AN INVESTIGATION OF THE
SEISMICITY AT REGIONAL AND TELESEISMIC DISTANCES
FOLLOWING UNDERGROUND NUCLEAR DETONATIONS

Final Technical Report

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ABSTRACT

The main emphasis of this investigation was to determine the seismicity of the Nevada Test Site area during a time period which encompassed a lull in the testing program. The time period studied extends from April 1, 1973 to October 1, 1975. The after-shock sequence of nuclear shots fired on Pahute Mesa during late 1975 and early 1976 were also included.

A tabulation of all earthquakes for 10- and 30-day intervals reveals an increase in seismic activity for those intervals between test shots and a decrease for those intervals incorporating test shots. The percent accumulated number of earthquakes increases most rapidly between the firing of Hybla Fair (10/28/74) and Topgallant (02/28/75) and increases little following Topgallant.

An investigation into the strain release for the Nevada Test Site reveals a decrease in strain release, for 10- and 30-day intervals, between the shots Ming Blade (06/19/74) and Hybla Fair and following Topgallant through September of 1975, and an increase in strain release between Hybla Fair and Topgallant. The two time spans of decreased strain release relate to periods of increased nuclear testing, and the time span of increased strain release incorporates no nuclear test shots. The percent accumulated strain release increases most rapidly between the detonation of Hybla Fair and Topgallant, and increases little, following Topgallant. For the entire period of April 1, 1973 to October 1, 1975, the strain release appears to be decreasing.

Determination of the seismic parameters for seismograph stations CPX, LSM, and MCV, demonstrates a decrease in b-values ($\log_{10} N = a - bM$) for N, both cumulative and interval, for the Test Site area, from 1973 to 1975. This is indicative of a decrease in seismic activity. An

increase in the b-values for aftershocks of nuclear test shots recorded on Pahute Mesa from 1975 to 1976 may indicate a reversal of the decreasing trend of seismic activity.

The detection capability of the NTS seismograph network was quantitatively investigated for time periods when only three stations were in operation continuously and for when the station configuration was expanded to 15 stations. The change in detection threshold as a function of average background noise was also determined.

PREFACE

This report was written to fulfill the contractual requirements of DOE Contract No. EY-76-S-02-2782, Modification No. M002. The report draws heavily upon the graduate thesis of one of the co-authors - Alan L. Stubenrauch whose research was sponsored primarily by this program.

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INTRODUCTION

The possible influence of man-made activity on the natural occurrence of earthquakes has been of considerable interest for many years. Investigations into the nature of such influences are significant, for example, to the problems of earthquake control, as it may prove possible to release the stress field of an impending large earthquake by triggering many smaller, less destructive earthquakes, or at least, trigger the larger earthquake at some approximately prescribed time. This would permit some measure of precaution to be exercised beforehand. Underground nuclear explosives may be utilized for canal excavation, mining and quarrying, or stimulating the flow of petroleum. The affect of these underground blasts on the area's natural seismic activity must be fully understood before the application of such procedures may be safely practiced.

The inducement of earthquakes by man has been achieved in a number of ways: surface loading, fluid injection, and the detonation of large underground explosives. One of the earliest documented cases on the generation of earthquakes by surface loading involved Hoover Dam (Mead and Carder, 1941). This massive dam was completed in 1936, and shortly after it was filled a pattern of earthquake activity began which persisted for many years. An increase in surface loading and an increase in the pore pressure in the underlying rock probably caused these earthquakes.

The injection of fluid wastes at the Rocky Mountain Arsenal during 1962 to 1965 was followed by a pattern of earthquakes near the Denver area (Hollister and Weimer, 1968). In a series of controlled tests by

the U.S. Geological Survey at the Rangely Oil Field in Colorado, scientists (Wallace, 1974) discovered they could control at will the generation of earthquakes by the injection into or withdrawal of fluids from the earth.

When underground nuclear explosives are detonated, they are usually followed by a series of aftershocks, defined here as the intense seismicity in the source region which correlates with the deterioration of the cavity formed by the detonation. These aftershocks may number into the thousands for the larger events. When the cavity collapses (anywhere from a few minutes to several days) this aftershock activity will normally completely cease (Hamilton and others, 1969). Tectonic events (natural-appearing earthquakes) will sometimes be generated at shallow depths (one to five kilometers) and at distances usually less than ten kilometers from the shot. These events are probably related to the regional stress fields in the shallow crustal rocks and to the perturbation of that stress field caused by the explosion-generated elastic waves. Increased pore pressure in the rocks caused by the explosion could also change the strength of surrounding rock and subject it to earlier failure due to the action of the regional stress field (Healy and Marshall, 1970).

The tectonic events and the aftershocks in the cavity region will register, at most, a magnitude of about 1.2-1.4 magnitude units lower than the initial explosion (Bath, 1973). Thus, the largest aftershock or generated earthquake of an explosion will have approximately only one percent of the seismic wave energy released from the shot itself. If sufficient stress has built up in the immediate vicinity

of the shot, it is conceivable that there could be a nearly simultaneous triggering of an earthquake that would be difficult to differentiate from the shot.

Objectives

The principal objective of this study was to investigate the earthquake activity in the local Nevada Test Site area, and in particular, to investigate for any variations in the Test Site's natural tectonics, within the time interval April 1, 1973 through October 1, 1975. Variations in the natural tectonic pattern were examined for any correlation with the Test Site's underground nuclear testing program. Seismic studies of the Nevada Test Site had been performed prior to April of 1973, and were resumed in October of 1975. Hence that time interval was important from the standpoint of not being previously investigated, and was an interval representing a lull in the testing program between large-scale nuclear tests.

Aftershock activity for the Nevada Test Site area was also studied with emphasis focusing on the larger events, since unusually large numbers of aftershocks would be indicative of natural stress build-up in the region.

Since April 1, 1973 there has been continued small scale underground nuclear testing with a resumption of large yield tests in May, 1975. This time interval thus represents a lull in the testing program. As such, it affords a unique opportunity to relate the Test Site's natural seismicity (with respect to small scale testing) to the seismic pattern of the Test Site under the influence of large-yield underground nuclear explosions.

Seismicity Measurements

Seismic data are extremely important to the understanding of tectonic processes that are taking place within the earth. Regions of high seismicity are associated with mountain building forces within the earth. The theory of plate tectonics and sea floor spreading shows that most earthquakes are associated with the boundaries of the lithospheric plates. These tectonic processes are now fairly well understood along most plate boundaries. However, the processes controlling earthquakes in the lower seismicity areas within the continental interiors away from these plate boundaries are not nearly as well understood. It is believed that the vertical crustal movements are caused by two main factors - tectonic factors and isostasy. There is no reason to believe that some of the forces exerted on the edge of a plate could not be transmitted into the interior regions of the plate or that the convection currents in the asthenosphere could not cause stresses in the overlying lithospheric plate. York and Oliver (1976) point out that the stresses in the intraplate regions such as the northeastern United States vary spatially and temporally as shown by both gravity and thrust faults which have varying strikes.

There exist numerous methods of representing the seismicity in a given region. These would include maps depicting epicenter locations and magnitudes, accumulative strain release maps (Allen and others, 1965), yearly perspective plots of cumulative strain release (Willis and others, 1974), space-time seismicity plots (along subduction zones) Kelleher and Savino, 1975, and Willis and others, 1972), stereo projections of seismic activity in time and location (Willis and others,

1974), and quantitative seismicity maps based on a and b values ($\log_{10} N = a - bM$) (Kaila and others, 1971, 1974, and 1975). With the exception of the latter, it is difficult to quantify the seismicity as the occurrence of large events dominates the display.

The empirical equation of Richter (1958) which relates the frequency of occurrence of earthquakes as a function of magnitude gives a simple method to compare the seismicities of different regions. This equation, also referred to as a recurrence curve, is given by

$$\log N = A - bM$$

where M = magnitude

N = number of earthquakes of magnitude M

or larger per unit of time, or the number of earthquakes in the magnitude interval M, M+dM.

A and b are empirical constants. A is the value of the 0 magnitude intercept, and b is the slope of the line described by the equation.

The above equation is a very basic statistical measure of seismic activity and has become widely used and generally accepted in recent years. It is thought that the value of b is related to the physical characteristics and the distribution of stress in a region. Isacks and Oliver (1964) reviewed the application of this equation to determine the seismicity of a region. They believed that the constant A varies between regions, but the constant b changes very little as a function of region, time or magnitude. Hence, if b is constant, it "implies that within a range of magnitudes governed by the linear log N vs M law, seismic activity is simply described by the constant A." If it could be established that b were constant, one could then take the

computed A determined from small magnitude earthquakes recorded by a microseismic monitoring network and predict the return period for larger magnitude earthquakes. Values of b shown in Table VII of Isacks and Oliver (1964) range from about 0.5 to 1.5 with most values between 0.7 and 1.0. The authors stated at the time of the article (1964), that the fluctuation in b values did not appear to be distinguishable from errors of measurement.

RECENT GLOBAL DETERMINATIONS OF SEISMICITY

Considerable research has been conducted on the seismicity of various regions of the world since Isacks and Oliver (1964) compiled the listing shown in their Table 7. A survey was made of the literature since 1964 and the results are shown in Table 1.

