

filled with glycerin. At 48 hours post-priming, each group was subdivided and tested for convulsibility with either the right ear open (-R) or the left (-L). The results are presented in Table 1. The proportions of clonic convulsions observed in unilateral inhibition groups, R-R and L-L, and in control groups, R-L and L-R, were 2 of 23 and 22 of 27, respectively ($\chi^2 = 23.5$, $P < 0.0001$). This indicates that inhibition can be localized to the side of acoustic input, and that within the same animal the processes leading to inhibition and induced convulsibility can develop independently and coincidentally. Mice of the unilateral inhibition groups which did not convulse at 48 hours were retained and tested with either the right or the left ear open at 120 hours post-priming. In R-R-R and L-L-L groups 10 of 10 mice convulsed, and in R-R-L and L-L-R groups 10 of 11 mice convulsed. Thus, the protective effect of unilateral inhibition was impermanent.

To determine whether inhibition at one site conferred immunity to convulsibility during bilateral testing, the following experiment was performed. SJL/J mice were bilaterally primed at 21 days and randomly allocated to R or L inhibition groups, or to a control group whose members had both ears flooded with glycerin. After priming, subjects were reexposed to sound stimulation at 12, 24, and 36 hours. At 48 hours postpriming, all mice were tested with both ears open. As is seen in Table 1, 96 percent of the mice in the control group convulsed whereas 72 percent of those in the inhibition groups convulsed ($\chi^2 = 4.59$, $P < 0.05$). In this within-subject test of competition, the side of input associated with inhibition afforded a slight reduction in the risk of seizure to bilateral stimulation. Although unilateral inhibition did not confer dramatic immunity to bilateral convulsibility, it did significantly lengthen the latencies to clonic convulsions. Whereas 10 of 26 mice of the control group had fast convulsions, only 1 of 23 mice of the inhibition

groups convulsed with latencies shorter than 18 seconds ($\chi^2 = 6.32$, $P < 0.025$).

Although the nature of this inhibition is unsettled, certain of its features are known. The phenomenon is a poststimulation refractory state having a relatively long time constant and is not an interference or retrograde process as was previously suggested (2). The inhibition is not simply a temporary deafening due to acoustic trauma. Within 2 minutes after a 1-minute exposure to bell ringing, as well as prior to later exposure, mice reliably exhibit pinna reflexes and startle responses to the presentation of soft clicks. In addition, unconditioned galvanic skin responses to sine wave stimuli are detectable in mice tested 15 minutes after cessation of bell ringing.

The locus of the inhibition phenomenon, like that of the sensitization process, is lateral and possibly peripheral. The selective inhibition of convulsibility in one ear does not spread to the contralateral side, confers limited protection to bilaterally induced convulsions, and dissipates within 72 hours after cessation of stimulation.

Dextral-convulsive or sinistral-convulsive mice may be prepared acoustically either by restricting the priming stimulus to one ear or by unilateral re-exposure to sound after bilateral priming. These mice, having convulsive "split personalities," provide useful new tools for studies of the physiological effects of intense sound.

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5. Supported by NIH grant MH-11327 and by an allocation from an American Cancer Society Institutional grant, IN-19. Standards of laboratory animal care as prescribed by the National Society for Medical Research are followed in this laboratory. I thank Dr. Roger M. Ward for helpful advice.

14 November 1969; revised 23 December 1969 ■

Earthquakes and Nuclear Detonations

The report by Emiliani *et al.* (1) asserts some statistical results which would be important if well substantiated. To the undersigned, their evidence appears inadequate. Since it is likely that the conclusions, if unchallenged, will be accepted as authorita-

tive, and misapplied by readers not well versed in the subject, critical remarks are offered.

We do not question triggering of minor seismic events by Nevada test shots, at distances up to about 20 km. We do question the alleged correlation

out to 860 km. This radius extends completely over the active areas of California, Nevada, and Utah; it includes two highly seismic zones, one off the northwest coast of California, the other extending from the Imperial Valley into the Gulf of California.

In the interval studied, 15 September 1961 to 29 September 1966, bulletins of the Pasadena laboratory report approximately 1330 earthquakes in southern California and in adjacent Mexico down to 32°N. Many smaller events, especially in Mexico, were registered but not reported. Bulletins from Berkeley (University of California) list comparable numbers of earthquakes for central and northern California. To the total should be added events in Nevada, Utah, Colorado, and so on. The list of Emiliani *et al.* included only 1109 events that probably represent no more than 30 percent of the information available in print, and a much smaller percentage of the earthquakes known to have occurred in the area.

