A SEISMOGRAPHIC STUDY OF MID-CONTINENTAL PRIMARY WAVE TRAVEL TIMES

by

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INTRODUCTION

A seismograph station was established at Kansas State University by St. Louis University in the fall of 1961. A research assistantship was granted at Kansas State to initiate seismic studies in addition to operation of the station for St. Louis. The purpose was to create a basic seismic program in the event that the Kansas State Geology Department takes over full operation of the station.

The text of this thesis is divided into two areas, (1) a discussion of the Manhattan Station's development and operation, and (2) basic research on travel times of primary waves in the mid-continent.

PROJECT VELA UNIFORM

Project VELA UNIFORM is one phase of a project known as VELA, which is responsible for research and development of a system for the detection of nuclear explosions, both underground and for high altitudes. In the event of a treaty for the cessation of nuclear testing a protective detection system would be needed. The Department of Defense assigned the development of this system to the Advance Research Projects Agency (ARPA) on September 2, 1959.

Project VELA is divided into three programs: VELA SIERRA for the detection of high altitude nuclear detonations by instruments located on the earth; VELA HOTEL for the detection of nuclear detonations in outer space by means of satellite-borne instruments; and VELA UNIFORM which is concerned with the detection of underground nuclear explosions.

A Panel on Seismic Improvement was established in December 1958 by the Special Assistant to the President for Science and Technology. A report from the panel, after a study of the seismic detection problem, served as a guide in developing the VELA UNIFORM program.

The United States has no single agency which is responsible for all the work involved, therefore several government agencies are handling the various portions of the program. ARPA heads the government agencies and issues an order defining the problem area and the funds available to the agents. The agent contracts each particular phase to various research centers or Universities and is responsible for the detailed technical supervision. Periodic reports are made, to the government agents and ARPA, which are reviewed and summerized. These reports are in turn passed on to higher agencies such as the President's Scientific Advisory Committee.

The Air Force Technical Applications Center (AFTAC) is the main participating government agent. They are the technical agent for the systems and on site inspection technique development tasks as well as for certain aspects of improved seismic instruments, data display and teleseismic measurement techniques.

The Atomic Energy Commission (AEC) is responsible for providing the nuclear devices, the sites, and direct measurements associated with the nuclear-chemical explosion series.

The Defense Atomic Support Agency (DASA) coordinates all Department of Defense activities at the shot sites, manages the necessary close-in measurement programs to observe the conversion of shock waves to elastic waves, and provides the public and technical information for this portion of VELA UNIFORM.

The Air Force Cambridge Research Laboratory (AFCRL) is the agent for applied seismology, the Air Force Office of Scientific Research (AFOSR) for basic seismology and allied sciences, and the Rome Air Development Center (RADC) is an agent for underground electro-magnetic pulse investigations.

The United States Geological Survey (USGS) and the United States Coast and Geodetic Survey (USC&GS) are prominent among the other agencies handling the balance of the research. The USGS is making crustal studies and conducting a major investigation of seismic wave propagation paths in southern California, Nevada and other parts of the United States. The USC&GS is setting up a world-wide standard seismic net and processing the data from it.

The government agencies mentioned are supervising the major contracted technical phases of the VELA UNIFORM program shown in Table 1.

Table 1. Vela Uniform Research Participants, 1 April, 1961

Seismic	
SOURCE MECHANISMS:	SIGNAL DETECTION:
University of California (Berkeley)	University of Michigan
Penn State	Columbia University
St. Louis University	California Institute of Technology
Columbia University	Geotech Corporation
United Electrodynamics	Jersey Production Research
Sandia Corporation	Texas Institute
	Dresser Industry
PROPAGATION:	Electro-Mechanics Company
U. S. Geological Survey	Rensselaer Institute
St. Louis University	
UCLA-Cal Tech.	
Uppsala University	
	SIGNAL ANALYSIS & DISPLAY:
PROPAGATION PHENOMENA:	University of Michigan
California Institute of Technology	University of California (LaJolla)
Columbia University	California Institute of Technology
Weizmann Institute	Columbia University
Stanford Research Institute	Massachusetts Institute of Tech.
University of Oklahoma	Texas Institute
California Research Corporation	Bell Laboratories

("Geotimes", vol. VI, no. 2, Sept. 1961, p. 14)

The preceding is only a brief outline of Project VELA UNIFORM, but it is under this program that an international seismological network with 125 sets of modern, calibrated and standardized instruments will be set up on a cooperative basis.

The ultimate aim of VELA UNIFORM, then, is to acquire the necessary seismic knowledge and to determine the systems requirements which will be needed by the United States government in order to obtain, at the earliest practicable date, a reliable system for detecting underground nuclear explosions. A more immediate goal of VELA UNIFORM is to improve the level of seismological research throughout the world and to develop a broad basic research program in wave propagation and structure of the earth.

SAINT LOUIS UNIVERSITY SPONSORSHIP

St. Louis University is one of the participating agencies in Project VELA UNIFORM. The Institute of Technology at St. Louis University, under a contract awarded by AFCRL, has established a quadrilateral network of seismograph stations in the central United States.

St. Louis University began seismological research in the early 1900's and was a member of the first Jesuit seismographic network established in 1910 by 15 Jesuit colleges and universities. Their background in seismic studies made them a likely participant in VELA.

The stations of the St. Louis network were located in Rolla, Missouri; Dubuque, Iowa; Bloomington, Indiana; and Manhattan, Kansas, providing a quadrilateral network with sides of 300-400 miles. The sites were selected on the basis of geographic location, geologic structure, and the willingness of responsible educational institutions to participate by operating the stations.

The station at Bloomington is under the supervision of the Department of Geology at Indiana University and the pier rests on the Harrodsburg Limestone of the Mississippian System. The Dubuque station is operated by the Department of Physics of Loras College and the pier is on the Galena Limestone of the Silurian System. The station at Manhattan is operated by the Department of Geology and Geography of Kansas State University and the pier rests on the Burr Limestone of the Permian System. The Rolla station is supervised by the Department of Mining Engineering of the University of Missouri School of Mines and is located 10 miles west of Rolla.

St. Louis University also operates a station in St. Louis, on the campus of the University, another at Florissant, Missouri, and has auxiliary stations at Southeast Missouri State College in Cape Girardeau, Missouri and in Little Rock, Arkansas. The Florissant station is one of the 125 world wide "Standard Stations" established by VELA UNIFORM under the USC&GS.

The original contract for the quadrilateral network, dated August 1, 1960, provided $215,000 for the construction and equipping of the stations and for the analysis of data. The contract has been modified and extended until July 31, 1965.

The main purpose of the St. Louis network is to study phase velocity of long-period surface waves which indicate the effect of structure of the upper mantle in the mid-continent and to gather data on secondary or shear waves to study the mechanical characteristics of the point of origin of the earthquake waves. The network was needed for the detailed examination of long-period surface waves and to study the direction of approach.

In the third Semi-Annual Technical report, 1 may 1962 Project Scientist William Stauder, S. J. reported that all stations became fully operational in late 1961. The following progress had been made at that time:

" (1) data from the network have been analysed to determine the fundamental mode Rayleigh wave velocities in the area of the network; (2) studies of crustal and upper mantle P and S wave velocities have been made for the GNOME shot and for a regional earthquake of 2 Feb. 1962; (3) a more general examination of P and S wave parameters was initiated; and (4) several computer programs for an IBM 1620 were developed as these were required for rapid and efficient processing of data".

The Role and Location of the Manhattan Station

The seismograph station at Manhattan may be used as an example of the stations in the St. Louis network and as such, one segment of Project Vela.

The station is located on the south side of a hill at the north end of the campus. The exact geographic location is 39°11'59" N latitude and 96°34' 54" W longitude and the elevation is 1,111.0 feet at floor level. The tract of land occupied by the seismograph building is in the NW$\frac{1}{4}$ Sec. 7, T. 10 S., R. 8 E. of the Sixth Principal Meridian. It is 1,190.4 feet east and 1,440 feet north of the southwest corner of this quarter section.

A geology graduate student operates the station on a salary paid by St. Louis University project money. His duties consist of placing the recording film on revolving drums every 24 hours, marking the time at the beginning and end of each record, developing the film, and mailing the records to St. Louis each week for processing. A log is kept of the time, temperature and wind readings for each 24 hour period and is included with the records. This procedure requires approximately one hour per day under normal conditions. The attendant also checks the equipment in the station, makes what corrections he can and sends word to the network maintenance man in St. Louis in case of major difficulties.

