UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 14

PRELIMINARY REPORT ON SEISMIC-REFRACTION STUDIES OF CRUSTAL STRUCTURE IN THE WESTERN, CENTRAL, AND SOUTHERN UNITED STATES*

by

J. C. Roller**, O. P. Strozier***,
W. H. Jackson**, and J. H. Healy**

DENVER, COLORADO

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DEPARTMENT OF THE INTERIOR
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Technical Letter
Crustal Studies-14
December 2, 1963

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defense
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

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by

J. C. Roller**, O. P. Strozier***,
W. H. Jackson**, and J. H. Healy**

This is a report on field work and preliminary results for our 1963 field season.

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.
*** United ElectroDynamics, Inc., Pasadena, California.

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Report on 1963 Field Season

Prepared by

United States Geological Survey

Department of the Interior

for

VELA UNIFORM

Advanced Research Projects Agency

Department of Defense

under

ARPA Order No. 193-63

Project Code No. 8100

* U. S. Geological Survey, Denver, Colorado.
** United ElectroDynamics, Inc., Pasadena, California.

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CONTENTS

CONTENTS (continued)

ILLUSTRATIONS

TABLES

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-14
December 2, 1963

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ABSTRACT

During 1963 the U. S. Geological Survey, with the assistance of United ElectroDynamics, Inc., recorded five separate reversed seismic profiles. In addition to these profiles, the U. S. Geological Survey participated in a seismic-calibration program for the DRIBBLE experiment at Tatum Dome, Mississippi, a 20,000-pound shot near Dexter, Missouri, and in a cooperative seismic experiment in the Lake Superior region. This work is a continuation of the program started in 1961; however, the emphasis has shifted from a detailed study of the earth's crust in the western United States to a study of crustal structure in various geologic environments including the Wyoming thrust belt, Colorado Plateaus, Central Lowlands, the Gulf Coastal Plain, and the southern part of the Canadian Shield. The U. S. Geological Survey has now completed reversed seismic-refraction profiles in nine different geologic provinces.

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*** United ElectroDynamics, Inc., Pasadena, California.

These data present a promising indication that it may be possible to predict the crustal structure in unexplored areas by considering the regional geologic and physiographic environment.

The following P_n velocities have been determined: 8.2 km/sec in the Wyoming thrust belt, 7.9 km/sec in the Colorado Plateaus, 8.1 km/sec in the Central Lowlands, and about 8.2 km/sec in the Gulf Coastal Plain. The data from the Lake Superior region have not yet been interpreted.

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INTRODUCTION

The U. S. Geological Survey has conducted, on behalf of VELA UNIFORM, three major field programs to study seismic traveltimes and crustal structure in the United States. The first of these programs was conducted from August to November of 1961; the second program, during the summer of 1962; and the most recent program, between May 22 and June 28, 1963. This report is concerned primarily with operational procedures and preliminary results of the recent 6-week recording program. The U. S. Geological Survey has also, during the past year, conducted a 10-day recording program in the vicinity of the Tatum Dome, Mississippi, to provide seismic-calibration data for the DRIBBLE experiment, in cooperation with the Lawrence Radiation Laboratory and the U. S. Coast and Geodetic Survey.

After the first field program, it was decided that preliminary results should be reported within a reasonably short time after completion of the field work. It was thought that the necessity for

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making these results available to other ARPA groups warranted the incomplete interpretation that time limitations required. It was decided to limit the interpretation almost exclusively to a study of the first-arrival data on each of the recorded profiles. The first report appeared to give some assistance to ARPA and led to an orderly beginning of a more detailed and systematic study of the seismograms. Issuance of a preliminary report following the completion of a major field program was continued following the 1962 field season (Roller and others, 1963) and with the present report. The results presented in earlier reports have required only minor modifications as the interpretation progressed, but because of the preliminary nature of these interpretations, the reports have been classified FOR OFFICIAL USE ONLY. The work was accomplished with the assistance of United ElectroDynamics, Inc., under the direction of the United States Geological Survey, in accordance with U. S. Department of Interior Contract No. 14-08-0001-7634, dated June 29, 1961 (modified May 11, 1962, and May 17, 1963).

PROGRAM OBJECTIVES

The objectives of the Geological Survey's program of crustal studies have undergone a change in emphasis as the program has progressed. During the initial stages of the program, the main objective was to obtain data on seismic traveltimes and the variations of traveltimes in different geologic environments. Accordingly, the first field program was conducted in the complex geologic setting of

California and Nevada, even though it was realized that it might be extremely difficult to interpret the data in terms of crustal structure. The first field season's work met the objective of determining the amount of variation in seismic traveltimes, and provided considerable information on the crustal structure of the region. In the second field season, more emphasis was placed on learning the details of crustal structure and on sampling additional geologic provinces. This second year of study provided detailed information on the crustal structures that had been investigated during the first season's work, and demonstrated that there were major changes in crustal structure and in mantle velocities between geologic provinces.

The emphasis in the third season's work, which is discussed in this report, was to sample crustal structure in a number of different geologic provinces. Knowledge of crustal structure and mantle velocity as related to the nature of geologic provinces could lead to an analog method for predicting crustal structure and mantle velocity in parts of the world that are not accessible for study. Regions sampled were the Colorado Plateaus, the Wyoming thrust belt, the Central Lowlands, the Gulf Coastal Plain, and the southern part of the Canadian Shield. There are, of course, many objectives that this program of study has attempted to meet. A detailed discussion of objectives is not appropriate here, but the reader is referred to the references at the end of this report. These include all published and unclassified administrative reports based on this work.

ROLE OF THE CONTRACTOR

Because the U. S. Geological Survey wished to avoid an excessive expansion in staff for a limited field program, and because it was realized that a major geophysical contract company could bring valuable experience and knowledge to the crustal-studies program, it was decided to seek the assistance of a contractor. A contract was negotiated with United ElectroDynamics, Inc., (UED) prior to the first field season, and UED has participated in each of the major field programs. The assistance of UED in this program has allowed a rate of progress that would not have been possible with the small U. S. Geological Survey staff engaged in crustal studies. UED has provided observers and junior observers to operate five of the ten recording trucks; in addition, they were primarily responsible for scouting and locating shotpoints, obtaining shooting and access permits, insurance coverage, shot-hole drilling, shotpoint management, surveying, supplying and loading explosive charges, transportation, and many miscellaneous tasks necessary to maintain the uninterrupted progress of the field program. The combined operation of a government agency and a private contractor presented some unusual management problems which we feel have been solved in an unusual and interesting management structure. The overall administration and operational policies were established by the Chief, Branch of Crustal Studies, U. S. Geological Survey, under whose direction there was established an integrated management structure (Fig. 1).

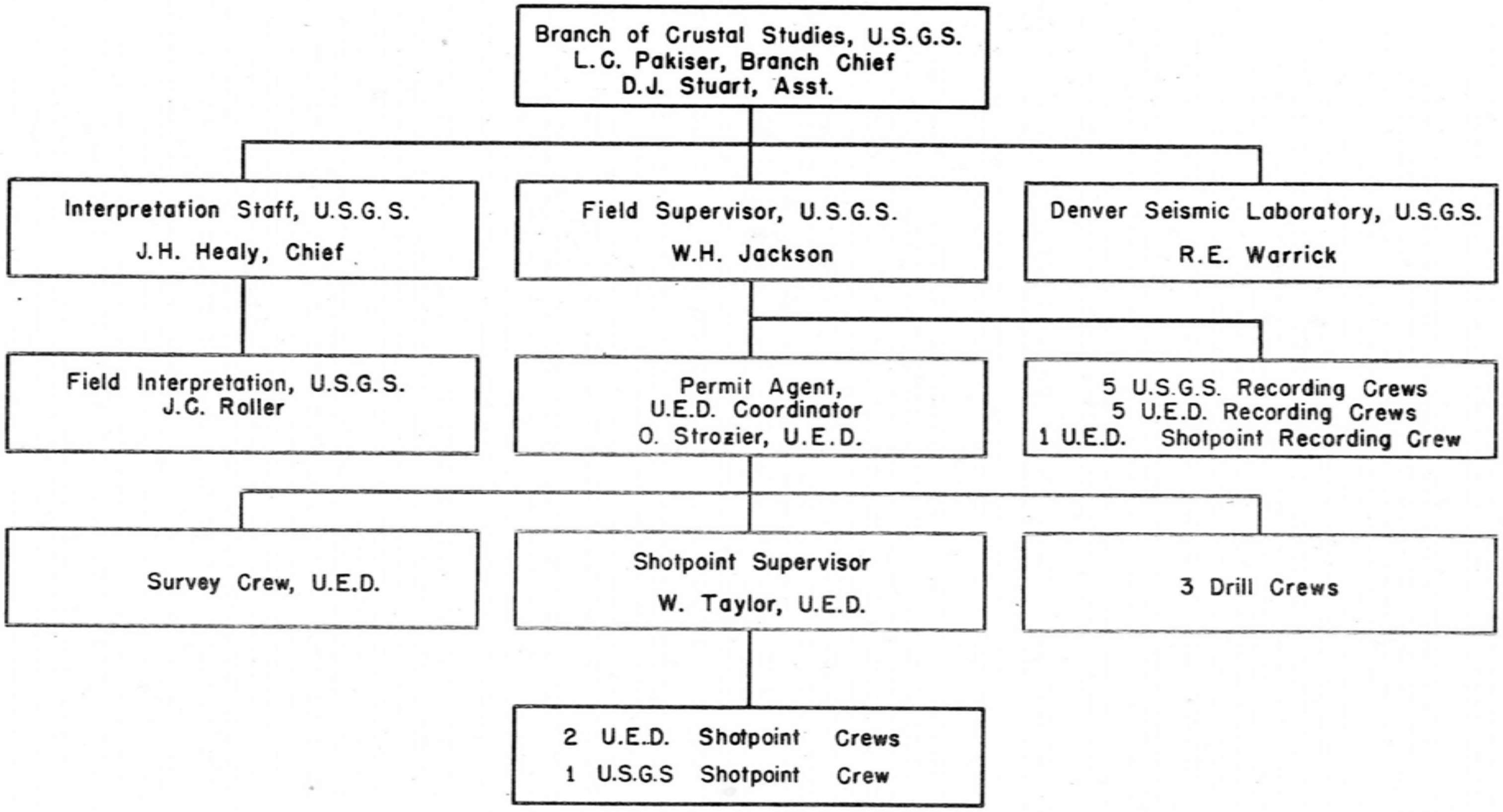

Figure 1.--Field-organization chart

SHOOTING AND RECORDING

During the period from May 22 to June 28, 1963, seismic-traveltime curves were obtained along 5 separate profiles ranging in length from 290 to 880 km (Fig. 2).

Shotpoints were located at the ends of the profiles and at intervals of 150 to 200 km between the end points. Charge sizes ranged from 1,000 lbs to 10,000 lbs of chemical explosives. A special 20,000-lb shot, designated BILLIKEN, was detonated near Dexter, Missouri, as a cooperative experiment of St. Louis University, Stanford Research Institute, and the U. S. Geological Survey.

Wherever possible, charges were detonated in lakes or rivers because of the increased energy transfer compared to drill holes. Three shotpoints were located in lakes and three in the Mississippi River. Seismic waves generated by the shots were recorded by 10 recording trucks located at approximately 10- to 12-km intervals along the profiles. The general scope of the crustal-recording program is summarized in Table 1.

PERMITTING

After the selection of a general area, a physical examination of specific locations was made to determine the most suitable site for a shotpoint, and arrangements were then made formally to permit the site chosen.

Most of the shotpoints were located in areas under the control of one or more government agencies who supplied special use permits for the work. Two shotpoints, BILLIKEN and St. Joseph, were on privately owned land and permission to use each of these sites was obtained from the land owners. All permits were obtained without charge.

