(*p*H 9 to 12). They were stored at 4°C for 18 hours and samples were taken for radioactivity determinations. Catecholamine complexes were relatively stable from *p*H 3 to *p*H 6; at higher *p*H they were very unstable (Fig. 1b). It appeared that at higher *p*H the norepinephrine and Sepharose complex formed by an amide linkage was less stable than that formed by a diazo linkage. Thus, at *p*H 8, 40 percent of the norepinephrine bound to SAE Sepharose and 20 percent bound to SDSD Sepharose were released, whereas only 2 to 5 percent of norepinephrine or epinephrine bound to PABE Sepharose or glass were released. Propranolol complexes were more stable at high than at lower *p*H's.

The biological activity of norepinephrine SAE Sepharose was determined by its ability to cause the contraction of vascular smooth muscle. Isolated rabbit aortic strips were prepared and bathed in 15 ml of Krebs-Henseleit solution to which 45 m*M* dextrose and 0.26 m*M* disodium ethylenediaminetetraacetate were added. The medium was maintained at 37°C aerated with 95 percent O_2 and 5 percent CO_2 to give a *p*H of 7.4 (*7*). Contractions were recorded on a kymograph. The norepinephrine SAE Sepharose complex caused the strips to contract, but most of the response could be attributed to free norepinephrine released by hydrolysis. In four experiments 36.43 ± 1.11 percent of the bound radioactivity was released into the medium within 30 minutes to give a free norepinephrine concentration of 78.25 ± 2.38 ng per milligram of SAE Sepharose in a milliliter of bath fluid.

Complexes of norepinephrine and epinephrine on glass (25 mg) were incubated in Krebs-Henseleit buffer (2 ml) aerated with 95 percent O_2 and 5 percent CO_2 at 32°C, and the released radioactivity was determined at intervals. Approximately 0.5 percent of the bound radioactivity was released after only 5 minutes of incubation (Fig. 2). This radioactivity represents 72 ng of amines. Moreover, the medium induced rabbit aortic strips to contract, indicating that the soluble radioactivity included considerable amounts of intact norepinephrine or epinephrine.

These data do not support the proposition that catecholamines chemically bound to glass exert their pharmacological effects on isolated tissue as covalently bound complexes (*3, 4*). Our results indicate that, although catecholamines and propranolol can readily be bound to either Sepharose or glass beads, a significant portion of the bound ligands can be gradually released into the supernatants. Furthermore, the rate of release depends on the *p*H and conditions used in biological experiments. It is not clear how a ligand complexed through a diazo linkage to a solid support is released, but partial hydrolysis can contribute to the release of a ligand complexed through an amide linkage. Recent studies have demonstrated that the apparent biological activity of bovine growth hormone and Sepharose complex (*8*) and of insulin and Sepharose complex (*9*) could largely be attributed to the release of free hormones from the Sepharose matrix. These limitations must be considered when "immobilized" hormones and drugs are tested for biological activity or used as specific adsorbents in affinity chromatographic separation.

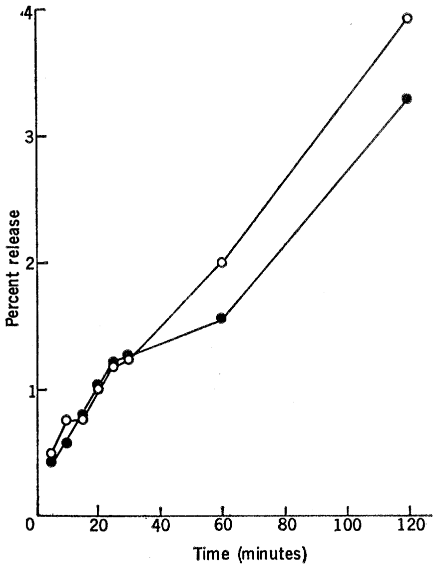

Fig. 2. Release of catecholamines covalently bound to glass beads in Krebs-Henseleit solution. The complexes were incubated in Krebs-Henseleit solution aerated with 95 percent O_2 and 5 percent CO_2 at 32°C. ○, Norepinephrine bound to glass; ●, epinephrine bound to glass.

