606573

CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION CFSTI
DOCUMENT MANAGEMENT BRANCH 410.11

LIMITATIONS IN REPRODUCTION QUALITY

ACCESSION # AD 606573

☑ 1. WE REGRET THAT LEGIBILITY OF THIS DOCUMENT IS IN PART UNSATISFACTORY. REPRODUCTION HAS BEEN MADE FROM BEST AVAILABLE COPY.

☑ 2. A PORTION OF THE ORIGINAL DOCUMENT CONTAINS FINE DETAIL WHICH MAY MAKE READING OF PHOTOCOPY DIFFICULT.

☐ 3. THE ORIGINAL DOCUMENT CONTAINS COLOR, BUT DISTRIBUTION COPIES ARE AVAILABLE IN BLACK-AND-WHITE REPRODUCTION ONLY.

☐ 4. THE INITIAL DISTRIBUTION COPIES CONTAIN COLOR WHICH WILL BE SHOWN IN BLACK-AND-WHITE WHEN IT IS NECESSARY TO REPRINT.

☐ 5. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED, DOCUMENT WILL BE AVAILABLE IN MICROFICHE ONLY.

☐ 6. LIMITED SUPPLY ON HAND: WHEN EXHAUSTED DOCUMENT WILL NOT BE AVAILABLE.

☐ 7. DOCUMENT IS AVAILABLE IN MICROFICHE ONLY.

☐ 8. DOCUMENT AVAILABLE ON LOAN FROM CFSTI (TT DOCUMENTS ONLY).

☐ 9.

PROCESSOR: *eL*

TSL-107-10/64

AFCRL-64-659

THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI

by

WILLIAM STAUDER, S.J.
JOHN DOWLING
WAYNE H. JACKSON

SAINT LOUIS UNIVERSITY
3507 Laclede Avenue
St. Louis, Missouri

Scientific Report 4

Contract AF 19(604)-7399
Project 8652, Task 865201

August, 1964

Prepared for

Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY
PROJECT VELA-UNIFORM

ARPA Order No. 292, Amendment 7
Project Code No. 3810, Task 2

AFCRL-64-659

THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI

by
William Stauder, S. J.
John Dowling
Wayne H. Jackson

Saint Louis University
3507 Laclede Avenue
St. Louis, Missouri

Scientific Report 4
Contract AF 19(604)-7399
Project 8652, Task 865201

August, 1964

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY

PROJECT VELA-UNIFORM

ARPA Order No. 292, Amendment 7
Project Code No. 3810, Task 2

Requests for additional copies by Agencies of the Department of Defense, their contractors, and other Government agencies should be directed to the:

DEFENSE DOCUMENTATION CENTER (DDC)
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

Department of Defense contractors must be established for DDC services or have their 'need-to-know' certified by the cognizant military agency of their project or contract.

All other persons and organizations should apply to the:

U. S. DEPARTMENT OF COMMERCE
OFFICE OF TECHNICAL SERVICES
WASHINGTON, D. C. 20230

Contents

THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI

Abstract

On June 28, 1963, a 20,000 lb. high-explosive "calibration-shot," code named BILLIKEN, was detonated near the epicenter of the magnitude 5 Southeast Missouri earthquake of March 3, 1963. The experiment was suggested by personnel of Stanford Research Institute after field units set up in the epicentral area failed to record aftershocks. The shot was sponsored by the Advanced Research Projects Agency and conducted jointly by the Crustal Studies Branch of the U. S. Geological Survey and Saint Louis University.

Using arrival times at stations comparable to those used in locating the March 3 earthquake, the instrumental epicenter of BILLIKEN was located within 2 to 4 kilometers of the shot point. This confirms the accuracy of epicenter locations in this area from the data of near-regional stations. The shot has also permitted the "calibration" of the area, making possible epicenter locations using time differences of arrivals at pairs of stations. To the east, north and west of the shot-point travel times from BILLIKEN agree with those of previous earthquake studies and of a current refractions survey; to the south negative residuals were obtained. A comparison of the (P_g-P_n) vs (S_g-P_g) time intervals from BILLIKEN with those for the earthquakes of 2 February 1962 and 3 March 1963 indicates a focal depth deep in the crust for the former, shallow for the latter.

The BILLIKEN Calibration Shot in Southeast Missouri

by William Stauder, S. J., John Dowling
and Wayne Jackson

1. Introduction

On March 3, 1963, a magnitude 5 earthquake occurred in the southeast Missouri area. Within hours of the occurrence of the earthquake word was sent to Stanford Research Institute giving the approximate magnitude and location of the shock. Immediately, as a part of its study of aftershocks of earthquakes, Stanford Research Institute took steps to establish temporary monitoring stations in the epicentral area. Three such stations were established and monitoring of aftershocks began on the fifth day after the main shock. Within the first twenty days, however, no aftershocks were recorded (see Lange and Westphal, 1963). The failure to record aftershocks occasioned the experiment which is here reported.

It was reasoned that the failure to record aftershocks could be explained by one of two causes: 1) no aftershocks actually occurred; 2) the monitoring teams, due to errors in the location of the epicenter of the earthquake, were not looking in the correct place. Accordingly, in a letter of March 20, 1963, to the Advanced Research Projects Agency, Stanford Research Institute suggested that the circumstances in southeast Missouri afforded good opportunity for a chemical high-explosive calibration shot. The purpose of the experiment would be to confirm the accuracy of the location of the epicenter of the earthquake of March 3, 1963, and to make possible a refinement of the location of the epicenters of future earthquakes which might occur in the same region. It was also suggested that the calibration shot would provide an explosion "seismic signature" to serve as a standard for the region or as a criterion to distinguish a given event as an earthquake or as an explosion.

Following the initial suggestion by Stanford Research Institute, on April 9 the Advanced Research Projects Agency sent notice of the plan to the Crustal Studies Branch of the U. S. Geological Survey, which was scheduled to conduct a cooperative crustal refraction survey in Missouri with Saint Louis University the latter part of June. ARPA suggested to the USGS that it might conduct the calibration experiment at this same time and requested a proposal to this intent. A proposal was submitted on May 16th, the experiment was authorized a few days later, and the calibration shot was scheduled for June 28th. The explosion took place on schedule at 5 A.M. EST, on that date. The shot was code named BILLIKEN.

2. Shot Point and Recording Operations

The epicenter and the isoseismal lines of the earthquake of March 3, 1963 are indicated in figure 1. The earthquake was felt quite widely, the radius of the felt region being about 200 miles. As indicated, the intensity in the immediate epicentral region was VII on the Modified Mercalli scale. The region of the epicenter is the alluviated bottomlands lying midway between Poplar Bluff and New Madrid, Missouri. The calibration shot was planned to be located as nearly as possible at the epicenter of the earthquake.

Recording Plan

Several government organizations, universities, and private corporations collaborated in the recording of the event. The plan for the recording is illustrated in figure 2. Since the explosion was intended as a check on the accuracy of the epicenter location, this aspect of the