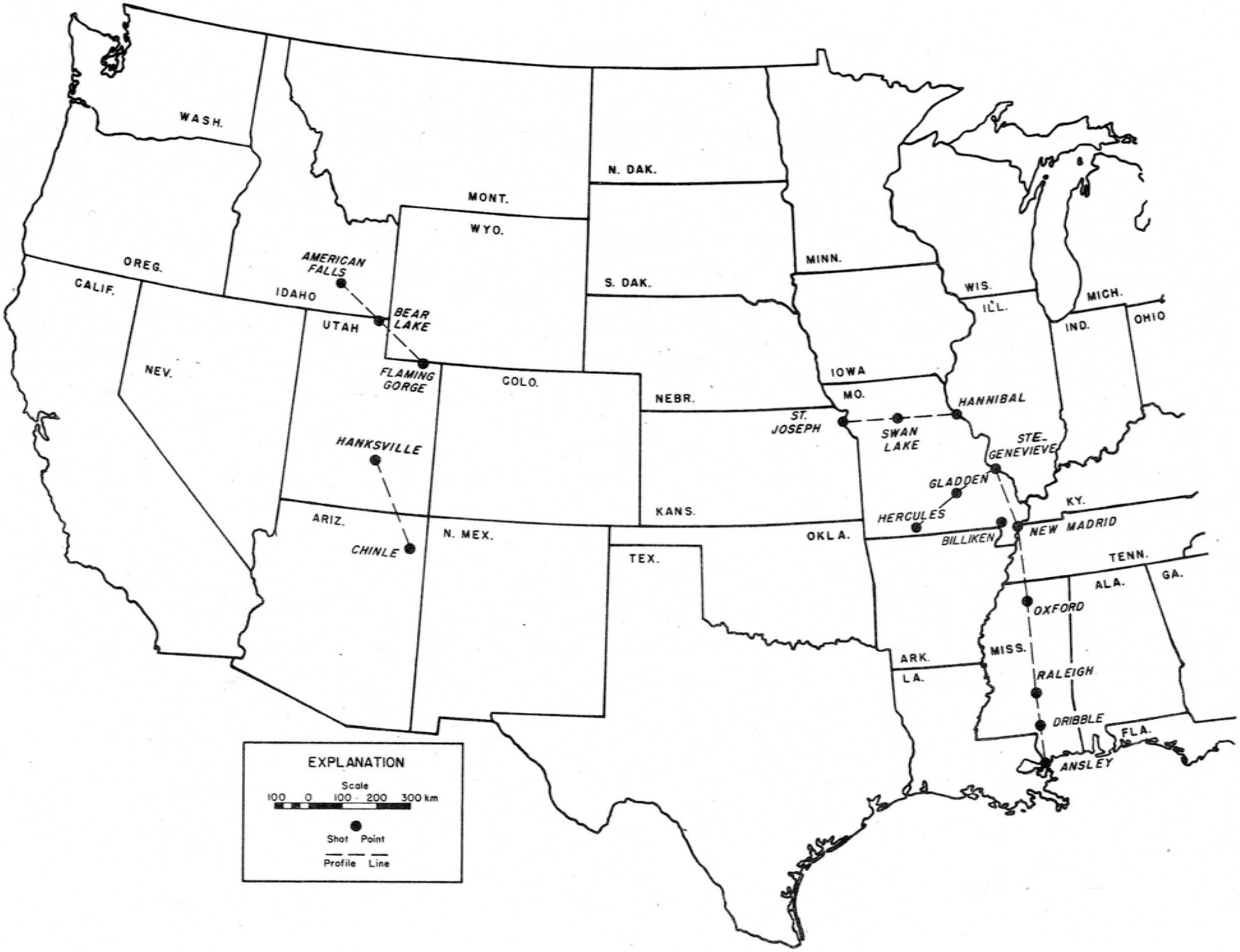

Figure 2.--Shotpoint Index Map

Table 1.--Summary of Crustal-Recording Program

Number of River Shotpoints	3
Number of Lake or Reservoir Shotpoints	3
Number of Drilled-Hole Shotpoints	10
Number of Production Days (including 6 move days)	30
Number of Shots (including two shots at DRIBBLE)	54
Number of Seismograms Recorded	543
Number of Kilometers of Profile Coverage	2,144
Total Footage Drilled	13,440
Number of Holes Drilled	79
Number of Bits Used	41 Rock Bits
	16 sets Blades
Drilling Mud Used (pounds)	4,750
Primary Explosive Used: Nitramon WW	95,350 lbs.
Super Tovex Gel	140,520 lbs.
Primers Used: EL - 637	272
HDP - 1	254
Number of WW Boosters Used	276
Number of Detonators Used	540
Number of Vehicles on Project	31
Approximate Total Vehicular Miles	330,000

Permitting of shotpoints started one month before field operations and continued essentially to the end of the program.

Table 2 is a list of shotpoints and the agencies and individuals from whom the permits were obtained.

DRILLING

Shot-hole drilling was done by two-man teams (driller and helper) using truck-mounted Failing or Mayhew drills equipped for either air or water drilling. Each drill was accompanied by a 1000-gallon water truck for use when air drilling was not feasible.

Ten shotpoints required drill holes (Table 3).

Six-inch holes were selected as an optimum size. Hole depths were nominally 200 ft, but ranged from 120 to 250 ft, depending primarily on charge size, tamping requirements, and on the shotpoint medium. A brief discussion of the drilling conditions at each of the shotpoint locations is given below:

1. Ansley. Holes were water-drilled to a depth of 200 ft in a delta deposit consisting mainly of sands and clays, the clay generally overlying the deeper sand section. Drilling was not difficult.
2. Chinle. Holes were water-drilled to a depth of 200 ft in shale with sandstone ledges below 100 ft. Drilling was not difficult.
3. BILLIKEN. A total of 10 holes were drilled to a depth of 120 ft to a contact between water-saturated sand and a coal seam of unknown thickness. Heavy drilling mud was necessary to keep

Table 2.--Shotpoint Permits

Shotpoint	Agency, and/or Individual Contacted
American Falls, Idaho	Mr. Robert L. Salter, Asst. Director Idaho Department of Fish and Game Boise, Idaho
	Mr. M. B. Austin, Regional Director Bureau of Reclamation Boise, Idaho
Ansley, Mississippi	Mr. Noble Mustin, Real Estate Division U. S. Army Engineer District, Mobile Mobile, Alabama
Bear Lake, Utah	Mr. Harold S. Crane, Director Utah Department of Fish and Game Salt Lake City, Utah
	Mr. Robert L. Salter, Asst. Director Idaho Department of Fish and Game Boise, Idaho
Chinle, Arizona	Mr. Nelson Damon, Acting Chairman Navajo Tribal Council Window Rock, Arizona
Billiken, Missouri	Mr. W. F. Webb, Land Owner 324 East Vine Street Dexter, Missouri
Flaming Gorge, Utah	Mr. B. P. Bellport, Chief Engineer Bureau of Reclamation Denver, Colorado
	Mr. Harold S. Crane, Director Utah Department of Fish and Game Salt Lake City, Utah
	Mr. Andy McComkie, Forest Supervisor U. S. Forest Service Vernal, Utah
Gladden, Missouri	Mr. C. L. Harrison, Forest Supervisor Clark National Forest, U. S. Forest Service Rolla, Missouri

Table 2.--Shotpoint Permits (continued)

Shotpoint	Agency, and/or Individual Contacted
	Mr. Maurice Christensen, District Ranger U. S. Forest Service, Salem District Salem, Missouri
Hanksville, Utah	Mr. Robert C. Krumm, District Manager Bureau of Land Management Richfield, Utah
Hannibal, Missouri	Lt. Col. H. B. Barke, Acting District Engineer U. S. Army Engineer District, St. Louis St. Louis, Missouri
	Cmdr. S. C. Putzke, Chief, Aids to Navigation U. S. Coast Guard District, St. Louis St. Louis, Missouri
	Mr. William T. Lodge, Director Illinois Department of Conservation Springfield, Illinois
	Mr. William E. Towell, Director Missouri Conservation Commission Jefferson City, Missouri
Hercules, Missouri	Mr. Henry W. DeBruin, Forest Supervisor Mark Twain National Forest U. S. Forest Service Springfield, Missouri
	Mr. Bruce Elliott, District Manager U. S. Forest Service, Ava District Ava, Missouri
New Madrid, Missouri	Capt. James F. Miley, Deputy District Engineer U. S. Army Engineer District, Memphis Memphis, Tennessee
	Mr. William E. Towell, Director Missouri Conservation Commission Jefferson City, Missouri

Table 2.--Shotpoint Permits (continued)

Shotpoint	Agency, and/or Individual Contacted
	Director, Tennessee Game and Fish Commission Nashville, Tennessee
	Comdr. S. G. Putzke, Chief-Aids to Navigation U. S. Coast Guard District, St. Louis St. Louis, Missouri
Oxford, Mississippi	Mr. J. L. Roselle, Chief-Real Estate Division U. S. Army Engineer District, Vicksburg Vicksburg, Mississippi
	Mr. James McBroom, Reservoir Superintendent Sardis Reservoir Area Sardis, Mississippi
Raleigh, Mississippi	Mr. J. E. Franson, Forest Supervisor Bienville National Forest U. S. Forest Service Jackson, Mississippi
	Mr. Ralph A. Jacobson, District Ranger U. S. Forest Service, Strong River District Raleigh, Mississippi
Ste. Genevieve, Missouri and Illinois	Lt. Col. H. B. Barke, Acting District Engineer U. S. Army Engineer District, St. Louis St. Louis, Missouri
	Cmdr. S. G. Putzke, Chief-Aids to Navigation U. S. Coast Guard District, St. Louis St. Louis, Missouri
	Mr. William T. Lodge, Director Illinois Department of Conservation Springfield, Illinois
	Mr. William E. Towell, Director Missouri Conservation Commission Jefferson City, Missouri
St. Joseph, Missouri	Mr. Lewis Sonnenmoser, Land Owner Rushville, Missouri

Table 2,--Shotpoint Permits (continued)

Shotpoint	Agency, and/or Individual Contacted
Swan Lake, Missouri	Mr. W. A. Elkins, Acting Regional Director U. S. Fish and Wildlife Service Minneapolis, Minnesota
	Mr. Leo Kirsch, Refuge Manager Swan Lake Natural Wildlife Refuge Sumner, Missouri

Table 3.--Shotpoint Locations

Shotpoint	Location	Latitude	Longitude
*American Falls, 1,2	American Falls Reservoir, Idaho	42°50.14'	112°48.66'
*American Falls, 3,4	American Falls Reservoir, Idaho	42°51.40'	112°47.68'
**Ansley	Ansley, Mississippi	30°16.02'	89°30.61'
*Bear Lake	Bear Lake, Utah	41°56.35'	111°17.10'
**Chinle	Chinle, Arizona	35°55.64'	109°34.44'
**BILLIKEN	Dexter, Missouri	36°43.00'	90°07.62'
*Flaming Gorge	Flaming Gorge Reservoir, Utah	40°56.77'	109°38.43'
**Gladden	Salem, Missouri	37°29.54'	91°20.58'
**Hanksville	Hanksville, Utah	38°21.99'	110°55.64'
*Hannibal	Mississippi River (near Hannibal, Missouri)	39°34.09'	91°10.71'
**Hercules	Bradleyville, Missouri	36°41.81'	92°54.12'
*New Madrid	Mississippi River (near Portageville, Missouri)	36°26.36'	89°33.13'
**Oxford	Oxford, Mississippi	34°33.28'	89°31.97'
**Raleigh	Raleigh, Mississippi	32°04.46'	89°36.11'
*Ste. Genevieve	Mississippi River (near Ste. Genevieve, Missouri)	38°00.40'	90°03.08'
**St. Joseph	Rushville, Missouri	39°36.68'	95°02.78'
**Swan Lake	Sumner, Missouri	39°36.16'	93°11.89'

* Water shotpoint
** Drilled-hole shotpoint

the hole walls from collapsing. A cavity was intentionally washed-out at the sand-coal contact. Drilling was not difficult, but lost circulation and hole-wall collapse were constant problems.

4. <u>Gladden</u>. Holes were air-drilled to a depth of 200 ft. The top 110 ft consisted of sand, gravel stringers, clay, and shale, underlain by 90 ft of dolomite. These holes were moderately difficult to drill, requiring rock bits for the dolomite section.

5. <u>Hanksville</u>. Holes were air-drilled to a depth of 200 ft in Mancos shale, with sandstone ledges below 100 ft. Drilling was not difficult, although soft-formation rock bits were required to drill the shale as well as the sandstone ledges.

6. <u>Hercules</u>. Holes were initially air-drilled to a depth of 200 ft. Holes that were required for an additional shot were drilled to a depth of 170 ft to reduce the time required for drilling. The holes were in hard limestone and dolomite from the surface to total depth and numerous rock bits were required to complete the total number of holes required. Average drilling time per 200 ft of hole was in excess of 24 hours. Of all shotpoints, this location was the most difficult to drill.

7. <u>Oxford</u>. Holes were water-drilled to a depth of 200 ft in a formation consisting of sand and clay. The holes were partially blind and required the use of drilling mud. Holes were moderately difficult to drill.

8. <u>Raleigh</u>. Holes were water-drilled to a depth of 200 ft in a formation consisting of sand and clay. Drilling was not difficult.

9. St. Joseph. Holes were water-drilled to a depth of 120 ft in water-saturated sand. Cavities were intentionally created at this depth by continuous circulation and washing. Drilling was not difficult.

10. Swan Lake. Holes were water-drilled to a depth of 120 ft. The section was clay to a depth of 10 ft, underlain by a water-saturated sand in which cavities were intentionally created by continuous circulation and washing. Although drilling mud was not required, drilling was moderately difficult.

SHOTPOINT OPERATIONS

Explosives were loaded by two-man teams consisting of a shotpoint manager and an experienced shooter. The charges were fired automatically with an S.I.E., Model SCD 2000 BA blaster, which was activated by a chronometer at a pre-selected time. For safety control, the shooter was stationed at a position which afforded an unobstructed view of the entire shotpoint area. The spring-loaded safety switch on the blaster was held by hand in the "shoot" position until the detonation occurred. This allowed the shooter to open the circuit and stop the shot at any moment preceding the actual detonation.