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The 25-km Discontinuity: Implications for Lunar History

Abstract. *The lunar velocity profile and laboratory data on terrestrial and lunar rocks are constraints on models of lunar history. They show that shock-induced microcracks are absent from the rocks present in the moon today at depths of 25 to 60 kilometers. All possible causes of this observation are examined, and the most likely explanations are that either the rocks at depths of 25 to 60 kilometers formed after the major impacts ceased or the microcracks have annealed at temperatures of about 600°C over geologically long times.*

Startling implications for lunar science are hidden in the combined analysis of the lunar seismic velocity profiles and the laboratory data on elastic properties of shocked rocks. Comparison of the two sets of data shows that the rocks in situ at depths greater than 25 km in mare regions do not now contain microcracks. If both sets of data are essentially correct, then only two explanations of this remarkable fact appear to be possible: (i) the rocks below 25 km have never been shock metamorphosed, or (ii) the rocks below 25 km have been shock metamorphosed but the shock effects have been removed by some process. Before discussing these two possibilities, we describe the data briefly and argue for their validity.

The velocity profile of Toksoz *et al.* (*1, 2*), shown in Fig. 1, does not differ in essential features from the earlier profile of Toksoz *et al.* (*3*), but includes additional data. The velocity profile is based mainly on the travel times of pulses from artificial impacts but is also consistent with the data from natural lunar events. This velocity model is preferred over the preliminary one reported by Latham *et al.* (*4*) because it meets additional constraints imposed by matching synthetic seismograms with lunar seismic signals. On the basis of the results of Toksoz *et al.* (*1, 2*) we conclude that microcracks exist in lunar rocks in situ down to 25 km but not below. Because the seismic data were obtained mainly over mare basins, our conclusions are valid strictly only for those areas.

The laboratory data consist of the velocity of compressional waves (V_p), the velocity of shear waves (V_s), and the isothermal (static) compressibility (β). The techniques for measuring these properties were developed for use on terrestrial rocks (*5*). They have been adapted, with minor modifications, for use on the returned lunar samples (*6, 7*). A major difference between the lunar and terrestrial samples that have been used for such measurements is their size. Terrestrial samples are commonly 5 to 10 cm long in the direction of measurement, lunar samples only 1 to 2 cm. The smaller size decreases the accuracy of V_p from 1 percent, or better, to perhaps 2 to 4 percent, and of V_s from 1.5 percent to 3 to 6 percent. The precision of β is not changed because a specimen length of 1 to 2 cm is adequate for the measurement. We conclude that the data obtained on the moon and in the laboratory are both adequate.

We accept the quality of the data as being adequate and assert that the rocks below 25 km do not contain microcracks. Consider the summary of laboratory data of Todd *et al.* (*7*) shown in Fig. 2, where the different effects of various processes on the velocity of compressional waves in rocks are clearly separated. For example, shock metamorphism of both lunar and terrestrial rocks produces microcracks with characteristics that cause the velocity to approach intrinsic values much more slowly with pressure than is the case for either thermally cycled rocks or for noncycled terrestrial igneous rocks. The in situ velocity of 7 km/sec is nearly constant between 25 and 60 km and is very near or above the intrinsic velocity of lunar samples, as well as the intrinsic velocity of such terrestrial rocks as anorthosite, diabase, gabbro, and metamorphic equivalents. Therefore, we infer that the densities of microcracks, of glass, and of roundish pores in the

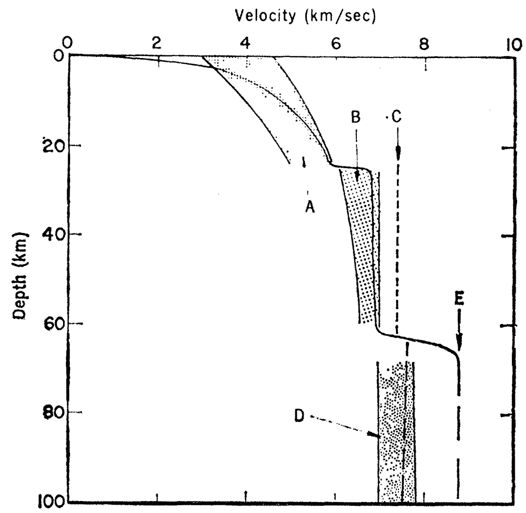


Fig. 1. Velocity of compressional waves in the moon. This profile is based on seismic data obtained with controlled impacts of various Apollo spacecraft. The letters indicate laboratory data: (A) lunar basalt, (B) lunar anorthositic gabbro, (C) terrestrial bytownite, (D) terrestrial pyroxenite, (E) garnet field. [Redrawn from Toksoz *et al.* (*4*)]

lunar rock in situ at depths greater than 25 km are insignificant.

