Testing the hypothesis of impact-triggered precipitation at Mojave Crater, Mars

For submission to ROSES-2014 Solar System Workings (NNH14ZDA001N-SSW)

2. Scientific/Technical/Management:

2.1 Summary.

The < 5 Mya Mojave impact crater on Mars contains unusually well-preserved and uncommonly well-developed alluvial fans whose morphology indicates overland flow of liquid water (runoff). Mars is a cold planet, so evidence for recent liquid water runoff on Mars' surface is surprising. Evidence points to the Mojave impact triggering the anomalously wet conditions recorded by the alluvial fans at Mojave. Our goal is to test the hypothesis of impact-triggered precipitation by simulating the atmospheric response to the Mojave impact (Fig 1). We will constrain the duration and extent of the impact-triggered environmental perturbation (microclimate) by using the Mars Regional Atmospheric Modeling System (MRAMS) to model impact-triggered clouds, snow and possible rainfall using geologically-constrained and Mojave-specific boundary conditions. To do this, we will improve the MRAMS by adding self-consistent treatment of water-dominated atmospheres to the dynamical core, together with liquid water aerosol microphysics and liquid-water radiative transfer. We hypothesize that MRAMS-predicted runoff will be geomorphically effective and sufficient to form the observed alluvial fans. Comparison of MRAMS output with the volume of sediment transport recorded by the alluvial fans at Mojave will allow us to test the hypothesis of impact-triggered precipitation. The proposed investigation will enhance our understanding of the local-to-regional effects of large impacts on Mars' environment in the geologically recent past, which has implications for the study of surface-atmosphere interactions and the hydrologic cycle earlier in Mars history.

2.2. Goals and Significance of the proposed study.

To achieve our overarching goal, we will address three primary objectives over this 3-year study, which is a continuation of our published preliminary work on localized precipitation on Mars (Kite et al. 2011a, b, §2.3.2). First, we will carry out numerical experiments on impact-induced precipitation with idealized boundary conditions, in order to define a scaling law for impact-induced precipitation as a function of crater diameter. Second, we will model precipitation triggered by the Mojave impact usings Mojave-specific boundary conditions. Finally, we will estimate erosion rates using simple erosion models, and carry out a data-model comparison at Mojave. Questions to be addressed by the proposed work include: What was the water source for the alluvial fans? What was the lifetime of the warm-wet Mojave environment? Did rain fall on Mars in the geologically recent past?

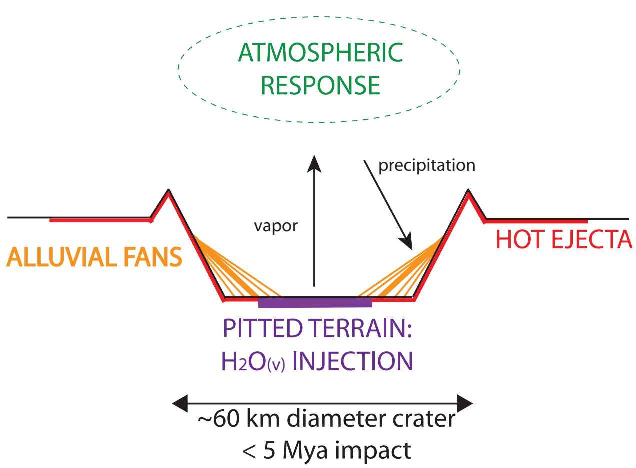
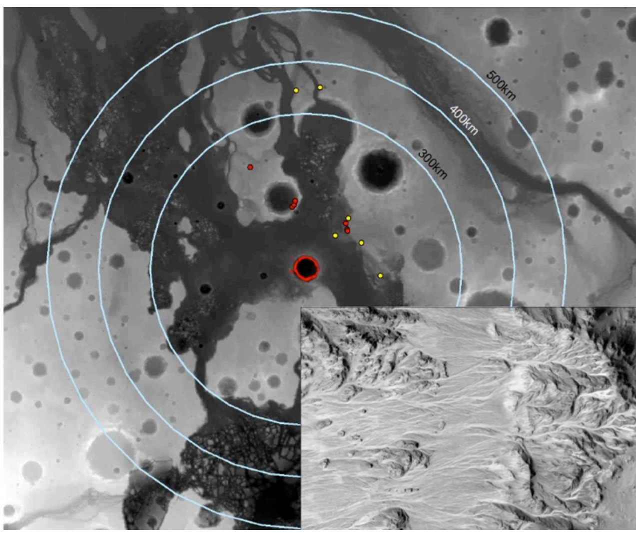


Fig. 1. Sketch showing the hypothesis of impact-induced precipitation. This will be tested in the proposed study by modeling the impact-triggered microclimate (atmospheric response).

2.3. Scientific Background & Summary of Preliminary Work.

< 5 Myr ago, a bolide struck the outflow channel Tiu Vallis, forming a ~60 km-diameter crater, Mojave (7.5°N 327°E) (McEwen et al. 2007, Werner et al., 2014). Subsequent to the $O(10^{22})$ J impact, volatile release formed pits on the crater floor, impact-generated slurries flowed viscously down the crater rim, and channelized alluvial fans formed within the crater and (patchily) up to 250km beyond the rim (Fig. 2) (McEwen et al., 2007; Zahnle & Colaprete, 2004; Williams & Malin, 2008; Goddard et al., 2014). The channels in Mojave run to within 10s of m of ridges (Fig. 2), suggesting precipitation-fed runoff (rain or snowmelt). The Mojave fans form the best-developed young impact-crater-hosted alluvial-fan bajadas on Mars, and the only similarly well-developed and finely-branched alluvial fans on Mars are all found within fresh impact craters containing pitted terrain – similar to Mojave (Tornabene et al. 2012, Boyce et al. 2012, Goddard et al., 2014). Crosscutting relationships with impact-generated slurries show that these impact-triggered slurries were still in motion as the fans began to form (Williams & Malin,



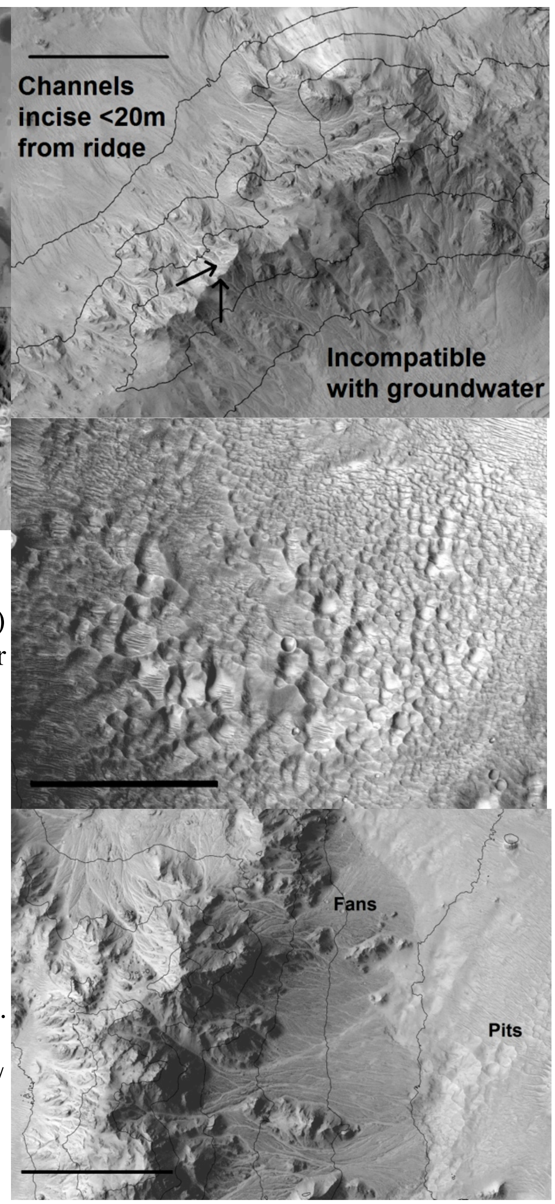


Fig. 2. Evidence for water at Mojave crater. *Top left:* Mojave (7.5°N, 327°E) in regional context, showing rapid falloff of young fluvial activity (red) with distance (pale blue rings) from the inner crater wall (red ring). Probable young fluvial activity shown by red dots, possible by yellow dots. >90% of fan area lies <1.2 crater radii from the center of Mojave crater. Background is MOLA topography (5km elevation range). Inset: 500m-wide subframe of HiRISE image PSP_001415_1875 shows detail of alluvial fans. *Top right:* Channels incising both sides of a ridge just NW of Mojave rim. Scale bars correspond to 500m. Channels on both sides of ridge incise within 20m of the ridge (black arrows). HiRISE orthorectified image with 50m contour intervals, using HiRISE DTM (PSP_001481_1875/ PSP_002167_1880). Fig. 1c. *Right center:* Detail of pitted terrain, from the same image. *Right bottom:* Detail of bajada, from the same image.

2008). Because of this close connection in space and time a with young impact event, and because Mojave's fans are <10° from the equator, they are unlikely to result from CO_2-frost-driven processes (e.g. Dundas et al. 2014), leaving water as the most likely erosive fluid (additional evidence supporting this inference is set out in §2.3.1). Because the fans are strongly concentrated within the crater, it is very difficult to account for runoff at this site except by appealing to the impact transient as water source, heat source, or both (Williams & Malin 2008, Goddard et al. 2014). Therefore, the alluvial fans are prima facie evidence for local-to-regional environmental change caused by the impact event – changes that can most appropriately be simulated by a mesoscale model such as MRAMS (§2.3.2). Given the potential importance of impact-triggered runoff and precipitation through Mars history (§2.3.3), it is surprising how basic are the open questions about the mechanisms linking impact to environmental change at Mojave: in particular, the fan-forming mechanism is unknown. We propose a focused investigation of this question by testing the hypothesis that the fan-forming mechanism was impact-triggered, localized precipitation.

2.3.1. Water runoff probably occurred <5 Mya at Mojave Crater on Mars.

The case for water runoff at Mojave crater (Fig. 2) consists of (i) the morphology of the alluvial fans; (ii) the distribution of the alluvial fans; (iii) evidence for rapid water release from pitted terrain within Mojave; and (iv) the context of Mojave and its fans relative to similar fans associated with young craters on Mars.

(i) *Fan morphology*. What makes Mojave distinct is the large number ($>10^2$) and excellent preservation state of the alluvial fans that motivate our study. Formation of the alluvial fans requires a low-viscosity fluid, most likely water (Williams & Malin, 2008). Water is favored at Mojave because of the fine branching and channelization of the fans, slope-area relationships consistent with debris-flow and alluvial processes, boulders that fine with distance from the fan apex (consistent with fluvial transport), the low viscosity of fan-forming flows (which is indicated by the shallow terminal slopes of the fans), the merging of fans to form a continuous bajada, and the branched dissection of fan headwaters by networks of fan-sourcing ravines (Williams et al., 2006; Williams & Malin, 2008; Conway et al., 2012; Goddard et al., 2014). Collectively, these attributes establish close similarity between alluvial fans at Mojave crater and alluvial fans on Earth (Williams et al. 2006, Conway et al. 2012), and these attributes also distinguish Mojave's low-latitude fans from the CO_2-formed (Dundas et al. 2014) mid-latitude gullies.

