could be found in the nickel tubes. The refractive index and viscosity of the droplets appeared to the eye to be similar to those of ordinary water droplets inside a similar vial, and both kinds of droplets froze and melted at about the same temperature, 0°C. The silica in the nickel tube was recovered as a pale green slurry (coesite bearing some Ni) which soon became dry. In one experiment water in a nickel tube was compressed to 40 kb at 25°C for 5 minutes, but only ordinary water was obtained in the product, as judged by measurements of viscosity and vapor pressure.

So far then no significant amounts of polywater have been obtained by cooling highly compressed liquid water from about 600°C at 60 kb, either in the presence or in the absence of silica. The catalytic powers of nickel and platinum also had no marked beneficial effects. If anomalous water exists as a polymorph of pure water, it is certainly not easy to form in measurable amounts under conditions that are more favorable thermodynamically than those previously used.

R. H. WENTORF, JR.
General Electric Research and Development Center, Schenectady, New York 12301

References and Notes

1. B. V. Deryagin and N. V. Churayev, *Priroda (Russian)* No. 4 (1968), p. 16; translation in *Joint Publ. Res. Serv. No. 45* (1968), p. 989.
2. E. R. Lippincott, R. R. Stromberg, W. H. Grant, G. L. Cessac, *Science* **164**, 1482 (1969).
3. G. A. Castellion, D. G. Grabar, J. Hession, H. Burkhard, *ibid.* **167**, 865 (1970); *Chem. Eng. News* (22 Sept. 1969), p. 39.
4. L. C. Allen and P. A. Kollman, *Science* **167**, 1443 (1970); R. P. Messmer, *ibid.* **168**, 479 (1970).
5. D. L. Rousseau and S. P. S. Porto, *ibid.* **167**, 1715 (1970); S. L. Kurtin, C. A. Mead, W. A. Mueller, B. C. Kurtin, E. D. Wolf, *ibid.*, p. 1720.
6. A. G. Leiga, D. W. Vance, A. T. Ward, *ibid.* **168**, 114 (1970).
7. L. F. Evans, *J. Appl. Phys.* **38**, 4930 (1967).
8. P. W. Bridgman, *Phys. Rev.* **48**, 893 (1935).
9. H. T. Hall, *Rev. Sci. Instrum.* **31**, 125 (1960).
10. Infrared spectra were recorded by R. Chrenko.

6 May 1970

Nuclear Explosions and Distant Earthquakes: A Search for Correlations

Abstract. *An apparent correlation between nuclear explosions and earthquakes has been reported for the events between September 1961 and September 1966. When data from the events between September 1966 and December 1968 are examined, this correlation disappears. No relationship between the size of the nuclear explosions and the number of distant earthquakes is apparent in the data.*

The possibility that nuclear explosions may trigger destructive earthquakes has been a matter of concern to seismologists, who have devoted an increasing amount of research to this question. It has been established that relatively small earthquakes are triggered close to the sites of some nuclear explosions, but attempts to show that the earthquakes extend more than a few tens of kilometers from those sites have been unsuccessful.

In a recent paper, Emiliani *et al.* (*1*) concluded that "Underground nuclear explosions trigger significant earthquake activity for at least 32 hours afterward and to distances up to at least 860 kilometers." Emiliani *et al.* go on to say, "By dividing the area under consideration into several annuli and by comparing, within each annulus, observed versus expected number of earthquakes, we have verified that the seismic effect of the explosion extends to the 860-km limit of our search."

This is an important conclusion, but it has not been borne out by our investigations or by the results of others who have looked for evidence of increased regional seismicity after nuclear tests. The conclusion of Emiliani *et al.* has not been effectively challenged (*2*), and a further clarification of the statistical nature of the data is appropriate.