A copy of one of the six daily recordings is retained by the Department of Geology and Geography each day for studies it is making. Copies of all six records are retained only when they show major earthquakes. The copies are for use in current and future research.

The land is property of Kansas State University and the building will revert to the University upon expiration of the project contract. The equipment in the building will be up for negotiation at the end of the project.

MANHATTAN SEISMOGRAPH STATION

The contract for construction of the Seismic Station was let to Green Construction Company of Manhattan in January of 1961. Construction was completed in August 1961 and the station started operation on September 4, 1961.

The over-all dimensions of the building, floor plan and section details shown on plate I, are 26' 4" by 18' 0", divided into three rooms.

Physical Plant

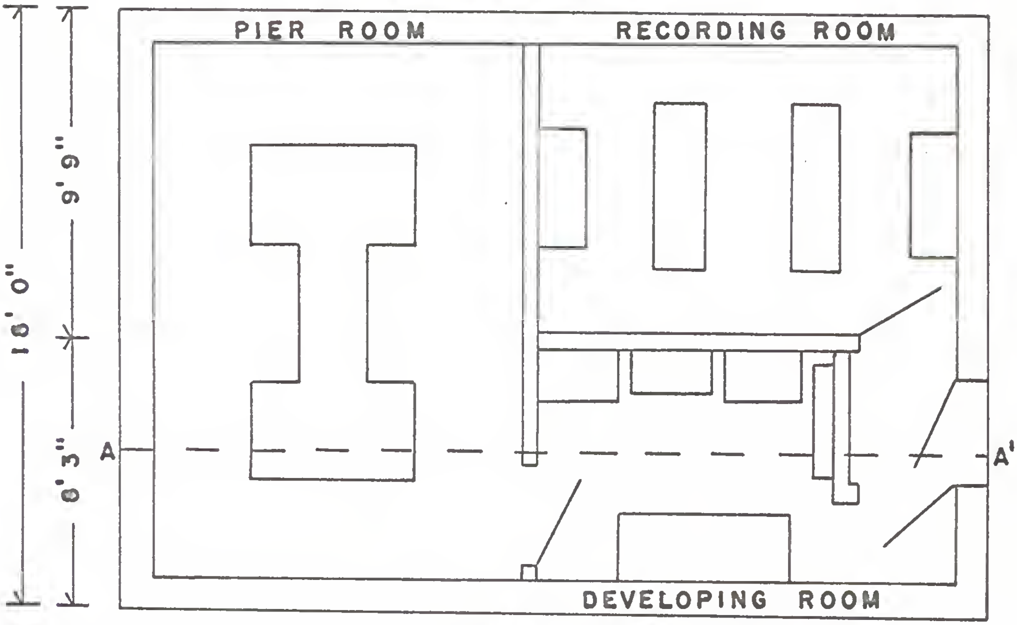
The west room, designated the Pier room, contains a pier or reinforced concrete inertia block which rests on bedrock nine feet below the floor of the station and stands two feet six inches above the floor. The bedrock is the Burr Limestone, which consists of two layers of limestone separated by a gray to black shale. The pier actually rests on the lower massive limestone unit which is three feet thick. The Burr is a member of the Grenola Formation, of the Council Grove Group, Wolfcamp Series, and Permian System.

The station is equipped with six seismometers which set on the " I "

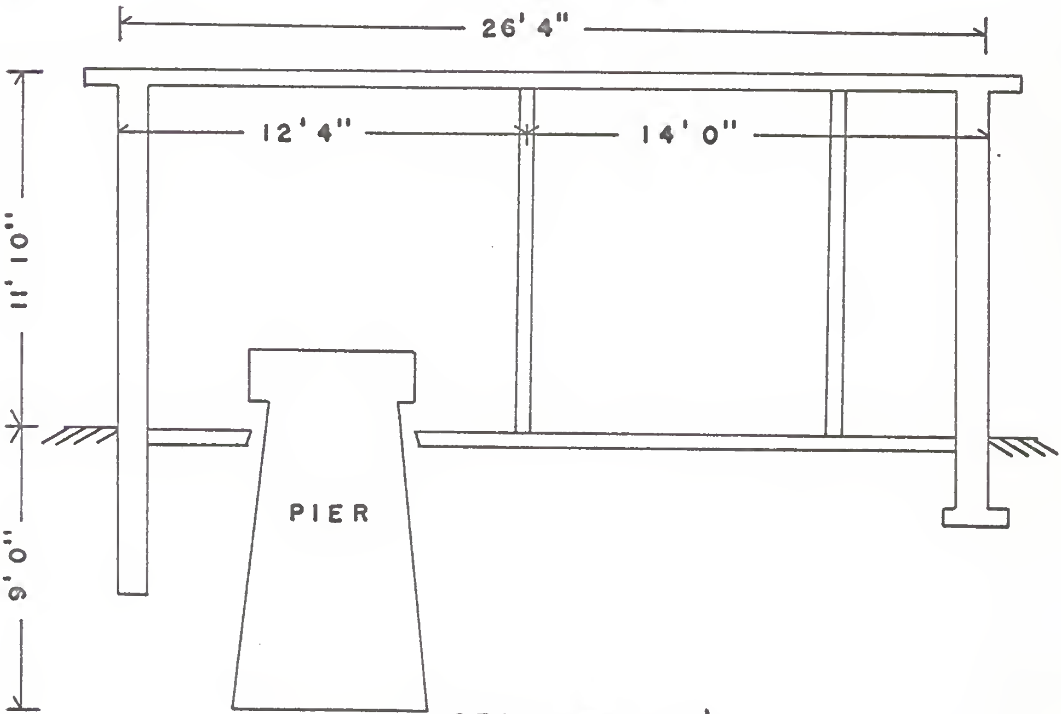
EXPLANATION OF PLATE I

Plan view of Manhattan Seismograph Station showing interior details. Section A-A' from W to E showing pier details.

PLATE I



PLAN VIEW



SECTION A-A'

shaped pier. There is one vertical and two horizontal Sprengnether long-period seismometers; also one vertical and two horizontal Benioff short-period seismometers. One extra long-period horizontal instrument is being used part-time in experiments which will be explained later.

Wires run from the seismometers into the recording room where they are connected to six galvanometers which transfer the earthquake signals from electrical impulses to traces on photographic film placed on two recording drums. The galvanometers rest on two 33 inch high concrete blocks. The short-period galvanometers are located along the west wall and the long-period along the east wall, and face the two recording drums in the center of the room.

The developing room contains the chronometer, radio receiver, developing equipment, contact printer, and the print drier.

Operation and Theory

Richter (1958) defines a seismograph as an instrument which writes a permanent continuous record of earthquake motion and a seismometer as a seismograph whose physical constants are known sufficiently for calibration, so that actual ground motion may be calculated from the seismogram.

Most seismographs, in recording earth motion, use some type of pendulum arrangement whereby an inverted mass is loosely coupled to the earth. The pendulum, supported by a frame setting on the pier, employs a spring or other restoring force which holds the mass and tends to retain it in a fixed position relative to the ground motion. Byerly (1942) describes the two kinds of forces that act on the pendulum. "One is a restoring force, which tends to move the pendulum bob into a new position in gravitional equilibrium with the new position of its support, which is anchored to the moving earth;

for small displacements of the bob relative to the new position of rest. The second force, which opposes the first, is the inertia force of the bob; this is proportional to the accleration of the pendulum."

A damping force must be introduced to prevent the pendulum from continuing to swing in its own free period, thereby obscuring the shorter or longer periods of the ground motion. Fluid or "viscous" damping is obtained in mechanical seismographs by use of dash-pots. Electromagnetic damping is gained by attaching a copper vane that passes closely between the poles of a powerful magnet fixed to the instrument frame, creating an induced magnetic field that opposes the movement of the pendulum. In electromagnetic seismographs (see below) the electromagnetic damping is achieved largely within the electrical circuit of the instrument and may be supplemented by the addition of a copper vane if necessary.

A great addition to the field of seismology was the development of the electromagnetic seismograph. There are other types of seismographs but the electromagnetic is by for the most widely used and will be discussed here because it is used at the Manhattan station.

Electromagnetic seismographs have the same components as the general type described but with the addition of an electrical transducer, or coil, attached to the pendulum. The coil moves between the poles of a magnet when the pendulum is displaced and an electrical current is generated. This principle was first applied by Prince B.B. Galitizin in Russia in 1906 and it has been developed since. Increased sensitivity, reduction in size of the mass, and greater magnification have resulted from this improvement of the seismograph.