Charges larger than 2000 lbs were fired in patterns; individual holes being separated at distances to provide partial surface-wave cancellation to minimize damage risk to surface installations.

Generally, charges of 2000 lbs were loaded in each hole. Caps and primers were placed at the bottom, middle, and top of each charge to ensure proper detonation.

Pattern shots were used at water shot points. The size of the individual charge and the spacing between the charges was dependent on the water depth at the shotpoints. Data collected from previous season's operations were used as a guide in selecting the optimum charge size and spacing to avoid venting of the explosions.

DuPont Nitramon WW in 50-lb cans was used for all water shots. These shots were detonated with DuPont EL-637 primers, WW boosters, and static-resistant electric blasting caps.

DuPont "Tovex-Gel" and "Super Tovex-Gel" was used for drilled-hole locations. Both Tovex-Gel and Super Tovex-Gel are slurry-type explosives; Super Tovex-Gel has a higher density. This explosive was selected because it completely fills the hole, improving shot-hole efficiency, and minimizes the depth of hole necessary to contain the charge. These charges were detonated with DuPont HDP-1 primers and static-resistant electric blasting caps.

Areas around most of the drilled-hole shotpoints required considerable renovation after the shooting had been completed. Large surface craters resulted at several of the holes where the charge had not been fully contained, and at others, small mounds or sinks were formed. Where necessary, bulldozers and loads of gravel, were used to restore the areas as nearly as possible to their former condition. The responsible agency or individual who gave permission to use the land usually made an inspection after renovation to ensure satisfactory restoration.

SHOTPOINT REFRACTION-PROFILING

Near-surface refraction data were obtained at 6 shotpoints: American Falls, BILLIKEN, Gladden, Hanksville, Oxford, and Swan Lake. A total of 18 spreads were recorded at these 6 locations.

Twelve seismic traces and 2 timing traces were recorded by a Texas Instruments Company 7000-B recording unit. A spread length of 2.75 km with a geophone spacing of 250 meters (one Hall-Sears 4.5 cycle geophone per trace) was used. Spreads were laid out in as straight a line from the shotpoint as practical, and one to three seismometer positions were overlapped so that common trace times would appear on records from successive shots. The overall coverage depended on the number of shots at each of the shotpoints.

Time-distance curves for the American Falls, Hanksville, and Oxford shotpoints are shown in Figures 3, 4, and 5, respectively.

SURVEYING

Surveying was limited to shotpoint locations and close-in recording-spread locations.

Survey traverses for the location of shotpoints were made by a UED survey crew, using a transit, metric stadia rod, and 50-meter chain. Short vertical and horizontal traverses were run to the

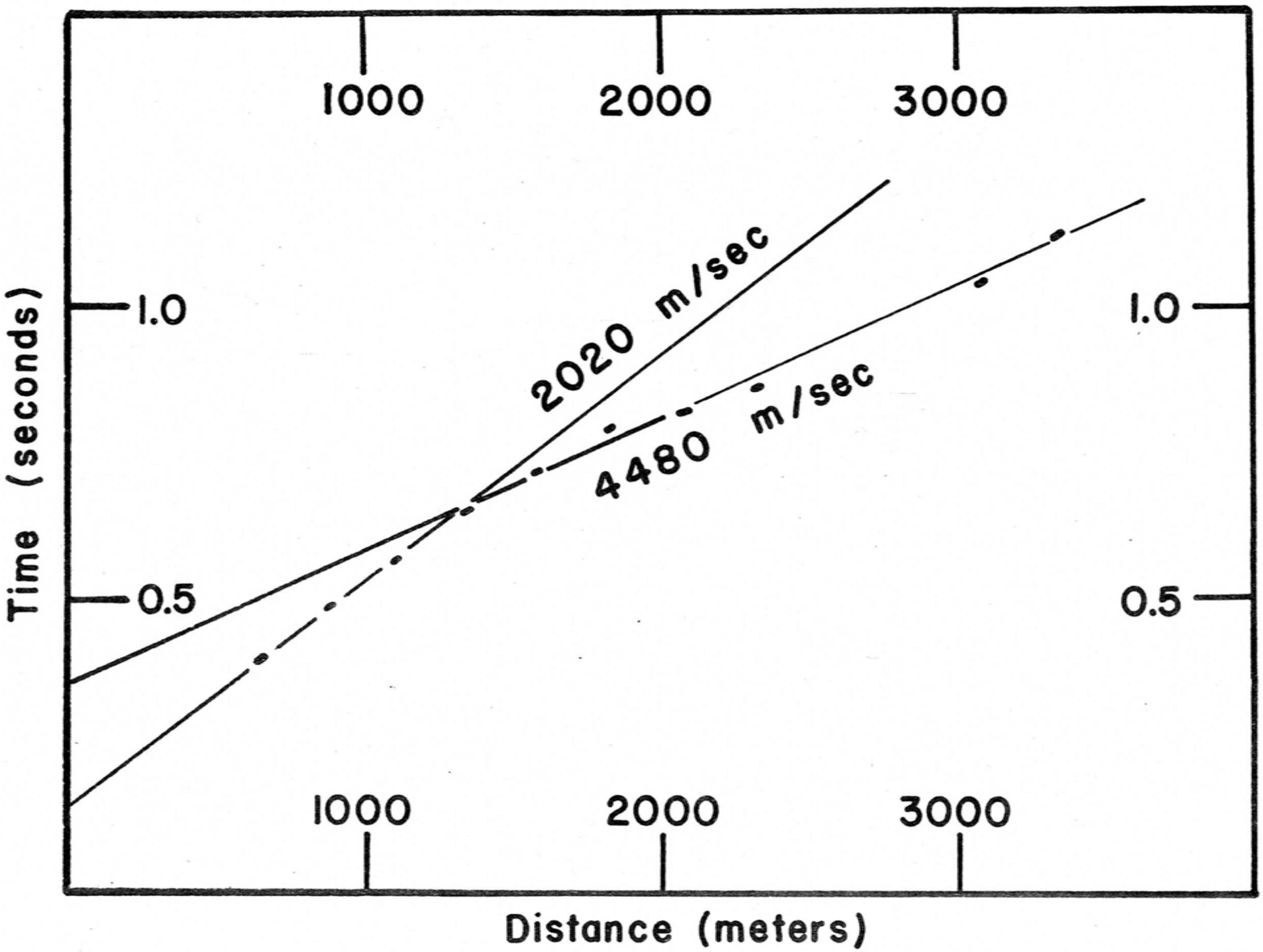

Figure 3.--Shotpoint refraction profile at American Falls Reservoir, Idaho

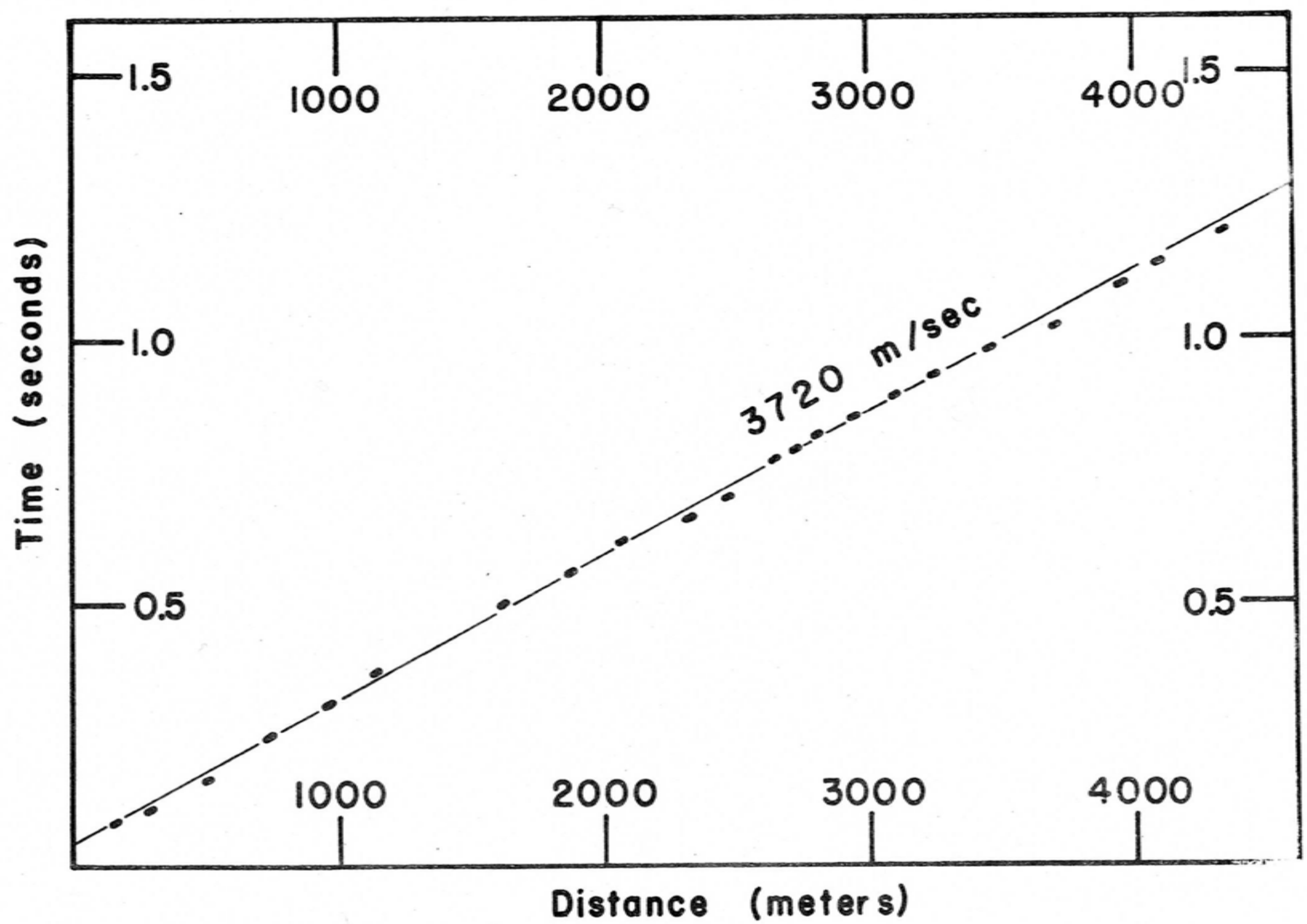

Figure 4.--Shotpoint refraction profile at Hanksville, Utah

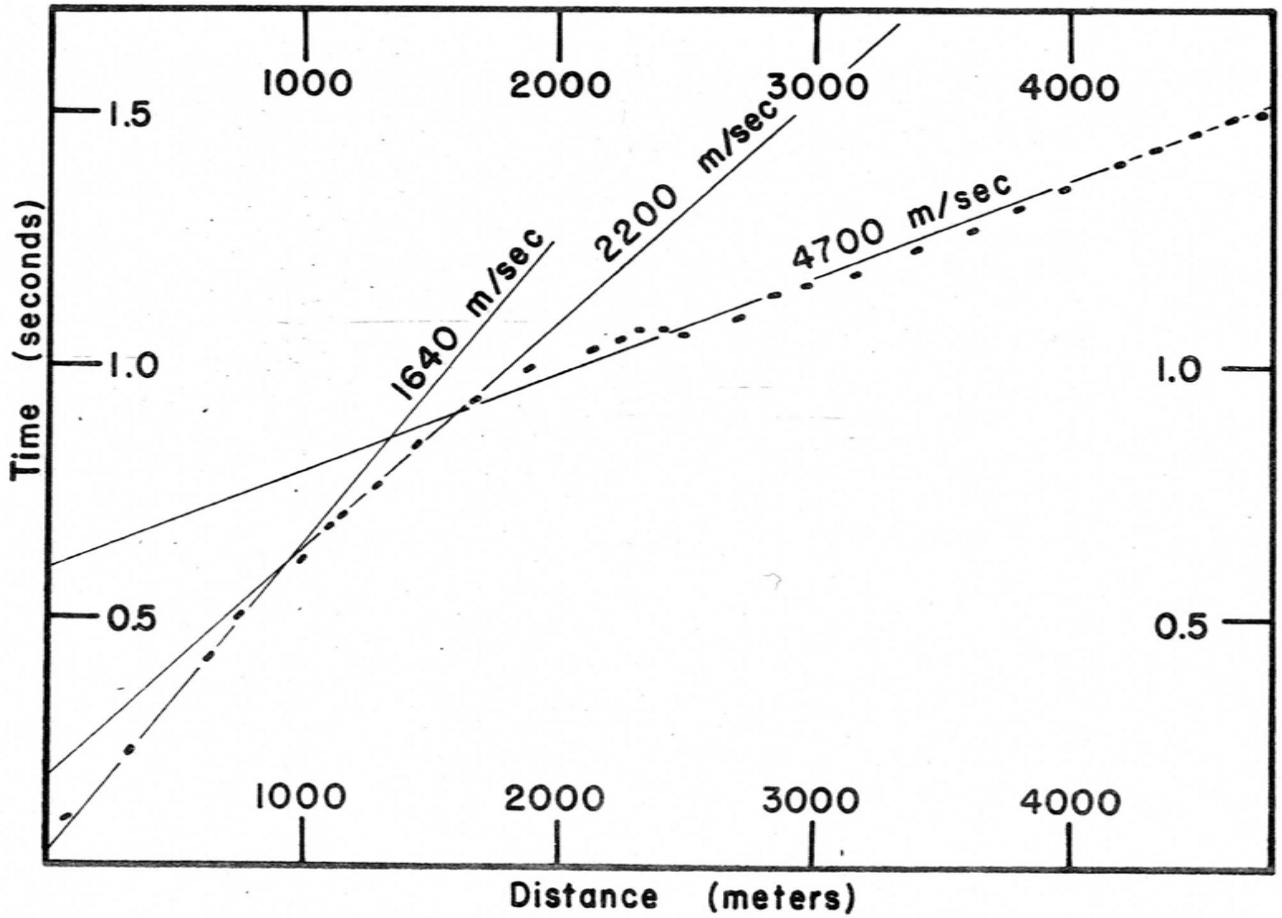

Figure 5.--Shotpoint refraction profile at Oxford, Mississippi

drilled-hole locations from benchmarks or triangulation stations. Similar traverses were run to establish flagged positions on the lakeshores and river banks, from which the marker buoys in the lake or river were located. Shotpoints were plotted on topographic sheets to determine their latitude and longitude.

