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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References and Notes

1. M. N. Toksoz, F. Press, A. M. Dainty, S. C. Solomon, K. R. Anderson (*2*, p. 734).
2. J. W. Chamberlain and C. Watkins, Eds., *Lunar Science IV* (Lunar Science Institute, Houston, Texas, 1972).
3. M. N. Toksoz, S. C. Solomon, J. W. Minear, D. H. Johnston, *Moon* **4**, 190 (1972).
4. G. V. Latham *et al.*, in *Apollo 16 Preliminary Science Report* (NASA SP-315, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 9-1.
5. For V_p and V_s see: Birch, *J. Geophys. Res.* **65**, 1083 (1960); G. Simmons, *ibid.* **69**, 1117, 1123 (1964); *Proc. IEEE* **53**, 1337 (1965). For β see: L. H. Adams and E. D. Williamson, *J. Franklin Inst.* **195**, 474 (1923); W. F. Brace, *J. Geophys. Res.* **70**, 391 (1965).
6. O. L. Anderson, C. Scholz, N. Soga, N. Warren, E. Schreiber, *Geochim. Cosmochim. Acta* **3** (Suppl. 1), 1959 (1970); H. Kanamori, A. Nur, D. H. Chung, G. Simmons, *ibid.*, p. 2289; H. Kanamori, H. Mizutani, Y. Hamano, *ibid.* (Suppl. 2), 2323 (1971); H. Wang, T. Todd, D. Weidner, G. Simmons, *ibid.*, p. 2327; N. Warren, E. Schreiber, C. Scholz, J. A. Morrison, P. R. Norton, M. Kumazawa, O. L. Anderson, *ibid.*, p. 2345; H. Mizutani, N. Fujii, Y. Hamano, M. Osako, *ibid.* (Suppl. 3), 2557 (1972); T. Todd, H. Wang, W. S. Baldridge, G. Simmons, *ibid.*, p. 2577; N. Warren, O. L. Anderson, N. Soga, *ibid.*, p. 2587; H. Mizutani and D. F. Newbigging (*2*, p. 528); T. Todd *et al.* (*7*); O. L. Anderson and N. Warren, (*2*, p. 43).
7. T. Todd, H. Wang, D. Richter, G. Simmons (*2*, p. 731).
8. D. R. Stephens and E. M. Lilley, *Geochim. Cosmochim. Acta* **3** (Suppl. 1), 2427 (1970).
9. F. Tera, D. A. Papanatassiou, G. J. Wasserburg (*2*, p. 723).
10. R. K. McConnell, Jr., and P. W. Gast, *Moon* **5**, 41 (1972).
11. P. D. Lowman, Jr., *J. Geol.* **80**, 125 (1972), and references therein.
12. The geologic evidence against large-scale overturn includes the widespread distribution of some geologic units, the extensive ray systems of some craters [see R. B. Baldwin, *Measure of The Moon* (Univ. of Chicago Press, Chicago, 1963), p. 350, for example], and the ages of the Apollo and Luna 20 landing sites. I. L. Barnes *et al.* (*2*, p. 51) give the ages of the Apollo 15 and Apollo 16 sites as greater than 4.0×10^9 years; J. C. Huneke, F. A. Podosek, and G. J. Wasserburg (*2*, p. 403) give 3.9×10^9 years for the Luna 20 site; E. Schonfeld and C. Meyer, Jr. (*2*, p. 660) give 4.4×10^9 years for the Imbrium event; D. A. Papanastassiou and G. J. Wasserburg [*Earth Planet. Sci. Lett.* **12**, 36 (1971)] give (4.3 to 4.6) $\times 10^9$ years for the Apollo 14 site; and F. Tera *et al.* (*9*) give (3.2 to 3.7) $\times 10^9$ years for mare basalts, (3.6 to 3.7) $\times 10^9$ years for the Apollo 11 site, and (3.9 to 4.0) $\times 10^9$ years for the Apollo 14 site.
13. W. Kingery, *Introduction to Ceramics* (Wiley, New York, 1960), pp. 394, 641–645.
14. S. S. Hafner and D. Virgo, *Geochim. Cosmochim. Acta* **3** (Suppl. 1), 2183 (1970).
15. F. J. Turner, *Metamorphic Petrology* (McGraw-Hill, New York, 1968), p. 366; O. F. Tuttle and N. L. Bowen, *Geol. Soc. Amer. Mem. 74* (1958).
16. G. Simmons and A. Nur, *Science* **162**, 789 (1968).
17. Financial support was provided by NASA contract NGR-22-009-540. We benefited from discussion of thermal models with T. McGetchin and have adapted one model from an unpublished manuscript of his. This report was improved as a result of comments by E. Anders, O. Anderson, B. French, P. Lowman, Jr., D. Walker, and D. Wones.

