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Earthquakes and Crustal Movement as Related to Water Load in the Mississippi Valley Region

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EARTHQUAKES AND CRUSTAL MOVEMENT AS RELATED TO WATER LOAD IN THE MISSISSIPPI VALLEY REGION

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ABSTRACT

An abnormally high number of earthquake epicenters occurring within 200 miles of New Madrid, Missouri, fall within an area bounded by the alluvial valleys of major rivers. The area is extensively fractured, with evidence of many major and minor faults. Pressures, caused by variations in water load in the valleys and exerted on the basement rocks, are as high as 5×10^5 dynes/cm^2. A curve of earthquake frequencies in the valleys has a one year period with a maximum frequency in January and a minimum in June. This curve is in phase with a differential curve of the river stage at Hickman, Kentucky. Strain-rebound curves of all earthquakes in the region exhibit variations in the rate of energy release. The time derivative of energy release for earthquakes occurring in the alluvial valley of the Mississippi River between Cairo, Illinois and Memphis, Tennessee, is shown to be related directly to water mass. From this relation, the rate of movement along faults ($\Delta X_f/\Delta t$) is shown also to be related directly to water mass, where Δt is in one year increments. It is concluded that the alluvial valley of the Mississippi is subsiding because (1) earthquake frequency increases with an increase in the rate of change of river stage, and (2) the rate of energy release increases with an increase in water mass. The addition of a water load could only aid the movements of a subsiding crust.

INTRODUCTION

Crustal movements of geosynclinal structures triggered by rainfall have been studied by Conrad (1946). The present paper deals with earthquakes as they are related to both precipitation and river load in the region within 200 miles of New Madrid, Missouri. The conclusions of Conrad (1946) have been used as a guide in this study. Those conclusions which are associated especially with the present investigation are listed below:

(1) "Rainfall over lowlands above geosynclinal structures represents clearly a situation in which subsiding geological tendencies are strengthened by the additional load of rainfall.
(2) The average annual variation of rainfall does not show a real relationship to the annual frequency curve of earthquakes.
(3) If r_k denotes the rainfall amount in a certain month, the differences $r_k - r_{k-1}$ are calculated. The resulting differential curve, called the tendency curve, represents the variations of the average rainfall load of the surface from month to month.
(4) The tendency curve is rather strongly related to the frequency curve....The variations, not the absolute amount of atmospheric pressure, appeared to be a likely trigger cause. The same is true of precipitation."

The following assumptions will be considered also in the study of the Mississippi region:

(1) Alluvial valleys are often associated with zones of crustal weakness where these zones exist.
(2) The rate of crustal movement and the rate of energy released by earthquakes are directly related.
(3) Variations in water load in the alluvial valleys are sufficient to trigger the intermittent release of energy in the form of earthquakes.
(4) Water load in the alluvial valley of the Mississippi is sufficient to affect the rate of crustal movement.
(5) All earthquakes are of the same type and of the same crustal environment. This assumption is probably in error, but there is no way of classifying earthquakes from the data available.

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HISTORY OF THE REGION

Summaries of earthquakes and their intensities have been compiled for the Mississippi River area from St. Louis, Missouri to Memphis, Tennessee, since 1811. In December of that year, the largest earthquake ever reported on the North American Continent occurred at New Madrid, Missouri; it was felt over an area of 2,000,000 square miles. In January and February of the following year, two earthquakes of similar intensity occurred in the same area. They were designated as having maximum intensity XII on the Modified Mercalli scale and have been well described (Eppley, 1958). Since these early earthquakes, many of lower intensity have occurred. The accuracies of epicentral locations and estimation of intensities have been increasing since the earliest reports. This report discusses (1) epicentral locations as they are related to faults and alluvial valleys, (2) frequency of earthquakes versus the rate of change of river stage, (3) strain-rebound in the region, and (4) a time derivative curve of energy release as it is related to water load. Earthquakes which occur within a radius of 200 miles of New Madrid are discussed, and then those earthquakes having epicenters bounded by the alluvial deposits of major rivers are studied in more detail. Only earthquakes of intensity V and over are considered here.

A summary of earthquakes and estimated intensities in the Mississippi Valley area from the time of earliest reports up to 1940 was written by Heinrich (1941). More recent works from which data were utilized include U. S. Coast and Geodetic Survey publications by Eppley (1958) and Brazee and Cloud (1960). USCGS cards giving preliminary determination of epicenters were used for the years 1957, 1959, 1960, 1961, and 1962. A series of reports by the U. S. Mississippi River Commission (1945, 1953, 1952-1959) provide the source of all data concerning stages and discharges of the Mississippi River. For the most part only discharge is given, but this is easily converted to stage. Precipitation figures are yearly averages in southern Illinois obtained from Climatological Data, Illinois, Annual Summary (1897-1961).

