., 2004). Although variations in neutron energies in these regions are primarily affected by local changes in hydrogen abundance (e.g. presence of hydrated mineralogies, buried water, or ice), changes in composition (i.e. local changes in rock or soil composition, the degree of alteration, or the presence of salts), can also modify neutron energy distributions through preferential absorption of low energy neutrons. Given the large spatial footprint of orbital neutron detection techniques (~600 km diameter), we know little of the small-scale spatial variability of hydrogen abundance in the equatorial latitudes. In regions where hydrogen abundance varies little, the dominant source of variation in neutron energy distributions is from variability in other elements, particularly those with high neutron absorption cross sections. On the lunar surface, the elements Gd and Sm were found to have a pronounced effect on neutron energies (Feldman et. al 2000). On Mars, Diez et. al, (2000) have shown that Cl has a significant effect on neutron energy distributions. The Mars Exploration Rovers have identified an array of rock and regolith types with significant variations in Cl and Fe abundance. Therefore, the purpose of this work will be to characterize the effects of variations in high neutron absorbing elements, particularly Cl and Fe, on neutron die-away measurements.

2. Background

2.1 Neutron Die-Away

The neutron die-away technique has been used in the oil and gas exploration industry since the early 1960's, and most previous studies of the technique have focused on borehole geometries relevant to this application. DAN is the

first spacecraft-based experiment to implement the neutron die-away technique. A detailed overview of the physics of neutron die-away is provided by Trombka *et al.* (1966). Neutron die-away measurements are initiated by producing a series of fast neutron (~ 14 MeV) pulses with a small accelerator, called a pulsed neutron generator (PNG). The high-energy neutrons from a given pulse penetrate into the surface, where they are scattered and/or absorbed. A portion of the scattered neutrons exit the surface with a new energy distribution that is dependent upon the amount of hydrogen in the near-surface, the depth of the buried hydrogen, and the macroscopic absorption cross section of the near-surface material. Hydrogen acts to shift the distribution to lower energies (i.e., moderate the energy distribution) because neutrons give up much of their kinetic energy in scattering interactions with the lightweight hydrogen nuclei. Assuming hydrogen is distributed homogeneously in the sub-surface, high-energy neutrons from the PNG will have less of a chance to interact with materials at greater depths as hydrogen content increases. The result is increasing hydrogen content will shift the mean arrival time of thermal neutrons to earlier times. If the hydrogen is instead confined to a layer, increasing the burial depth of the hydrogen-rich layer will also shift the neutron energy distribution to lower energies and will shift the average arrival of thermal neutrons at the detectors to later times as thermalized neutrons will take longer to reach the detector. Instead of shifting the energy distribution, an increase in the number of high absorption cross section elements will result in an overall decrease of thermal neutrons that can be detected, as thermal neutrons are absorbed and removed from the energy distribution. Once the neutrons “leak” from the surface, they may be counted by the instrument’s detector tubes. In neutron die-away methods, the neutron counts from the tubes are binned by time intervals which are much smaller than the total duration of the neutron die-away. Higher energy (faster) neutrons arrive at the detectors first, while lower energy (slower) neutrons arrive at the detectors later. Discrimination of higher versus lower energy neutrons is provided through the use of a jacket of cadmium on one of the tubes. Cd has a high absorption coefficient for low energy neutrons, so this tube will only count higher energy neutrons. The other (non-Cd wrapped, or “bare”) tube is sensitive to both higher and lower energy neutrons, so differencing the counts between the two tubes provides the counts of lower-energy neutrons. As is the convention in previous studies of planetary neutron remote sensing, in this work we refer to low energy neutrons (those below the cadmium capture cutoff energy of ~ 0.3 eV) as “thermal.”. Energies above 0.3 eV are referred to as “epithermal.”

As previously described, the overall number of thermal and epithermal neutrons and arrival times of thermal neutrons are a function of the hydrogen content of each layer, the layer depths, and the macroscopic absorption cross section. Unfortunately, changes to any one of these variables do not have a unique effect on the thermal neutron die-away curve, so it is not possible to uniquely derive these physical parameters of the subsurface from die-away measurements alone. Rather, candidate models of the subsurface must be used to find parameters that are consistent with the measurements. The family of possible subsurface models can be constrained using arguments of geologic plausibility based on other relevant measurements. We will show how changes in hydrogen abundance and macroscopic absorption cross section that are plausible for Mars can affect both neutron arrival times at the detector and the total thermal and epithermal neutron fluxes.

Neutron die-away can be used to quantify the abundance of and depth to hydrogen-rich layers in the shallow (up to ~50 cm) subsurface of a planet. This is accomplished by measuring the total number of detected thermal and epithermal neutrons, which will vary with increasing hydrogen content. The time for neutrons of a given energy to reach the detector will increase with increasing depth of the hydrogen-rich layer. In addition to these effects, high macroscopic absorption cross section elements can reduce the total number of thermal neutrons that reach the detector, as well as shift the arrival times of thermal neutrons.

2.2 Dynamic Albedo of Neutrons (DAN) Instrument

The DAN instrument utilizes the neutron die-away technique as described above. The DAN PNG produces 14.1 MeV neutrons at an interval of 100 ms (10 Hz), in pulses with durations of 1 μ s. DAN will use two detectors to discriminate neutron energy distributions, one coated in a 1-mm-thick layer of Cd and one unshielded, as described above.. Each detector consists of a 6-cm-long by 5-cm wide cylinder filled with He^3 pressurized at 10 atm (Litvak *et al.*, 2008). The detector tubes are proportional counters in that the charge deposited within the tube is proportional to the sum of the incident neutron energy and the energy of the He^3 -n reaction (Knoll, 2000). The charge deposited within the tube is then sent through a series of pulse shaping and signal processing circuits housed within the DAN electronics box. The counts are then binned by time and the resulting thermal neutrons are calculated by

differencing the counts on the uncoated tube and the counts on the Cd-coated tube. The epithermal neutron counts are simply the counts on the Cd-coated tube.

In all previous implementations of neutron detectors for planetary exploration spacecraft, galactic cosmic rays provide the source of neutrons through spallation with nuclei in the planetary surface (Mars Odyssey, Lunar Reconnaissance Orbiter, Lunar Prospector, Messenger, DAWN). For thin-atmosphered planetary bodies these high-energy ($\sim$ GeV) particles, predominantly protons, bombard the planetary surface creating high-energy neutrons through spallation. These neutrons interact with, and subsequently leak from the surface, where they can be detected. Measuring neutrons from a rover platform offers two advantages over orbital measurements. First, because the neutron detectors that have been used on spacecraft missions are not directionally sensitive, the effective footprint of the instrument is proportional to the detector's height above the ground, such that a rover-based instrument has an effective horizontal footprint of $\sim$ 1 meter as opposed to an orbital-based instrument with an effective footprint of (for Mars orbiters) $\sim$ 600 km (Boynton et al., 2004). Second, the proximity of the ground in a rover-based detector allows for use of an active neutron source in the form of a ^{252}Cf .

Neutron die-away curves are controlled by variations in the hydrogen abundance of the near-surface ($\sim$ 50 cm depth), the depth of a buried hydrogen-rich layer, and the macroscopic absorption cross section of the surface (Litvak et al., 2008; Busch et al., 2009). A full instrument description for DAN, as well as modeling results showing thermal neutron die-away curves for 0-25 wt. % water, are provided by Litvak et al., (2008). Additionally, Litvak et al., (2009) present results for a sample transect of the DAN instrument towards a hydrogen-rich target as well as modeling results for a buried layer of the hydrated mineral nontronite. Busch et al., (2009) derived an equation for a suite of geologically plausible thermal-neutron die-away curves, taking into account variations in density, the depth to the buried hydrogen-rich layer, and the amount of hydrogen in the upper and lower layers. The derived equation can be used to constrain the water content in the top 50 cm of the near-surface to within 1 wt.%. When the hydrogen content of the near surface is known, either through other instruments or assumption, the analytical solution provided by Busch et al. (2009) can be used to constrain the hydrogen stratigraphy of the top 15 cm of the near-surface.

While the work described above is significant in understanding future results from DAN, it only takes into account changes in macroscopic scattering cross sections for geologic surfaces on the thermal neutron die-away curves. Total macroscopic scattering, which is primarily a function of the abundance of hydrogen, affects the energies of neutrons leaking from the near-surface by increasing the number of low energy (thermal) neutrons and decreasing the number of higher energy (epithermal) neutrons. Not considered by Litvak et al. (2008) and Busch et al. (2009) was another important effect, that of variations in the total macroscopic absorption cross sections of the near-surface composition. The macroscopic absorption cross section, which is a function of the absorption cross sections of the elemental constituents of the near-surface materials (top 50 cm) weighted by their abundances, can significantly reduce thermal neutron flux through the removal of thermal neutrons from the leaked energy distribution (Feldman et al., 2009; Diez et al., 2009). Previous studies on the effects of neutron macroscopic absorption cross sections have only looked at the case of orbital neutron detection with cosmic background as a source, while in this study, we will explore the effects of macroscopic absorption cross section on neutron die-away measurements.

On a rover platform, DAN will acquire data across hundreds of meters of terrain. Given the variety of rock and regolith types identified by MER, we anticipate MSL will traverse across changes in local near-surface conditions that may not only harbor materials with variable amounts of hydrogen, but also rocks and soils of varying elemental compositions produced by a several geologic processes. Evaporitic mineral precipitation, acidic weathering, or aqueous alteration may result in near-surface enrichments or depletions of elements such as chlorine and iron. In this study, we present simulations of thermal and epithermal neutron die-away for geologically plausible compositions containing variable amounts of chlorine and other neutron absorbing elements. We use these results to determine how changes in macroscopic absorption cross section can affect interpretations of hydrogen abundance in the near-surface.

2.3 Effects of Absorption Cross Section on Neutron Flux

Feldman et al., (2000) provided a detailed treatment of the effects of variations in macroscopic scattering and absorption cross sections on neutron fluxes for orbital neutron measurements with a cosmic ray source of neutrons. They found that when hydrogen content in the Martian regolith is fixed, changes to the macroscopic absorption

cross section dominate the total number of observed thermal neutrons and their energies. In neutron scattering interactions, the approximate magnitude of the neutron energy loss due to scattering with any element is inversely proportional to the element's atomic mass. The result is that a hydrogen nucleus, having the same mass as a neutron, reduces a neutron's energy by $\sim 1/2$ with each scattering event. This magnitude of this effect is represented by the element's macroscopic scattering cross section. The macroscopic absorption cross section is a measure of the probability that a neutron will be absorbed while transiting 1 cm of a material, and is a function of the energy of the neutron. The macroscopic absorption cross section is the average of the absorption cross sections of the individual elements in the material. Therefore, elements with high absorption cross sections can significantly influence the macroscopic absorption cross section of the soil or rock if they are abundant. If high neutron absorption cross section elements are present in a soil, thermalized neutrons will have a greater probability of being captured, thereby reducing the total number of thermal neutrons measured by the detector. If a correction for this effect is not applied during data analysis, the inferred water-equivalent hydrogen content of the soil will be underestimated.

The effects of the high absorption cross section elements Gd and Sm on orbital neutron measurements have been characterized for lunar soils by Feldman et al., (2000), and the effects of Cl were used to reinterpret inferred hydrogen burial depths for a region of Mars by Diez et al., (2009). Thermal neutron counts from MONS have been used to constrain the depth of the hydrogen layer, however, a lack of detailed high absorption cross section elemental data leads to an uncertainty of $\pm 10\%$ in the depth to the hydrogen layer (Diez et al., 2008). Prettyman et al., (2004), found that modeled soil compositions depleted by 80 wt.% of the average Cl abundance best fit the total thermal neutron counts for Mars Odyssey Neutron Spectrometer (MONS) data. While Diez and Prettyman explored a small subset of compositions for orbital neutron measurements of Mars with the galactic cosmic background as a neutron source, we sample a larger suite of Cl and H₂O abundances for rover-based neutron die-away measurements with a pulsed neutron generator source, as appropriate for the DAN experiment on MSL. Table C1 shows the scattering and absorption cross sections of various elements of geologic interest on Mars. The effects of high absorption cross section elements on neutron fluxes from planetary surfaces have been studied for several planets and shown to be important in the interpretation of hydrogen abundance in the near-surface.

2.4 Variability of H₂O, Fe, and Cl on Mars

Previous studies of the elemental composition of the Martian surface from several different missions using several different techniques have revealed significant variability in the abundances of the high absorption cross section elements Cl and Fe. Mars Odyssey Neutron Spectrometer (MONS) epithermal and fast neutron fluxes have been used to create water-equivalent hydrogen (WEH) maps for the entire surface of Mars. WEH was found to vary between 20% and 100% at latitudes poleward of 50 degrees and between 2% and 10% in equatorial regions between +/-45 degrees latitude (Feldman et al., 2004). For our models we vary water-equivalent hydrogen between 0 and 25 wt.%, which represents reasonable upper and lower limits on hydrogen abundances for the equatorial regions of Mars.

Of the elements listed in Table C1, Cl and Fe are the best candidates to have significant effects on neutron die-away curves acquired on the Martian surface. Even though elements such as Si and O are more abundant, they both have relatively low absorption cross sections and variations in their abundance result in small or negligible effects on the energy distribution of leaked neutrons. Other elements with relatively high absorption cross sections, such as Mn, Br, and Ti, may also play a role in capturing thermal neutrons; however, they are present in such low abundances and vary relatively little in both Spirit and Opportunity APXS data that their effects are not expected to be as significant as Cl or Fe. Combined APXS-derived abundances for the highest absorption cross section elements Cl, Mn, Ti and Fe (excluding the Fe-rich meteorite, Heat Shield Rock) are presented in Table C2, along with the average standard deviation for those elements across all APXS measurements. In Section 4, we present results for thermal neutron fluxes where the most abundant elements in Table C2 (Cl, Fe and Ti) are varied by one APXS-derived standard deviation of that element's abundance. The most variable of these elements is Fe, however, the absorption cross section of Fe is ~1/13th that of Cl. In addition, APXS-derived Fe abundances vary by about ~25% of the average Fe abundance while Cl abundances vary by ~33% of its average abundance. Although we expect the influence of Cl on neutron die-away to be greater than Fe, we model variations in geochemistries from both elements.