The geomorphology of Mojave is complex and includes numerous types of viscous flow suggestive of impact melts and slurries, also seen at other Martian craters and on the Moon (Mouginis-Mark & Boyce, 2012). These boulder-poor viscous flows are easily distinguished from the boulder-rich alluvial fans both in HiRISE images (Williams & Malin, 2008; Goddard et al., 2014) and in THEMIS TI mosaics, and we exclude them from this study.

(ii) *Fan distribution*. The fans are largely contained within Mojave crater, with only a few others within 500 km (and all of those are associated with Mojave secondaries) (Goddard et al. 2014) (Fig. 2). This is consistent with the hypothesis that energy from the Mojave impact drove fan formation, directly or indirectly. Although channels are not found dissecting the central peak and ponded materials, this can be reconciled with the hypothesis of impact-induced precipitation because ground temperatures >7°C at the central peak would lead to internal boiling of surface water, preventing runoff (Boyce et al. 2012).

(iii) *Evidence for volatile release from pitted terrain.* Pitted materials within Mojave released volatiles to the atmosphere (Boyce et al., 2012; Tornabene et al., 2012). The pits resemble phreatogmagmatic explosion scars formed by steam escaping at speeds as high as 300 m/s (Boyce et al. 2012); pit morphology is inconsistent with sublimation pits (Tornabene et al. 2012). Pitted materials drain to form viscous, lobate fans, confirming that pitted materials contain volatiles. Crater-related pitted terrain is only found within otherwise-smooth flow features associated with the ejecta of young impacts on Mars; similar features are absent from lunar impact melt sheets (Bray et al., 2010; Wagner & Robinson 2014). The ultimate source of pitted-terrain volatiles could be relict outflow-channel ice or hydrated minerals in the target (Warner et al. 2010), ground ice emplaced at modestly higher obliquity (Mellon & Jakosky 1995), or volatiles in the impactor (Zahnle & Colaprete, 2004). CO_2 is not a plausible alternative pit-forming volatile in part because CO_2 is not stable at Mojave's latitude. Previous studies of crater-related pitted terrain in Tooting (similar to those at Mojave; Tornabene et al. 2012) concluded that ~1 km^3 liquid-water equivalent was injected into the atmosphere in "hours to a few tens of days" (Boyce et al. 2012, Mouginis-Mark & Boyce 2012). The total water column estimated from pit depths and analogy to suevite vent pipes at the terrestrial crater Ries (Boyce et al. 2012, Newsom et al. 1986) is consistent with forming Mojave's alluvial fans by one-pass precipitation of pit-sourced vapor (3-60m total precipitation; Williams & Malin 2008). These large water fluxes raise the possibility that water in the near-Mojave atmosphere was a major and perhaps dominant component of the atmosphere; self-consistently simulating such an atmosphere will require modification of the MRAMS (§2.4.1). The presence of alluvial fans at Mojave (diameter ~ 60 km) and their absence at Tooting (diameter = 27 km) suggests a threshold crater size for fan formation. We will test this hypothesis in §2.4.2.

(iv) *Overall context.* Mojave is the best-preserved member of a class of young craters containing alluvial fans (Goddard et al., 2014). Evaporative cooling in $O(10^1)$ mbar atmospheres expected $\lesssim 10^8$ ya suppresses large-scale ice/snow melting driven by insolation alone (Hecht 2002). Therefore climatic melting is unlikely, and microclimates or low-volume eutectic brines are probably required for runoff (Chevrier and Rivera-Valentin 2012, Dundas et al. 2014). This suggests that formation of alluvial fans within (and thus postdating) these young craters (Werner et al. 2014) required a disequilibrium/non-climatic source of energy, such as the impact event.

Having reviewed the evidence for water runoff at Mojave, we now consider specific hypothetical mechanisms linking the impact process to runoff. In simulation, Mojave-sized impacts create groundwater activity by melting ground ice, driving hydrothermal circulation, which allows for low-discharge groundwater springs (e.g. Abramov & Kring 2005, Barnhart et al. 2010). However, groundwater is an unlikely water source for the alluvial fans at Mojave. This is because the alluvial-fan-sourcing channels head at ridgelines (Fig. 2). Groundwater discharge would be expected at low elevations and not at ridgelines (Freeze & Cherry, 1979). The absence of alluvial fans at Mojave's central peak further disfavors groundwater springs as a water source for the alluvial fans. That is because (in the current cold climate) impact-induced hydrothermal discharge is focused at and most persistent at the central peak (Barnhart et al. 2010, Schwenzer et al. 2012). Shock blast or immediately post-impact melting of ground ice is also probably insufficient to account for the Mojave alluvial fans. Ejecta melting of preexisting ground ice or snowpack (Walder 2000a,b) would form slurries, not densely branching channel networks.

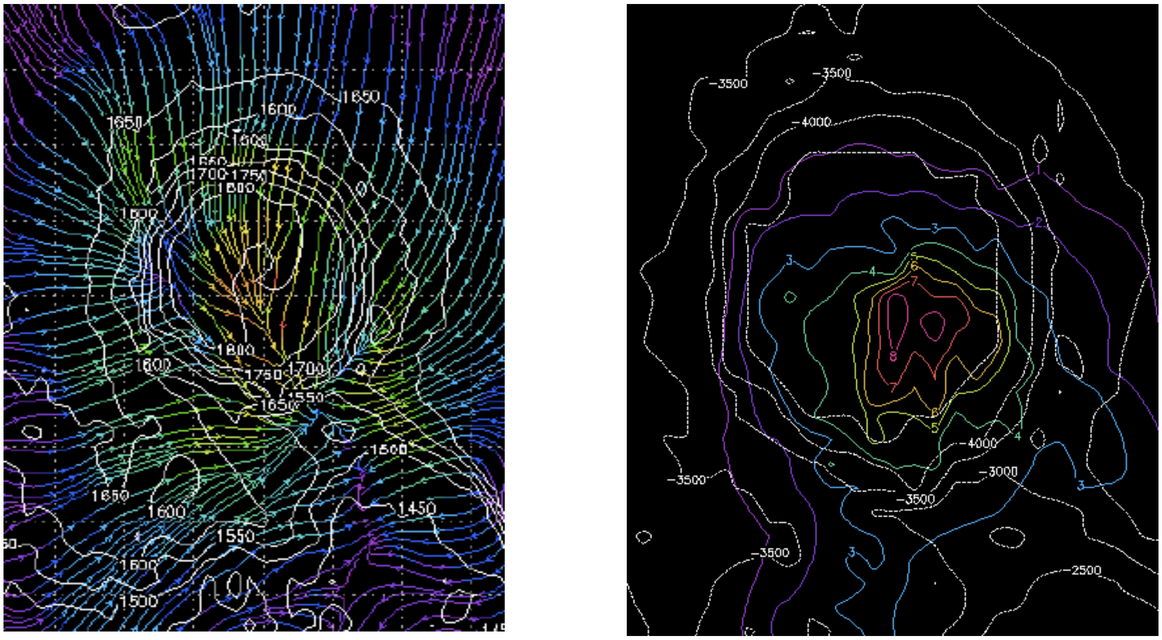


Fig. 3. Map views of innermost domain of MRAMS impact-induced precipitation simulation output (Kite et al. 2012) with cool-lake vapor injection boundary condition: *Left:* Near-surface atmospheric convergence driven by vapor release from crater (color scale shows wind speed, peaking at 30 m/s in crater center); labels and white contours show pressure in Pa for this "6+6 mbar" simulation (Phillips et al. 2011). Storm clouds (not shown) reach 20 km altitude. 100 km x 100 km view. Mojave is ~60 km in diameter. *Right:* Zoom showing peak precipitation rate (colors, mm/hr water equivalent, peak 8 mm/hr) from sols 3-5. All precipitation in this simulation falls as snow, and melts on contact with the ground, so the precipitation rate is a melt rate. Heat flow from ejecta (not shown) is self-consistently tracked. White contours correspond to elevation (m).

Rainout from the ejecta plume is possible, but as modeling of vapor condensation on ballistic timescales (Johnson & Melosh 2012) is computationally intensive and poorly understood, it is beyond the scope of this proposal. Liquefaction triggered by seismic shaking from Mojave, and impact overpressure/fracturing of a cryosphere allowing groundwater release (e.g., Wang et al. 2005) are both physically plausible water sources, but they are both inconsistent with channels heading at ridgelines (Fig. 2). The remaining, more likely hypotheses (Tornabene et al. 2007) for Mojave's alluvial fans include (a) hot-ejecta melting of frozen precipitation, (b) impact-induced rainfall, and (c) ejecta dewatering. We propose to test hypothesis (a) and hypothesis (b). If both hypotheses fail our test, then by elimination that would favor hypothesis (c).

2.3.2. There is a well-established physical basis for localized precipitation on Mars.

Because of the low volumetric heat capacity of the low-density Mars atmosphere, deep convection can be triggered by the condensation of small amounts of water vapor (Kite et al. 2011a). Convection initiation is also made more likely by Mars' low atmospheric temperatures. Once established, the buoyant plume lifts more vapor above condensation level, and so deep convection favors localized precipitation (Emanuel 1994). In our previous work on localized precipitation on Mars (Kite et al. 2011a,b), we found that the presence or absence of localized precipitation is controlled by the spatial extent of the perturbation, the vapor flux, and the atmospheric pressure; it is almost independent of latitude, season, and solar luminosity. Once established, deep convection will persist as long as the vapor source injects sufficient vapor into the atmosphere (Kite et al. 2011a,b). In summary, localized precipitation is much easier to trigger on Mars than on Earth.

