SHALLOW LUNAR STRUCTURE
DETERMINED FROM THE PASSIVE SEISMIC EXPERIMENT

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Abstract. Data relevant to the shallow structure of the Moon obtained at the Apollo seismic stations are compared with previously published results of the active seismic experiments. It is concluded that the lunar surface is covered by a layer of low seismic velocity ($V_p \simeq 100$ m s^{-1}), which appears to be equivalent to the lunar regolith defined previously by geological observations. This layer is underlain by a zone of distinctly higher seismic velocity at all of the Apollo landing sites. The regolith thicknesses at the Apollo 11, 12, and 15 sites are estimated from the shear-wave resonance to be 4.4, 3.7, and 4.4 m, respectively. These thicknesses and those determined at the other Apollo sites by the active seismic experiments appear to be correlated with the age determinations and the abundances of extra-lunar components at the sites.

1. Introduction

Lunar seismograph stations were established at Apollo landing sites 11, 12, 14, 15, and 16 as part of the Passive Seismic Experiment (PSE). All but the Apollo 11 station are still in operation. In addition, arrays of geophones, used in active seismic experiments, were installed at stations 14, 16, and 17. Although the primary objective of the Passive Seismic Experiment is to determine the structure and processes in the deep interior of the Moon, the seismic properties of the surficial zone can also be inferred from the observed seismic signals, thus adding data complementary to those obtained by the active seismic experiments described by Watkins and Kovach (1973) and Cooper *et al.* (1974).

In this paper, we present three sets of data, namely (1) overall signal characteristics, (2) signals from the lift-off of the Lunar Module ascent stages, and (3) horizontal amplification of seismic signals. We then discuss the seismic properties of the lunar surface zone based on these data. Descriptions of the instruments and the experiment have been given elsewhere (Latham *et al.*, 1969).

2. Seismic Data Relevant to the Near-Surface Properties

2.1. Seismic signal characteristics

As described in previous papers by Latham *et al.* (1970, 1973), the characteristics of lunar seismic signals are markedly different from those of their terrestrial counterparts, particularly for those signals that originate at or near the surface of the Moon. Examples of these signals are shown in Figure 1. The noteworthy features of these signals are the gradual beginning and the extremely gradual decay of signals. Signals from starting and stopping of the lunar roving vehicles similarly showed very gradual changes in the signal level after a delay of several minutes (Latham *et al.*, 1972). These properties have been attributed to extensive scattering of seismic waves at or near the

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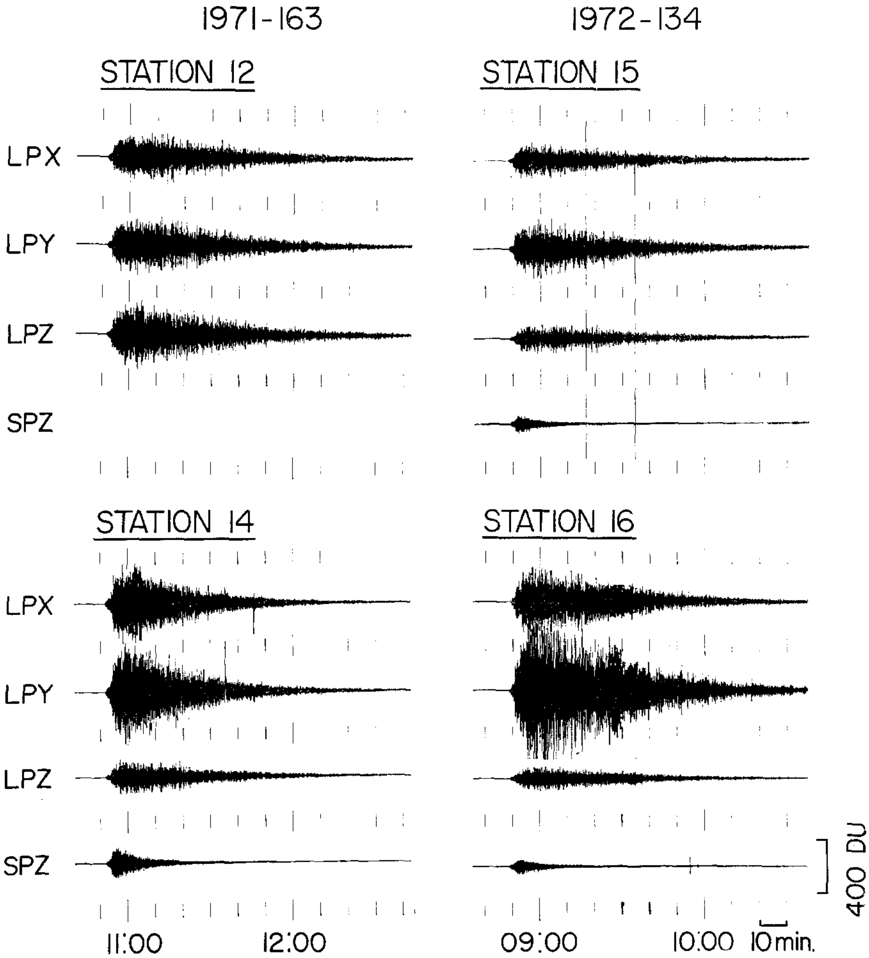