TABLE 1 (From Willis, 1977)

Values of b for Various Regions

Reference	Region & Time Interval	Number of Earthquakes	Magnitude Range	Magnitude Measures	+ b
Brazee & Stover 1969	Global 1964-65 Shallow $h \leq 70\text{KM}$ Intermediate $70 < h \leq 300\text{KM}$ Deep $h > 300\text{KM}$ Total	7,811 1,879 586 10,276	3.0-6.9	m_b	1.361 1.124 1.138 1.306
Evernden 1970	World 1963-1968 Shallow	$\approx 5,200$	5.0-5.5	m_b	1.23
Stover 1968	So. Atlantic Ocean, 29 yrs. 1923-1951	51	6.0-7.2	M_S	1.01
	So. Atlantic Ocean, 3 yrs. 1964-1967	83	4.7-5.9	m_b	1.04
Stover 1966	Indian Ocean, 30 yrs, 1922-1951	76	6.0-	M_S	0.91
Sykes 1965	Arctic, 9 yrs. 1955-1963	267	4.0-6.8	M_S	0.91
Papazachos & Comninakis 1971	Aegean Arc, 1911-1969 Shallow $h < 60\text{KM}$ Intermediate $60 < h \leq 170$	1300 109	4.9-6.8 4.9-6.8	M M	0.94 0.54
Sacuiu & Zorilescu, 1970	Romania 1937-1962		3.5-7.2	M	0.70
Crampin 1969	Iran, 1968 Aftershock sequence	297 10	2.5-3.5 5.0-5.5	m_b m_b	1.18 1.20
Hedayati, et al. 1976	Iran 1974	198 198	3.0-5.2 1.5-4.6	m_b M_L (coda length)	0.79 0.64
Menke & Jacob 1976	Pakistan/India 6/15/74-2/12/75	357	2.4-5.5	M_L (coda length)	0.73 (0.70, 0.72, 1.02)

TABLE 1
(Continued)

Reference	Region & Time Interval	Number of Earthquakes	Magnitude Range	Magnitude Measure	+b
Curtis, 1973	Papua, New Guinea, & Solomon Islands 1961-1970 All depths 0-125KM 126-250KM 251-700KM	≈1000	4.9-7.0	m _b	1.41 1.45 1.04 0.86
Koyanagi, et al, 1966	Hawaii, 1962 Aftershocks	1137	0.5-3.5	M _L	0.98
Page, 1968	Alaska, 1964 Aftershocks	293 383	4.5-5.7 (4-50mm)	m _b (trace amp.)	0.88 0.81
Willis, et al, 1972	Aleutians 1969-1971	520	4.5-6.1	m _b	0.33
Smith, et al, 1968	Mold Bay, Canada 1965, Swarm	2026	-1.0-2.7	M _L	0.68
Anglin	Yellowknife, Canada 3rd zone distances 99 days - 1968 12 regions	≈1000	4.0-5.7	m _b	0.63- 1.67
	Avg. for all regions	≈1000	4.0-5.7	m _b	0.99
Suyehiro 1966	Chile - 1960 Foreshocks	31	(2-62mm)	(trace amp.)	(Slope= 0.55)
	Aftershocks	122	(2-16mm)	(trace amp.)	(Slope= 1.13)
Lahr & Pomeroy, 1970	Congo - 1966 Foreshocks Aftershocks	35 779	3.3-4.8 3.3-6.0	m _b m _b	1.06 1.05
Tryggvason 1973	Iceland 1946 Swarms - largest event only	≈ 37/yr.	3.5-7.5	M	0.79
Cook & Smith 1967	Utah, 1850-1965	332	3.0-6.9	M	0.6

TABLE 1
(Continued)

Reference	Region & Time Interval	Number of Earthquakes	Magnitude Range	Magnitude Measure	+b
Sanford & Holmes, 1962	New Mexico 9/61-1/62	173	(160-10,000 Angstroms)	(trace amp.)	0.79
Gibbs, et al, 1973	Rangely, Colo. 1962-1970	320	1.0-3.5	M_L	0.91
Unger & Decker, 1970	Mt. Rainer, Wash. 7/13/68-8/11/68	50	-0.50-0.75	M	0.82
Rogers & Lee, 1976	Lake Mead, Nev./Ariz.	1360	1.6-2.9	M_L	1.45
Reichle, et al, 1976	Gulf of California 1963-1975	50 ⁺	5.0-6.9	M_S	0.64
Eaton, et al, 1970	Parkfield, Calif. 1966 aftershocks h=8-10KM	600	-1.0-3.5	M_L	0.6
		85		(Coda length)	
	Other depths	279		M_L (Coda length)	0.95
Fitch, 1969	Parkfield, Calif. 1966 aftershocks	≈ 950	-1.5-2.0	M_L	0.52 to 0.63 0.59 avg.
Aki, 1969	Parkfield, Calif. 1966 aftershocks	≈ 45	1.2-2.6	M_L^*	1.44
McEvilly, 1966	Parkfield, Calif.	85	1.0-5.5	M_L	0.41 (prelim) 0.63 (revised)
Bolt & Miller, 1971	North & Central California, 1965-1969	661	3.0-5.1	M_L	0.78
	Cape Mendocino, Calif	162	3.5-6.0	M_L	0.67**
	Coastal area, Central Calif.	265	3.0-4.4	M_L	1.00

* Based on conversion from seismic moment using coda amplitudes.

** b value from Ryall, et al. (1966) which generally fits these data although there is considerable scatter.

TABLE 1
(Continued)

Reference	Region & Time Interval	Number of Earthquakes	Magnitude Range	Magnitude Measure	+b
Lee, et al., 1971	Danville, Calif 1970	426	1.2-4.2	Equivalent M_L	0.7
McEvelly & Casaday 1967	Antioch, Calif. 1965	≈40	1.5-3.0	M_L	0.78
McEvelly 1966	Corralitos, Calif. 1964	42	1.5-3.0	M_L	0.63
Greensfelder 1968	Truckee, Calif. 1966	3200 20	-1.5-0.8 1.5-4.4	M_L M_L	1.40 0.40
Udias, 1965	Salinas-Watsonville, Calif. 1963	95	1.0-5.0	M_L	0.41
Bollinger 1973	Southeastern U.S. 1770-1969	694	($V \leq I_0 \leq VIII$)	Intensity	(Slope=0.59)
Bollinger 1972	South Carolina 1886-1971	60	($IV \leq I_0 \leq VIII$)	Intensity	(Slope=0.31) Equivalent b=0.5±0.1
	3 mos. 1971	61	0.5-1.5	M_L	1.8±.5
Long 1974	Seneca, S.C. July 1971				
	ATL-WWSS	14	2.5-3.2	M_L	0.9
	Microearthquake	40	0.2-1.2	M_L	1.7
	McCormick, S.C. 5/69-9/69	40	2.2-2.8	M_L	1.3
Lammlein, et al. 1971	New Madrid 1950-1964	32	2.0-5.0	M_L	)
	Microearthquakes 11 days - 1968	44	-1.0-1.0	M_L	) 0.6
Nuttli 1974	Central Miss. Valley 1833-1972	487	2.9-6.3	m_b	0.87
Stauder, et al, 1976	SE Missouri 7/1/74-12/31/75 (1.5°x1.5° area)	185 (288)	1.0-4.4	m_b	0.8

TABLE 1
(Continued)

Reference	Region & Time Interval	Number of Earthquakes	Magnitude Range	Magnitude Measure	+b
Sbar, et al. 1970	Lake Hopatcong, N.J., Microearthquakes 10/16/69-11/9/69	19	(.3-1.2)	(log half amp.)	(1.8±1.1)
	OGD-4 mos. 1969	40	(.4-1.7)	(log half amp.)	(1.9±0.8)
Sbar, et al. 1972	Adirondacks, N.Y. Swarm of 1971 (3 mos.)	364	-4.0(?) - 3.6	M _L	
			(0.65-1.8)	log ampli- tude	1.5

m_b is body wave magnitude or Nuttli's equivalent
body wave magnitude based on L_g.

M_s is surface wave magnitude.

M_L is local magnitude.

M represents the various authors' undesignated
magnitude.

Each magnitude shown is that reported by the various authors.

Rothe (1969) gives a b value of 1.25 for all earthquakes on a global basis at any depth for magnitudes between 6.2 and 8.0. His data base included 1297 earthquakes which occurred between 1953 and 1965. Evernden (1970) in a compilation of seismicity data lists the following b values:

TABLE 2

Location	$+b$	Linear Range in Magnitude	Magnitude Measured
Kern County California	0.80	3.25-6.25	M
San Bernardino Mts., Calif.	0.85	3.25-6.5	M
Owens Valley, Calif.	0.84	3.75-5.25	M
San Andreas Fault, Calif.	0.86	2.75-5	M
Imperial Valley, Calif.	0.85	3.75-6.75	M
Los Angeles Basin, Calif.	1.02	2.75-5.5	M
Southern California	0.75	4-7	M
San Andreas Fault north of Tehachopi, Calif.	0.90	4.2-6.5	M
Mendocino Escarpment, Calif.	0.67	4.0-6.4	M
Calif.-Nevada	0.80	4.2-7.8	M
Truckee aftershocks, Calif.	0.80	2.2-3.5	M
USA, 35°N-49°N, 90°W-110°W	1.29	4.0-5.0	m_D
Ogdensburg, N.J.	0.95	1.0-4.3	M
Alaska, 1904-1964	0.65	6.0-8.4	M
Alaska, 1968	0.68	3.0-6.5	M
Mold Bay, Canada	0.68	-0.8-2.2	M_L

Location	+b	Linear Range in Magnitude	Magnitude Measured
Arctic	0.90	4.3-6.7	M
Japan, 1926-1956	1.03	5.0-7.1	M
Niigata, Japan aftershocks	0.96	3.8-6.2	M
Kamchatka/Kuriles/Japan 1966-67	0.93	4.5-5.5	m_b
USSR-Kamchatka/Kuriles 1965	1.04	4.0-5.6	m_b

The designations for M, M_L , and m_b are the same as those in Table 1.