Impacts are over in minutes, but their effect on regional weather and climate can endure for weeks or months (conceivably much longer; Segura et al. 2012). Previous work by others (e.g. Colaprete et al. 2003, Plesko et al. 2009, Segura & Colaprete 2009, Segura et al. 2013) adapts GCMs or 1D models. Our selection of MRAMS is justified for this problem because it is nonhydrostatic (appropriate for the Mach 0.2 vertical velocities obtained in preliminary output and detailed in Kite et al. 2011a) and tailored for the higher spatial resolution necessary to model local-to-regional environmental changes recorded at Mojave. Preliminary results for Mojave crater are shown in Fig. 3 (Kite et al. 2012). Initial conditions – layered-target impact hydrocode output – were supplied by Collaborator Sarah Stewart. Atmospheric boundary conditions are obtained from the Ames MGCM (Haberle et al. 1993). The surface vapor injection boundary condition is varied: the simplest, a lake, is used in Fig. 3. The precipitation output is used to compute melting and erosion. In the runs shown in Fig. 3, impact-induced precipitation occurs as snow, and melts when it lands on the ejecta. Erosion allows heat to be mined from deeper within the ejecta blanket – a positive feedback between erosion and melting that prolongs runoff. We assume that shock waves and reentering ejecta from the impact do not strongly affect the global circulation (the GCM windfield) on timescales of days. This is justified based on energy scaling (1% of impact energy ~ only 1 hour of Mars insolation), and detailed numerical calculations for Earth (e.g., Golden 2008). However, we will test for the sensitivity of our results to the potentially longer-lasting radiative effects of globally dispersed fine-grained ejecta.

In our preliminary Mojave-specific analyses (Kite 2012), we have found that water substance availability is unlikely to be limiting for precipitation-fed runoff. That is because a ~10m column-equivalent of water is sufficient to form the fans (Williams & Malin 2008), and water is stable as ground ice at Mojave's latitude for most past obliquities (≥32°; Mellon & Jakosky 1995, Laskar et al. 2004) or as hydrated minerals at any obliquity. This is consistent with H detections from orbit (e.g. Feldman et al. 2004) and with crater-ejecta morphology (Barlow & Perez, 2003). Constraints on Mojave's age (Werner et al. 2014) do not constrain the stability of ground ice at Mojave at fan-formation time, and ground ice may persist metastably on Mars at depth <0.1 km for >5 Myr (e.g. Mellon et al. 1997, Kress & Head, 2008). Therefore we do *not* think that the details of Mojave's alluvial fans are a detailed probe of the subsurface distribution of volatiles in the target (q.v. Weiss & Head 2013), or the physics of post-impact ice/hot-rock interaction. Conversely, we do not think that alluvial-fan formation at Mojave was sensitive to inevitable uncertainties in the detailed distribution of subsurface volatiles at the time of impact. We also found in our preliminary work that the total heat content of the ejecta blanket is unlikely to be limiting for melting of impact-induced snowfall (snowfall shuts down while the ground is still warm). Therefore we do *not* think that the details of Mojave's alluvial fans are a detailed probe of the physics of the contact, compression or excavation stage of the impact event itself. Similarly, we do not think that alluvial-fan formation at Mojave is sensitive to remaining uncertainties in the physics of these early stages of impact (Melosh 1989, Senft & Stewart 2009). Instead, our preliminary work indicates that the limiting step in providing runoff is local condensation of vapor to produce precipitation (i.e., the atmospheric response).

In summary, preliminary work by the proposal team and by the broader community has sharpened the question 'Did impact-induced precipitation occur in the geologically recent past on

Mars?,' allowing for a focused, well-posed investigation of appropriate scope for a three-year Solar System Workings study. Perhaps most importantly, global surveys have confirmed that Mojave contains the best-developed young impact-crater-hosted alluvial-fan bajadas on Mars (Tornabene et al. 2012, Goddard et al. 2014, Werner et al. 2014), so Mojave is the best site for this hypothesis test. The key remaining question is not whether enough volatiles were available in the impact event for precipitation (multiple plausible sources exist), nor whether the Mojave impact was energetic enough for large-scale volatilization (the pitted terrain shows that volatilization occurred). Rather, the key remaining question is: is vapor that is vented to the atmosphere as a consequence of the impact dispersed to distant cold traps, or is it concentrated and made available for localized runoff by the localized deep convection process described above (and in Kite et al. 2011a, b)? In other words, what is the mesoscale atmospheric response to the Mojave impact? We propose to simulate this critical, limiting step in detail.

2.3.3. Testing localized precipitation at Mojave crater has global significance.

Considerable uncertainty remains in the erosional effectiveness of impact-induced precipitation (and whether and under what conditions it occurred on Mars). Reducing this uncertainty is a major motivation for the proposed work, because many of the valley networks on Mars require precipitation (rain or snowmelt). Theory predicts that Mojave-sized impacts are energetically sufficient to trigger precipitation, at least regionally (Colaprete et al. 2005, Segura et al. 2008), but this theory has never been tested against a local geologic record, and direct comparison to the global record of ancient runoff has not led to consensus (Hynek et al. 2010, Segura et al. 2013).

Impact-induced runoff cannot account for all alluvial fans on Mars (e.g. Morgan et al. 2014), but remains an attractive hypothesis for at least part of Mars' early erosional record (Senft & Stewart 2008) because of (i) the disconnect between geomorphic and aqueous-mineral records, favoring intermittent runoff (Ehlmann et al. 2011), (ii) the difficulty of warming Mars to melting point with CO_2+H_2O contrasted to the relative ease of doing so with short-lived volcanogenic or impact-released gases (Forget et al. 2013, Mischna et al. 2013), (iii) the observations that impacts into icy Martian crust have triggered short-duration high-discharge localized floods (Jones 2011, Mangold 2012), mobilized slurries (Morgan & Head 2009, El-Maarry et al. 2013), and possibly breached preexisting aquifers (Harrison et al. 2010), (iv) evidence for impact-triggered alluvial-fan formation at younger sites including Mojave. Our simulations will not directly test the early Mars impact greenhouse theories, because Early Mars has different boundary conditions of lower solar luminosity and (probably) higher atmospheric pressure (Kite et al. 2014) than for the geologically recent times that we will simulate. However, analysis of the ancient geomorphic record has not led to consensus on the importance of impact-induced precipitation. The record of impact-triggered environmental changes is most easily recovered when there is minimal subsequent geomorphic overprint, and so the alluvial fans associated with the <5 Mya Mojave impact are the best-preserved record of the environmental effects of a large impact yet discovered (McEwen et al. 2007, Werner et al. 2014). These uncertainties at older sites motivate a focused test of the localized precipitation hypothesis that makes use of the very young alluvial fans in Mojave crater.

2.4. Technical Approach and Methodology.

We hypothesize that Mojave impact-induced precipitation can generate enough runoff to form Mojave's alluvial fans. At Mojave, there is strong geologic evidence for volatile release including steam vents / phreatomagmatic explosion pits (Tornabene et al. 2012, Boyce et al. 2012). Theory, and analogy to water-rock interactions in the aftermath of Novarupta 1912 and Mt. St. Helens 1980, predicts that an impact into an ice-bearing target creates steam vents / phreatomagmatic explosion pits, as well as possibly transient lakes (Zies 1921, Lipman & Mullineux 1981, Moyer & Swanson 1987, Newsom et al. 1996, Hildreth & Fierstein 2012). All these mechanisms cause rapid vapor release. In preliminary work (Fig. 2, Kite et al. 2011a & b, 2012) we have shown that rapid vapor release into a thin cold (modern-Mars-like) atmosphere produces deep moist convection and localized precipitation (a continuous storm). Therefore, we propose a test of the impact-induced precipitation hypothesis at Mojave crater. We will test this by numerical simulation with a range of Mojave-specific boundary conditions. The small horizontal scale of the geological observables (Fig. 2), and the Mach 0.2 vertical velocities obtained in preliminary output (Kite et al. 2011a), favor the use of a 3D mesoscale nonhydrostatic model (Markowski & Richardson 2011). Because we are interested in events with a recurrence interval much longer than the spacecraft era, we need a cloud microphysics capability that is physics-based (minimally tuned to spacecraft-era weather) so that we can understand the sensitivity of our model output to physical assumptions. We also require radiatively active clouds in order to track self-blanketing (localized-greenhouse) feedbacks extending warm-wet microclimate lifetime. These considerations all strongly favor the use of MRAMS. The following papers document the progress leading to our proposed use of MRAMS: terrestrial code base (Pielke et al. 1992); Mars dynamical core (Rafkin et al. 2001); initial Mars LES capabilities (Michaels et al. 2004); addition of cloud microphysics capabilities (Michaels et al. 2006); localized precipitation simulations with idealized boundary conditions (Kite et al. 2011a); localized precipitation simulations with geologically realistic boundary conditions (Kite et al. 2011b); preliminary simulations of impact-triggered storms (Kite et al. 2012).

Dust serves as water ice nuclei, and as such is scavenged during cloud formation. Water ice microphysics are implemented using 18 mass bins (minimum radius of 0.072 mm, mass ratio between bins is 7.2). Microphysical dust and water ice particles are advected, gravitationally sedimented, and diffused in the model. (Further details of MRAMS aerosol handling can be found in Appendix A of Kite et al. 2011b). Both water ice and dust are treated as being radiatively active, using a two-stream radiative transfer algorithm (based on Toon et al. 1989). Optical parameters for these aerosol particles are calculated with a Mie code.

2.4.1. Improvement of the Mars Regional Atmospheric Modeling System to permit self-consistent treatment of water-dominated atmospheres and of rainfall.

The main proposed advance in our use of MRAMS relative to the current state-of-the-art is the simulation of an atmosphere with a potentially very large water-vapor fraction (and rainfall) caused by steam venting and/or geysering into a tenuous atmosphere. The requirement for this new capability is set by the high vapor fluxes predicted by the pitted-terrain steam-venting model of Boyce et al. (2012), and found in our preliminary runs with a lake-surface vapor flux boundary condition (Fig. 3). We propose to rigorously track the effects of a locally water-dominated atmosphere, which is a new code development that could be applied to other Mars problems in future (e.g., orographic precipitation; Scanlon et al. 2013)**.** MRAMS already has radiative transfer that can deal with large amounts of water vapor. Although MRAMS currently does not have moisture terms in the dynamical equations, the Titan RAMS (TRAMS; Barth & Rafkin 2007) does include these pressure and virtual-temperature effects, and based on our experience it should be quick and easy to add this capability to MRAMS. Based on our preliminary work we anticipate that runs with modestly higher atmospheric pressure and/or higher dust optical depth could produce atmospheric conditions consistent with liquid-phase water aerosol and rainfall. MRAMS currently does not have the capability to track liquid-phase water aerosol, but the capability is already extant in the Earth version of the aerosol (sub)model that MRAMS uses (CARMA v2.3; Colarco et al. 2003, Michaels et al. 2006). We propose to also add this capability to the model as a model enhancement, enabling mesoscale modeling of rain on Mars. Specifically, we will add liquid-phase and mixed-phase water aerosol microphysics to MRAMS, being mindful of the need for the algorithms to work properly under Mars-specific extremes of temperature and atmospheric pressure. We will also add Mie-code-based radiative transfer for liquid H_2O spheres.

2.4.2 Forward modeling of the environmental consequences of impacts using the MRAMS for both Mojave-specific and idealized boundary conditions.