Fig. 1. Representative compressed-time-scale records of lunar seismic signals. Those on the left are for an event on June 12, 1971, observed at Apollo stations 12 and 14, and those on the right are for an event on May 13, 1972, observed at Apollo stations 15 and 16. Signal characteristics suggest that both of these events result from meteoroid impacts. LPX, LPY, LPZ, and SPZ stand for two long-period horizontal, a long-period vertical and a short-period vertical components, respectively.

lunar surface in material with high order of heterogeneity, extremely low absorption and strong vertical velocity gradient.

2.2. SIGNALS FROM LUNAR MODULE LIFT-OFF

More specific properties of the surficial zone of the Moon are obtained from the Lunar Module (LM) lift-off signals. These signals were recorded by the seismometers of the Passive Seismic Experiment during missions 12, 14, and 15 at distances ranging from 110 to 178 m; and by the geophones of the active seismic experiments during missions 16 and 17. The seismic signals as recorded by the short-period components of the Passive Seismic Experiment are shown in Figure 2. At these stations,

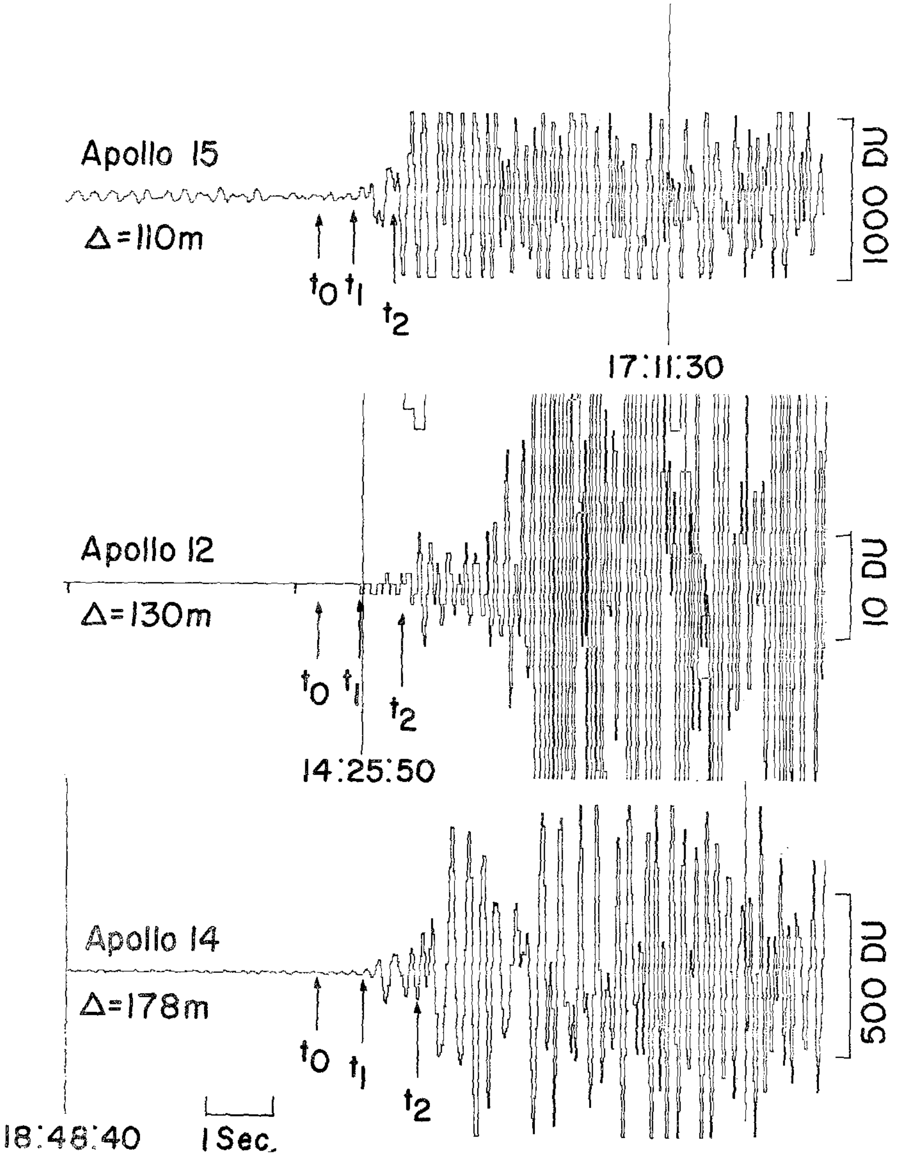