Previous geochemical analyses of the Martian surface have revealed a wide range of Cl abundances in both rocks and soils. Analysis of Viking XRF data showed that the global abundance of Cl in Martian fines is greater than in

terrestrial systems (Clark et al., 1982). More recently, MER Pathfinder APXS data have confirmed that Cl can vary significantly on a more local scale (Rieder et al., 1997). In the regions explored by MER, APXS data confirm that Cl abundances through sol 1503 (from arrival on Mars in January, 2004 to March, 2008) vary between 0.2 and 2.6 wt.% (Ming et al., 2008). While results from both Spirit and Opportunity APXS measurements have shown variability in Cl abundance of surface materials, Spirit's front right wheel trenching has provided a unique observation of sub-surface materials that could also be detected by DAN. A unique class of high-Cl soils (Eileen Dean), identified by Spirit near Home Plate, was found to contain 1.8 wt.% Cl. Detailed study by the Spirit rover over two years has identified several features, in the vicinity of a feature known as Home Plate, that indicate the area was a source of volcanism as well as hydrothermal activity (Squyres et al., 2007). The presence of high-Cl deposits on the western side of Home Plate indicates it was subjected to extensive low-temperature alteration (Schmidt et al., 2009). In addition, several rocks classes were found to be enriched in Cl with respect to Adirondack class basalts, which are found extensively across the floor of Gusev Crater and contain 0.3 wt.% Cl. These rocks include the Watchtower class (1.2 wt.% Cl), Barnhill class (1.6 wt.% Cl), Everett class, and Good Question class (both ~1.4 wt.% Cl). In addition to relatively high Cl content, Eileen Dean class soils are high in magnetite and Mg, similar to Everett class rocks, and are also enriched in Ni, Zn, and Br which indicates possible alteration by hydrothermal water or vapors. The Barnhill subclass, on the northwestern side of Home Plate, is interpreted to be an altered volcanoclastic sediments that are enriched in Cl, S, and Br. Similarly, the Watchtower class of rocks in the Columbia Hills contain enrichments of Cl, S and Br and show a high degree of alteration (Ming et al., 2008). Observations from MER have shown that Cl is both variable in Martian surface materials and can be concentrated in localities that have experienced near-surface fluvial alteration.

APXS data have shown that Fe abundances through sol 1503 (from arrival on Mars in January, 2004 to March, 2008) vary between 0.7 - 94 wt.% (avg ~13 wt.%, with 94 wt.% representing the Heat Shield Rock meteorite) (Schroder et al., 2008). Regionally, changes in the relative differentiation of parent magmas affects the Fe abundances of basaltic surface rocks on Mars (McSween et al., 2006). Although the neutron absorption cross section of Fe is not as high as Cl, a large enough variation in the abundance of Fe on a local scale could also have a significant effect on the overall neutron flux. Pervasive hematite concretions in Meridiani Planum are suggested to have precipitated from rocks that were exposed to groundwater and subsequently deposited as a lag surface (Morris

et al., 2006). It may also be possible to distinguish buried hematite-rich (“blueberry”) layers with a neutron die-away technique, if these materials are enriched in the near-surface.

Based upon the elemental variabilities presented above, we test the following through modeling. 1) We hypothesize that the dominant source of variability in surface-measured neutron leakage spectra associated with the macroscopic absorption cross sections for plausible Martian geochemical compositions is Cl, followed by Fe. 2) We hypothesize that neutron instruments like DAN will be sensitive to interesting and unusual materials other than hydrogen that are at or below the surface. For example, hydrothermally altered soils, buried high-silica deposits or hematite concretions, all of which have significantly anomalous macroscopic neutron absorption cross sections, should be relatively simple to detect by virtue of the effect they have on thermal and epithermal neutron fluxes.

3. Methods

3.1 MCNPX

Because there is no analytical model to describe the probabilistic interactions of neutron transport in a variety of geometries, compositions and energies, we utilize the Monte Carlo Neutral Particle eXtended (MCNPX) code to simulate a suite of results. MCNPX simulates the transport and interactions of individual neutrons in a user-defined geometry using scattering and absorption coefficients from particle data libraries (McKinney et al., 2006; Pelowitz et al., 2005). To determine the effects of soil compositions enriched in high absorption cross section elements on neutron die-away, MCNPX is used to model the thermal neutron flux for soil compositions that are anomalously rich or poor in these elements in a simple Mars soil composition (described below). A 14.1 MeV fast neutron source at the height of the PNG mounted on the MSL rover (80 cm) are modeled. All neutron fluxes are reported at the detector position, 80 cm above the ground and 1 meter horizontally from the source, to simulate the DAN detector geometry. In any given simulation, MCNPX models the history of individual neutrons (total number is specified by the user) and data libraries are used as look-up tables for determination of the appropriate scattering and absorption cross sections for every neutron interaction. There are several data libraries available for neutron cross section data, and we use the most recently acquired MCNPX cross section library for each element within the modeled soil

composition. The most recent library varies from element to element, thus, several were chosen. These libraries are .50c, .55c, .60c and .66c. A detailed description of the cross section data libraries is provided by Pelowitz et al., (2006). When discrete cross section data are not available for the neutron energies involved, MCNPX uses models to derive a best fit. Errors associated with cross section libraries or model assumptions are propagated throughout the MCNPX simulation and folded into the reported relative error when the simulation is complete. An example MCNPX input file is shown in Appendix C.

Because no DAN instrument response model has been published as of yet, where neutron die-away curves and the total number of neutrons are presented, data are shown in flux units of neutrons/cm²/sec/source-particle. This value is the total number of neutrons that are incident on 1 cm² at the detector position per source-particle. For DAN, there are $\sim 10^7$ neutrons emitted per PNG pulse, however, the total number of neutrons detected will be dependent upon the pulse rate (in Hz) of the PNG, the integration time, and the efficiency of the detectors and electronics. Presenting the neutron flux in “per source particle” units alleviates need for discussion of specific DAN instrument response as well as operational modes (i.e. specific pulse rates and integration times). In Section 5, we discuss the determination of uncertainties in counting rates based on Poisson statistics to show that, if DAN signal to noise is low, the changes we will present should be detectable.

To interpret thermal neutron die-away curves quantitatively, we examine both the total neutron flux as well as the timing component of each curve. To quantify the timing of a die-away curve, we define a parameter we call the flux weighted time average (FWTA) as the average arrival time for all thermal neutrons, weighted by the flux at each small time interval of the die-away period. We discuss the relative changes in thermal and epithermal neutron energy distributions for die-away curves as well as relative changes to the flux weighted time average for a suite of hydrogen, Cl and Fe abundances that have been chosen based on actual compositions measured on the Martian surface.

3.2 Newton Cluster Computing System

For the majority of simulations, we have used the Newton cluster computing system, which is housed at the University of Tennessee, Knoxville. The cluster consists of over 250 64-bit computer nodes with a total of over 2400 processor cores and 5 TBytes of RAM. All nodes are connected via 1Gbit Ethernet and Infiniband interconnect (either DDR at 20Gbit/sec and QDR at 40 Gbit/sec). The operating system is Scientific Linux 5.4 (Redhat Enterprise compatible) and MCNPX jobs are submitted via the Sun Grid Engine batch-queue system. The high computing capacity of this system allows us to simulate a large number of particles for each run in a relatively short period of time. For example, a standard MCNPX simulation from this work models the transport of $2 \cdot 10^9$ neutrons. Using Newton, with an allocation of only 450 processors, this calculation can be completed in approximately 20 minutes with low relative errors ($<10\%$, see Section 5.4, below).

3.3 Compositions

To choose our suite of modeled soil compositions, data acquired by the Mars Exploration Rovers' APXS experiment were used to 1) provide a bulk estimate of soil composition, 2) provide constraints on the abundances of high neutron absorption cross section elements (specifically Cl and Fe), and 3) provide specific examples of well-characterized surfaces on Mars with known abundances of high absorption cross section elements. The bulk soil composition and the range of variation for Cl abundances used in the models are presented in Table C1. The specific localities from MER were chosen based upon their abundance of high absorption cross section elements and their importance for understanding the geologic history of the Martian surface. High absorption cross section elements like Cl and Fe tend to be more abundant in locations that have experienced aqueous alteration (Squyres et al., 2006; Squyres et al., 2007; Squyres et al., 2008). Table C1 also shows the Mars Exploration Rover APXS data used for specific high and low Cl and Fe compositions.

To explore a range of plausible values for both H₂O and Cl, we use APXS data acquired from Spirit and Opportunity and vary the abundance of Cl within our generic Mars soil from 0 to 5 wt.%. We also vary H₂O content from 0 to 25 wt.% based upon Mars Odyssey Neutron Spectrometer data for equatorial regions of Mars (Feldman et al., 2004). Table C2 shows MER APXS-derived elemental abundances and variability for high absorption cross section

elements. Although 5 wt.% Cl is well above reported values by APXS, the reason we have chosen to model these higher abundances is two-fold. First, we expect that a salt-rich deposit, composed of a cation bound to a Cl atom (~50 wt.% Cl depending upon the cation), should include more than 5 wt.% Cl and would be an important location to study for understanding the history of near-surface water on Mars. Second, as we will demonstrate in Section 6, the effects of Cl in abundances much less than 5 wt.% are significant enough to influence thermal neutron die-away curves.

For specific soil compositions, we use publicly available APXS geochemical data for well-studied localities on Mars that are thought to have experienced near-surface aqueous activity in the past. As described in Section 4, these compositions are 1) Eileen Dean, a Cl-rich soil. We use compositional data from Ming *et al.*, (2008) and model the soil as a continuous layer 4 cm deep as well as a discrete layer, 4 cm thick and 4 cm deep; 2) Jack Russell, hematite-rich “blueberries” found in Endeavor Crater. Although this composition has been found at the surface, it would be significant to discover shallowly buried hematite concretions as this would indicate a change from aqueous alteration of surface materials to deposition of aeolian drift deposits, therefore, we model the case where these lag deposits have been buried by a layer of aeolian dust or soil. We use compositional data from Rieder *et al.*, (2004), which includes the Jack Russell APXS observation of the predominantly hematite-rich “blueberries”. We also model this composition as a continuous layer, 4 cm deep as well as a discrete layer 4 cm thick and 4 cm deep; 3) Kenosha Comets, a Si-rich soil found in the Eastern Valley of Gusev Crater. Kenosha Comets is a soil devoid of high scattering and high absorption cross section elements, such that relatively little neutron moderation can occur. We use the compositional data from Squyres *et al.*, (2008) with soil geometries the same as for Eileen Dean and Jack Russell. The soil depth chosen (4 cm) is chosen as a representational depth for all these compositions, as mixing of the materials surrounding the trench are mixed with the soil compositions, obscuring the exact soil horizon where these compositions appear. Eileen Dean and Kenosha Comets are cited as appearing at a depth of at least several centimeters (Ming *et al.*, 2008; Squyres *et al.*, 2008). Reports of trench depths for other MER targets range from several centimeters to 11 cm (Wang *et al.*, 2006). All three soil compositions are presented in Table C1.

3.4 Error

MCNPX-calculated neutron fluxes for each time in the neutron die-away curve have an associated relative error. This error is a statistical error that describes the convergence of the simulation to the flux value reported. Included within MCNPX are ten statistical tests of the convergence of this reported value, which are run at the end of each simulation. A full description of the statistical tests and reliable values of relative error appears in Pelowitz *et al.*, (2006). Relative errors of less than 10% are generally reliable, and in this study we only report results for neutron fluxes where the mean relative error is less than 10%. For each of the following sub-sections of Section 6, we report the mean relative error for each set of simulations as well as the resulting uncertainty in neutron flux. It is important to note that this error is purely statistical and does not take into account uncertainties inherent to the measurement of actual neutrons by the DAN detectors and electronics. In this work we demonstrate the expected relative changes in neutron flux for a variety of geologic scenarios, however, we do not provide specific changes in neutron counting rates for the DAN instrument. In Section 5, we discuss the uncertainty in count rates for a specific DAN operational mode, based upon Poisson statistics. This analysis is sufficient to determine that the trends reported in Section 5 are possible to be detected, assuming that the uncertainties introduced by the DAN instrument response function, noise and signal processing electronics are not substantial.

4. Results

4.1 Cosmic Background Contribution

We first model the thermal and epithermal neutron flux from Galactic Cosmic Rays (GCRs) for non-timing based DAN observations to determine if GCRs need to be considered in timing based DAN observations. Neutrons produced by GCRs interacting with the surface and atmosphere of Mars result in a continuous background flux that is indistinguishable from that produced by the pulsed neutron source except by timing. We use MCNPX to model the neutron flux as a function of energy produced by GCR interaction with a typical Martian surface composition with 3 % H₂O and a 12 g/cm² atmosphere (Figure C1). Both upward and downward fluxes were calculated at the height of the neutron detectors. The calculations were normalized to a GCR flux of ~1 protons/cm². The neutron flux in neutrons/cm²/sec/source-particle from 1•10⁻⁹ to 14 MeV is shown in Figure C1 for both neutrons produced

by the pulsed source and those from GCRs. The mean relative error for the DAN neutron flux is 2.8%, which results in a mean uncertainty in flux of $4.84 \cdot 10^{-9}$ neutrons/cm²/sec/source-particle. The mean relative error for the GCR neutron flux is 2.9% which results in a mean uncertainty of $2.41 \cdot 10^{-10}$ neutrons/cm²/sec/source-particle. Both of these uncertainties are smaller than the data points themselves, therefore, error bars are not shown in Fig. C1.

To approximate an example operational mode for DAN, we model the pulsed neutron source with a frequency of ~10 Hz and a detector integration time of ~30 minutes. Within the total measurement time of $2 \cdot 10^3$ seconds, a fluence/cm² of approximately 1.4 thermal neutrons and 2.4 epithermal neutrons from each PNG pulse arrive at the detector, while for GCRs, the fluence of neutrons is 6.7 n/cm² in the same energy range. This assumes a GCR rate of 2/cm²/s. The GCR neutron rate in the 2 millisecond interval measuring time for the PNG neutrons would be ~1/50 times the rate from the PNG, about 0.13 neutrons/cm² or 3% of the fluence. The neutron background due to GCR is, therefore, much smaller than neutrons originating from the PNG. Thus, in this work, we have elected to model only the PNG source and do not include neutrons produced by the GCR. A complete analysis of using GCRs to constrain hydrogen content and burial depth for surface-based neutron measurements is presented in Vincke *et al.*, (2003).

4.2 Neutron Timing and Energy

We first present an example result for a generic Mars soil composition (Table C1) with 1 wt.% H₂O to illustrate the timing of detected neutrons at various energies (thermal, epithermal and fast). Figure C2 shows the arrival times for neutrons from 0-14 MeV, binned by thermal, epithermal and fast energy ranges from the start of the pulse. at 0 microseconds, to 1 millisecond. Note that no thermal neutrons are detected in the first ~100 microseconds after the PNG pulse, but that all the neutrons coming after this time are thermal neutrons. Qualitatively, the distribution of energies with time can be understood first based upon the travel times for neutrons within each energy range. Using the approximation that neutron velocity is proportional to the square root of its energy, we find that high-energy neutrons from the pulse travel at extremely high speeds (> 5000 cm/microsecond) entering the soil and interacting with the nuclei of the near-surface materials. The amount of time these neutrons spend within the near-surface is

dependent upon the number of interactions it has and how much energy is lost with each interaction. If these high-energy neutrons interact with hydrogen, their energy distribution is shifted to lower energies, thus reducing the speed of these neutrons, increasing the amount of time spent in the near-surface, and therefore, the amount of time it will take to reach the detectors. We find that thermal neutrons (<0.3 eV) travel approximately 80 cm in 100 microseconds, which is the same as the first arrival of thermal neutrons at the detectors in Fig. C2 and the height of the detectors above the surface. Therefore, neutrons arriving at earlier times are of higher energy and have interacted with materials closer to the surface. This illustrates how 1) neutrons that arrive at the detector after ~ 100 microseconds (thermal neutrons) are sensitive to nuclei at depth and 2) analysis of the thermal neutron energy portion of Fig. C2 can be used to interpret geochemical information of the near-surface. The mean relative errors in thermal, epithermal and fast neutrons fluxes are 2.40%, 6.91%, and 4.86% respectively. The resulting mean uncertainties in neutron fluxes for all energy ranges are smaller than the data points in Fig. C2. Therefore, in Fig. C2 and all subsequent figures the error values are not shown but are cited in the appropriate section of text.

