MORE FAR-SIDE DEEP MOONQUAKE NESTS DISCOVERED. Y. Nakamura, Institute for Geophysics, John A. & Katherine G. Jackson School of Geosciences, The University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin, TX 78759-8500; yosio@utig.ig.utexas.edu.

Introduction: As reported last year [1], we started to reanalyze the seismic data acquired from 1969 to 1977 with a network of stations established on the Moon during the Apollo mission. The reason for the reanalysis was because recent advances in computer technology make it possible to employ much more sophisticated analysis techniques than was possible previously. The primary objective of the reanalysis was to search for deep moonquakes on the far side of the Moon and, if found, to use them to infer the structure of the Moon's deep interior, including a possible central core.

The first step was to identify any new deep moonquakes that escaped our earlier search by applying a combination of waveform cross-correlation and single-link cluster analysis, and then to see if any of them are from previously unknown nests of deep moonquakes. We positively identified 7245 deep moonquakes, more than a five-fold increase from the previous 1360. We also found at least 88 previously unknown deep-moonquake nests [2].

The question was whether any of these newly discovered nets were on the far side of the Moon, and we now report that our analysis of the data indicates that some of them are indeed on the far side.

Waveform Stacking: Deep moonquake signals are extremely small, often of amplitude barely above the smallest digitizing level used for recording the data. For such small signals, it is nearly impossible to identify arriving phases on individual seismic traces. Fortunately, many events with nearly identical waveforms occur repeatedly at each nest, and their waveforms can be 'stacked' to improve the signal-to-noise ratio. Thus we have used an optimum stacking technique based on estimated signal-to-noise ratio of individual traces [3] to enhance the signals.

Arrival Time Picks: Locating each deep moonquake nest requires at least four arrival times from three or more stations. Determining these arrival times, however, turned out to be often difficult even after waveforms are stacked to enhance the signal-to-noise ratio. S-wave arrival picks are relatively easier because of their larger amplitudes, although sometimes interference from large P-wave coda and possible S-to-P conversion at an interface below the station obscures the S-wave arrival [4]. P-wave arrival picks are much harder to make because of their small amplitudes. They are often not identifiable even after stacking of traces. We need a better way to identify arrivals, as will be discussed later. With this problem in mind, we did make tentative arrival picks on stacked seismograms, sometimes comparing stacked waveforms with a set of individual traces to ascertain the reliability of each arrival pick.

Tentative Locations: Using the tentatively determined arrival-time picks above, and based on the lunar velocity model of Nakamura [5], we have now located each of the deep moonquake nests, both old and new, whenever a sufficient number of picks are available. Of the 165 (77 old and 88 new) nests identified in the initial step, 115 (55 old and 60 new) nests are clearly located on the near side of the Moon. The identity of one new nest, A247, is now in doubt, possibly consisting of a glitch-infested group of events. This leaves 49 (11 old and 38 new) nests as candidates for possible far-side nests. P- and S-wave arrival times, to the nearest second, of these 49 nests are listed in Table 1.

Of these 49 nests, four nests have enough arrival picks for their hypocenters to be located (Table 2). Of these four, two of them (one old: A33 and one new: A285) are definitely on the far side, but the epicenters of the other two (both new) are near the limb and could be on either side of the Moon. The new A285 nest shows signal characteristics quite similar to those of the sole previously known far-side nest, A33, having clear S-wave arrivals at stations 15 and 16, and clear P- but no clear S-wave arrival at station 14.

All of the remaining 45 (10 old and 35 new) nests of Table 1 provide no clearly readable P-wave arrival at any of the stations, and thus their locations are uncertain. All of them are missing clear S-wave arrivals at one (26 nests; next to the last column of Table 1) or two (19 nests; the last column of Table 1) corners of the network of seismic stations. (The stations form a near-equilateral-triangular array, nearly 40° (1120-1180 km) on each side, centered near the sub-Earth point with stations 12 and 14 occupying one corner.) This can mean either the nest was on the far side or the signal was simply too weak. Thus these nests need more careful examination.

We detected no nests where clear S-wave arrivals were absent at all three corners of the array. Since the S-wave shadow for deep moonquakes starts at around 120° from the epicenter, this means that no nests within roughly 40° radius of the antipode of the Moon were identified. Such an area constitutes about 12% of the surface area of the Moon. In comparison, 56 nests were found within a 40° radius of the sub-Earth point. Whether this is entirely due to the distribution of seismic stations or to some other causes must be investigated.

Table 1. Tentative arrival time picks

A#	Tp*				Ts*				Located	No S at	
	12	14	15	16	12	14	15	16		1 c	2 c's
2					220	228					x
12					211	219					x
31							243	271		x	
33		133	102	94			310	293	x	x	
57					203	208					x
72						213		267		x	
75					235	245					x
79					228	238					x
89						277		231		x	
90						270		237		x	
98								221			x
205					203			210		x	
206					229	239					x
207					228	234					x
211						282		236		x	
213						383	272			x	
214							234	348		x	
215					227	220					x
217					227	239					x
220					242	245					x
221					262	251					x
222					232	242					x
227						274					x
228						226		218		x	
232							285	269		x	
235							200	236		x	
240						291		323		x	
241				70		278		231	x	x	
252						289		243		x	
253						244		340		x	
254						225		246		x	
256						305		240		x	
261								290			x
262						282		230		x	
263						301	219			x	
264						220		300		x	
265						297	247			x	
268								240			x
269								193			x
270						237		232		x	
273						222		190		x	
274						291		233		x	
275								175			x
277						267	227			x	
278								238			x
282			110	95		338	238	279	x		
284							268	243		x	
285		170		95			242	285	x	x	
288						185		280		x	

* Tp and Ts arrival times are relative to an arbitrary reference time.

Table 2. Estimated nest hypocenter locations

A#	Latitude	Longitude	Depth, km
33	5±3°N	116±9°E	877±112
241	69±4°S	75±25°E	*
282	16±2°N	97±12°E	1141±74
285	43±4°N	104±13°E	*

* Focal depth assumed to be at 933±109 km, the mean and standard deviation of the depths of deep moonquakes located earlier [6].

Next Steps: The results so far give us up to four located far-side deep moonquake nests. However, they are too far from the antipode of the Moon to provide any new information on the deep interior of the Moon. Our best chance to see the deeper interior of the Moon will be to extract further information from the remaining 45 nests listed on Table 1. This may be a difficult task. One way to improve this situation is to find a better way to identify arrivals, especially of P-waves. We are currently looking into possible use of receiver functions [e.g., 7] to achieve this goal.

Another possibility is to use information other than the arrival times, such as relative amplitudes, to provided added constraints on possible locations. We have had a preliminary look into using amplitude information, but the result so far is inconclusive.

If there is no breakthrough in this effort, we may have to wait till we acquire more data from the Moon. The Japanese Lunar-A probe to the Moon [8] is now scheduled to be launched late this summer with seismometers, one to be deployed on the near side and the other on the far side. A combined analysis of the data expected from this mission with the currently available Apollo data may prove to be quite useful for inferring the Moon's deeper structure.

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