SPATIAL EXTENT OF A DEEP MOONQUAKE NEST — A PRELIMINARY REPORT OF REEXAMINATION.

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Introduction: Deep moonquakes, occurring at depths about halfway to the center of the Moon, were discovered during the Apollo lunar landing missions, 1969-1972. Their near-monthly occurrence with nearly identical waveforms at any given seismic station suggests that they are strongly influenced by tides, caused by the Earth and the Sun, acting on certain limited regions of the deep lunar interior. However, much about them is unknown, why they are restricted to certain depths and to limited source regions (nests), and what they tell us about the nature of the material and dynamics of the interior of the Moon.

A piece of information helpful to decipher their true nature is the spatial extent and distribution of their hypocenters. The occurrence of nearly identical waveforms suggests groups of hypocenters appear in close proximity to one another, but can we tell how closely they are located and how they are distributed?

The Apollo PSE (Passive Seismic Experiment) data from all stations of the seismic network were received in real time at a common receiving station on Earth in digital form. This provided extremely high inter-station timing accuracy not achievable for most earthquake data on Earth at that time. We took advantage of this to compute relative locations of waveform-matched events, and concluded that deep moonquake foci in the A1 moonquake nest were concentrated on a nearly horizontal plane of less than 1 km in diameter [1].

This earlier study was based on deep moonquake events visually identified on seismograms. As such, the events used for the analysis were limited to those having highly similar waveforms, and this may have influenced the earlier results. In particular, the limited spatial extent of each hypocenter group may have been an artifact of this selection process.

A recent reanalysis of earlier unidentified seismic events fully utilizing the high capability of present-day computers expanded the list of positively identified deep moonquakes by more than a factor of five [2]. The new list contains many events that are not visually matched in waveforms, yet correlated at a significant level when cross-correlated with a computer. Thus it became imperative to reexamine the spatial distribution of deep moonquake hypocenters including the newly identified events. We expected that expanding the list to include events of lower waveform correlation might extend the size of their source region, and might also alter the spatial distribution of foci.

A1 Moonquakes: We concentrate our initial analysis to A1 moonquakes, which represent the most active deep moonquake nest of all observed during the Apollo project. It is located near 16°S, 37°W, about 18° SW of Apollo station 12, at a depth of about 870 km [3]. In addition to the well defined monthly periodicity, their temporal occurrence pattern includes semi-monthly periodicity as well as multiple events within a few-day interval [4]. Our earlier study [1] lists 141 events belonging to A1, and our latest event catalog [available on-line at ftp://ig.utexas.edu/pub/PSE/catsrepts, file name levent.0704] lists 318 events. A recent computer search [5] added 101 previously uncatalogued events that belong to this group. The analysis reported here is based on the second list.

Precise Determination of Relative Seismic Arrival Times: Relative arrival times of seismic phases, either between two different phases at a given station or same phases between two different stations, can be determined at a very high accuracy from the frequency derivative of the cross phase spectrum of the two phases [1]. By using the long codas following P- and S-wave arrivals that are characteristic of all deep moonquake signals, timing accuracy that is a small fraction of the sampling interval (151 ms in case of PSE long-period data) can be achieved.

Variability of S-P Times: A small variation of S-P arrival time interval relative to a reference event is computed for each event. (1976 day 76 event was used as a reference.) This variation is directly related to the variation in hypocentral distance from each station.

Results. Except for a few cases where data quality was poor, the computed variation of S-P times was mostly within ±40 ms from the reference event at each of the stations 12 and 14. (P-wave arrivals at stations 15 and 16 were too weak to give meaningful results at these stations.) An example is shown in Fig. 1. S-P time variation of ±40 ms corresponds to a variation in hypocentral distance of about ±400 m, assuming P-wave velocity of 8.0 km/s and S-wave velocity of 4.5 km/s in the hypocentral region.

We also looked for any correlation between the values of the relative S-P time and cross-correlation coefficient of waveforms, expecting to see a negative correlation, as it would be if lower waveform cross-correlation were due to larger spatial separation between the two events. Contrary to our expectation, however, no such correlation was found.

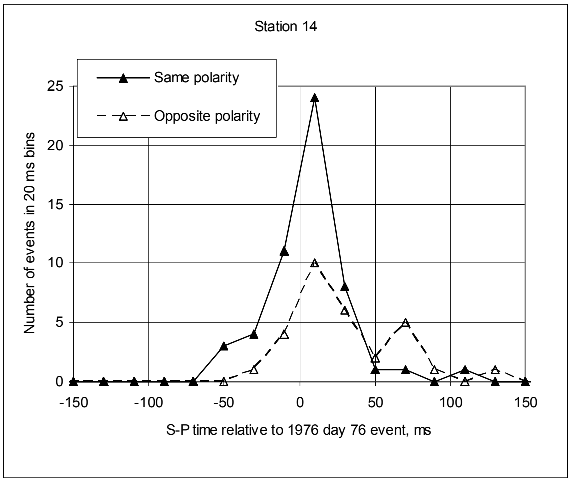

Fig. 1. An example of distribution of S-P times relative to the reference event of 1976 day 76. Events of polarity same as and opposite to the reference event are plotted separately.

Variability of S Arrival Time Differences: A small variation of S arrival time differences between a pair of stations relative to that for a reference event is computed for each event and for each pair of stations. This variation points to a variation in the difference in hypocentral distances between stations.

Results. The computed variation of S-wave arrival time differences was mostly within ±100 ms from the reference event for all pairs of stations. The distribution is skewed for some station pairs, suggesting that more events are located closer to one station than the reference event. This is particularly clear when station 16 is one of the pair. The variation of ±100 ms corresponds to a variation in difference of hypocentral distances between stations of about ±450 m, assuming S-wave velocity of 4.5 km/s in the hypocentral region.

The correlation between the values of relative S-wave arrival time differences and waveform cross-correlation coefficient was again not apparent.

Preliminary Conclusion: The variability of both S-P times and S arrival time differences turned out to be about the same as those found earlier with a highly correlated data set [1]. This is contrary to our initial expectation. Furthermore, no clear negative correlation between the arrival time deviation and waveform cross-correlation also contradicts our earlier expectation. Thus we must conclude that the range of waveform correlation observed is not primarily due to a large spatial spread of deep moonquake foci, but is due to something else. One possibility that comes to our mind is a change of focal mechanisms from one event to the next in the same source region. In fact, our earlier study did indicate rotation of seismic slip direction with changing tidal stress [1]. This may be sufficient to explain the observed variation in seismic waveforms without spatially relocating the source by a large distance.

The confinement of deep moonquake hypocenters to such a small region, much smaller than most earthquakes here on Earth observed along and around a fault of appreciable length, must be explained in terms of the mechanism of their generation.

Continuing Analyses: From the relative arrival times computed above, we are now in the process of determining the 3-D distribution of hypocenters in the A1 source region. Once this is done, we will look to see if there is any correlation between hypocentral location and other parameters, such as signal polarity suggesting seismic slip directions and time of occurrence, which relates to tidal stress variation. We also plan to extend the analysis to look at source regions other than A1 to see if they may reveal anything different.

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