Fig. C3a shows a suite of thermal die-away curves for variable H_2O content, from 0.5 wt.% to 25 wt.%, with the remainder of the soil composition proportioned as shown in Table C1. As hydrogen content of the near-surface increases the total number of thermal neutrons increases and more high-energy source neutrons are shifted to lower energies. In addition, the flux weighted time average shifts to earlier times with increasing hydrogen content. Hydrogen is added to the modeled soil homogeneously, therefore, as hydrogen content is increased neutrons have a greater chance of interacting with hydrogen immediately upon entering the surface. This results in a shifting of thermal neutron arrival times to earlier times. Fig. C3b shows how the flux weighted time average decreases with increasing H_2O content. As expected from Litvak et al. (2008) and Busch et al. (2009) the total thermal flux increases with H_2O content ($\sim 86\%$ decrease from 0 to 25 wt.% H_2O) and the flux weighted time average (FWTA) decreases by 33%. Figs. 3a and 3b demonstrate that as H_2O content increases, the FWTA decreases nearly linearly, while the peak in thermal neutron die-away flux shifts to earlier times as H_2O content increases from 0 to 1 wt.% and then to later times as H_2O content increases beyond 1 wt.%. This indicates the FWTA is a more appropriate quantity than the peak in thermal neutron die-away to use in interpreting trends between various neutron die-away curves.

4.3 Effects of Cl, Fe, Ti, Br, Mn on Thermal Neutron Die-Away

Using the results from averaged MER Spirit and Opportunity APXS data presented in Table C2, we perform a set of MCNPX runs to determine which of these high absorption cross section elements influences thermal neutron die-away curves most significantly. We use the average standard deviation for each of these elements, such that our determination of the relative importance of each element is dependent not only upon its absorption cross section, but its anticipated variability during a potential MSL traverse. For Cl, Ti, Br, and Mn we normalize the generic Mars soil composition presented in Table C1 to include the average abundances of Cl, Ti, Br and Mn. For Fe we use the generic composition presented in Table C1. For each element, we perform two MCNPX simulations, the first with the average abundance for each element, and the second where we increase the average abundance by one standard deviation. We find that, in order of decreasing importance, increasing Cl by 0.40 wt.% results in a decrease in thermal neutron flux of ~11.6%, increasing Fe by 5.2 wt.% results in a decrease in thermal neutron flux of ~8.6%, increasing Mn by 0.07 wt.% results in a decrease in thermal neutron flux of ~8.14%, increasing Br by 0.01 wt.% results in a decrease in thermal neutron flux of ~2%, increasing Ti by 0.27 wt.% results in a decrease in thermal neutron flux of ~1.4%. Based on these analyses, and the relative average abundances of these elements (Table C2), we find that Cl and Fe are the most likely candidates to strongly influence thermal neutron die-away curves.

4.4 Chlorine

We have shown how the total thermal flux increases (Fig. C3a) and FWTa decreases (Fig. C3b) with increasing H₂O content from 0.5 to 25 wt.% and no Cl. To explore the effects of introducing high absorption cross section elements into the soil, we add 0.5 wt.% Cl into the soil as an initial test. The thermal neutron die-away curves for 0 and 0.5 wt.% Cl with 0 and 3 wt.% H₂O (Fig. C4a) demonstrate the significant effects of Cl on both the total thermal neutron flux as well as the FWTa. Figs. 4b and 4c show the effects of adding 0.5 wt.% Cl on the total thermal neutron flux (Fig. C3a) and the FWTa (Fig. C3b) for H₂O contents ranging from 0 to 25 wt.%. For low H₂O content (0-5 wt.%), adding a small amount of Cl (0.5 wt.%) shifts the FWTa to earlier times by approximately 10-27% and reduces the total thermal neutron flux by approximately 20-43%. The magnitude of the effect of Cl on thermal neutron flux and FWTa are dependent upon both the initial H₂O and Cl content of the soil. Table C3 shows

how the effects of Cl change the total thermal neutron flux and FWTa for 0, 1, 3, and 5 wt.% H₂O and 0, 0.5, and 1 wt.% Cl.

The full suite of neutron die-away results, for H₂O content varying from 0-25 wt.% and Cl content varying from 0-5 wt.% are presented in Figs. 5-6. The data are plotted in 3 dimensions (Figs. 5a and 5b), defining a surface that constrains the thermal neutron fluxes or values of FWTa that are possible for a given H₂O and Cl content. These data may also be presented on contour plots, which are shown in Figs. 6a and 6b.

The results presented in Figs. 5, 6, and Table C3 demonstrate that the amount of Cl in the surface can influence the interpretation of the hydrogen content if Cl content is not known and correctly taken into account. A surface with 5 wt.% H₂O and no Cl would give the same total thermal neutron flux as a surface with 10 wt.% H₂O with 0.5 wt.% Cl. Similarly, the total thermal flux for a thermal neutron die-away curve for 10 wt.% H₂O is also consistent with almost 25 wt.% H₂O and 0.5 wt.% Cl.

For the purposes of MSL operations and DAN data analysis, Figs. 6a and 6b suggest a strategy for using neutron measurements to place constraints on Cl and H₂O content. The total thermal neutron flux from the die-away curve determines the possible range of Cl and H₂O contents (Fig. C6a), while the FWTa can then be used to further constrain the H₂O and Cl contents within the range determined by the total thermal neutron flux (Fig. C6b). By tracking changes to these variables in thermal neutron die-away along traverses by the MSL rover, locations for more detailed study can be identified based upon the indications of potential Cl-rich evaporites or buried hydrogen-rich materials. An alternate method for constraining hydrogen abundance could be provided by the acquisition of epithermal neutron die-away curves by DAN, a method not discussed by Litvak et al., (2008) or Busch et al., (2009).

Epithermal neutrons may also be counted from the cadmium-coated He³ tube (up to ~700 KeV). Epithermal neutrons are primarily sensitive to the hydrogen abundance of the soil and do not show variations with changes in absorption cross section (Prettyman et al., 2003). Since thermal neutron fluxes are highly dependent upon the combination of hydrogen content and absorption cross section, epithermal neutrons can be used to constrain the hydrogen content on Figs. 5 and 6. Used in combination, the epithermal neutron fluxes can be used to determine the

hydrogen content while thermal neutrons can be used to determine the Cl content. Determination of the FWTa for epithermal neutrons is ambiguous, as fast neutrons from the source are mixed with epithermal leakage neutrons in the first tens of microseconds after the pulse (See Fig. C2a). We have shown, however, that in die-away measurements the total epithermal neutron flux is sensitive to variations in hydrogen content but does not vary significantly with Cl content (Fig. C7a). Figure C7a demonstrates the sensitivity of epithermal neutrons to H₂O content by showing both epithermal and thermal neutron fluxes for 0, 1, 2 and 3 wt.% H₂O with 0 wt.% Cl. In addition, Fig. C7a shows an epithermal neutron die-away curve for 3 wt.% H₂O with the addition 0.5 wt.% Cl, which is indistinguishable from the epithermal neutron die-away curve for 3 wt.% H₂O and 0 wt.% Cl, to demonstrate the insensitivity of epithermal neutrons to the presence of high thermal neutron absorption cross section elements. Epithermal neutrons can, therefore, be used to determine if changes in thermal neutron die-away are due to variations in hydrogen abundance or in macroscopic absorption cross section. We have also modeled the total epithermal neutron flux for 0 to 25 wt.% H₂O and 0 to 5 wt.% Cl. These results are presented in Figure C8. The epithermal neutron flux contours are nearly vertical for the range of modeled H₂O abundances, indicating they constrain only the hydrogen content of the near-surface.

4.5 Specific Locations on Mars

In this section we use the results from MER Spirit and Opportunity APXS geochemical data to model the thermal neutron flux for well studied, local-scale geologic features in Meridiani Planum and Gusev Crater that 1) contain an unique chemistry with an abundance or absence of high neutron absorption cross section elements, and 2) are thought to provide evidence for the presence or past-action of near-surface water. The geochemical compositions chosen are Eileen Dean, a subsurface Cl-rich soil identified near Home Plate within Gusev Crater, Jack Russell, a mixture of hematite-rich “blueberries” and surrounding surface materials identified within the Berry Bowl in Endeavor Crater, and Kenosha Comets, a buried Silica-rich soil identified in a location named the Eastern Valley, within Gusev Crater, and the Heat Shield Rock meteorite found by the Opportunity Rover in Meridiani Planum. While there are no plans to send the MSL rover (or any other mission) to either MER landing site, these sites serve as examples of the high degree of localized geochemical variability that can be found on Mars when exploring a well-chosen site with a surface mission.

4.5.1 Cl-rich Eileen Dean soil

Home Plate is a region on Mars thought to harbor volcanoclastic and hydrothermally altered sediments (Ming *et al.*, 2008). As described in Section 4.4, the Spirit rover has discovered several classes of rocks and soils that are relatively enriched in Cl. Cl enhancements are found in individual rocks as well as buried soils that were exposed by dragging the rover's front right wheel. We have modeled the Eileen Dean class of soils as both a thin, discrete subsurface layer (4 cm deep, 4 cm thick) and a thick subsurface layer (also buried 4 cm deep) that extends well below the depths where the neutrons interact. Based on the results presented in Section 4.3, the APXS-derived abundance of Cl for the Eileen Dean class of soils (1.7 wt. % Cl) is high enough to have a strong effect on thermal neutron die-away. The composition of the surrounding soil and the composition of Eileen Dean are shown in Table C1. Modeled thermal neutron die-away curves for the DAN neutron detectors positioned above the thin and thick layers of Eileen Dean composition, as well as above a homogeneous, dry surface are presented in Figure C9.

For the case of a continuous layer of Eileen Dean composition, the total thermal flux is reduced by ~47%, while for a discrete 4 cm thick layer, the total thermal flux is reduced by ~8%. For the continuous layer, the FWTa is shifted to earlier times by 12%, while for the discrete layer the FWTa is shifted by 1%. Comparing these changes to our results for increasing hydrogen with no Cl, a 47% decrease in total thermal flux gives the same change in FWTa as an ~5 wt.% decrease in water-equivalent hydrogen in the near-surface. The FWTa, however, allows us to further interpret the cause of this decrease in thermal neutron flux. As described in Section 4.3, the FWTa decreases with increasing Cl content and increases with decreasing hydrogen content, such that the effect of the Eileen Dean layer is to shift the FWTa to earlier times. If hydrogen content were decreasing, DAN would observe an increase in the FWTa. Therefore, in both the continuous and discrete Eileen Dean layer scenarios, DAN would identify the presence of a high macroscopic absorption element (presumably Cl or Fe) in the near-surface. There is no significant change in the epithermal neutron flux for any of these scenarios, as there is no hydrogen in each simulated composition.

4.5.2 Fe-rich “blueberry”-rich soil

A pervasive surface component of Meridiani Planum are hematite concretions known as “blueberries”. These nearly spherical, hematite-rich materials are observed to be eroding from nearby outcrops, collecting on the surface as a lag deposit (Squyres *et al.*, 2006). The unique mineralogy and chemistry of the blueberries suggests that they were formed as stagnant groundwater saturated the sulfate-rich Meridiani rocks and sands, leaching Fe-oxide from these materials, and re-precipitating it in the subsurface as hematite spherules. The presence of blueberries at Meridiani is one of the many features discovered by the Opportunity rover that indicate interaction of water with near-surface materials. Because percolation of groundwater into the surrounding rocks is the most plausible explanation for the presence of the blueberries, Fe-rich materials are likely to be present just below the surface either in outcrop or as a lag deposit that was later buried by aelian drift. As the absorption cross section of Fe is relatively high (Table C2), we expect that if the concentration of hematite-rich materials were high its effects would be recorded in thermal neutron die-away curves acquired by DAN. For input to our model, we use the composition of blueberry materials from the Jack Russell observation within the Berry Bowl in Endeavor Crater shown in Table C1 (Rieder *et al.*, 2006). This observation was chosen because the surface concentration of blueberries was so spatially dense that the derived chemical data can be approximated as the composition of the blueberries themselves. Using this composition also maintains the geologic plausibility of the simulated experiment, as any hematite-rich blueberries will not occur in isolation, and instead will be mixed with the surrounding rocks from which they have eroded.

Figure C10 shows the thermal neutron die-away results for three separate simulations, a dry Mars soil, a continuous hematite-rich soil horizon below 4 cm, and a discrete hematite-rich soil composition 4 cm deep and 4 cm thick. The effects of the hematite-rich compositions are significant, with a reduction of total thermal flux by ~33% for the continuous layer and ~4% for the discrete layer. A shift in FWTa to ~5% earlier times is observed for the continuous layer while there is only a shift to <1% earlier times for a discrete layer. Even with an enrichment of Fe just over 10 wt.% the nominal Fe value, these results do not influence the thermal neutron die-away curve as much as a mere 1 wt.% increase in Cl from the nominal Cl value, as seen in the Eileen Dean results (Section 6.3.1).

4.5.3 Si-rich, Kenosha Comets soil

In Gusev Crater, the Spirit rover investigated a region called the Eastern Valley between Home Plate and the Middletree/Low Ridge complex where extremely high silica content (~91 wt.%) deposits were uncovered by trenching of the rover's right front wheel (Squyres *et al.*, 2008). Due to the proximity of these soils to the volcanoclastic and hydrothermal environments at Home Plate, the Kenosha Comets soils are interpreted to have formed in a hydrothermal environment. In terrestrial systems, high silica deposits are formed in a variety of ways in hydrothermal environments, specifically through the evaporation of groundwater or acid leaching of basaltic materials (Squyres *et al.*, 2008).

Although Si is not a high absorption cross section or scattering cross section element (Table C1), it forms such a high percentage of the bulk composition of the Kenosha Comets material that many other elements – for example, the neutron moderating and absorbing elements (H, Cl and Fe) – are present in greatly reduced abundances compared to less unusual Martian compositions. This should result in a significantly reduced total thermal neutron flux, as nearly all the collisions between high-energy neutrons and the elemental constituents of the soil result in negligible neutron energy loss. Fig. C11 shows that indeed, the total thermal neutron flux is reduced by >99% for a continuous layer of Kenosha Comets soil buried at 4 cm depth. For a discrete layer buried at 4 cm, 4 cm thick, the thermal neutron flux is reduced by ~75%. We note that the abundance of Ti, a high absorption cross section element (Table C2), is greater for Kenosha Comets than surrounding Gusev soils. The presence of Ti further reduces the overall thermal neutron flux. The FWTa is shifted to earlier times by 60% for a continuous layer and ~34% for a discrete layer. The mean relative error in thermal neutron flux 3.3%, which results in a mean error in thermal neutron flux of $2.08 \cdot 10^{-12}$ neutrons/cm²/sec/source-particle.