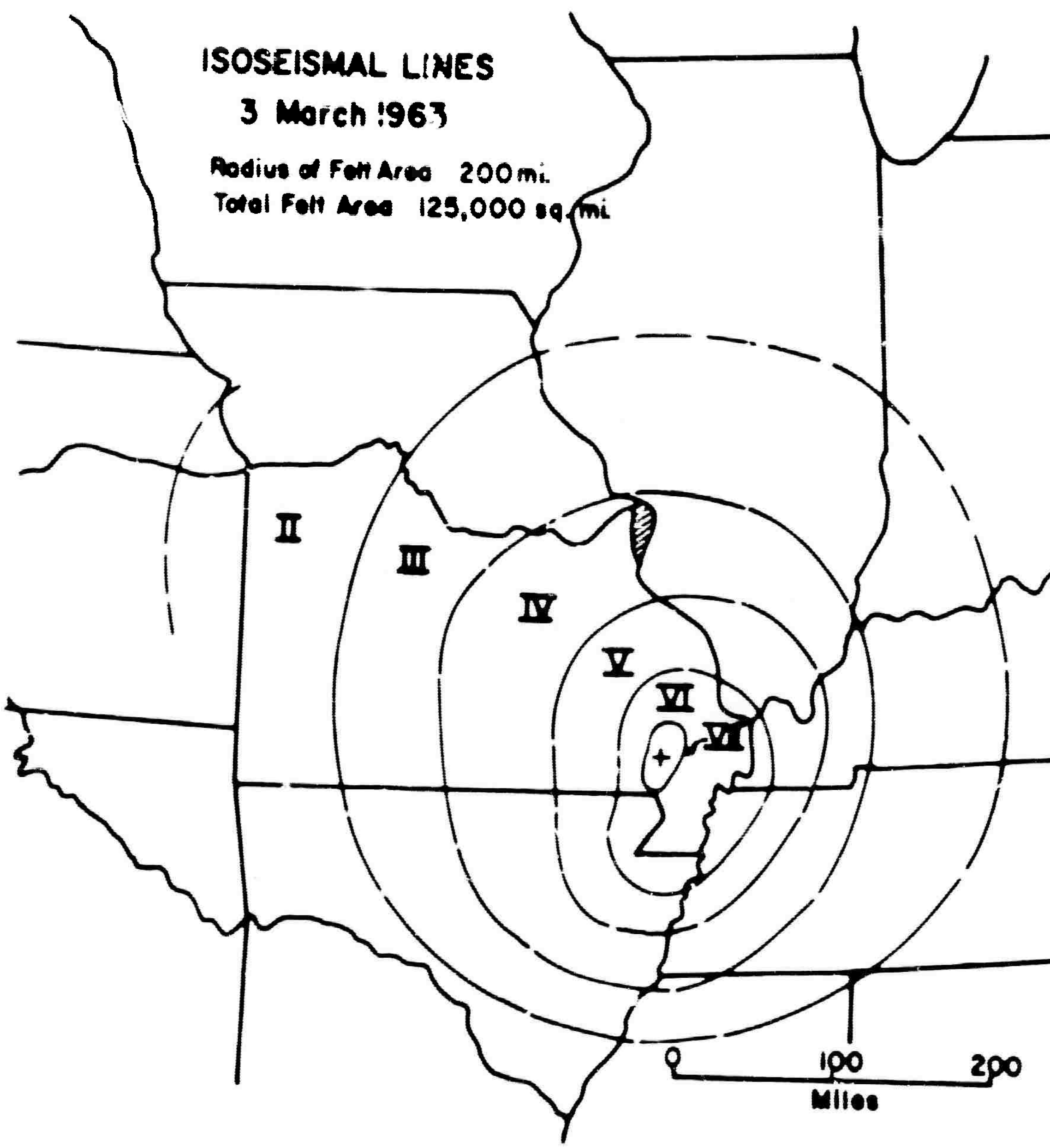


Figure 1. Isoseismal lines of earthquake of 3 March 1963, M = 5

experiment could best be obtained by recording at the permanent seismographic stations in the region. These are indicated by the black dots on the map. With the exception of Cape Girardeau, the nearest seismographic station is at an epicentral distance of over 200 kilometers. The magnification at most of these stations is of the order of 50,000. Consequently, it was feared that the signals of the explosion might not have sufficient amplitude to be recorded at the permanent stations. This circumstance controlled one aspect of the dispersal of the available recording units; certain of the more sensitive field recording units were located either side of or near the permanent stations. It also seemed advisable, as much as possible, to establish continuous lines in various directions from the shot point; this consideration provided a second control over the disposal of the recording units.

The foremost and highest quality field-recording potential was that provided by the presence of the field teams of the U. S. Geological Survey Crustal Studies Branch. Ten recording trucks were in the region for the crustal refraction survey in Missouri. Each truck was capable of putting out six vertical seismometers at 500 meter intervals along a line 2.5 kilometers in length. These USGS units were selected for dispersal so as to provide travel time information in the vicinity of the permanent seismographic stations of the Saint Louis University net. At Rolla and Bloomington one USGS field unit was placed about 20 kilometers either side of the permanent station. At stations more distant from the shot point the field units were located along lines in the direction of the station from the shot point.

In addition to the permanent stations, Saint Louis University established four temporary recording units with Benioff seismometers and

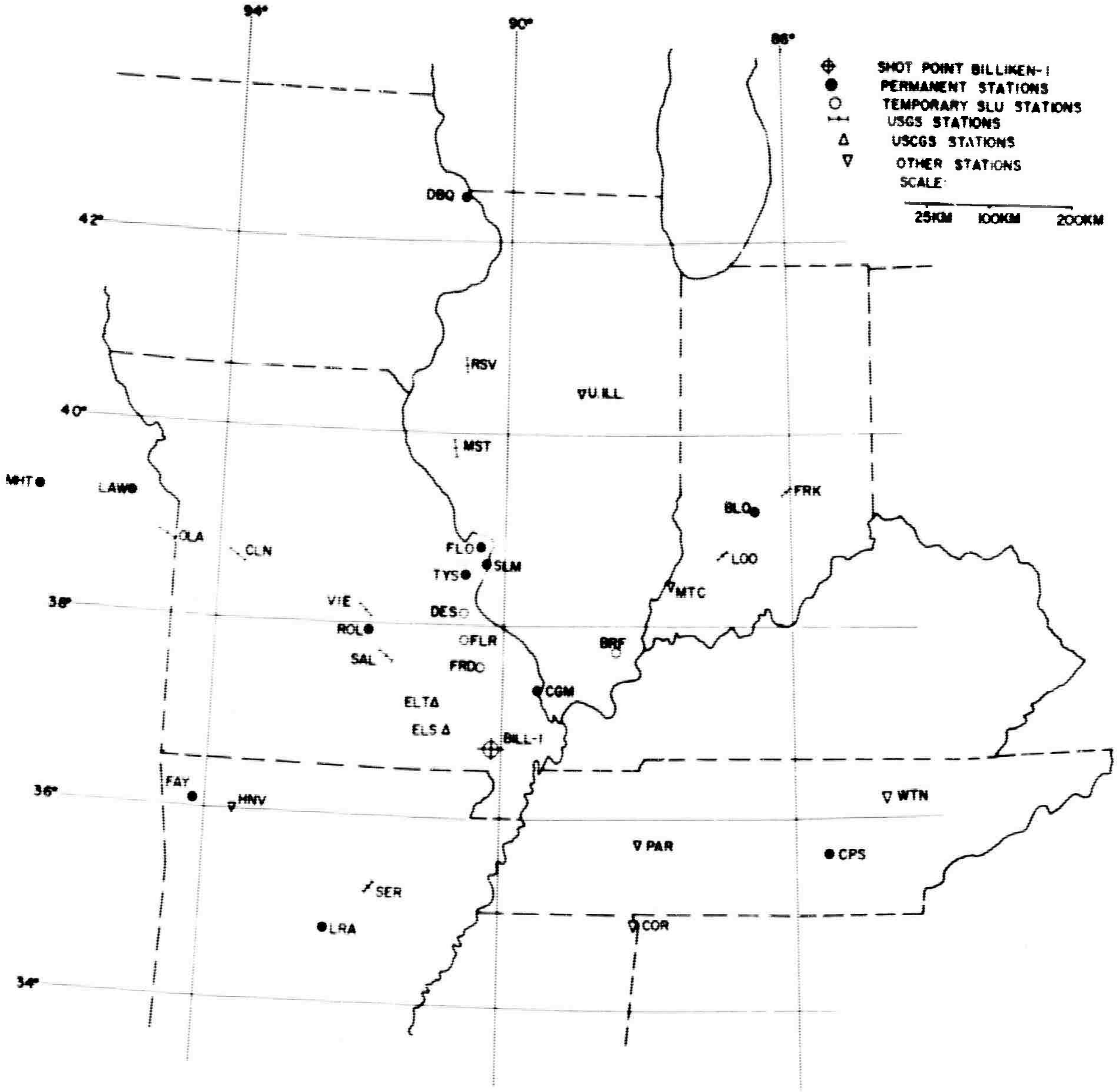


Figure 2. Permanent stations and disposition of recording teams for the BILLIKEN calibration shot of 28 June 1963.

with conventional photographic-recording used in earthquake seismology. Three of these units were located along a line between St. Louis and the shot point. The fourth was located in sourthern Illinois along a line towards Bloomington, Indiana.

Two field units were made available by the U. S. Coast and Geodetic Survey. These were located at 60 and 85 km from the shot point in the direction towards Rolla. At these sites the recording spread consisted of six two cycle per second seismometers located at the corners of a hexagon whose lateral extent was 300 feet.

The Geotechnical Corporation fielded two single component units. The first of these occupied a former LRSM site near Parsons, Tennessee; the second was located near Huntsville, Arkansas. The University of Michigan provided one field station which was located near Corinth, Mississippi. The Geological Surveys of Illinois and Indiana each fielded a seismic refraction unit; these were located near Champaign-Urbana and near Mt. Carmel, Indiana, respectively.

Thus, as much as possible, there was provided good recording at or near the permanent seismographic stations of the region, and recording along lines extending in several directions from the shot point.

