CONSTRUCTING A PRELIMINARY PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR THE MOON.

Lisa S. Schleicher[1] , Nicholas C. Schmerr[2], Thomas R.Watters[3], Maria E. Banks[3,4], and Michelle Bensi[5], [1]Independent Researcher, lisaschleicher.org (lisasschleicher@gmail.com), [2]University of Maryland, Department of Geology, College Park, MD 20742, USA (nschmerr@umd.edu), [3]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA (WattersT@si.edu), [4]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (maria.e.banks@nasa.gov) [5]University of Maryland, Department of Civil and Environmental Engineering, College Park, MD 20742, USA (mbensi@umd.edu).

Introduction: Global coverage with high resolution images and altimetry data from the Lunar Reconnaissance Orbiter (LRO) spacecraft have allowed detailed mapping of tectonic features on the Moon, including lobate scarps, wrinkle ridges, and graben [1–7]. Lobate scarps are widely distributed, small-scale contractional tectonic landforms, interpreted to be surface expression of thrust faults [1–4]. To date, over 3,500 of these fault scarps have been identified using Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images (Fig. 1).

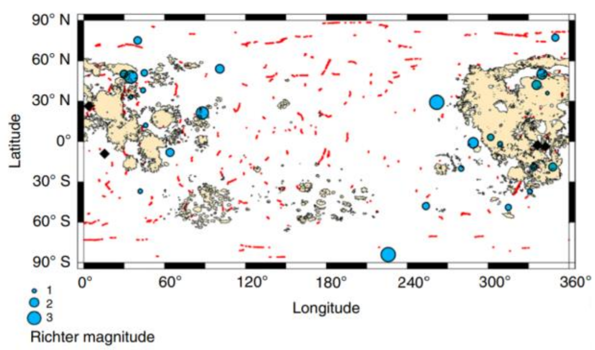

Figure 1. Map of lobate scarp thrust faults on the Moon (red lines), epicentral locations of shallow moonquakes (blue dots), Apollo Seismic Network Seismometers (black diamonds), and mare basalt units (tan polygons) (figure modified from [1]).

The locations of the young fault scarps can now be combined with our understanding of the impact crater production rate, evidence for and characteristics of recent activity along faults (crisp morphologies, cross-cutting relationships with small craters, associated small-scale graben, crater-size frequency distribution analyses of surfaces surrounding the faults), newly developed lunar seismic ground motion scenario shakemaps (Fig. 2) [1], and data from the Apollo-era seismic network on the nature of the subsurface [8–10]. These data and information collectively offer the components needed to develop a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon.

In this study we explore the application of PSHA methods utilized in the nuclear industry [11–12] (and more broadly) to selected test sites on the Moon. These methods may provide a useful resource for evaluating seismic hazards on the lunar surface. Such a hazard evaluation is essential to support the future design and construction of structures, systems, and components (especially possible nuclear-based power source options) that are being explored. Such hazard evaluations are particularly timely in lieu of renewed interest in the lunar surface operating environment and NASA's Artemis lunar exploration program. The results of this study will also aid in exploring the development of future lunar seismic monitoring networks.

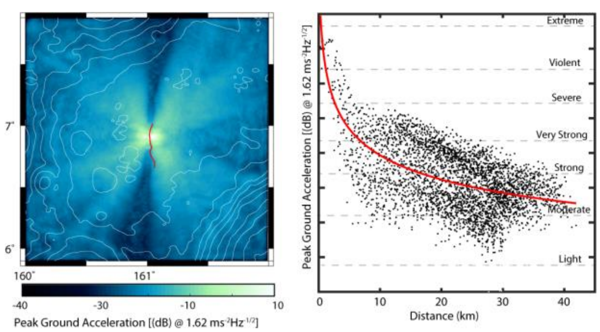

Figure 2. Shakemap (left panel) and expected peak ground acceleration (right panel) for a moment magnitude (*M*w) 6.36 slip event on a lunar thrust fault (red line, right panel) in the Mandel'shtam cluster (6.90°N, 161.02°E) (figure modified from [1]).

Methods: Traditional PSHA calculations involve integrating information regarding the location and magnitude of possible seismic sources and their estimated frequencies of occurrence (seismic source model), estimates of ground motion attenuation (ground motion model), and the effect of the near-surface on the amplification of ground motions (site response), to estimate the probability and severity of expected ground motion at a site of interest on the surface (Fig. 3) [13]. Results of a PSHA are typically presented as a seismic hazard curve, which presents a measure of ground motion severity (e.g., peak ground acceleration) on one axis and the (annual) frequency of exceedance on the other axis. Additional information on the basic elements of a PSHA can be found in Figure 1-1 of [14] or Figure 2.4 of [15].

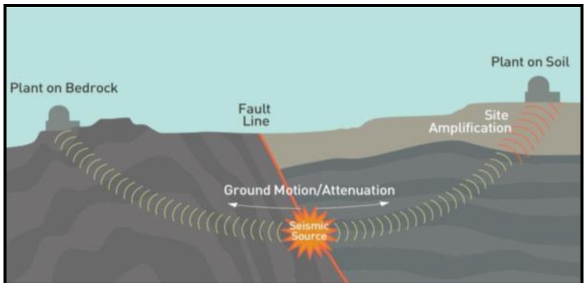

Figure 3. Schematic diagram of PSHA components (seismic source model, ground motion model, and site response) (modified from [13]).

For this study we will develop a seismic source model, ground motion model, and site response model to estimate the seismic hazard at selected test sites on the lunar surface using the following information for each of these PSHA components [14]:

Seismic Source Model. A preliminary seismic source model can be constructed using the location of potential fault sources (i.e. global distribution of lobate scarps) [1–7] and distributed seismicity data from the Apollo era seismic catalog. We plan to develop magnitude-recurrence relationships for these sources by considering established models from the literature (e.g.,Gutenberg-Richter relationship) [8–10] for source scaling and event production rates. We will also incorporate the potential for meteorite impact generated ground motions using crater production rate statistics for the lunar surface. The distribution of site-to-source distance (i.e., the distance from any randomly occurring earthquake to the site of interest) will be defined using spatial geometry information.

Ground Motion Model. A simple ground motion model can be developed using information from lunar shakemaps, as developed in [1] (see Fig. 2). In particular, we can estimate the seismic shakemap near any given active scarp with Serpentine Wave Propagation [15], a code that solves in 3D Cartesian mesh geometry the time-acceleration history of each individual rupture event. Local structural effects include topography in the vicinity of each scarp, scattering from 25% root mean square heterogeneity in V_s and V_p wave velocities in the uppermost 1 km of the model, and the subsurface model of [16]. These shakemaps provide synthetic data that support development of a preliminary ground motion prediction equation that can be used in development of the PSHA (e.g., see curve in Fig 2).

Site Response Model – We plan to use seismic waveforms measured from seismic instruments deployed during the Apollo era [8–10] to derive the velocity of the upper 30 m in the near-surface (V_{s30}) as an input into our site response model using the horizontal-to-vertical spectral ratio method [17–18]. Data recorded by the Passive Seismic Experiments of the impacts of the Saturn Launch Vehicle Third Stage (SIVB) and Lunar Modules will provide measurements of calibrated ground motion in relation to source magnitude.

The results of this analysis will demonstrate the development of preliminary hazard curves at selected locations, which can be used to estimate seismic hazard on the lunar surface. This analysis will help target areas where additional data may be needed to develop a more robust PSHA for design purposes.

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