The frequencies of earthquake vibration vary over a wide range and no one seismometer can record all vibrations present in an earthquake. Periods of vibration may vary from a few hundredths of a second each, to a minute or more. Generally, most waves from distant earthquakes have long-periods and long wave lengths which require a long-period pendulum to obtain a measurable difference between the moving pendulum and the moving ground. Long-period instruments have a natural period of oscillation of more than 10 seconds and best record earthquake motion when the epicentral distance is over 750 miles. The Manhattan long-period seismometers have a period of 15 seconds.

Earthquakes which originate less than 750 miles from a station cause ground vibrations with short-periods, therefore, necessitating short-period instruments with a natural period of oscillation less than two seconds. Manhattan's short-period seismometers operate with a period of one second.

To record the three dimensional character of earthquake ground motion the horizontal seismometers are mounted so that their pendulums move in north-south and east-west arcs. A vertical seismometer completes the three-dimensional setup, and makes it possible to determine whether the initial phase was compressional or rarefractional.

The characteristics of the seismometer in the Manhattan station were determined by St. Louis University to obtain the best results for their studies, and are shown in Table 2.

Table 2. Seismometer Characteristics

	Vertical	Horizontal
Mass...................................	11.2 kilograms	10.7 kilograms
Distance to Center of Mass.................	12.12 inches	13.6 inches
Distance to Center of Oscillation..........	14.03 inches	14.08 inches
Distance to Coil..........................	13.70 inches	14.0 inches

Table 2 (Concl.).

	Vertical	Horizontal
Transducer Constant........................ (one coil-500 ohms)	.89volts/ $\frac{cm.}{sec}$	.89volts/ $\frac{cm.}{sec}$
(two coils-1000 ohms)	1.78volts/ $\frac{cm.}{sec}$	1.78volts/ $\frac{cm.}{sec}$

(Adapted from, "Earthquakes Notes", Table I, vol. XXXII, Sept.-Dec., 1961)

The electrical current from the transducer, on the seismometer, is used as the input to the sensitive galvanometers. A small mirror on the moving coil of the galvanometer deflects a light beam to obtain a record of the motion on photographic paper.

The recording film is placed on two similar sized, geared, rotating drums, which are placed opposite the two sets of galvanometers. The long-period drum is geared to make one revolution per hour and will run for approximately 26 hours. The short-period drum revolves four times as fast but is geared so the horizontal movement is less for each revolution and therefore also runs for 26 hours. The light source and recording drums are shown diagramatically on Plate II.

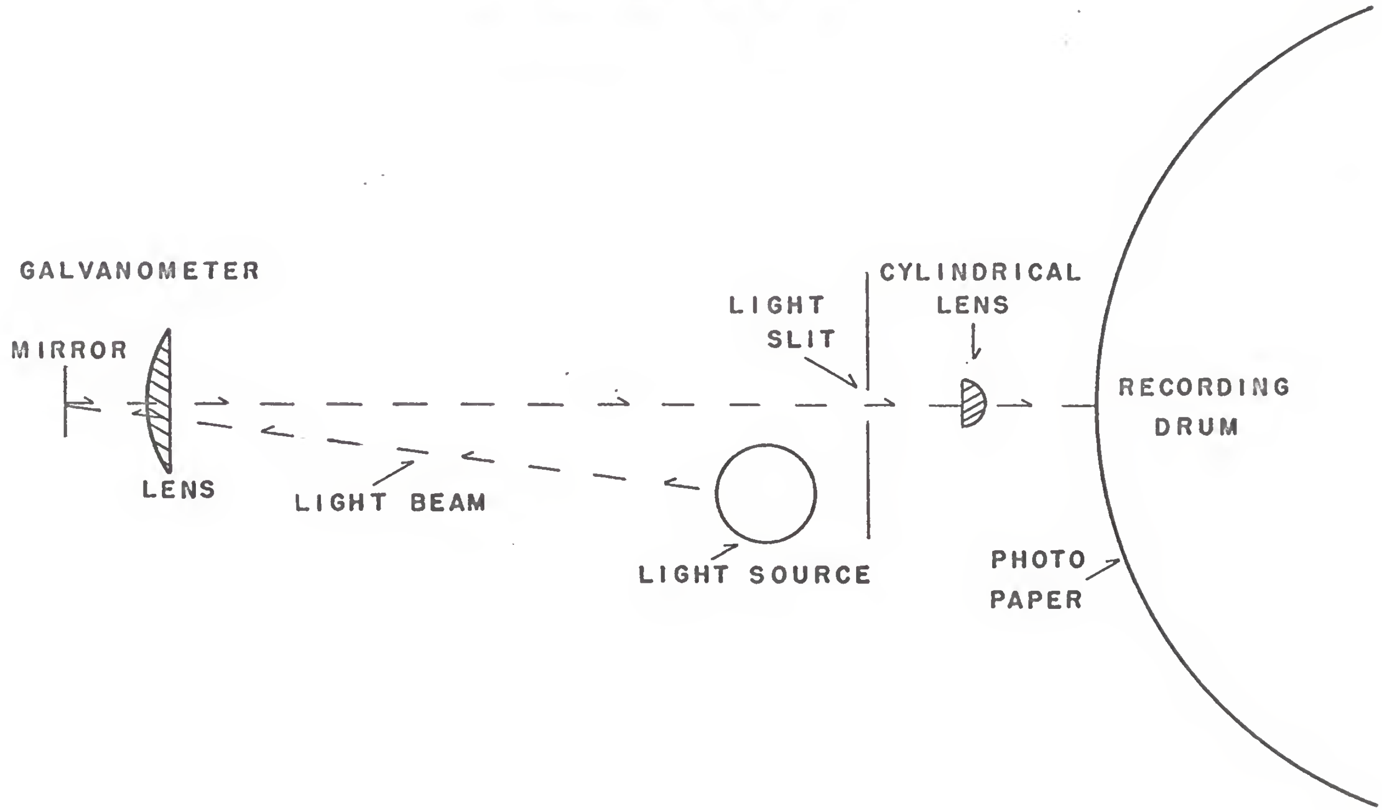
Sheets of Kodagraph Fast Projection film, 36" by 11½", are used for the records. The film is held on the drum by clips and tape and each record is marked for its component. Records also have "Manhattan, Kansas", the date, and central standard time stamped on them with an electric time stamp.

Precise time control is a highly important phase of seismology. Each record must be indexed with accurate time marks so that disturbances from all over the world can be compared. A three second deflection of the light beam automatically marks the recording trace every minute and a 20 second

EXPLANATION OF PLATE II

Section view of Light Source, galvanometer and recording drum.

PLATE II



ADAPTED FROM FIG. 7, "INSTRUCTION BOOK", SPRENGNETHER INSTRUMENT CO.

deflection is made every hour. Radio signal marks at the beginning and end of each record are seven second deflections made by throwing a switch as the radio gives the correct times.

The clock is a Times Chronometer Model TS-3, manufactured by Times Facsimile Corporation New York City, N.Y. The chronometer has numerical minute and hour indicators on a 24 hour system, a 60 second dial with one revolution per minute, and a tenths-of-seconds dial with one revolution per second. It has a minimum timing accuracy of one second in 12 days and provides the hour and minute marks.

The radio receiver for the station is a Model SR-7 receiver manufactured by Specific Products Company. It is designed specifically for receiving radio transmission from the National Bureau of Standards through station WWV or WWVH, 2.5, 5, 10, 15, and 20 megacycles, in Washington D. C. The time signals, of extreme accuracy, are given every five minutes.

Kodagraph developer and fixer are used in the standard developing procedure. The exposed film is brought in from the recording room, placed in the developer tray for approximately two minutes, run through a water stop bath to remove the developer, then placed in a tray of fixer for five to ten minutes, and finally placed in the water bath for 20 to 30 minutes. The film is dried on a Peerless, Senior belt-type print dryer made by the Simplex Speciality Company Inc.

The drive shaft for the chronometer will stop in case of even a momentary power failure and the chronometer must be started again manually. A 12 volt wet celled battery has been installed to sustain the power in case of failure. The power system now consists of a low ripple battery eliminator and charger for D C power supply, an invertor and battery in parallel, and a control box. The D C power supplier is plugged into the A C line and contains a voltmeter indicating voltage to the battery and an ammeter indicating total current. The control box also contains two meters, an A C voltmeter indicating the voltage supplied to the clock and a D C ammeter indicating the current to the battery. This system keeps the battery charged and uses it for the power if the A C line power fails.