As Evernden points out there appears to be a real variation in the slope of the recurrence curves throughout the California and Nevada region with b values ranging from 0.67 to 1.02. The central United States has a b value of 1.29 for m_b greater than approximately 4.0. The b values for Alaska (0.65 and 0.68) are unusually low. The magnitude values are probably M_S values determined at teleseismic distances.

Hileman et. al. (1973) published a detailed report on the seismicity of Southern California for 1932 through 1971. The area included is shown in Figure 1. Their b values are given in Table 3 and are shown in Figure 2.

Figure 1. Outlines of the various areas for which recurrence curves are presented in Figure 2. - Note the heavy outline for the entire southern California area of coverage, excluding northern Mexico. Modified from Hileman et.al.(1973)

Figure 2. Interval recurrence curves for each of the areas shown in Figure 1. Note that the ordinate scales are identical for all curves except for the curves for the southern California network and north Mexico areas.

From Hileman et.al.(1973)

TABLE 3

Values of b for Southern California

Region	Area (km ²)	Number of Events	Lower Magnitude Cutoff	+b
Southern Calif.	238,600	3404	3.5	0.98
No. Mexico	47,200	606	4.5	0.92
Los Angeles	26,622	1373	3.0	0.93
White Wolf Fault (1932-1951)	8,400	93	3.0	0.85
White Wolf Fault (1952-1971)	8,400	986	3.0	0.87
Santa Barbara Channel	10,200	328	3.0	1.00
No. Sierra Nevada	10,600	144	4.0	1.01
So. Sierra Nevada	8,450	555	3.0	0.98
Parkfield Area	15,000	694	3.0	0.80
Imperial Valley	15,102	786	3.5	0.85

The U.S. Geological Survey installed a dense network of seismograph stations in central California to monitor seismic activity along the San Andreas, Calaveras and Hayward faults. The typical station has a magnification of 3×10^6 at 12 to 14 Hz. The station configuration used during 1971 is shown in Figure 3 and the earthquake epicenters for 1971 are shown in Figure 4. A 1° by 1° area shown in Figure 3 which contains 36 seismograph stations was selected for study. The yearly interval recurrence curves for this area for the time period 1969-1972 are shown in Figures 5-8. The data are summarized in Table 4.

Figure 3. Map showing seismograph stations used in locating earthquakes. (Fourteen additional stations are outside this map). 1971. Modified from Lee et al (1972)

Figure 4. Map showing earthquake epicenters reported in the Appendix (1971). Earthquakes in the dashed region are generally well recorded and located.
From Lee et.al. (1972)

Figure 5. Interval recurrence curve for the Central California region shown in Figure 9 for 1969.

Figure 6. Interval recurrence curve for the Central California region shown in Figure 9 for 1970.

Figure 7. Interval recurrence curve for the Central California region shown in Figure 9 for 1971.

Figure 8. Interval recurrence curve for the Central California region shown in Figure 9 for 1972.

TABLE 4

Seismicity of $1^{\circ} \times 1^{\circ}$ Area of Central California
(36.33° to 37.33° North and 121° to 122° West)

Time Period	Total No. of Events	Values of A at 95% Confidence Interval	Values of b at 95% Confidence Interval
1969	785	3.20 (± 0.25)	0.916 (± 0.102)
1970	816*	2.90 (± 0.40)	0.797 (± 0.161)
1971	1262	3.41 (± 0.36)	0.933 (± 0.148)
1972	3944	3.59 (± 0.21)	0.846 (± 0.083)

The magnitude interval in Table 4 is 0.1 unit, and the range considered for computing A and b is $1.5 \leq M_L \leq 3.4$.

The 95% confidence intervals show a relatively small range in values over this four year period and the data are consistent from one year to the next. The lower value of A for 1970 is caused by an incomplete data set. Only eight months of data were available for that year. The small variation in A and b can be attributed to the large number of events and the selection of a range of magnitude values ($1.5 \leq M_L \leq 3.4$) over which $\log N$ vs M is linear. The interval recurrence curves show that the detection and location of events below $M_L = 1.5$ are incomplete in spite of the fact that there are 36 high gain micro-earthquake stations located within the study area and that there are additional stations just outside of the study area. One of the major objectives in seismicity studies is to predict return periods for the larger magnitude events. However, the b values obtained above are

*Only eight months of data were available during this time period.

shown not to be valid to project the occurrence of earthquakes with magnitudes above 3.5. See Figs. 5-8.

GEOLOGIC SETTING

The Nevada Test Site is located in Nye County, Nevada, approximately 112 kilometers northwest of Las Vegas, Nevada. The site encompasses about 3550 square kilometers with about 1540 square kilometers reserved for nuclear testing. The Test Site area lies north and east of the Las Vegas Valley-Walker Lane shear zone and between the east boundary of the Paleozoic Cordilleran miogeosyncline and the east boundary of the Cordilleran euogeosyncline, within the Basin and Range province of Southern Nevada (see figures 9 and 10).

The Upper Precambrian and Lower Cambrian rocks of the Test Site are dominantly clastic, with quartzite the chief lithology. Rocks of Middle Cambrian through Middle Devonian age are dominantly carbonates. In Late Devonian and Mississippian time, clastic rocks were deposited which included coarse gravels derived from erosion of the Roberts Mountain thrust plate in the northwest (Ekren, 1968). The Late Mississippian age Eleana formation is the most lithologically diverse unit in the area. In the Test Site area, the Eleana formation consists of a conglomerate, quartzite, and shale facies. Less than 80 kilometers to the south, this formation is entirely limestone and dolomite. This abrupt sedimentary facies change to the south may be due in part to shortening of the earth's crust by thrust faulting (Johnson and Hibbard, 1957). Following this orogenic episode and throughout the remainder of the Paleozoic Era was continued carbonate deposition. In aggregate thickness, the uppermost Precambrian and Paleozoic sediments total

Figure 9 Index map of the Nevada Test Site area showing the average east boundary of eugeosyncline (E), the average east boundary of miogeosyncline (M), and the Walker Lane (WL)-Las Vegas Valley (LVV) shear zone. (Modified from Ekren, 1968, p. 12).

Figure 10. Generalized geology of the Nevada Test Site with location of principal seismic recording stations. (Modified from Ekren, 1968, p. 276).

nearly 40,000 feet and comprise approximately 30 percent of all outcrops in the region.

The Test Site area is devoid of any Mesozoic age rocks with the exception of local granitic intrusions. These intrusions of probable Late Cretaceous age have metamorphosed and mineralized some of the Paleozoic sediments.

The Tertiary rocks have a thickness of more than 30,000 feet and are dominantly volcanic in origin. These volcanic rocks consist mainly of rhyolite and tuff and overlie marly, fossiliferous limestones of probable Miocene age. At one time, the volcanic extrusives probably covered the entire Test Site area. The Tertiary volcanics have been used as a test media for many of the underground nuclear detonations. Table 5 lists the principal Tertiary volcanic units at the Test Site, the K/Ar dates, the lateral extent, and volume of each unit. The Belted Range Tuff and younger volcanic units form the bedrock for most of the Test Site. Dikes of Tertiary age occupy normal faults in the northeastern region of the Test Site area. The fairly abundant, small deposits of gold and silver in the region are all related to volcanic centers of Tertiary age.

The Quaternary deposits, reaching a thickness of more than 2000 feet, consist of detritus derived from bedrock areas and range in texture from clay-sized particles to cobbles and boulders. This Quaternary fill forms and underlies the two major valleys of the Test Site area: Yucca Flat to the north and Frenchman Flat to the south. The Quaternary de-

TABLE 5

Principal volcanic units at Nevada Test Site.

Age	K/Ar Date in Million Years	Unit	Lateral Extent in Miles	Volume in Cubic Miles
Tertiary	---	Basalt lavas	---	---
	7.5	Thirsty Canyon Tuff	80	50
	11	Timber Mountain Tuff	100	500
	---	Paintbrush Tuff	70	120
	13.8	Belted Range Tuff	60	70-100
	17.5	Fraction Tuff	120+	500+
	---	Dacite and Latite lavas	---	---
	---	White Blotch Spring Tuff	120+	500+
	26.5	Monotony Valley Tuff	120+	1000+

(Modified from Ekren, 1961, p. 14)

posits contain some caliche and fanglomerates.

The Nevada Test Site is structurally complex. Six significant folds, five in the Paleozoic rocks and one in the Tertiary volcanic rocks, several thrust faults, and many normal faults are present. The fold axes and thrust traces trend north and conform to the general pattern of the Great Basin structure. To produce this pattern, compression was applied along an east-west plane, perpendicular to fold and fault trends. Evidence indicates that the active compression was applied from the west (Johnson and Hibbard, 1957).

Normal faulting has affected almost every part of the Test Site area and has resulted in displacements of several thousands of feet. The faults of the northern part of the Test Site area trend north. In the southern portion of the area, however, the faults change trend from north to northeast, as the Las Vegas Valley shear zone is approached from the north. Several of these northeast trending faults show left-lateral movement. This left-lateral displacement may have resulted from rotary slippage during right-lateral movement along the Las Vegas Valley shear zone (Ekren, 1968). The relative fault displacements are generally the same in the valley and bedrock areas; the southeastern blocks upthrown in relation to the northwestern blocks.