Shot Point

The BILLIKEN shot point was located about three km from the instrumentally located epicenter of the March 3rd earthquake. The explosion consisted of a total of 18,400 pounds of DuPont Super "Tovex" gel fired in a 10-~~inch~~ hole pattern. The shot-hole pattern (see figure 3) was designed to provide some cancellation of the horizontal components of surface waves to minimize destructive effects of the explosion on nearby structures. Six-inch holes were drilled to a depth of

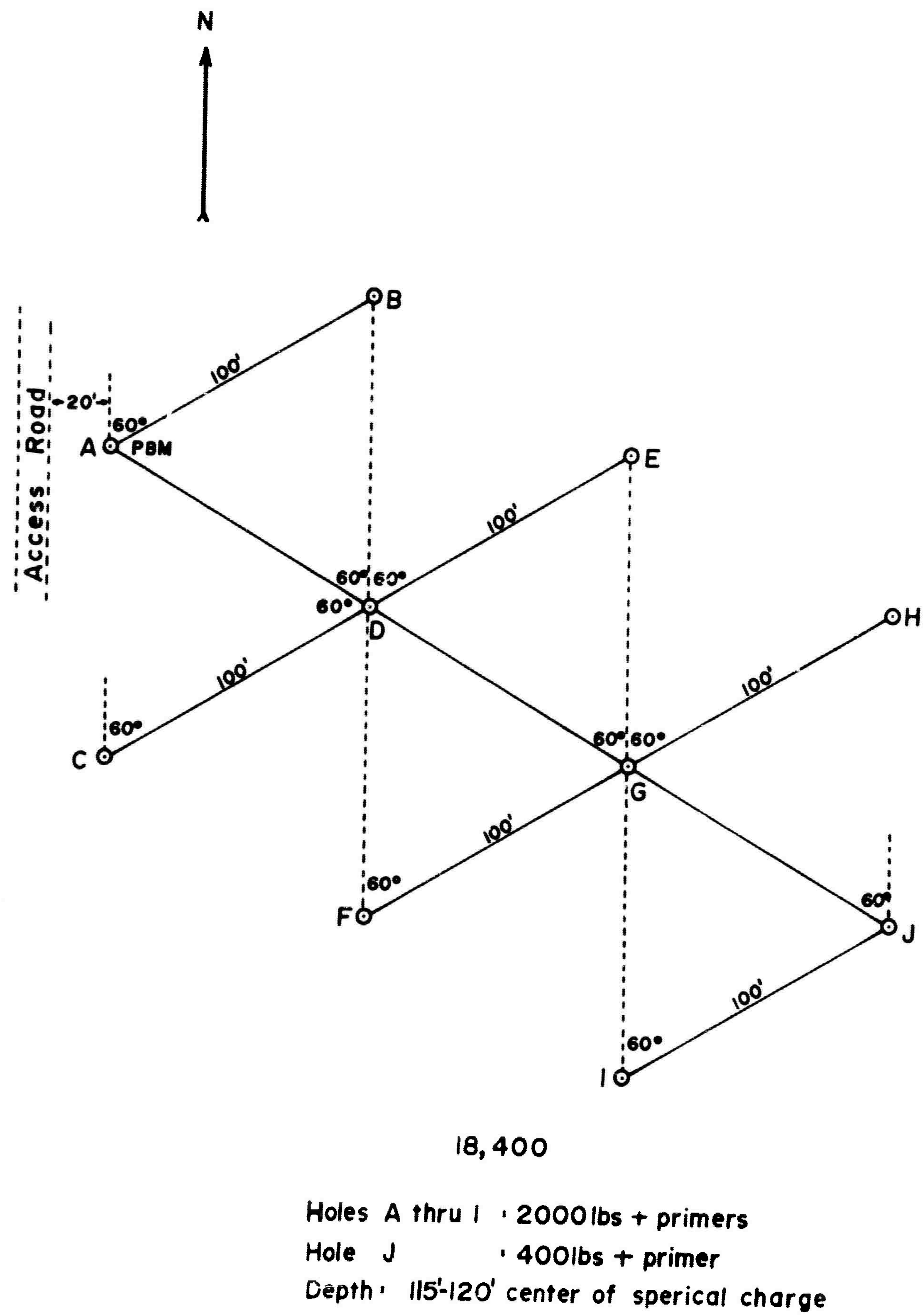


Figure 3. Plan of the shot-hole pattern at t
BILLIKEN shotpoint.

120 ft and their bottoms were enlarged by prolonged washing with the drill bit. The material drilled through was primarily saturated clays on the surface trending toward sandy clay to pure sand at the base of the holes. Super "Tovex," which is a high-energy, high-density explosive, was bulk loaded in order to fill the entire cross-section of the hole. Holes A through I (figure 3) were loaded with 2,000 pounds each and hole J was loaded with 400 pounds. The density of Super "Tovex" is 1.7 gm/cm^3 and the weight is approximately 100 pounds/ft^3.

The charge was detonated automatically by a firing circuit activated by an electronic chronometer phased to coincide closely with WWV timing signals. The time break, radio tones and other instrumental and timing information were recorded on photographic paper operating at 5 inches/sec. The time of detonation can be determined to within 5 millisec or less.

The shot point coordinates including location and shot time are as follows:

Latitude	36° 43.00' N
Longitude	90° 07.62' W
Shot time	10-00-00.13 GCT

3. Interpretation of Results

Signals were recorded from the BILLIKEN calibration shot at 29 stations. The time of arrival of the first recorded P motion is given in Table 1. The times reported at stations occupied by the USGS field units are the arrival times at the first and the last seismometer of the spread. At several stations, e.g., Mt. Sterling, Illinois, P_n did not record; the first recorded motion at these stations is listed in the column headed "P_g". The residuals ("Δt") given in the last column of the Table correspond to the difference between the observed arrival time and the arrival time computed by the travel time curves used in the epicenter

Table 1. Recording sites and time of arrival of first recorded P motion, BILLIKEN shot, 28 June 1963.

Station	Group	Δ	P_g, P^*, P_n	P_g	Δt
Ellsinor, Mo.	USCGS	59.32	10-00-10.16		+0.25
Cape Girardeau, Mo.	SLU	85.00	10-00-14.10		+0.03
Ellington, Mo.	USCGS	88.02	10-00-14.41		-0.13
Fredericktown, Mo.	SLU	94.85	10-00-16.10		+0.45
Flat River, Mo.	SLU	129.57	10-00-21.80		+0.74
DeSoto, Mo.	SLU	161.39	10-00-25.50		-0.75
Salem, Mo.	USGS	168.06	10-00-27.62		+0.30
Salem, Mo.	USGS	170.42	10-00-27.95		
Berry Farm, Ill.	SLU	188.21	10-00-30.70		+0.25
Tyson, Mo.	SPRENG	203.41	10-00-32.70		+0.10
Rolla, Mo.	SLU	203.98	10-00-33.10		+0.50
Parsons, Tenn.	GEO	209.46	10-00-31.40		-2.30
St. Louis, Mo.	SLU	213.26	10-00-35.00		+1.10
Searcy, Ark.	USGS	221.88	10-00-36.47		+1.57
Vienna, Mo.	USGS	220.77	10-00-35.10		+ .21
Vienna, Mo.	USGS	223.23	10-00-35.35		
Florissant, Mo.	SLU	232.40	10-00-37.50		+0.30
Corinth, Miss.	MICH	267.18	10-00-38.20		-2.30
Mt. Carmel, Ind.	INDGS	287.45		10-00-45.07	+2.0
Little Rock, Ark.	SLU	294.00			
Huntsville, Ark.	GEO	326.68	10-00-49.80		+2.0
Mt. Sterling, Ill.	USGS	350.27		10-00-54.01	+3.41
Mt. Sterling, Ill.	USGS	352.72		10-00-54.30	
Loogootee, Ind.	USGS	354.85	10-00-52.36		+1.06
Loogootee, Ind.	USGS	356.58	10-00-52.58		
Fayetteville, Ark.	UARK	370.58		10-00-01.2	+8.2
Clinton, Mo.	USGS	373.56	10-00-54.93		+1.13
Clinton, Mo.	USGS	375.76	10-00-55.18		
Bloomington, Ind.	SLU	420.31		10-01-06.27	+7.10
McMinnville, Tn.	CPSO	428.43	10-01-01.00		+ .70
Roseville, Ill.	USGS	443.76	10-01-02.97		+ .77
Roseville, Ill.	USGS	446.21	10-01-03.16		
Franklin, Ind.	USGS	463.38	10-01-05.63		+1.13
Franklin, Ind.	USGS	464.98	10-01-05.75		
Olathe, Kans.	USGS	471.15	10-01-05.58		+0.08
Olathe, Kans.	USGS	472.56	10-01-05.81		
Wartburg, Tn.	LRSM	486.21		10-01-17.50	+10.2
Manhattan, Kans.	SLU	630.38			
Dubuque, Ia.	SLU	644.62			
Grapevine, Tx.	GEO	758.62	10-01-41.30		+0.7