Because terrestrial rocks with intrinsic velocities above 7 km/sec do exist, a model that incorporated (i) a change of rock type at 25 km to account for the sudden jump in velocity and (ii) a continuous change of composition coupled closely with the closing of microcracks with depth due to pressure to account for the constant velocity in the interval 25 to 60 km would satisfy all observations. We reject this model because of its great complexity.

Two observations indicate to us that the 25-km discontinuity cannot be due solely to the closing of cracks by overburden pressure in rocks in situ. First, the confining pressure at that depth, approximately 1.2 kbar, is inadequate to close the cracks in shocked rocks [see Fig. 2b and (*7, 8*)]. Second, the steep and sudden increase in V_p at 25 km in the moon contrasts sharply with the gradual increase measured in the laboratory and caused by closing of microcracks with confining pressure.

The set of all logical possibilities to account for the lunar velocity profile may be based on the question, Were rocks now below 25 km ever shock metamorphosed? If the answer is no, then either (1.1) the rocks formed after impacts, or (1.2) the rocks near 25 km were formerly deeper and at the time of impacts were too deep to be shocked, or (1.3) the rocks were always at 25 km or deeper and shock effects did not extend to that depth. If the answer is yes, then either (2.1) cracks have been annealed, or (2.2) cracks were filled with liquids that subsequently solidified, or (2.3) liquids are now present in the moon, beginning at a depth of 25 km. We will now examine the consequences of these possibilities.

Hypothesis 1.1: The rocks now below 25 km have never been shock metamorphosed, and the rocks now at 25 to 60 km were formed after all large impacts ceased.

This hypothesis appears to us to be possible. A model lunar history that accounts adequately for the observations is the following: During an initial stage 1, an outer shell, hundreds of kilometers thick, was liquid and the interior of the moon was solid. If impacts occurred, the resulting surface features would not have been preserved. During stage 2, the moon cooled, forming a crust that began at the surface and increased in thickness. All major impacts (that is, those which produced shock effects at depths of 25 km or more) must have ceased just when the crust had reached a thickness of 25 km. During stage 3, the crust continued to thicken and the zone of melt thinned, but no large impacts occurred.

This model history is consistent with the impact history described by Tera *et al.* (*9*), who on the basis of a summary of age dates of lunar rocks concluded that "either the Imbrium blanket has dominated all the material so far studied or we must conclude that the major impacts peaked in a relatively short period near 4.0 AE." We believe that our combined analysis of the 25-km discontinuity and the laboratory data shows that the distribution of age dates of lunar samples resulted from the cessation of impacts rather than the extensive contamination of surface rocks by the Imbrium ejecta blanket. Our model history is also consistent with the general features of the thermal history calculated by Toksoz *et al.* (*3*) and McConnell and Gast (*10*), but not with the specific details of any one of their models. The present analysis provides a constraint that can be used to improve the thermal models, namely that the crust at 4.0 AE (4.0 $\times$ 10^9 years) was 25 km thick.

This model history may not be consistent with certain geologic observations. Many postbasin, premare craters indicate that significant time (of the order of 200 million years) elapsed between the formation of the large circular mare basins and lava eruptions which filled the larger basins (*11*). However, the model can be made consistent with these observations by including features of hypotheses 2.1 or 2.2, discussed below.

Hypothesis 1.2: The rocks now at depths of 25 to 60 km were formerly deeper and below the depths to which shock effects reached. Some time after impacts ceased, the rocks reached their present position.

This hypothesis seems unlikely to us because it would require a general overturn of a significant part of the front side of the moon after the outer 100 km had solidified. On the basis of geologic observations (*12*) we argue that such an event has not occurred and reject this hypothesis.

Hypothesis 1.3: The shock effects associated with the impacts that produced the lunar craters and maria did not extend below 25 km, and the horizon now at 25 km was never shallower in the past. If it was shallower, then either no impacts occurred during the time when it was shallower, or the impacts were sufficiently small that shock metamorphism did not reach below the horizon.