The process by which the partial list was selected should have no relation to hours of occurrence; but the results would meet with more confidence if more data had been used. It is common experience in seismology that deviations from expected means, which look significant when small numbers of events are studied, decrease or disappear when more data are included.

Although much stress is laid on the correlation out to 860 km, it is not documented. Totals are shown only for the entire area. Totals are stated to have been counted for successive annuli; these should be reported, or at least totals should be given separately for the larger radii, say from 400 to 860 km.

Two simple significance tests have been neglected: (i) incidence of earthquakes in 8-hour intervals following the nuclear tests should be compared with incidence in corresponding intervals preceding them (2), and (ii) the whole counting process should be repeated after dates and hours when no shots were fired, selected systematically (say by adding 3 months to the day and hour of each actual firing time used).

The procedure lumps earthquakes of all sizes together; necessarily the great majority are small, so that any definite results refer to these. However, if any large regional earthquakes chance to fall in the selected time intervals, their small aftershocks will add to the count. We presume that collapse events have

been eliminated, although this is not stated.

Since most of the shots were fired in morning hours (usually 5 to 10 a.m., local time), correlation may merely refer to the time of day. In that case this is a "rediscovery" of the rather dubious 24-hour period which has sometimes been found (3). It is suspicious that the total given for 24 to 32 hours after the shots is close to that for 0 to 8 hours, and exceeds the two intervening totals.

Two minor points should be noted: (i) in their first sentence, Emiliani *et al.* recognize only two artificial mechanisms for triggering earthquakes, and neglect the rapidly increasing evidence for triggering by reservoir loading (4), and (ii) the heading of their table is misleading; it should read "Numbers of earthquakes in given 8-hour intervals following explosions, totaled for all explosions considered."

The suggestions about ultimate control of earthquakes, and those with regard to the Amchitka test, reflect current discussion among seismologists, and call for no special remarks.

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1. C. Emiliani, C. G. A. Harrison, M. Swanson, *Science* **165**, 1255 (1969).
2. Study at Pasadena of earthquakes in southern California in relation to ten Nevada test shots during 1954 to 1967 showed no recognizable effect; there was even a slight majority of earthquakes on days preceding over those on days following the test shots (D. L. Anderson and T. Hanks, unpublished).
3. For evidence of a daily maximum at about 6 hours local time, see B. Gutenberg and C. F. Richter, *Seismicity of the Earth* (Princeton Univ. Press, Princeton, N.J., ed. 2, 1954; reprinted, Stechert-Haffner, New York, 1965), p. 25.
4. For references see D. M. Evans, *Eos* **50**, 387 (1969).
5. This is contribution No. 1690 of the Division of Geological Sciences, California Institute of Technology, Pasadena.

23 October 1969

Emiliani *et al.* (1) describe an apparent increase in seismic activity over a large area which is attributed to underground detonations of nuclear devices. For the 5-year period studied their data indicate a 62 percent increase above normal earthquake activity within an 860-km radius of the test site during the first four 8-hour intervals following detonations. On the basis of these data they suggested the possibility of releasing accumulated

seismic stresses in tectonically active areas by periodic (10 to 25 years) detonation of high-yield, deeply buried nuclear devices.

To the earthquake trigger mechanisms which they attribute to man (1) there should be added the creation of large areal surface loads by the back-filling of lakes behind man-made dams. Carder (2) described the increase of local earthquake activity as Lake Mead was originally filled, and Galanopoulos (3) reported similar variations in local seismicity of the Attic Basin corresponding to changes in level of Lake Marathon.

Emiliani *et al.* assumed a uniform distribution of earthquake occurrences during 8-hour intervals covering the 5 years they studied. Such an assumption is not likely to hold for smaller areas or shorter time intervals because of the frequent occurrence of earthquake swarms and the common grouping of a main shock followed by several aftershocks; however, for the area and time studied their assumption seems supported by the data. It is unfortunate that no results were given for the four (or thirteen) 8-hour intervals prior to the detonations.

In order to appreciate the implications of the proposal to reduce stress accumulations within the lithosphere by exploding deeply buried nuclear devices, it is instructive to examine further their given data in light of the accepted relationship between seismic energy release and recorded magnitude of body waves, m_b (4, 5). From (1) we have: (i) total expected number of naturally occurring earthquakes in the first four 8-hour intervals following detonations, 141; (ii) observed number of earthquakes during these intervals, 228; (iii) number of earthquakes attributed to explosions, 87; (iv) number of explosions, 171; and (v) number of explosions to trigger one earthquake, 1.97.