4.5.4 Fe-meteorite, Heat Shield Rock

The Opportunity rover has discovered several meteorites which were found by APXS to contain nearly 94 wt.% Fe (Schroder, 2006). Heat Shield Rock is an IAB iron meteorite, of ~30 cm maximum dimension, found near the lander's heat shield that was dropped during its decent to the surface. Upon initial examination the smooth, metallic

surface and pitted texture suggested the rock to be a meteorite. Further mid-infrared analysis showed the rock to be of low emissivity, characteristic of metals and iron meteorites. A full analysis by the APXS revealed Heat Shield Rock to have a bulk elemental composition of 93% Fe, 7% Ni, ~300 ppm Ge and <100 ppm Ga. We model Heat Shield Rock as a 30 cm by 30 cm box, buried just below the surface with a composition shown in Table C1. Figure C12 shows the thermal neutron die-away results for the rover directly above the meteorite and for generic, Mars dry soil. The overall reduction of thermal neutron flux with the meteorite is only 0.018% while the FWTa only shifts to earlier times by 0.003%. As we will discuss in Section 5, such small changes are not anticipated to be detectable by DAN.

5. Discussion

It is reasonable to question whether or not the variabilities presented in the preceding sections have the potential to be detected by DAN. Although we do not have an instrument response model, we can make several assumptions based on statistics inherent to the radiation detection instrument. As an estimate of the uncertainty associated with the detection of a single neutron, we can assume the counting statistics follow a Poisson distribution such that the uncertainty associated with a measurement at any given time bin is the square root of the total number of counts (Knoll, 2000). In addition, we assume the following operational modes for DAN 1) a pulse rate of 10 Hz and 2) an integration time of 5 minutes. We also assume a modest thermal neutron detection efficiency for He-3 of 95% (Mills, 1963). In Fig. C10 we have shown a relatively small decrease in thermal neutron flux (~4%) for the presence of a discrete Fe-rich “blueberry” layer. Assuming the above operational modes and Poisson error, we find that for a maximum count rate with the Fe-rich layer of 5305 counts/sec the uncertainty is 73 counts/sec. Without an Fe-rich layer, the maximum count rate is 5768 counts/sec with an uncertainty of 76 counts/sec. Reductions in thermal flux of ~4%, therefore, should be detectable assuming the instrument response, noise, and signal processing do not introduce significant uncertainties in count rates.

We have shown that thermal neutron counts and timing are dependent on a combination of the abundance of high absorption cross section elements (Cl, Fe) and hydrogen. Estimates of near-surface hydrogen abundance, however, can be made by using epithermal neutron die-away alone. Once constraints are placed on the hydrogen content based

on epithermal neutrons, thermal neutron counts can be used to determine the macroscopic absorption cross section of the surface. As we have shown in Section 4.2, the most likely high absorption cross section element on Mars that will strongly influence thermal neutron die-away is Cl; however, observations from other rover instruments may be necessary to constrain the most plausible element. The importance of using epithermal neutrons in combination with thermal neutrons has been shown in Section 4.3, where we have demonstrated that the effects of Cl on the total thermal neutron flux are significant. A total thermal neutron flux consistent with 5 wt.% H₂O and no Cl could represent 10 wt.% H₂O with 0.5 wt.% Cl, while a total thermal neutron flux consistent with 10 wt.% H₂O is also consistent with almost 25 wt.% H₂O and 0.5 wt.% Cl.

In the absence of epithermal neutron counts, we have shown that some analysis can still be performed using thermal neutron counts and timing alone. When hydrogen abundance decreases, the FWTa shifts to later times. This is opposite to the effects on FWTa by high absorption cross section elements. The addition of high absorption cross section elements shifts the FWTa to earlier times and decreases the total thermal neutron flux. In order to distinguish changes in thermal neutron die-away caused by hydrogen and those caused by high absorption cross section elements, we need only compare the changes in total thermal flux with the FWTa. Assuming measurements are acquired with DAN at regular intervals along a traverse and that changes in subsurface composition are relatively smooth then we can use thermal neutron die-away in the following manner. If the total thermal neutron flux increases and the FWTa shifts to earlier times, then hydrogen content is increasing. Alternatively, if the total thermal neutron flux is decreasing and the FWTa shifts to earlier times, the abundance of high absorption cross section elements is increasing. There are, of course, pathologic cases where the amount of hydrogen is allowed to vary in a buried layer such that the hydrogen content is increased enough to compensate for the addition of high absorption cross section elements. In this scenario, interpretation of DAN die-away curves will rely heavily upon data from other instruments on-board MSL or assumed parameters that provide bulk geochemistries, burial depths or hydrogen content. Without fixing at least one of these parameters, there will be significant uncertainty in thermal neutron die-away interpretations. These results, combined with the data from the both MER APXS instruments that have identified up to 2.6 wt.% Cl in some locations, demonstrate that the effects of elements like Cl can significantly influence neutron die-away measurements.

The contour plots (Figs. 6a and 6b) show that the effects of hydrogen on the thermal neutron die-away curve are strongest when Cl abundances are low. The nearly vertical contours for low values of H₂O, and across all values of Cl, show that the dominant control on total thermal flux is H₂O when H₂O abundance is low. Above ~5 wt.% H₂O, however, the effect of macroscopic absorption cross section dominates both surface and contour plots. At values of H₂O above ~5 wt.% the thermal flux contours are nearly horizontal, indicating the macroscopic absorption cross section has an increasingly dominant effect on thermal neutron flux. The FWTa contours more clearly demonstrate the abundance of Cl at which macroscopic absorption cross section appears to have a dominant effect. Fig. C6b shows FWTa contours decreasing nearly linearly for low Cl abundances but beginning to bend sharply upward as Cl abundances increase. This results in an inversion for contours above ~1.7 wt.% Cl and ~1 wt.% H₂O. Above this Cl abundance, the effects of macroscopic absorption cross section dominate the range of possible FWTa values. We can use this effect to demonstrate how FWTa can constrain Cl abundance. Figure C13 is a cross section through the FWTa contour plot shown in Fig. C6b. For lines of constant H₂O abundance and Cl abundances from 0 to 5 wt.%, FWTa values of less than ~500 microseconds all correspond to Cl abundances greater than 1.7 wt.%. Conversely, FWTa values greater than ~500 microseconds correspond to Cl abundances less than 1.7 wt.%. The absolute time of this diagnostic FWTa is subject to change based on the rover configuration above the ground, the accuracy of the timing electronics, efficiency of the detectors, and the real Mars near-surface composition, however, better estimates on these conditions can be used in MCNPX simulations to solve for this diagnostic FWTa once MSL has landed, using data from the landing site as well as other MSL instruments.

6. Conclusions

The effects of high absorption cross section elements on thermal neutron fluxes have been well documented for a variety of spacecraft instruments (Feldman et al., 2000; Feldman et al., 2004; Prettyman et al., 2003; Prettyman et al., 2004). In this work, we have demonstrated the effects of high absorption cross section elements on thermal neutron die-away curves similar to those that will be acquired by the DAN instrument on-board MSL. Strong reductions in the total number of thermal neutrons and shifts in the time-weighted thermal flux average along a traverse by MSL may be indicative of hydrothermal and evaporitic deposits, as well as Fe-rich concretions that result from groundwater percolation which contain an abundance of high absorption cross section elements. We

have shown that the timing component of the thermal neutron die-away as well as the epithermal neutron die-away curves can be used to distinguish changes in near-surface hydrogen from changes in macroscopic absorption cross section. These data can be used to understand the underlying causes for observed changes in thermal and epithermal neutron die-away curves acquired during the MSL mission. Our results show that DAN can not only detect changes in hydrogen content, but that epithermal and thermal neutron die-away curves can be used in combination to identify buried Cl- or Fe-rich soils.

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Appendix C

Table C1: Scattering and absorption cross sections of various elements of geologic interest on Mars. Also shown are the average soil composition used, the range of variation for Cl and Fe abundances, and the Mars Exploration Rover APXS data used for specific high and low Cl and Fe compositions.

	Scattering Cross Section*,**	Absorption Cross Section*,**	Base Soil Mass Fraction***	Cl-rich Home Plate, 'Eileen Dean'****	Hematite-rich, 'DogPark - Jack Russell'*****	High-Silica, 'Kenosha Comets'*****	Iron Meteorite, 'Heat Shield Rock' **+	Variations in Composition
O	4.2320	0.0002	0.4424	0.4321	0.3979	0.5353	-	-
Si	2.1670	0.1710	0.2076	0.2314	0.1767	0.4230	-	-
Al	1.5030	0.2310	0.0159	0.0323	0.0381	0.0005	-	-
Ca	2.8300	0.4300	0.0175	0.0271	0.0368	0.0051	-	-
Fe	11.6200	2.5600	0.1319	0.1251	0.2596	0.0109	0.94	-
Mg	3.7100	0.0630	0.1724	0.0953	0.0386	0.0139	-	-
Na	3.2800	0.5300	0.0023	0.0104	0.0119	0.0024	-	-
Ti	4.3500	6.0900	0.0100	0.0030	0.0042	0.0073	-	-
Mn	2.1500	13.3000	-	0.0019	0.0022	0.0002	-	-
K	1.9600	2.1000	-	0.0035	0.0031	-	-	-
P	3.3120	0.1720	-	0.0029	0.0033	-	-	-
S	1.0260	0.5300	-	0.0124	0.0192	-	-	-
Cr	3.4900	3.0500	-	0.0036	0.0025	-	-	-
Ni	18.5000	4.4900	-	0.0007	0.0011	-	0.07	-
Zn	4.1310	1.1100	-	0.0011	0.0003	-	-	-
Br	5.9000	6.9000	-	0.0001	0.0000	-	-	-
H	82.0200	0.3326	-	-	-	-	-	0 - 25 wt.% as H ₂ O [in 1 wt.% increments]
Cl	16.8000	33.5000	-	0.0170	0.0046	0.0014	-	0 - 5 wt.% [in 0.5 wt.% increments]
Cd*++	6.5000	2520.0000	-	-	-	-	-	-

*units in barns

**<http://www.nist.gov/resources/n-lengths/> Neutron News, Vol. 3, No. 3, 1992, pp.29-37

***Longhi et. al, 1992

****Ming et. al, JGR Planets, 2008

*****Reider et al., Science, 2004

*****Squyres, et al., Science, 2008

*+Schroder, et al., JGR Planets, 2008

*++Cadmium is a detector material that coats one He-3 tube to filter out neutrons with energies lower (thermalized) than 0.4 eV.

Table C2: Combined APXS-derived abundances for the highest absorption cross section elements Cl, Mn, Ti and Fe (excluding Heat Shield rock).

	MER -A & B	MER -A & B	
	Avg wt. %	STDEV	Absorption Cross Section [barns]
Cl	0.93505	0.4032	33.5
Mn	0.30605	0.0686	13.3
Br	0.01415	0.0173	6.9
Ti	1.02565	0.2719	6.09
Fe	21.4949	5.2134	2.56

Table C3: Changes to thermal flux and FWTa for a variety of H₂O and Cl contents.

H ₂ O	Cl	Total Thermal Flux	FWTA	% Decrease in Thermal Flux from Cl-free composition	% Shift in FWTa from Cl-free composition	Change in FWTa [μ s] from Cl-free abundance
0	0	3.00224E-08	910.118	-	-	-
0	0.5	1.71098E-08	661.021	43.01%	27.37%	249.097
0	1	1.14047E-08	584.72	62.01%	35.75%	325.398
1	0	6.69765E-08	861.761	-	-	-
1	0.5	4.26062E-08	639.09	36.39%	25.84%	222.671
1	1	3.13507E-08	563.383	53.19%	34.62%	298.378
3	0	1.08842E-07	742.184	-	-	-
3	0.5	7.62809E-08	634.375	29.92%	14.53%	107.809
3	1	5.8596E-08	567.963	46.16%	23.47%	174.221
5	0	1.37641E-07	722.255	-	-	-
5	0.5	9.92968E-08	627.158	27.86%	13.17%	95.097
5	1	7.78443E-08	568.508	43.45%	21.29%	153.747

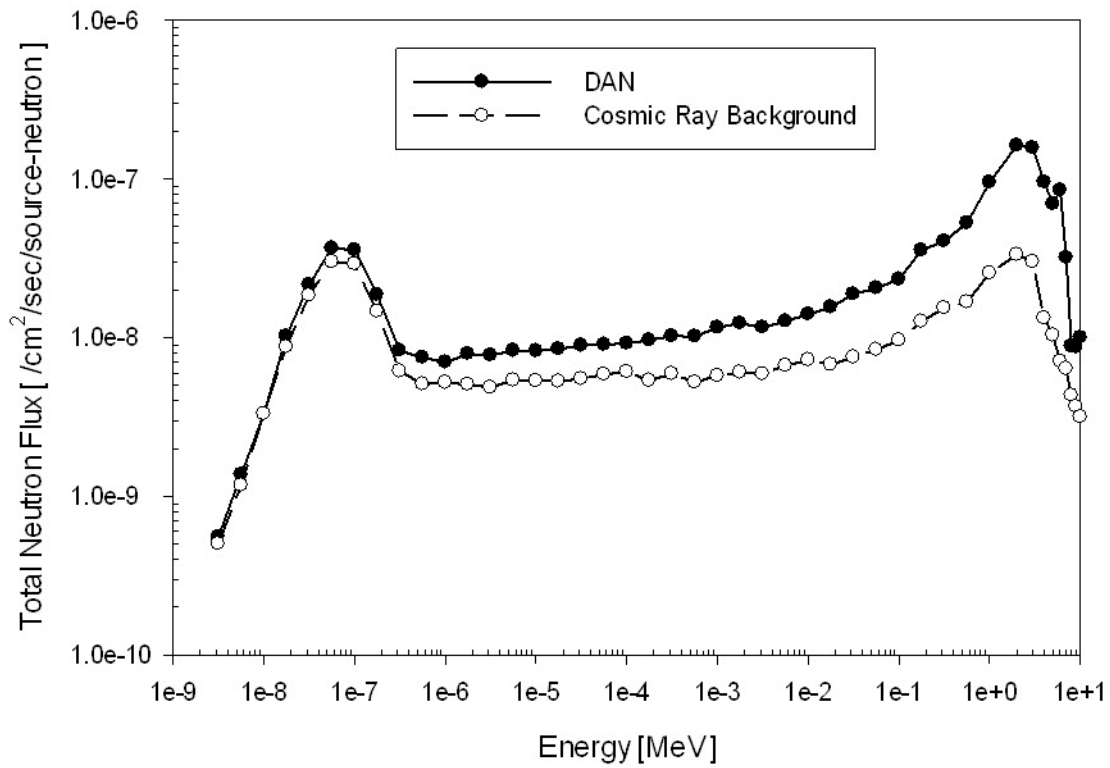


Figure C1: Flux at the DAN neutron detectors due to the GCR and PNG produced neutrons. The curves are normalized to show similarities at low energies. The high-energy peak in the DAN spectrum is due to the direct source neutrons.