This hypothesis appears very unlikely. The data shown in Fig. 1 were obtained with seismic waves that traveled along paths under and near very large craters and maria. Surely the shock effects of the impacts that produced these features extended to greater depths than 25 km, a small fraction of the radii of several craters.

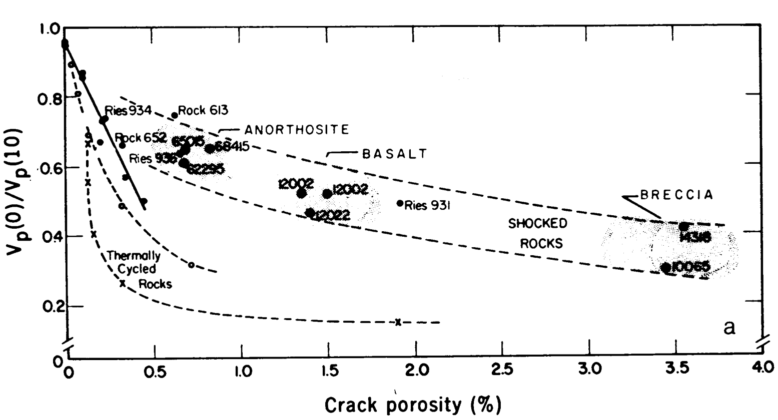
Hypothesis 2.1: The rocks now below 25 km were shock metamorphosed and the shock effects have since been annealed.

Annealing is a thermally activated process (*13*) and the present temperature at 25 km is unlikely to exceed 250°C. We know of no data on the annealing of cracks in rocks. But from the high temperatures (1000°C or higher) required for hot pressing and sintering oxides and silicates (*13*) we infer that temperatures significantly nigher than the present temperature are necessary for this hypothesis to be valid. Geologic time is somewhat interchangeable with high temperatures in most processes and we guess that temperatures as low as 600° to 700°C for geologic periods might be sufficient to anneal cracks. Data on the cation distributions in lunar pyroxenes determined with heating experiments imply that at least some lunar rocks were exposed to temperatures of 500° to 600°C for geologically long times (*14*). The effects of water pressure on regional metamorphism and on the melting of granites and basalts (*15*) suggest that even lower temperatures combined with small amounts of water might anneal cracks in rocks.

If the rocks now at 25 km have always been at depths of 25 km or less, and no water was ever present, then the temperatures must have been initially low (so that cracking could occur), have increased to 600° to 1000°C (for annealing), and then have decreased to the present 150° to 250°C. But if the rocks now at 25 km arrived from greater depth, then the shock effects could have been annealed by the higher temperatures. If they originated at depths of 25 km or less, then the excursion below 25 km could have annealed the cracks.

These excursions in temperature or depth (or both) would cover a large part of the front side of the moon. In addition, the high temperatures would reduce the strength of the rocks below that needed to support mascons. We believe that the likelihood of the higher temperatures occurring after the impacts is small.