Ryall and Savage (6) gave the body wave magnitude of the 1.2-megaton (7) Boxcar events as $m_b = 6.42$. Any two seismic events, regardless of source, which produce body waves that differ in magnitude by one unit will have their respective energies in a ratio $E_m/E_{m-1} \approx 237$ (8). If all aftershocks caused by a nuclear detonation were of the maximum observed magnitude, one unit less than the trigger shock, 237 aftershocks of magnitude $m_b = 5.4$ would be required in order to release the earth-coupled energy equivalent to a single nuclear event having $m_b = 6.4$.

If, as proposed, 10-megaton underground nuclear detonations were employed, each capable of producing a measured body wave shock equivalent to an earthquake with $m_b = 6.8$, then there would be required 237×237 or 56,169 aftershocks with $m_b = 5.8$ in order to release the energy equivalent to a single $m_b = 7.8$ ($M_s = 8.4$) earthquake comparable to the estimated $M_s = 8.25$ for San Francisco 1906. If approximately two explosions are needed to trigger one earthquake and if some 56,000 of these earthquakes are required to release the accumulated stress, then over 112,000 10-megaton nuclear detonations would be needed to do the job. If these 112,000 detonations were spread over one century at 10-year intervals, we could have 40 detonations per day excluding Sundays and holidays for 1 year in each 10-year interval. In addition, these 40 detonations per day would be accompanied by an expected 20 additional earthquakes per day with magnitudes $m_b = 5.8$, roughly three large seismic events every hour!

Richter (5) pointed out the logarithmic difficulty in decreasing seismic stress by frequent small earthquakes. Also, a distinct possibility exists that the test-induced earthquakes represent only superficial adjustments of near-surface stress; whereas larger earthquakes may result from conditions at depths not affected by the tests. Finally, there is no assurance that setting off a large underground explosion in a tectonically unstable area such as the San Andreas fault zone might not yield an aftershock of one or two units of magnitude greater than the trigger device. This could be devastating along the densely populated West Coast.

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5 November 1969

Emiliani *et al.* (1) statistically analyzed the number of earthquakes occurring in a 2,300,000 km² region centered on the Nevada Test Site during equal periods of time (104 hours) following underground nuclear explosions. They assumed randomness for the events studied and used a cumulative count of earthquakes after 171 explosions and claimed that "underground nuclear explosions trigger significant earthquake activity for at least 32 hours afterward and to distances up to at least 860 km" from the Nevada Test Site. Based on this finding, they suggest that properly spaced and properly timed underground nuclear tests be used to "release stresses in the lithosphere and therefore limit the severity of earthquakes."

The idea of inducing fault creep in active seismic areas, by fluid injection or other means, has been suggested (2) and may have merit for further investigation. However, we wish to take issue with the main finding of Emiliani *et al.* that underground testing in Nevada has influenced earthquake activity over most of the conterminous western United States. Their statistical analysis reveals a departure from randomness in the times of occurrence of earthquakes in this region. They interpret this to mean that the time periods shortly after nuclear explosions contain an extraordinary number of earthquakes. In reality, however, the assumption that earthquakes occur randomly in time is invalid. On the contrary, most of the earthquakes listed for this region (3) are easily seen to belong to two categories—aftershock sequences and swarms of small events. This may be shown to invalidate the analysis of Emiliani *et al.* in the following way.

Based on the historic seismicity of the western United States (4), one would expect approximately ten earthquakes per year of magnitude (M) ≥ 5 to occur in the region considered by Emiliani *et al.* Of this number, 2.8 per year would be expected to have $M \geq 5.5$, and 1.3 would have $M \geq 6$. If earthquakes with $M \geq 5.5$ can be assumed to have an aftershock sequence lasting, on the average, 3 to 4 weeks, then we would expect approximately one-fourth of the explosions fired during a given year to occur during on-going sequences of aftershocks. Further, inasmuch as the 5-year period of analysis used by Emiliani *et al.* contained 425 periods of 104 hours' duration, the chance of an earthquake with

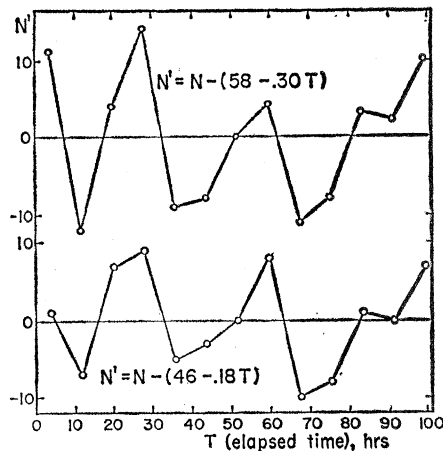


Fig. 1. Cumulative earthquake counts for 13 8-hour periods following underground tests. Top trace represents data from Emiliani *et al.* (1) with linear trend removed; bottom trace represents same data, with removal of events at the Nevada Test Site, Truckee aftershocks, Idaho earthquakes, and a linear trend.

