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Apollo 17 Seismic Profiling: Probing the Lunar Crust

Abstract. *Apollo 17 seismic data are interpreted to determine the structure of the lunar crust to a depth of several kilometers. Seismic velocity increases in a marked stepwise manner beneath the Taurus-Littrow region at the Apollo 17 site. A thickness of about 1200 meters is indicated for the infilling mare basalts at Taurus-Littrow. The apparent velocity is high (about 4 kilometers per second) in the material immediately underlying the basalts.*

The successful installation of a geophysical station at the Taurus-Littrow landing site of the Apollo 17 mission marked the culmination of an exciting period of manned lunar exploration and vastly improved our knowledge of the lunar interior. Before the Apollo 17 mission there was a surprising gap in our knowledge concerning the nature of the upper 10 km of the lunar crust because of the absence of pertinent seismic travel time data at distances closer than 30 km. Travel times of seismic waves are inverted to determine the seismic velocity structure and provide the direct means of probing the lunar interior.

The seismic velocity in the moon was known to increase rapidly from values of 100 to 300 m/sec in the upper 100 m to a value of about 6 km/sec at a depth of 15 to 20 km. Even though the seismic velocity variation was believed to be a smooth increase with depth it was surmised (*1*) that such a rapid increase of velocity (approximately 2 km/sec per kilometer) could not be explained solely by the effect of increasing pressure on dry rocks with macroscopic and microscopic cracks or by the self-compression of any granular rock powder.

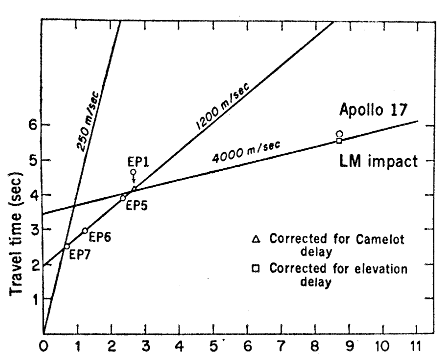

Fig. 1. Travel times of seismic *P*-wave pulses as a function of distance for Apollo 17 explosive charges and the LM impact. The data points defining the 250-m/sec line are omitted for brevity. The travel time for explosive package 1 (EP1) was corrected for propagation delay through a large crater, Camelot, and the LM impact travel time was corrected for an elevation effect.

Laboratory velocity measurements on returned lunar soils and on terrestrial sands and basaltic ash (*2*) have indicated velocity-depth gradients of 0.4 to 0.8 km/sec per kilometer, but such gradients occur only to pressures of about 50 bars (corresponding to a lunar depth of about 1 km). An examination of these experimental data led to the inference that compositional or textural changes must be important in the upper 5 km of the moon (*1*).

The purpose of the Apollo 17 lunar seismic profiling experiment was to record on a triangular array of four seismometers the vibrations of the lunar surface as induced by explosive charges, the thrust of the lunar module (LM) ascent engine, and the crash of the LM ascent stage.

Strong seismic signals were recorded from the detonation of eight explosive charges, which were armed and placed on the lunar surface by the Apollo 17 crew at various points along the traverses. The weights of the explosive charges ranged from 0.06 to 2.7 kg. Recording of these signals generated seismic travel time data in the distance range from 0.1 to 2.7 km.

One of the more significant events of the Apollo 17 mission was the recording of the seismic signal from the LM ascent stage, which struck the lunar surface 8.7 km southwest of the landing site in the highlands of the South Massif. The seismic signals from this impact were observed at a greater depth of penetration than could be achieved solely with the use of small explosive charges. The impact signal was similar in character to previous impact signals, having an emergent beginning and a long duration (*3, 4*).

The observed travel times for the detonation of the explosive charges can be combined with the observed travel time for the LM impact to provide information about the seismic velocity to a depth of several kilometers beneath the Apollo 17 landing site. Since the LM impacted at an elevation of 1.2 km above the recording seismometer array the LM travel time has been adjusted to the same reference elevation as the geophone array. The correction is small and decreases the observed time of 5.75 seconds by 0.18 second. Travel time data from the LM impact and the explosive charges are plotted against distance in Fig. 1. Three *P*-wave (compressional wave) velocities are represented in the travel time data: 250, 1200, and 4000 m/sec. There is some uncertainty in the apparent velocity of 4000 m/sec determined primarily by the LM impact data point at a distance

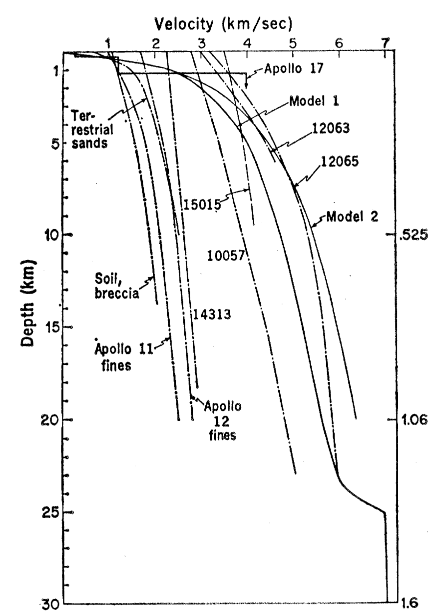

Fig. 2. Velocity model from the Apollo 17 results compared to earlier lunar models [models 1 and 2 (*4*)] and to velocities for lunar rocks and terrestrial sands measured in the laboratory as a function of pressure. Lunar rocks are identified by sample numbers.

of 8.7 km, but the important fact is that high-velocity material (≥ 4000 m/sec) must lie beneath the 1200-m/sec material. The 1200-m/sec material is 925 m thick and it is overlain by a layer with a thickness of 248 m and a velocity of 250 m/sec.