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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.

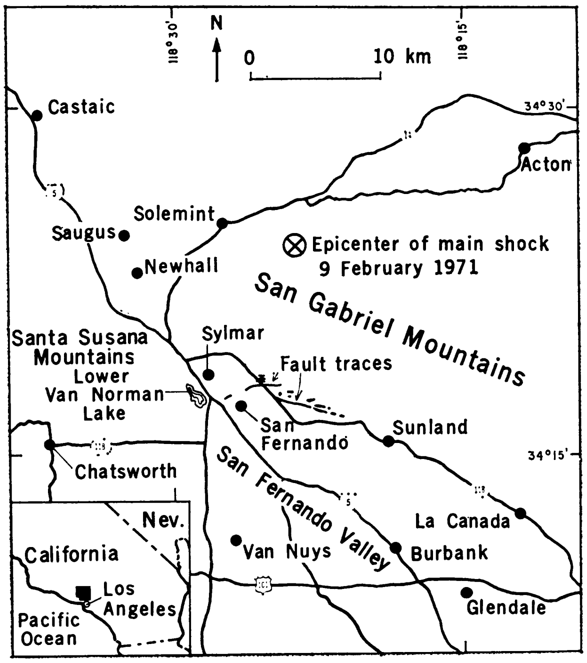

Fig. 1. Index map of the San Fernando Valley and vicinity, showing the location of Lower Van Norman Lake and the epicenter of and fault traces associated with the 9 February 1971 San Fernando earthquake.

runoff and its sediment load varied and were undetermined.

The sediments deposited during the 56-year life of Lower Van Norman Lake are predominantly thinly to thickly laminated silt and clay, and less commonly coarse silt laminae and very fine sandy laminae and partings (Fig. 2). The lake sediment ranges in thickness from 0 to 51 cm and averages about 40 cm. After the lake was drained, the sediments dried and separated into pclygonal prisms. Fresh vertical sections of the lake sediments were exposed by small channels cut during the drainage of the lake and by artificial cuts. Also exposed were the underlying sediments present at the site before the construction of the reservoir and the topography developed on them. Most of the lake sediments studied rest on slopes of less than 1 in 50 (1.15°), with none on slopes of more than 1 in 30 (1.9°).

Entire sediment prisms could be lifted out intact for close examination. The various layers were easily separated, and the stratigraphic succession could be established in detail. The sections clearly exposed three zones of sedimentary structures that occur everywhere in the lake sediments at specific stratigraphic intervals.

Deformational structures developed on the upper surface and upper 4 or 5 cm of the lake sediment (zone 1) are primarily of two types: (i) low-amplitude folds (Fig. 3) and (ii) load-type structures that vary in magnitude from penetrating pseudonodules (?) (Fig. 2A) to more upward-penetrating heave structures to low-amplitude load structures approximately 1 cm deep (Fig. 2B).

Deformational structures observed within the sediments are all low-amplitude, symmetrical load structures (Fig. 2C). Two zones of structures occur at locality 1, one at the surface (zone 1) and one buried (zone 2) (Table 1). Three zones occur at all other localities (Table 1), one at the surface (zone 1) and two buried (zones 2 and 3). Deformation in the zones involves two stratigraphic units—a lower interval that has failed and moved away and a second, upper unit which has sagged down and filled a circular depression in the lower unit, yielding a radially symmetrical load cast (Fig. 2D). Movement of the two stratigraphic units caused the disruption and partial breakup of the beds involved. The load structures are overlain by parallel laminated or, less commonly, undeformed massive silts and clays, which suggests that the deformed zones were at the sediment-water interface when deformation occurred.