A general geologic history of the structural deformation for the Test Site area includes thrusting and folding during Early and Middle Mesozoic time, granitic intrusions in the Late Mesozoic Era, normal faulting in the Late Mesozoic Era or Early Tertiary period, and eruption and

deposition of volcanic rocks from the Oligocene through Pliocene epoch.

One of the latest structural developments of the Test Site area is the intrusion of a series of dikes following this Tertiary volcanic deposition. Normal faulting continues to the present day. ,

THEORETICAL CONSIDERATIONS

Magnitude-Frequency Relationship

The relationship between the frequency of earthquake occurrence and magnitude is of fundamental importance in earthquake statistics, as it provides a means by which to quantify seismicity. Various approximations exist for this relation. The relation most often used, and one employed in this study, is the empirical relation of Richter (1958), given as

$$\text{Log}_{10} N_C = \bar{a} - \bar{b}M \quad (1)$$

where M = magnitude, $\bar{a}$ and $\bar{b}$ are parameters; $\bar{a}$ is the value of the zero magnitude intercept, and $\bar{b}$ is the slope of the line described by equation (1), and N_C , as defined by Richter (1958), is the number of earthquakes of magnitude M or greater per unit of time. When N_C is thusly defined, the equation (1) is referred to as the cumulative frequency relationship or the cumulative recurrence relationship.

Besides the cumulative number of events, N may be described as the number of events for some given magnitude interval ($M, M+dM$), such that (1) becomes

$$\text{Log}_{10} N_I = A - BM \quad (2)$$

where M = magnitude, A and B are again parameters, found as in equation (1), and N_I is the number of earthquakes in the interval ($M, M+dM$). This equation (2) is referred to as the simple or normal frequency rela-

tionship, and also as the interval recurrence relationship.

The dependence between the number of earthquakes and magnitude in the relations (1) and (2) must be investigated in the interval $(M_{\min}, M_{\max})$, where $M_{\min}$ is the magnitude of the smallest possible earthquake and $M_{\max}$ the greatest possible earthquake in the given study area. $M_{\min}$ is greatly dependent on the network of stations, sensitivity of the recording instruments, and background noise level, while $M_{\max}$ is limited by the length of observation (Procházková, 1976). The magnitude-frequency relations are not usually linear over the entire range of magnitudes in the interval $(M_{\min}, M_{\max})$. As such, an interval of magnitudes (M_1, M_2) contained in $(M_{\min}, M_{\max})$ where the $\log_{10} N_C$ and $\log_{10} N_I$ relations are linear are defined.

Both of the magnitude-frequency relations are well known in seismology. The interval recurrence relation is often easier and more accurate to obtain than the cumulative recurrence relation, because of the ability to test the data set for completeness in various magnitude ranges, although seismic risk analysis models require the cumulative recurrence relation (Herrmann, 1977).

As a result of the definitions (1) and (2), the relation between cumulative and interval frequency can be defined as

$$N_C(M_k) = \sum_{i=k}^n N(M_i) dM_i$$

(Procházková, 1970) (3)

where n is the number of different values of magnitude M which have

been arranged in an ascending series $M_1, M_2, \dots, M_n$, and $k = 1, 2, \dots, n$. In an attempt to determine the differences in parameters $\bar{a}$, A , $\bar{b}$, and B , the summation in equation (3) has often been substituted by an integral (Procházková, 1970, 1976). As this integral definition can only be substituted in (3) if $dM_1 \rightarrow 0$, i.e. if the number of magnitudes is continuous, the substitution is invalid, since this integral assumption is not satisfied by the interval distribution of magnitudes (Procházková, 1970). The integral definition of (3) will lead to the conclusion that $\bar{b} = B$, and for $\bar{b} > 0.43$, it follows that $A > \bar{a}$ and $N_C(M) < N_I(M)$, which are contradictory to actual calculations (Procházková, 1970).

Using the assumptions 1) the magnitude interval used is constant, and 2) equation (2) may be used to substitute for $N(M_1)$, to simplify equation (3), Procházková (1970) showed that $N_C(M) \geq N_I(M)$, $A \leq \bar{a}$, and that the equality of B and $\bar{b}$ is not necessary. These are the relations that are encountered in practical measurements.

The method of computation used in determining the seismic parameters in (1) and (2), the magnitude interval (M_1, M_2), and the interval length dM , all affect the values of $\bar{a}$, $\bar{b}$, A , and B . Thus, only when a unified and consistent procedure is exercised, can comparisons of these parameters be made.

Magnitude and Energy Determinations

All earthquake magnitudes were computed using the coda length relation employed in the United States Geological Survey's computer

program, HYPO71 (Revised): A Computer Program for Determining Hypocenter, Magnitude, and First Motion Pattern of Local Earthquakes (Lee and Lahr, 1975). The equation is given as

$$MD = -0.87 + 2\log_{10}(T) + 0.0035(D) \quad (4)$$

where,

MD = coda length magnitude, approximately

equal to the local Richter magnitude, M_L

T = signal duration in seconds

D = epicentral distance in kilometers.

The term $0.0035(D)$ in equation (4) will not be applied in this study as only earthquakes in the immediate Test Site area are analyzed and because of the limited number of stations that record the small earthquakes, reducing the accuracy of epicenter determinations.

When available, local magnitudes for earthquakes in the Test Site area, as computed in the Preliminary Determination of Epicenters' monthly listings, were compared to coda length magnitude determinations. Both magnitude values were, in most cases, within one or two tenths magnitude of agreement, especially for those magnitudes below 4.5.

The duration of an earthquake seismogram is, in general, the duration of both the body and surface waves. In this study, the duration, as adopted from Real and Teng (1973), is defined as the time interval between the onset of the first arrival and the point at which the earthquake signal falls and remains below the background noise level, i.e.,

where the signal-to-noise ratio becomes one. When defining the end of the record in terms of the background noise, the duration becomes independent of a subsequent change in the instrument gain since increasing the magnification would amplify the noise as well as the earthquake signal (Real and Teng, 1973). If the gain for a seismograph station is set such that background noise is not being recorded, i.e., the recording trace is flat, then the magnitude of an event determined by means of (4) will be underestimated for the event, since the duration of the event may be reduced. The background noise, however, was usually evident on the seismograms.

Strain release computations are based on surface wave magnitudes (M_S). To convert the coda length magnitude (M_D), assuming equivalence with local magnitudes (M_L), to surface wave magnitude, the relations of Richter (1958) and Willis and others (1974) are utilized. Using earthquake data from southern California and Nevada, Willis and others (1974) established a second degree approximation which represented the data set more accurately than the original Richter relationship (1958), for M_L greater than 2.5, as shown in figure 11. Plotted in this figure are the NEIS (USGS) m_b vs. Pasadena M_L for earthquakes in southern California and Nevada that are listed in the NEIS earthquake data file for 1961 - 1972. Thus, for M_L greater than 2.5,

$$m_b = 3.73 - 0.16M_L + 0.08M_L^2$$

(Willis and others, 1974) (5)

and for M_L less than 2.5, using the original Richter relationship,

$$m_b = 1.7 + 0.8M_L + 0.08M_L^2$$

(Richter, 1958) (6)

where, m_b = body wave magnitude. The final conversion of m_b to M_s is accomplished by use of the relationship

$$M_s = 1.59m_b - 3.97$$

(Richter, 1958) (7)

The relationship between M_L , M_s , and m_b (equations (4), (5), (6), and (7)) is demonstrated in figure 12, where the dependent variables M_L , M_s , and m_b are plotted against the independent variable, M_L .

The strain release ($E^{1/2}$) is computed by taking the square root of the seismic wave energy (E) as defined by

$$\log_{10} E = 12.24 + 1.44M_s$$

(Båth, 1973) (8)

or

$$E^{1/2} = 10^{(6.12 + 0.72 M_s)}$$

(9)

where E is in ergs. The strain release ($E^{1/2}$) is not measurable strain in a physical sense and could be more definitively referred to as quasi-strain or quasi-strain release; however, in keeping with convention the term strain release will be used to refer to the quantity $E^{1/2}$ (George,

Figure 11. Relationship between body wave magnitude (m_b) and local magnitude (M_L) for earthquakes located in Southern California and Nevada. (From George, 1974, p. 22).

1974). The equation (8) has previously only been deduced for M_s greater than 5 (Båth, 1973). Hence, the validity of (8) has not been shown for lower magnitude earthquakes, and must be assumed in this study.

The cumulative strain release ($E_c^{1/2}$) is defined as the summation of the strain release per individual earthquake:

$$E_c^{1/2} = \sum_{i=1}^n E_i^{1/2} \quad (10)$$

Decibel values are calculated using the relationship

$$db = 20 \log_{10} \left(\sum_{i=1}^n (E_i^{1/2}) / (E_o^{1/2}) \right) \quad (11)$$

(George, 1974)

where $E_o^{1/2}$ is the strain release of a surface wave magnitude zero earthquake or $1.318 \times 10^6 \text{ ergs}^{1/2}$.