We have examined the U.S. Coast and Geodetic Survey hypocenter data file (*3*) in an effort to find correlations between explosions and earthquakes and between earthquakes and other distant earthquakes. We studied the earthquakes in a large rectangular area that covered most of the western United States (Fig. 1) and found no correlations between earthquakes or between earthquakes and explosions other than the expected correlations within an aftershock sequence. One part of our study of the data was very similar to the study reported by Emiliani *et al.* We examined the data on earthquakes that occurred between 15 September 1961 and 19 December 1968 in an area bounded by latitudes 31.25° and 42.00°N and longitudes 109.00° and 124.50°W. From this data set, the earthquakes in a 2° by 2° square that includes the Nevada Test Site were excluded (see Fig. 1). We found that 446 earthquakes occurred in the 104-hour periods immediately following the 235 nuclear explosions and that 447 earthquakes occurred within similar periods immediately preceding the explosions (*4*).

These results differ markedly from the data presented by Emiliani *et al.* (*1*), even though the studies were similar. We therefore recomputed the figures, using the same time intervals and area (Table 1, column a). Although there are small differences, our calculation confirms their result.

Since it is well known that nuclear explosions are always followed by small earthquakes, which originate in the collapse zone above the cavity or along faults in its immediate vicinity (*5*), we removed the earthquakes near the explosions from the data set; that is, from a circle with an 860-km radius centered at 37.07°N, 116.25°W, we removed a 2° by 2° rectangle that includes the Nevada Test Site and tabulated the earthquakes for the time interval 15 September 1961 to 29 September 1966, excluding the test site (Table 1, column b). These data also showed more earthquakes in periods immediately following nuclear explosions than in similar periods immediately preceding the explosions. But when the data were extended to include the time interval between 29 September 1966 and 19 December 1968, this apparent correlation disappeared (Table 1, column d). Between September 1966 and December 1968 there were 205 earthquakes before the shots and 150 after the shots (Table 1, column c). These figures might be regarded as indicating that, in the first period, the nuclear explosions triggered the earthquakes and, in the second period, the earthquakes triggered the nuclear explosions—a ridiculous conclusion that dramatizes the danger of oversimplifying our statistical model.

If nuclear explosions do affect regional seismicity, the larger explosions presumably would cause more extensive earthquakes than smaller explosions. Of the explosions listed by the Atomic Energy Commission (AEC),

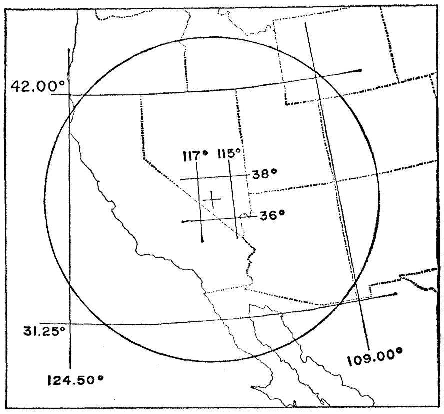

Fig. 1. Boundaries of study areas. Circle of 860-km radius indicates the outer limit of study by Emiliani *et al.* (*1*); large rectangular area indicates area of our study; small rectangular area encloses portion of total area removed to eliminate earthquakes close to the explosion sites.

the yield is given for only a few; explosions for which the yield is not given in megatons are said to be low, low-intermediate, or intermediate (an explosion yielding about 200 kilotons is classed as intermediate). Table 2 lists the explosions reported by the AEC to have a yield of 200 kilotons or more, and it gives statistics for each earthquake that occurred within 24 hours before and after each of those explosions. Except for the Stones and Bilby tests, which may have been contemporaneous with natural aftershocks, none of the nuclear explosions appears to have given rise to earthquakes.

A better statistical model might reveal some relationship between earthquakes and nuclear tests that we have not been able to detect. It is possible, for example, that some seismic zones might be affected more than others, or that the effects of some explosions may have been so small that they did not stand out against the background of natural activity.

There are human factors that might introduce an apparent correlation between earthquakes and explosions. In 1962, 1963, and 1964 intensive study of seismic waves from nuclear explosions formed a part of the Vela Uniform program, the purpose of which was to develop techniques for detecting underground nuclear explosions and to distinguish their effects from those of earthquakes. It would be very difficult to assess accurately the effect of this varying level of seismic research, but these factors have certainly had a major effect on the data sample.