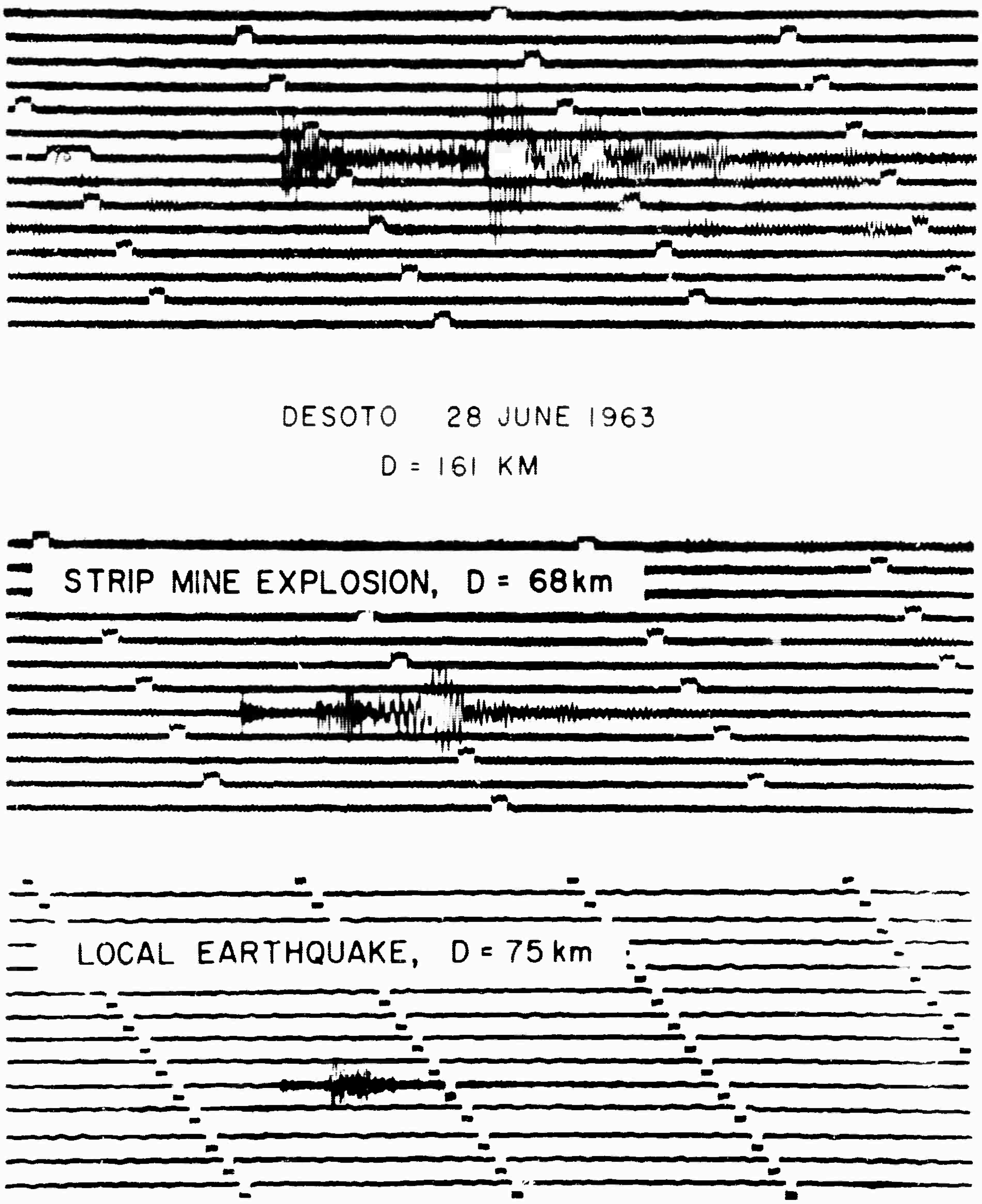


Figure 4. Comparison of records from BILLIKEN and other small seismic sources of the Missouri area. 4a (top) BILLIKEN record at DeSoto, Missouri, 4b (middle) strip mine explosion, also recorded at DeSoto. 4c (bottom) small local earthquake recorded near Poplar Bluff.

determination. The records obtained were sufficient to achieve the principal objectives of the experiment. Particularly at the larger distances, however, the recordings are minimal and the data are of limited usefulness for certain types of studies.

Character of the Seismic Signature

Figure 4a shows the recording of the BILLIKEN event at one of the temporary stations, using traditional earthquake recording equipment. The record shown was written at DeSoto at a distance of 161 km from the source. The paper speed was 120 mm per minute. Clear P_g and S_g phases are here recorded. It is noteworthy that no significant surface wave train appears on the record. This is contrary to the signatures normally obtained from explosions in this region. Figure 4b, for instance, shows the characteristic record which is obtained from strip mine explosions in the area, whereas figure 4c shows a record which is characteristic of small local earthquakes. As a general rule records from industrial explosions in the Illinois-Missouri area feature a well-developed short period surface wave train, such as that seen in figure 4b, which may easily be recorded to distances of 200 km and greater. The records from small earthquakes, on the other hand, are notably lacking in the surface wave trains. The contrast between the BILLIKEN explosion record and those from industrial explosions may well be due to the source environment. BILLIKEN was detonated in alluvium overlying recent loosely consolidated sediments. The industrial explosions normally occur in well indurated carbonate rock.

Epicenter Location

Signals identified as P wave first arrivals were recorded from

BILLIKEN at 22 stations. In order to achieve the principal purpose of the experiment these data were used in an epicenter location program. Figure 5 will illustrate this phase of the data interpretation. The cross on the figure marks the location of the instrumental epicenter for the earthquake of March 3, 1963, as located independently by the U. S. Coast and Geodetic Survey and by Saint Louis University. Each of these determinations was to the nearest tenth of a degree and the two determinations were in exact agreement. The BILLIKEN shot location, as indicated on the figure, was situated as close to the instrumental epicenter as was practical.

A second instrumental epicenter of the March 3rd earthquake was determined by Saint Louis University after a computer epicenter determination program was developed late in the summer of 1963. Using data from seven stations - five stations of the Saint Louis University net (St. Louis, Florissant, Manhattan, Little Rock, Bloomington) plus the arrival time at Lawrence and at the Cumberland Plateau Seismological Observatory (CPSO), McMinnville, Tennessee - a revised epicenter was determined. In this determination the travel time curves

$$P_g = \quad + \frac{\Delta}{6.08}, \quad 0 < \Delta < 150$$

$$P^* = 3.2 + \frac{\Delta}{6.41}, \quad 150 < \Delta < 170$$

$$P_n = 6.0 + \Delta/8.24, \quad \Delta > 170$$

were used. These travel time curves correspond to a focal depth of 15-20 km. The least squares program as used in this determination holds the focal depth fixed. The resulting epicenter was

36.649°N, 90.026°W,
0 = 17-30-12.66 GCT
Std. dev. of travel times = .14 sec.