The relationship between local Richter magnitude, surface wave magnitude, seismic wave energy (ergs), strain release ($\text{ergs}^{1/2}$), and decibel values (equations (4), (7), (8), (9), and (10)) is illustrated in figure 13. For example, one magnitude (M_L) 2.0 earthquake releases approximately 9.71×10^{13} ergs of seismic wave energy (E). This is equivalent to $9.85 \times 10^6 \text{ ergs}^{1/2}$ of strain release or 17.5 decibels. It would take nearly 57 magnitude (M_L) 1.0 earthquakes to release the same amount of seismic wave energy (E) as one 2.0 M_L earthquake. The use of decibel values rather than strain release will introduce a smoothing factor into the presented data.

Figure 12. Theoretical relationship of local magnitude (M_L), body wave magnitude (m_b), and surface wave magnitude (M_s).

The non-linearity of the local magnitudes (M_L) in figure 11 comes as a result of using two different relationships relating M_L and m_b (equations (5) and (6)). It is felt that this combination of relationships more accurately represents the relation of M_L and m_b for the Nevada Test Site, than the singular relationship of Richter (1958) (equation (6)).

Figure 13. Relationship between local magnitude (M_L), surface wave magnitude (M_S), seismic wave energy (ergs), strain release (ergs^{1/2}), and decibels (db) (referenced to the strain release of a surface wave magnitude zero earthquake). (Modified from George, 1974, p. 27.)

Figure 13

STATION COVERAGE AND DATA SOURCES

The seismic activity of the Southern Nevada area, including the Nevada Test Site, is monitored by a network of seismograph stations, operated by the Branch of Seismic Engineering of the U. S. Geological Survey. This network of stations is being continuously recorded on 16 millimeter film at Las Vegas, Nevada. Investigation into the earthquake activity in the Test Site area is based on data obtained from this seismograph network.

In particular, for the time interval April 1, 1973 to October 1, 1975, the local coverage of the Nevada Test Site was performed principally by three seismograph stations within the Southern Nevada network: Control Point #1 (CPX), Little Skull Mountain (LSM), and Mercury (MCV). Specific information concerning these stations is given in table 6. The seismometers for these stations are all short-period, vertical component, velocity-type transducers.

Although continuously monitored, one or more of the Southern Nevada seismograph stations will occasionally cease to function, i.e. fail to record the seismic activity for a period of time. The non-functioning days for stations CPX, LSM, and MCV are given in figure 14. This figure shows that for the time period April 1, 1973 through October 1, 1975, only about ten days time exists where all three of the Test Site seismograph stations were off simultaneously. Also shown are the days for which the 16 millimeter films were unavailable.

Table 6. Latitude, longitude, elevation, and medium for seismograph stations CPX, LSM, and MCV of the Nevada Test Site. (Modified from Bayer, 1974, p. 5.)

SEISMIC STATION CONSTANTS
Nevada Test Site

<u>CODE</u>	<u>STATION NAME</u>	<u>LATITUDE</u> <u>(North)</u>	<u>LONGITUDE</u> <u>(West)</u>	<u>ELEVATION</u> <u>(Meters)</u>	<u>MEDIUM</u>
CPX	Control Point #1	36°55.92'	116°03.33'	1285	dolomite
LSM	Little Skull Mountain	36°44.32'	116°16.68'	1146	hardrock
MCV	Mercury	36°38.01'	115°59.99'	1158	hardrock

Figure 14 Chart showing days when Nevada Test Site
seismometers were not recording,
(CPX = , LSM = ,
MCV =), and days with
unavailable records ( ).

FIGURE 14

FIGURE 14, Continued

UNDERGROUND NUCLEAR EXPLOSIONS

Within the time interval April 1, 1973 to October 1, 1975, there were twenty-five announced U. S. underground nuclear test shots at the Nevada Test Site. The names, dates, and yields for these shots are given in table 7; shot-point locations are shown in figure 15. Of the four largest test shots, (200 kiloton to 1 megaton range), one occurs near the beginning of the above time interval (Almendo), and three occur near the end of the time interval (Tybo, Mast, and Camembert). As of October 1, 1975, the total number of nuclear tests at the Nevada Test Site was 449 (Jackson, 1975). The symbols assigned to each shot in table 4 will be used to identify the shot throughout this study.

In general, the larger the yield for a nuclear shot, the larger the magnitude of the resulting seismic event. For example, the Dido Queen shot (less than 20 kiloton range) resulted in a seismic event with a body wave magnitude of 5.1 ($M_L = 5.3$), while the larger Almendo shot (200 kiloton to 1 megaton range) resulted in a seismic event with a body wave magnitude of 6.1 ($M_L = 6.5$) (Preliminary Determination of Epicenters, monthly listing, June, 1973). Hence, it would take approximately 194 nuclear explosions, equivalent to the yield of Dido Queen, to equal the seismic wave energy (E) of the Almendo event.

Throughout this study, all underground nuclear test shots and all subsequent aftershocks, have been removed from the earthquake data in order to evaluate only the natural seismicity of the Test Site, as affected by the test shots.

Table 7

Names, dates, and yields of announced U. S. underground nuclear test shots within the time period April 1, 1973 to October 1, 1975 at the Nevada Test Site. KT =kiloton, MT = megaton. (Modified from Jackson, 1975).

<u>EVENT</u>	<u>SYMBOL</u>	<u>DATE</u>	<u>YIELD</u>
Angus	An	04/25/73	20 to 200 KT
Starwort	St	04/26/73	85 KT
Dido Queen	Dq	06/05/73	less than 20 KT
Almendro	Al	06/06/73	200 KT to 1 MT
Portulaca	Po	06/28/73	20 to 200 KT
Husky Ace	Ha	10/12/73	less than 20 KT
Bernal	Be	11/28/73	less than 20 KT
Latir	La	02/27/74	20 to 200 KT
Ming Blade	Mb	06/19/74	less than 20 KT
Escabosa	Es	07/10/74	20 to 200 KT
Puye	Pu	08/14/74	less than 20 KT
Portmanteau	Pr	08/30/74	20 to 200 KT
Stanyan	Sn	09/26/74	20 to 200 KT
Hybla Fair	Hf	10/28/74	less than 20 KT
Topgallant	To	02/28/75	20 to 200 KT
Cabrillo	Ca	03/07/75	20 to 200 KT
Dining Car	Dc	04/05/75	less than 20 KT
Edam	Ed	04/24/75	20 to 200 KT
Obar	Ob	04/30/75	20 to 200 KT

Table 7 (continued)

<u>EVENT</u>	<u>SYMBOL</u>	<u>DATE</u>	<u>YIELD</u>
Tybo	Ty	05/14/75	200 KT to 1 MT
Stilton	Sl	06/03/75	20 to 200 KT
Mizzen	Ml	06/03/75	20 to 200 KT
Mast	Ma	06/19/75	200 KT to 1 MT
Camembert	Cm	06/26/75	200 KT to 1 MT
Marsh	Mr	09/06/75	less than 20 KT

Figure 15. Shot-point locations within the Nevada Test Site for underground nuclear tests conducted from April 1, 1973 to October 1, 1975. Key for nuclear shot symbols is in table 4. (Exact location for the Hybla Fair (Hf) event is unknown.)

Figure 15

Recent seismic data from the Pahute Mesa region of the Nevada Test Site, for the interval October 28, 1975 to March 17, 1976, have been acquired from the U. S. Geological Survey which incorporates a series of large-yield nuclear test shots. The names, dates, and yields of the explosions are given in table 8. Shot-point locations are shown in figure 16.

Table 8

Names, dates, and yields for announced U. S. underground nuclear test shots conducted on Pahute Mesa in the Nevada Test Site, October 28, 1975 to March 17, 1976. KT = kiloton, MT = megaton.

	<u>NAME</u>	<u>DATE</u>	<u>YIELD</u>
1.	KASSERI	10/28/75	200 KT - 1 MT
2.	INLET	11/20/75	200 KT - 1 MT
3.	MUENSTER	01/03/76	200 KT - 1 MT
4.	FONTINA	02/12/76	200 KT - 1 MT
5.	CHESHIRE	02/14/76	200 - 500 KT
6.	ESTUARY	03/09/76	200 - 500 KT
7.	COLBY	03/14/76	500 KT - 1 MT
8.	POOL	03/17/76	200 - 500 KT

Figure 16. Shot-point locations on Pahute Mesa, within the Nevada Test Site, for underground nuclear tests conducted from October 28, 1975 to March 17, 1976. Key for nuclear shot symbols is in table 8.

Figure 16

NTS SEISMICITY

Earthquake Frequency

For the time interval April 1, 1973 through October 1, 1975, a total of 635 earthquakes was recorded within the Nevada Test Site. Magnitudes (M_L) for these events range from 0.7 to 3.6. Figure 17 is a plot of the number of earthquakes per 10-day intervals, beginning April 1, 1973. Figure 17 also shows those 10-day intervals which incorporate nuclear test shots.

The intervals of highest seismic activity, as indicated by the largest number of events, are, in general, intervals with few or no test shots. Those few test shots within intervals of high seismic activity are all of low (less than 20 KT) or medium (20 to 200 KT) yield. The intervals of lowest seismic activity, as indicated by the least number of events, are, in general, those intervals where the testing program was most active, and especially those intervals incorporating large (200 KT to 1 MT) yield tests.