Shotpoint-refraction-spread locations were surveyed by the UED survey crew. Individual geophone positions were surveyed and horizontal distances between the geophone positions were determined both by chaining and by reading stadia distances. Vertical and horizontal control for these spreads were tied to the shotpoints.

The accuracy of the surveyed locations of both the drilled-hole and the lake and river shotpoints was considered to be within the limits of accuracy of third-order surveying. However, the possibility of small error exists in locating the position of the charge relative to the buoys in the lakes and rivers. In many instances, the distance from charge to buoy could not be precisely determined due to current, wind, and rough water. In those instances, the error may be as great as 50 meters, owing to the movement of the boat during loading and the consequent dragging of the charge along the bottom of the lake or river.

Geographic locations of all shotpoints are shown in Table 3. Charge sizes and shot dates and times are listed in Table 4.

Table 4.--Shot Sizes, Dates, and Times

Shot Number	Date	Size	Time
Flaming Gorge 1	5-22-63	6,000	7:00:00.10 MST
Flaming Gorge 2	5-23-63	4,000	6:59:59.84 do
Flaming Gorge 3	5-24-63	2,000	7:09:59.79 do
Flaming Gorge 4	5-25-63	2,000	6:59:59.95 do
American Falls 1	5-22-63	2,000	8:00:00.12 do
American Falls 2	5-23-63	2,000	7:50:00.04 do
American Falls 3	5-24-63	4,000	8:59:59.02 do
American Falls 4	5-25-63	6,000	7:30:00.21 do
Bear Lake 1	5-22-63	4,000	8:30:00.35 do
Bear Lake 2	5-23-63	2,000	7:20:00.70 do
Bear Lake 3	5-24-63	2,000	7:30:00.19 do
Hanksville 1	5-27-63	1,000	7:20:00.31 do
Hanksville 2	5-27-63	2,000	10:30:00.31 do
Hanksville 3	5-28-63	2,000	7:20:00.26 do
Hanksville 4	5-29-63	10,000	6:59:59.72 do
Chinle 1	5-27-63	6,000	7:00:00.25 do
Chinle 2	5-28-63	4,000	7:00:00.05 do
Chinle 3	5-29-63	2,000	7:20:00.00 do
Chinle 4	5-30-63	2,000	7:00:00.41 do
Ste. Genevieve 1	6-7-63	2,000	8:00:00.02 EST
Ste. Genevieve 2	6-8-63	6,000	9:09:59.97 do
Ste. Genevieve 3	6-19-63	6,000	12:14:59.99 do
Ste. Genevieve 4	6-20-63	4,000	8:30:00.15 do
Ste. Genevieve 5	6-21-63	2,000	8:00:00.61 do
New Madrid 1	6-7-63	6,000	12:09:29.46 do
New Madrid 2	6-8-63	2,000	7:00:00.96 do
New Madrid 3	6-9-63	6,000	7:00:00.02 do
New Madrid 4	6-22-63	6,000	5:59:59.93 do
Oxford 1	6-8-63	6,000	7:40:00.97 do
Oxford 2	6-9-63	2,000	6:40:00.41 do
Oxford 3	6-11-63	6,000	5:40:00.34 do
Raleigh 5	6-10-63	6,000	4:59:59.93 do
Raleigh 6	6-11-63	3,000	5:59:59.96 do

Table 4.--Shot Sizes, Dates, and Times (continued)

Shot Number	Date	Size	Time
Ansley 3	6-12-63	8,000	5:00:03.11 EST
Hercules 1	6-19-63	2,000	5:20:00.18 do
Hercules 2	6-20-63	4,000	5:00:00.13 do
Hercules 3	6-21-63	6,000	5:00:00.15 do
Hercules 4	6-27-63	8,000	7:40:00.18 do
Gladden 1	6-19-63	4,000	6:34:59.96 do
Gladden 2	6-20-63	2,000	5:20:00.05 do
Gladden 3	6-21-63	4,000	5:20:01.42 do
St. Joseph 1	6-23-63	6,000	8:40:00.32 do
St. Joseph 2	6-24-63	4,000	5:00:00.10 do
St. Joseph 3	6-25-63	2,000	5:20:00.19 do
Swan Lake 1	6-23-63	4,000	5:20:00.25 do
Swan Lake 2	6-24-63	2,000	5:19:00.99 do
Swan Lake 3	6-25-63	4,000	5:00:00.07 do
Hannibal 1	6-23-63	2,000	5:39:59.95 do
Hannibal 2	6-24-63	4,000	5:40:00.10 do
Hannibal 3	6-25-63	8,000	5:39:59.97 do
BILLIKEN	6-28-63	20,000	5:00:00.13 do

CONCLUSIONS

During the 1963 field season, a large amount of data was collected. These data will help to fulfill many of the basic objectives of the crustal-studies program as related to a detection system.

The U. S. Geological Survey has now completed reversed seismic-refraction profiles in nine different geologic provinces. These data present a promising indication that it may be possible to predict seismic-wave traveltimes in unexplored regions by considering the regional geologic and physiographic environment, without an extensive geophysical program. Areas that have more recently been geologically active (e.g., the Basin and Range province) usually have a lower mantle velocity than areas that have been stable in relatively recent geologic time (e.g., the Central Lowlands and the Great Plains provinces of the United States or the lowlands and stable platforms of the U.S.S.R.).

Studies of the nature of seismic signals, such as first motion, attenuation with distance, frequency, and scatter can now be extended to include a wider variety of crustal models. Much of our work to date has been confined to the California-Nevada region. The study of one's ability to observe the direction of first motion of seismic energy, an important criterion in determining the nature of the source, can now be expanded to include different types and sizes of explosions in several geologic provinces. The attenuation of different seismic waves with distance in various geologic environment is related to these first-motion studies. From these data it may be possible to determine which waves will be the most useful in detecting seismic sources and in predicting their nature.

The efficiency of the shotpoints used during the 1963 field season ranged from excellent at American Falls, Idaho, to very poor at Oxford, Mississippi. Many of the poorer shotpoints generate more high-frequency seismic waves than do the more efficient shotpoints. A study is planned to determine if a correlation exists between the frequency spectrum of the first motion and the distance that first motion can be determined.

Random scatter in arrivals is caused by near-surface geology, and to a lesser extent by elevation changes. The scatter is much less in areas such as the Central Lowlands and Great Plains, where the surface geology is simple, than in areas such as the Basin and Range province, where surface geology is complex. Also, some of the scatter is related to inability to pick the first arrivals accurately.

TIME-DISTANCE PROFILES

The following sections of this report show the time-distance curves of the first arrivals recorded during the 1963 field season. The seismograms contain many secondary events which have not been evaluated at this time. The grading system used is the same as that of Healy and others (1962). Generally, only seismograms having first arrivals that can be timed with a reasonable degree of confidence have been used to construct the time-distance curves. The poor seismograms will be used at a later date to study secondary events, wave amplitudes, and background noise.

American Falls, Idaho, to Flaming Gorge, Utah.--This profile extends from American Falls Reservoir in Idaho southeastward to Flaming Gorge Reservoir in Utah. An intermediate shotpoint was located in Bear Lake near the Utah-Idaho border. All three of these shotpoints were efficient sources of seismic energy, and American Falls was one of the most efficient shotpoints used in the crustal-studies program to date.

In the distance range less than 200 km, the first-arrival times from American Falls on 12 fair-to-good seismograms can be fitted by a straight line indicating an apparent velocity for P_g of 6.20 km/sec (Fig. 6). The maximum deviation of the plotted times from this straight line is ± 0.4 sec. Between 200 km and 340 km, 13 fair seismograms define an arrival identified as P_n, which can be fit by a straight line with an apparent velocity of 8.20 km/sec. Most of the points fall within ± 0.5 sec of this line. One point 299 km from American Falls appears to be 0.8 sec early. This anomalous time may be caused by an error in location resulting from poor map control in this area.

The first-arrival times from Flaming Gorge can be approximated by three straight-line segments. Near the shotpoint an apparent velocity of 4.6 km/sec is defined by 3 arrivals of good quality. These events are interpreted as arrivals from a thick sedimentary section. Between 8 km and 195 km from the shotpoint, 13 seismograms of good-to-fair quality define an apparent velocity of 6.45 km/sec.

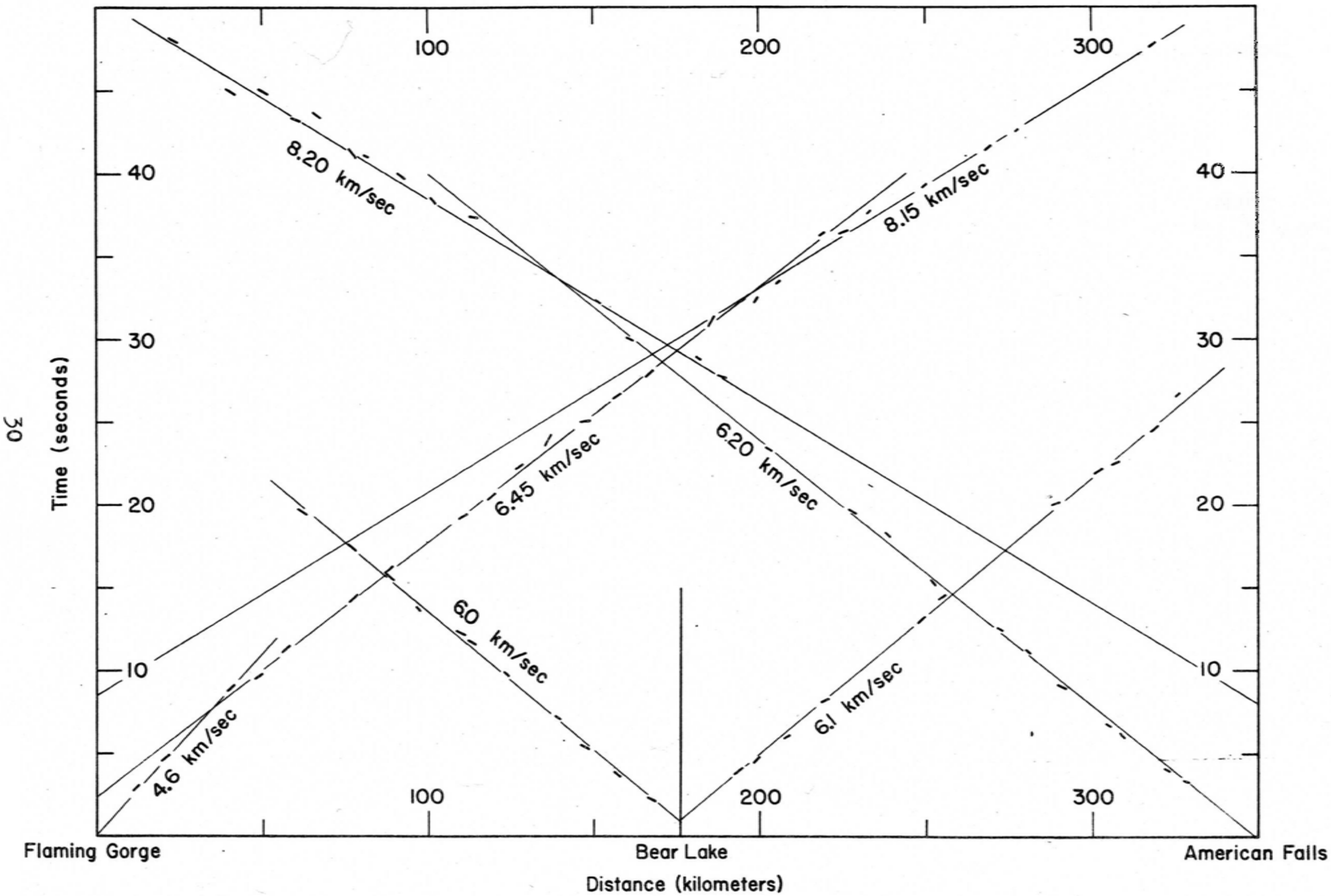

Figure 6.--Time-distance profile, American Falls, Idaho, to Flaming Gorge, Utah

This arrival is identified as P_g. The apparent velocity of P_g from Bear Lake is 6.0 km/sec. These velocities for P_g, together with the apparently-thick sedimentary section at Flaming Gorge, indicate a thinning sedimentary section between Flaming Gorge and Bear Lake. This interpretation suggests that the true velocity of P_g is 6.2 km/sec which compares with the 6.2 and 6.1 velocity of P_g recorded between American Falls and Bear Lake. In the distance range, 200 to 320 km, the first arrivals on 9 seismograms of poor-to-fair quality are identified as P_n with a velocity of 8.15 km/sec. Because of the large scatter in these data, this velocity could be in error by ± 0.2 km/sec.