Mojave-specific simulations: Atmospheric boundary conditions for MRAMS will be supplied by the NASA Ames MGCM. Although we will track GCM-supplied synoptic water vapor and water ice, in practice we expect that the local supply of water will be overwhelmingly dominant (Kite et al. 2011a). Topographic boundary conditions will be supplied by downsampling MOLA (supplemented by HRSC DTM H2002_0001_DA4, which is available on the PDS). We hold topography constant with time, which is justified by the small volume of fans relative to crater volume and the small scale of synfluvial tectonism. Initial surface temperature will be conservatively selected as the cooler of two options: (1) shock heating computed using a Murnaghan equation of state, combined with Rayleigh-Z scaling for distribution of shock-heated ejecta (Barnhart et al. 2010, Barnhart & Nimmo 2011) (the PI has previously published work using these scalings – Mangold, Kite, et al. 2012); (2) the output from Mojave-tailored CTH simulations with an 8km-diameter impactor striking a 10m water-ice layer over basalt half-space, supplied by Collaborator Sarah Stewart (an example is shown in Fig. 4). As part of preliminary work underlying Fig. 3, we have already written and tested the scripts that ingest axisymmetric CTH output, extract and grid the surface temperatures, and georeference them to Mojave. The MRAMS code is already compiled and running in parallel on the Midway cluster at the PI's institution. Although the CTH code can also be used to supply local volatile/rock ratios, we choose to use geologically constrained water vapor flux boundary conditions, detailed below.

We will use five MRAMS grids with the outermost being hemispheric and a horizontal resolution of ~1.5 km on the inmost grid. Vertical resolution varies from 2.3 km at the top of the model to 30 m near the ground. Output will be sampled every 1/100 sol (~880s). The following variables will be stored and analyzed: atmospheric winds and temperatures; extent, rate and variability of precipitation; surface temperatures; upwelling and downwelling radiative fluxes; and water vapor and water aerosol (liquid and ice) distributions. The time step in MRAMS is now adaptive, which is particularly useful in our application for tracking storm updrafts. The time step on the inmost grid will never exceed 3.75 s. In preliminary work, our spinup procedure included 24 Mars-hours with no vapor release, 3 Mars-hours with vapor release but cloud microphysics off, and the remainder of the run with aerosol microphysics on. We observed that

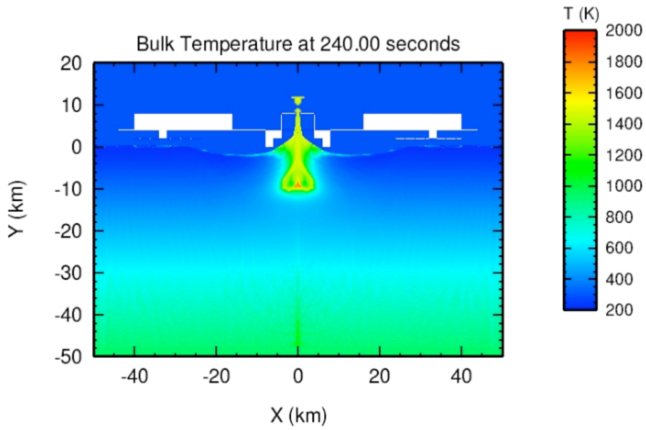


Fig. 4. Mojave-specific CTH output from Collaborator Sarah Stewart. The 10^2-10^3m thick sheet of mixed ice and rock at 300-1000K at the surface sets the boundary condition for the environmental response on timescales relevant to alluvial fan formation.

obvious spin-up transients had died away after ~60 Mars-hours. We will adjust spinup procedure as necessary in the proposed work. Based on our previous work (Fig. 3; Kite et al. 2011a, 2011b), the two most important control parameters for a localized-precipitation simulation are the sustained flux of energy to the system (in the form of latent and sensible heat), and the capacity of the atmosphere to dilute and dissipate that flux (for surface perturbations much broader than an atmospheric scale height, this capacity scales as atmospheric pressure). For impact-induced precipitation simulations, the absorption of infrared radiation from the ejecta blanket by the atmosphere (dusty in the immediate aftermath of the impact) may also be important. MRAMS microphysical capabilities allow us to self-consistently track dust settling and removal by precipitation. The prevailing synoptic wind field (which is modestly dependent on season and on orbital conditions; e.g, Fenton & Richardson 2001) influences the distribution of distal fans. Other parameters (Fig. 5) are less important. Therefore, we will consider (in order of importance) 4 water vapor fluxes, 3 atmospheric pressures, 2 dust loadings, and 2 synoptic wind fields, requiring 48 model runs. Parameters are detailed below. (We will also carry out 12 control simulations with no water vapor injection, which run very quickly compared to runs with microphysics, and 1 sensitivity test with horizontal resolution increased by a factor of 3, for a total of 61 runs). Computer requirements for this parameter sweep can comfortably be accommodated with UChicago and SETI Institute F&E (§6.1.2), and the number of runs allows ample time for data analysis and also ample CPU time for any further runs suggested by the data analysis.

- *Water vapor injection (F).* The water vapor injection flux boundary condition, *F*, will be applied only to the current area of pitted terrain on the floor of Mojave. Temperature will be fixed in the area of water vapor injection. In the much more extensive area of hot ejecta, temperatures evolve to balance conduction, radiation, and turbulent exchange with the atmosphere. We will consider both physically motivated and terrestrial-analog values for *F*, as follows:-
(1) F_{lake} – we flood Mojave to the elevation of fan toes with liquid water assumed buffered to 278.15K by (unmodelled) hydrothermal processes. Clear evidence for a lake within Mojave is lacking, but Irwin & Zimbelman (2012) have shown that short-lived lakes can leave little or no geomorphic signature. (2) $F_{Yellowstone}$ - Impact into a target with an ice content that varied with depth could create a 'Yellowstone-like' system with silicate melt underlying a mixture of hot rock and water. Fournier (1989) gives ~3 m^3/s 'deep-sourced water' for the Yellowstone system based on the chlorine-enthalpy method. We will divide this by the area of Yellowstone geysers active in the recent past (using the USGS digital map of Yellowstone; USGS, 1999), then apply this flux to the entire floor of Mojave as a steady flux. (3) $F_{Novarupta}$ – Pyroclastic deposits from the 1912 Novarupta eruption were cooled by steam venting including both "roaring jets" and "ubiquitous diffuse steam emanations" that persisted for >17 years in a cold climate:

the Valley of Ten Thousand Smokes (Hildreth & Fierstein 2012). We will apply the steam venting rate (kg/m^2/s) inferred at the time of the first scientific expedition 5 years after the eruption (Zies 1921, Griggs 1922) as a steady flux. (4) F_{pits} – we will impose fluxes predicted by the theory of Boyce et al. (2012), which was developed specifically to explain steam venting from Mojave-like pitted terrain on Mars. This theory requires the depth and water content of the venting layer to be specified. We will set pit volume equal to the floor area of Mojave, multiplied by the average depth of pits in the DTEEC_001481_1875_002167 _1880_U01 DTM, which covers part of Mojave. This method of determining pit volume is conservative, because there has been some infilling of pits by young aeolian materials. We will then define the depth of the layer by dividing the pit volume by a (conservative) assumed post-impact water content of 3% (Litvak et al. 2014). We will not consider the momentum transfer from the vents to the atmosphere.

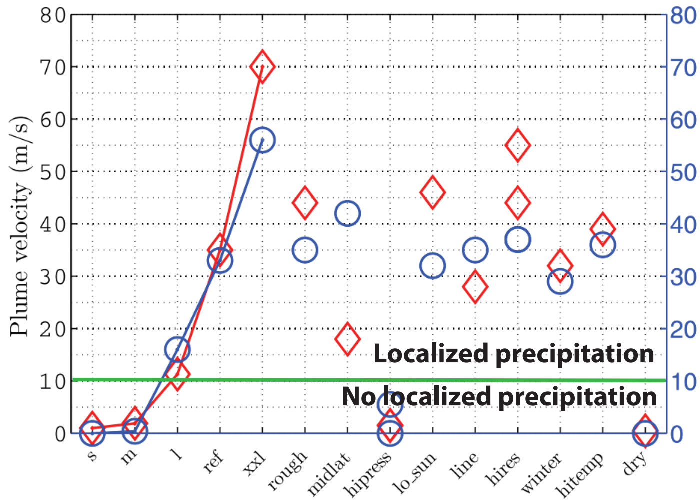


Fig. 5. To show robustness of localized precipitation (runs above green line) to all parameters except water vapor injection flux and atmospheric pressure. Red diamonds correspond to peak time-averaged plume velocity; blue circles correspond to plume height. Lines connect 5 simulations in which only size of vapor source was varied. The corresponding water loss rates are 150 m^3/s for `s`, 300 m^3/s for `m`, 1000 m^3/s for `l`, 3000 m^3/s for `ref`, and 2.3 x 10^4 m^3/s for `xxl`. '`hipress`' is ~60 mbar. The other runs show that localized precipitation is robust to reasonable variations in (from left to right) surface roughness, latitude, solar luminosity, vapor source geometry, model resolution, season, and lake temperature. See Kite et al. (2011a) for details of these sensitivity tests.

We expect the range of fluxes (1)-(4) will include values both below and above the storm initiation threshold (Fig. 4). If not, we will (as appropriate) either reduce simulated lake level (thus lake area) or extrapolate $F_{Novarupta}$ to earlier years by curve fitting to the post-1917 decline in steam venting.

- *Atmospheric Pressure (P).* We will consider 1x Present Atmospheric Level (PAL) CO_2, 2x PAL, and 8x PAL conditions. We will obtain corresponding boundary conditions from already-completed runs by the NASA Ames MGCM group. The motivation for the 1x PAL condition is the geologic youth of Mojave, and the motivation for the 2x PAL condition is the discovery of ~6 mbar-equivalent of buried CO_2 ice by SHARAD that could be released at high obliquity (Phillips et al. 2011). 8x PAL is a reasonable upper bound for P at times <5 Mya (the time of Mojave formation; Werner et al. 2014) based on theoretical estimates (Manning et al. 2006) and the apparently-low modern rate of escape to space (Lundin et al. 2013). We will determine if 8x PAL is sufficient to suppress localized storms (Kite et al. 2011a).
- *Dust loading*. We will separately consider "global dust storm" conditions (representing global dispersal of fine-grained ejecta after impact) and "normal" (low-dust) conditions (representing conditions after dust has settled over most of the planet). Because these choices bracket the possible effects of dust on the model output, we do not intend to track dynamic dust/debris lifting by wind or by steam blasts.

- <u>*Synoptic wind field.*</u> Atmospheric circulation on Mars today is driven largely by differential heating due to local topography and time-of-day. Although the background wind does not strongly influence the presence or absence of near-equatorial impact-induced storms (Fig. 8), it may modulate their intensity (e.g., via reduced or enhanced moisture convergence). Wind direction at Mojave is relatively insensitive to season, dust loading, and orbital conditions (Haberle et al. 2003, Millour et al. 2012, and our own unpublished preliminary work). Nevertheless, in order to assess any (minor) sensitivity of the system to background wind, we will consider the wind fields for two disparate modern-day insolation states (i.e., at perihelion-season and aphelion-season).