The dates of deformation were estimated on the basis of the apparent annual sedimentation rates (total sediment thickness divided by 56 years) (Table 1). However, because the lake was open to local runoff, the amount of sediment deposited annually is considered approximately proportional to the annual precipitation. Rainfall data for the period 1931–1971 are derived from the gauge at Lower Van Norman Dam (Los Angeles County Flood Con-

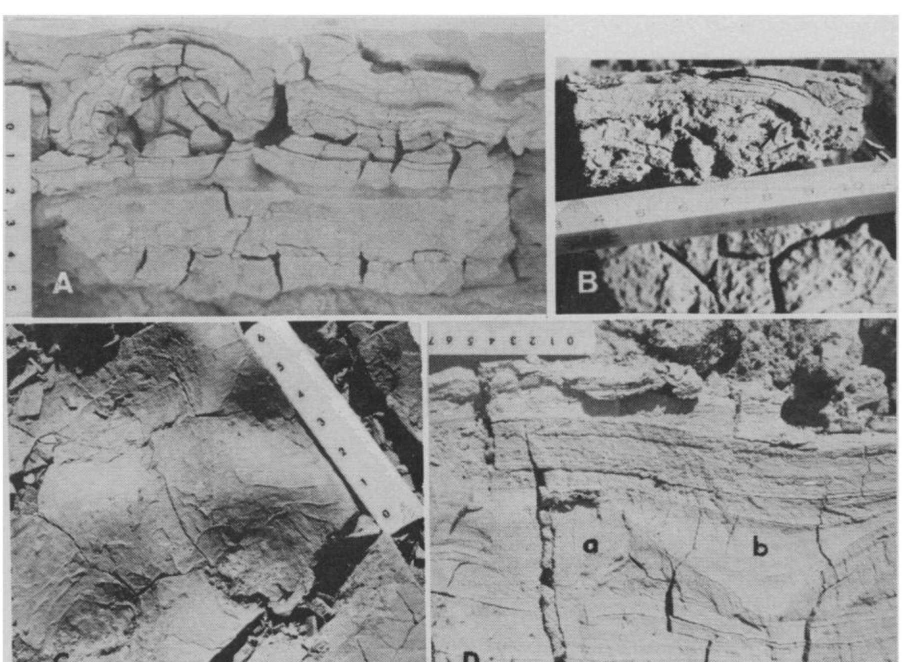

Fig. 2. Earthquake-induced sedimentary structures (scales in centimeters): (A) pseudonodules and convoluted lamination in the upper 4 cm of sediment, deformation attributed to the 9 February 1971 earthquake having an intensity of VIII to IX; (B) low-amplitude load structure in the upper 2 cm of sediment (arrows) attributed to the 9 February 1971 earthquake; (C) vertical view of excavated load molds, attributed to the 21 July 1952 earthquake; and (D) vertical section of the load structure, with unit *a* equivalent to (C) and unit *b* equivalent to the material removed in (C); this structure is attributed to the 21 July 1952 earthquake.

trol District rain gauge 293). Rainfall data for Lower Van Norman Lake for the period 1915–1931 are lacking; however, the data are complete for Los Angeles. Linear regression analysis of Los Angeles rainfall data and Van Norman Dam rainfall data for the period July 1931–June 1932 through July 1970–June 1971 gave the equation

$$y = 3.73 + 0.92x$$

with a correlation coefficient r of .885 and a standard error of estimate $S_{x \cdot y}$ of 3.20. Thus the data for 1931–1971 are strongly correlated, and the rainfall for Lower Van Norman Lake during the period July 1914–June 1915 through July 1930–June 1931 can be estimated from the Los Angeles data.

Using the annual deviation from the mean annual rainfall, I calculated weighting factors for yearly sediment accumulation from the equation

$$\delta x_i / \bar{x} = f_i$$

where δx_i is the annual deviation from the mean annual rainfall and $\bar{x}$ is the mean annual rainfall. I then calculated the annual sediment increment (S_i), using these factors:

$$R + R(f_i) = S_i$$

where R is the mean annual sedimentation rate (total sediment thickness divided by 56 years). Each annual sediment increment was cumulated (ΣS_i) and recorded for each year from 1915 to 1971. In this way a zone of structures may be dated by measuring the thickness of sediment to the top of the deformed zone and determining the year corresponding to this thickness from the table of ΣS_i.

A search of earthquake records shows that moderate to strong shocks affected the San Fernando Valley four times since Lower Van Norman Dam was built: (i) 30 August 1930 (Richter magnitude 5.2), epicenter originally placed in Santa Monica Bay, but probably closer to San Fernando (*1*), with a felt intensity (modified Mercalli scale) of VI at San Fernando; (ii) 10 March 1933 (Richter magnitude 6.3), epicenter near Long Beach, California, with a felt intensity of V at San Fernando; (iii) 21 July 1952 (Richter magnitude 7.7) in Kern County (Arvin-Tehachapi), with a felt intensity of VI at San Fernando; (iv) 9 February 1971 (Richter magnitude 6.5), epicenter about 12 km north of San Fernando, with a felt intensity of VIII to IX.

