ACTIVE SOURCE SEISMIC INVESTIGATION OF THE SAN FRANCISCO VOLCANIC FIELD ALONG SIMULATED LUNAR TRAVERSES.

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Introduction: Lunar surface traverses during Apollo and analog human lunar mission simulations have commonly focused on routes to locations that prioritize surface observations and sample collection activities. Along the way, geophysical measurements may be made, but the traverses were not designed to optimize the information geophysics can provide about a fieldsite. Terrestrial volcanic fields, such as the San Francisco Volcanic Field (SFVF), located to the north of Flagstaff, AZ, have been used as scientific and operational analogs for the seismic studies of features similar to those that have been and will be examined on the lunar surface [1,2,3,4]. In 2010, NASA simulated a multi-week human lunar rover traverse mission in the SFVF, as part of the Desert Research and Technology Studies (RATS) project [5]. The traverse routes and associated science station locations for this simulation were selected based on addressing questions requiring surface observation and sampling tasks. Geophysical studies were not included in this simulation. We returned to the as-executed Desert RATS 2010 traverse routes and obtained active seismic refraction data from nineteen geophone lines placed at science station locations accessed during the simulation.

Study Area: Our field site is an approximately 50 km^2 portion of the SFVF that is that is centered on the SP Crater cinder cone (Figure 1). The study site is characterized by numerous cinder cone volcanoes, lava flows, and faults [6]; all features that resemble their lunar counterparts. This field area includes 19 of the science station locations visited by the 2010 crews [7].

Approach: For this study, we performed a series of nineteen active source seismic geophone lines similar to the active seismic experiments conducted during Apollo 14 and 16. These consisted of three geophones at 46 m spacing and an astronaut activated source known as a thumper with a predominant frequency of 22 to 29 Hz [8,9]. The locations of our seismic lines were selected prior to entering the field, based on criteria associated with the 2010 Desert RATS simulation. There are two parts to the criteria. First, each line had to have a point located within 100 m of a science station. Second, the line was to be oriented to cross as many of the accessible geologic units, as mapped by the Desert RATS precursor analysis (Figure 1), as possible. If needed, the line location selections were then modified in the field, to accommodate terrain and to account for field observations of the area. Our geophone lines were 115-meter long lines comprised of twenty-four 4.5 Hz vertical-component geophones spaced at 5 m increments. Our active source was a manually slung 4.5-kg sledge hammer striking an approximately 0.5-meter square by 1-centimeter thick aluminum metal plate, producing seismic waves with a frequency content from 10-250 Hz. The seismic shots were conducted at 30-meter intervals with offset distances of up to 60 m prior to the first geophone and 65 m beyond the final geophone. The seismic waves are recorded upon arrival at the geophones after being refracted and reflected at subsurface velocity discontinuities.

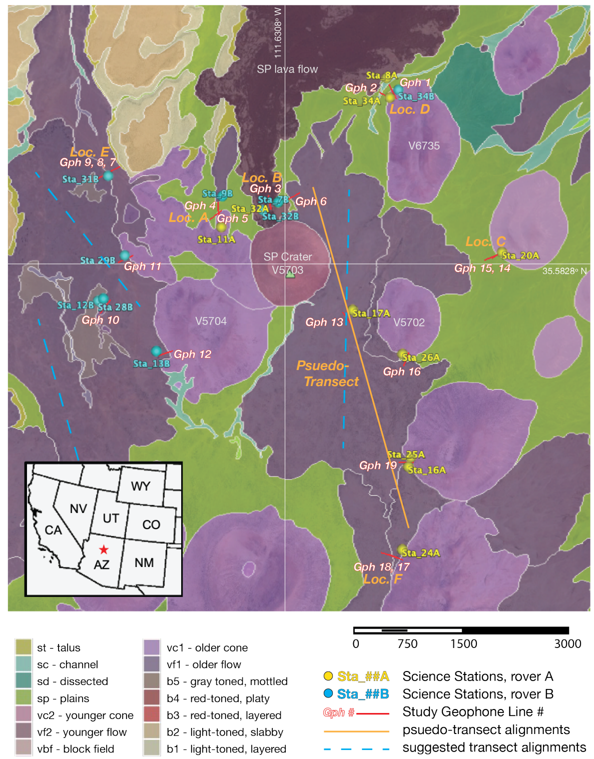

Figure 1: Overview of SFVF field area, with geologic units as defined by Skinner & Fortezzo [10] for the NASA Desert RATS 2010 lunar rover simulation. Modifications show science stations (blue & yellow dots), this study's geophone lines (red lines), analysis groups (Loc. A-F), pseudo-transects (orange lines), and suggested transects (blue dashed lines).

