Apollo 14 Active Seismic Experiment

Abstract. *Explosion seismic refraction data indicate that the lunar near-surface rocks at the Apollo 14 site consist of a regolith 8.5 meters thick and characterized by a compressional wave velocity of 104 meters per second. The regolith is underlain by a layer with a compressional wave velocity of 299 meters per second. The thickness of this layer, which we interpret to be the Fra Mauro Formation, is between 16 and 76 meters. The layer immediately beneath this has a velocity greater than 370 meters per second. We found no evidence of permafrost.*

A seismic refraction experiment was carried out during the Apollo 14 mission with the purpose of determining the near-surface properties of the moon to a depth of approximately 460 m (1500 feet). This experiment, called the Active Seismic Experiment (ASE), differs from the Passive Seismic Experiment in that it utilizes explosive sources and an array of geophones. The experiment also operates in a passive mode during intermittent listening periods.

Two seismic energy sources are used, a thumper device activated by the astronauts and a mortar package containing four high-explosive grenades. The grenades are launched by rocket by command from the earth and are designed to impact at ranges up to 1524 m (5000 feet).

Apollo 14 astronauts detonated 13 of 21 explosive initiators and deployed the mortar package during the mission. Because of possible hazards to other experiments in the vicinity, the four grenades will be launched later, when the collection of essential data in other experiments is complete. The instrumentation for the experiment has been described elsewhere (*1*).

Typical seismic data recorded from thumper shots are shown in Fig. 1. The ASE operates in a passive listening mode for a 30-minute period each week. (Since the ASE data stream preempts all other experimental data, the experiment cannot be left on continuously.) Data for two events, recorded in the passive mode on 19 February 1971, are shown in Fig. 2. The signal amplitude is largest at a single geophone. The signal is discernible above the ambient noise level but greatly reduced in amplitude on the other geophone channels.

The signals recorded in the passive mode are similar to those produced by thumper firings close to a geophone but 100 to 200 times smaller in amplitude. They are also strikingly similar to the signals for type-X events (impulsive beginnings and relatively short durations, normally less than 10 seconds) recorded during the Apollo 11 mission (*2*). The latter may have been produced by direct micrometeoroid impacts on the Passive Seismic Experiment (PSE).

Figure 3 is a section of a composite record of all the thumper data recorded by geophone 2. This figure shows the change in wave form and shift in arrival time of wavelets as a function of the distance from source to receiver.

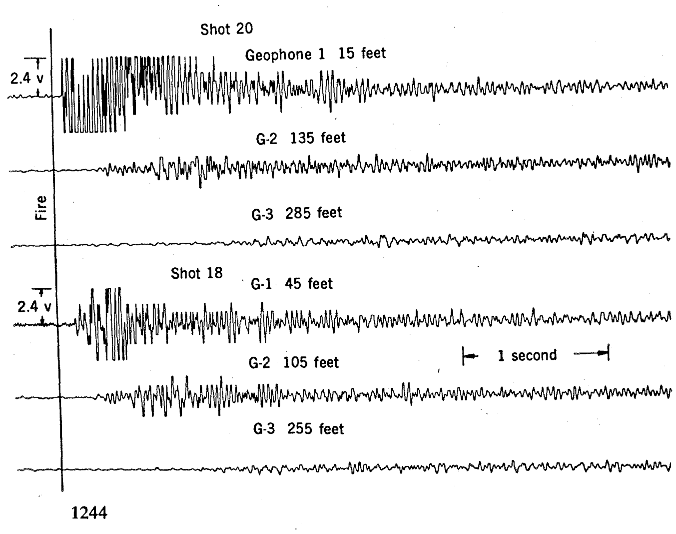
Two P-wave (compressional wave) velocities are represented in the travel-time data, 104 m/sec for a direct arrival and 299 m/sec for a faster arrival. The layers of material characterized by these velocities are designated A (104 m/sec) and B (299 m/sec). No variation appears in P-wave velocities across the section sampled.

Seismic signals were also generated by the ascent of the lunar module and recorded by the Apollo 14 PSE at a distance of 178 m (584 feet). The travel time for the second arrival is nearly identical to that predicted for a direct seismic wave propagating with a velocity of 104 m/sec. A first arrival has a travel time somewhat faster than that predicted from a refraction from the top of the horizon (layer B), which suggests that a material with a faster intrinsic compressional wave velocity lies beneath layer B.