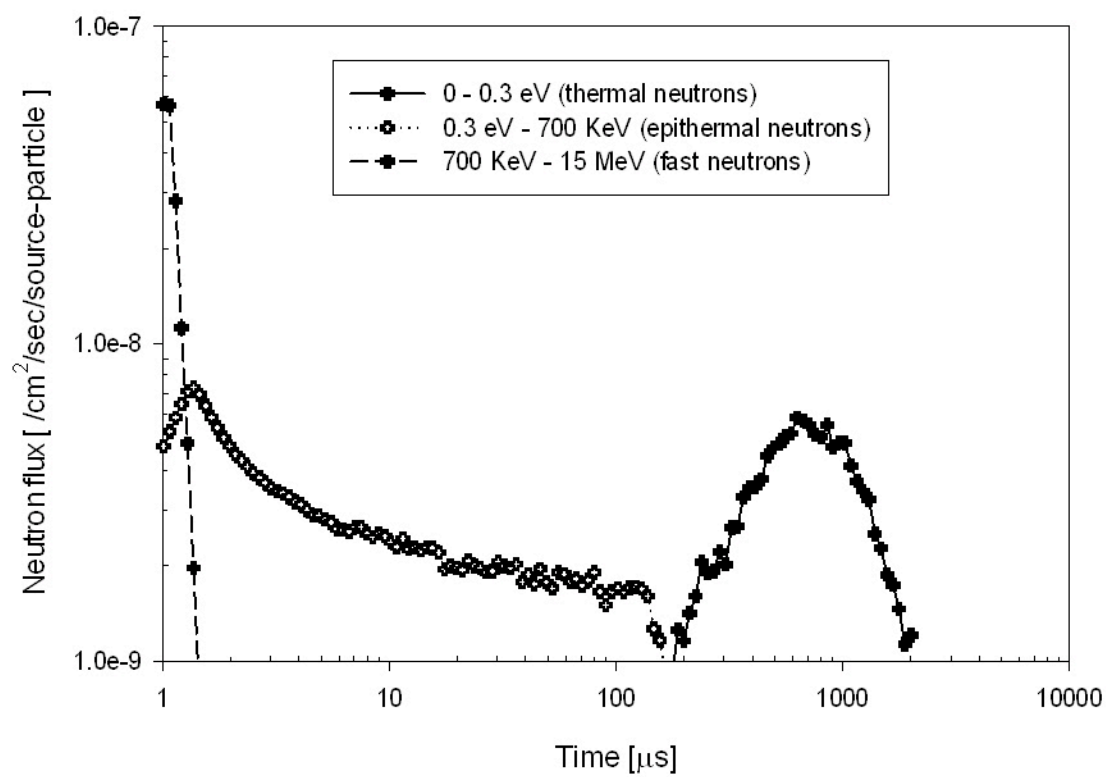


Figure C2: Neutron flux at the He³ neutron detector versus time of arrival. Energy intervals are given in the legend.

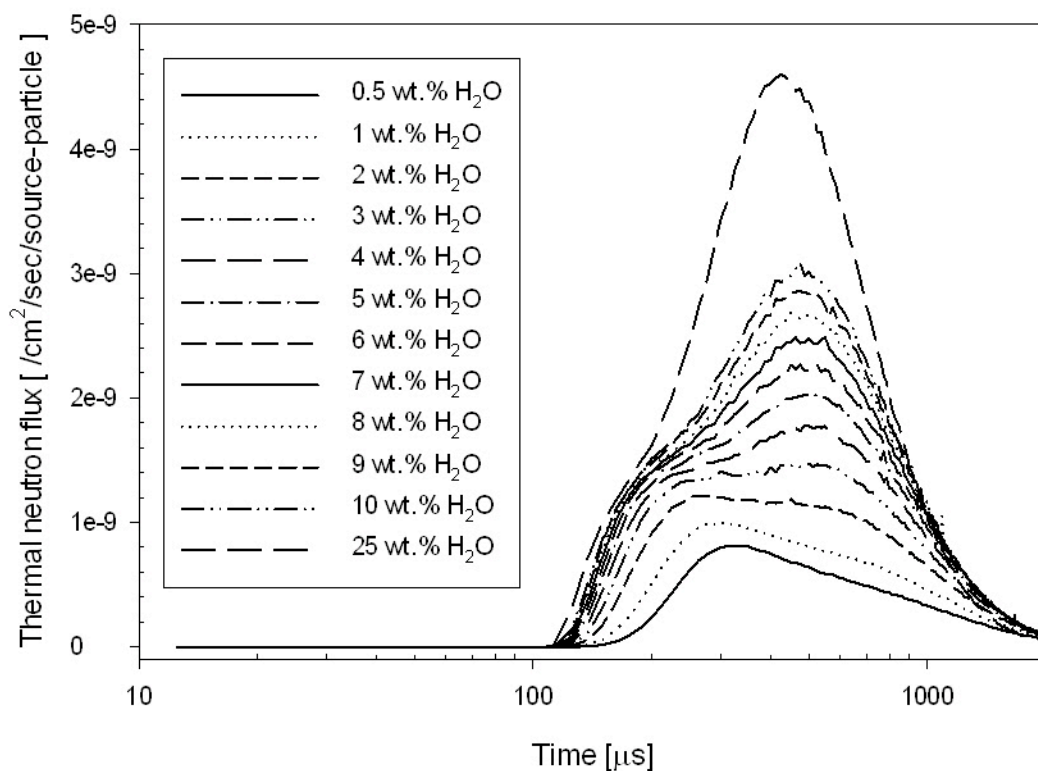


Figure C3A: Arrival times at the detector for neutrons with energies less than 0.3 eV for H₂O content from 0-25 wt.%. The legend identifies the weight percent H₂O content of the soil. This figure shows that the escape of low energy neutrons increases as the hydrogen content of the soil increases even though the macroscopic capture cross section increases. Data points are not shown for ease of readability. The average relative error is 1.7%, with an uncertainty in the thermal neutron flux of $1.43 \cdot 10^{-11}$ neutrons/cm²/sec/source-particle.

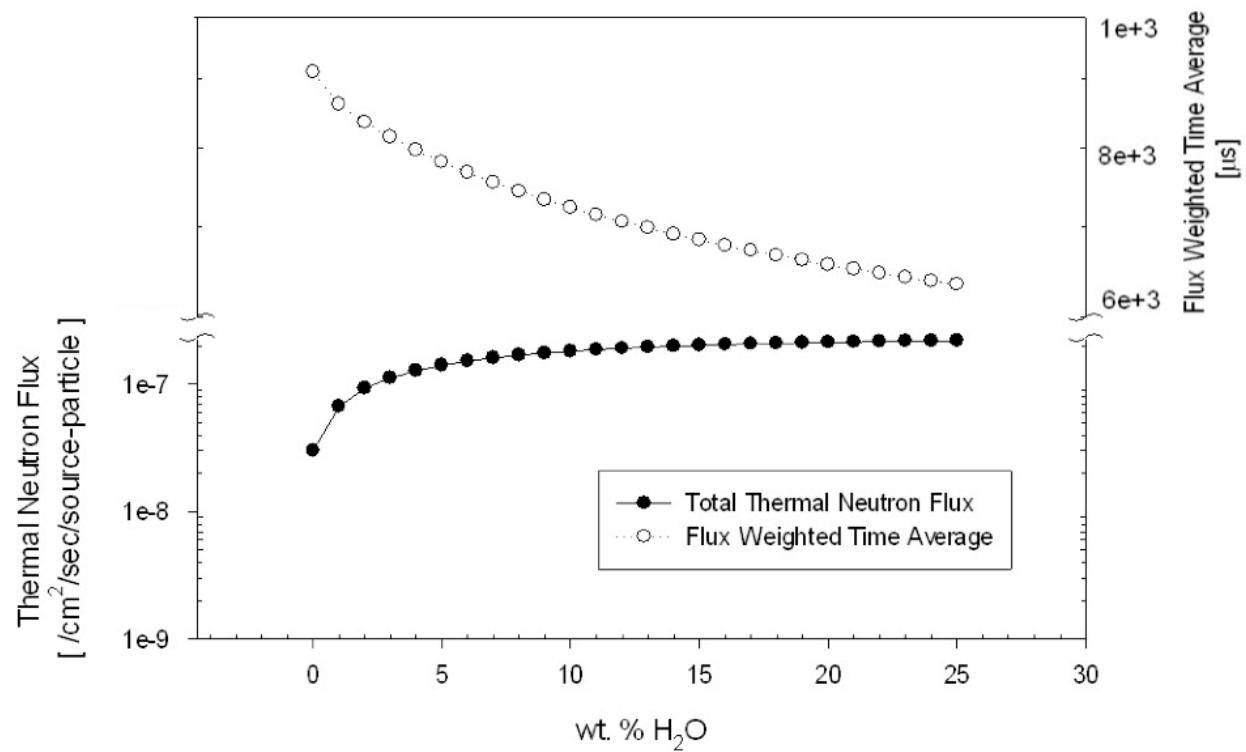


Figure C3B: Total thermal neutron flux and the flux weighted time average (FWTA) vs. H₂O content with no Cl.

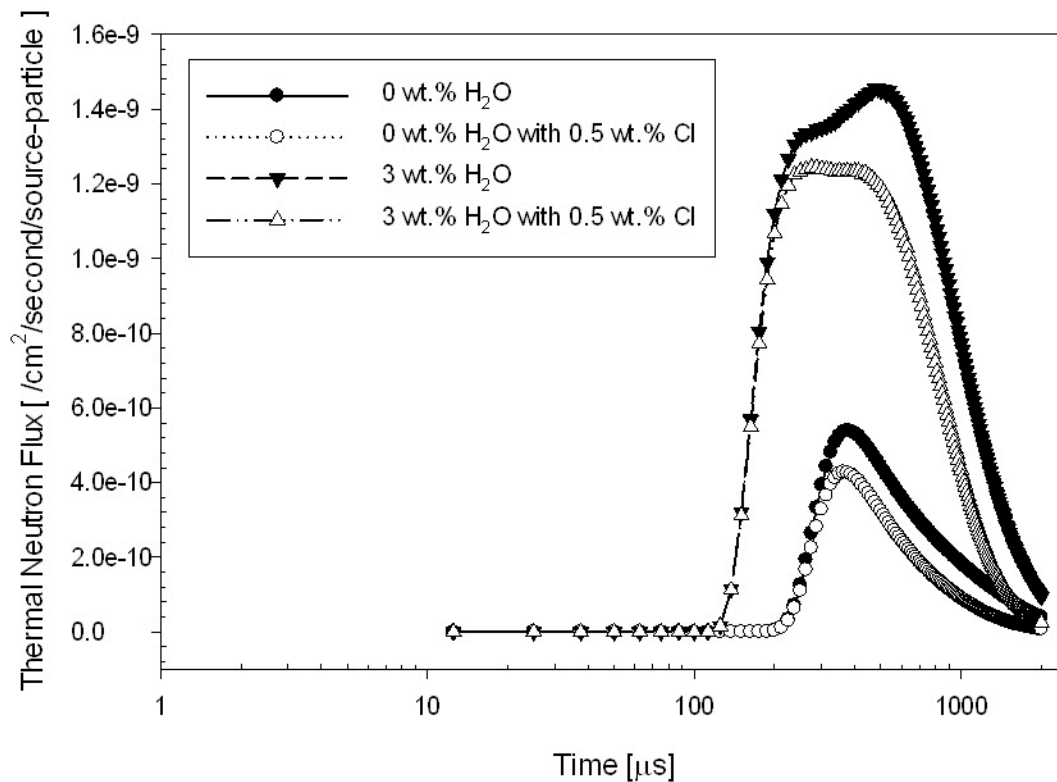


Figure C4A: Arrival times at the detector for neutrons less than 0.4 eV for selected low H₂O and Cl concentrations.

The legend indicates H₂O and Cl concentration in weight percent. This figure shows that the addition of 0.5 weight percent Cl captures ~40 % of the low energy neutrons.

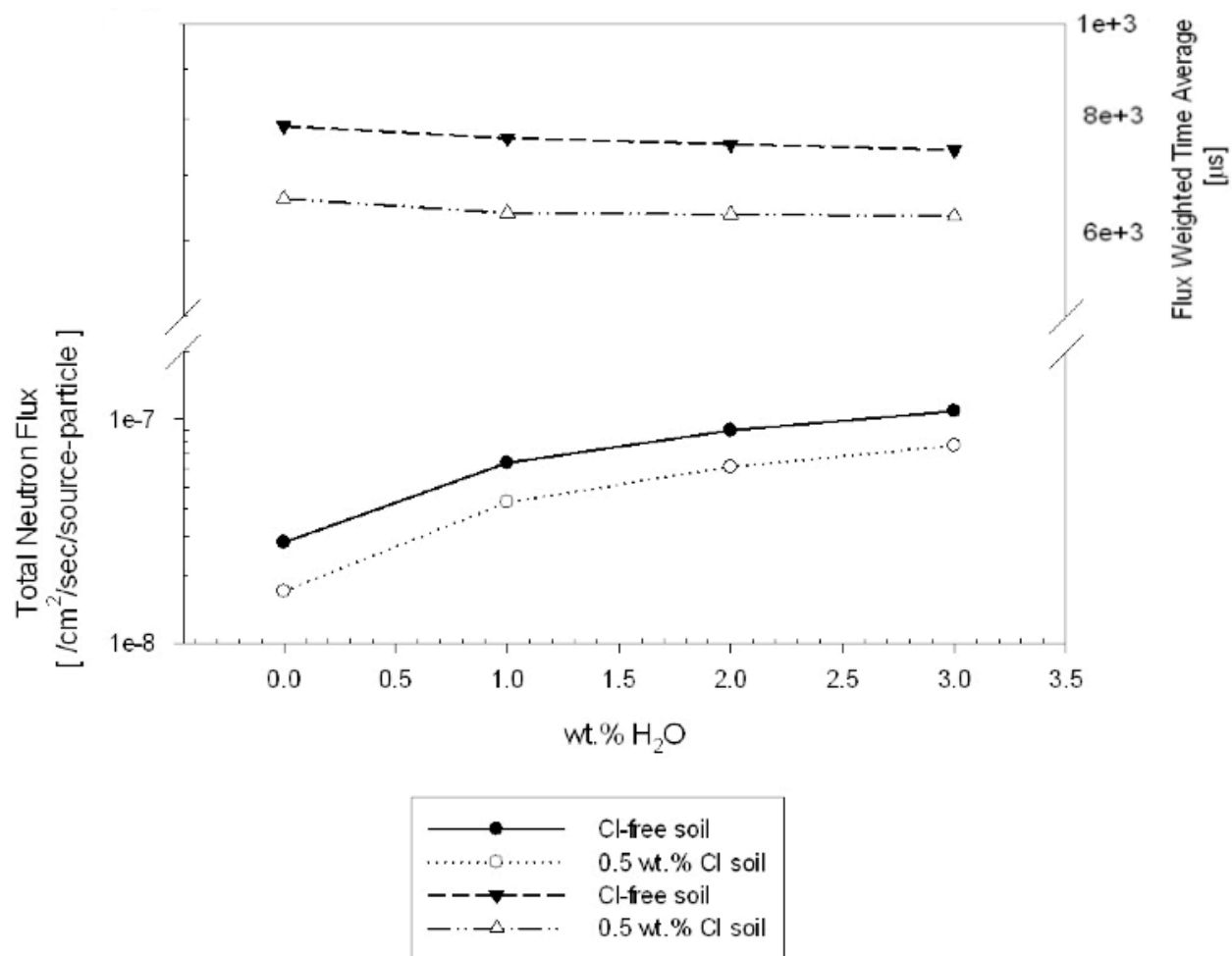


Figure C4B: The average time of arrival (FWTA) for low energy neutrons for 0 and 0.5 weight percent Cl as a function of H₂O concentration. This shows that the Cl captures the slower part of the low energy neutron flux, making for shorter average arrival times. The total thermal neutron flux for 0 and 0.5 wt. % Cl as a function of H₂O concentration is also shown. Cl reduces the relative low energy neutron flux by about the same fraction independent of H₂O concentration.