In our judgment, the data that we have examined do not show that nuclear explosions have causative relationships with distant earthquakes. Even the most powerful explosions have not had a noticeable effect on the number of earthquakes detected by seismic networks, except in areas very close to the sites of the explosions.

Table 1. Total numbers of earthquakes at 8-hour intervals before and after each explosion in a circle of 860-km radius around the Nevada Test Site (NTS) (boundary center at 37.07°N, 116.25°W). The NTS (36.0° to 38.0°N, 115.0° to 117.0°W) is included only in column a.

Elapsed time (hours)	Earthquakes (No.)							
	September 1961 to September 1966				September 1966 to December 1968		September 1961 to December 1968	
	a*		b†		c†		d†	
	Before	After	Before	After	Before	After	Before	After
0–8	31	62	28	42	21	7	49	49
8–16	28	45	26	43	17	10	43	53
16–24	41	51	39	45	9	9	48	54
24–32	52	59	48	51	15	14	63	65
32–40	34	39	34	35	17	13	51	48
40–48	33	31	29	25	12	14	41	39
48–56	22	40	22	35	20	11	42	46
56–64	31	44	29	43	18	12	47	55
64–72	29	25	28	25	13	18	41	43
72–80	20	27	20	26	13	11	33	37
80–88	34	34	34	33	21	7	55	40
88–96	30	31	29	28	11	11	40	39
96–104	50	36	49	35	18	13	67	48
Totals	435	524	415	466	205	150	620	616

* NTS included. † NTS removed.

Table 2. Earthquakes recorded in 24-hour periods before and after intermediate range explosions in a circle of 860-km radius around the Nevada Test Site, with earthquakes in the NTS not included (see Table 1 for location of circle center and NTS).

Event	Date	Earthquakes (No.)	
		Before	After
Mississippi	5 Oct. 1962	0	0
Stones	22 May 1963	0	3
Bilby	13 Sept. 1963	1	9
Clearwater	16 Oct. 1963	1	1
Corduroy	3 Dec. 1965	1	1
Halfbeak	30 June 1966	1	1
Greeley	20 Dec. 1966	0	0
Commodor	20 May 1967	0	1
Faultless	19 Jan. 1968	0	0
Boxcar	26 Apr. 1968	1	0
Benham	19 Dec. 1968	0	0

It is true that between September 1961 and September 1966 there were more recorded earthquakes in the 24-hour periods following individual explosions than in the 24-hour periods preceding those explosions, even in areas far from the test sites. But between September 1966 and December 1968, the reverse is true; and when the two periods are taken together, there were as many recorded earthquakes before the tests as after the tests.

Perhaps the most important conclusion that can be reached from this study is that conclusions about the triggering of earthquakes should not be based solely on a statistical analysis of earthquake data. Such a study should incorporate a physical model for triggering that can be rechecked against the observations.

J. H. Healy
P. Anthony Marshall
National Center for Earthquake Research, U.S. Geological Survey, Menlo Park, California 94025

References and Notes

1. C. Emiliani, C. G. A. Harrison, M. Swanson, *Science* **165**, 1255 (1969).
2. A. L. Anderson, C. B. Archambeau, J. N. Brune, C. F. Richter, S. W. Smith, *ibid.* **167**, 1011 (1970); J. H. Allen and L. F. Bailey, *ibid.*, p. 1012; A. Ryall and G. Boucher, *ibid.*, p. 1013; C. Emiliani, G. C. A. Harrison, M. Swanson, *ibid.*, p. 1013.
3. The Hypocenter Data File was provided on magnetic tape by Leonard Murphy, Chief, Seismicity Division, U.S. Coast and Geodetic Survey, Environmental Science Services Administration.
4. List of underground nuclear explosions obtained from U.S. Atomic Energy Commission.
5. R. M. Hamilton, F. A. McKeown, J. H. Healy, *Science* **166**, 601 (1969).

6 April 1970