Both the rate of precipitation and the total amount of precipitation are important in calculating sediment transport (§2.4.3). To calculate total precipitation, we will run to "equilibrium" (~5-7 simulated sols) with constant surface vapor injection boundary conditions, take the average of the last 3 simulated sols, then extrapolate to durations >>1 sol using offline calculations of the overall Mojave energy budget and vapor-injection flux versus time (similar to the approach taken in Kite et al. 2011a, 2011b). This will include some interpolation between simulations. Although we will track cumulative snowfall, we will not track the effects of precipitation on surface temperature, because this depends on assumptions about mass wasting and erosional efficiency (for example latent heat cools the surface, but fluvial erosion exposes hotter layers deeper within the ejecta). Modeling of erosion will be done in post-processing (§2.4.3). Finally, using overall energy balance (initial ejecta energy, minus latent-heat cooling, radiation to space, and lateral energy transport) we will compute the maximum lifetime of the impact-induced storm system. We will use the flux of volatiles escaping local cold trapping in our model output to determine the thickness of ice deposited after the impact assuming (i) globally uniform deposition and (ii) deposition confined to the present-day area of the North Polar Layered Deposits (see §8 and Fig. 11 in Kite et al. 2011b).

Idealized simulations: Observations of degraded Mojave-like alluvial fans within other fresh primary craters on Mars (including 19N 170E, 10N 95E, Cerulli, 9S 79E, and 31S 109E) indicate that impact-triggered fan formation was not restricted to Mojave crater. None of these fan-hosting fresh primary craters are smaller than ~20 km diameter, suggesting that the fan-forming process does not operate for smaller craters. We hypothesize that localized precipitation does not occur for craters smaller than ~20km diameter. To test this hypothesis, we propose to use the MRAMS to model localized precipitation in craters with diameters of 5, 10, 20, 40, 80, and 160 km diameter on flat topography. We will adopt Rayleigh-Z scaling for the ejecta temperature initial condition (Barnhart et al. 2010, Barnhart & Nimmo 2011), set $F = F_{pits}$, and use Mojave's topography (azimuthally average, and scaled appropriately following measurements of pristine craters on Mars; Tornabene et al. 2013) as the crater-topography boundary condition. (6 additional runs).

2.4.3. Data-Model Comparison.

The purpose of the data-model comparison is to determine the geomorphic effectiveness of impact-induced precipitation and to compare it to the observed volume of sediment transported at Mojave. Because of uncertainty in key geomorphic parameters, such as grain-size, we use a range of simple sediment-transport models. By using a range of models with different physical and process assumptions, we aim to bracket outcomes. By using only simple sediment-transport models, we will have a clear understanding of why model output differs.

The first step is to go from precipitation P to total surface liquid water availability Q. For rain, $Q = P - E - I$, where E is evaporation and I is infiltration. E can be found self-consistently using the wind speeds and humidities in the surface layer that are output by MRAMS, and I can be calculated using a soil transmissivity, which we will vary over a range corresponding to laboratory data for sand-gravel mixtures. For frozen precipitation, we need to additionally calculate what portion of the snow that is melted on contact with hot ejecta. We will do this by applying a 1D Stefan model developed by the PI (Fig. 6) (Mangold, Kite et al. 2012) at all locations within the model domain. The Stefan model is appropriate for frozen precipitation (Mangold, Kite, et al., 2012). Its key advantage is energetic self-consistency. Melt production is limited by heat conduction from ejecta. Erosion of the ejecta blanket will tend to remove the boundary layer of the ejecta that is chilled by the latent heat of melting. This increases heat flow into the snow and allowing erosion to continue at a high rate. Both meltwater, and eroded sediment, are assumed to drain into channels as soon as they are produced.

The second step is to go from total liquid water availability (rain, plus melted snow) to sediment transport. We will calculate sediment transport in three different ways:-

- Constant sediment:water ratio, for ratios of 2×10^{-4} (average sediment concentration of terrestrial rivers), 0.01 (dense fluvial flow), and 0.4 (debris flow) (Williams & Malin 2008; Williams et al. 2011; Morgan et al., 2014; Palucis et al., 2014).
- SHALSTAB-predicted debris-flow sediment transport. SHALSTAB is a 2D community landslide-prediction model that predicts probable locations of shallow infinite-slope type landslides (Montgomery & Dietrich 1994). A key advantage is the ability to simulate debris flows. SHALSTAB is computationally inexpensive, open-source software (http://calm.geo.berkeley.edu/geomorph/shalstab/shalstab.zip). We shall use SHALSTAB in cohesionless mode, with a soil bulk density of 1600 kg/m^3, and a (conservatively steep) friction angle of 40°. SHALSTAB takes steady-state liquid-water input, which we will approximate as the 6-hour average Q (neglecting infiltration). Infiltration is accounted for in SHALSTAB using a soil transmissivity, which we will vary over a range corresponding to laboratory data for sand-gravel mixtures (analog measurements are not suitable for our purposes because all Earth craters of comparable diameter to Mojave are heavily weathered).
- Sediment transport predicted using a streampower (bedrock erosion) parameterization $\partial z/\partial t = k_e(QA)^{0.5}S$ implemented in GOLEM (Tucker & Slingerland, 1997). We will set ke following Ferrier et al.'s (2013) measurements of the basaltic island Kaua'i (with correction for Mars gravity). The streampower parameterization is standard in terrestrial fluvial-erosion modeling (e.g., Ferrier et al. 2013). The key advantage of this streampower model is that it allows tracking the 2D evolution of catchments. GOLEM is much less sophisticated than the CHILD model, but has fewer free parameters and its output is easier to interpret and analyze. GOLEM is computationally inexpensive, open-source software and is obtained from http://csdms.colorado.edu/wiki/Model:GOLEM.

SHALSTAB and the streampower model both require initial topography (to define drainage area A and slope S). This initial topography will be taken from the publicly-available HiRISE PDS DTM of Mojave (downsampled to 50m resolution), and from the 75m-resolution HRSC 2002_0001 DTM (resampled at 50m resolution). Total erosion will be computed by running these models (updating topography every 6 hours of simulated erosion) for the duration of the impact-induced storm system constrained by energy balance. Using the sediment transport output from these methods, we will compare model predictions to published volume estimates for

Mojave crater fans (Williams & Malin, 2008), and with the observed pattern of fan formation (concentrated around the inner rim of the crater, with only minor fan formation beyond the rim).

The sediment transport calculated using these methods will be conservative, for the following reasons. First, we are using present-day Mojave topography as our initial condition. This topography is post-fluvial, and therefore partially equilibrated to runoff. The true initial (fully unequilibrated) Mojave topography would produce stronger landslides / more incision. Second, the k_e calibrated using Kaua'i corresponds to erosion of intact bedrock, likely lower than appropriate for impact-fractured bedrock. Third, we assume the precipitation output from the MRAMS model is only 'used' for sediment transport once, but in reality a localized hydrologic cycle may develop, with a given water molecule repeatedly vaporizing, condensing, precipitating, transporting sediment, then vaporizing again.

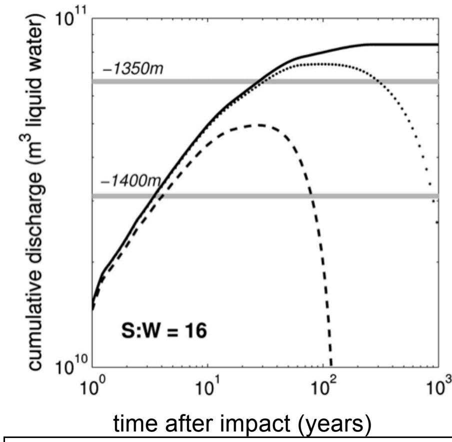


Fig. 6. Example output from PI's Stefan code for a ~5000 km^2 catchment. Solid, dotted and dashed lines show the effect of increasing infiltration (from Mangold, Kite, et al., 2012).

2.5. Perceived Impact of the Proposed Work.

What makes Mojave crater interesting is that it is a probe of process: because of its youth, large size, clear context and exceptional preservation state, Mojave is a natural laboratory for studying the response of planetary atmospheres and regional environments to large impacts. We can directly test model assumptions about impact-triggered precipitation and erosion using the geologic record at this site. This matters because a fundamental unsolved problem in the study of planetary habitability is the relative role of long-term geochemical cycles, versus transient environmental shocks accompanying asteroid/comet impacts, in steering planetary environmental evolution (Walker et al. 1981, Alvarez et al. 1980, Halevy et al. 2007, Toon et al. 2010). On Mars in particular, impact-induced precipitation is one of the two leading theories for valley network formation (e.g., Toon et al. 2010, Segura et al. 2013), the other being persistent clement climate conditions (e.g., Hynek et al. 2010). These hypotheses have very different implications for Mars' habitability. The truth is probably in between - i.e. that some, but not all, Mars valleys were formed by impact transients. However, it is important to have a physical basis for determining what proportion of Mars valleys were formed by impact, and which ones, for example in the context of landing-site selection. A self-consistent and geologically tested physical model of impact-induced precipitation is a necessary step along this path.

The proposed work will enhance the scientific return from MRO and ODY, by using data from multiple instruments to constrain the environmental consequences of a geologically-recent impact. The proposed model enhancements will also enhance the state-of-the-art, by adding self-consistent rainfall to a Mars mesoscale model.

2.6. Relevance of the Proposed Work.

Our proposed work is within the scope of Solar System Workings call, specifically "Evolution and modification of surfaces" (develop theoretical bases for understanding physical features of planetary surfaces), and "Planetary atmospheres: climate change" (characterize planetary climates over short time scales by reconstructing the history of atmospheric volatile inventories, and resolving the role that disruptive events play in providing perturbations in the global climate.) The proposed work also addresses several high-priority Investigations described in the most recent Mars Exploration Program Analysis Group reports (MEPAG 2010/2012), including II.A.4 "Search for microclimates […] recently wet or warm locales", III.A.6 "Characterize surface-atmosphere interactions on Mars, as recorded by […] processes that have operated within the recent past", and I.C.1 "Characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs."