An apparent velocity for P_g of 6.1 km/sec is defined northwest of Bear Lake by 11 fair-to-good seismograms. A 6.0 km/sec apparent velocity is indicated by 11 seismograms of fair-to-good quality recorded from Bear Lake to Flaming Gorge.

A true P_g velocity of 6.2 km/sec and a true P_n velocity of 8.2 km/sec are indicated for this region.

Hanksville, Utah, to Chinle, Arizona.--This profile extends northward from Chinle, Arizona, to a point 50 km beyond Hanksville, Utah, and is entirely within the Colorado Plateaus province. Shots at both the Hanksville and Chinle shotpoints generated relatively-weak seismic signals, but the unusually low background noise in this area made it possible to record these weak signals at distances sufficient to complete the profile.

An apparent velocity for P_g of 6.2 km/sec is defined by 23 seismograms of generally-fair quality between the Chinle shotpoint and a point 235 km toward Hanksville (Fig. 7). The time residuals are ± 0.3 sec. Beyond 235 km, 9 recordings of poor-to-fair arrivals are identified as P_n with a velocity of 7.8 km/sec.

Between Hanksville and a point 240 km toward Chinle, 15 seismograms of generally-fair quality record arrivals that are identified as P_g with an apparent velocity of 6.25 km/sec. Beyond 240 km, only 3 seismograms have recognizable first arrivals. These events are thought to be P_n arrivals but the data are too poor to estimate a reliable P_n velocity. Seismograms recorded on this profile contain coherent secondary arrivals that will help to delineate crustal structure and velocity in a more detailed analysis.

Ste. Genevieve, Missouri, to New Madrid, Missouri.--This is one of a long line of profiles that extends from a point in the Mississippi River near St. Louis, Missouri, to a point at Ansley, Mississippi, a short distance north of the Gulf of Mexico. High seismic-noise levels were a serious problem along the entire profile. Seismic noise produced signals from the seismometer that reached 100 microvolts at many of the recording locations. This noise level can be compared with those of 1 microvolt or less in the Colorado Plateaus profile. Some improvement in the signal-to-noise ratio was achieved by filtering and by firing the shots during the early morning hours when the noise caused by wind and human activity was at a minimum. The New Madrid and Ste. Genevieve

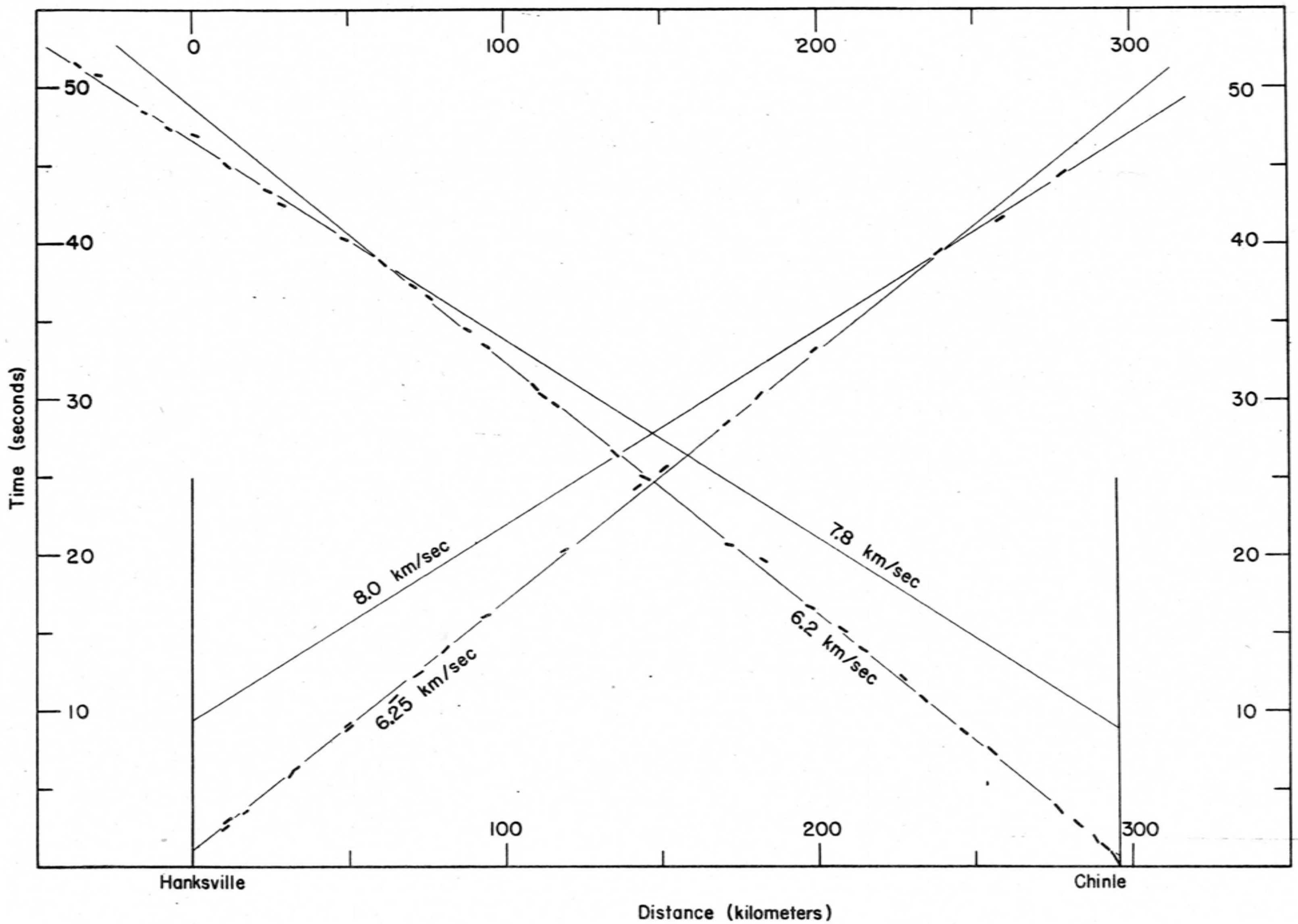

Figure 7.--Time-distance profile, Hanksville, Utah, to Chinle, Arizona

shotpoints were in the Mississippi River at depths of 50 and 25 feet, respectively. Both were considered to be average in shotpoint efficiency.

For shots at New Madrid, an apparent velocity for P_g of 6.3 km/sec is closely defined by 8 seismograms of fair-to-poor quality with time residuals on the straight-line fit usually less than ± 0.2 sec (Fig. 8). The P_n arrival recorded on 5 poor seismograms suggests a velocity of 8.3 km/sec.

For shots at Ste. Genevieve, an apparent velocity for P_g of 6.2 km/sec is defined by 8 seismograms of fair-to-poor quality. Arrivals of P_n recorded on 2 seismograms of poor quality suggest a velocity of 8.3 km/sec.

<u>New Madrid, Missouri, to Oxford, Mississippi</u>.--The shotpoint at Oxford was a very inefficient source of seismic energy. No recognizable seismic signals were recorded from this shotpoint beyond a point 25 km to the north, or a point 90 km to the south (Fig. 9). Charges were fired in water-saturated clay, that normally provides a good shooting medium.

An apparent velocity for P_g of 6.2 km/sec is defined by 5 fair-to-poor seismograms recorded from the New Madrid shotpoint toward the south. An arrival with an apparent velocity of 7.5 km/sec was recorded at distances beyond 160 km. This velocity is abnormally low for a P_n arrival and may represent dip on the M-discontinuity or arrivals from

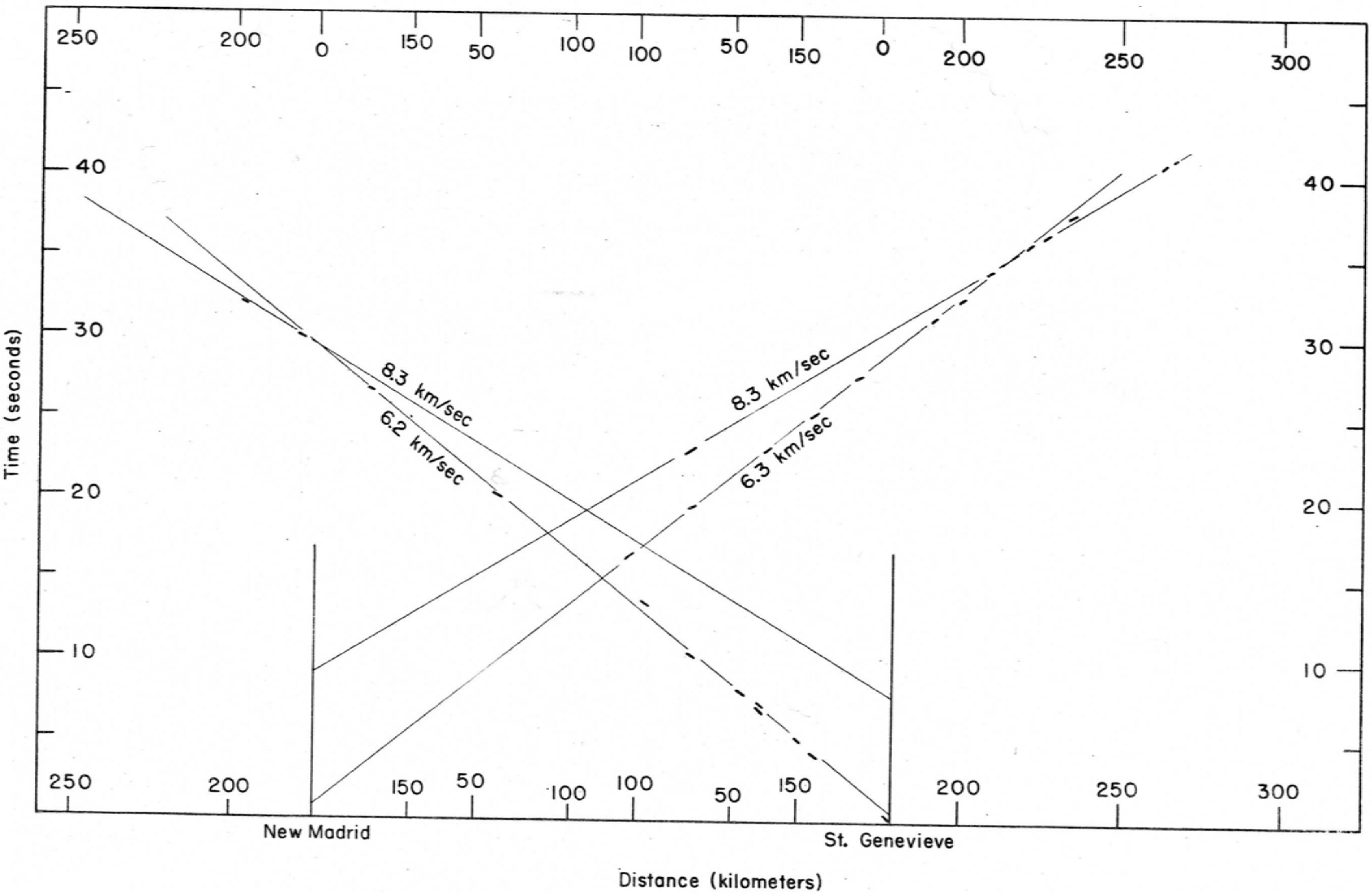

Figure 8.--Time-distance profile, Ste. Genevieve, Missouri, to New Madrid, Missouri

