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Steps towards the determination of deep moonquake source orientations

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1. Introduction

The Apollo Passive Seismic Experiment (PSE) consisted of four seismometers deployed on the lunar surface between 1969 and 1972. Data from these instruments were recorded continuously until late 1977. Several types of seismic signals were recorded by the lunar seismic network, including natural impacts (meteoroids), artificial impacts (booster rockets from the Apollo spacecraft, and the lander ascent stages), shallow moonquakes (natural events occurring in the upper 50 to 220 km of the Moon), and deep moonquakes (natural events occurring between 700 and 1000 km depth).

Deep moonquakes comprise approximately half of the over 12,000 cataloged seismic events [1.]. These deep events are known to originate from over 300 distinct source regions within the Moon (often referred to as "clusters"), with each source emitting its own characteristic waveform. Seismograms from a given cluster are highly similar and can be stacked to enhance the signal-to-noise ratio. This similarity means that all events of a cluster occur within a small volume compared to the dominant wavelength, and that they all share the same source mechanism. In addition, deep moonquakes exhibit periodicity, with events from a given source occurring approximately every 27 days. This periodicity is consistent with tidal forcing, and suggests a relationship between tidal stress and moonquake occurrence (e.g. [2.]).

An important limitation in studies of the relationship between moonquakes and tides is our lack of knowledge regarding deep moonquake source mechanisms. The quality of the lunar seismic data and the limited source/receiver geometries of the Apollo seismic network prohibit the determination of deep moonquake fault parameters using traditional terrestrial techniques [3.]. Without being able to resolve tidal stress onto a known failure plane, we can examine only gross qualities of the tidal stress tensor

fully address the role of tidal stress in moonquake generation. We will attempt to address this deficiency by fitting double couple mechanisms to observed deep moonquake P and S arrival amplitudes.

2. Inversion Procedure

The orientation of a double couple source (the source type typical for fracture processes) in space is defined by three angles: strike, dip, and slip. Strike and dip define the orientation of a plane with respect to the north and horizontal directions, whereas the slip angle defines the direction of motion on that plane.

The textbook method to determine source orientations is to determine the signs of the P wave arrivals at many different stations, project them back on a sphere centered on the hypocenter and then fit the radiation pattern of a double couple to the distribution of pluses and minuses on this sphere. This approach, however, is of limited use for lunar deep quakes, since no more than four seismic stations are available which cover only a small fraction of the focal sphere. As long as the area spanned by the network is not crossed by one of the two nodal planes of the radiation pattern, this method will not provide enough information to constrain the source orientation significantly.

A stronger constraint is posed if not only signs are used, but amplitudes, since these vary strongly with direction. Amplitude, however, is affected by many processes, for which corrections need to be applied. These will be described in the next section.

The fault plane orientation that best fits the observed amplitudes is determined using a grid search approach. All three parameters that define the source orientation are varied over their respective ranges of admissible values (0° to 360° for strike and slip, and 0° to 90° for dip). A least squares misfit is computed to quantify the goodness of fit, and a threshold misfit between acceptable and falsified orientations. The result of the procedure is a complete scan of the parameter space, with a best fitting solution marked and an uncertainty region around the best fit. Preliminary results for a synthetic moonquake are shown in Figure 1.

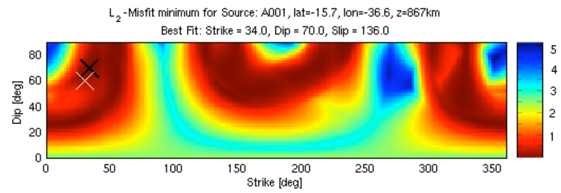

Figure 1: Using a set of amplitude ratios measured at the four Apollo stations from a synthetic event with known focal mechanism (strike=30°, dip=70°, rake=120°), the minimum L-2 misfit computed at 2-degree increments of strike and dip. The best-fitting (minimum-misfit) grid space (corresponding to the labeled fault parameters) is marked with a black X. The input focal mechanism is marked with a white X.

Before we can proceed with this method using real moonquake data, we must explore the necessary amplitude corrections to be applied to the seismograms as measured by the Apollo instruments.

3. Site Corrections

The amplitude of a wave that arrives at a seismic station is affected by several different effects, including source strength, source-receiver separation, geometric spreading of the wave front, anelastic attenuation, scattering, receiver side amplification in thin layers underneath the receiver, and the free surface boundary condition. By taking not the P amplitude alone, but the ratio of P and S amplitudes, and assuming that the ratio of P and S wave velocities is constant along the ray (supported by Earth experience and from known rock properties), most of these effects can be removed, because P and S waves then follow essentially the same paths and distance-controlled effects cancel out. Also, the P/S amplitude ratio is a strong constraint on orientation, since the P and S radiation patterns have different shapes and only few directions offer a certain ratio.

Other effects, especially those of receiver side layering which can hardly be addressed in waveform modeling, are removed using an empirical site correction. For this correction, the distribution of the logarithm of all S/P ratios measured at a given site is

large set of randomly oriented sources, i.e. with the distribution of log(S/P) over the entire focal sphere [4.]. Figure 2 shows an example using earthquake data. The observed log(S/P) distribution will be shifted compared to the theoretical one, thus defining a site specific correction factor which is then applied to all amplitude ratios measured at this site. The site corrections themselves are bulk characterizations of the receiver subsurface and may be useful for the planning of future landing sites with similar geological context.

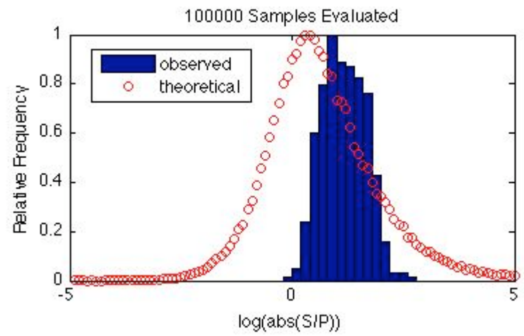

Figure 2: Histogram of the observed log(S/P) amplitudes for a series of earthquake aftershocks. The red curve shows the theoretical distribution assimung that the observations evenly sample the focal sphere.

4. Future work

Once we have applied the site corrections to P and S arrival amplitudes measured from the Apollo data, the corrected amplitudes will be used to constrain the strike, dip, and slip angles of deep moonquake fault planes with respect to the lunar surface.

References

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