$M \geq 5.5$ occurring within any 104-hour period is $5 \times 2.8/425$, or $1/30$. For 171 such periods, one would expect the cumulative earthquake count to contain the beginnings of 171/30, or five or six sizable earthquake sequences, even in the absence of any nuclear explosion triggering effects.

The probability that 35 to 40 underground tests during the 5-year period were fired during on-going aftershock sequences, together with the observation that aftershock activity generally dies off approximately as t^{-1} (5), leads one to expect that a cumulative count of earthquakes for periods (104 hours) much shorter than the duration of an average sequence of aftershocks (3 to 4 weeks) would show a gradual decrease in activity with elapsed time. Superimposed on this decrease in earthquake occurrence, one would expect to see five or six peaks, representing intensive activity during the first few hours of aftershock sequences.

A couple of examples should suffice to show that these factors have indeed affected the analysis of Emiliani *et al.* On 12 September 1966, a low-yield underground test was followed within 8 hours by the beginning of an earthquake sequence near Truckee, California. For this 8-hour period, the USCGS located ten events large enough to be recorded at several seismographic stations. The first and largest of these was an earthquake with $M = 5.4$; the other nine shocks must be considered aftershocks of this earthquake, not events triggered by a relatively small explosion 400 km away.

Beginning on 6 September 1963, an earthquake swarm occurred near Stanley, Idaho, for which the USCGS lists 59 epicenters in 17 days. The largest of these was a shock with $M = 4.9$ on the fifth day of the swarm, and it was followed by 31 events during a 3-day period. On 13 September, in the middle of this burst of activity, two tests were detonated at the Nevada Test Site. Depending on the exact way in which Emiliani *et al.* carried out their analysis, either 8 or 11 of the Idaho shocks would have been counted as earthquakes triggered by the blast for one 8-hour period, in spite of their obvious relationship to a natural earthquake 2 days before the explosion.

The effect of eliminating from the cumulative count the first 8 hours of the Truckee sequence, 8 hours' worth of Idaho earthquakes, and 11 events at the Nevada Test Site that occurred within 8 hours of explosions is shown in Fig. 1. The removal of only these few events is seen to have a significant effect on the "triggering" influence of explosions. The slope of the lower curve ($-.18$) is only three-fifths that ($-.30$) found for the original data, and the amplitude of the 0- to 8-hour peak of activity is reduced to almost zero. Analysis of the complete list of earthquakes used by Emiliani *et al.*, incorporating careful elimination of all aftershocks from the data sample, would very likely remove any remaining correlation between underground tests in Nevada and earthquakes at distances of hundreds of kilometers from the test site.

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27 October 1969

Following the above comments by Anderson *et al.*, Allen and Bailey, and Ryall and Boucher, we now provide additional data in support of our thesis. The fourth column (Table 1) shows the number of earthquakes in the region between 430 km and 860 km from the Nevada Test Site for the intervals shown, summed over all explosions. The ex-

Table 1. Number of earthquakes at 8-hour intervals after explosion. The expected number in the total area in columns 2 and 3 is 35.26, in the area from 430 to 860 km from the test site in column 4 is 20.01.

Interval (hours)	Number of earthquakes		
	In total area	In area from 430 to 860 km from test site in intervals from detonation	
0-8	48	39	33
8-16	28	32	32
16-24	33	61	30
24-32	22	31	41
32-40	29	29	23
40-48	31	42	17
48-56	24	45	27
56-64	33	29	20
64-72	35	45	15
72-80	58	37	12
80-88	45	16	27
88-96	27	26	17
96-104	35	37	25

pected number for this area is 20.01 in each interval. The first four numbers are all two standard deviations above the expected number, strongly suggesting that seismic activity was indeed stimulated in this region.

The numbers of earthquakes in the 8-hour intervals immediately preceding the explosions are reported in column 2 (Table 1), the last number in this column being the number of earthquakes falling in the interval 0 to 8 hours immediately preceding the explosions. As may be seen, there is no pattern whatsoever in the numbers. We also added 2160 hours (90 days) to the times of the explosions and counted the numbers of earthquakes in the 8-hour intervals following these new times (Table 1, column 3). Again, there is no recognizable pattern.