Our results have shown that, at least beneath the Taurus-Littrow site, the seismic velocity increases in a stepwise manner in the upper several kilometers. It is of interest to examine our in situ velocity information in the light of the surface geological investigations at the Apollo 17 site, laboratory velocity measurements from returned lunar samples, and seismic velocity measurements on terrestrial lunar analogs.

Premission analyses have shown that much of the Apollo 17 landing site area is covered by a dark mantling material. Observations by the Apollo 17 crew on the lunar surface revealed that any boundary between an overlying thin regolith and the dark mantling material was not readily discernible. Because our closest distance between an explosive charge and the receiver was about 100 m we could not resolve the properties of the upper 20 m or so, and cannot determine whether the interface between the dark mantling material and the subfloor represents a sharp seismic discontinuity or is gradational. However, our data indicate that any horizon, if present, would be less than 20 m from the lunar surface.

Underlying the dark mantling material the dominant rock type observed by the Apollo 17 crew is a medium-grained vesicular basalt believed to be primarily mare-type basalt. Observations in crater walls revealed textural variations, suggesting that individual flow units are involved. Our seismic observations have indicated 248 m of 250-m/sec material overlying 925 m of 1200-m/sec material.

The abrupt change in seismic velocity (and, by inference, in other physical properties) from 250 to 1200 m/sec is suggestive of a major change in the nature of the evolution or deposition of the Apollo 17 subfloor basalts. However, a similar range of seismic velocities is observed with refraction surveys in lava flows on the earth (*5*).

The velocities observed in terrestrial lava flows bracket the velocities measured at the Apollo 17 site and therefore support the presence of lava flows in the Taurus-Littrow valley. Whether the velocity of 250 m/sec is representative of a separate flow or several flows separated by lower-velocity layers of ash or ejecta cannot be resolved from the seismic data. Individual flows may be fractured or brecciated, which could further decrease their seismic velocities. Surface layers of fractured loose blocky material merging into more welded flows are common occurrences on the earth. We believe that the total thickness of the materials with seismic velocities of 250 and 1200 m/sec (1173 m) represents the full thickness of the subfloor basalts at the Apollo 17 site (*6*).

The nature of the 4000-m/sec material underlying the basalts is difficult to unambiguously assign to any particular rock type. It seems likely, based on the geological evidence, that the highland massif material which rings the narrow graben-like valley at the Apollo 17 site underlies the basalt flow or flows. Several rock types were recognized in North Massif and South Massif but the dominant rock type is apparently a coherent breccia believed to be similar to breccias sampled at the Apennine front (Apollo 15) and Descartes (Apollo 16).

Laboratory velocity measurements have been reported for two Apollo 15 breccias, 15418 and 15015 (*7*). Sample 15418 is described as a dark grey breccia of chemical composition similar to anorthite-rich gabbro. Sample 15015 is a more friable breccia of unknown composition. The in situ value of approximately 4000 m/sec is close to the values measured in the laboratory for sample 15015.

Before the Apollo 17 mission the question of how the *P*-wave velocity increased from 100 to 300 m/sec near the surface to about 6 km/sec at a depth of 15 to 20 km was most uncertain. The Apollo 17 lunar seismic profiling results (Fig. 2) have demonstrated that the seismic velocity increases in a sharp stepwise manner in the upper 2.5 km. When our Apollo 17 results are combined with earlier travel time data for direct and surface-reflected arrivals from earlier LM and Saturn (S-IV B) impacts it will be possible to construct a velocity model for the upper lunar crust representative for a lunar mare basin.

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Condensation Nucleus Discriminator Making Optical Measurements on Fog: A Tool for Environmental Research

Abstract. An instrument providing a new, rapid, and accurate method of determining the number and critical radii of condensation nuclei with radii under 200 angstroms is described. Based on the principle of the cloud chamber, the instrument measures transient changes in the attenuation and scattering of a monochromatic light beam by the growing fog droplets. From data obtained the absolute number concentration and radii of condensation nuclei can be calculated. Preliminary studies of aerosol formation in beta-irradiated mixtures of air and sulfur dioxide showed that carbon monoxide and methane inhibit the formation of nuclei; relative rate constants can be deduced. Some applications of this instrument for environmental and basic research are pointed out.

Condensation nuclei spewed out by factories, homes, and automobiles, as well as by the land and the sea, help to create smog and fog. The importance of condensation nuclei in the environment has been discussed by Shaefer (*1*), who pointed out that removal of visible smoke from a chim-