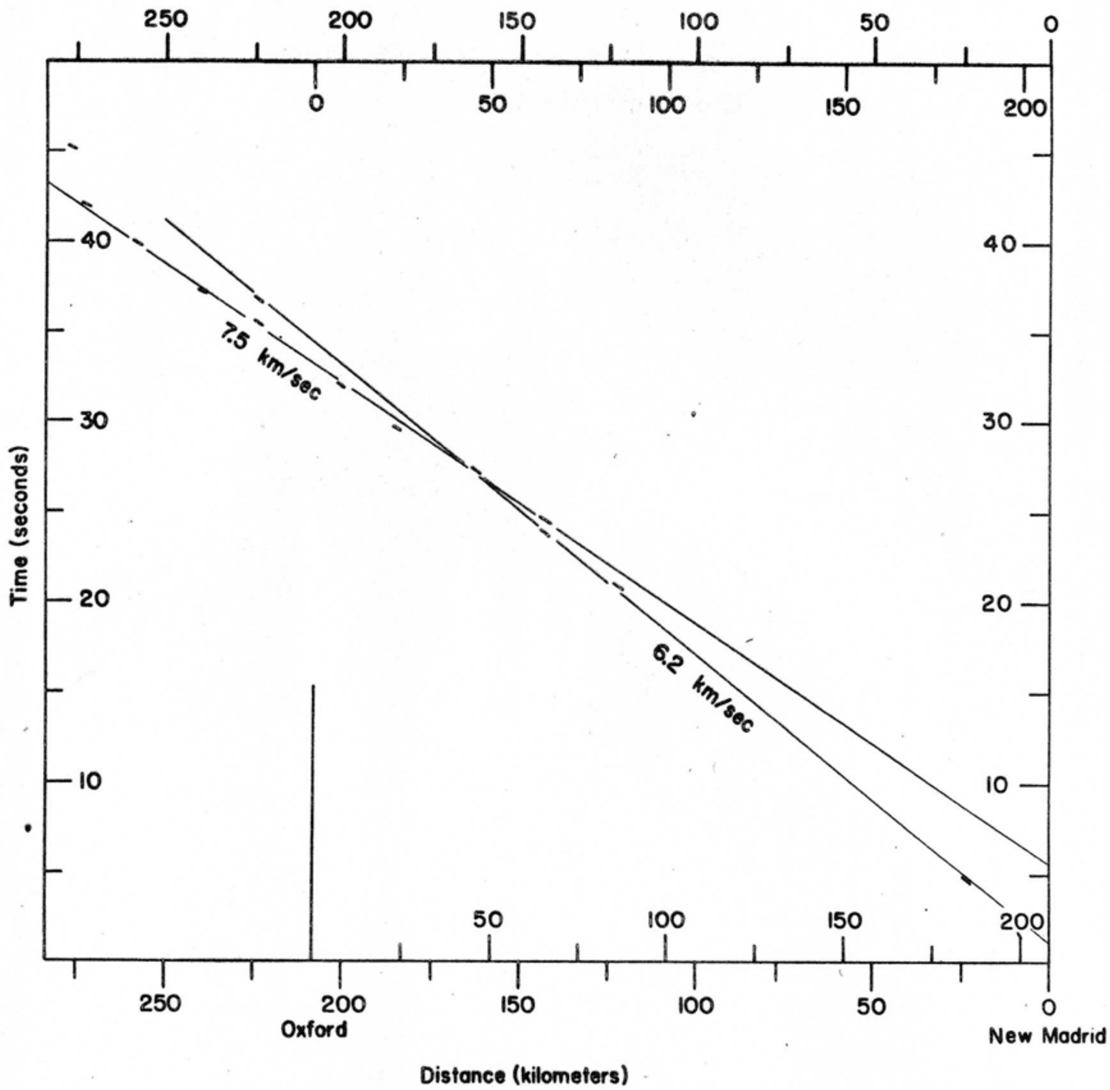

Figure 9.--Time-distance profile, New Madrid, Missouri, to Oxford, Mississippi

an intermediate-velocity layer. Unfortunately, the poor energy transmission at the Oxford shotpoint prevented reversal of apparent velocities in this area. The seismograms that define the 7.5 km/sec velocity are of poor quality.

Oxford, Mississippi, to Raleigh, Mississippi.--An apparent velocity for P_g of 6.1 km/sec is defined northward from Raleigh by 6 seismograms of poor-to-fair quality (Fig. 10). An apparent velocity for P_n of approximately 8.0 km/sec is defined by 4 seismograms of poor quality. Poor quality of the seismograms is attributed primarily to the extremely-high seismic-noise levels. The Raleigh shotpoint is the northernmost shotpoint on the profile recorded across the DRIBBLE site. Data recorded between Raleigh and Oxford, when combined with recordings of the nuclear shot at the DRIBBLE site, should permit a more detailed interpretation of crustal structure and mantle velocities in this area.

Hercules, Missouri, to Ste. Genevieve, Missouri.--This profile, which was recorded as a cooperative experiment with St. Louis University, extends from a point near Hercules in the Ozark Plateau 290 km northeast to Ste. Genevieve in the Central Lowlands, with an intermediate shotpoint at Gladden. All three of these shotpoints are classified as good.

An apparent velocity for P_g of 6.0 km/sec is defined by 17 good-to-fair seismograms recorded to a distance of 187 km from Hercules toward Ste. Genevieve (Fig. 11). Beyond 187 km, events on 10 fair seismograms are identified as the P_n arrival with an apparent velocity of 8.2 km/sec.

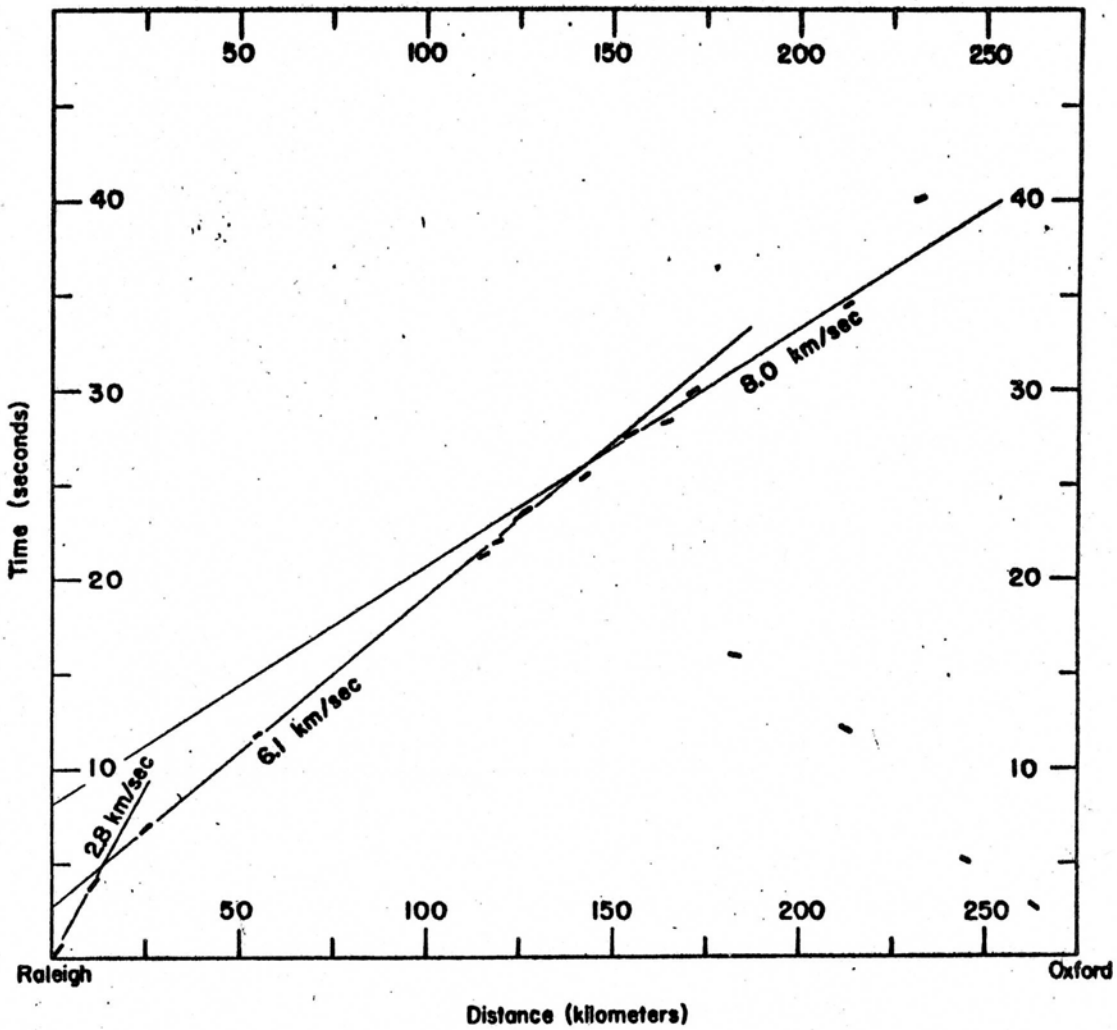

Figure 10.--Time-distance profile, Oxford, Mississippi, to Raleigh, Mississippi

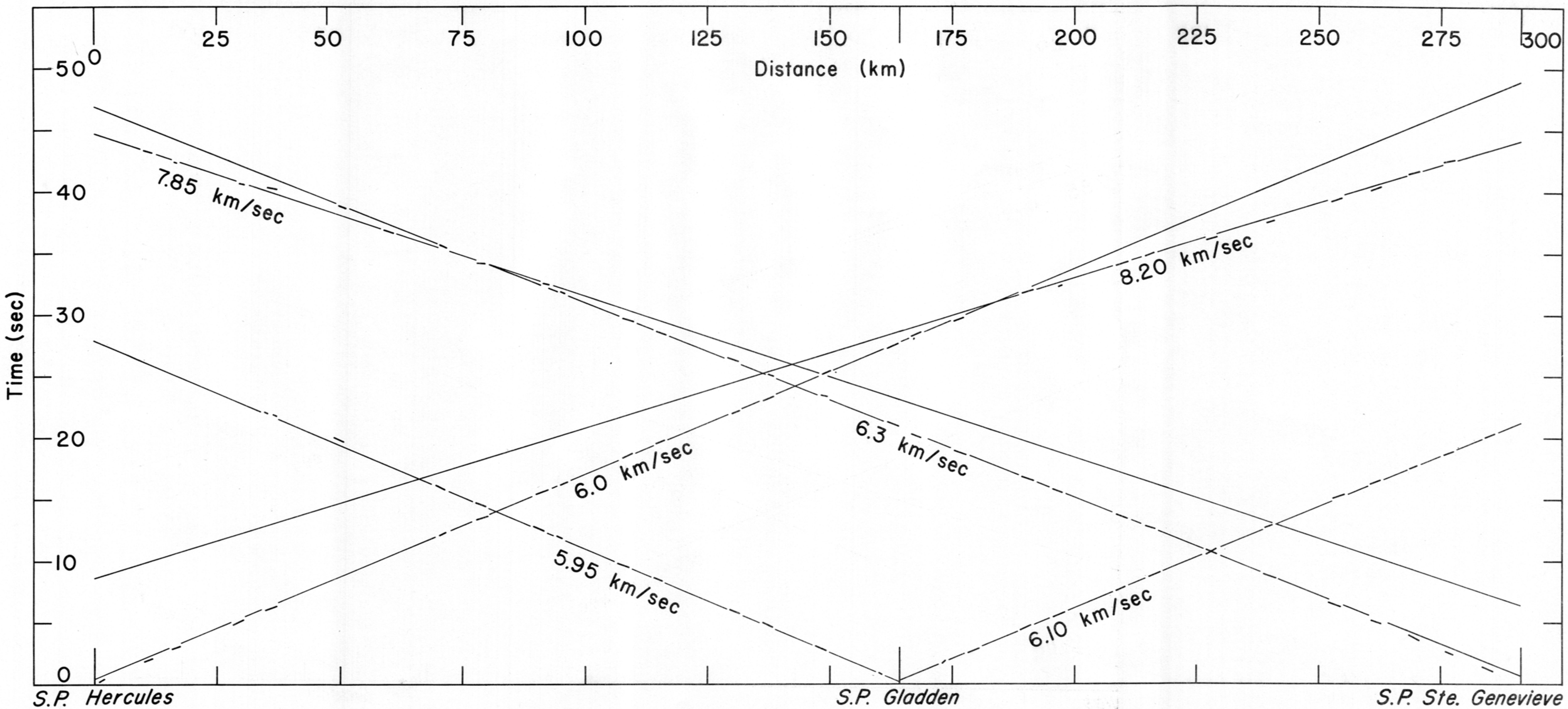

Figure 11.--Time-distance Profile, Hercules, Missouri, to Ste. Genevieve, Missouri.

An apparent velocity for P_g of 6.3 km/sec is defined by 21 good-to-fair recordings for a distance of 210 km toward Hercules from Ste. Genevieve. At distances beyond 210 km, arrivals on 6 poor-to-fair recordings are identified as P_n with an apparent velocity of 7.85 km/sec.