This epicenter is indicated on the map in figure 5 by the black dot. This

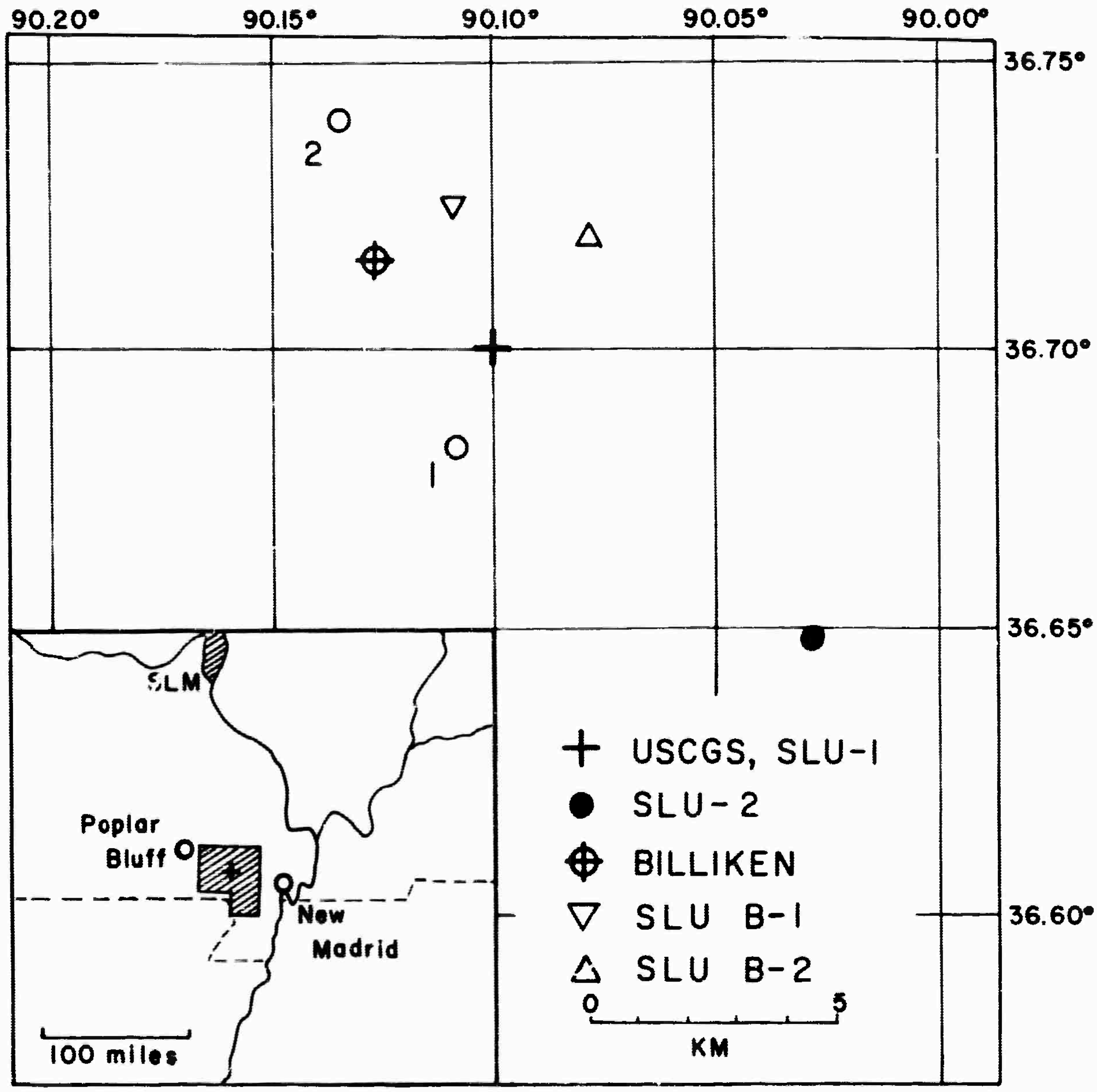


Figure 5. Index map of southeast Missouri area showing the location of epicenters of the earthquake of 3 March 1963 and of BILLIKEN (see text).

Table 2. Tabulation of data relevant to the determination of the epicenter of the BILLIKEN event.

ST LOUIS UNIV EPICENTER PROGRAM, AUG 1963- TVM, MLG

DATE- 062863 ASSUMED DEPTH 0

9 Km 6.1 Km/sec
11 Km 6.4 km/sec
20 km 6.7 Km/sec
8.15 km/sec

TRAVEL TIME DATA USED AT LESS THAN 1000 KM
VEL, KM/SEC 6.10 6.40 6.70 8.15
TIME INTERCEPTS 0.00 .92 2.27 7.57
CROSS OVER DIST, KM 120.00 193.00 200.

EPICENTER	TIME	LATITUDE	LONGITUDE	STD. DEV.	NO. TRIALS
BILL	10 00 00.10	36.6821	90.108	.87567	1

STA	DIST.-KM	DIST.-DEG		ARR TIME	TRV TIME-SEC	DEV-SEC
ELLS	62.2936	.5602	1	10.16	10.05	-.1608
CGM	87.0782	.7831	1	14.10	13.98	-.2855
ELLI	91.7322	.8250	1	14.41	14.29	-.7388
FRED	98.9290	.8897	1	16.10	15.99	-.2266
FLAT	133.7705	1.2030	1	21.80	21.69	-.1316
SALE	171.8253	1.5453	1	27.62	27.51	-.2565
BERR	189.2798	1.7023	1	30.70	30.58	.0942
TYSN	207.5398	1.8665	1	32.70	32.59	-.4442
ROL	207.8233	1.8690	1	33.10	32.99	-.0794
SLM	217.1895	1.9533	1	35.00	34.89	.6721
SEAR	220.1802	1.9802	1	36.47	36.36	1.7740
VIEN	227.1634	2.0430	1	35.10	34.99	-.4508
FLO	236.3488	2.1256	1	37.50	37.38	.8197
LOOG	357.7710	3.2176	1	52.36	52.25	.7821
CLIN	377.0583	3.3911	1	54.93	54.82	.9859
CPSO	425.7022	3.8286	1	1 01.00	60.88	1.0833
ROSE	447.8199	4.0275	1	1 02.97	62.85	.3423
FRAN	464.5608	4.1789	1	1 05.63	65.51	.9327
OLAT	474.6101	4.2684	1	1 05.58	65.46	-.3347
DESO	165.5544	1.4889	1	25.50	25.39	-1.3970
PARS	206.0667	1.8532	1	31.40	31.29	-1.5630
CORI	263.2134	2.3672	1	38.20	38.09	-1.7745

revised epicenter is approximately the center of gravity of several determinations at Southern Methodist University, (Taggart, personal communication). It is distant about 8 km from the first epicenter location.

In order to locate the BILLIKEN event after the manner in which an earthquake in this region would be located, the arrival times were selected from five stations (Rolla, St. Louis, Florissant, Searcy, Franklin; also CPSO) of the Saint Louis University network, or, where one or other of these stations failed to record the event, from one of the nearby USGS field units. The arrival time from McMinnville was also used. From these data, using the same travel time curves as in the location of the revised earthquake epicenter, the following location for BILLIKEN was obtained:

36.725° N, 90.108° W
0 = 05-00-03.32
Std. dev. of travel time = 0.14 sec.

This location is indicated by the inverted triangle on the map. Using a slightly different P_n velocity of 8.10 km/sec. and a time intercept to correspond to a surface focus, data from these same stations gave the second Saint Louis University epicenter indicated on the figure. These epicenters are 2 and 4 km distant from the shot point, respectively.

To make better use of all of the data from the BILLIKEN experiment a third epicenter determination was made using the data from all 22 stations which recorded P wave first arrivals. These data are tabulated in Table 2. The previous epicenters were located using a two-layer crust with a 6.08 and 6.41 velocities, respectively. As a result of the crustal refraction survey conducted during the summer of 1963, and also as a result from surface wave studies in the region, a better knowledge of a crustal structure is now available. The more recent studies indicate the probable presence of velocity gradients within the crust, or, if the crustal structure is to be approximated by constant velocity layers, that a three-layer crust is probably more applicable. Accordingly, a three-layered crust with velocities as indicated in Table 2 was used in determining the epicenter from the P arrival times listed in the table. The resulting epicenter, given by the open circle numbered 1 in the figure is

36.682° N, 90.108° W
0 = 10-00-00.10
Std. dev. of travel times = 0.876 sec.

The last three stations listed in the table have larger than average residuals in their travel time from the actual shot point and shot time (see below) than do the other stations. Rejecting these last three stations, another epicenter determination was made using the same crustal model. This gave the epicenter, marked by the open circle numbered 2

36.743° N, 90.135° W
0 = 10-00-01.00
Std. dev. = 0.460 sec.

All of the above epicenters fall within 2 to 4 km of the actual BILLIKEN shot point. As a result it is concluded that the reliability of the travel time curves which have been developed for this region is established, and that by using these curves epicenter determinations can be made from arrival times at local and regional stations with an accuracy, certainly, of within 10 km.