Fig. 2. Short-period (SPZ) seismograms of Lunar Module lift-off. Distances (Δ) are measured from the seismometer to the nearest footpad of the Lunar Module descent stage. t_0, t_1 and t_2, indicate the origin time and the first and the second arrivals. A digital unit (DU) is the smallest step in the signal digitization performed on the Moon.

and also at stations 16 and 17 as observed by the active seismic experiments, two distinct arrivals can be identified preceding the disturbances caused by the direct gas impingement from the ascent engine. Arrival times and other relevant data are listed in Table I. Figure 3 shows the travel time-distance diagram for these arrivals.

Comparison with the results of the active seismic experiment suggest that the two

TABLE I

Arrival times of lunar module lift-off signals

Apollo station	12	14	15
Date	November 20, 1969	February 6, 1971	August 2, 1971
Ignition (h:m:s GMT)	14:25:47.68	8:48:42.01	17:11:23.15
Engine build-up (s)	0.39	0.39	0.39
Down-link transit (s)	1.26	1.30	1.27
Adjusted origin time (t_0)	14:25:49.33	18:48:43.70	17:11:24.81
Arrival times			
First (t_1)	14:24:49.93	18:48:44.37	17:11:25.32
Second (t_2)	14:25:50.60	18:48:45.43	17:11:25.92