All earthquake data includes epicenter location (longitude and latitude or geographic description), intensity (Modified Mercalli), year and date (see table 1). Intensity is modified to magnitude for analysis by the empirical relation of Gutenberg and Richter (1942) for shallow earthquakes

$$M = 1.3 + 0.6I \text{ max} \tag{1}$$

where M is magnitude and I max is the maximum Mercalli Intensity observed. It is realized that magnitudes obtained in this manner are very rough estimations; but in order to determine the variation in rate of energy release, if there is a variation, and relate it to other events that may influence energy release, a general idea of earthquake magnitudes is required. More recent formulae relating M and I have been developed for various regions, but these would be no more accurate for this study than the formula used here. Richter (1958) has stated that caution must be used in applying the empirical relation determined in California to other regions. Since a relationship between M and I has not been determined for the Mississippi Valley region, it was decided to use that of Gutenberg and Richter. Howell (1959) discusses the merits and derivations of the equations relating magnitude and energy. According to Howell, the energy released by an earthquake can be determined from the relations

$$\log E_T = K + 1.8 M \tag{2}$$

and

$$\log E_T^{\frac{1}{2}} = 4.5 + 0.9 M \tag{3}$$

where E_T is total energy, K is a constant ranging from 9 to 12, and M is magnitude. In equation 3, K is given a value of 9 for experimental purposes. More exact equations relating M, I, and E would be preferred, but since they are not available for the Mississippi region at the present time, these must suffice. The use of the experimental constant K will not affect the general appearance of the curves plotted from this data, nor will it influence greatly the relationships derived. Cumulative

TABLE 1 - EARTHQUAKE DATA

No.	Date	Locality	N lat.	W long.	Intensity
1	Dec. 16, 1811	New Madrid, Mo.	36.6	89.6	XII
2	Jan. 23, 1812	New Madrid, Mo.	36.6	89.6	XII
3	Feb. 7, 1812	New Madrid, Mo.	36.6	89.6	XII
4	Nov. 9, 1820	Cape Girardeau, Mo.	37.3	89.5	VI?
5	June 9, 1838	St. Louis, Mo.	38.5	90.3	VI
6	Jan. 4, 1843	Memphis, Tenn.	35.2	90.0	VIII
7	Oct. 8, 1857	St. Louis, Mo.	38.5	90.3	VI
8	Aug. 17, 1865	Southeast Missouri	36.5	89.5	VII
9	Sept. 25, 1876	Evansville, Indiana	38.5	87.7	VI
10	March 12, 1878	Columbus, Kentucky	36.8	89.2	V
11	Nov. 18, 1878	Southeast Missouri	36.7	90.4	VI
12	July 20, 1882	South Illinois	38.0	90.0	V
13	Sept. 27, 1882	South Illinois	39.0	90.0	VI
14	Oct. 15, 1882	South Illinois	39.0	90.0	V
15	Jan. 11, 1883	Cairo, Illinois	37.0	89.2	VI
16	April 12, 1883	Cairo, Illinois	37.0	89.2	VI-VII
17	June 11, 1883	Memphis, Tenn.	35.2	90.1	V
18	Dec. 5, 1883	Izard County, Ark.	36.3	91.8	V
19	Feb. 6, 1887	Vincennes, Ind.	38.7	87.5	VI
20	Aug. 2, 1887	Cairo, Illinois	37.0	89.2	V
21	Oct. 31, 1895	Charleston, Mo.	37.0	89.4	VIII
22	April 29, 1899	SW Indiana SE Ill.	38.5	87.0	VI-VII
23	Jan. 24, 1902	Missouri	38.6	90.3	VI
24	Feb. 8, 1903	St. Louis, Mo.	38.5	90.3	VI
25	Nov. 4, 1903	St. Louis, Mo.	38.5	90.3	VI-VII
26	Nov. 27, 1903	New Madrid, Mo.	36.5	89.5	V
27	Aug. 21, 1905	Southeast Missouri	-	-	VI
28	May 11, 1906	Petersburg, Ind.	38.5	87.2	V
29	May 21, 1906	Flora, Ill.	38.7	88.5	V
30	July 4, 1907	Farmington, Mo.	37.7	90.4	V
31	Oct. 23, 1909	SE Missouri	37.0	89.5	V
32	Oct. 26, 1915	Mayfield, Kentucky	36.7	88.6	V
33	Dec. 7, 1915	Near Mouth Ohio R.	36.7	89.1	V-VI
34	Dec. 18, 1916	Hickman, Kentucky	36.6	89.3	VI-VII
35	April 6, 1917	East Missouri	38.1	90.6	VI
36	Oct. 15, 1918	West Tennessee	35.2	89.2	V
37	May 25, 1919	South Indiana	38.5	87.5	V