The only other equipment in the developing room is a contact printer, made by GeoTech Instrument Corporation Model 8442, for making the record copies kept by the Geology Department.

Temperature control is very important for the entire station. Temperature changes of a few degrees change the equilibrium of the long-period instruments, especially the vertical, and cause the light spot to drift, sometimes off the record. The building is heated with base board heaters in every room and an electric coil type heater in the developing room. A combination heating and air cooling unit located on the roof with vents to each room provides some extra heating, and the cooling for summer. Temperatures of 65 to 75 degrees are maintained in the building.

Difficulty was experienced the first two winters in keeping the heat pump of the roof unit in operation but extra electric heaters have been added to this unit to aid in heating.

A major problem at the Manhattan station is the background noise which sometimes renders records useless. Background noise or microseisms, are small vibrations generated by atmospheric pressure changes, strong wind, heavy traffic, trains, wave action on a shore-line, and other similar phenomena.

The wind causes the most trouble at Manhattan. On very windy days, especially with south winds, the long-period records are ruined. It is believed that the 11 foot high walls, unprotected from the south and west, are affected enough by strong winds to disturb the sensitive instruments. The long-period seismometers have been covered with styrofoam to protect from air currents in the building but this has not solved the problem.

The high noise level lead to an attempt to determine how much of it was caused by the wind. It was reasoned that by burying a seismometer the effect of the wind on the wall could be studied. Other factors should remain relatively constant. A pit, approximately 2½ feet deep and 3½ feet across, was dug and two cyclindrical sections of corrugated steel, culvert pipe placed in it. The inner pipe, 36 inches in diameter, was set in concrete and the larger pipe, 42 inches in diameter, placed on the concrete around the smaller pipe. Four inches of concrete was poured on the upper limestone of the Neva limestone. The pit is approximately 23 feet higher than the station pier, and located 175 feet north. The pipe sections were covered with plywood and water proof plastic sheets and the entire pit covered with straw, for insulation, and a tarpaulin.

A north-south long-period seismometer was placed in the pit and connected to the long-period controls in the station. A double throw switch allowed either the inside or outside long-period seismometer to be used. Although the bedrock was too near the surface and caused the seismometer to be very sensitive to near by traffic, the records from the pit were better than those of the long-period east-west instruments on windy days.

The arrival times, of the initial phase, for all recorded disturbances are noted before sending a week's records to St. Louis. Each arrival time, measured to the nearest tenth second, the date, type of emergence, and if possible the direction of initial motion are listed, then later checked against the U. S. Coast & Geodetic Survey Preliminary Determination of Epicenter cards to determine the location of the earthquake.

A time sheet (See Plate III), that contains information from the log book, is prepared each week and sent to St. Louis with the records. The radio signal time, temperatures, humidity, balance of the pendulum, wind direction, a chronometer check, and comments on anything out of the ordinary are included to aid in the interpretation of the records.

SEISMOGRAPHIC STUDY OF MID-CONTINENTAL PRIMARY WAVE TRAVEL TIMES

Numerous earthquakes are recorded at the Manhattan Seismograph Station from southern Mexico and from the west coast of the United States. The distances to the epicenters of these quakes, ranging from 1900 to 2500 kilometers, are of the same relative magnitude and the travel routes are entirely continental. The geology of the travel routes, however, is quite different. The proposal was made to study the time-distance curves, primary wave travel times, surface wave velocities, and other data of the various recorded earthquakes to learn their characteristics and to study any differences which were found to exist.

The current research was limited to the study of the initial or primary wave travel times because they are the only phases that can be studied from the short-period records available. The travel times were analyzed to find any geographic or geologic variations.

Characteristics of Primary Waves

Earthquakes, using the definition from the American Geological Institute's, Glossary of Geology and Related Sciences, "are groups of elastic waves propagating in the earth, set up by a transient disturbance of the elastic equilibrium of a portion of the earth". A key word in this definition is transient, temporary or not enduring. This excludes from the definition the more or less continuous, minute vibrations or microseisms

EXPLANATION OF PLATE III

Sample time sheet showing information sent to St. Louis University with each weeks seismic records.

PLATE III

KANSAS STATE UNIVERSITY

June 3, 1963

DATE	TIME Signal ON	Signal OFF	TEMPERATURE Record. room	Pier room	LP Z	LP Hor.	HUMIDITY Record. room	Develop. room
5 26 63	1505 GCT R	1405 GCT R	66	67	66	68	57	60
5 27 63	1430 "	1425 "	66	66	66	65	57	60
5 28 63	1455 "	1405 "	66	66	66	66	55	60
5 29 63	1455 "	1410 "	68	67	67	67	55	62
5 30 63	1445 "	1410 "	70	68	68	69	57	64
5 31 63	1445 "	1405 "	70	68	68	68	58	65
6 1 63	1445 "	1405 "	69	67	67	67	58	64

DATE	BALANCE LP Z	LP NS	LP EW	CHRONOMETER	WIND
5 26 63	4.5mm low	1mm S	level	OK	N breeze
5 27 63	4.5mm low	1mm S	.5mm W	.2sec fast retarded	No wind
5 28 63	4mm low	.75mm S	.5mm W	OK	N breeze
5 29 63	3.5mm low	.5mm S	.75mm W	OK	No wind
5 30 63	2.75mm low	.5mm S	1mm W	OK	SW breeze
5 31 63	2.25mm low	.5mm S	1.25mm W	OK	S wind
6 1 63	3mm low	.5mm S	1mm W	OK	S breeze

Comments

5 29 63 Voltmeter on battery charger & eliminator out, other meters still OK

mentioned earlier. Byerly (1942) subdivides earthquakes into two classes, artifical and natural; where artifical earthquakes are those disturbances caused by some type of large explosion. Natural earthquakes, or those resulting from the working of the geologic processes, are mainly tectonic, some are deep focus, some are volcanic, and a few originate from various minor causes such as cave collapse or rockslides.

The earthquakes that were studied here are of a tectonic nature and therefore it is necessary to further examine their characteristics. Tectonic earthquakes result from a deformation of the rocks relatively near to the surface of the earth. Richter (1958) gives the following definition. "The energy source for tectonic earthquakes is the potential energy stored in the crustal rocks during a long growth of strain. When the accompanying elastic stresses accumulate beyond the competence of the rocks, there is fracture; the distorted blocks snap back toward equilibrium, and this produces the earthquake. Energy is drawn from a wide zone on both sides of the actual fracture."

Byerly (1942) comments that it is by the sharp division of the vibrations into groups of waves that an earthquake stands distinct from microseisms on a seismogram. The division results from a sudden disturbance of the elastic equilibrium which causes the propagation of two types of elastic waves from the area of disturbance. This theory was recognized long before the study of earthquake records began and it has since been proven by observation and laboratory experiment. The vibration of one wave is longitudinal to the direction of propagation. The vibration of the other wave is transverse or at right angles to the first wave and the deformation is a shear. The longitudinal waves are compression-rarefraction waves like sound waves. The compressional phase passing the station causes the ground to be compressed and the pier moves slightly in the direction in which the wave is traveling but as the rarefraction phase passes the ground is dilated and the pier moves toward the epicenter. Deformation as the longitudinal wave passes causes a change in volume but not shape. The longitudinal wave travels faster giving it the name P or primary wave, and S or secondary is used to designate the transverse wave.

A. Mohorovicic made the discovery in the early 1900's that at distances less than 100 to 150 kilometers the primary waves begin with a sharp initial motion. At distances greater than 150 kilometers, he found that the initial motion was not as sharp and was followed by a sharper and larger primary phase. Further studies revealed the sharp initial phase at the shorter distances was a direct wave, $\overline{P}$, from the focus or origin of the earthquake, to the recording station. The time-distance curve of the wave from distances over 150 kilometers, Pn, was continuous with those of primary waves from much greater distances, so Mohorovicic theorized that Pn must be refracted below a disconutinuity where a greater velocity would compensate for the longer path and past the critical distance Pn would arrive before $\overline{P}$. The velocities observed for $\overline{P}$ and Pn from their time-distance curves were 5.5 and 8.2 kilometers per second, respectively. Several variations are now recognized in the velocity in the crust or upper 33$\pm$kilometers of the earth but the 8.2 kilometers per second below the Mohorovicic discontinuity does not vary over two or three seconds anywhere around the world.

Calculations

The first stage, in investigating the continental travel times, was to examine each of the Preliminary Determination of Epicenter cards of the USC&GS and list all of the earthquakes occurring in the United States and

Mexico since record copies were kept. The Preliminary Determination of Epicenter cards list the date, origin time (O), latitude and longitude, focus depth (h), approximate geographic area, and the number of recording stations, for all reported earthquakes.

