Dissertation outline for Jacob Richardson

Chapters:

1. Role of sills in the development of volcanic fields: Insights from LiDAR mapping surveys of the San Rafael Swell, Utah*
2. Volcanic recurrence and magma delivery rates for latest volcanism at Arsia Mons, Mars
3. The volcanic history of Syria Planum, Mars*
4. Validating lava flow emplacement algorithms with standard benchmarks
5. Spatial density characteristics of volcano clusters on Earth, Mars, and Venus

*Published

Role of sills in the development of volcanic fields: Insights from LiDAR mapping surveys of the San Rafael Swell, Utah

J. Richardson, C. Connor, P. Wetmore, L. Connor, E. Gallant

Accepted for publication in *Geology*, doi:10.1130/G37094.1

Abstract: Analysis of airborne and terrestrial LiDAR data demonstrates that >0.4 km^3 of magma cooled in sills at shallow (< 1 km) depth in the now eroded Pliocene San Rafael Swell distributed volcanic field, Utah. The volumes of each of seven sills are estimated from 3D models of the LiDAR data and range from 10^{-4} -10^{-1} km^3 . Directions of magma flow during emplacement are interpreted from precise sill thickness measurements and measurements of linear vertical offsets within the sills, helping to identify feeder conduits and dikes; 3D map relationships derived from LiDAR data demonstrate that magma flowed into and out of sills from these active dikes and eruptive conduits. Mapped sill volumes account for >92% of intrusive material within the 50 km^2 study area. We conclude that sills played a significant role in modifying eruption dynamics during activity in San Rafael, and suggest that monitoring of sill inflation and deflation in active distributed volcanic fields may provide key information about unrest and potential eruption dynamics.

Volcanic recurrence and magma delivery rates for latest volcanism at Arsia Mons, Mars

J. Richardson, J. Wilson, C. Connor, and J. Bleacher

Greeley and Schneid (1991) produced one of the first extrusive magma flux estimates for the surface of Mars and used terrestrial intrusive/extrusive rations to calculate that 6.5×10^{8} km³ of magma has been generated on Mars in the past 3.8 Ga. For the most recent 500 Ma, the production was observed to wane, and only 2.11×10^{6} km³ of magma was modeled to have erupted (Greeley and Schneid, 1991). This global extrusive magma flux of 0.004 km³/yr (0.13 m³/s) remains one of few such estimates. On central Elysium Planitia, Vaucher et al. (2009) calculated a time-averaged magma flux of 1.4×10^{-2}-1.8×10^{-2} m³/s over the most recent 234 Myr, through volume estimates of lava flows and a crater retention rate study. Wilson et al. (2001) constrained magma flux underneath the Tharsis Montes by modeling the magma necessary to sustain magma bodies at depth associated with large extant caldera. Their study indicated that the magma flux to the base of these large volcanoes must have been 1-30 m³/s for hundreds of thousands of years at a time, followed by orders of magnitude longer periods of quiescence.

Constraining the rate of magma delivery to the surface and the recurrence rate of magma delivery is essential to understanding 1) the long-term evolution of the surface of Mars (Wilson and Head, 1994), 2) climatic shifts in the Martian atmosphere (Mouginis-Mark, 2002), and 3) the ability for regions of Mars to sustain biotic or pre-biotic material over time (Scanlon et al., 2015). To constrain recurrence rate and surfacial mass flux, we have applied a Volcanic Event Recurrence Rate Model (VERRM) to 28 volcanic edifices in the caldera of Arsia Mons. VERRM is a monte carlo model which uses age models (i.e. crater retention age estimates) and stratigraphic information to simulate the range of possible recurrence rates. By identifying the range of possible volcanic timelines, the uncertainty of the rate of volcanic event production through time is better understood.

Arsia Mons is a major shield volcano on Mars and a member of the Tharsis Montes. With a diameter of over 300 km and slopes of 5° (Plescia, 2004), the surface of Arsia contains lava flows, which served as the primary construction material of the shield (Mouginis-Mark and Rowland, 2008), prodigious ash deposits (Mouginis-Mark, 2002), and glacial deposits (Head and Marchant, 2009) emplaced under both cold- and warm-based glacial conditions (Scanlon et al., 2015). At the summit of Arsia is a single collapse caldera measuring ~4000 km³ in volume (Wilson et al., 2001). Within this 110 km wide caldera, a linear cluster of secondary shield volcanoes comprise one of the youngest geologic units in the Arsia region (Carr et al., 1977; Scott and Zimbelman, 1995). No craters larger than 1 km exist within the caldera and several detailed crater retention studies with different image datasets have independently produced 130 Ma as a single age estimate of the entire caldera floor (Neukum et al., 2004; Werner, 2009; Robbins et al., 2011).

Within the crater, we have mapped 29 lava flows units, each in association with one endogenous vent (Richardson et al., 2015). The volumes of these edifices have been modeled to be from 1-10 km³. Our initial finding shows that the flow field might have been active for the last 230 Ma, giving an averaged volumetric output of 1,200 m³/yr.