TABLE 1 - Continued

No.	Date	Locality	N lat.	W long.	Intensity
38	May 1, 1920	Missouri	38.5	90.5	V
39	March 22, 1922	South Illinois	37.3	88.6	V
40	March 23, 1922	South Illinois	37.3	88.6	V?
41	Oct. 28, 1923	Arkansas	35.5	90.3	VII
42	Dec. 31, 1923	Arkansas	35.4	90.3	V
43	March 2, 1924	Kentucky	36.9	89.1	V
44	April 26, 1925	Indiana	38.0	87.5	V
45	May 13, 1925	Kentucky	36.7	88.6	V
46	Sept. 2, 1925	Kentucky	37.8	87.6	V-VI
47	May 7, 1927	Mississippi Valley	36.5	89.0	VII
48	Dec. 16, 1931	North Mississippi	34.0	89.7	VI-VII
49	Dec. 9, 1933	Manila, Ark.	35.8	90.2	VI
50	Aug. 19, 1934	Rodney, Mo.	37.0	89.2	VII
51	Nov. 17, 1937	Centralia, Ill.	38.6	89.1	V
52	Nov. 23, 1939	Griggs, Ill.	38.2	90.1	V
53	Nov. 23, 1940	Waterloo, Ill.	38.2	90.1	VI
54	Nov. 16, 1941	Covington, Tenn.	35.4	89.5	V-VI
55	June 29, 1947	Near St. Louis, Mo.	38.4	90.2	VI
56	Feb. 20, 1952	Tenn.-Mo. border	36.4	89.5	V
57	July 16, 1952	Dyersburg, Tenn.	36.2	89.6	VI
58	Feb. 2, 1954	Poplar Bluff, Mo.	36.7	90.3	VI
59	April 26, 1954	Memphis, Tenn.	35.2	90.1	V
60	Jan. 25, 1955	Tenn.-Ark.-Mo. border	35.6	90.3	VI
61	March 29, 1955	Finley, Tenn.	36.0	89.5	VI
62	April 9, 1955	West of Sparta, Ill.	38.1	89.8	VI
63	Sept. 5, 1955	Finley, Tenn.	36.0	89.5	V
64	Dec. 13, 1955	Dyer County, Tenn.	36.0	89.5	V
65	Jan. 28, 1956	Tenn.-Ark. border	35.6	89.6	VI
66	Oct. 29, 1956	Caruthersville, Mo.	36.1	89.7	V
67	Nov. 25, 1956	Wayne County, Mo.	37.1	90.6	VI
68	Jan. 26, 1958	Memphis	35.2	90.0	V
69	Jan. 27, 1958	Ill.-Ken.-Mo.	-	-	V
70	April 8, 1958	Obion Co., Tenn.	-	-	V
71	April 26, 1958	Lake Co., Tenn.	-	-	V
72	Nov. 7, 1958	Illinois-Indiana	38.4	87.9	VI
73	Feb. 2, 1962	Northwest Tennessee	36.3	89.4	V?
74	June 27, 1962	Southern Illinois	37.7	88.5	V-VI

release of strain energy versus time can be plotted now, and relationships between energy release and different stress producing mechanisms can be studied. Plotting energy release in this manner implies a mechanical relationship between all active faults in the area. Benioff (1949, 1951, 1955), using this implication, has produced cumulative strain release curves for deep and shallow earthquakes at a number of localities in various earthquake regions and for the entire earth.

It is pertinent here to define terms as used in this paper. Intensity is the degree of violence of an earthquake determined by noting the conditions under which the shaking is perceptible to humans, the degree to which man made structures are damaged, and the nature of any visible deformation to the earth itself (Howell, 1959). The most recent description of the Modified Mercalli Intensity is given by Richter (1958). Intensities range from those of scale I (not felt except by few under favorable circumstances) to those of scale degree XII (panic and total destruction). Magnitude is defined by Richter (1935) as the logarithm of the largest amplitude, measured in microns (0.001 mm), on the record made by a standard Wood-Anderson torsion seismometer at a distance of 100 km from the epicenter of the earthquake. Epicenter is used here as the point on the surface of the earth which lies directly above the hypocenter, the source of energy of the earthquake. Shallow earthquakes range in depth from 0 to 70 km, intermediate 70 to 300 km, and deep earthquakes greater than 300 km. Most earthquakes originate within the upper 50 km of the earth's crust. In the area under study, most of the earthquakes are probably shallow (Nuttli, personal communication). For example, Walter (1940) assumes the average hypocentral depth of six earthquakes south of St. Louis to be 5 km.

EPICENTER LOCATIONS, ALLUVIAL VALLEYS, AND FAULTS

Epicenters of 70 earthquakes having intensities of V and over that occurred in the Mississippi region since 1811, are shown in the large circle in figure 1. Four earthquakes that occurred in the Mississippi Valley, but with longitude and latitude not given (table 1, nos. 27, 69, 70, and 71), are used in the interpretations but are not shown on the map. In this paper, if an epicenter falls on the alluvial deposits of one of the major rivers, it is considered as being associated with the river. Major rivers in the region are the Mississippi, Ohio, Wabash, Illinois, and Missouri. The alluvial deposits are considered as the criteria for the physiographic separation of epicenters because (a) their groundwater supply is so closely associated with river levels, (b) they are a rough guide to flood plain areas, and (c) they mark the boundaries of old river courses. Since 1811, 65 percent of all epicenters in the region fall within the alluvial fill area (shaded portion of fig. 1) of the major river valleys while the alluvial fill comprises only about 17.5 percent of the total area. If the total area were denoted A (125,600 square miles) and the shaded region S (21,930 square miles), we would expect $nS/A = 12.9$ earthquakes in the shaded region, where n is the total number of earthquakes (74) considered. Now let n_1 = the number of earthquakes in the shaded region plus the 4 that occurred in the Mississippi Valley without exact locations, and let n_2 = the number of earthquakes in the unshaded region. The observed numbers ($n_1 = 48$ and $n_2 = 26$) differ considerably from those expected on the basis of randomness. Applying the chi square distribution (Dixon and Massey, 1951)