The lack of seismic activity from interval number 72 through 80 in Figure 17 may be, to some extent, biased toward a low number of earthquakes. This range of intervals includes a period of time when all three seismograph stations (CPX, LSM, MCV) in the Test Site were not functioning, and also a period of time when two of the three stations were nonfunctioning (see figure 14). It is felt, though, that the recorded low level of activity during the above intervals, when the stations were operating, and the extended, low level of activity after the stations

Figure 17. Number of earthquakes (N) per 10-day intervals and underground nuclear test shots, from April 1, 1973 to October 1, 1975. Lines connecting the number of earthquakes computed for each 10-day interval are drawn for illustrative purposes only. Key for nuclear shot symbols is in table 4.

FIGURE 17

resumed operation, is indicative of a continuous period of subsided seismicity. This particular period of reduced seismic activity is contemporaneous with an activated interval of large yield (200 KT to 1 MT) nuclear testing.

Figure 18 is a plot of the number of earthquakes per 30-day intervals, beginning April 1, 1973. Again, those intervals incorporating nuclear test shots are indicated. On this larger scale, the affect of an increase in testing activity on the number of earthquakes in the Test Site is more apparent; an increase in the number and yield of nuclear test shots, for the most part, corresponds to a decrease in the number of earthquakes.

Figures 19 and 20 are plots of the present accumulative number of earthquakes for 10- and 30-day intervals, respectively, for the time period April 1, 1973 to October 1, 1975. The most notable feature of these figures is the marked increase in the percent accumulation for the time intervals between the Hybla Fair (Hf) and Topgallant (To) detonations, where 31.25% of the total accumulative number of earthquakes for approximately 14% of the total period of study were released. Also evident are two intervals where the gain in the percent accumulation of earthquakes remained relatively low over an extended period of time. The first period immediately precedes and the second period immediately follows the sharp increase in percent accumulation mentioned previously. The period of time preceding this percent increase includes six nuclear test shots. The interval from the first of the six

Figure 18. Number of earthquakes (N) per 30-day intervals and underground nuclear test shots, from April 1, 1973 to October 1, 1975. Lines connecting the number of earthquakes computed for each 30-day interval are drawn for illustrative purposes only. Key for nuclear shot symbols is in table 4.

FIGURE 18

Figure 19. Percent accumulative number of earthquakes per 10-day intervals, from April 1, 1973 to October 1, 1975. Key for nuclear shot symbols is in table 4.

FIGURE 19

NUCLEAR
TEST SHOTS

An
Si

Dq
Al

Pb

Ha

Bo

La

Mb

Es

Pu

Pr

Sn

Hf

To

Ca

Dc

Ed

Ty

Ob

Si

Ma

Cm

Mr

Figure 20. Percent accumulative number of earthquakes per 30-day intervals, from April 1, 1973 to October 1, 1975. Key for nuclear shot symbols is in table 4.

FIGURE 20

test shots (Ming Blade) to the last of the six test shots (Hybla Fair) represents only 6.25% of the total accumulation of earthquakes for nearly 15% of the total period of study. The second interval of low activity which follows the rapid increase in percent accumulation, extends to the end of the study period, and accounts for nearly 24% of the time from April 1, 1973 to October 1, 1975. Eleven underground nuclear test shots were fired in this interval of low earthquake activity; three of these shots were of large yields (200 KT to 1 MT). Following the first of these eleven shots (Topgallant) to the end of the study period (October 1, 1975), only 2.5% of the total accumulative number of earthquakes were released.

Strain Release

A more accurate description of the seismic activity for a given region, as compared to tabulating earthquake numbers, involves the measurement of strain release ($E^{1/2}$). For a given large number of earthquakes, their total energy released may be insignificant when compared to the energy released from a few larger magnitude earthquakes.

Figures 21 and 22 are plots of the strain release for the Nevada Test Site from April 1, 1973 to October 1, 1975, in 10- and 30-day intervals, respectively. For this entire time period, the strain release totaled 74.75 decibels (referenced to the strain release of a surface wave magnitude zero earthquake), or the equivalent strain release of

Figure 21. Strain release in decibels per 10-day intervals, from April 1, 1973 to October 1, 1975. Lines connecting the decibel values are drawn for illustrative purposes only. Open gaps represent intervals with no recorded earthquakes. Key for nuclear shot symbols is in table 7. (Decibels referenced to the strain release of a surface wave magnitude zero earthquake.)

Figure 21

Figure 22: Strain Release in decibels per 30-day intervals, from April 1, 1973 to October 1, 1975. Dashed line indicates decreasing trend in strain release with time drawn by inspection only. Lines connecting the decibel values are drawn for illustrative purposes only; open gaps represent intervals with no recorded earthquakes. Key for nuclear shot symbols is in table 4. (Decibels referenced to the strain release of a surface wave magnitude zero earthquake.)

Figure 22

one magnitude (M_L) 6.14 earthquake. The open gaps in figures 21 and 22 result from those particular time intervals during which no earthquakes were recorded. These intervals cannot be assigned a value of zero decibels, as this would imply an earthquake existed within the time period of magnitude (M_L) approximately equal to 1.0.

In figure 21 a general pattern is evident when relating the occurrence of nuclear test shots to the strain release of the Test Site. There is a decrease in the overall strain release for the intervals between the Ming Blade (Mb) and Hybla Fair (Hf) events, an increase in overall strain release for the intervals following the Hybla Fair (Hf) event up to the Topgallant (To) test shot, and, once again, a general decrease in strain release for the entire time period following the Topgallant (To) shot. The two time spans of decreased strain release relate to periods of an increase in the nuclear testing program. The time span of increased strain release encompasses no underground nuclear test shots. It is interesting to note that the other test shots generally also relate to a decrease in strain release, but on a smaller time scale.

Figure 22, using 30-day intervals, also demonstrates, in general, the pattern of decreased strain release with an increase in nuclear testing and an increase in strain release when few or no nuclear shots are detonated. An interesting feature of this particular plot is the general decreasing trend in strain release for the entire time period from 1973 to 1975 (shown by the dashed line).

The percent accumulative strain release for 10- and 30-day inter-

vals is shown in figures 23 and 24 respectively, for the time period April 1, 1973 to October 1, 1975. The most apparent feature in these plots is the period of rapid increase in the percent accumulation. This increase corresponds to the sharp increase noted in the percent accumulated number of earthquakes (figures 19 and 20). In only approximately 14% of the total time intervals, nearly 37.5% of the total accumulated strain release is released. Prior to the rise in the percent accumulated strain release, there occurs a period of time where the accumulated percentage generally levels off. This interval of time incorporates the test shots from Ming Blade (Mb) to Hybla Fair (Hf), or approximately 15% of the total time intervals. Only 6.25% of the total accumulated strain release was released in this 15% interval. Following the sharp rise in the percent accumulated strain release, after the Topgallant (T) event, till the end of the study period (representing approximately 21% of the total time intervals) only 1.5% of the total accumulated strain was released.

Seismic Parameters $\bar{a}$ and b
($\log_{10} N = \bar{a} - bM$)

The $\bar{a}$ and b values are computed for seismograph stations CPX, LSM, and MCV for the three year intervals 1973, 1974, and 1975, from April 1, 1973 to October 1, 1975. Both cumulative and interval recurrence relationships (equations 1 and 2) are used to determine these seismic parameters.

Figure 23... Percent accumulative strain release per 10-day intervals, from April 1, 1973 to October 1, 1975. Key for nuclear shot symbols is in table 7.

Figure 23

Figure 24. Percent accumulative strain release per 30-day intervals, from April 1, 1973 to October 1, 1975. Key for nuclear shot symbols is in table 7.

Figure 24

Figures 25, 26 and 27 are plots of the cumulative number of earthquakes (N_C) greater than or equal to a given magnitude (M_L) for stations CPX, LSM, and MCV, respectively ($\log_{10} N_C = \bar{a} - \bar{b}M_L$). Each figure separates the 1973, 1974, and 1975 data, and a straight-line, least-squares fit is drawn in each case. The magnitude range for the straight-line, least-squares fits is determined by the linear portion of the data. Table 9 lists the seismic parameters $\bar{a}$ and $\bar{b}$ at 95% confidence level, determined by the least-squares fits, and the linear magnitude ranges of figures 25 through 27.

The most significant feature of figures 25, 26, and 27, and table 9, is the decline in the slope of the straight-line, least-squares fit from 1973 to 1975, for each of the three seismograph stations. The slope is equivalent to the $\bar{b}$ -value. In general, for the given methods of calculation, the $\bar{b}$ -values for the Nevada Test Site area drop from a few tenths above 1.0 to a few tenths below 1.0, from 1973 to 1975. This is indicative of a decrease in the seismic activity for the region, into 1975.

An interesting feature in figure 25 is the apparent similarity between the slopes of the 1973 and 1974 data. This particular seismograph station (CPX), as opposed to the other two stations, is located near the area where many of the underground nuclear test shots are detonated. It may be possible that this long period of testing activity has influenced the natural seismicity in the vicinity of station CPX more so than for the other stations.

Figure 25. Cumulative recurrence curves for seismograph station CPK, for three year intervals, 1973 (+), 1974 (O), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the cumulative number of earthquakes (N_C) greater than or equal to a given magnitude (M_L), with straight-line, least-squares fits: 1973 = ———, 1974 = — — —, 1975 = - - - - -.

FIGURE 25.

Figure 26. Cumulative recurrence curves for seismograph station LSM, for three year intervals, 1973 (+), 1974 (O), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the cumulative number of earthquakes (N_C) greater than or equal to a given magnitude (M_L), with straight-line, least-squares fits: 1973 = _____, 1974 = — — — — —, 1975 = - - - - -.