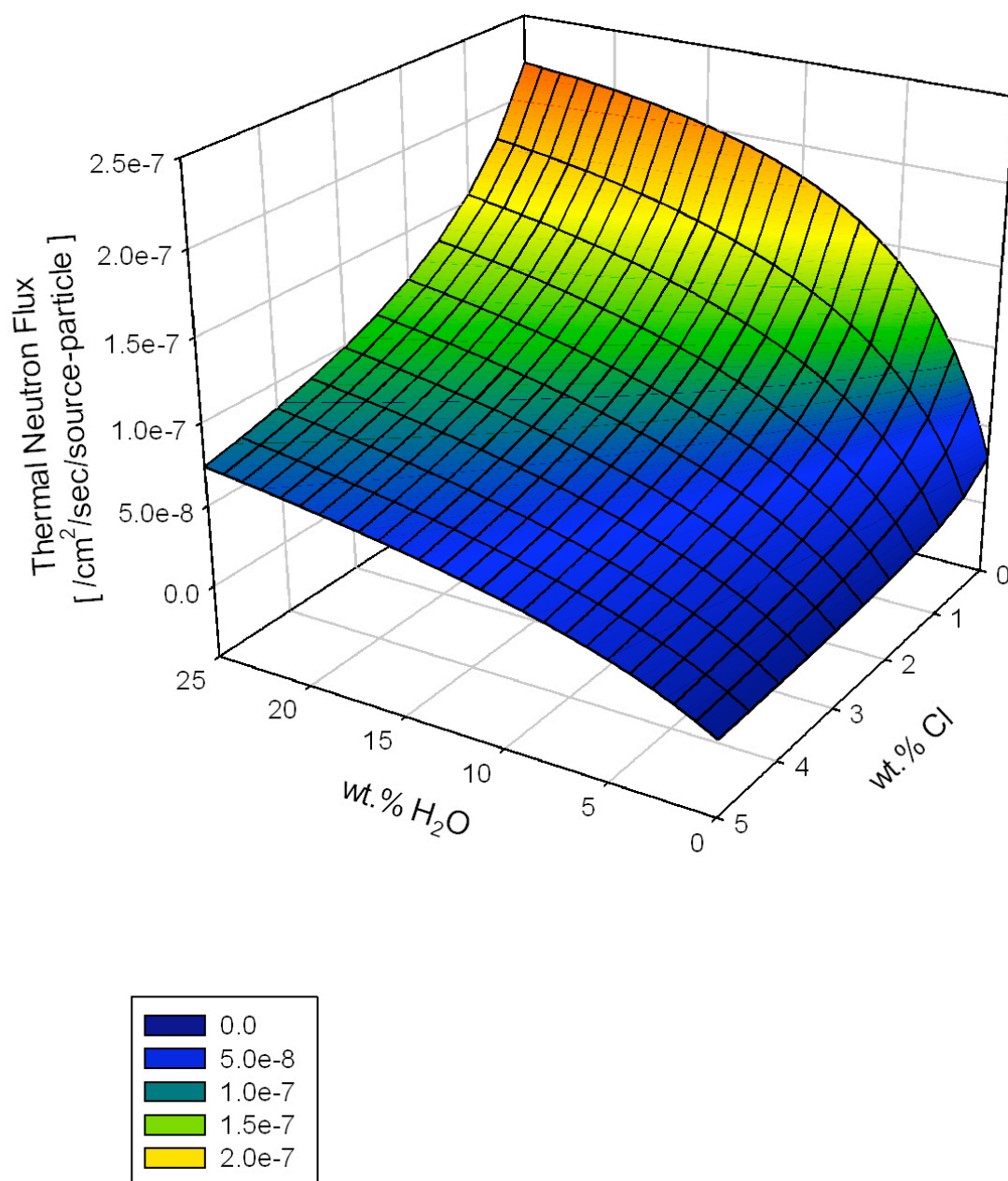


Figure C5A: Surface plot showing the thermal neutron flux as a function of H₂O and Cl concentration. Axes are adjusted so the surface variations are better revealed.

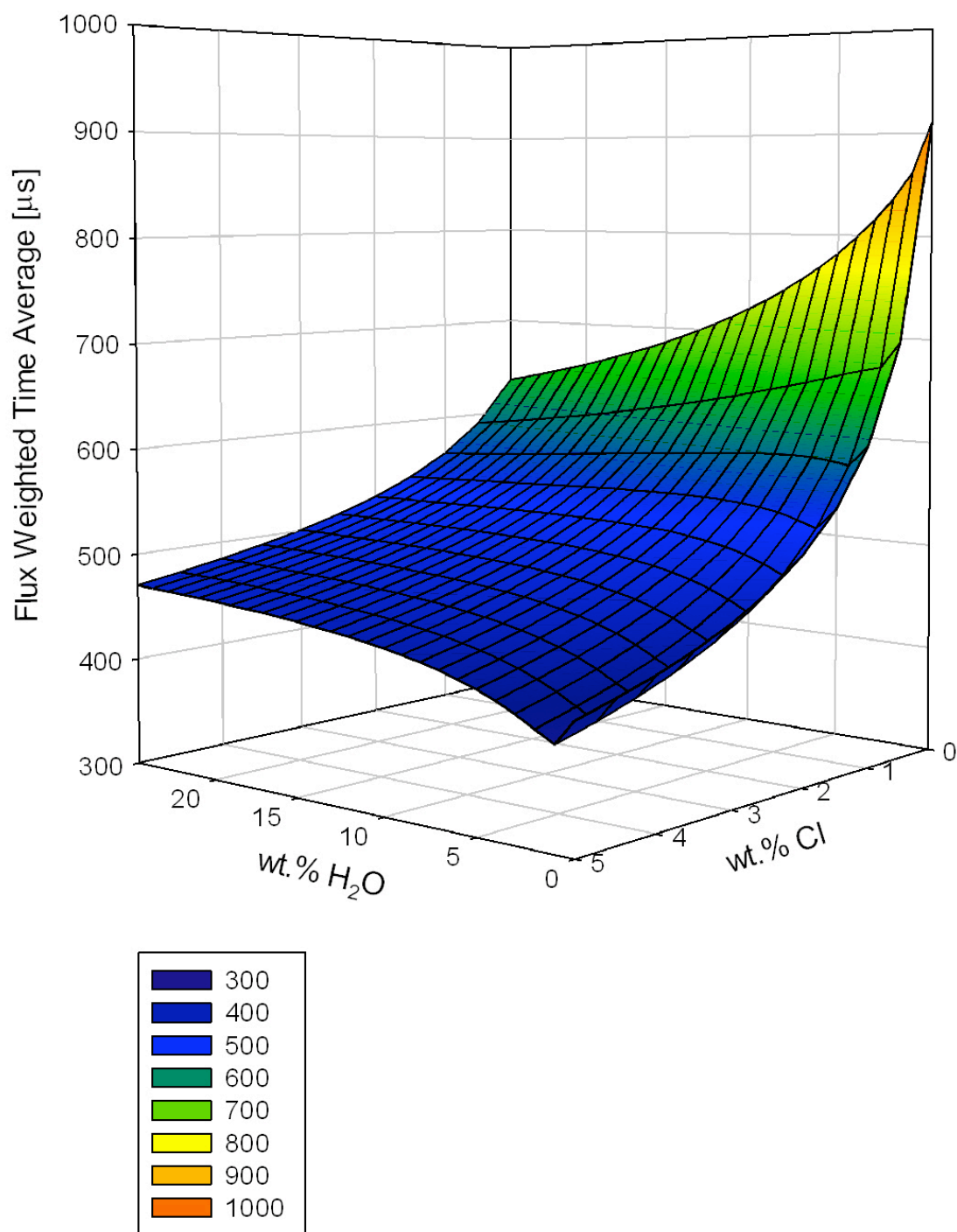


Figure C5B: Surface plot showing the flux weighted time average (FWTA) as a function of H_2O and Cl. Axes are adjusted so surface variations are better revealed.

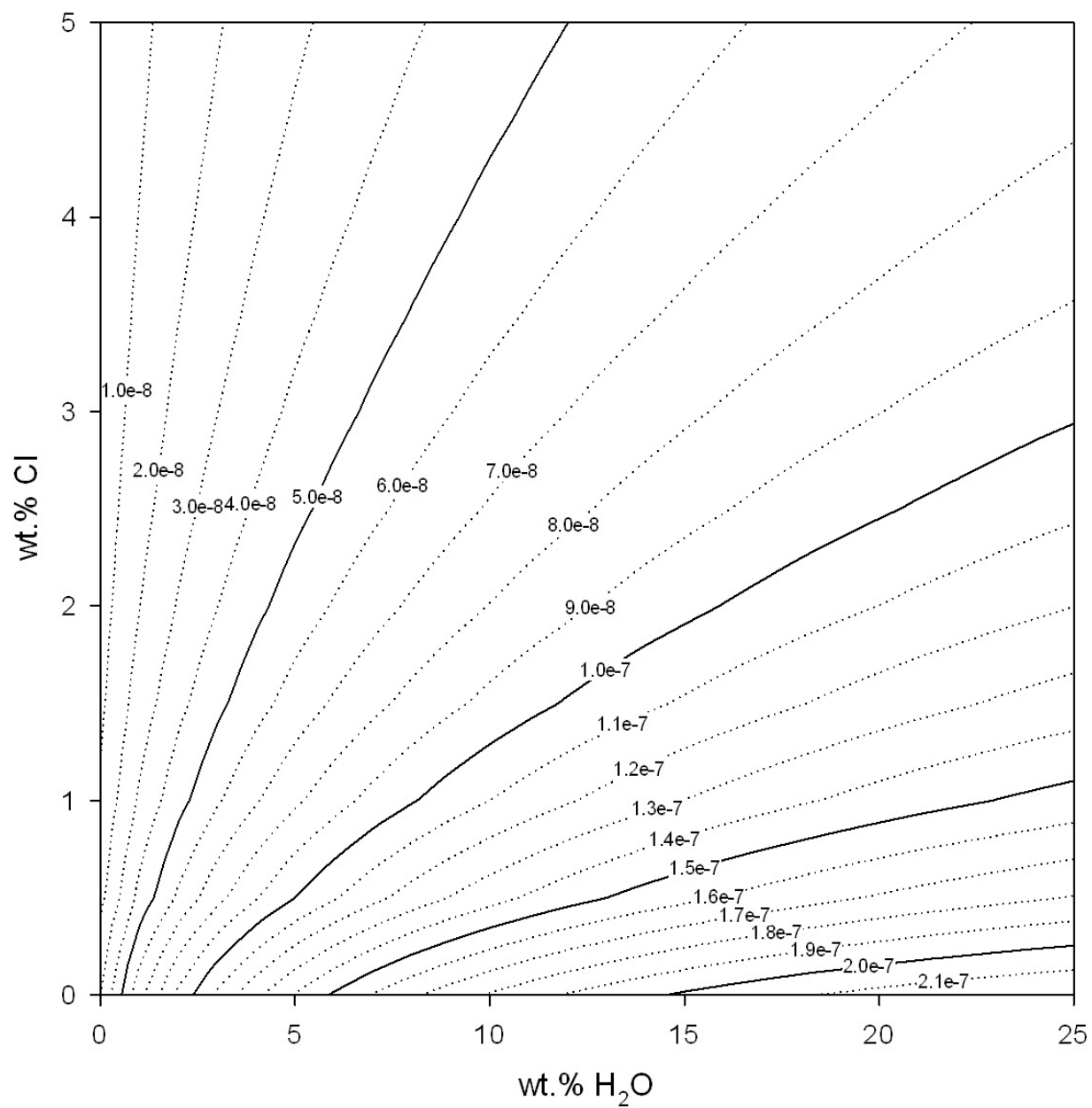


Figure C6A: Contour plot showing the thermal neutron flux as a function of H₂O and Cl concentration. Contours are in units of neutrons/cm²/sec/source-particle.