Analysis: Here we analyze the refracted P-waves resulting from our hammer source. For this analysis, we make the assumption that the seismic velocity continually increases with depth. The arrival time of the refracted P-waves at each of the geophones were picked by a seismic operator. These travel time picks were then analyzed using a 1-D seismic Bayesian inversion method [11] to determine the one-dimensional subsurface seismic structure beneath each geophone line. For each of our 19 seismic lines, the Bayesian analysis provides an ensemble of 2000 1-D seismic velocity models that fall within the uncertainty of the travel time picks.

From each ensemble we determine the most likely P-wave seismic velocity structure in the upper 60 m of the subsurface at one-sigma uncertainty level for each of the nineteen individual locations. By combining all the ensembles, we create a histogram (Figure 2) to determine the range of velocities and layers found across the nineteen geophone line locations.

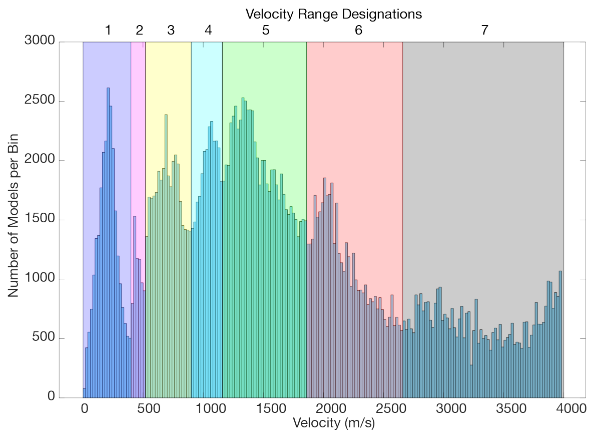

Figure 2: Histogram of velocities from all nineteen geophone line refraction analysis ensembles. Velocity ranges shown by colored regions and designated as 1 thru 7.

Results: In our data from the refraction analysis, we identified seven distinct seismic velocity ranges beneath the SFVF region. Beginning at the surface, the first velocity range (VR1) is identified to a depth of 1 m to 3 m with a mean velocity of 206 m/s ± 83 m/s. We interpret this as a veneer of regolith at the surface that is consistent with observed basaltic ash velocities between 240 and 370 m/s [9]. VR2, with a velocity from 400 to 520 m/s, is interpreted to be primarily cinder, possibly including ash and filling an upper highly fractured basalt layer. VR3 is bounded between 520 to 900 m/s, and interpreted to consist of primarily fractured basaltic lava flow, which is consistent with previously collected in-situ velocity range of 750 to 1200 m/s [12]. VR4 with a narrow range of 900 to 1160 m/s, is interpreted to be a transitional layer from the fractured basalt of VR3, to consolidating lava flows of VR5 & VR6. VR5 encompasses velocities from 1160 to 1860 m/s, and VR 6 bounded from 1860 to 2660 m/s. VR5 and VR6, appear to be two distinct layers of increasing consolidation of lava flows. Finally, VR7 includes any velocities above 2660 m/s, with mean of 3411 m/s. It is interpreted to be the local country rock which consists of the basement sedimentary Kaibab limestone, which has a previously documented seismic velocity of 4167 m/s with a standard deviation of +/- 1129 m/s [13].

Our seismic refraction enables us to establish the seismic velocity ranges that are associated with the different geological layers present beneath our field area. Thus, we are able to interpret the depth and geological context of the underlying layers that exist beneath each study site. These regionalized layer definitions help to constrain unit thickness for each of the 1-D profiles, and establish the regolith thickness beneath each study site.

Implications for Future Missions: Our traverse-based approach lacked flexibility to locate the seismic lines to address specific geophysical questions, and limited the identification of structural trends or generalizing characteristics of specific features or structures. Without the context of multiple sites, interpretation of the seismic velocities would be non-unique and difficult to ascribe to particular geological units. We recommend that the return from geophysical studies is maximized through proper pre-mission (pre-field deployment) planning of data sampling locations, similar to conducting surface geologic observations and sample collection. It is recommended that seismic line deployment locations include a systematic selection of geologic units, and when possible ground truth of local stratigraphy from outcrops and craters co-located to seismic line positions. Our study provides understanding for the application of terrestrial active source seismic fieldwork methods to future seismic studies within lunar surface traverses. For future lunar surface missions, we suggest use of traverse plans containing a balanced approach to complementary geophysical and geologic tasks to address the investigations, and maximize the scientific return.

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