FIGURE 26

Figure 27. Cumulative recurrence curves for seismograph station MCV, for three year intervals, 1973 (+), 1974 (°), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the cumulative number of earthquakes (N_C) greater than or equal to a given magnitude (M_L), with straight-line, least-squares fits: 1973 = ——— , 1974 = — — — — , 1975 = - - - - - .

FIGURE 27

Table 9

Seismic parameters $\bar{a}$ and $\bar{b}$ ($\log_{10} N_C = \bar{a} - \bar{b}M_L$) at 95% confidence level, determined by straight-line, least-squares fit, for seismograph stations CPX, LSM, and MCV, and time intervals 1973, 1974, and 1975 (April 1, 1973 to October 1, 1975).

<u>YEAR</u>	<u>$\bar{a}$ AT 95% CONFIDENCE LEVEL</u>	<u>$\bar{b}$ AT 95% CONFIDENCE LEVEL</u>	<u>LINEAR MAGNITUDE RANGE (M_L)</u>
SEISMOGRAPH STATION CPX			
1973	3.96 ± 0.17	1.06 ± 0.06	1.9 - 3.2
1974	3.84 ± 0.05	1.05 ± 0.02	1.9 - 2.9
1975	3.00 ± 0.22	0.77 ± 0.09	1.9 - 3.2
SEISMOGRAPH STATION LSM			
1973	4.62 ± 0.24	1.28 ± 0.10	1.9 - 3.2
1974	4.11 ± 0.25	1.06 ± 0.10	1.9 - 3.1
1975	3.54 ± 0.12	0.88 ± 0.05	1.9 - 3.4
SEISMOGRAPH STATION MCV			
1973	4.19 ± 0.21	1.17 ± 0.08	1.9 - 3.2
1974	3.68 ± 0.23	1.01 ± 0.10	1.9 - 2.8
1975	3.23 ± 0.23	0.88 ± 0.09	1.9 - 3.1

Because the time intervals for the 1973, 1974, and 1975 seismic data are of unequal length, a direct comparison of the $\bar{a}$ -values derived from the straight-line, least-squares fits of figures 25 through 27 cannot be made. Thus, in order to compare the $\bar{a}$ -values, the intervals must be normalized to some equal time span. In table 10, the $\bar{a}$ -values derived from the straight-line, least-squares fits of the cumulative recurrence data in figures 25 through 27 have been normalized to a 365-day time period. Days for which the stations were not recording are also taken into account. This normalization procedure makes one important assumption: the level of seismic activity for the extrapolated period of time remains equal to that of the recorded period of time. The normalized $\bar{a}$ -values are found to decrease from 1973 to 1974, and increase in 1975. The anomalously high normalized $\bar{a}$ -value for station LSM in 1975 may indicate that the assumption of constant seismic activity in 1975 is invalid. If such were the case, the level of seismic activity for the extrapolated period of time must be lower than that of the recorded time in 1975, in order to reduce the normalized $\bar{a}$ -value. Thus, the level of seismic activity for the extrapolated period of time was most likely lower than the seismic activity for the measured time intervals.

Figures 28, 29, and 30 are plots of the number of earthquakes (N_I) within the magnitude (M_L) interval of ± 0.1 units for stations CPX, LSM, and MCV, respectively ($\log_{10} N_I = A - BM_L$). Each figure separates the 1973, 1974, and 1975 data, and a straight-line, least-squares fit

Table 10

$\bar{a}$ -values ($\log_{10} N_C = \bar{a} - \bar{b}M_L$) normalized to a 365-day time interval for seismograph stations CPX, LSM, and MCV. The $\bar{a}$ -values are derived from the straight-line, least-squares fits of the cumulative recurrence data from April 1, 1973 to October 1, 1975.

<u>STATION</u>	<u>INITIAL $\bar{a}$-VALUE</u>	<u>NORMALIZED $\bar{a}$-VALUE</u>
	<u>1973</u>	
CPX	3.96	6.73
LSM	4.62	6.47
MCV	4.19	6.29
	<u>1974</u>	
CPX	3.84	5.38
LSM	4.11	5.34
MCV	3.68	5.89
	<u>1975</u>	
CPX	3.00	5.70
LSM	3.54	10.97
MCV	3.23	7.43

Figure 28. Interval recurrence curves for seismograph station CPX, for three year intervals 1973 (+), 1974 (O), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the number of earthquakes (N_L) within the magnitude (M_L) interval ($M_L \pm 0.1$), with straight-line, least-squares fits: 1973 = _____, 1974 = _____, 1975 = -----

FIGURE 28

Figure 29. Interval recurrence curves for seismograph station LSM, for three year intervals (1973 (+), 1974 (°), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the number of earthquakes (N_L) within the magnitude (M_L) interval ($M_L \pm 0.1$), with straight-line, least-squares fits:
1973 = _____ , 1974 = — — — — — ,
1975 = - - - - - .

FIGURE 29

Figure 30. Interval recurrence curves for seismograph station MCV, for three year intervals 1973 (+), 1974 (O), and 1975 (Δ), from April 1, 1973 to October 1, 1975. Plotted are the number of earthquakes (N_L) within the magnitude (M_L) interval ($M_L \pm 0.1$), with straight-line, least-squares fits:
1973 = _____ , 1974 = — — — — — ,
1975 = - - - - - .

FIGURE 30

is drawn in each case. In general, the slope, or B-value, of the straight-line, least-squares fit decreases from 1973 into 1975, for each of the three stations. This is the same pattern evident in the cumulative recurrence data. Table 11 lists the seismic parameters A and B at 95% confidence level, determined by the least-squares fits, of figures 28 through 30, and the magnitude range employed. The large intervals of the 95% confidence levels result from the scatter of the data. From this table a decrease in B-values from 1973 to 1975 is evident. This decrease in B-values reflects a decrease in the seismic activity for the Nevada Test Site area.

The A-values derived from the straight-line, least-squares fits of the interval recurrence data in figures 28 through 30, are normalized to a 365-day time period in table 12. These normalized A-values are found to decrease from 1973 to 1974, and increase into 1975. As with the normalized cumulative recurrence $\bar{a}$ -values, this apparent increase may be the result of the invalid assumption of constant seismic activity.

The results of the straight-line, least-squares fits for the cumulative and interval recurrence data follow the relations encountered in other practical measurements and those derived theoretically by Prochazkova (1970), i.e. $N_C(M) \geq N_I(M)$, $A \leq \bar{a}$, and $B \leq \bar{b}$.

The turn-over present in the curves in figures 25 through 30 results from the inability of the seismic recording stations to record all earthquakes of very small magnitudes.

Table 11

Seismic parameters A and B ($\log_{10} N_I = A - BM_I$) at 95% confidence level, determined by straight-line, least-squares fit, for seismograph stations CPX, LSM, and MCV, and time intervals 1973, 1974, and 1975 (April 1, 1973 to October 1, 1975).

<u>YEAR</u>	<u>A AT 95% CONFIDENCE LEVEL</u>	<u>B AT 95% CONFIDENCE LEVEL</u>	<u>LINEAR MAGNITUDE RANGE (M_L)</u>
SEISMOGRAPH STATION CPX			
1973	3.39 ± 0.37	0.91 ± 0.13	1.9 - 3.4
1974	3.09 ± 0.77	0.82 ± 0.30	1.9 - 3.1
1975	2.23 ± 1.23	0.59 ± 0.45	1.9 - 3.4
SEISMOGRAPH STATION LSM			
1973	4.30 ± 0.89	1.22 ± 0.33	1.9 - 3.4
1974	3.25 ± 1.12	0.81 ± 0.44	1.9 - 3.1
1975	3.03 ± 0.47	0.79 ± 0.17	1.9 - 3.7
SEISMOGRAPH STATION MCV			
1973	3.74 ± 0.86	1.06 ± 0.32	1.9 - 3.4
1974	2.85 ± 2.16	0.72 ± 1.49	1.9 - 2.8
1975	2.42 ± 0.80	0.66 ± 0.29	1.9 - 3.4

Table 12

A-values ($\log_{10} N_I = A - BM_I$) normalized to a 365-day time interval for seismograph stations CPX, LSM, and MCV. The A-values are derived from the straight-line, least-squares fits of the interval recurrence data from April 1, 1973 to October 1, 1975.

<u>STATION</u>	<u>INITIAL A-VALUE</u>	<u>NORMALIZED A-VALUE</u>
	<u>1973</u>	
CPX	3.39	5.76
LSM	4.30	6.02
MCV	3.74	5.61
	<u>1974</u>	
CPX	3.09	3.71
LSM	3.25	4.23
MCV	2.85	4.56
	<u>1975</u>	
CPX	3.23	6.14
LSM	3.03	9.39
MCV	2.42	5.57

Aftershocks

In 1975, there was a resumption of large-yield (200 KT to 1 MT) underground nuclear test shots at the Nevada Test Site. From January 1, 1975 to October 1, 1975, a total of eleven nuclear tests were conducted at the Test Site.

Figure 31 is a plot of the number of aftershocks from nuclear test shots per 10-day intervals, within the time span January 1, 1975 to October 1, 1975. Shown also are those intervals incorporating nuclear shots. The greatest number of aftershocks occur within the eighteenth 10-day interval with the detonation of Mast and Camembert. Both shots are large-yield events (200 KT to 1 MT). The second largest interval of aftershocks occurs with the test shot Topgallant. This shot is of medium-yield (20 to 200 KT). Preceding the Topgallant event, there occurred four months' absence of any nuclear test shots. The large number of aftershocks associated with the large Mast and Camembert shots, and, in particular, with the Topgallant shot, may be indicative of a natural stress build-up for the region, prior to the 1975 test shots.