The next step was to check the appropriate Manhattan record copy to see which earthquakes were recorded here. The arrival time of the first phase was read to the nearest tenth second with a good milimeter scale. It is important to note the sharpness of the initial deflection. The initial motion is marked " i " (for impetus or sudden beginning-sharp) when the deflection is distinct and " e " (for emersio or gradual beginning) when the deflection is indistinct. " ei " is used in this paper where the initial deflection is good but the reading may be off one or two tenths of a second.

A basic requirement in the study of travel times is the epicentral distance. Calculating this distance from the Manhattan station to the epicenter of an earthquake involves a problem in spherical trigonometry. The distance, Δ corresponds to the angle at the center of the earth between the radii of the epicenter and the station. To determine this angular distance accurately it is first necessary to correct for the ellipticity of the earth by using the geocentric latitude rather than the geographic latitude in the calculations. The geographic latitude, ϕg, of a point is the angle between a line normal to the surface at that point, if the earth were a sphere, and the plane of the equator. The geocentric latitude, ϕc, is the angle between a line from the earth's center to the point and the plane of the equator, thus correcting for the ellipticity by using the earth's actual surface rather than a sphere. The difference is represented by

$$\tan \phi c = (1 - f)^2 \tan \phi g = 0.993277 \tan \phi g$$

where f is the flattening of the earth, taken as 1/297. The correction is made for both the station and epicentral locations.

The epicentral distance is calculated by using the direction-cosines of the station and epicenter, which are the cosines of the lines joining the earth's center to the epicenter and the recording station. The cosine equation

$$\cos\Delta = 1 - \tfrac{1}{2}\left[(A - a)^2 + (B - b)^2 + (C - c)^2\right]$$

is the best to use for computing distances when, Δ is less than 60°, standard error of only 0.05° at 1° to 0.007° at 20°. A B C are the parameters for the epicenter and a b c the corresponding parameters of the station. The parameters Aa Bb Cc are derived from the coordinates of the station and epicenter, where, λ is the longitude measured positively to the east from Greenwich and, ϕ, is the latitude measured positively in the northern hemisphere. The parameters are derived by

$$A = \cos\phi c \cos\lambda, \quad B = \cos\phi c \sin\lambda, \quad C = \sin\phi c.$$

The direction-cosine method of calculating the epicentral distance is not difficult but rather lengthy when five place natural trigonometric function tables are used. The angular distance can be converted to kilometers by multiplying by 111.09 kilometers per degree.

A sample calculation is shown below.

Southern California June 11, 1963 0 = 15:23:42.3 h = 33km

$\phi g = 31.8°$ N $\lambda = 116.2°$ W

tan ϕg = .62003 tan ϕc = .62003 x .99328 = .61586

ϕc = 31° 37.6' cos ϕc = .85148 sin ϕ = .52438

A=.85148 x -.44151= -.37594 B=.85148 x -.89726 = -.76400 C=.52438

a=.77703 x -.11461= -.08905 b=.77703 x -.99342 = -.77191 c=.62947

Sample calculation (concl.)

$$\cos\Delta = 1 - \tfrac{1}{2}\left[\begin{matrix}-.37594 \\ +.08905 \\ \overline{(-.28689)^2}\end{matrix} + \begin{matrix}+.77191 \\ -.76400 \\ \overline{(+.00791)^2}\end{matrix} + \begin{matrix}+.62947 \\ -.52438 \\ \overline{(+.10509)^2}\end{matrix}\right]$$

$$\cos\Delta = 1 - \tfrac{1}{2}\ (\ .08231\ +\ .00006\ +\ .01104\ )$$

$$\cos\Delta = .95329 \quad = 17.58^\circ$$

$$\Delta = 17.58^\circ \times 111.09 = 1952.96 \text{ kilometers}$$

Travel Times

The travel times of the Pn waves are found by subtracting the Manhattan arrival time from the origin time given on the USC&GS data cards. A 8.2 kilometers per second velocity below the Mohorovicic discontinuity would give uniform travel times for earthquakes all over the world. However, small but consistant variations have been observed, a notable example being in the central Mississippi Valley of the United States. One method of detecting any variations is to compare observed or actual travel times with standard theoretical travel time curves or tables.

Various seismologists (Gutenburg and Richter, Jeffreys and Bullen) have prepared travel time curves or tables from observation and theory. The Jeffreys-Bullen travel time tables were selected by the International Seismological Summary as a basis of comparsion and as such are the most widely accepted tables in use.

The tables were compiled, by Dr. Harold Jeffreys and Dr. K. E. Bullen in 1935 and corrected in 1958, mostly from European observations of European and American earthquakes. The travel times represent the average of the observed times processed by statistical methods. Listed in the P wave table is the focus depth and arc distance from 0 to 105 degrees.

Over 350 earthquakes were listed on the Preliminary Determination of

Epicenter cards, from United States and Mexico. Seventy of these have been recorded at the Manhattan station, where the initial motion was clear enough to be read. The arrival time was recorded and the epicentral distance calculated for these quakes, and are listed in Appendix I.

Twenty-seven of the recorded quakes with sharp initial motion " i " were compared with the Jeffreys-Bullen tables. The correct Jeffreys-Bullen time for the given distance and depth was interpolated from the tables. Table 3 lists the date, location, distance, Manhattan and Jeffreys-Bullen travel times and the residual (R), or difference between the Manhattan and Jeffreys-Bullen times, for the 27 quakes studied.

Table 3. Manhattan and Jeffreys-Bullen P-Wave Travel Times

#		Date	Location		h	Distance arc °	Distance km	Travel Time Manh.	Travel Time J-B	R
34	i	12 31 62	47.1 N	122.0 W	33	20.10	2232.91	4 32.5	4 33.5	+1.0
39	i	3 7 63	44.8 N	123.4 W	33	20.66	2295.12	4 37.8	4 39.4	+1.6
37	i	8 23 62	41.8 N	124.1 W	33	21.06	2339.56	4 40.0	4 43.5	+3.5
44	ei	12 22 61	40.7 N	126.0 W	25	22.37	2485.08	5 05.1	4 47,8	-7.3
25	ei	4 14 62	40.3 N	125.1 W	25	21.92	2435.09	4 55.4	4 53.2	-2.2
28	i	7 14 62	40.3 N	124.4 W	25	21.39	2376.22	4 51.6	4 47.9	-3.7
70	ei	5 22 63	37.0 N	123.1 W	14	20.96	2328.45	4 45.8	4 45.1	-0.7
30	i	9 16 63	35.8 N	118.1 W	10	17.41	1934.08	4 05.8	4 04.6	-1.2
24	i	3 5 62	34.6 N	121.6 W	25	20.51	2278.46	4 39.0	4 38.9	-0.1
31	ei	10 29 62	34.3 N	117.0 W	33	17.07	1896.31	3 59.4	3 57.6	-1.8
76	i	6 11 63	31.8 N	116.2 W	33	17.58	1952.96	4 05.2	4 03.9	-1.3
26	i	5 3 62	29.1 N	115.5 W	25	18.59	2065.46	4 18.9	4 17.5	-1.4
35	ei	1 20 63	26.4 N	110.7 W	27	17.40	1932.97	4 03.9	4 02.5	-1.4
9	i	8 28 62	18.6 N	105.8 W	33	22.03	2447.31	4 54.3	4 53.2	-1.1
21	i	3 11 62	17.6 N	100.8 W	33	21.83	2425.09	4 51.7	4 51.2	-0.5
4	i	5 19 62	17.2 N	99.5 W	20	22.07	2451.75	4 56.2	4 55.4	-0.8
14	i	11 17 62	16.3 N	98.2 W	12	22.86	2539.50	5 04.2	5 04.2	-0.0
1	i	3 27 62	16.9 N	99.9 W	25	22.41	2489.53	4 57.6	4 58.1	+0.5
46	ei	3 25 63	36.0 N	114.9 W	33	14.87	1651.91	3 32.3	3 29.5	-2.8
32	i	1 27 63	44.3 N	114.5 W	31	14.31	1589.70	3 24.2	3 22.6	-1.6

Table 3 (Concl.).