The correspondence of these dates to those identified for deformation of the sediments of Lower Van Norman Lake is strong evidence that the structures in each zone were formed by earthquake shaking and not by sedimentary processes. The load structures in the lake sediments are not typical of load casts from turbidite sequences (*4*) or from other environments (*5*). However, when closely examined, some Van Norman Lake structures are similar to the pseudonodules formed in shaking experiments by Kuenen (*6*). Because Kuenen did not measure or control the energy input in his experiments, the intensity of shaking is unknown. It may be that only very-high-intensity (> VIII) earthquakes form pseudonodules because in these cases greater amounts of energy are released and the duration of ground shaking is generally longer.

Load-casts are not peculiar to any specific sedimentary environment. However, specific styles of structures are stratigraphically restricted in the Lower Van Norman Lake sediments. Furthermore, most of these structures (zones 2 and 3) are low amplitude and radially symmetrical, with only slightly disrupted sediments correlated with earthquakes having felt intensities of about VI at Lower Van Norman Lake. In contrast, the more penetrative types of structures are associated with the 9 February 1971 earthquake (intensity VIII to IX).

The data presented here demonstrate that the seismic history, known for 56 years, of a single artificial lake can be tentatively correlated with the deformational structures in its sediments. The date of the lowest zone of structures does not agree exactly with the 1930 or 1933 earthquakes; this lack of agreement is at least partly attributable to the lack of pre-1930 rainfall data for Burbank and partly to the closeness in time of the two events. Similarly, the date of the middle zone of structures does not agree exactly with the 1952 earthquake, and here, again, the lack of agreement is at least partly attributable to the lack of pre-1930 rainfall data. The errors inherent in the method of estimating rainfall, and thus the weighting factors, yield dates that are not precisely correlative with dates of the earliest earthquakes that affected the Van Norman Lake region. In addition, undetermined compaction of the older sediments may introduce further error into the age estimates of the deformational structures formed in these sediments.

Further testing of this hypothesis may yield a tool for determining earthquake recurrence intervals for Holocene time, and perhaps even late Quaternary time. Earthquake recurrence histories for more than the last 1000 to 2000 years would materially aid in interpreting the timing and location of historic earthquakes, the record of which is distressingly inadequate.

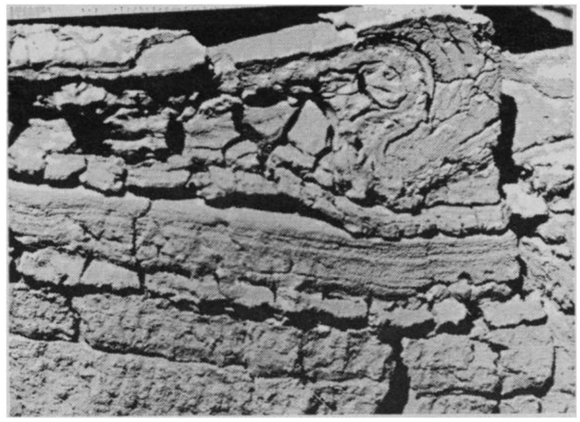

Fig. 3. Recumbent fold developed in the upper 2 cm of sediment of Van Norman Lake. The formation of this structure is attributed to the 9 February 1971 earthquake that shook the San Fernando Valley in southern California.

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References and Notes

1. C. R. Allen, *U.S. Geol. Surv. Prof. Pap. 733* (1971), pp. 7–10.
2. ———, G. R. Engen, T. C. Hawk, J. M. Nordquist, W. R. Thatcher, *ibid.*, pp. 17–20.
3. T. L. Youd and H. W. Olsen, *ibid.*, pp. 126–132; frontispiece in *ibid.*, p. ii.
4. S. Dzulynski and E. K. Walton, *Sedimentary Features of Flysch and Greywackes* (Elsevier, Amsterdam, 1965), p. 223; A. H. Bouma, *Sedimentology of Some Flysch Deposits* (Elsevier, Amsterdam, 1962), plate E2.
5. F. J. Pettijohn and P. E. Potter, *Atlas and Glossary of Primary Sedimentary Structures* (Springer-Verlag, New York, 1964).
6. Ph. H. Kuenen, *Trans. Geol. Soc. Glasgow* **23**, 1 (1958).
7. I thank H. D. Gower, U.S. Geological Survey, for stimulating me to look for earthquake-induced sedimentary structures in Lower Van Norman Lake. I also thank H. E. Clifton, U.S. Geological Survey, for visiting with me in the field and for discussions concerning the nature and significance of these structures.

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