The volcanic history of Syria Planum, Mars

J. Richardson, J. Bleacher, and L. Glaze

Published 2013 in *Journal of Volcanology and Geothermal Research*,
doi:10.1016/j.jvolgeores.2012.11.007

Abstract: A field of small (10s of km in diameter) volcanoes in the Syria Planum region of Mars is mapped to determine abundance, distribution, and alignments of vents. These data are used to assess possible variations in eruption style across space and time. Each eruption site is assigned a point location. Nearest neighbor and two-point azimuth analyses are conducted to assess the spacing and orientations between vents across the study area. Two vent fields are identified as unique volcanic units along with the previously identified Syria Mons volcano. Superposition relationships and crater retention rates indicate that these three volcanic episodes span ~ 900 Ma, beginning in the early Hesperian and ending in the Early Amazonian. No clear hiatus in eruptive activity is identified between these events, although a progression from eruptions at Syria Mons, to regionally distributed eruptions that form the bulk of the Syria Planum plains, to a final migration of dispersed eruptions to Syria's northwest is identified. Nearest neighbor analyses suggest a non-random distribution among the entire population of Syria Planum, which is interpreted as resulting from the interaction of independent magma bodies ascending through the crust during different stress regimes throughout the region's eruptive history. Two-point azimuth results identify three orientations of enhanced alignments, which match well with radial extensions of three major tectonic centers to the south, east, and northwest of the study area. As such, Syria Planum volcanism evolved from a central vent volcano to dispersed shield field development over several hundred million years, during which the independent magma bodies related to each small volcano interacted to some extent with one or more of at least three buried tectonic patterns in the older crust. These results show a strong relationship between independent mapping efforts of tectonic and volcanic features. Continued integration of volcano-tectonic mapping should provide direct constraints for future geodynamic models of magma production and thermal evolution of the Tharsis province.

Validating lava flow emplacement algorithms with standard benchmarks

J. Richardson, L. Connor, C. Connor, and S. Charbonnier

A major existing need in assessing lava flow simulators is a common set of validation benchmark tests. We propose three levels of benchmarks which test model output against increasingly complex standards. First, simulated lava flows from valid emplacement algorithms should remain unchanged given effectively identical input parameter spaces (e.g. length of a flow run over a simple slope should not change if the underlying slope is rotated). Second, lava flows simulated in simple parameter spaces can be tested against analytical solutions or empirical relationships seen in Bingham fluids. For instance, a lava flow simulated on a flat surface should produce a circular outline. Third, lava flows simulated over real world topography can be compared to recent real world lava flows, such as those at Tolbachik, Russia, and Fogo, Cape Verde.

Success or failure of emplacement algorithms in these validation benchmarks can be determined using a Bayesian approach, which directly tests the ability of an emplacement algorithm to correctly forecast lava inundation. Here we focus on two posterior metrics, P(A|B) and P(\A|\B), which describe the positive and negative predictive value of flow algorithms. This is an improvement on less direct statistics such as model sensitivity and the Jaccard fitness coefficient.

We have performed these validation benchmarks on a new, modular lava flow emplacement simulator that we have developed. This simulator, which we call MOLASSES, follows a Cellular Automata (CA) method. The code is developed in several interchangeable modules, which enables quick modification of the distribution algorithm from cell locations to their neighbors. By assessing several different distribution schemes with the benchmark tests, we have improved the performance of MOLASSES to correctly match early stages of the 2012-3 Tolbachik Flow, Kamchakta Russia, to 80%. We also can evaluate model performance given uncertain input parameters using a Monte Carlo setup. This illuminates sensitivity to model uncertainty.

Spatial density characteristics of volcano clusters on Earth, Mars, and Venus

J. Richardson, C. Connor, L. Connor, J. Bleacher, L. Glaze

Non–parametric kernel density estimation provides a new tool in planetary geology for quantifying the spatial arrangement of vent fields and volcanic provinces. Unlike parametric methods where spatial density, and thus the spatial arrangement of volcanic vents, is simplified to fit a standard statistical distribution, non–parametric methods offer more objective and data–driven techniques to characterize volcanic vent fields. This method is applied to volcanic fields on Mars and Venus. The spatial densities are then compared to terrestrial volcanic fields.

Spatial density can be estimated using a kernel function, which is simply a spatial density about a point, the center of a volcanic vent. These kernels are summed to calculate the spatial density of vents for any location in the region of interest. Kernel functions are dependent on a smoothing parameter, or bandwidth, which is analogous to standard deviation of a Gaussian distribution. For one kernel function (Wand and Jones, 1995), the bandwidth is given as a 2×2 element matrix, H, used to estimate spatial density, λ, at any given location. The bandwidth is here optimized using a smoothed asymptotic mean integrated squared error (SAMSE) method, developed by Duong and Hazelton (2003).

Initial findings of this exercise show a "planetary signature" within bandwidth sizes produced for distributed volcanic fields on Earth, Mars, and Venus. On Earth, volcanoes in such fields tend to cluster on the order of one vent per 10s km^2 of land; on Venus the spatial ordering is one vent per 100s km^2 of land; and on Mars, each volcanic edifice is given 1000s km^2 of space. It has also been seen on Mars that volcanoes in different clusters might be spaced even further apart, and in some clusters, such as those in the caldera of Arsia Mons, volcanoes might be more "Venus-like" or "Earth-like".

The clustering of volcanic edifices as modeled through KDE can be interpreted in many ways, but might ultimately be controlled by a small number of factors including 1) magma productivity, 2) source depth, and 3) source areal extent.