#		Date	Location		h	Distance arc °	Distance km	Travel Time Manh.	Travel Time J-B	R
41	i	12 10 61	32.3 N	103.9 W	0	9.09	1009.81	2 11.6	2 15.4	+3.8
33	ei	12 5 62	39.9 N	104.6 W	33	6.24	693.20	1 34.6	1 34.1	-0.5
23	i	2 2 62	36.3 N	89.4 W	25	6.38	708.75	1 34.2	1 34.9	+0.7
27	i	6 27 62	37.7 N	88.5 W	25	6.52	724.30	1 35.8	1 36.9	+1.1
36	i	3 3 63	36.7 N	90.1 W	18	5.08	564.34	1 12.9	1 17.3	+4.4
43	i	12 31 62	44.4 N	100.5 W	16	5.90	655.43	1 33.9	1 29.1	+4.8
42	i	12 25 61	38.9 N	94.6 W	25	1.58	175.52	26.2	26.8	+0.6

The location of the individual earthquakes, corresponding to the number given in Table 3, is plotted on Plate IV.

The residuals plotted as functions of the distance for various areas are shown on Plates V and VI.

Summary

Travel time residuals do exist, as shown in Table 3. All calculations and readings used to compile Table 3 were rechecked for accuracy.

All residuals where the Jeffreys-Bullen travel times are greater than the Manhattan travel times are designated as positive (+). A positive residual means that the actual, observed travel times are faster than the standard comparsion times for the particular travel routes in question. A negative (-) residual simply means the opposite, that the actual travel times are slower than the standard comparsion times.

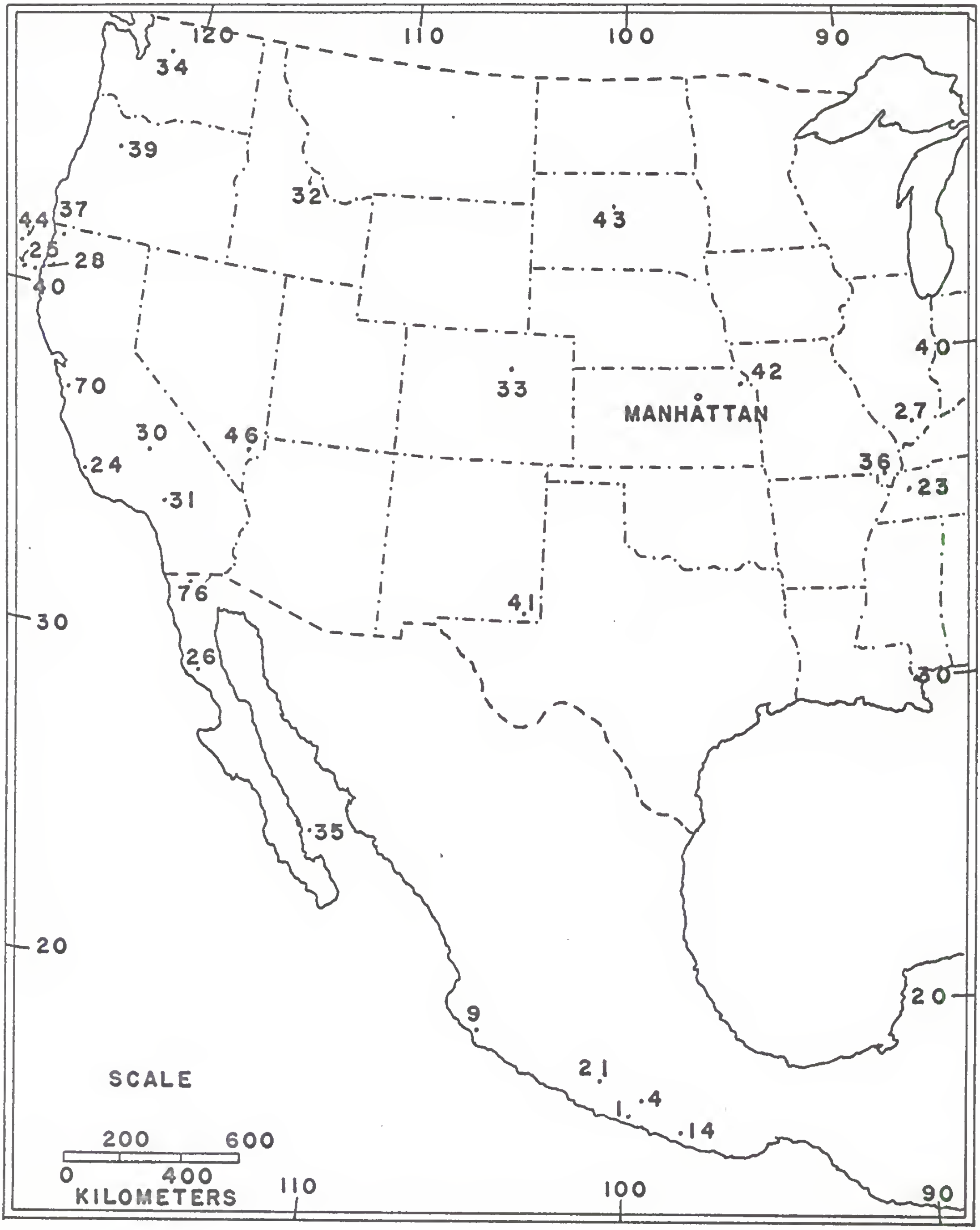
Earthquakes number 34, 39, and 37 have positive residuals ranging from +1.0 to +3.5 seconds faster than Jeffreys-Bullen times.

Rather large negative residuals were found for numbers 44, 25, and 28. These readings are somewhat in question because their epicentral locations

EXPLANATION OF PLATE IV

Index map showing the location of the 27 earthquakes selected for comparsion with the Jeffreys-Bullen tables.

PLATE IV

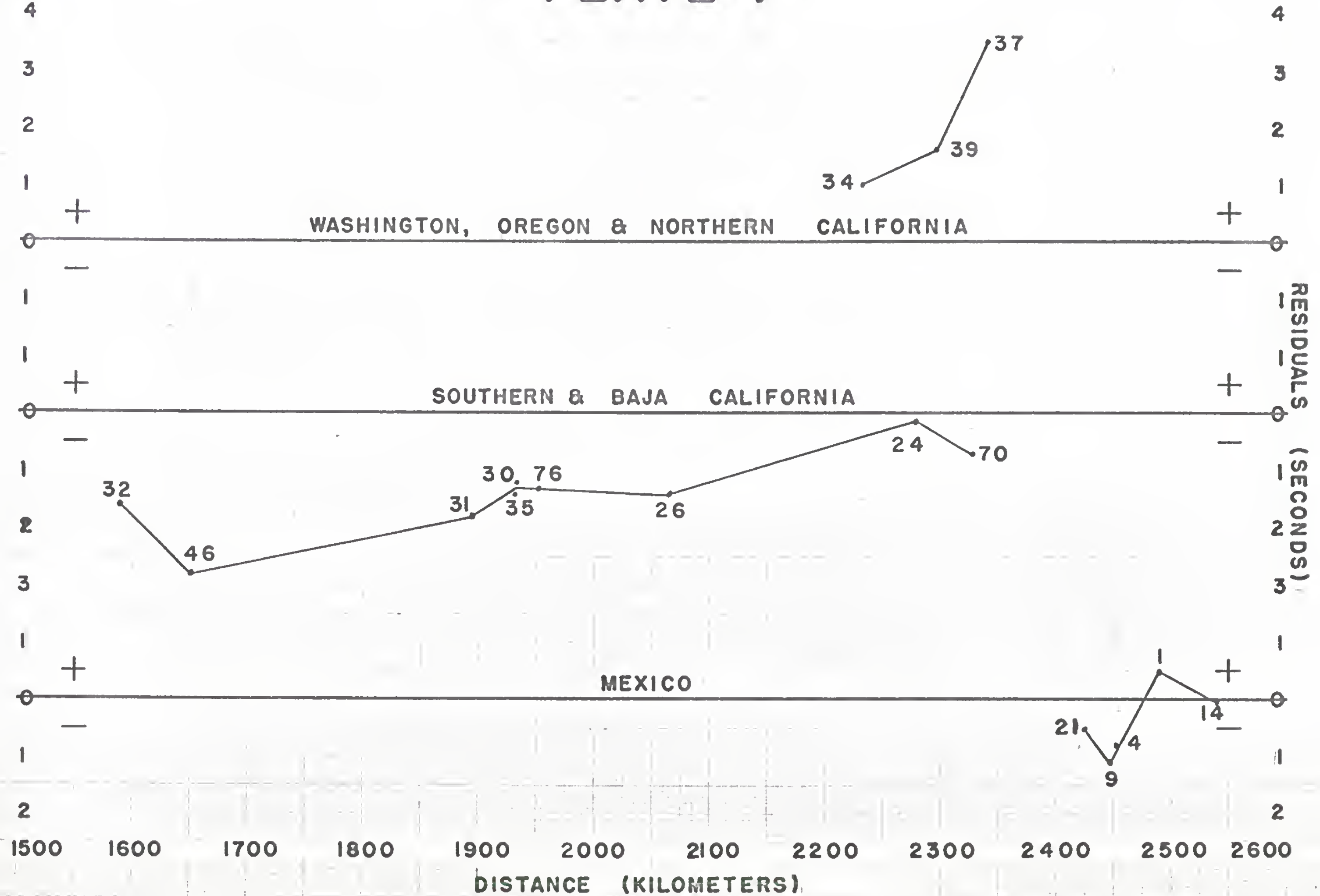


120
110
100
90
34
39
32
43
37
44
25
28
40
70
33
42
MANHATTAN
40
27
30
46
24
36
31
23
76
41
30
26
30
35
20
20
9
21
1
4
14
SCALE
200
600
0
400
KILOMETERS
110
100
90