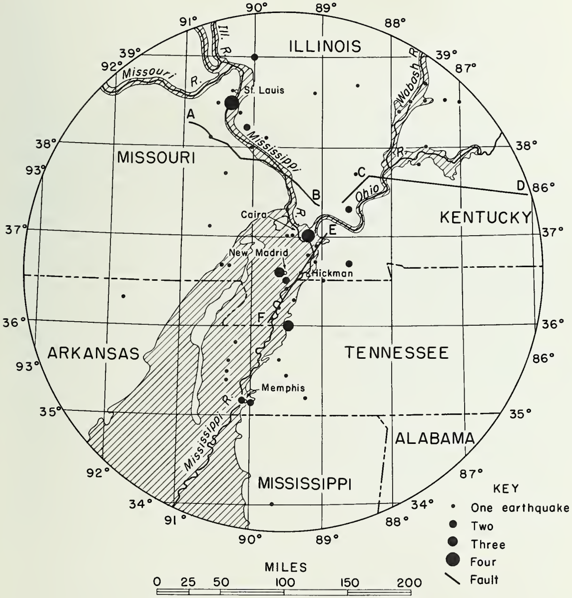

Fig. 1 - Epicenter locations and alluvial valley area. Size of dot indicates number of earthquakes having intensities equal to or greater than V.

to determine randomness:

$$\chi^2 = \sum_{i=1}^{n} \frac{(f_i - F_i)^2}{F_i} \tag{4}$$

where f_i is observed frequency and F_i is theoretical frequency, we get $\chi^2 = 115$, which is vastly greater than could be expected if the distribution were random.

It may be argued that most reports of earthquakes are obtained from inhabitants in a shaken area and, since people have always settled near rivers, epicenters and rivers would thus be brought together. Since 1925, the year detailed earthquake study of the region was begun (Heinrich, 1941), 31 earthquakes having intensities over V shook the area under consideration, and of these 31, 61 percent have epicenters in alluvial valleys. It is one of the purposes of this paper to see if a relationship exists between the two. If a relationship does exist between earthquake epicenters and alluvial valleys, a relationship between crustal structures and valleys is implied. It will be shown that, in this region, zones of crustal weakness are associated with drainage and the drainage in turn, by variations in water load, affects the time of fracture of these weakness zones.

Heinrich (1949), in his discussion of three Ozark earthquakes, has briefly described the geologic setting of the region in which are found the Ozark Uplift, the Mississippi Embayment, and the Eastern Interior Basin. He has described three major faults zones of the "Middle Mississippi Basin" (fig. 1). Two of these zones, the Shawneetown-Rough Creek zone (C-D) and the Ste. Genevieve Zone (A-B), are well documented by geological evidence. The Ste. Genevieve Zone intersects the Mississippi River south of St. Louis, while the Shawneetown-Rough Creek Zone intersects the Ohio River south of its confluence with the Wabash River. The third fault zone, the "Mississippi Embayment Zone" (E-F), has been inferred on the basis of intensive earthquake activity and parallels the Mississippi River south of Cairo. Another fault zone of considerable size is the Cap Au Grès flexure which disappears beneath the broad alluvial valley of the Mississippi River north of St. Louis (Rubey, 1952). The extensiveness of other faulting in the Illinois portion of the area is well illustrated by Stonehouse and Wilson (1955).

Faulting is believed to continue southward from the area mapped by Stonehouse and Wilson although these faults are covered by Cretaceous strata not known to be faulted. The Ohio and Wabash Rivers are nearly paralleled by northeastward trending structures throughout the extent of the area mapped by Stonehouse and Wilson. Most of the faults are steeply-dipping normal faults. Nuttli (personal communication, 1962) has mentioned that the Missouri River makes a large bend near St. Louis and does not take the obvious path suggested by topography. From gravity and magnetic surveys there is evidence of basement faulting. Thus, from the above discussion it is evident that rivers and faults often do coincide where geologic structure is known.

With the coincidence in geographic location of many zones of geologic weakness, as evidenced by the numerous faults, and large surface and subsurface forces resulting from the seasonal change of load in rivers and ground water, this area is well endowed with the requirements for the mechanical triggering of earthquakes. Numerous earthquake triggering devices have been postulated.

Among these mechanisms are changes in atmospheric pressure and precipitation (Conrad, 1946), atmospheric pressure changes (Heinrich, personal communication, 1962), sea level changes, groundwater and surface water load (Leypoldt, 1941), lunar tides (McMurry, 1941), and variations in the gravitational constant caused by variations in earth-sun distance (Morgan, Stoner, and Dicke, 1961). Conrad (1946) has concluded that rainfall over lowlands above geosynclinal structures represents a situation in which subsiding geological tendencies are strengthened by the additional load of rainfall. Heinrich (1950) has strongly suggested the possible relation between floods and earthquakes in the Mississippi River area, but concluded that the question cannot be answered.

Carder (1945) has described the influence of reservoir loading on earthquake activity in the Boulder Dam (now Hoover Dam) area in Arizona and Nevada. Here the tectonic equilibrium was sufficiently delicate to be disturbed by the addition of 10^{10} tons of water, which is a small part of the weight of the crustal blocks being displaced. Fisk (1947) suggests a similar type of equilibrium for the Mississippi Valley when he states: "All available data indicate a delicate adjustment between the Mississippi River, the alluvial deposits through which it flows and the slope of the alluvial valley."

