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MICROEARTHQUAKE MONITORING AT CORPS OF ENGINEERS FACILITIES

by

David M. Patrick

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P. O. Box 631, Vicksburg, Miss. 39180

February 1977
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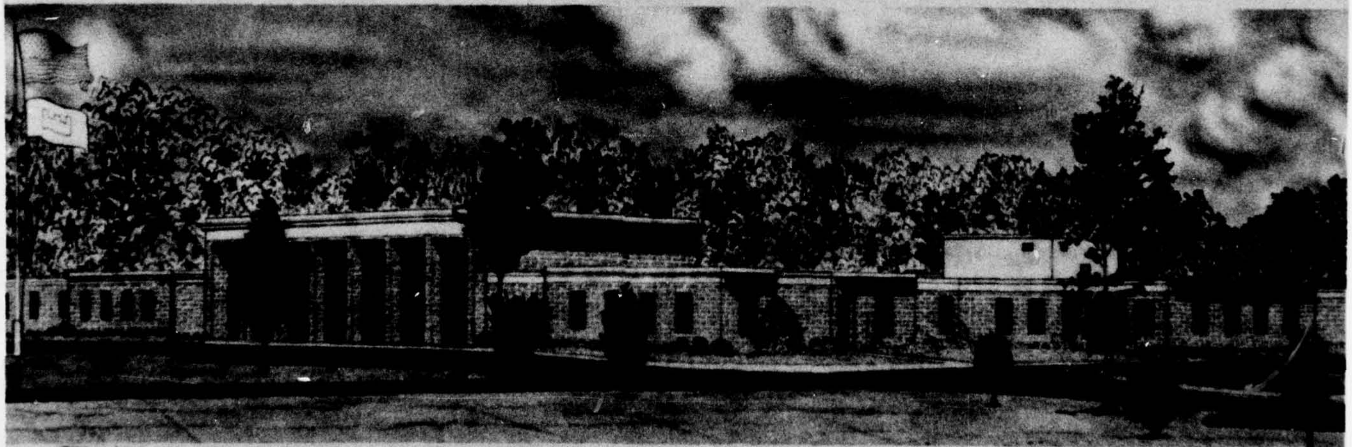

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Awareness of potential seismicity induced by the filling of large reservoirs or by the injection of fluids in boreholes has prompted the Corps of Engineers and others to conduct microseismic monitoring programs at ten damsites and at one injection well. Two other damsites have been monitored by other organizations in cooperation with the Corps of Engineers and one is proposed. These programs were developed to measure and compare ambient seismicity in the environs of the installations and the seismicity present during either reservoir filling or → next page
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fluid injection. These programs have been performed chiefly under contract with the U. S. Geological Survey and academic institutions. Monitoring consists of judiciously positioning an array of three to eight short-period, vertical component seismometers around the reservoir or injection well. Earthquake events detected by the seismometers are amplified at the site and either modulated there or at a location central to the array. The modulated signals are telemetered to a removed location where demodulation, recording, and data analyses are performed. These programs have been designed to monitor for a period of four to five years in order to include pre-, during-, and post-filling or injection phases. The average cost per year of monitoring is approximately $35,000. Equipment purchase, telemetry, and data analysis are the principal expenses. Analysis of available data from completed or nearly completed programs reveals no definite indications of seismicity induced by reservoir filling or fluid injection at Corps of Engineers installations. There is some indication that reservoir pool level may induce low-level seismicity at one site in the southeastern United States although there is other evidence that this may not be true. Monitoring programs must be based upon firm geological and seismological understanding of the installation sites. Arrays should be so situated, and consist of sufficient instruments, that accurate epicentral locations, focal depths, and magnitudes may be determined. Duration of monitoring must be sufficiently long that a reliable statistical significance can be attached to the data. The analysis of data must consist of either graphical or statistical comparisons of levels of seismicity during various phases of either filling or injection. Unless the monitoring period starts two or more years before reservoir filling, misleading results can be obtained.