If the assumption is made that this underlying material possesses an infinite compressional wave velocity, a maximum estimate of the thickness of layer B can be derived. Similarly, if it is assumed that the critical distance for the arrival of the head wave traveling through the underlying material is 100 m (that is, at the end of the geophone line), a minimum velocity of 370 m/sec is obtained in this layer, which is designated layer C. Calculations indicate that the range of possible thicknesses for layer B is between 16 and 76 m.

The velocity 104 m/sec is characteristic of a porous and highly brecciated rock material such as the lunar regolith. This layer (A) is 8.5 m thick. The nature of layer B is less clear. The geophone line lies in part on Eratosthenian Crater cluster material, which Offield (*3*) interpreted as having been derived from clusters of primary craters or secondary craters of an unknown source. Craters from which such cluster material is derived are not large (300 to 400 m in diameter), and the minimum thickness of 16 m that we calculate for layer B is more than one would expect from craters of this size.

A more likely explanation for the origin of this layer is that it is either the smooth terrain material of Offield (*3*) or the Fra Mauro Formation. According to Offield, the smooth terrain material is "similar to nearby plains material of presumed volcanic origin . . . of uncertain thickness," and the Fra Mauro Formation consists of "material



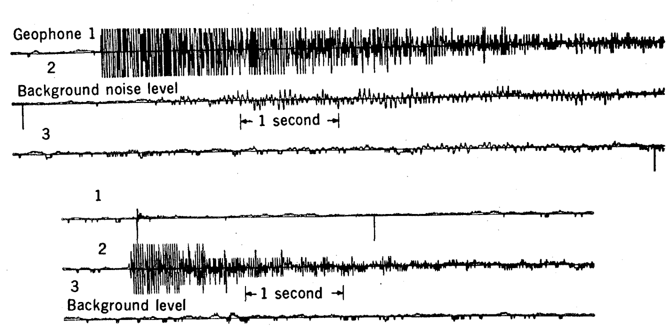


Fig. 1 (left). Seismic signals produced by thumper firings 18 and 20 on the lunar surface (1 foot = 0.3 m). Fig. 2 (right). Signals recorded during the passive listening mode on 19 February 1971.

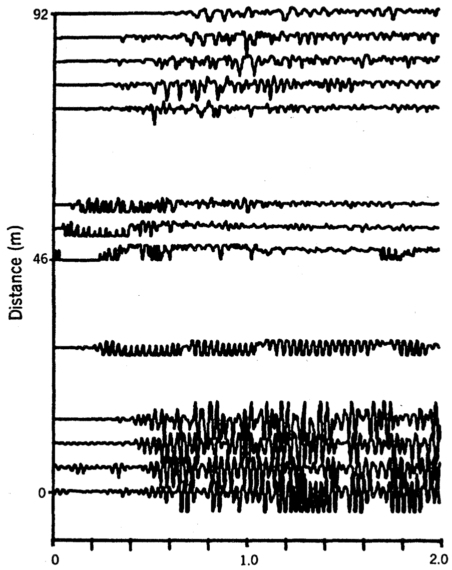


Fig. 3. Seismic signals produced by thumper firings, as recorded at geophone 2. The traces are aligned at the instant of firing of the thumper.

of ejecta blanket surrounding the Imbrium basin."

We have examined two aspects of the Apollo 14 seismic data in an attempt to deduce evidence supporting one or the other of the above models, that is, smooth terrain material or Fra Mauro Formation. First, we calculated the thicknesses of overlapping ejecta blankets from craters near the Apollo 14 site. We considered only those craters younger than the Fra Mauro Formation and extended our calculations to a maximum distance of 1000 km. Details of the results of these calculations are forthcoming [see Hu and Watkins (*4*)]. The calculation scheme was empirical but appears to have given good results.

For the Apollo 14 site, the calculated regolith thickness is 3.9 to 7.2 m. The calculated range of thickness of the Fra Mauro Formation is 5.5 to 15.6 m (*4*). The observed thickness of layer A and the minimum thickness of layer B calculated from seismic data are thus approximately the same as the maximum thicknesses calculated for the regolith and the Fra Mauro Formation, respectively (*4*).