2.7 Personnel and Qualifications.

(For FTE information, see §6, Budget Justification). PI **Edwin Kite** is currently a Princeton postdoc and a research associate at the University of Chicago (UChicago); he will be an Assistant Professor at UChicago from 1 Jan 2015. As PI, he will participate to some degree in all aspects of the proposed work and oversee its implementation. Co-I **Timothy Michaels** will be responsible for implementation and refinement of the MRAMS model of crater-atmosphere interactions; he will contribute to data analysis and paper-writing. Collaborators **Scot Rafkin** and **Sarah Stewart** will support Task 2 by (respectively) assisting in the interpretation of the MRAMS model output, and supplying Mojave-specific CTH output. A **graduate student** at UChicago will carry out a substantial portion of the erosion modeling, and take part in running and analyzing the MRAMS models. All personnel will participate in interpretation of results. The PI, Co-I, and Collaborator Rafkin have worked together to publish two papers describing preliminary work on this proposal (Kite, Michaels, Rafkin et al. 2011a; Kite, Rafkin, Michaels et al. 2011b). That work was carried out and published while Kite was a graduate student at UC Berkeley, and was funded by NASA grants NNX08AN13G and NNX09AN18G.

2.8 Plan of Work

	Activities/Milestones	**Deliverables**
Year 1	• Incorporate liquid water into MRAMS aerosol microphysical routines and incorporate pressure and virtual temperature effects of water vapor into the MRAMS dynamical core. • Train grad student on MRAMS analysis. • Run and analyze idealized MRAMS models. • Initiate Mojave-specific MRAMS runs. • Assemble and refine simple geomorphic models.	✓ LPSC presentation on sensitivity of impact-induced precipitation to crater size. ✓ Detailed manuscript on idealized runs: report results of test of hypothesis of threshold diameter for crater-storm initiation. (*Year 1 results, for submission in Year 2*).
Year 2	• Complete Mojave-specific MRAMS runs. • Analyze Mojave-specific MRAMS runs. • Apply simple geomorphic models to obtain constraints on sediment and water fluxes and timescale.	✓ LPSC presentation on sensitivity of Mojave-specific MRAMS runs to vapor flux, atmospheric pressure, and dust loading. ✓ Detailed manuscript documenting kilometer-scale mesoscale simulation of impact-induced precipitation at Mojave, Mars. (*Year 2 results, for submission in Year 3*).
Year 3	• Carry out any additional forward-model runs suggested by the data analysis and feed forward to the data-model comparison. • Carry out data-model comparison.	✓ Short GRL-length data-model comparison paper, including the results of erosion modeling.

3. References and citations.

Abramov, Oleg; Kring, David A. (2005), Impact-induced hydrothermal activity on early Mars, Journal of Geophysical Research, Volume 110, Issue E12, CiteID E12S09.

Alvarez, Luis W.; Alvarez, Walter; Asaro, Frank; Michel, Helen V. (1980), Extraterrestrial Cause for the Cretaceous-Tertiary Extinction, Science, 208, 1095-1108.

Balme, M., et al. (2006), Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data, J. Geophys. Res., 111, E5, CiteID E05001.

Barlow, N., & Perez, C. (2003), Martian impact crater ejecta morphologies as indicators of the distribution of subsurface volatiles, J. Geophys. Res. 108(E8), CiteID 5085.

Barnhart, Charles J.; Nimmo, Francis; Travis, Bryan J. (2010), Martian post-impact hydrothermal systems incorporating freezing, Icarus, 208, 101-117.

Barnhart, C. J. & Nimmo, F. (2011), Role of impact excavation in distributing clays over Noachian surfaces, Journal of Geophysical Research, 116, E1, CiteID E01009.

Barth, Erika L.; Rafkin, Scot C. R. (2007), TRAMS: A new dynamic cloud model for Titan's methane clouds, Geophysical Research Letters, 34, CiteID L03203.

Boyce, Joseph M.; Wilson, Lionel; Mouginis-Mark, Peter J.; Hamilton, Christopher W.; Tornabene, Livio L. (2012), Origin of small pits in martian impact craters, Icarus, 221, 262-275.

Bray, V. J.; Tornabene, L. L.; Keszthelyi, L. P.; McEwen, A. S.; Hawke, B. R.; Giguere, T. A.; Kattenhorn, S. A.; Garry, W. B.; Rizk, B.; Caudill, C. M.; Gaddis, L. R.; van der Bogert, C. H. (2010), New insight into lunar impact melt mobility from the LRO camera, Geophysical Research Letters, Volume 37, Issue 21, CiteID L21202.

Carbonneau, P.; Goddard, K.; Densmore, A. L.; Gupta, S. (2010), Continuous Particle Size Mapping of Alluvial Fan Material in Mojave Crater from HiRISE Imagery, American Geophysical Union, Fall Meeting 2010, abstract #P53A-1490.

Chevrier, Vincent F.; Rivera-Valentin, Edgard G. (2012), Formation of recurring slope lineae by liquid brines on present-day Mars, Geophysical Research Letters, Volume 39, Issue 21, CiteID L21202.

Colaprete, A.; Haberle, R. M.; Segura, T. L.; Toon, O. B.; Zahnle, K. (2005), The Effect of Impacts on the Martian Climate, Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters, held July 11-14, 2005 in Laurel, Maryland. LPI Contribution No. 1273, p.32-33

Colarco, P. R., et al. (2003), Saharan dust transport to the Caribbean during PRIDE: 2. Transport, vertical profiles, and deposition in simulations of in situ and remote sensing observations, J. Geophys. Res., 108, 8590, D19.

Conway, Susan J.; Balme, Matthew R.; Murray, John; Towner, Martin C.; Okubo, Chris H. and Grindrod, Peter M. (2011). The indication of Martian gully formation processes by slope-area analysis. Geological Society, London, Special Publications, 356(1), pp. 171–201.

Daubar, I. J.; McEwen, A. S.; Byrne, S.; Kennedy, M. R.; Ivanov, B. (2013), The current martian cratering rate, Icarus, 225, 506-516.

Denevi, B.W., et al. (2012), Pitted terrain on Vesta and implications for the presence of volatiles, Science, 348, 246-249.

Dietrich, William E.; Wilson, Cathy J.; Montgomery, David R.; McKean, James; Bauer, Romy (1992), Erosion thresholds and land surface morphology, Geology, 20, 675-.
Dundas, Colin M., Diniega, S., and McEwen, A.S. (2014), Long-term monitoring of martian gully formation and evolution with MRO/HiRISE, Icarus, in press, corrected proof.
Ehlmann, B.L. et al. (2011), Subsurface water and clay mineral formation during the early history of Mars, Nature, 479, 53–60.
El-Maarry, M. R.; Dohm, J. M.; Michael, G.; Thomas, N.; Maruyama, S. (2013), Morphology and evolution of the ejecta of Hale crater in Argyre basin, Mars: Results from high resolution mapping, Icarus, Volume 226, Issue 1, p. 905-922.
Emanuel, K. (1994) Atmospheric convection, Oxford University Press.
Emanuel, K., et al. (1995), Hypercanes: A possible link in global extinction scenarios, J. Geophys. Res. – Atmospheres, 100, 13755–13765.
Feldman, W.C., et al. (2004), Recharge mechanism of near-equatorial hydrogen on Mars: atmospheric redistribution or sub-surface aquifer, Geophys. Res. Lett. 31, L18701.
Fenton, Lori K.; Richardson, Mark I. (2001), Martian surface winds: Insensitivity to orbital changes and implications for aeolian processes, Journal of Geophysical Research, 106, E12, 32885-32902
Ferrier K.L., Huppert K.L., Perron J.T. (2013), Climatic control of bedrock river incision. Nature, 496, 206-209, doi: 10.1038/nature11982.
Forget, F., et al. (2013), 3D modelling of the early martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds, Icarus, 222, 1, 81-99.
Fournier, Robert O. (1989), Geochemistry and Dynamics of the Yellowstone National Park Hydrothermal System, Annual Review of Earth and Planetary Sciences, 17, 13-
Frankel, K. L., Dolan, J. F. (2007). Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data. J. Geophys. Res. 112, doi:10.1029/2006JF000644.
Freeze, R.A., and J.A. Cherry (1979), Groundwater, Prentice Hall, 604 pp.
Grant, John A.; Wilson, Sharon A. (2012), A possible synoptic source of water for alluvial fan formation in southern Margaritifer Terra, Mars, Planetary and Space Science, 72, 1, 44-52.
Griggs, R.F (1922), The Valley of Ten Thousand Smokes: Washington, D.C., National Geographic Society, 340 p.
Goddard, Kate, Warner, Nicholas, Gupta, Sanjeev, and Jung-Rack Kim (2014), Mechanisms and timescales of fluvial activity at Mojave and other young Martian craters, J. Geophys. Res. – Planets, DOI: 10.1002/2013JE004564.
Golden, T.J., (2008), Atmospheric interactions during global deposition of Chicxulub impact ejecta, PhD thesis, U. Arizona.
Haberle, R.M., J. B. Pollack, J. R. Barnes, R. W. Zurek, C. B. Leovy, J. R., Murphy, H. Lee, and J. Schaeffer (1993), Mars atmospheric dynamics as simulated by the NASA Ames General Circulation Model: 1. The zonal-mean circulation, J. Geophys. Res., 98, 3093–3123.
Haberle, Robert M.; Murphy, James R.; Schaeffer, James (2003), Orbital change experiments with a Mars general circulation model, Icarus, 161, 66-89
Halevy, Itay; Zuber, Maria T.; Schrag, Daniel P. (2007), A Sulfur Dioxide Climate Feedback on Early Mars, Science, 318, 1903-
Harrison, Tanya N.; Malin, Michael C.; Edgett, Kenneth S.; Shean, David E.; Kennedy, Megan R.; Lipkaman, Leslie J.; Cantor, Bruce A.; Posiolova, Liliya V. (2010), Impact-induced

overland fluid flow and channelized erosion at Lyot Crater, Mars, Geophysical Research Letters, 37, 21, CiteID L21201.

Hecht, Michael H. (2002), Metastability of Liquid Water on Mars, Icarus, 156, 373-386.

Hildreth, Wes, and Fierstein, Judy (2012), The Novarupta-Katmai Eruption of 1912 – Largest Eruption of the Twentieth Century: Centennial Perspectives, U.S.G.S. Professional Paper 1791, 259 p., U.S. Geological Survey.

Hynek, Brian M.; Beach, Michael; Hoke, Monica R. T. (2010), Updated global map of Martian valley networks and implications for climate and hydrologic processes, Journal of Geophysical Research, 115, CiteID E09008.

Irwin, R. P. (2013), Testing Links Between Impacts and Fluvial Erosion on Post-Noachian Mars, 44th Lunar and Planetary Science Conference, held March 18-22, 2013 in The Woodlands, Texas. LPI Contribution No. 1719, p.2958.

Irwin, Rossman P., III; Zimbelman, James R. (2012), Morphometry of Great Basin pluvial shore landforms: Implications for paleolake basins on Mars, J. Geophys. Res., 117, CiteID E07004.

Jarrett, R. D. & Costa, J. E. (1988), Evaluation of the floodwater hydrology in the Colorado Front Range using precipitation, streamflow, and paleoflood data for the Big Thompson River basin, USGS Water-Resources Investigations Report: 87-4117, U.S. Geologic Survey.