PREFACE

This study is a part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) in Civil Works Investigation Studies, Project 901, Task 312, Unit 31039, entitled "Seismic Effects of Reservoir Loading and Fluid Injection," sponsored by the Office, Chief of Engineers, U. S. Army.

The report was written by Dr. David M. Patrick under the general supervision of Dr. E. L. Krinitzsky, Chief, Engineering Geology Research Facility, Mr. Don C. Banks, Chief, Engineering Geology and Rock Mechanics Division (EGRMD), and Mr. James P. Sale, Chief, Soils and Pavements Laboratory. Dr. Richard Lutton, Research Group, EGRMD, contributed sections on site geology.

The information contained in this report has been derived from numerous unpublished reports, interoffice correspondence, memoranda for record, and from telephone correspondence with monitoring contractors, District geologists, and personnel of the U. S. Geological Survey. The author acknowledges assistance provided by the following individuals: Drs. Maurice Major, Colorado School of Mines; L. T. Long, Georgia Institute of Technology; and Anthony Qamar, University of Montana; and Messrs. Jerry Triggs, Tulsa District; John Bertram, Huntington District; and Rick Lester, U. S. Geological Survey.

This report was reviewed by Messrs. Stanley J. Johnson and Robert F. Ballard, Jr., Soils and Pavements Laboratory, and Dr. Robert B. Herrmann, St. Louis University.

Directors of WES during preparation of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square miles (U. S. statute)	2.589988	square kilometres
acre-feet	1233.482	cubic metres
pounds (mass)	0.4535924	kilograms
tons (2000 lb, mass)	907.1847	kilograms
feet per second	0.3048	metres per second
degrees (angular)	0.01745329	radians

MICROEARTHQUAKE MONITORING AT CORPS OF ENGINEERS FACILITIES

PART I: INTRODUCTION

Purpose

1. The apparent causal relationship between increased seismicity and the impoundment of water in certain large reservoirs or the injection of fluids at depth in boreholes prompted the Corps of Engineers (CE) to conduct microseismic monitoring investigations at selected new and existing projects.[1]

2. The purpose of this report is to describe and discuss the current status of microearthquake monitoring conducted at CE projects in the United States. This report describes the instrumentation, site layout, generalized local and regional seismicity, and the results and interpretations of the monitoring program at 13 damsites and 1 injection well.

Scope

3. This report is limited to a description of microearthquake investigations and excludes other monitoring programs using strong-motion instruments. However, both types of investigations are being conducted concurrently at some CE dams. This report is concerned with monitoring programs designed to compare background seismicity with seismicity during and after fluid injection or reservoir filling.

Microseismicity

4. The terms microearthquake and microseismicity do not have universally accepted definitions; however, a microearthquake is generally considered a small earthquake event exhibiting a magnitude less than

3.5 on the Richter scale.* Microseismicity is then the occurrence of earthquake events with magnitudes less than 2 to 4. These microseismic events are too small to produce structural damage.** Microearthquakes may occur at frequent or infrequent intervals in areas of high or low overall seismic activity. The occurrence or nonoccurrence of these small events constitutes the background seismicity in an area. Increased frequency of occurrence of these small earthquakes may precede the occurrence of larger, perhaps damaging earthquakes, but such increased frequency is not a prerequisite for large earthquakes. In any event, increased frequency of occurrence or increase in magnitude of events may signal a change in stress conditions within the earth. Monitoring programs may thus be required to monitor both small and large events.

5. These small earthquakes are caused by fault movement in the crust and may be attributed to tectonic stresses or to works of man. Landslides, blasts, and other movements may generate seismic waves similar to those of microearthquakes. These events are not of concern in this report; however, one must be aware of them when analyzing seismograph records.

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* Magnitude is related to the energy expended during an earthquake.

** The degree of ground shaking at a site is expressed in terms of earthquake intensity. The Modified Mercalli Intensity Scale is presented in Appendix A.