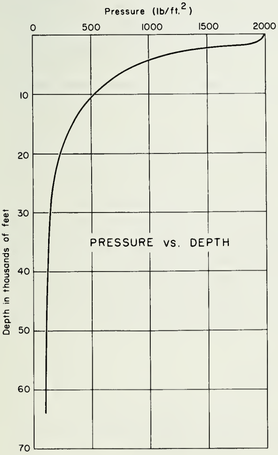

Fig. 2 - Pressure versus depth curve beneath the Mississippi River at Hickman, Kentucky.

EARTHQUAKE FREQUENCY AND CHANGE IN RIVER LOAD

Stage and discharge of the Mississippi River at Hickman, Kentucky, (approximately the center of the large circle in fig. 1) have been recorded since the 1800's by the U. S. Mississippi River Commission (1953, 1954-1959). For almost every year the difference between the highest and lowest stage was somewhat greater than 32 feet, which is equivalent to a pressure of one ton per square foot. When this figure is multiplied by the area covered by the river from north of St. Louis, Missouri, to south of Memphis, Tennessee, a total weight of more than 10^{10} tons is derived. The average width of the river was assumed to be 4000 feet. A curve showing changes of pressure with depth, beneath the center of the river, for a changing load of one ton per square foot is shown in figure 2. The pressure was calculated using the Newmark Chart method (Terzaghi and Peck, 1948) knowing the surficial distribution of the river at Hickman, Kentucky. Thus, yearly pressure changes as high as 1000 pounds per square foot may be exerted on the basement rocks in the vicinity of the river, since basement here is about 5000 feet (Steinhart and Meyer, 1961). The resulting stress, approximately 5×10^5 dynes/cm^2, is almost ten times greater than the largest stress-producing mechanism which might trigger earthquakes as suggested by Morgan, et al., (1961), and this figure is reached without considering the increased water in the ground water reservoir caused by rising river water and precipitation. Thus, it is possible that localized stress, such as that exerted by load changes in rivers and ground water reservoirs, may contribute to the triggering of potential energy built up within the earth by tectonic movements.

Figure 3a shows the mean monthly river stages at Hickman, Kentucky, averaged over a period of 9 years and plotted against month. The resulting curve shows a yearly cycle with a high stage occurring between March and April and a low between September and October. If the first derivative ($\Delta s/\Delta t$) is taken of this curve, the resulting curve (fig. 3b) showing the rate of change of river stage has a maximum between January and February and a minimum in June. Next, a plot of the frequency of earthquakes having epicenters in the alluvial fill of the major valleys versus month is shown (Fig. 3c). The number of earthquakes occurring during two month periods, January and February, March and April, May and June, etc., are plotted. The shape of this curve is similar to that of the differential curve mentioned previously, with a maximum occurring between January and February and a minimum between May and June.

A chi square test may again be run on this data as a check on randomness. Data for the two month periods are as follows:

month	J F	M A	M J	J A	S O	N D
observed	n_1	n_2	n_3	n_4	n_5	n_6
expected	n/6	n/6	n/6	n/6	n/6	n/6

where $n = 48$, $n_1 = 12$, $n_2 = 8$, $n_3 = 3$, $n_4 = 6$, $n_5 = 8$, and $n_6 = 11$. The observed value $\chi^2 = 6.75$ is not large enough to cause us to reject the hypothesis that the proportion of earthquakes in each two month period is random, but it is large enough to suggest the possibility that randomness does not exist. The fact that the distribution of frequencies does suggest a curve with an annual period is also evidence against randomness. As more data become available through further earthquake studies in the region, the hypotheses of an annual cycle can be further substantiated.

STRAIN REBOUND

The mechanics of earthquakes and the elastic rebound theory have been described by Reid (1933). Stresses are slowly built up within the rigid portion of the earth and are released suddenly as a strain energy in the form of earthquakes when the elastic limits of the earth are reached. Benioff (1949, 1951, 1955) has made use of this energy release to plot strain release curves in various earthquake regions. The energy of an earthquake is determined from the magnitude and then a cumulative energy versus time curve is drawn. Figure 4 is a cumulative plot of the square root of the energy released by each earthquake within the area under study

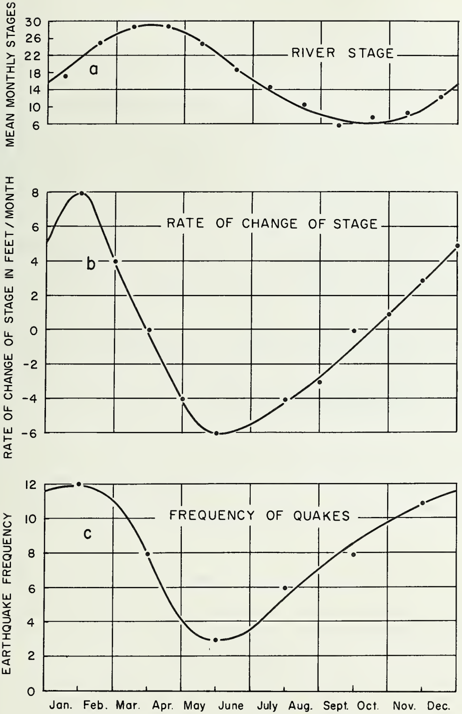

Fig. 3 - (a) Average monthly river stage of the Mississippi at Hickman, Ky.; (b) Derivative of stage; (c) Frequency of earthquakes occurring in alluvial valleys in two-month intervals.