Calibration of the SE Missouri Region

Another approach to the same question and a benefit derived from the BILLIKEN experiment is the "calibration" of the southeast Missouri seismic region. Signals from the BILLIKEN experiment make it possible to

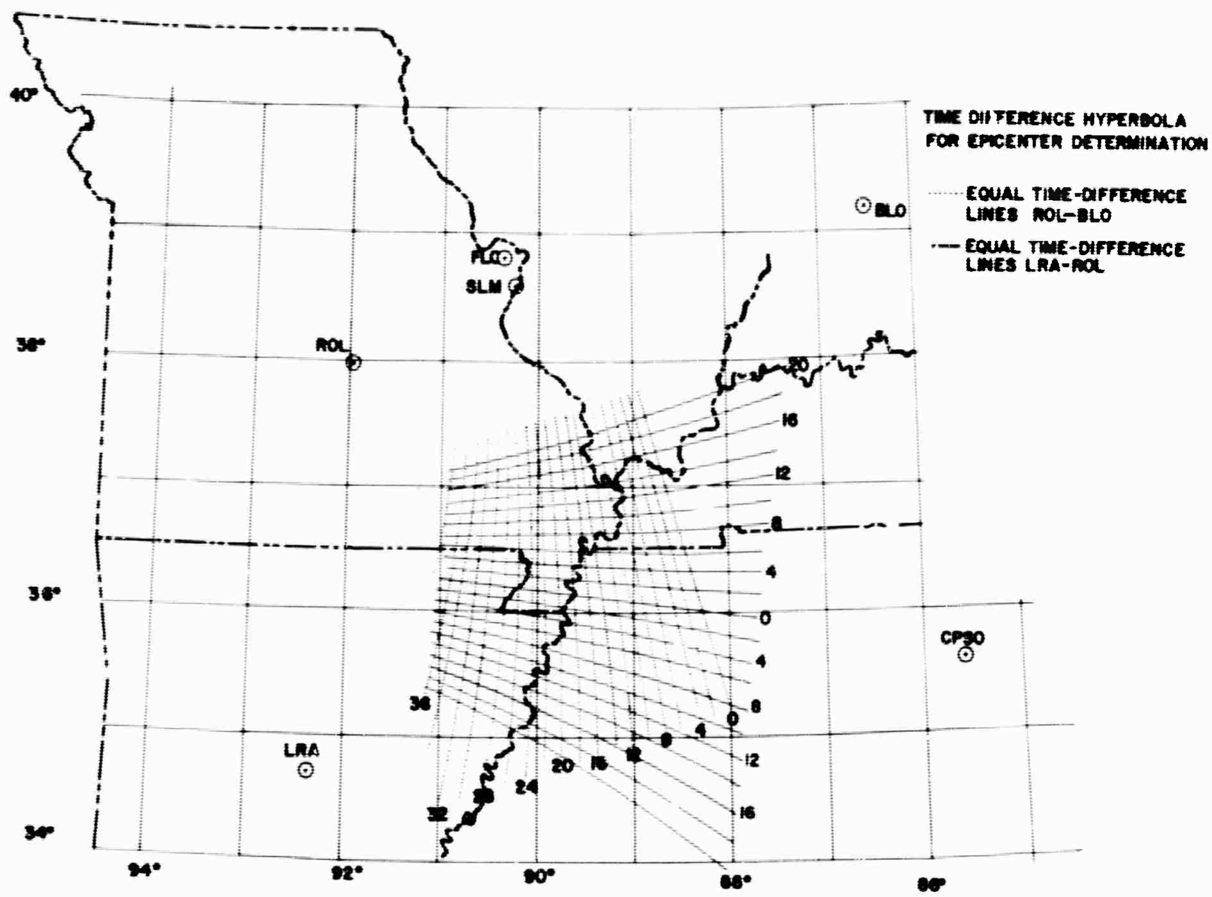


Figure 6. Time difference hyperbolas, based on calibration of the southeast Missouri area by travel times from the BILLIKEN event.

determine the time difference from a fixed point (the shot point) to any two pairs of the permanent seismographic stations of the region. Independent of structure, therefore, with an assumption only as concerns the P_n velocity, curves of equal time difference may be plotted. Figure 6, for instance, shows the time difference hyperbolas for Rolla and St. Louis and for St. Louis and Bloomington. The intersection of lines of equal time difference for two or more pairs of stations permit the location of an epicenter.

The time difference curves have been used to locate several earthquakes occurring in the southeast Missouri seismic area. Table 3 compares the time difference location, based on the BILLIKEN calibration curves,

Table 3. Comparison of Least-Square and Time-Difference Epicenter Determinations

	Epicenter Determination		
Earthquake	Least-Square	Time-Difference	Est. Acc.
2 February, 1962	36.493°N, 89.592°W	36.40°N, 89.63°W	±0.1°
3 March, 1963	36.649°N, 90.026°W	36.65°N, 90.10°W	±0.05°
6 Apr (08^h), 1963	36.42° N, 89.72° W	36.47°N, 90.00°W	±0.2°

and the computer determined epicenters based on knowledge of the crustal structure gained from numerous previous studies in the region. The BILLIKEN based epicenters differ little from those determined by normal procedures.

The use of time difference curves has been applied in the areas of other networks. The only distinction in the present case is that the time differences are calibrated with reference to a known source location. In SE Missouri the knowledge that is at present available of the crustal structure of the region is such that the time difference method offers no real advantage over the usual P-O least square solution. The results presented in table 3 indicate that a calibration shot in a region of poorly known crustal structure might be used to improve the accuracy of location of a previously recorded event. In SE Missouri the time difference curves also afford a means for obtaining a rapid preliminary epicenter.

4. Other Studies

A comparison has also been made of the BILLIKEN data with the results of regional crustal studies. The data themselves are not too suitable for use in crustal studies, for nowhere are there truly continuous profiles nor are the profiles reversed. On the other hand, the data are better than those provided by any previous earthquake study. Consequently, certain comparisons are of advantage.

Travel Times

Figure 7 presents all of the P wave arrivals on a reduced travel-time curve. The times are reduced by $\Delta/6.0$ km per second. The large circles represent observations at single stations. A pair of smaller circles joined by a line segment represents an observation at a spread of seismometers at one of the USGS units. The times of arrival of secondary phases or of successive crests or troughs after the first breaks are also plotted.

The travel-time curve shown in the figure is based on data from a refraction survey and has been proposed by Stewart and Stauder (1964) as a possible interpretation. It assumes velocity gradients in the crust. As is evident, there is general agreement between the BILLIKEN