Jerolmack, Douglas J.; Mohrig, David; Zuber, Maria T.; Byrne, Shane (2004), A minimum time for the formation of Holden Northeast fan, Mars, Geophysical Research Letters, 31, CiteID L21701.

Johnson, B. C. & Melosh, H. J. (2012) Formation of spherules in impact produced vapor plumes. Icarus, 217, 416–430.

Jones, A. P.; McEwen, A. S.; Tornabene, L. L.; Baker, V. R.; Melosh, H. J.; Berman, D. C. (2011), A geomorphic analysis of Hale crater, Mars: The effects of impact into ice-rich crust, Icarus, 211, 259-272.

Kirk, R.L., et al. (2008), Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites, J. Geophys. Res. 113, E00A24.

Kite, E.S. (2011), Net assessment of the impact hypothesis for fluvial activity at Eberswalde and tests with MSL, talk, 5th MSL Landing Site Workshop.

Kite, E.S., Michaels, T.I., Rafkin, S.C.R., Manga, M., & W.E. Dietrich (2011a). Localized precipitation and runoff on Mars, J. Geophys. Res. Planets, 116, E07002.

Kite, E.S., Rafkin, S.C.R., Michaels, T.I., Dietrich, W.E., & Manga, M., (2011b). Chaos terrain, storms, and past climate on Mars, J. Geophys. Res. Planets, 116, E10002.

Kite, E.S. & Manga, M. (2012), Seasonal Snowmelt Versus Impact-Triggered Runoff in Mars' Geologic Record of Surface Liquid Water, Third Conference on Early Mars. LPI Contribution No. 1680, id.7081.

Kite, E.S., Williams, J.-P., Lucas, A., & Aharonson, O., 2014, Low paleopressure of Mars' atmosphere estimated from small ancient craters, Nature Geoscience, 7, 335-339.

Kress, Ailish M.; Head, James W. (2008), Ring-mold craters in lineated valley fill and lobate debris aprons on Mars: Evidence for subsurface glacial ice, Geophysical Research Letters, Volume 35, Issue 23, CiteID L23206

Laskar, J.; Correia, A. C. M.; Gastineau, M.; Joutel, F.; Levrard, B.; Robutel, P. (2004), Long term evolution and chaotic diffusion of the insolation quantities of Mars, Icarus, 170, 343-364.

Lipman, Peter W., & Mullineaux, Donal Ray (1981), The 1980 eruptions of Mount St. Helens, Washington, USGS Professional Paper Series Number 1250, 844 pp.

Litvak, M.L., et al. (2014), Local variations of bulk hydrogen and chlorine-equivalent neutron absorption content measured at the content between the Sheepbed and Gillespie Lake units in Yellowknife Bay, Gale Crater, using the DAN instrument onboard Curiosity, J. Geophys. Res., doi:10.1002/2013JE004556.

Lundin, R.; Barabash, S.; Holmström, M.; Nilsson, H.; Futaana, Y.; Ramstad, R.; Yamauchi, M.; Dubinin, E.; Fraenz, M. (2013), Solar cycle effects on the ion escape from Mars, Geophysical Research Letters, Volume 40, Issue 23, pp. 6028-6032.

Malin, Michael C.; Edgett, Kenneth S. (2003), Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars, Science, 302, 1931-1934.

Mangold, N. (2012), Fluvial landforms on fresh impact ejecta on Mars, Planetary and Space Science, 62, 69-85.

Mangold, N., Kite, E.S., Kleinhans, M., Newsom, H.E., Ansan, V., Hauber, E., Kraal, E., Quantin-Nataf, C. & K. Tanaka (2012), The origin and timing of fluvial activity at Eberswalde Crater, Mars, Icarus, 220, 530-551.

Manning, Curtis V.; McKay, Christopher P.; Zahnle, Kevin J. (2006), Thick and thin models of the evolution of carbon dioxide on Mars, Icarus, 180, 38-59.

Marcelo Garcia (Ed.) (2008), Sedimentation Engineering (Manual 110), American Society of Civil Engineers Measurements, Modeling, and Practice, Manuals of Practice (MOP) 110, 1132 pp., American Society of Civil Engineers.

Markowski, P/., & Richardson, Y. (2011), Mesoscale Meteorology in Midlatitudes (Advancing Weather and Climate Science), Wiley-Blackwell.

McEwen, A. S.; et al. (2007), A Closer Look at Water-Related Geologic Activity on Mars, Science, 317, 1706-

Mellon, Michael T.; Jakosky, Bruce M. (1995), The distribution and behavior of Martian ground ice during past and present epochs, Journal of Geophysical Research, 100(E6), 11781-11799.

Mellon, Michael T.; Jakosky, Bruce M.; Postawko, Susan E. (1997), The persistence of equatorial ground ice on Mars, Journal of Geophysical Research, Volume 102, Issue E8, p. 19357-19370

Melosh, H. J. (1989), Impact cratering: A geologic process, New York, Oxford University Press (Oxford Monographs on Geology and Geophysics, No. 11), 253 p.

MEPAG (2010/2012), Mars Scientific Goals, Objectives, Investigations, and Priorities: J.R. Johnson, ed., (2010 version, and 2012 version for review), both posted by the Mars Exploration Program Analysis Group, at http://mepag.jpl.nasa.gov/reports/index.html.

Michaels, T. I., A. Colaprete, and S. C. R. Rafkin (2006), Significant vertical water transport by mountain-induced circulations on Mars, Geophys. Res. Lett., 33, L16201.

Millour, E., Forget, F., Lewis, S.R. (2012), Mars Climate Database v5.0 User Manual, http://www-mars.lmd.jussieu.fr/mars/info_web/user_manual_5.0.pdf

Mischna, M.A., et al. (2013), Effects of obliquity and water vapor/trace gas greenhouses in the early martian climate, J. Geophys. Res. Planets, 118, 560–576.

Montgomery, DR; Dietrich, WE (1994), A physically-based model for the topographic control on shallow landsliding, Water Resources Research, 30, 1153-1171.

Mouginis-Mark, PJ & Boyce, JM (2012), Tooting crater: Geology and geomorphology of the archetype large, fresh, impact crater on Mars, Chemie der Erde - Geochemistry, 72, 1-23.

Morgan, Gareth A.; Head, James W. (2009), Sinton crater, Mars: Evidence for impact into a plateau icefield and melting to produce valley networks at the Hesperian-Amazonian boundary, Icarus, 202, 39-59.
Morgan, A.M., et al. (2014) Sedimentology and climatic environment of alluvial fans in the martian Saheki crater and a comparison with terrestrial fans in the Atacama Desert, Icarus 229, 131-156.
Moyer, T., and Swanson, D. (1987), Secondary hydroeruptions in pyroclastic-flow deposits: Examples from Mount St. Helens, Journal of Volcanology and Geothermal Research, 32, 299-319.
Newsom, Horton E.; Graup, Günther; Sewards, Terry; Keil, Klaus (1986), Fluidization and hydrothermal alteration of the suevite deposit at the Ries crater, West Germany, and implications for Mars, Journal of Geophysical Research, 91(B13), E239-E252.
Newsom, Horton E.; Brittelle, Gregory E.; Hibbitts, Charles A.; Crossey, Laura J.; Kudo, Albert M. (1996), Impact crater lakes on Mars, Journal of Geophysical Research, 101(E6), 14951-14956.
Nicholas, Andrew P.; Quine, Timothy A. (2007), Modeling alluvial landform change in the absence of external environmental forcing, Geology, 35, 527.
Olsen, A., Rimstidt, J. (2007). Using a mineral lifetime diagram to evaluate the persistence of olivine on Mars. Am. Mineral. 92, 598–602.
Parker, G., Paola, C., Whipple, K.X., and Mohrig, D. (1998), Alluvial fans formed by channelized fluvial and sheet flow. I: Theory. Journal of Hydraulic Engineering, 124, 985-995.
Pelletier, J. (2008), Quantitative modeling of Earth surface processes, Cambridge University Press.
Phillips, Roger J., et al. (2011), Massive CO_2 ice deposits sequestered in the south polar layered deposits of Mars, Science 332, 838-
Pielke, R. A., et al. (1992), A comprehensive meteorological modeling system—RAMS, Meteorol. Atmos. Phys., 49, 69–91.
Pielke, R. A. (2002), Mesoscale Meteorological Modeling, Int. Geophys. Ser., vol. 78, 2nd ed., Academic Press, San Diego, Calif.
Plesko, C. S. et al. (2009), Initial Conditions of an Impact-generated Greenhouse Event from Hydrocode Models of Large Impacts on Noachian Mars, 40th Lunar and Planetary Science Conference, The Woodlands, Texas, id.2167.
Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, (2007) Numerical Recipes: The Art of Scientific Computing, Third Edition, 1235 pp. (New York: Cambridge University Press).
Rafkin, S. C. R., R. M. Haberle, and T. I. Michaels (2001), The Mars Regional Atmospheric Modeling System (MRAMS): Model description and selected simulations, Icarus, 151, 228–256.
Scanlon, Kathleen E.; Head, James W.; Madeleine, Jean-Baptiste; Wordsworth, Robin D.; Forget, François (2013), Orographic precipitation in valley network headwaters: Constraints on the ancient Martian atmosphere, Geophysical Research Letters, Volume 40, Issue 16, pp. 4182-4187.
Schulte, P., et al. (2010), The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary, Science, 327, 1214-1218.