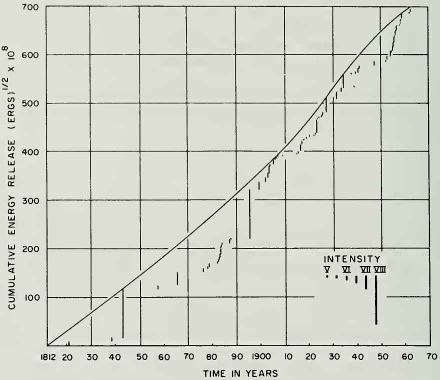

Fig. 4 - Strain-rebound curve of all earthquakes occurring within 200 miles of New Madrid, Mo. (1812-1962).

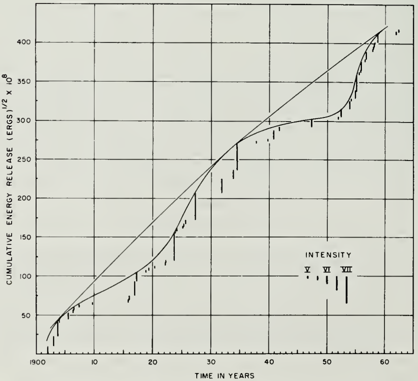

Fig. 5 - Strain-rebound curve of all earthquakes occurring within 200 miles of New Madrid, Mo. (1900-1962).

since the last major shock early in 1812.

From 1812 to 1930 the strain release rate increased. From 1930 to the present time the rate appears to be decreasing slightly. The apparent increase in strain release rate before 1930 is probably due to lack of any systematic study or reporting during this period. The decrease in rate since 1930 cannot be considered as indicative of diminishing energy release in the region, since the time interval of 32 years is too short and the decrease in rate is slight.

Shorter period changes in the rate of energy release are apparent within the long term rate. The shorter period curve is shown in figure 5 from the year 1900 to the present. Two complete fluctuations, having periods of about 30 years, are evident. A fluctuation may be composed of a few large energy earthquakes as shown in the second peak of figure 5 where three earthquakes of intensity VII account for nearly all the energy released, or a larger number of smaller earthquakes may account for a maximum as in the last fluctuation. When energy is released as in the latter case, damage to property is less likely. An earthquake having an intensity greater than VI has not been felt in the area since 1934 when one of VII occurred near Rodney, Missouri (latitude 37.0°, longitude 89.2°). During the 1950's a large series of earthquakes, having intensities of VI and smaller, dissipated enough of the accumulating strain to return the curve of short period fluctuations to the smoother curve.

Richter (1958) states that, "once a major strain has accumulated it can only be relieved by a major earthquake or by a highly abnormal number of small shocks." Thus, both types of release are illustrated in figure 5, where the first fluctuation is composed of a few large intensity earthquakes and the last fluctuation is composed of many smaller intensity earthquakes. Nuttli (personal communication) states that the energy released by all the Mississippi Valley earthquakes since 1812 would be insignificant compared to that released by the 3 large ones in 1811 and 1812. Therefore, it is probable that the curves of figures 4 and 5 are indicative of only a small portion of all the accumulating strain. The early 1960's seem to be the beginning of a period of low rate of energy release. The fact that earthquakes are a common occurrence in this region is evidence of an adjusting crust. Variations in the rate of adjustment are indicated by the strain-rebound curve in figure 5. A mechanism that may influence the variations in rate will now be investigated.

WATER LOAD VERSUS THE TIME DERIVATIVE OF $E^{\frac{1}{2}}$

A close examination of yearly mean river stage and precipitation in southern Illinois reveals long period trends upon which are superimposed violent, short term fluctuations (fig. 6). The long term variations appear to have durations of about the same length as the shorter period fluctuations mentioned above in the strain release curve. In order to eliminate the yearly variations in the river stage and precipitation and gain a better look at the longer period variations, moving averages of the data are taken (fig. 6). Starting with the year 1900, the yearly mean stages through 1908 are averaged. This value is taken as the average stage at the end of 1904. Next, eight years beginning with 1901 are averaged and this value is taken as the average stage at the end of 1905. This method of obtaining moving averages is continued to the present time. Observation of this curve of moving averages versus time shows the long term trends as suggested above. However, undesirable fluctuations are still evident. In order to smooth the curve