BLANK PAGE

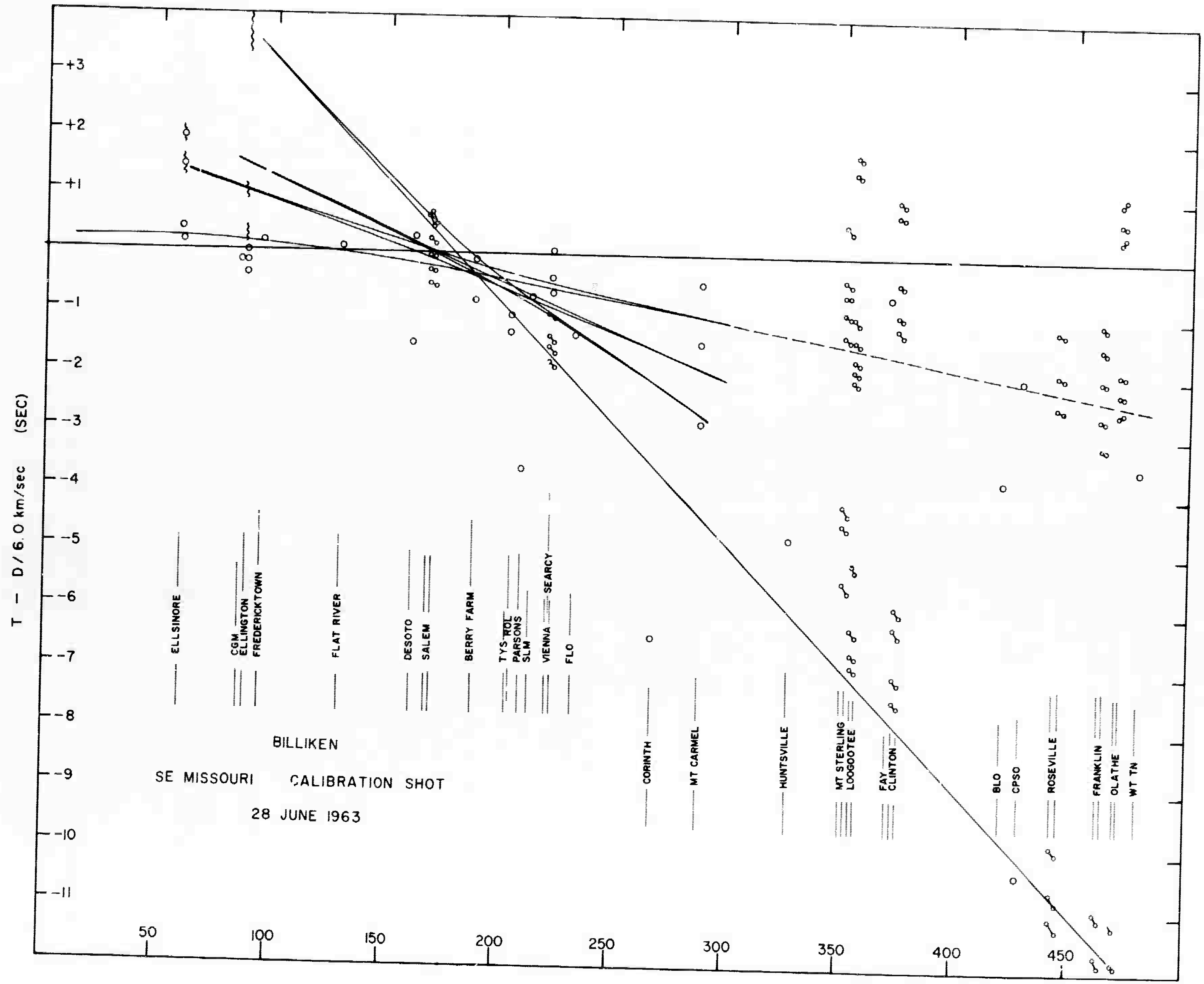


Figure 7. Reduced travel time curve for all arrival times for the BILLIKEN event. The travel-time curve superposed is from a crustal refraction survey.

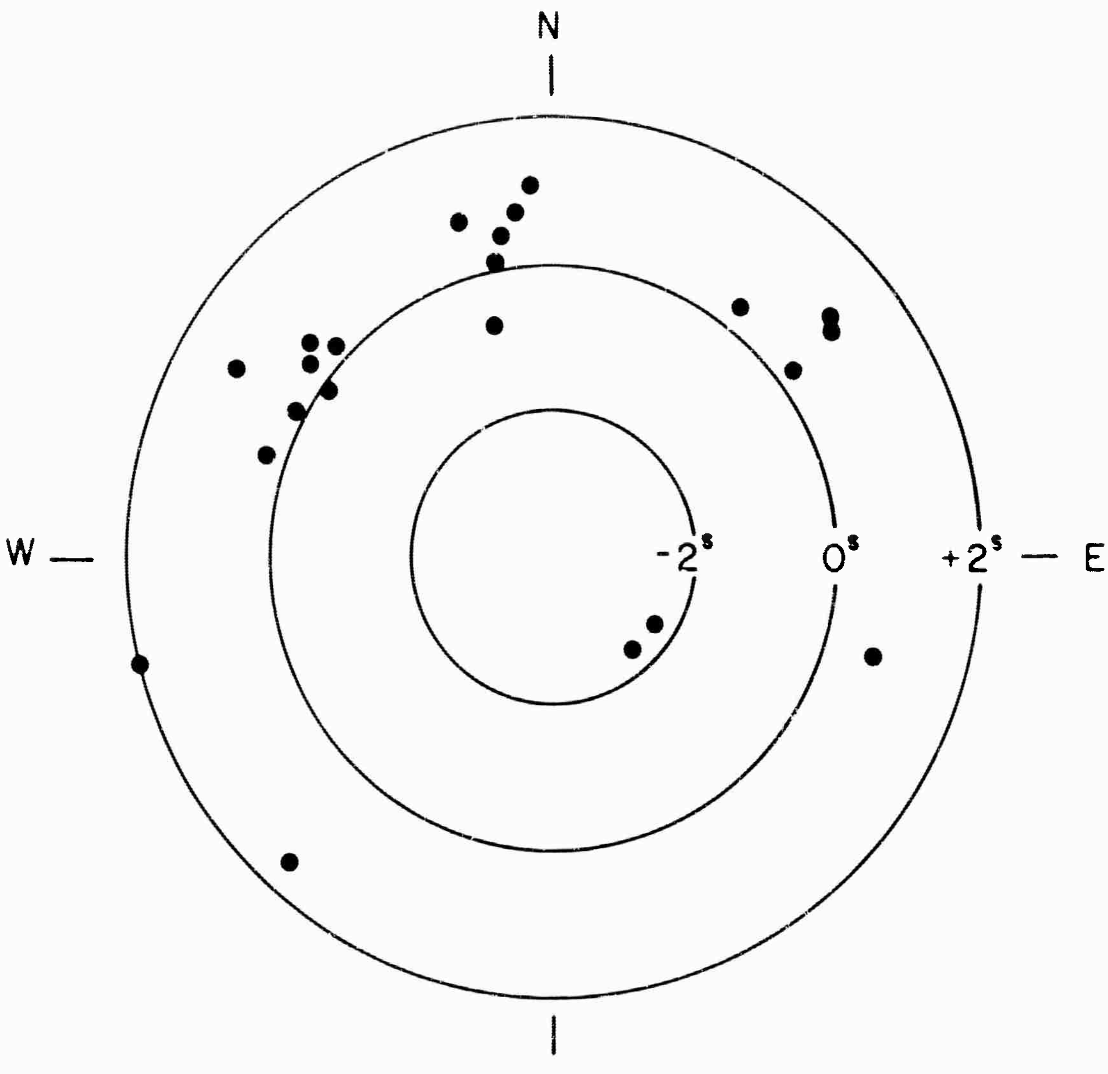
20

data and that of the refraction survey. There are some deviations about the line of first arrivals. For the most part, however, these are small. Three stations form an exception: DeSoto, Missouri, Parsons, Tennessee, and Corinth, Mississippi. At these stations the residuals amount to as much as 2 seconds. These arrival times have been carefully checked. It does not seem possible to "explain away" these arrivals unless there is some gross error in time correction or in station location.

In figure 8 the residuals of all first arrivals of the P wave are plotted as a function of azimuth. The residuals are the observed arrival times minus the theoretical travel times from the actual BILLIKEN shot point for the same model used in the previous portions of this paper, that is, a three-layered, 40 km crust with velocities of 6.1, 6.4, and 6.7 per sec. and with a P_n velocity of 8.15 km/sec. The average of the residuals is a few tenths of a second positive. This probably implies a slight correction to the thickness of the model or to the P_n velocity. From 90° west to 120° east there is no notable effect of azimuth. To the southeast, however, the two stations, Parsons, Tennessee, and Corinth, Mississippi, have residuals of minus 2 seconds, whereas to the southwest at Searcy and Huntsville, Arkansas, the residuals are positive by almost 2 seconds. The stations in these two quadrants are too few to draw any further conclusions. However, the observations noted merit to be borne in mind in future considerations of travel times in these directions.

Focal Depth

The occurrence of the BILLIKEN shot, a known surface event, also presents an opportunity to investigate evidence of focal depth for earthquakes occurring in the same region. Figure 9 presents a plot of the



RESIDUALS IN BILLIKEN TRAVEL TIMES

(MODEL: 9 km - 6.1 km/sec, 11 - 6.4, 20 - 6.7, 8.15)

Figure 8. Residuals in travel time of initial P arrival.