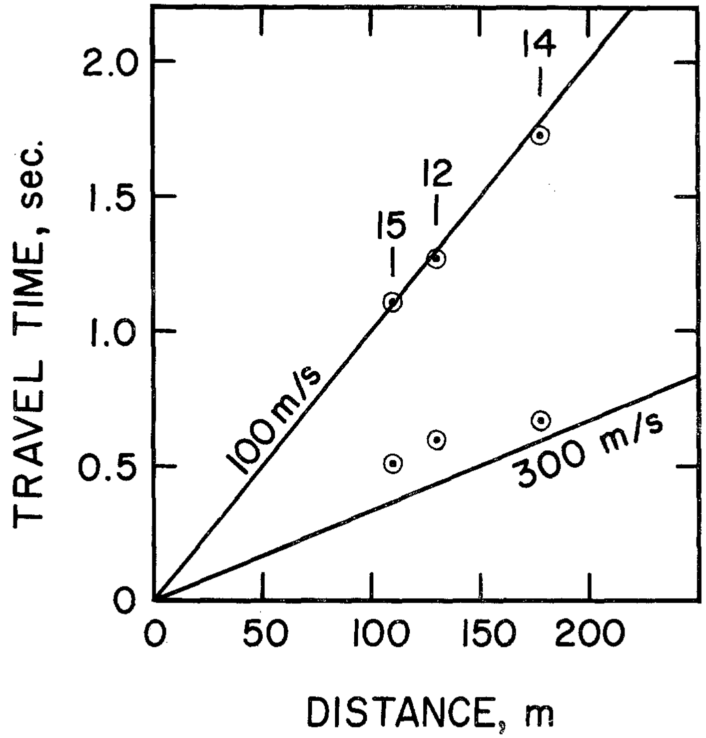

Fig. 3. Travel time-distance diagram of the Lunar Module lift-off signals. The number above each set of points indicates an Apollo site. The two lines through the origin represent seismic velocities as indicated, and are for reference purposes only.

arrivals are the head wave from a discontinuity beneath the surface and the direct P-wave arrival through the surface layer. The P-wave velocity in the surface layer, represented by the second arrivals, is determined to be 102, 103, and 99 m s^{-1} at Apollo sites 12, 14, and 15, respectively. The corresponding values obtained at the 16 and 17 sites by the active seismic experiments are 114 and 100 m s^{-1}, respectively (Cooper *et al.*, 1974). The remarkable uniformity of the seismic velocity of the surface layer suggests that the physical state of the material is the controlling factor. Otherwise, we would expect larger velocity variations corresponding to differences in mineralogy and chemistry among the various Apollo landing sites.

The existence of two arrivals over a large range of distances is consistent with a hypothesis that the lower boundary of the surface layer at all sites is marked by a large change in elastic properties. The seismic P-wave velocity increases to a value between 250 and 400 m s^{-1} (Cooper *et al.*, 1974; Duennebier *et al.*, 1974) in the zone below this boundary, which we shall refer to as the 300 m s^{-1} zone.

2.3. HORIZONTAL AMPLIFICATION OF SEISMIC SIGNALS

Additional evidence of the gross properties of the surface layer comes from the observed amplification of the horizontal component relative to the vertical component of ground motion. Figure 1 shows typical amplitude relationships, namely, that the horizontal components are several times stronger than the vertical for recordings at stations 16 and 14, that horizontal amplification is less pronounced at station 15, and that all components are typically of equal amplitude at station 12. We note that motion on all seismograms is dominated by frequencies near the peak of instrumental response, 0.45 Hz. The effect of sharply peaked resonance is minimized if we examine the ratios of horizontal to vertical spectra, as in Figure 4. Each spectrum shows a peak of horizontal amplification at a frequency which is characteristic of the corresponding station, and different from those of the other stations. The apparent high sensitivity of the horizontal component at station 16 is explained here by the fact that horizontal amplification for this station peaks near the frequency of maximum seismometer sensitivity. The spectral ratios for stations 14, 15, 11, and 12, in that order, peak at successively higher frequencies which are farther removed from the frequency of maximum instrumental sensitivity.

We interpret the spectral content of the signal, as represented in Figure 4, in terms of surface (Rayleigh and Love) wave properties. It is well known that the horizontal-to-vertical spectral ratios of Rayleigh waves depend on the vertical distribution of elastic properties in the medium whereas Love waves have no vertical component. Therefore, vertical motion indicates the presence of Rayleigh waves. Though contamination by Love waves may change the height of the spectral peaks in Figure 4, it would not affect the frequency of the peaks unless the excitation spectrum of Love waves in the surface layer is a strong function of frequency. For the simplest case of a single uniform layer over a substratum of substantially higher seismic velocity, the spectral amplitude ratio for the fundamental-mode Rayleigh wave generally has a single peak at the frequency corresponding to the quarter-wavelength resonance of shear waves in the top layer (Mooney and Bolt, 1966). The same is true where the surface zone is bounded below by a strong gradient rather than a sharp discontinuity of seismic velocity. For more complicated structures or for higher-order modes, additional interferences produce a shift in the peak frequency and often multiple peaks.