Hypothesis 2.2: The rocks now be-



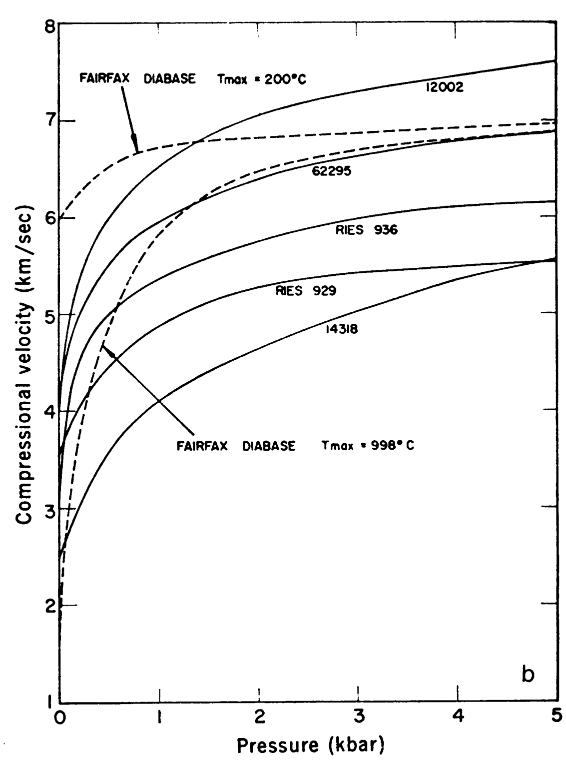


Fig. 2 (a). Effect of microcracks in rocks on the velocity of compressional waves. The ratio of the velocity at a confining pressure of 1 bar to that at 10 kbar is $V_p\ (0)/V_p\ (10)$. The solid line represents typical terrestrial igneous rocks. Thermally cycled igneous rocks and shocked rocks separate into two distinct and widely separated fields. The three Ries rocks are granitic samples from the Ries Crater in Germany. The lunar samples separate into distinct groupings with the zone of shocked rocks. [Modified from Todd *et al.* (*7*)] (b) Effect of confining pressure on the velocity of compressional waves in several rocks. The effect of pressure, included implicitly in (a), is shown here explicitly. The two samples of Fairfax diabase were thermally cycled to different maximum temperatures, T_{max}, and illustrate the large effect of microcrack density. [Courtesy of Todd *et al.* (*7*)] low 25 km were shock metamorphosed and the cracks were filled with silicate or sulfide liquids that subsequently solidified.

For either silicate or sulfide liquids to fill the microcracks in very large volumes of rock on the front side of the moon, high temperatures throughout shallow regions of the moon are required, the mechanisms discussed for hypothesis 2.1 would be needed, and the same objections would hold.

Hypothesis 2.3: The rocks now below 25 km were shock metamorphosed and the cracks are now filled with liquids at depths greater than 25 km.

The dramatic effect on the velocity of compressional waves of completely filling the microcracks in rocks with a liquid, such as water, was discovered by Simmons and Nur (*16*). If the lunar rocks in situ were completely saturated with a liquid beginning at 25 km, then the velocity profile would approximate the one shown in Fig. 1. We tentatively reject this hypothesis because of the absence of hydrous minerals in the lunar samples examined on the earth.

In conclusion, we have examined all logical possibilities for the explanation of the seismically determined discontinuity in the moon at a depth of 25 km. Two hypotheses appear equally plausible to us: (1.1) the rocks now below 25 km have never been shock metamorphosed and the rocks now at 25 to 60 km were formed after all large impacts ceased, and (2.1) the rocks now below 25 km were shock metamorphosed and the shock effects have since been annealed. Perhaps the annealing of rocks below 25 km was contemporaneous with the formation of mare basalts.

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Earthquake-Induced Structures in Sediments of Van Norman Lake, San Fernando, California

Abstract. *The 9 February 1971 earthquake in the San Fernando Valley damaged the Lower Van Norman Dam severely enough to warrant draining the reservoir. In March 1972 the sediment deposited on the reservoir floor was examined to determine whether the 1971 earthquake had induced sediment deformation and, if so, what types. A zone of deformational structures characterized by small-scale loads and slightly recumbent folds associated with the 1971 earthquake was discovered, in addition to two older zones of load structures. Each of the zones has been tentatively correlated with an historic earthquake.*

Lower Van Norman Dam (Fig. 1) was built in 1915. On 30 August 1930, an earthquake (Richter magnitude 5.2) caused minor damage to Lower Van Norman Dam and nearby Chatsworth Dam (*1*). On 9 February 1971, an earthquake with an epicenter in the nearby San Gabriel Mountains of Richter magnitude 6.5 (*2*) severely damaged Lower Van Norman Dam (*3*). The principal damage to the dam consisted of massive upstream slope failure. The dam appeared to be near failure, which would have caused catastrophic inundation of the heavily populated area below. The water level of the lake was lowered immediately, and subsequently the entire lake was drained. Throughout its history, the lake has been open to local runoff. However, the amount of

Table 1. Inferred dates of deformed zones in Lower Van Norman Lake sediments.

Locality	Total sediment thickness (cm)	Sedimentation rate (uncorrected) (cm year^{-1})	Dates of deformation (uncorrected)	Dates of deformation (corrected)*
1†	20	0.48	1971, 1959, †	1971, 1953, †
9	51	.91	1971, 1958, 1942	1971, 1953, 1942
10	40	.71	1971, 1953, 1939	1971, 1952, 1936
12	30	.54	1971, 1954, 1935	1971, 1951, 1930
13	41	.73	1971, 1955, 1930	1971, 1955, 1929

* Corrected dates were determined from the table of ΣS_i (see text). † Locality was not inundated until after 1930.