EXPLANATION OF PLATE V

Graphic plots of Pn Wave residuals versus epicentral distances for Washington, Oregon, Southern and Baja California, and Mexican located earthquakes.

PLATE V



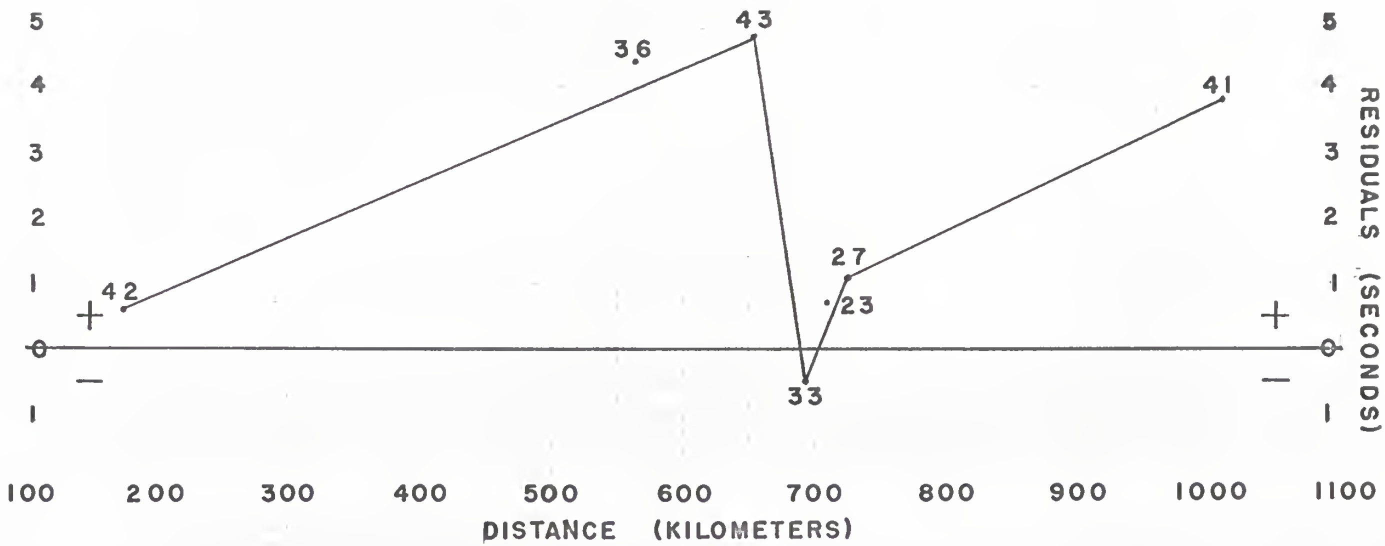
WASHINGTON, OREGON & NORTHERN CALIFORNIA
SOUTHERN & BAJA CALIFORNIA
MEXICO
RESIDUALS (SECONDS)
DISTANCE (KILOMETERS)
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
34
39
37
32
46
31
30
76
35
26
24
70
21
9
4
1
14

EXPLANATION OF PLATE VI

Graphic plot of Pn Wave residuals versus epicentral distances of Central United States earthquakes.

PLATE VI

CENTRAL UNITED STATES



are off coast and therefore subject to errors in preliminary determination.

The earthquakes from southern and Baja California all have negative residuals and range from -0.1 to -1.8 seconds slower than the standard comparsion times.

The actual travel times from the earthquakes located in Mexico agree quite closely to the Jeffreys-Bullen times, with only one reading being off as much as one second.

Earthquakes number 46 and 32 have negative residuals comparable to those from southern California.

The residuals for the rest of the earthquakes from shorter distances vary, but are all positive except for a -0.5 reading from Colorado.

Conclusion

The extremely accurate time control and very sensitive short-period Benioff seismometers insure that the observed residuals are significant, but the present data are not fully sufficient to determine the average deviation for a given area or make a final analysis of the cause. However, possible factors contributing to the variations can be examined.

First, the comparsion with the Manhattan times is a check of the Jeffreys-Bullen averages of observed travel times, to find any systematic geographic or geologic errors for the area studied. Further observations of this type will lead to the establishment of corrected local travel time tables.

The Pn wave, as mentioned before, is the primary wave which is refracted below the Mohorovicic discontinuity. As such, it is directly effected by the crustal layers only at the focus of the earthquake and as it approaches the recording station. Therefore most of the significant variations in Pn velocities would result from conditions in the upper mantle. Numerous authors have found variations in Pn velocities; notably Lehmann (1953) and Gutenberg (1954).

Gutenberg (1954), after several approaches to the problem, has made the hypothesis that in the outer 600 kilometers of the earth there are two low velocity layers, at 10-20 kilometers and another between 60-150 kilometers. The lower zone, called the asthenosphere by Gutenberg, has been established by various authors and many observations. Gutenberg attributes the low velocity to an increase in temperature at the depths of the asthenosphere that approaches the melting point, and therefore the effect of the increase in temperature with depth is not entirely compensated by the opposite effect of the increase in pressure. The abnormal increase in temperature would decrease the wave velocity in this channel while above and below the effect of an increase in pressure with depth would prevail, resulting in the normal increase in velocity.

The negative residuals found in this investigation from earthquakes in southern and Baja California agree with the one-two second late arrival times observed by Gutenberg. The concave travel route of Pn waves from distances of 2,000 kilometers reach a depth of approximately 200 kilometers and therefore would travel a good part of the time in the proposed asthenosphere.

The earthquakes studied from Mexico have very close agreement with the Jeffreys-Bullen travel times. A great part of the travel routes from these quakes is through areas of little recent tectonic activity and very possibly there is less heat flow associated with the area.

Less control for locating earthquakes in northern California and the northwest could account for some of the observed differences in this area.

The positive residuals that do exist can possibly be explained by deeper focus depths located below the Mohorovicic discontinuity.

An additional factor increasing the complexity of the problem is the varying depth of the Mohorovicic discontinuity. The Sierra Nevada root has been demonstrated to delay the arrival times of earthquake waves originating on one side and recorded on the other. The travel times observed here (# 30 & 31) were slower for those quakes located nearer to the root.

The travel times for the earthquakes from the Central United States vary as much as +4.8 seconds from the Jeffreys-Bullen tables. These differences result mainly from lack of control in this area and from systematic errors in the Jeffreys-Bullen tables for shorter distances.

The summary and conclusion of this thesis just begins to show the possible areas for further research with the equipment available at the Manhattan Seismograph Station. Study of many more travel times to build local travel time tables and detailed investigation of surface waves to explore the crustal structure are examples of possible future research.