Since observed spectral amplitude ratios have single peaks at all stations, and since

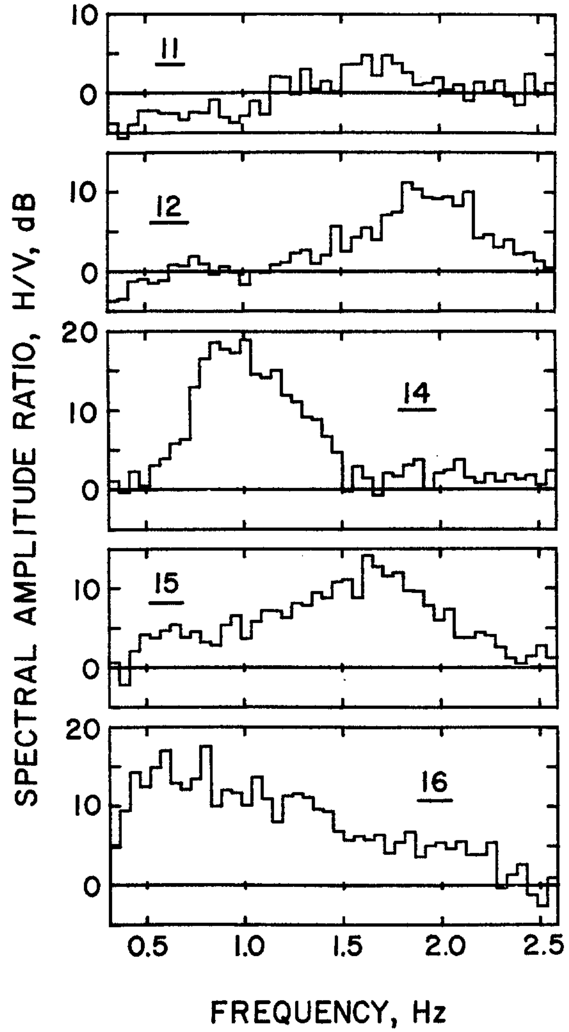

Fig. 4. Spectral amplitude ratios, H/V, vs frequency of selected seismic signals, where $H = [(X^2 + Y^2)/2]^{1/2}$ and X, Y, and V are the spectral amplitudes of the two horizontal and the verical components. The underlined numbers are Apollo station numbers. The events used are Apollo 11: moonquake on August 24, 1969; Apollo 12: Apollo 16 S-IVB impact; Apollo 14: Apollo 14 LM impact; Apollo 15: Apollo 17 S-IVB impact; Apollo 16: meteoroid impact on May 13, 1972. Data used for the computation are 10 min segments near the peak of each signal.

the velocity contrast determined earlier is sufficiently large, we assume here that these peaks are due to the quarter-wavelength resonance of shear waves in the surface layer. With this assumption, the vertical shear wave transit times through the surface layer are calculated from the observed peak frequencies. These values are plotted in Figure 5 for stations 14 and 16 against the thickness of the surface layer known from the Active Seismic Experiment (ASE). The line *a* through these two points is seen to connect smoothly with the shear-wave velocity curve *b* at the surface obtained by