Schwenzer, S.P., et al. (2021), Puncturing Mars: How impact craters interact with the Martian cryosphere, Earth & Planet Sci. Lett. 335-336, 9-17.
Segura, T. L.; Colaprete, A. (2009), Global Modeling of Impact-induced Greenhouse Warming on Early Mars, 40th Lunar and Planetary Science Conference.
Segura, Teresa L.; McKay, Christopher P.; Toon, Owen B. (2012), An impact-induced, stable, runaway climate on Mars, Icarus, 220, 144-148.
Segura, Teresa L., Zahnle, K., Toon, O.B., and McKay, C.B. (2013), The effects of impacts on the climates of terrestrial planets, pp. 417-438 in Mackwell, S., et al., Comparative Climatology of the Terrestrial Planets, University of Arizona Press.
Senft, L. E.; Stewart, S. T. (2008), Impact crater formation in icy layered terrains on Mars, Meteoritics & Planetary Science, 43, 1993-2013.
Senft, L. E., S. T. Stewart (2009), Dynamic Fault Weakening and the Formation of Large Impact Craters, Earth and Planetary Science Letters, 287, 471-482.
Stock, J, & Dietrich, WE (2003), Valley incision by debris flows: Evidence of a topographic signature, Water Resources Research, 39(4), Article Number: 1089.
Stock, J. D.; Schmidt, K. M.; Miller, D. M. (2008), Controls on alluvial fan long-profiles Geological Society of America Bulletin, 120, 619-640.
Toon, O. B., R. P. Turco, D. Westphal, R. Malone, M. Liu (1988), A Multidimensional Model for Aerosols: Description of Computational Analogs. J. Atmos. Sci., 45, 2123–2144.
Toon, O. B., C. P. McKay, T. P. Ackerman, and K. Santhanam (1989), Rapid calculation of radiative heating rates and photodissociation rates in inhomogeneous multiple scattering atmospheres, J. Geophys. Res., 94, 16,287–16,301.
Toon, Owen B.; Segura, Teresa; Zahnle, Kevin (2010), The Formation of Martian River Valleys by Impacts, Annual Review of Earth and Planetary Sciences, 38, 303-322.
Tornabene, L. L.; McEwen, A. S.; Osinski, G. R.; Mouginis-Mark, P. J.; Boyce, J. M.; Williams, R. M. E.; Wray, J. J.; Grant, J. A.; HiRISE Team (2007), Impact Melting and the Role of Sub-Surface Volatiles: Implications for the Formation of Valley Networks and Phyllosilicate-rich Lithologies on Early Mars, Seventh International Conference on Mars, LPI Contribution No. 1353, p.3288.
Tornabene, Livio L.; Osinski, Gordon R.; McEwen, Alfred S.; Boyce, Joseph M.; Bray, Veronica J.; Caudill, Christy M.; Grant, John A.; Hamilton, Christopher W.; Mattson, Sarah; Mouginis-Mark, Peter J. (2012), Widespread crater-related pitted materials on Mars: Further evidence for the role of target volatiles during the impact process, Icarus, 220, 348-368.
Tornabene, L. L.; Ling, V.; Osinski, G. R.; Boyce, J. M.; Harrison, T. N.; McEwen, A. S. (2013), A Revised Global Depth-Diameter Scaling Relationship for Mars Based on Pitted Impact Melt-Bearing Craters, 44th Lunar and Planetary Science Conference, held March 18-22, 2013 in The Woodlands, Texas. LPI Contribution No. 1719, p.2592
Tucker, Gregory E.; Slingerland, Rudy (1997), Drainage basin responses to climate change, Water Resources Research, Volume 33, Issue 8, pp. 2031-2047.
USGS (1999), Digital geologic map of Yellowstone National Park, Idaho, Montana, pubs.er.usgs.gov/publication/ofr99174.
Wagner, Robert V.; Robinson, Mark S. (2014), Distribution, formation mechanisms, and significance of lunar pits, Icarus, Volume 237, p. 52-60.
Walder, JS (2000a), Pyroclast/snow interactions and thermally driven slurry formation. Part 1: Theory for monodisperse grain beds, Bulletin of Volcanology 62, 105-118.

Walder, JS (2000b), Pyroclast/snow interactions and thermally driven slurry formation. Part 2: Experiments and theoretical extension to polydisperse tephra, Bulletin of Volcanology, 62, 119-129.
Walker, J. C. G.; Hays, P. B.; Kasting, J. F. (1981), A negative feedback mechanism for the long-term stabilization of the earth's surface temperature, Journal of Geophysical Research, 86, 9776-9782.
Warner, N., Gupta, S., Kim, J., Lin, S., and Muller, J. (2010). Hesperian equatorial thermokarst lakes in Ares Vallis as evidence for transient warm conditions on Mars, Geology, 38, 71-74.
Wang, Chi-Yuen; Manga, Michael; Wong, Alex (2005), Floods on Mars released from groundwater by impact, Icarus, 175, 551-555.
Weiss, David K.; Head, James W (2013), Formation of double-layered ejecta craters on Mars: A glacial substrate model, Geophysical Research Letters, 40, 3819-3824.
Werner, Stephanie C., Ody, Anouck, and Poulet, Francois (2014), The source crater of Martian shergottite meteorites, Science, 343, 1343-1346.
Whipple, K.X., and Dunne, T. (1992), The influence of debris-flow rheology on fan morphology, Owens Valley, California, Geological Society of America Bulletin, 104, 887-900.
Williams, Rebecca M. E.; Malin, Michael C. (2008), Sub-kilometer fans in Mojave Crater, Mars, Icarus, 198, 365-383.
Williams, Rebecca M. E.; Deanne Rogers, A.; Chojnacki, Matthew; Boyce, Joseph; Seelos, Kimberly D.; Hardgrove, Craig; Chuang, Frank (2011), Evidence for episodic alluvial fan formation in far western Terra Tyrrhena, Mars, Icarus, Volume 211, Issue 1, p. 222-237.
Williams, Rebecca M. E.; Zimbelman, James R.; Johnston, Andrew K. (2006), Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars, Geophysical Research Letters, Volume 33, Issue 10, CiteID L10201.
Williams, R. M. E.; Edgett, K. S.; Malin, M. C. (2004), Young Fans in an Equatorial Crater in Xanthe Terra, Mars, 35th Lunar and Planetary Science Conference, abstract no. 1415.
Zahnle, K.; Colaprete, A. (2004), A Unique Origin for Mojave Crater?, American Geophysical Union, Fall Meeting 2004, abstract #P41A-089.
Zies, E. G. (1921) Hot springs of the Valley of Ten Thousand Smokes, Journal of Geology, 32(4), 302-310.

4. Biographical Sketches.

Edwin S. Kite (Principal Investigator).

Professional preparation:
B.A. Cambridge University (Natural Sciences Tripos – Geological Sciences), June 2007
M.Sci. Cambridge University (Natural Sciences Tripos – Geological Sciences), June 2007
Ph.D. University of California Berkeley (Earth and Planetary Science), December 2011

Appointments:
Assistant Professor, Department of the Geophysical Sciences, University of Chicago
from January 2015
(*research associate with PI status from August 2013*)
Harry Hess Fellow (Astrophysical Sciences & Geoscience Departments), Princeton University
from January 2014 – December 2014
O.K. Earl Fellow, Geological and Planetary Sciences Division, Caltech
January 2012 – January 2014.

Mars papers from the past 36 months:

Kite, E.S., Williams, J.-P., Lucas, A., & Aharonson, O., 2014, "Low paleopressure of Mars' atmosphere estimated from small ancient craters," *Nature Geoscience*, 7, 335-339.

Kite, E.S., Lewis, K.W., Lamb, M.P., Newman, C.E., & Richardson, M.I., 2013, "Growth and form of the mound in Gale Crater, Mars: Slope-wind enhanced erosion and transport," *Geology*, 41, 543-546. ("Highlight of the Meeting" at Science).

Kite, E.S., Halevy, I., Kahre, M.A., Manga, M., & Wolff, M., 2013, "Seasonal melting and the formation of sedimentary rocks on Mars," *Icarus*, 223, 181-210.

Kite, E.S., Lucas, A., & C.I. Fassett, "Pacing Early Mars river activity: Embedded craters in the Aeolis Dorsa region imply river activity spanned ≳(1-20) Myr," *Icarus*, 225, 850-855.

Manga, M., Patel, A., Dufek, J., & **Kite, E.S**., 2012. "Wet surface and dense atmosphere on early Mars inferred from the bomb sag at Home Plate, Mars," *Geophys. Res. Lett.*, doi:10.1029/2011GL050192.

Kite, E.S., Michaels, T.I., Rafkin, S.C.R., Manga, M., & W.E. Dietrich, 2011. "Localized precipitation and runoff on Mars," *J. Geophys. Res. Planets*, 116, E07002, 20 pp. doi:10.1029/2010JE003783. **[**On the direct path to the proposed work**]**

Kite, E.S., Rafkin, S.C.R., Michaels, T.I., Dietrich, W.E., & Manga, M., 2011. "Chaos terrain, storms, and past climate on Mars," *J. Geophys. Res. Planets*, 116, E10002, 26 pp., doi:10.1029/2010JE003792 ("Research Highlight" at Nature Geoscience).
[On the direct path to the proposed work**]**

Mangold, N., **Kite, E.S.,** Kleinhans, M., Newsom, H.E., Ansan, V., Hauber, E., Kraal, E., Quantin-Nataf, C. & K. Tanaka, 2012, "The origin and timing of fluvial activity at Eberswalde Crater, Mars," *Icarus*, 220, 530-551 **[**Describes 1.5D ejecta-runoff model**]**

(*Page 1 of 2*)

Additional papers on Mars or planetary habitability:

Šrámek, O., McDonough, W., **Kite, E.S.**, Lekic, V., Zhong, S.T., & Dye, W.F., Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle, *Earth Planet. Sci. Lett.*, doi:10.1016/j.epsl.2012.11.001. ("Research Highlight" at Nature).

Kite, E.S., Gaidos, E. & M. Manga, 2011. "Climate instability on tidally locked exoplanets," *Astrophys. J.*, 743, 41, 12 pp.

Rappaport, S., Levine, A., Chiang, E., El Mellah, I., Jenkin, J., Kalomeni, B., **Kite, E.S.**, Kotson, M., Nelson, L., Rousseau-Nepton, & Tran, K., 2012, "Possible disintegrating short-period Super-Mercury orbiting KIC 12557548," *Astrophys. J.*, 752, 1.

Kite, E.S., Manga, M., & Gaidos, E., 2009. "Geodynamics and rate of volcanism on massive Earth-like planets," *Astrophys. J.*, 700, 1732-1749.

Chiang, E., **Kite, E.**, Kalas, P., Graham, J. R., & Clampin, M., 2009. "Fomalhaut's Debris Disk and Planet: Inferring the Mass and Orbit of Fomalhaut b Using Disk Morphology," *Astrophys. J.*, 693, 734-749.

Kite, E.S., Matsuyama, I., Manga, M., Perron, J.T., & Mitrovica, J.X., 2009, "True polar wander driven by late-stage volcanism and the distribution of paleopolar deposits on Mars," *Earth Planet. Sci. Lett*, 280, 254-267.

Kalas, P., Graham, J. R., Chiang, E., Fitzgerald, M. P., Clampin, M., **Kite, E. S.,** Stapelfeldt, K., Marois, C., & Krist, J., 2008. "Optical Images of a Planet 25 Light Years from Earth," *Science*, 322, 1345-1348 ("Breakthrough of the Year #2" at Science; AAAS Newcomb Cleveland Prize).

Kite, E.S., & R.C.A. Hindmarsh, 2007. "Did ice streams shape the largest channels on Mars?", *Geophys. Res. Lett.*, 34, L19202.

Telescope experience:

Hubble Space Telescope: Co-I on GO/DD Program 11818 (PI: Paul Kalas).
Spitzer Space Telescope: Warm IRAC phase curves of exoplanet HAT-P-7b (PI: Heather Knutson).

Field geology experience:

Central India (Proterozoic paleobiology). Greece, SE Spain, England, Scotland, California, Hawaii (fieldwork, mapping courses). NW Spain (independent mapping project, 6 weeks). Utah (GSI for Professor W. Alvarez).

(*Page 2 of 2)*