In particular, the Camembert shot resulted in the greatest total number of aftershocks for the January 1 to October 1 time span, in 1975. The number of aftershocks per day, for two weeks following the detonation of Camembert, is plotted in figure 32. The number of aftershocks per day decreases immediately following the initial blast, except for the fifth day following the shot, when there occurs a brief period of renewed aftershock activity. After the two weeks ensuing Camembert,

Figure 31. Number of aftershocks (N) per 10-day intervals, from January 1, 1975 to October 1, 1975. Key for nuclear shot symbols is in table 4.

Figure 32. Number of aftershocks (N) per day following the detonation of Camembert, for a period of two weeks.

FIGURE 32

the aftershock activity is sporadic.

Cumulative and interval recurrence curves are plotted for the Camembert aftershocks, in figures 33 and 34 respectively. A straight-line, least-squares fit is computed for each curve.

Recent hypocenter data from the Pahute Mesa region of the Nevada Test Site has been acquired on punched cards which list the seismic events of the Pahute Mesa, their magnitudes, and locations, for the time interval October 28, 1975 to March 17, 1976. The events were detected by an array of seventeen seismograph stations; ten stations recording within the Test Site (Wuollet, personal communication, 1977). Within this interval of time, eight underground nuclear tests were conducted on the Pahute Mesa (see table 8). The shot-point locations for these tests are given in figure 16.

In general, each of the recorded Pahute Mesa events, for the given time interval, occurred within ten kilometers of the preceding nuclear test shot, and may thus be regarded as aftershocks of the test shots. Cumulative and interval recurrence curves are plotted for the October 28, 1975 to March 17, 1976 Pahute Mesa data, in figures 35 and 36, respectively. A straight-line, least-squares fit is computed for each curve.

The increase in $\bar{b}$ - and B-values for the October, 1975 to March, 1976 Pahute Mesa data over the aftershock data of Camembert, also detonated on Pahute Mesa, may reflect an increase in the seismic activity for the Northern Nevada Test Site following the Camembert

Figure 33 Cumulative recurrence curve for Camembert aftershocks with straight-line, least-squares fit at 95% confidence level, over the given magnitude range. Plotted are the cumulative number of aftershocks (N_C) greater than or equal to a given magnitude (M_L).

Figure 34. Interval recurrence curve for Camembert aftershocks with straight-line, least-squares fit at 95% confidence level, over the given magnitude range. Plotted are the number of aftershocks (N_L) within the magnitude (M_L) interval ($M_L \pm 0.1$).

Figure 34

Figure 35 . Cumulative recurrence curve for Pahute Mesa aftershocks, October 28, 1975 to March 17, 1976, with straight-line, least-square fit at 95% confidence level, over the given magnitude range. Plotted are the number of aftershocks (N_C) greater than or equal to a given magnitude (M_L).

Figure 36. Interval recurrence curve for Pahute Mesa aftershocks, October 28, 1975 to March 17, 1976, with straight-line, least-squares fit at 95% confidence level, over the given magnitude range. Plotted are the number of aftershocks (N_L) within the magnitude (M_L) interval ($M_L \pm 0.1$).

Figure 36

$$\text{Log}_{10} N_I = (6.48 \pm 0.57) - (1.40 \pm 0.16)M_L$$

$$M_L = 3.0 - 4.8$$

event. There were no announced nuclear test shots detonated on Pahute Mesa between the large-yield Camembert (June 26, 1975) and Kasserni (October 28, 1975) shots. It is interesting to note the similarity between the $\bar{b}$ -values derived for the October, 1975 to March, 1976 Pahute Mesa data, and those derived by Hamilton and others (1971) for the Pahute Mesa area from December 8, 1968 to December 31, 1970.

The $\bar{b}$ -value derived from the October, 1975 to March, 1976 Pahute Mesa data is comparable to the $\bar{b}$ -value derived from the Camembert data, as the range of magnitudes considered is above the threshold detection level in each case. Thus, the effect of increased station coverage in October, 1975 has little effect on the comparison of $\bar{b}$ -values.

Detection Capability of the NTS Network

Using a technique described in a previous report (Willis et al, 1974) the minimum magnitude detection threshold was determined for the southern Nevada region using various station configurations and seismic background noise levels. The criterion used was that there existed an 80% probability that at least three stations of the network would detect the event and that a location could be made on that three station detection. The latter is the minimum necessary and the location accuracy, in practice using only three stations, is marginal. These calculations were performed on a 0.25° grid for a $4^\circ \times 4^\circ$ area of southern Nevada. The station locations are shown in Figure 37. The minimum magnitude detection surface for stations CPX, LSM and MCV is shown in Figure 38. The threshold shown here assumes a constant seismic background noise level of two millimicrons. Figure 39 is for the same three stations with an assumed background noise level of 50 millimicrons. The test site area is outlined on each figure. The values shown are the magnitude detection threshold at the intersection of each 0.25° grid. The detection threshold can be seen to be strongly effected by the background noise level. The technique assumes that the station gain is optimized for the level of background noise. The average magnitude threshold within the NTS area for the low background level is 0.4 and 1.9 for the high noise level. It is also obvious from the location of these three stations (see Figure 37) that the best detection is obtained for the southern half of the test site.

The detection threshold for the expanded USGS net installed in the Fall of 1975 is shown in Figure 40. The fifteen stations of this

Figure 37. Location map of seismograph stations in southern Nevada. (Courtesy of U.S.G.S.)

Figure 38. Minimum detection surface for stations CPX, LSM, and MCV with background level at 2 millimicrons.

Figure 39. Minimum detection surface for stations CPX, LSM, and NCV with background level at 50 millimicrons.

net include the following: BMT, EPN, NRM, NPN, SSP, TMN, GLR, CPX, LSM, MCV, PRN, LVW, APK, DAC and TPH. The average actual seismic background noise levels (supplied by Wuollet, 1976) at each station were used for this calculation. The larger number of stations and better distribution gave a significantly lower threshold within the Test Site area. Similar graphs were determined for other station configurations and background noise levels and are presented in Willis and Taylor (1977). Also found in the latter are detection surfaces which take into account the radiation pattern generated by natural events. Stations placed on or near nulls of natural radiation patterns could have significantly less detection capability than stations placed near peaks of radiation patterns. For a point source the radiation pattern would be azimuthally uniform unless tectonic stresses were released simultaneously at the time of the shot.

Figure 40. Minimum magnitude detection surface for the 15 stations of the current U.S.G.S. net.

CONCLUSIONS

From April 1, 1973 to October 1, 1975, there were 635 recorded earthquakes in the Nevada Test Site area. Their magnitudes (M_L) ranged from 0.7 to 3.6. The time intervals (10- and 30- day) of highest seismic activity, between April 1, 1973 and October 1, 1975, as indicated by the larger number of earthquakes, were generally those intervals with few or no underground nuclear shots. The underground nuclear shots that were detonated within the intervals of high seismic activity were of low (less than 20 KT) or medium (20 to 200 KT) yield. Those time intervals of lowest seismic activity, as indicated by the fewest number of earthquakes, were generally those intervals where the nuclear testing program was most active, and incorporated large-yield (200 KT to 1 MT) shots.

There was a sharp rise in seismicity as reflected in the accumulated number of earthquakes and the accumulated strain release between the detonation of the low yield Hybla Fair event (10/28/74) and the medium yield Topgallant event (2/28/75). Following Topgallant, up to October 1, 1975, the percent accumulated number of accumulated strain release increased only slightly.

The total strain released by the 635 recorded earthquakes in the Nevada Test Site area, from April 1, 1973 to October 1, 1975 was 74.75 decibels (referenced to the strain release of a surface wave magnitude zero earthquake). This was the equivalent strain release of one 6.14 magnitude (M_L) earthquake.

There was a decrease in the overall strain release for the time interval between the low yield Ming Blade event (06/19/74) and Hybla Fair (10/28/74) event, and for the entire time period following Topgallant (02/28/75) until October 1, 1975. There was an increase in

overall strain release for the intervals between Hybla Fair and Topgallant. The two time spans of decreased strain release relate, in general, to periods of increased nuclear testing, and the time span of increased strain release incorporates no nuclear test shots. Overall there appeared to be a decreasing trend in strain release for the entire time period, April 1, 1973 to October 1, 1975.

A decrease in b values was observed for seismograph stations CPX, LSM, and MCV for Nevada Test Site earthquakes between 1973 and 1975. This is also indicative of a decrease in seismic activity.

The large number of aftershocks during the 10-day time intervals encompassing the Topgallant, Mast, and Camembert shots, may reflect a natural stress build-up for the region, prior to the 1975 test shots. For the time interval January 1, 1975 to October 1, 1975, the Camembert shot had the largest number of aftershocks. The number of aftershocks per day decreased immediately following the initial blast, except for the fifth day following the shot, when there occurred a brief period of renewed aftershock activity. There was an increase in the b-values for the October 28, 1975 to March 17, 1976 Pahute Mesa aftershock data compared to the Camembert aftershock data (06/25/75 to 07/10/75).

In general, it appears that the decrease in the underground nuclear testing program at the Nevada Test Site from April 1, 1973 to October 1, 1975, has affected the natural seismicity of the local Test Site area on a short-term basis, and that the overall seismic activity for the Test Site region has decreased from April of 1973 into October of 1975.

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