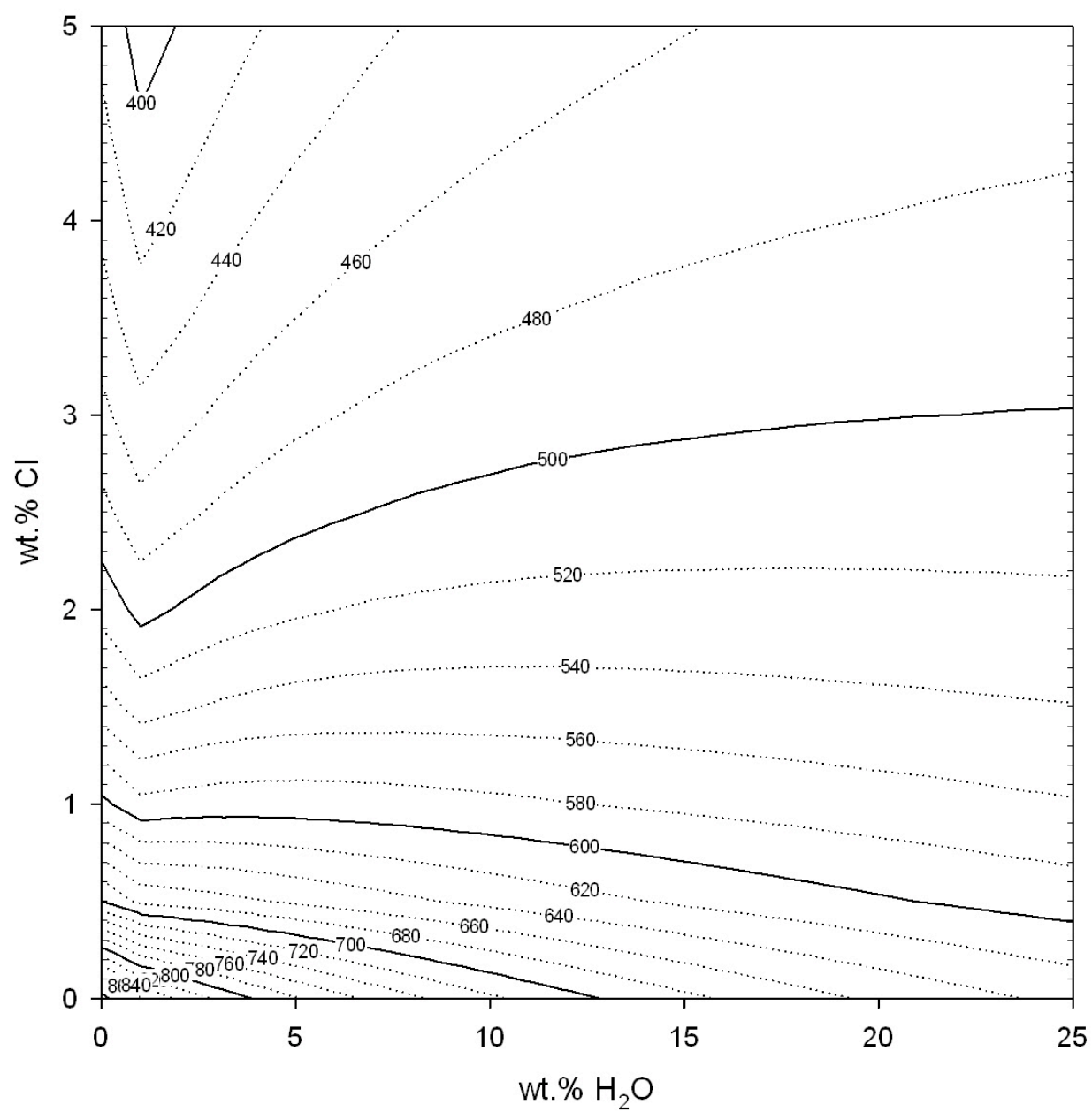


Figure C6B: Contour plot showing the flux weighted time average (FWTA) as a function of H₂O and Cl. Contours are in units of μs.

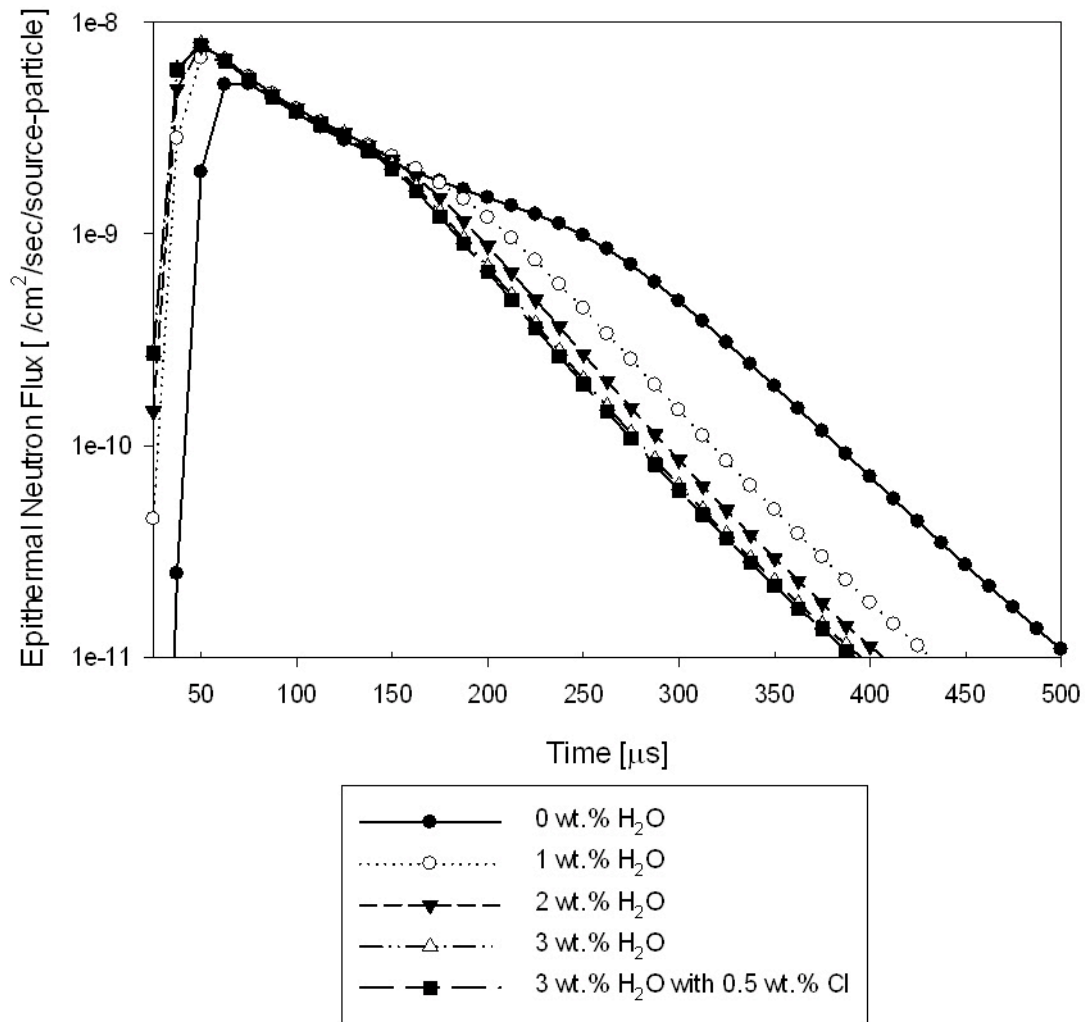


Figure C7: Epithermal arrival times at the detector for select H₂O and Cl concentrations. Epithermal neutrons are strongly moderated by hydrogen but are not absorbed by high absorption cross section elements. Plots of epithermal arrival times for 1, 2, and 3 wt.% H₂O are shown as well as 3 wt.% H₂O with 0.5 wt.% Cl. Epithermal arrival times for 3 wt.% H₂O and 3 wt.% H₂O with 0.5 wt.% Cl are nearly identical.

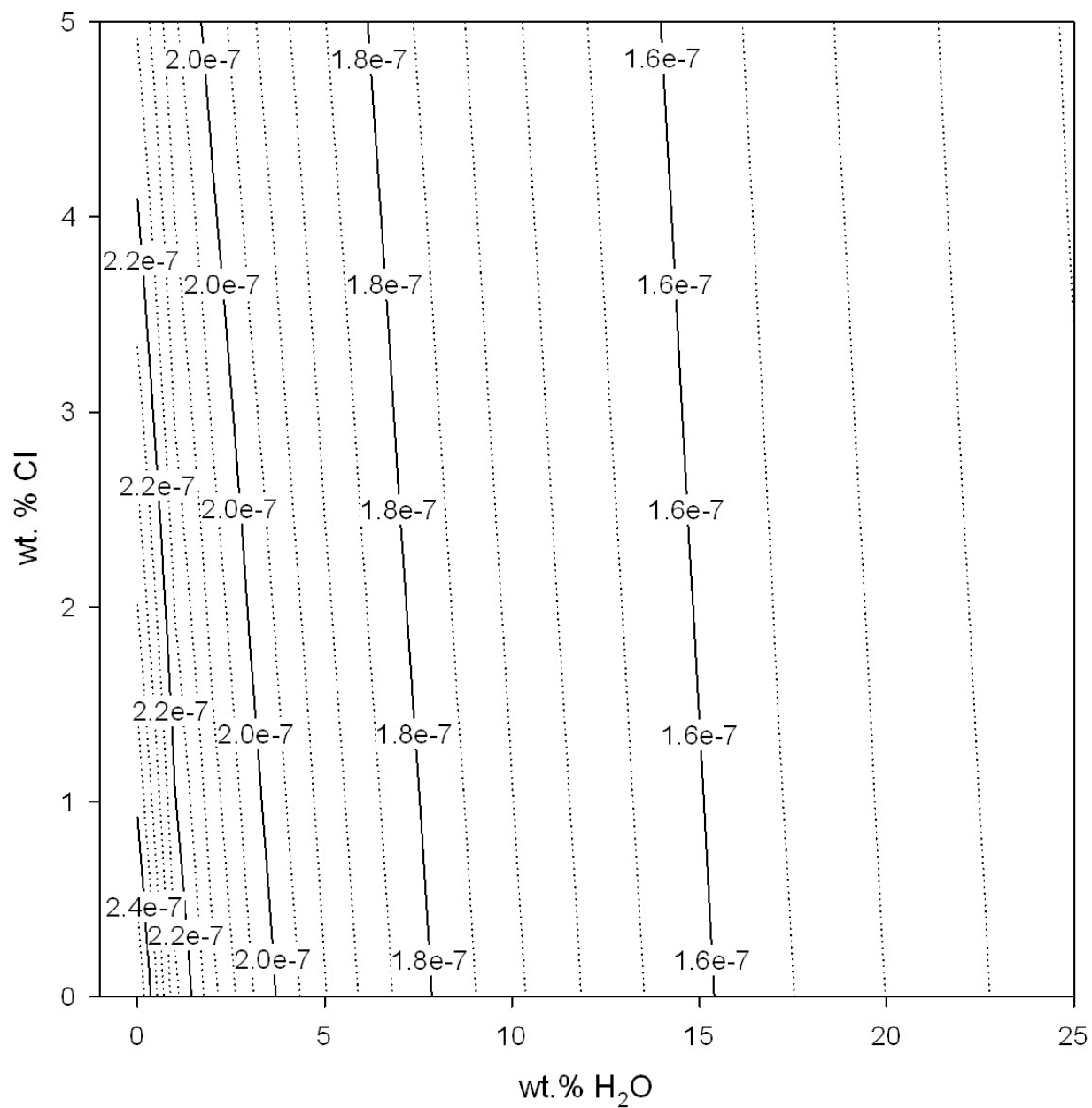


Figure C8: Contour plot of the epithermal neutron flux as a function of H₂O and Cl. This plot shows that there is only a small flux dependence on the Cl concentration. This is clearly due to the decrease of capture cross sections as the inverse of the neutron velocity.

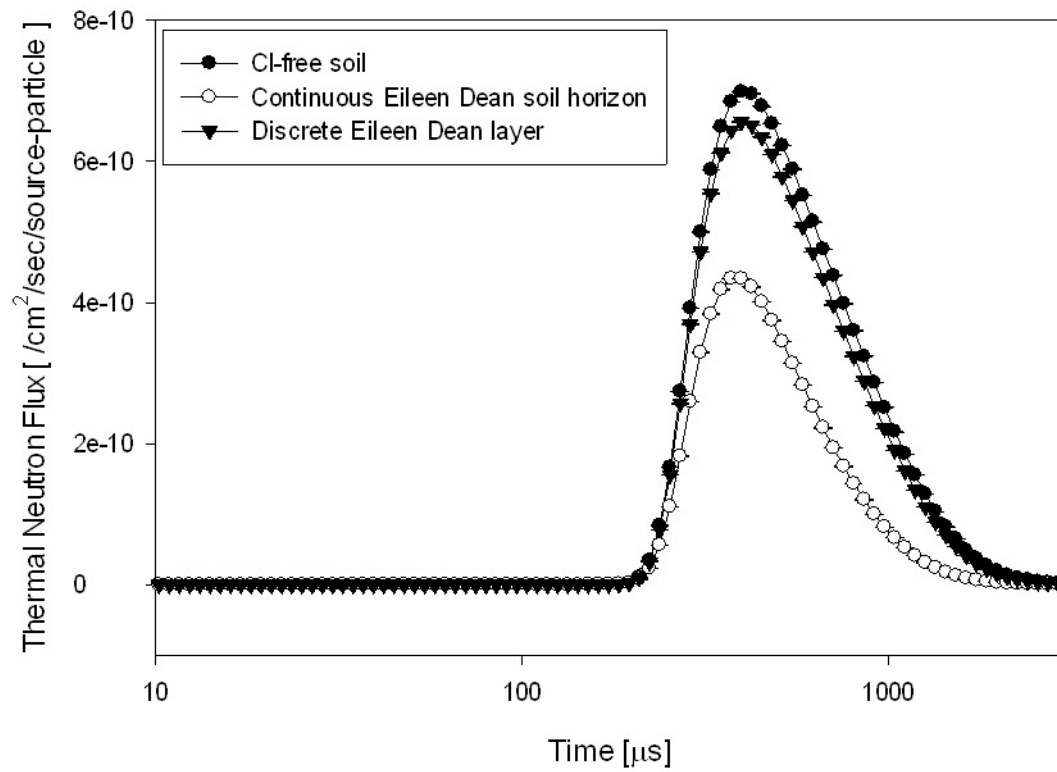


Figure C9: Thermal and epithermal neutron flux for dry soil composition, dry soil composition with a discrete layer (4 cm thick, 4 cm deep) of Eileen Dean composition and dry soil composition with a soil horizon of Eileen Dean composition at 4 cm deep.

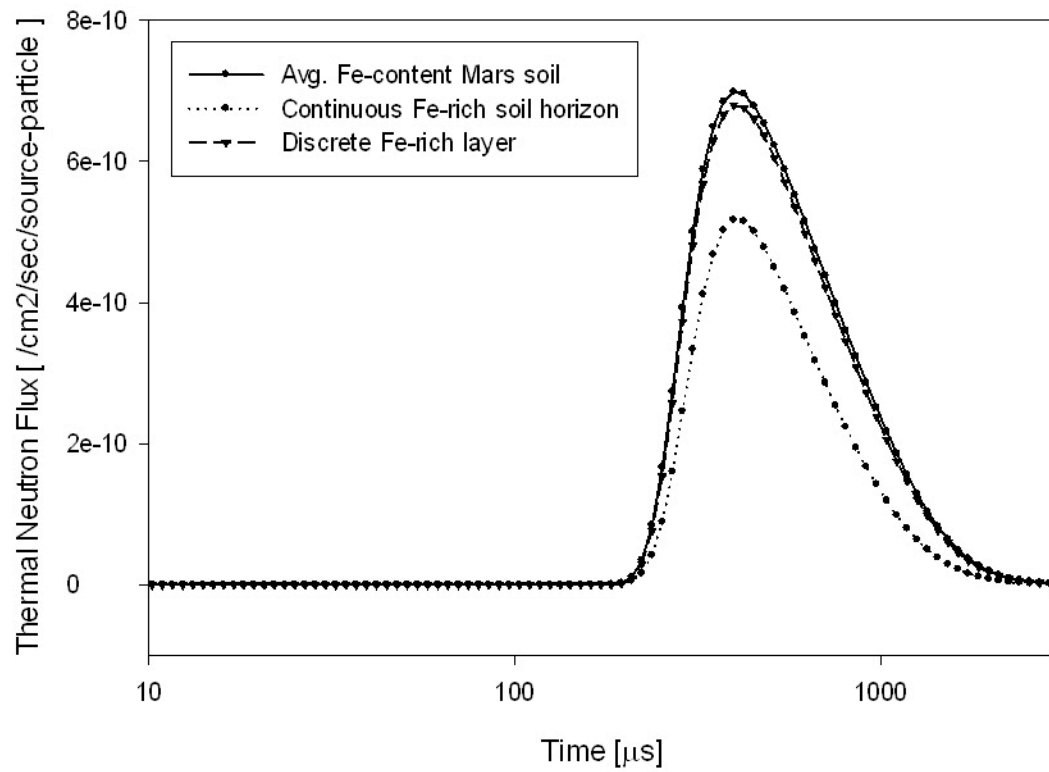


Figure C10: Thermal flux for dry soil composition, dry soil composition with discrete layer (4 cm thick, 4 cm deep) of hematite-rich composition and dry soil composition with a soil horizon of hematite-rich composition at 4 cm deep.