Neither our original data nor the new ones presented in Table 1 can be interpreted as a "rediscovery" of the dubious 24-hour period, as suggested by Anderson *et al.* For, in our original data, this should have been manifested in high values not only for the first and fourth numbers, but also for the seventh, tenth, and thirteenth numbers. The seventh, tenth, and thirteenth numbers in our original table (1) add up to 106 earthquakes, compared to an expected number of 105.78 earthquakes. Columns 2 and 3 of Table 1 also show the absence of the 24-hour period. Of the 26 numbers in these columns, nine are in the appropriate time intervals. Their sum is 324, compared to an expected number of 317.34.

The data in columns 2 and 3 of Table 1 show that the model suggested by Ryall and Boucher is incorrect. According to these authors, our analytical procedure should produce a linear decrease of numbers of earthquakes with increasing time, on which are superimposed five or six peaks representing intensive activity during the first few hours of aftershock sequences. Column 2 of Table 1 actually shows a small increase with time, but the correlation coefficient (0.2903) is not significant. Column 3 shows a small decrease with time but, again, the correlation coefficient (-0.3151) is not significant.

Allen and Bailey miss entirely the main point of our thesis. Underground nuclear tests conducted so far have been presumably made at locations and depths chosen so as to avoid the release of large amounts of seismic energy. Our contention is that underground nuclear tests conducted at suitable locations and depths could trig-

ger the release of large amounts of seismic energy. The very meaning of the word *trigger* signifies an energy output greater than the input. Clearly, only if this were the case could underground nuclear explosions be conceivably used to control earthquakes (2).

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2. The first suggestion in print to use underground nuclear explosions for earthquake control is not in (1) above, as we thought, but in a paper by Brune and Pomeroy [*J. Geophys. Res.* **68**, 5020 (1963)], a contribution that escaped our attention when we wrote our paper.
3. Supported by NSF grants GA-4302 and GA-10082; computer work supported by the University of Miami. Contribution No. 1148 from the School of Marine and Atmospheric Sciences, University of Miami.

26 December 1969

Bentonite Landslides

The essential conditions cited by Anderson *et al.* (1) for development of bentonite debris flows in Northern Alaska include "easily hydrated interbedded bentonite deposits . . . slopes of 5 to 20 degrees . . . and water in moderate quantities for at least several weeks duration." Anderson *et al.* consider these landforms and this geomorphic process to be unique to the arctic environment. This conclusion is contradictory to other published reports and evidence presented here. Yatsu discusses the widespread occurrence of landslides of the flow type associated with the hydration of swelling clay minerals, such as montmorillonite. Using examples of landslide materials from Japan, Scandinavia, and Canada, Yatsu concludes, "if bedrock contains some components of swelling clay minerals it swells with pressure when afforded with water and is apt to become unconsolidated clayey debris. Such detritus is easily affected by mass-movement of slip or flow types" (2).

Similarly, in a discussion of the chemical stabilization of an active landslide in Des Moines, Iowa, Handy and Williams report that "x-ray and grain-size analyses of the sliding soil indicated that it contains 25 to 30 percent calcium-saturated montmorillonite clay" (3).

Our work confirms the presence of

other bentonite landslides in widely differing climatic areas. Mudflows with very similar morphological characteristics to those in Alaska have been described in Northern Ireland, 54°50'N, 05°50'W. These have three distinct parts, a source area, a flow track zone through which debris is transported, and a depositional toe zone. X-ray

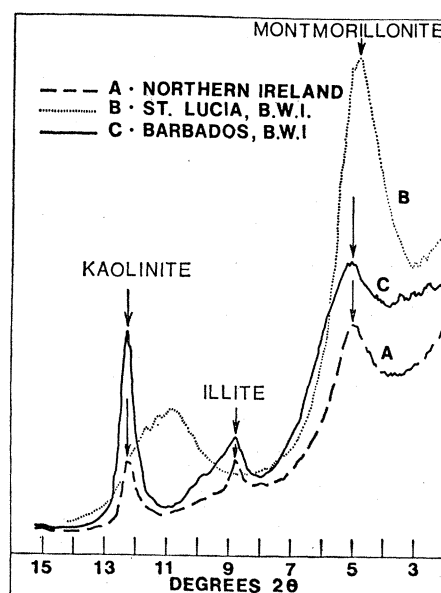


Fig. 1. X-ray diffractometer traces of landslide materials from Northern Ireland, St. Lucia, B.W.I., and Barbados, B.W.I. (CuK α radiation).