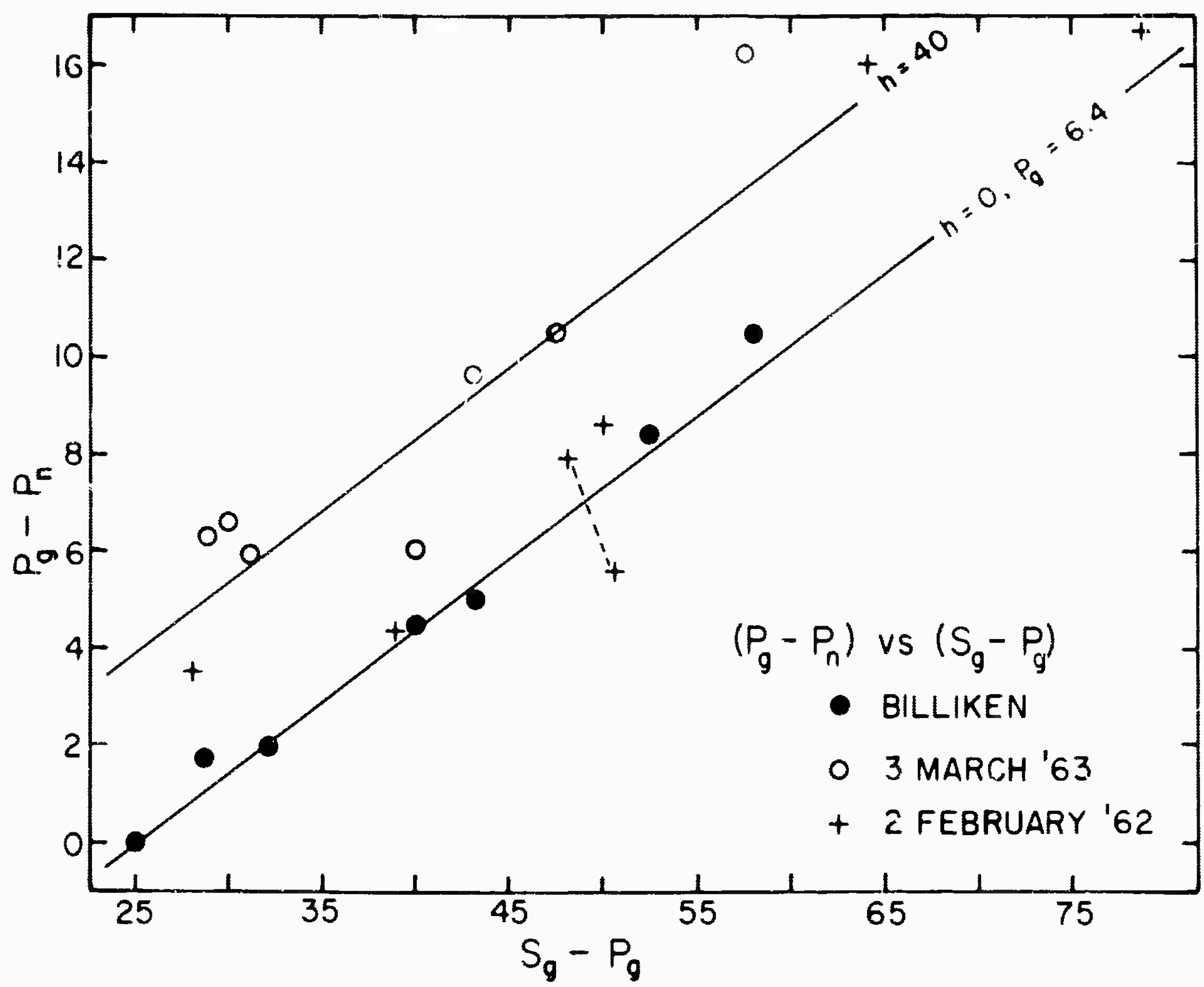


Figure 9. Focal depth investigation based on $(P_g - P_n)$ vs $(S_g - P_g)$ intervals.

(P_g-P_n) time interval vs. (S_g-P_g). This is, of course, an application of the so-called Thirlaway method. As a first approach, a simple one-layered crust of 40 km thickness and a P_g velocity of 6.4 km/sec was considered. The lower of the two diagonal lines represents the relation of (P_g-P_n) vs. (S_g-P_g) for a surface focus for this model. The upper line represents this same relation for a focal depth of 40 km. At seven stations the records of the BILLIKEN event permitted the reading of P_n, P_g and S_g. The corresponding (P_g-P_n) and (S_g-P_n) times are represented by the black dots on the figure. As may be seen, these points correspond satisfactorily to the surface focus line. For the earthquake of March 3, 1963, P_n, P_g, and S_g were readable at another seven stations, and permit the plotting of the points shown by the open circles. Data published by Stauder and Bollinger (1963) for the earthquake of the 2nd of February, 1962, permit the plotting of the points indicated by the crosses. At one of these stations (Bloomington) the point fell below the surface focus line. Re-examination of the record showed that 1.3 seconds after the event read as P_g the amplitude suddenly increases fourfold and the record is whited out from that point on. Taking this time as P_g the point may be re-plotted at the position shown. As is usual in this method, there is a fair degree of scatter of the data points and the onsets of P_g and S_g are not entirely unambiguous. However, the indication is that the earthquake of March 3rd has a focus deep in the crust, whereas that of February 2nd occurred in the upper part of the crust.

Acknowledgment

The Geophysics Department of Saint Louis University wishes to thank all the organizations which took part in the recording of the BILLIKEN event. Particular thanks are due the U. S. Geological Survey for cosponsoring of the project and to the Advanced Research Projects Agency for authorization of the experiment. The Saint Louis University contribution to this research was supported by Air Force Cambridge Research Laboratories Contract AF 19(604)-7399 as part of the Advanced Research Project Agency's Project VELA Uniform.

References

Lange, A. L., and W. H. Westphal.

1963. "Seismic Aftershock Investigations - Project Vela Uniform, Fisk, Missouri, Earthquake of 3 March 1963," Technical Report No. 3 prepared for Advanced Research Projects Agency by Stanford Research Institute under Contract AF 49(638)-1205.

Stewart, S. W., and William Stauder.

1964. "Application of Continuous Velocity-Depth Functions to Interpretation of Crustal Refraction Data in Missouri" Abstract, published in Program of 16th Annual Meeting, Cardilleran Section Geol. Sec. Am., Seattle, March 27-28, 1964.

Stauder, William, and G. A. Bollinger.

1963. "P_n Velocity and Other Seismic Studies from the Data of Recent Southeast Missouri Earthquakes," Bull. Seismol. Soc. Am., 53, 661-680.

Saint Louis University

and

United States Geological Survey

Saint Louis University, THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI, by William Stauder, et al., Air Force Cambridge Research Laboratories, Bedford, Mass. Scientific Report Number AFCRL-64-659, 26 pages, August 1964.
Unclassified Report

A high explosive "calibration shot" was detonated near the epicenter of a regional earthquake of 3 March 1963. Purpose of the explosion was to check the accuracy of the epicenter location and to test a calibration procedure suggested as an on-site inspection technique for investigating a suspicious event. The accuracy of the epicenter location is confirmed. Data from the shot are also used to obtain an indication of focal depth from earthquakes in the region.

1. Epicenter Location
2. Velocity Calibration
3. Focal Depth
4. Seismology

I. Project No. 8652, Task No. 865201
II. Contract AF 19(604)-7399
III. St. Louis University St. Louis, Mo.
IV. Stauder, et al.
V. In DDC collection.

Saint Louis University, THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI, by William Stauder, et al., Air Force Cambridge Research Laboratories, Bedford, Mass. Scientific Report Number AFCRL-64-659, 26 pages, August 1964.
Unclassified Report

A high explosive "calibration shot" was detonated near the epicenter of a regional earthquake of 3 March 1963. Purpose of the explosion was to check the accuracy of the epicenter location and to test a calibration procedure suggested as an on-site inspection technique for investigating a suspicious event. The accuracy of the epicenter location is confirmed. Data from the shot are also used to obtain an indication of focal depth from earthquakes in the region.

1. Epicenter Location
2. Velocity Calibration
3. Focal Depth
4. Seismology

I. Project No. 8652, Task No. 865201
II. Contract AF 19(604)-7399
III. St. Louis University St. Louis, Mo.
IV. Stauder, et al.
V. In DDC collection.

Saint Louis University, THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI, by William Stauder, et al., Air Force Cambridge Research Laboratories, Bedford, Mass. Scientific Report Number AFCRL-64-659, 26 pages, August 1964.
Unclassified Report

A high explosive "calibration shot" was detonated near the epicenter of a regional earthquake of 3 March 1963. Purpose of the explosion was to check the accuracy of the epicenter location and to test a calibration procedure suggested as an on-site inspection technique for investigating a suspicious event. The accuracy of the epicenter location is confirmed. Data from the shot are also used to obtain an indication of focal depth from earthquakes in the region.

1. Epicenter Location
2. Velocity Calibration
3. Focal Depth
4. Seismology

I. Project No. 8652, Task No. 865201
II. Contract AF 19(604)-7399
III. St. Louis University St. Louis, Mo.
IV. Stauder, at al.
V. In DDC collection.

Saint Louis University, THE BILLIKEN CALIBRATION SHOT IN SOUTHEAST MISSOURI, by William Stauder, et al., Air Force Cambridge Research Laboratories, Bedford, Mass. Scientific Report Number AFCRL-64-659, 26 pages, August 1964.
Unclassified Report

A high explosive "calibration shot" was detonated near the epicenter of a regional earthquake of 3 March 1963. Purpose of the explosion was to check the accuracy of the epicenter location and to test a calibration procedure suggested as an on-site inspection technique for investigating a suspicious event. The accuracy of the epicenter location is confirmed. Data from the shot are also used to obtain an indication of focal depth from earthquakes in the region.

1. Epicenter Location
2. Velocity Calibration
3. Focal Depth
4. Seismology

I. Project No. 8652, Task No. 865201
II. Contract AF 19(604)-7399
III. St. Louis University St. Louis, Mo.
IV. Stauder, et al.
V. In DDC collection.