Watkins *et al.* (*5*) measured in situ velocities in a number of different rock types with possible lunar analogs. Their results are compared with lunar data in Fig. 4. Lunar data and data from the Meteor Crater, Arizona, ejecta blanket are shown in solid circles. The porosity of the Apollo 14 regolith was assumed to be the same as that of the Apollo 11 regolith (*6*). The relatively lower velocities of the lunar rocks in comparison with terrestrial rocks of comparable porosities is probably due to the greater degree of brecciation of the lunar and Meteor Crater rocks.

Because of brecciation in lunar rock, it is more meaningful to estimate the porosity of layer B and compare it with the porosities of terrestrial rocks than to compare the velocities directly. A solid line in Fig. 4 indicates our estimated range of porosity of layer B, 35 to 55 percent. Watkins *et al.* (*5*) include three terrestrial rock units whose velocities or structure, or both, might be appropriate: (i) ejecta blanket, Meteor Crater, porosity 40 percent; (ii) rhyolite ash and lapilli, Mono Craters, California, porosity 46 percent; and (iii) S. P. andesitic lava flow, Arizona, porosity 56 percent.

We conclude that layer A is the lunar regolith. The layer is 8.5 m thick beneath the geophone line at the Apollo 14 site, and it appears to be comprised mainly of overlapping ejecta blankets from post-Fra Mauro craters.

This layer is underlain by a layer whose thickness is calculated to be from 16 to 76 m and whose characteristic wave velocity is 299 m/sec. The abrupt change in seismic velocity and, by inference, in other physical properties of layer B indicate a major change in the nature of the evolution of lunar near-surface rocks. The estimated porosity of layer B, between 35 and 55 percent (layer A has an inferred porosity of 48 percent), indicates that it is not solid rock, but is very porous and possibly highly fractured.

The calculated thickness of the Fra Mauro Formation at the Apollo 14 site is slightly less than the minimum thickness inferred for layer B, but, if variations in the thickness of the Fra Mauro Formation and inaccuracies in the calculations are taken into account, the discrepancy does not seem unreasonable.

Photogeologic mapping of the area around the Apollo 14 site suggests that layer B might consist of Fra Mauro material or possibly of volcanics. Both explanations are consistent with the observed velocities. However, if layer B is volcanic, it is difficult to understand why so few igneous rocks were returned by Apollo 14 astronauts (*7*), since a number of young craters in the vicinity have penetrated into and through the layer.

The velocity and inferred porosity of layer B are comparable with those observed in the upper part of Meteor Crater ejecta (40 percent porosity) and, thus, quite reasonable for ejecta from Mare Imbrium. The change in inferred porosity between layer A and layer B is small but significant. For a porous, highly fractured rock such as one would expect in the Mare Imbrium ejecta, continued bombardment and diminution of particle size would increase the porosity only slightly. We, therefore, conclude that layer B is the Fra Mauro Formation.

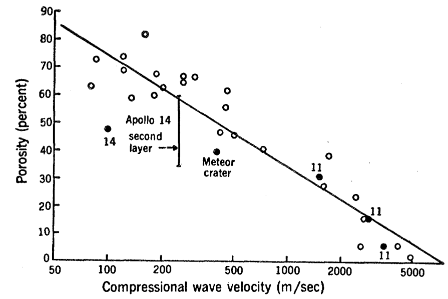


Fig. 4. Comparison of terrestrial velocity and porosity data with lunar data. (Open circles) Terrestrial data. (Solid circles) lunar data of Meteor Crater, Arizona, data. The numbers refer to the Apollo missions that provided the data.

Evidence regarding the underlying layer (C) is inconclusive at the present time. The relatively low compressional wave velocities that were measured by the ASE argue against the presence of substantial amounts of permafrost in the lunar near-surface at this particular site. Velocities in permafrost vary greatly—depending on such factors as lithology, porosity, and degree of interstitial freezing—but typically range from 2438 to 4572 m/sec (*8*).

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References and Notes

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9. Supported by NASA contract NAS 9-5632.

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