An apparent velocity for P_g of 5.95 km/sec from Gladden toward Hercules is defined by 13 good-to-fair recordings. An apparent velocity for P_g of 6.10 km/sec is defined by 13 good-to-fair recordings from Gladden toward Ste. Genevieve. The scatter in arrival times from all of these profiles is very small. Most of the arrivals have time residuals of less than 0.2 sec from the best straight-line fits to the traveltime curves.

St. Joseph, Missouri, to Hannibal, Missouri.--This profile, which also was recorded as a cooperative experiment with St. Louis University, extends from a point near St. Joseph eastward to Hannibal for a distance of 330 km with an intermediate shotpoint at Swan Lake, Missouri. All three of these shotpoints were classified as good. This profile is entirely within the Central Lowlands province.

An apparent velocity for P_g of 6.1 km/sec is defined by 17 fair-to-good recordings for a distance of 200 km from St. Joseph toward Hannibal (Fig. 12). Beyond the P_g-P_n crossover an apparent P_n velocity line of 8.15 km/sec is defined by 9 recordings of generally-fair quality. The scatter in these data is small.

An apparent velocity for P_g of 6.1 km/sec is defined by 17 fair-to-good recordings for a distance of 195 km from Hannibal toward St. Joseph. An apparent velocity for P_n of 8.1 km/sec is defined by 12 poor-to-fair recordings. The scatter in these data is small.

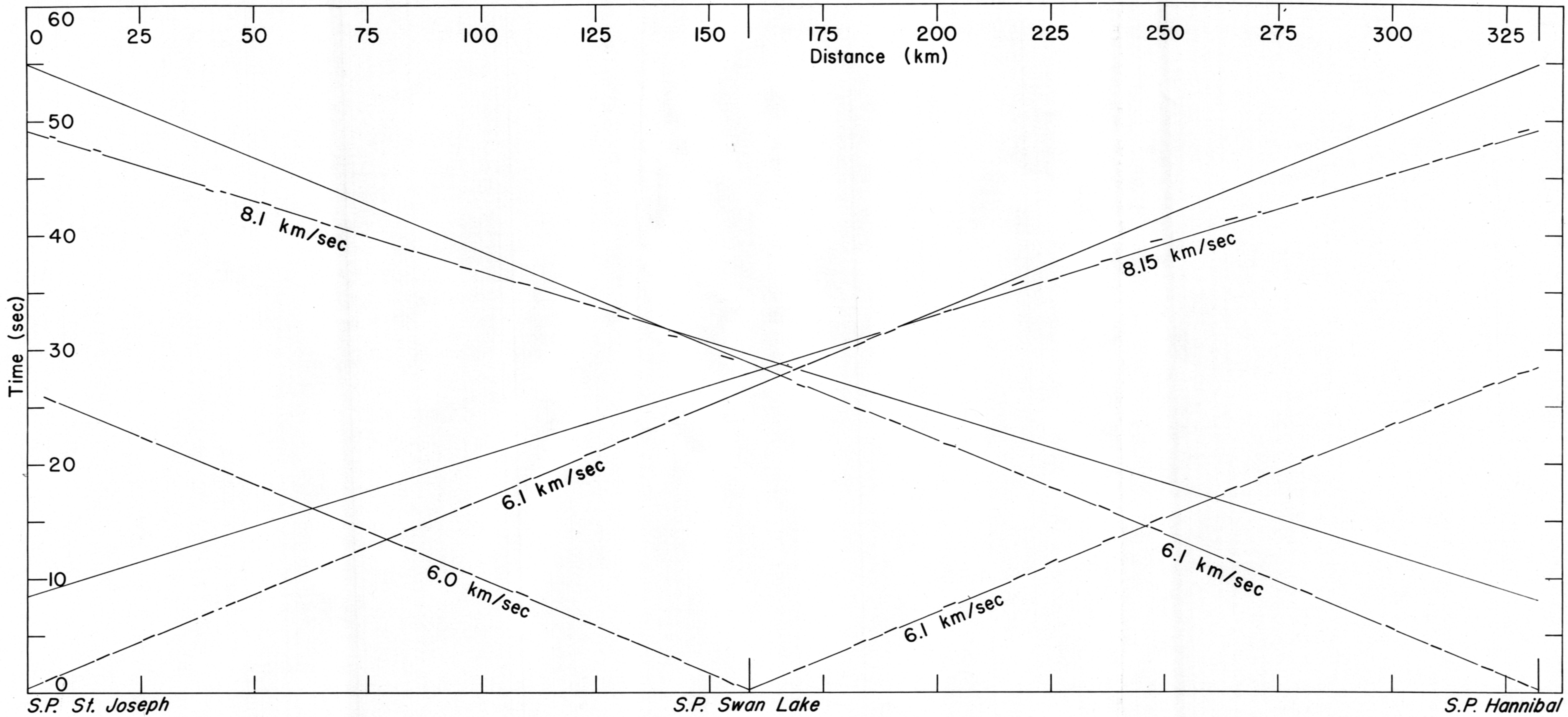

Figure 12.--Time-distance Profile, St. Joseph, Missouri, to Hannibal, Missouri.

An apparent velocity for P_g of 6.0 km/sec is defined by 12 records of fair-to-good quality from Swan Lake westward toward St. Joseph, and an apparent velocity for P_g of 6.1 km/sec is defined by 15 fair-to-good recordings from Swan Lake toward Hannibal. The scatter in these data is very small, as most points fall within ± 0.1 sec of the lines.

No discussion of the data recorded from the BILLIKEN and Ansley shotpoints are included in this report, as separate preliminary reports will be prepared on these data.

PRELIMINARY SEISMIC-REFRACTION STUDIES FOR PROJECT DRIBBLE

The major objective of project DRIBBLE is to evaluate the feasibility of seismically decoupling a nuclear explosion by firing at the center of a large cavity. In project DRIBBLE a 100-ton shot will be fired in a cavity of salt and will be compared with another 100-ton shot tamped in salt. The mechanism of decoupling will be studied by recording the ground motion near the shots in the salt and by studying the seismic waves that are propagated out of the salt and are recorded at distances less than 200 km from the site of the explosion. The site of the detonations is the Tatum salt dome, which appears to be a typical Gulf Coast salt dome that has intruded Mesozoic and Cenozoic sedimentary rocks to within 1500 ft of the surface.

It was recognized that the seismic recording program for the decoupled and coupled explosions in salt was faced with two serious difficulties: first, for recordings at distances less than 30 km, the seismic energy will propagate laterally through a complex sedimentary section which alters the shape of the seismic waves; second, at distances greater than about 30 km, the signal from the decoupled shot is of the same order as the average seismic-noise level in this region. The preliminary seismic-refraction program, which was conducted in cooperation with the Lawrence Radiation Laboratory and the U. S. Coast and Geodetic Survey, was designed to evaluate these problems and to provide data for the design of seismic-recording programs so that these difficulties could be minimized.

The experiment was designed to compare the propagation of a shot fired in salt to the propagation of a shot fired at shallow depth off the dome. The field operation for this program was carried out during an intensive 10-day recording program, followed later by a 2-day recording program to record high-explosive shots fired in the salt dome. Results of this program have been reported in a letter report of limited distribution and will only be summarized here. It was determined that the seismic efficiency of a shot in salt was far below the comparable efficiency of a shot in sediments near the surface. Deep burial in salt apparently has the effect of raising the seismic energy into the high-frequency part of the spectrum and this energy is, in turn, rapidly attenuated on propagation. The relatively-low signal expected from the 100-ton decoupled shot in salt, therefore requires that recording units be placed within about 30 km of the dome. Distortion of the wave shape by lateral propagation through a sedimentary section seriously distorts the seismic signals at distances less than 10 km from the dome, but in the distance range between 10 and 30 km from the dome, satisfactory recording locations can be found.

Shots were fired at 5 locations along a line extending north from the Gulf Coast through Tatum Dome (labeled DRIBBLE in Figure 13). The shotpoints were spaced about 50 km apart and designated Ansley (A), McNeill (M), DRIBBLE (D), Collins (C), and Raleigh (R), from south to north. The shotpoints, with the exception of DRIBBLE, were named after nearby Mississippi towns. The preliminary interpretation of the travel-time data is presented in Figure 14.

LAKE SUPERIOR EXPERIMENT

During the month of July, the U. S. Geological Survey participated in a cooperative seismic experiment in the region of Lake Superior, and not as a part of VELA UNIFORM. The work is reported herein, however, because of general interest and its relation to VELA UNIFORM objectives. This experiment was organized and financed by a group of American and Canadian universities, government agencies, and non-profit research institutions, with the support of the National Science Foundation. The Geological Survey provided 8 recording units which were set up as two arrays: one near the western shore of Lake Superior in the vicinity of Duluth, and the other on the Keweenaw Peninsula. Shots were fired along a line extending from the western shore of Lake Superior, past the Keweenaw Peninsula, to the eastern shore of the Lake on the Canadian border. More than 70 shots were fired in this experiment, and the data obtained is of generally high quality. The interpretation of these data awaits the tedious job of working up the shotpoint positions from