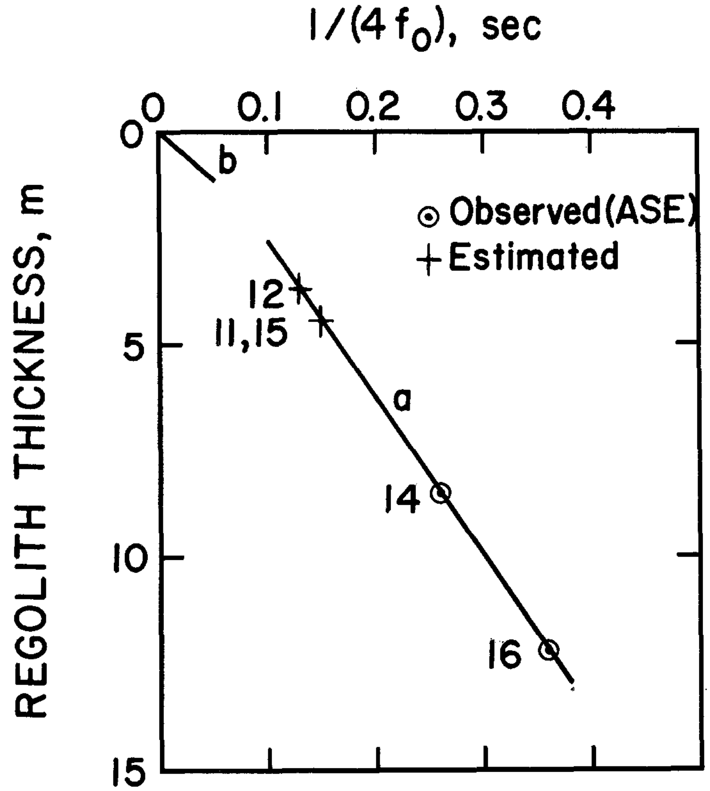

Fig. 5. The quantity $1/(4f_0)$ vs regolith thickness, where f_0 is the peak frequency of the spectral amplitude ratios. We take the quantity $1/(4f_0)$ to be approximately the vertical transit time of shear waves through the regolith layer. Numbers to the left of symbols indicate Apollo sites. Circles are based on observations by the active seismic experiment (Cooper *et al.*, 1974), and crosses are for thickness estimations through the extrapolation of the former. See the text for further explanations.

Sutton and Duennebier (1970), thus supporting the assumption that the peaks in the spectral amplitude ratios are indeed due to the resonance effect. The slope of line *a* represents a shear-wave velocity of 37 m s^{-1}. By extrapolation, the thickness of the surface layers at the other three sites are estimated from the observed resonance frequencies, and are tabulated in Table II.

It should be noted that the resonance method is only approximate, and the existence of a resonance peak does not by itself prove the existence of a distinct layer. On the contrary, we feel that the best evidence for an identifiable layer with relatively uniform properties overlying another zone of contrasting properties comes from the observation of two distinct seismic arrivals over a considerable range of distances at several landing sites. It then seems reasonable to take the frequency of the observed resonance peaks as indicating the approximate thickness of this layer.

Regarding a more rigorous approach, we may consider perfectly layered media (elastic properties are a function of depth only). It is then possible to find a velocity-depth function which precisely explains the shape of an observed spectral amplitude

TABLE II

Observed and estimated regolith thickness

Apollo station	Peak of spectral ratio f_0 Hz	$1/(4f_0)$ s	Regolith thickness Observed (ASE) m	Estimated (PSE) m
11	1.65	0.15		4.4
12	1.95	0.13		3.7
14	0.95	0.26	8.5[a]	
15	1.65	0.15		4.4
16	0.70	0.36	12.2[a]	
17	–[c]	–[c]	4.0[a], 8.5[b]	

[a] Cooper *et al.* (1974).
[b] Duennebier *et al.* (1974).
[c] No PSE seismometer at Apollo station 17.

ratio curve (Mark and Sutton, 1975). The solution to this problem may be a rather complicated function of depth and is generally not unique. Instead, it would seem that imperfections of the medium in the form of gross horizontal variations of properties make it impossible to calculate the precise nature of the elastic layering.

3. Discussion

From the results described above, we infer that the lunar surface is covered by a layer of low-velocity material ranging in thickness between 3.7 and 12.2 m at the Apollo landing sites. The thickness estimates are in good agreement with the minimum crater depths at which blocks are ejected, implying the penetration of an indurated material at depth corresponding to the 300 m s^{-1} zone. In such studies, the term 'regolith' has been used to describe the surface layer. The seismic results presented here support the notion of a surficial layer with distinctive physical properties overlying a more coherent material. The P-wave velocity of the underlying material is lower than that for competent terrestrial rock. Yet, the velocity is too high to be a consequence simply of gravitational compaction of regolith material at its present depth of burial (Johnson *et al.*, 1975). In any case, the acoustical contrast between the two zones suggests differing origins. The thickness of the second layer is uncertain. The fact that the spectral amplitude ratios at Apollo sites 11, 12, 14, 15, and 16 are well explained by the existence of a single regolith layer also means that there are no additional major seismic discontinuities at depths shallower than about 100 m at these sites. If there were, corresponding resonances would be present in the observed spectral ratios.