APPENDIX I

Pn Wave Data

Pn Wave Data

Date	Area	Location λ	Øg	Øc	Emergence	Depth h	Distance Δ	Distance km	Travel Time
11 11 61	Colorado	106.1 W	38.9 N	38.7 N	ei	19	7.42	824.29	1 49.8
12 3 61	Mexico	99.3 W	17.9 N	17.8 N	ei	31	21.36	2372.88	4 49.3
12 10 61	GNOME	103.9 W	32.1 N	32.1 N	i	1084'	9.09	1009.81	2 11.6
12 22 61	California	126.0 W	40.7 N	40.5 N	ei	25	22.37	2485.08	5 04.9
12 25 61	Kansas	94.6 W	38.9 N	38.7 N	ei	25	1.58	175.52	0 26.1
12 25 61	Kansas	94.6 W	38.9 N	38.7 N	ei	25	1.58	175.52	0 26.3
12 31 61	South Dakota	100.5 W	44.4 N	44.2 N	i	16	5.90	655.43	1 33.9
12 31 61	Mexico	105.8 W	18.2 N	18.1 N	e	32	22.41	2489.53	5 02.3
2 2 62	Tennessee	89.4 W	36.3 N	36.1 N	i	25	6.38	708.75	1 34.2
2 26 62	California	115.1 W	27.4 N	27.2 N	e	25	19.46	2161.81	4 30.1
3 5 62	California	121.6 W	34.6 N	34.4 N	i	25	20.51	2278.46	4 39.0
3 5 62	California	125.1 W	40.3 N	40.1 N	ei	25	21.92	2435.09	4 57.0
3 27 62	Mexico	99.9 W	16.9 N	16.8 N	i	25	22.41	2489.53	4 57.6
3 28 62	Mexico	108.6 W	19.4 N	19.3 N	e	43	22.30	2477.31	4 58.0
4 14 62	California	125.1 W	40.3 N	40.1 N	i	25	21.92	2435.09	4 55.4
5 3 62	California	115.5 W	29.1 N	28.9 N	i	25	18.59	2065.16	4 18.9
5 11 62	Mexico	99.7 W	17.0 N	16.9 N	e	25	22.92	2476.20	4 55.6
5 19 62	Mexico	99.5 W	17.2 N	17.1 N	i	20	22.07	2451.75	4 56.2
5 27 62	California	115.6 W	31.7 N	31.5 N	e	25	17.19	1808.64	4 09.3
6 27 62	Illinois	88.5 W	37.7 N	37.5 N	i	25	6.52	724.30	1 35.8
7 6 62	SEDAN	116.0 W	37.2 N	37.0 N	e	630'	15.44	1715.23	3 36.3
7 14 62	California	124.4 W	40.3 N	40.1 N	i	25	21.39	2376.22	4 51.6
7 17 62	Mexico	92.9 W	14.8 N	14.7 N	i	120	24.52	2723.93	5 09.6
7 24 62	Mexico	92.5 W	15.5 N	15.4 N	i	129	25.25	2805.02	5 02.2
7 28 62	Mexico	93.0 W	14.8 N	14.7 N	i	71	24.51	2722.81	5 17.2
8 13 62	Mexico	93.0 W	14.6 N	14.5 N	ei	118	24.71	2745.03	5 10.9
8 20 62	California	114.1 W	31.1 N	30.9 N	e	14	16.43	1825.21	3 52.3
8 23 62	California	124.1 W	41.8 N	41.6 N	i	33	21.06	2339.56	4 40.0
8 28 62	Mexico	105.8 W	18.6 N	18.5 N	i	33	22.03	2447.31	4 54.3
8 30 62	Utah	111.8 W	41.8 N	41.6 N	ei	37	11.88	1319.75	2 49.6
9 4 62	California	124.0 W	41.0 N	40.8 N	e	48	19.35	2149.59	4 40.4

Pn Wave Data (cont.)

Date	Area	Location λ	Øg	Øc	Emergence	Depth h	Distance Δ	km	Travel Time
9 16 62	Mexico	103.1 W	19.3 N	19.2 N	i	100	20.62	2290.68	4 33.9
9 16 62	California	118.1 W	35.8 N	35.6 N	i	10	17.41	1934.08	4 05.8
10 19 62	Mexico	108.3 W	19.8 N	19.7 N	ei	53	19.26	2139.59	4 51.7
10 24 62	Mexico	108.2 W	19.4 N	19.3 N	e	33	22.15	2460.64	4 55.1
10 28 62	Mexico	93.6 W	16.0 N	15.9 N	i	33	23.26	2583.95	4 58.3
10 29 62	California	117.0 W	34.3 N	34.1 N	ei	33	17.07	1896.31	3 59.4
11 17 62	Mexico	98.2 W	16.3 N	16.2 N	i	12	22.86	2539.52	5 04.2
11 22 62	Mexico	92.7 W	14.3 N	14.2 N	e	33	25.03	2780.58	5 22.5
11 25 62	Mexico	94.2 W	16.3 N	16.2 N	i	100	24.08	2545.07	4 55.0
11 30 62	Mexico	99.6 W	17.4 N	17.3 N	i	51	21.88	2430.65	4 50.1
12 4 62	Colorado	104.7 W	39.8 N	39.6 N	e	33	6.31	700.98	1 34.7
12 5 62	Colorado	104.6 W	39.9 N	39.7 N	i	33	6.24	693.20	1 34.6
12 15 62	Nevada	117.5 W	40.7 N	40.5 N	ei	33	16.11	1789.66	3 50.9
12 31 62	Washington	122.0 W	47.1 N	46.9 N	i	33	20.10	2232.91	4 32.5
1 6 63	California	108.6 W	23.6 N	23.4 N	e	33	18.60	2066.27	4 17.5
1 20 63	California	110.7 W	26.4 N	26.2 N	ei	27	17.40	1932.97	4 04.4
1 27 63	California	115.7 W	31.6 N	31.4 N	e	33	17.32	1924.08	4 01.9
1 27 63	Idaho	114.5 W	44.3 N	44.1 N	i	31	14.31	1589.70	3 24.2
1 30 63	Colorado	104.6 W	39.8 N	39.6 N	e	33	6.24	693.20	1 40.0
2 25 63	Wyoming	109.0 W	42.8 N	42.6 N	e	33	9.44	1048.69	2 46.9
2 27 63	Mexico	100.5 W	16.9 N	16.8 N	e	33	22.48	2497.30	4 59.7
3 1 63	California	119.3 W	34.8 N	34.6 N	e	25	18.66	2072.94	4 22.6
3 1 63	Mexico	93.1 W	15.6 N	15.5 N	ei	33	23.71	2633.94	5 10.0
3 3 63	Missouri	90.1 W	36.7 N	36.5 N	i	18	5.08	564.34	1 12.9
3 7 63	Oregon	123.4 W	44.8 N	44.6 N	i	33	20.66	2072.94	4 37.8
3 11 63	Mexico	100.8 W	17.6 N	17.5 N	i	33	21.83	2425.09	4 51.7
3 25 63	Nevada	114.9 W	36.0 N	35.8 N	ei	33	14.87	1651.91	3 32.3
4 8 63	Colorado	104.9 W	39.6 N	39.4 N	e	33	6.46	717.64	1 55.7
5 22 63	California	123.1 W	37.0 N	36.8 N	ei	14	20.96	2328.45	4 45.8
5 23 63	California	115.3 W	32.5 N	32.3 N	e	14	16.57	1840.76	3 52.4
6 11 63	California	116.2 W	31.8 N	31.6 N	i	33	17.58	1952.96	4 05.2

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A SEISMOGRAPHIC STUDY OF MID-CONTINENTAL PRIMARY WAVE TRAVEL TIMES

by

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B. S., Kansas State University, 1961

AN ABSTRACT OF THE THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology and Geography

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1964

The purpose of this thesis was to conduct a seismographic study of mid-continental primary wave travel times. The research was made possible thru the VELA UNIFORM program.

Project VELA UNIFORM was developed by the United States Department of Defense to determine the requirements of a network of seismograph stations, needed for reliable detection of underground nuclear explosions. Saint Louis University as one of the participating agencies in VELA UNIFORM established a quadrilateral network of seismograph stations, located in Rolla, Missouri; Dubuque, Iowa; Bloomington, Indiana; and Manhattan, Kansas. The purpose of the network was to study the effect of mid-continental geologic structure on long period surface waves and to gather data on secondary waves. The network stations send their seismic records to St. Louis for processing.

The Manhattan Seismograph Station began operation September 4, 1961. The station has three Sprengnether long-period and three Benioff short-period seismometers to record all phases of earthquake ground motion. Equipment for recording the ground motion and developing the recording film are also housed in the station.

Numerous earthquakes from the United States and Mexico, which have entirely continental travel routes, are recorded at the Manhattan station. It was proposed to compare the primary wave travel times of these earthquakes with standard comparsion tables. Residuals, or differences between the actual and comparsion travel times, were found to exist.

The travel times from selected earthquakes in Mexico were found to agree quite closely to the standard comparsion travel times. Earthquakes from Washington, Oregon, and northern California had travel times that were faster than those of the comparsion tables. The travel times from southern and

Baja California were greater than the comparsion times. Significant deviations from the comparsion times would indicate geological variations of the upper mantle.