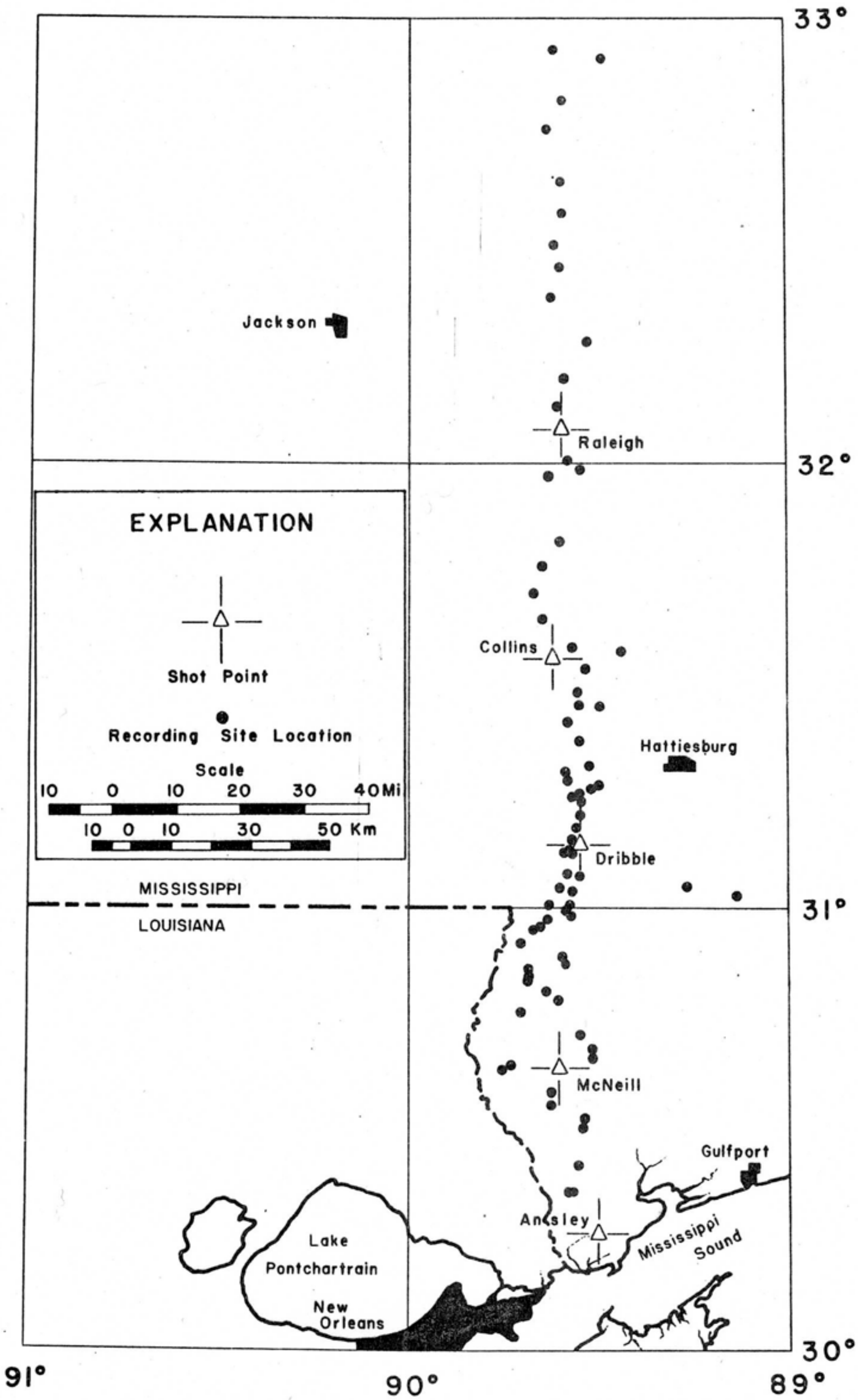

Figure 13.--Index map of pre-DRIBBLE shotpoints and recording sites

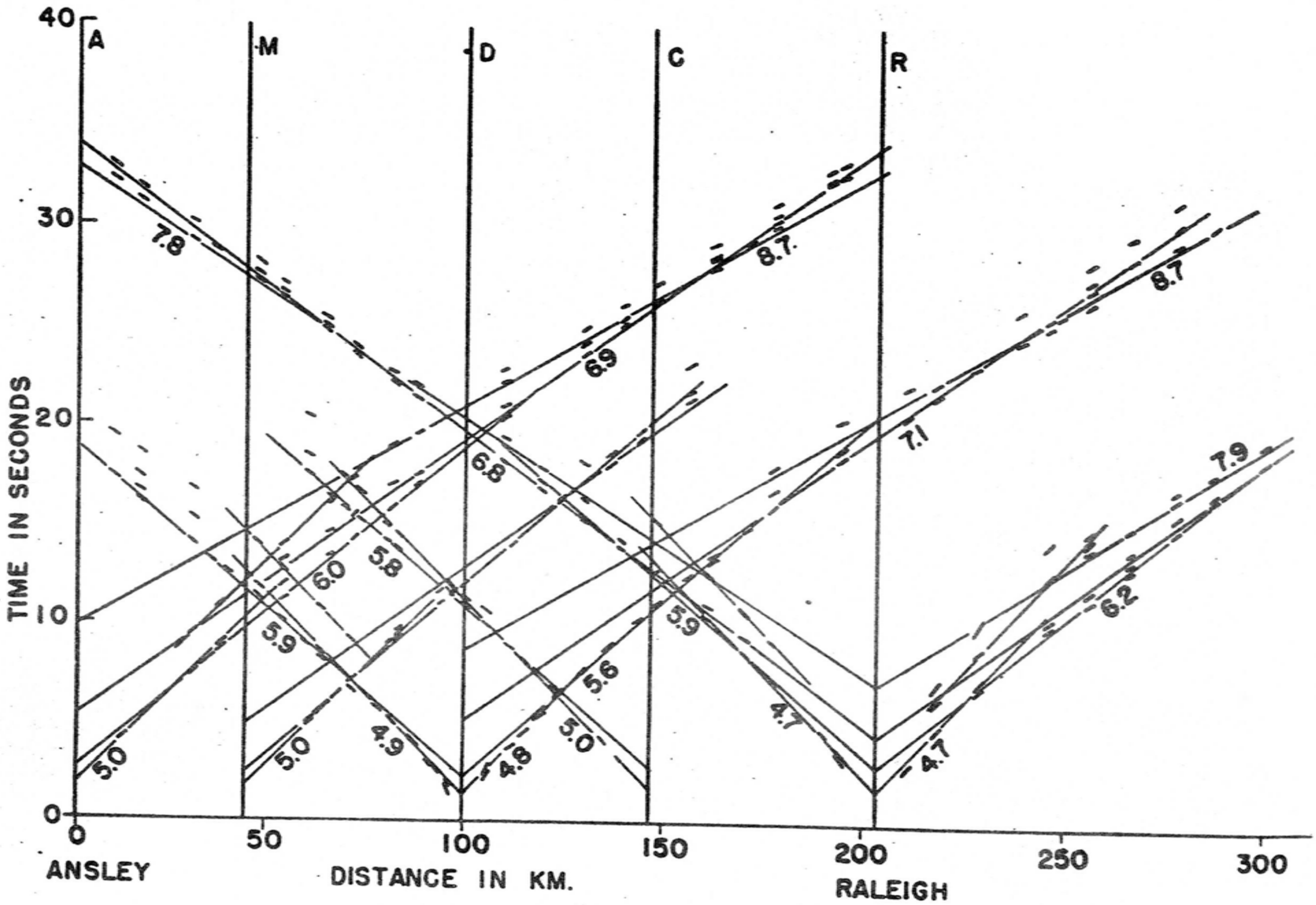

Figure 14.--Time-distance profile of pre-DRIBBLE recordings

hydrophone data. Preliminary examination of the seismograms indicates that the experiment will provide detailed knowledge of crustal structure in this region, and an opportunity to evaluate the applicability of various array-processing techniques to the identification of seismic phases and the study of crustal structure.

GENERAL SUMMARY

Table 5 presents the time-distance curves in terms of intercept times and velocities.

The velocities of P_g range from 5.95 to 6.45 km/sec and average 6.1 km/sec. The velocities of P_n range from 7.5 to 8.3 km/sec, and average 8.0 km/sec. The 7.5 km/sec velocity from New Madrid to Oxford is probably not a true P_n velocity.

Table 6 presents a statistical summary of first-arrival times at 50 km intervals along the profiles. The mean deviation of first-arrival times average approximately 0.5 seconds, and the maximum deviations range as high as 1.8 sec.

Figure 15 shows the grades of the records for 50 km intervals. The seismograms from the Gulf Coastal Plain are much poorer than those from the other provinces investigated. This was the result of poor shotpoint efficiency and of high background noise.

Table 5.--Time-Distance Data in Terms of Intercept Times and Velocities

Profile	P_g sec	P_n sec	Remarks
Chinle to Hanksville	$0.7 + \Delta/6.1$	$8.8 + \Delta/7.8$	P_n well defined
Hanksville to Chinle	$1.1 + \Delta/6.25$	$9.4 + \Delta/8.0$	P_n velocity poorly defined
American Falls to Flaming Gorge	$1.9 + \Delta/6.2$	$9.2 + \Delta/8.2$	Both P_n & P_g well defined
Flaming Gorge to American Falls	$2.4 + \Delta/6.45$	$8.5 + \Delta/8.15$	Both P_n & P_g well defined
Bear Lake - American Falls	$1.0 + \Delta/6.1$	Intermediate SP	No P_n Recorded
Bear Lake - Flaming Gorge	$0.9 + \Delta/6.0$		
Raleigh to Oxford	$2.7 + \Delta/6.1$	$8.1 + \Delta/8.0$	Very poor records
New Madrid to Oxford	$1.0 + \Delta/6.2$	$5.5 + \Delta/7.5$	Low P_n - could be intermediate layer or steep dip
Ste. Genevieve to New Madrid	$0.5 + \Delta/6.2$	$7.7 + \Delta/8.3$	P_n poorly defined
New Madrid to Ste. Genevieve	$0.9 + \Delta/6.3$	$9.1 + \Delta/8.3$	P_n poorly defined
Hercules - Ste. Genevieve	$0.3 + \Delta/6.0$	$8.7 + \Delta/8.1$	Both P_g & P_n well defined
Ste. Genevieve - Hercules	$0.6 + \Delta/6.3$	$6.5 + \Delta/7.85$	
Gladden - Hercules	$0.2 + \Delta/5.95$	Intermediate SP	No P_n Recorded
Gladden - Ste. Genevieve	$0.3 + \Delta/6.1$		
St. Joseph - Hannibal	$0.4 + \Delta/6.1$	$8.5 + \Delta/8.15$	Both P_g & P_n well defined
Hannibal - St. Joseph	$0.2 + \Delta/6.1$	$7.3 + \Delta/8.1$	Both P_g & P_n well defined
Swan Lake - Hannibal	$0.3 + \Delta/6.1$	Intermediate SP	No P_n Recorded
Swan Lake - St. Joseph	$0.2 + \Delta/6.05$		

Table 6.--Statistical Summary of First-Arrival Times

Profile	Distance in km					
	50	100	150	200	250	300
	Time in seconds					
Flaming Gorge - American Falls	10.1	17.7	25.5	33.1	39.2	45.4
American Falls - Flaming Gorge	9.4	17.4	25.5	33.6	39.7	45.8
Bear Lake - American Falls	9.2	17.6	25.9			
Bear Lake - Flaming Gorge	9.2	17.6				
Hanksville - Chinle	9.1	17.1	25.1	33.1	40.7	47.0
Chinle - Hanksville	8.7	16.9	25.0	33.0	40.6	47.2
New Madrid - Ste. Genevieve	8.8	16.7	24.7	32.6	39.3	
Ste. Genevieve - New Madrid	8.6	16.2	24.6	32.5	38.8	
New Madrid - Oxford	9.1	17.1	25.1	32.1		
Raleigh - Oxford	10.7	18.9	26.9	33.1		
Hercules - Ste. Genevieve	8.6	17.0	25.2	32.8	39.1	
Ste. Genevieve - Hercules	8.5	16.5	24.4	32.4	39.3	
Gladden - Ste. Genevieve	8.5	17.8				
Gladden - Hercules	8.6	17.1				
St. Joseph - Hannibal	8.6	16.8	25.1	32.9	39.1	45.2
Hannibal - St. Joseph	8.4	16.6	24.6	32.6	38.6	45.1
Swan Lake - Hannibal	8.4	16.5	24.6			
Swan Lake - St. Joseph	8.4	16.7	25.0			
Average	8.9	17.1	25.1	32.8	39.4	46.0
Mean deviation	0.46	0.47	0.35	0.40	0.46	0.78
Total range	8.4-10.7	16.2-18.9	24.4-26.9	32.1-33.6	38.6-40.7	4.51-47.2
Max. deviation	1.8	1.8	1.8	0.8	1.3	1.2

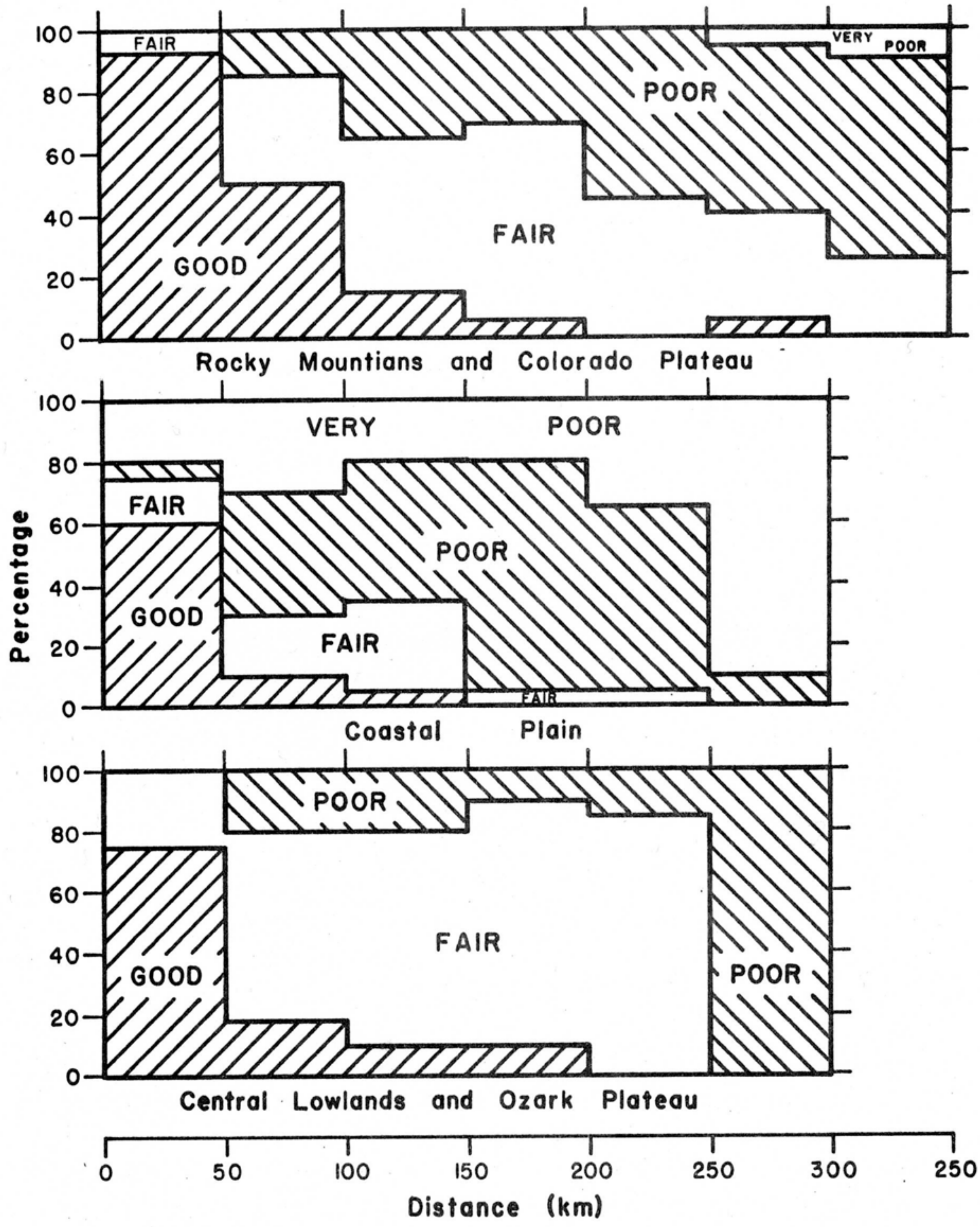

Figure 15.--Record grades for various regions

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