The major questions to be answered, then, are: (1) What does the lower boundary of the regolith layer represent; and (2) What is the underlying zone? Some of the materials that might have the elastic properties of the underlying zone are: (1) highly vesicular basalts (Cooper *et al.*, 1974); (2) welded tuff deposited by major impacts; (3) extensively fractured rock.

The regolith thicknesses given here appear to be correlated with other independently determined properties of the regolith. For example, a correlation with the ages of lunar samples believed to have originated near the top of the underlying zone is suggested by the limited data at hand as shown in Figure 6; the older sites at stations 14, 16, and 17 having greater thicknesses than the younger sites at stations 11, 12, and 15. A linear fit to the age-depth data gives an accumulation rate of about 10 m G.y.$^{-1}$ (G.y. = 10^9 yr) prior to 3.2 G.y. ago and an addition of less than 4 m since that time.

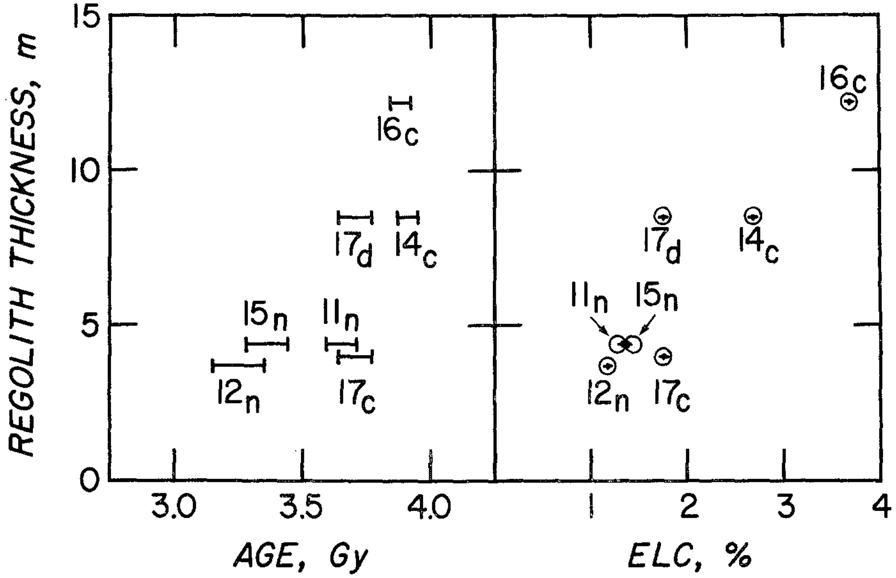

Fig. 6. Apparent correlations of the regolith thickness (left diagram) with the ages of lunar rock samples believed to have come from the top of the underlying zone (age data are from personal communication, Papanastassiou and Wasserburg) and (right diagram) with the percentage of extralunar component (ELC) found in regolith samples (ELC data are from those presented by Wasson *et al.* at this conference). Numbers represent Apollo sites, and the subscripts indicate the sources of the regolith-thickness data as follows: c = Cooper *et al.* (1974); d = Duennebier *et al.* (1974); n = this paper.

Another correlation is suggested between the regolith thickness and the abundance of extralunar components (ELC) in regolith material at each site, as shown in Figure 6. Except for the Apollo 17 site, for which the thickness determinations are believed to be less accurate than for the other sites, the correlation is very good, giving a linear relation, ELC(%) = 3.1h, where h is the regolith thickness in m. It appears that the thicker (and older?) the regolith, the greater the contribution of extralunar material.

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