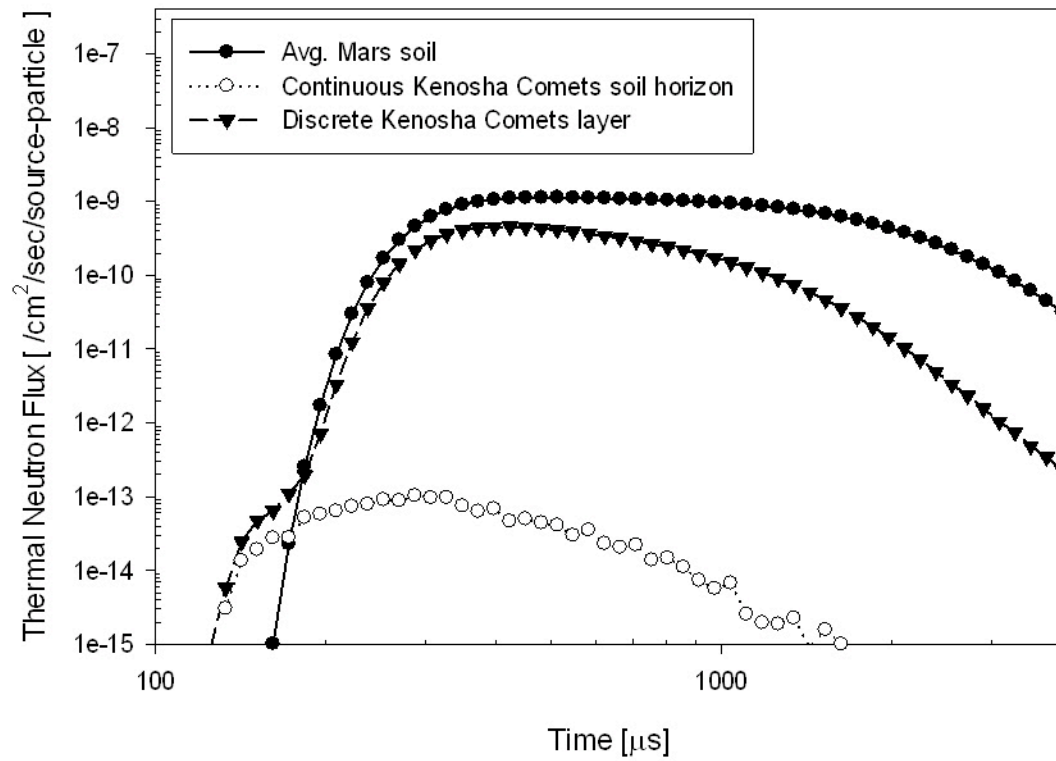


Figure C11: Thermal neutron flux for dry soil composition, dry soil composition with discrete layer (4 cm thick, 4 cm deep) of Kenosha Comets composition, and dry soil composition with a soil horizon of Kenosha Comets composition at 4 cm deep. Data is presented on a log-log plot in order to show all three thermal die-away curves.

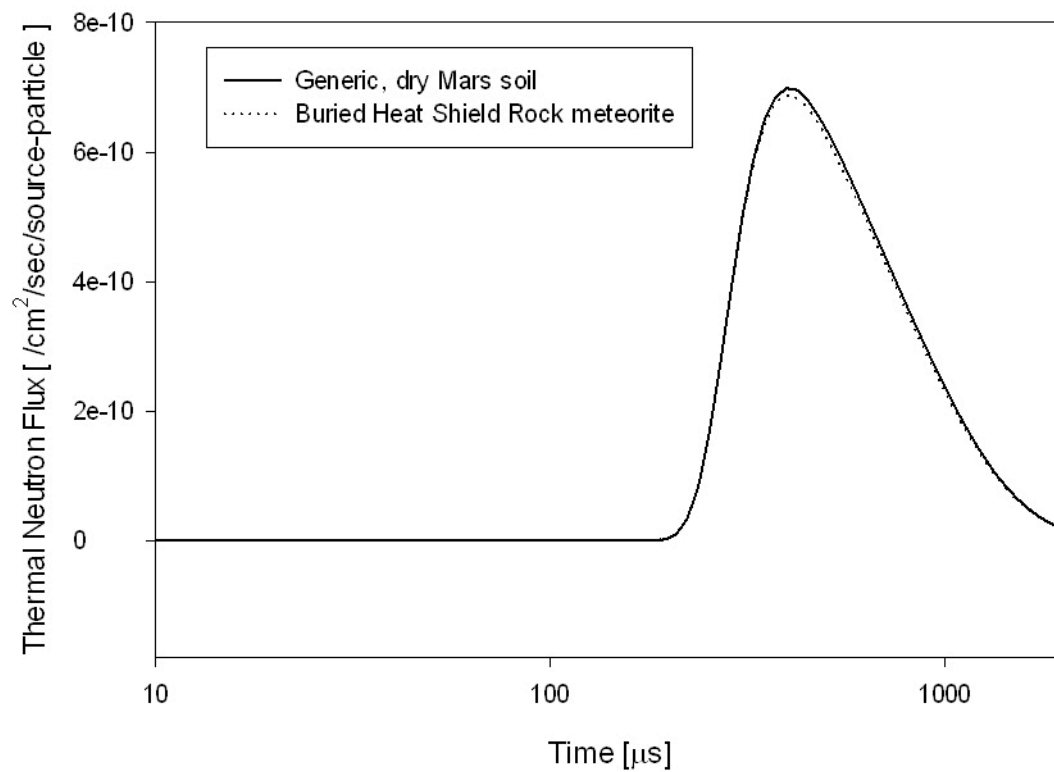


Figure C12: Thermal neutron die-away for generic, dry Mars soil and for a shallowly buried Fe-meteorite of the same composition as Heat Shield Rock (Table 1). Data points are not shown so that both curves can be discerned.

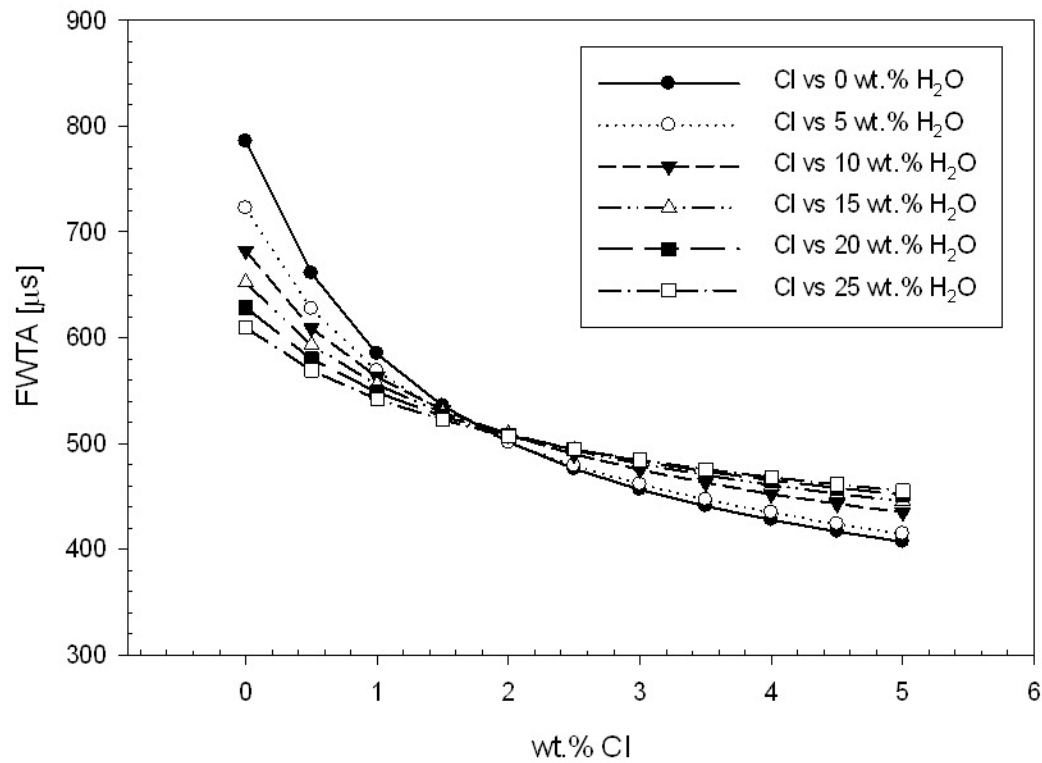


Figure C13: FWTa vs. wt.% Cl for a variety of H₂O concentrations. The inflection point of all these curves are approximately 500 microseconds, indicating that (for the modeled soil composition, detector configuration, etc.) thermal neutron die-away curves with a FWTa below 500 microseconds have a concentration of Cl equal to or greater than ~1.7 wt.%.

Sample MNPX Input File

C CELLS

```

17 7 -.0013 -19 17 -18      IMP:N=1 IMP:P=1 $ 3 he counter
18 7 -.0013 -20 17 -18      IMP:N=1 IMP:P=1 $ second 3 he
19 6 -8.65 20 -21 17 -18    IMP:N=1 IMP:P=1 $ cadmium cover
112 5 -2 -550 560 -610      IMP:N=1 IMP:P=1 $top layer of soil
113 5 -2 -560 570 -610      IMP:N=1 IMP:P=1 $2nd layer of soil
114 5 -2 -570 580 -610      IMP:N=1 IMP:P=1 $3rd layer of soil
115 5 -2 -580 590 -610      IMP:N=1 IMP:P=1 $4th layer of soil
116 5 -2 -590 600 -610      IMP:N=1 IMP:P=1 $5th layer of soil
117 5 -2 -600 -610          IMP:N=1 IMP:P=1 $6th layer of soil
120 0 610                   IMP:N=0 IMP:P=0 $rest of world
121 0 -610 550 #17 #18 #19  IMP:N=1 IMP:P=1 $ mt top

```

C SURFACES

C

```

17 px -5 $ inner end of 3He counter
18 px -1 $ outer end of counter
19 c/x 100 0 2.54 $ cylinder parallel to x at y=106,z=0
20 c/x 106 0 2.54 $ cylinder parallel to x at y=106,z=0
21 c/x 106 0 2.74 $ cadmium sheet
550 PZ -80 $ top layer soil
560 PZ -84 $ 2nd layer soil
570 PZ -88 $ 3rd layer soil
580 PZ -92 $ 4th layer soil
590 PZ -96 $ 5th layer soil
600 PZ -100 $ 6th layer soil
610 SO 17500 $ 17500 cm sphere around target

```

MODE N

SDEF POS 0 0 -0.80 ERG=D1 PAR=1

```

SP1 -4 -14.0 -1 $Gaussian fusion distribution for DT
F5z:n -0 100 10 $ Thermal Flux Neutron Detector
fc5 Die-away measurements (Source is on 0-1 usec), NEUT. FLUX
fq5 t f
fu5 112 113 114 115 116
ft5 icd TMC 0 1e2 $ Source is on 0-1 usec
t5 0 159i 2e5
M1 016032 -.219
009019 -.781
M2 013027 -1.000
M4 029063 -0.692
029065 -0.308
M5 1001 -1.111E-03
8016 -4.429E-01
13027 -1.560E-02
26000 -1.294E-01
12000 -1.786E-01
14000 -2.036E-01
20000 -1.717E-02
11023 -2.256E-03
22000 -2.943E-04
17000 -9.000E-03

```

```
35000 -0.0145
25000 -0.30605
m6 48000.50c 1
m7 2003.50c 1
M998 6000.60c .2609 8016.60c .6959 7014.60C .0271C
nps 2e9
prdmp 3j 1
PRINT 40
```


Part 5

Conclusions

In Part 2, I have shown that remote thermal images offer a new way to perform initial reconnaissance of many sedimentary features on alluvial fans. High spatial resolution thermal images may be especially useful on Mars, where ground truth is not available, and where evidence for surface water and overland flow would be a significant result. For regions on Earth with very little near-surface moisture content, where the primary controls on surface temperature are particle size and degree of surface induration, thermal images can be used to provide a quick reconnaissance of alluvial fans, suggest what processes have most recently acted on the surface of a fan, and to prioritize sites for detailed study on the ground. Thermal images, when combined with ground measurements and visible images, are a useful tool for any geologist studying alluvial fans in an arid climate.

In Part 3, I have expanded the database of alluvial fans and the inventory of sedimentological features that can be identified with thermal images. Understanding the thermophysical signature of terrestrial sedimentary features is an important part of determining the characteristics and origins of similar sedimentary deposits on Mars. Providing an accurate classification of various sedimentary features through the use of themophysical methods will allow orbital observations of Mars in the thermal-infrared to tell us about not only the composition, but the potential origin of the sedimentary feature based upon terrestrial thermophysical signatures.

In Part 4, I have characterized neutron die-away curves for geologically plausible ranges of hydrogen abundances and high absorption cross section elements that may be encountered during a rover traverse across the Martian surface. In addition, this study will contribute to our understanding of rover-based neutron die-away from pulsed neutron sources and provide a useful means to identify areas of interest for further scientific exploration with other instruments in the rover payload.

Vita

Craig James Hardgrove was born on August 29th, 1981 in Point Pleasant, NJ. He moved to Atlanta in 1989, when he was 9 years old, where he completed his grade school education. In August of 1999 he began his freshman year at Georgia Tech, as an Aerospace Engineering major. After taking countless courses and working an internship at Boeing in Houston, TX, he discovered that his interests were primarily in the natural sciences and changed his major to Physics in late 2002. In May of 2004, he completed his Bachelor of Science degree in Physics from Georgia Tech and in August of 2004 entered the PhD program in the Earth and Planetary Sciences Department at the University of Tennessee. He will complete his PhD in Geology from the University of Tennessee in November of 2010 and upon graduation will begin work as a postdoctoral researcher at Stony Brook University in New York.