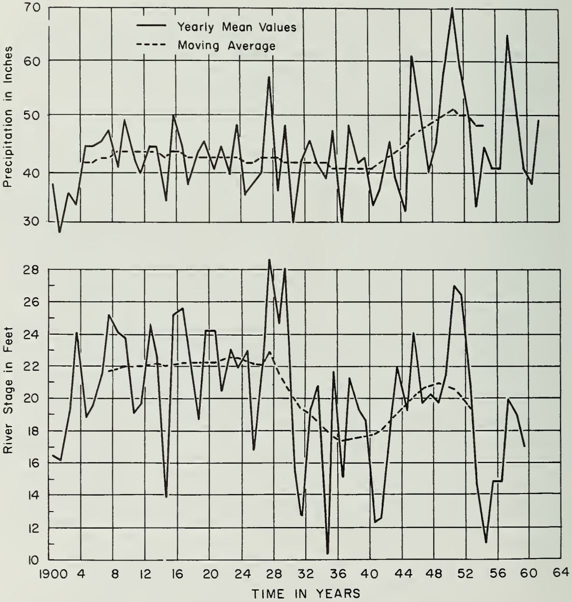

Fig. 6 - Yearly river stage and precipitation and their moving averages.

still more, moving averages of these values are taken, again using the averages of eight years for the final curve. The final curve is a weighted curve with each average value influenced by values from a period of 15 years with those years near the center of the 15 year spread contributing more to the final value than those years at the extremities of the spread. The same method is repeated for southern Illinois precipitation; results are shown in figure 6.

To determine the combined effect of river stage and precipitation on earthquake energy release, changes in the mass of water must be calculated. If only a segment of the area under study is considered, specifically, the alluvial valley of the Mississippi River from Cairo, Illinois to Memphis, Tennessee (about 150 miles), the change in water mass due to variations in river stage and precipitation can be determined at any time (see fig. 7a). The minimum values of both river stage and precipitation during the period of time represented on the curve in figure 7a were subtracted from the curve; therefore, the curve shows variations from a minimum mass. After deriving the average mass for each one year period, a moving average of the resulting curve was taken to eliminate short term fluctuations. It was found that by using only 10 percent of the mass of precipitation, plus all of the mass caused by variations in river stage, a good correlation between mass and the derivative of $E^{\frac{1}{2}}$ (fig. 7b) with respect to time resulted. Other reasons for using only 10 percent of the precipitation are suggested below.

Most of the precipitation is either evaporated directly or is transpired by plants, and therefore, has an effect only for a limited amount of time. Also, some of the precipitation runs off immediately and is measured in the river stage. Thus, the portion of precipitation which might influence the rate of energy release is only a fraction of the total precipitation, probably that fraction entering the ground water reservoir. Total precipitation may produce a load which acts as a short term triggering force (Conrad, 1946) but not as a long term load that would affect the rate of energy release.

The area with which we are dealing is about 9,760 square miles, and in this area since 1900, 24 earthquakes (having $I \,\bar{>}\, V$) have been reported. A plot of the square root of the energy released each year by these earthquakes versus time shows the intermittent nature of energy release (fig. 7c). Moving averages of the energy release are taken in the same manner as described for river stage and precipitation. Values of $\Delta E^{\frac{1}{2}}/\Delta t$ are then derived and a curve is plotted using moving average values. Each of these curves, $E^{\frac{1}{2}}$ vs. time (fig. 7c) and $\Delta E^{\frac{1}{2}}/\Delta t$ vs. time (fig. 7b), are compared with the Δ mass-time curve (fig. 7a). The curve of $\Delta E^{\frac{1}{2}}/\Delta t$ - time is in phase with the curve showing mass-time.

The relationship between the curves of mass and rate of change of $E^{\frac{1}{2}}$ is striking. A least square plot of the relationship is shown in figure 8 with rate of change of $E^{\frac{1}{2}}$ plotted on the vertical and mass difference ΔM on the horizontal scale. The equation of the least square line is:

$$\Delta E^{\frac{1}{2}}/\Delta t = .1\Delta M - 4.6 \tag{5}$$

where $\Delta E^{\frac{1}{2}}/\Delta t$ is in $\text{Ergs}^{\frac{1}{2}}/\text{yr} \times 10^7$ and ΔM is in tons $\times 10^7$. The coefficient of correlation between the two curves is + .85 which indicates that $\Delta E^{\frac{1}{2}}/\Delta t$ increases with ΔM and also indicates a very high degree of association between the curves. Thus, an addition of mass to the area of alluvial fill between Cairo and Memphis

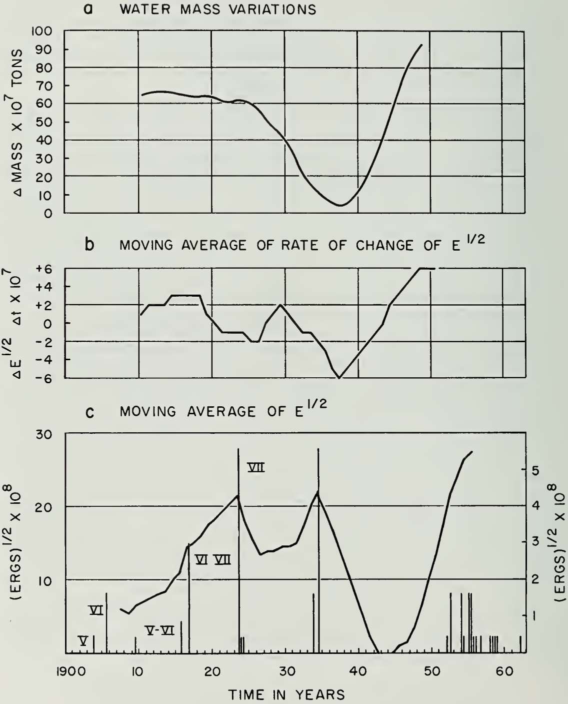

Fig. 7 - Curves exhibiting the relationship between energy release and water mass; (a) Mass of water caused by variations in river stage and precipitation; (b) Time derivative of energy released; (c) Energy released by each earthquake and a curve of moving averages of this energy release (1900-1962);

coincides with an increase in the rate of energy released by earthquakes and a decrease in mass corresponds to a decrease in the rate.

According to Benioff (1949), the amount of movement along a fault (X_f) is related to the total energy release ($E_T^{\frac{1}{2}}$) by the relationship:

$$E_T^{\frac{1}{2}} = C_1 X_f \tag{6}$$

where C_1 is a constant. Therefore:

$$\Delta E_T^{\frac{1}{2}}/\Delta t = C_1 \Delta X_f/\Delta t \tag{7}$$

and substituting from equation 5:

$$\Delta X_f/\Delta t = K_1 \Delta M - K_2 \tag{8}$$

where $K_1 = 0.1/C_1$ and $K_2 = 4.6/C_1$. Thus, the rate of movement along the faults is proportional to the mass of water times a constant which contains $1/C_1$ as defined by Benioff. The acceleration of gravity is also a factor which must be considered when dealing further with this equation, but since it is a constant it will not change the relationship as shown in equation 8.

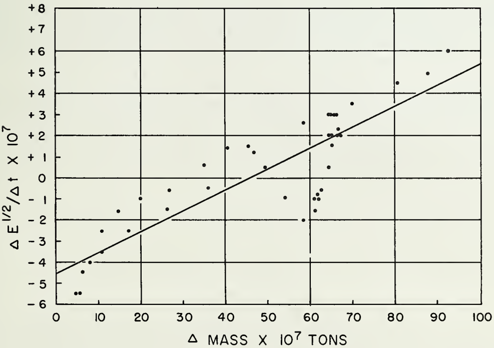

Fig. 8 - Least square plot of the time derivative of $E^{\frac{1}{2}}$ and water load.

CONCLUSIONS

Earthquake triggering mechanisms have been suggested by many authors (Conrad, 1946; Heinrich, 1950; Leypoldt, 1941; McMurry, 1941; and Morgan, Stoner and Dicke, 1961). Some of these mechanisms may contribute to the triggering of earthquakes in the Mississippi valley region, but the author believes the most obvious and most influential mechanism is the change in force caused by the seasonal change in water load in alluvial valleys. The factors leading to this belief are the large number of known faults in the valleys and the abnormally high proportion of earthquake epicenters located in the valleys. Curves of the first time derivative of the mean monthly river stage at Hickman, Kentucky, and the frequency of earthquakes occurring in the major alluvial valleys show maxima in late January and minima in June (fig. 3). A seasonal relationship for the two curves is suggested. It is also noted that the seasonal change in force caused by variations in water load applied to the basement rocks is approximately 10 times that suggested by other authors as enough to trigger earthquakes. Observation of the curves would suggest that an increase in the rate of change of water load tends to increase earthquake activity and a decrease in the rate brings about quiescence. This relationship has the characteristics of a subsiding crust (Conrad, 1946) since fault frequency increases with an increase in the rate of change of water load.

The rate of subsidence may be affected also by long-term changes in water load. The existence of such load changes is indicated by the variations in river stage and precipitation (figs. 6 and 7a). Since the rate of energy released by earthquakes is directly related to the rate of crustal movement (equation 7) the strain-rebound curve (fig. 5) should provide evidence of variations in any tectonic activity. Strain-rebound increments, as described by Benioff (1949), can be used to show the tectonic interrelationships of an earthquake-active region. If a region is undergoing tectonic movements, earth fractures caused by the movements can be treated as a single fault and the energy released can be plotted on a single graph of accumulated energy increments versus time. The resulting curve represents the actual intermittent motion of the entire region undergoing adjustment (fig. 5).

The time derivative of a curve (fig. 7a) of moving averages of energy released in the alluvial valley of the Mississippi river results in a curve (fig. 7b) showing the rate of change of energy release for each year from 1900 to 1962. The coefficient of correlation between this curve and the mass variations curve (fig. 7a) is + .85. The equation of the least square line showing the association between $\Delta E^{\frac{1}{2}}/\Delta t$ and ΔM is:

$$\Delta E^{\frac{1}{2}}/\Delta t = .1\Delta M - 4.6 \qquad (5)$$

and can now be combined with equation 7 to give:

$$\Delta X_f/\Delta t = K_1\Delta M - K_2 \qquad (8)$$

indicating that the movement per year along the faults $\Delta X_f/\Delta t$ in the alluvial valley region between Cairo and Memphis is directly related to the differences in water load (ΔM).

Based on the above relationships the earth's crust between Cairo and Memphis is subsiding. Also, variations in the mass of water resting on the crust may operate in two different ways. They are (1) as an impulsive triggering mechanism, where a load is applied for a short period of time in the form of floods and heavy precipitation. This mechanism is illustrated in figure 3 where the rate of change of water load appears to be associated with earthquake frequency; and (2) as a long term mechanism which may influence the rate of crustal adjustment by long periods of excess or shortage of water (fig. 7).

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