PART II: INDUCED SEISMICITY

General

6. The seismicity in a particular region is dependent upon the overall tectonic and geologic environment of the region.[2] Thus the location of the site with respect to plate boundaries, active faults, epeirogenic crustal motions, and even unknown causal factors contribute individually or in combination to produce a regional seismic pattern in an area. These patterns may be well understood in regions of high seismic activity such as the Western United States; however, in other areas, little may be known of the causes.

7. Regional seismic patterns occasionally are significantly affected by the works of man, such as the impoundment of water behind large dams or the injection of fluids under pressure in boreholes. Both impoundment and injection alter the existing stresses in the earth and may, under some conditions, result in increased seismic activity and earthquakes.

Reservoir Filling

8. There are several cases in which increased seismic activity has been directly attributed to the filling of large reservoirs.[3] A large reservoir has been defined to be one having a capacity larger than 1.25×10^9 m^3 or having a dam higher than 100 m. This is not meant to imply that the filling of smaller reservoirs will not produce damaging earthquakes (several smaller ones have exhibited induced seismicity), but impoundments with the dimensions given above are of critical interest.

9. The Koyna Dam in India is of particular interest because it represents a large concrete gravity structure situated in what was believed to be an aseismic area. However, within 5-1/2 years of filling,

the vicinity of the dam experienced a large earthquake (M = 6.5) which resulted in a number of deaths and some structural damage including that to the dam itself. Other examples of reservoir-induced seismicity include that from Lake Kariba, Rhodesia; Hsinfengkiang Reservoir, People's Republic of China; Kremasta Dam, Greece; Monteynard Reservoir, France; and Hoover Dam, U.S.A. The dam and reservoir dimensions and the resulting earthquake magnitudes of these examples are tabulated below.[3]

Dam	Location	Reservoir Capacity, 10^6 m^3	Dam Height, m	Seismicity
Koyna	India	2,780	103	M = 6.5
Kariba	Rhodesia	160,368	128	M = 5.8
Kremasta	Greece	4,750	165	M = 6.3
Hsinfengkiang	People's Republic of China	10,500	105	M = 6.1
Monteynard	France	240	155	M = 4.9
Hoover	U.S.A.	36,703	221	M = 5.0

10. Nevertheless, many large reservoirs in the world have not exhibited induced seismicity. This indicates that special site conditions must be present for induced seismicity to occur.

11. It is important to bear in mind that the determination of a relationship between a seismic event and the filling of a reservoir or the injection of fluid in a borehole must be based upon a knowledge of normal regional "background" seismicity. This knowledge can only be deduced from measurements of background seismicity taken prior to the filling or injection.

Fluid Injection

12. The pressure injection of fluids at depth in boreholes for the purposes of waste disposal or secondary petroleum recovery may trigger earthquakes by interactions with the existing stress conditions within the earth. Again, the determination of causal relationships between seismic events and the injection must be based upon knowledge of the background seismicity.

Mechanisms of Induced Seismicity[4,5]

13. The mechanisms producing induced seismicity are not well understood although two theories have been presented. Both attribute the resulting seismicity to movement on a fault but differ in the manner in which the induced stress field causes the movement to occur. One theory attributes the movement to a buildup of total stress due to the incumbent load of the water in the reservoir itself. This theory disregards the effects of the water in the reservoir on the neutral or pore water pressures in the rock at the fault. The second theory considers that the overlying pool of water in the reservoir (or the injected fluid) will cause an increase in stress in the pore water of the rocks at the fault. These increased pore water stresses result in a decreased effective stress at the fault, and if the effective stress is sufficiently decreased, movement may then occur. Both processes may contribute to induced seismicity at reservoirs.

Depth of Induced Seismicity[5]

14. Snow[5] concluded that reservoir-induced seismicity may be related to the following factors:

a. Geomorphic and tectonic history.
b. Effective porosity and permeability.
c. Fault and fracture systems.
d. Water level variation in reservoir.
e. Type of fault.

The first four factors determine effective stress conditions at faults beneath and in the local area around a reservoir. Depending upon these five factors, the fault may be tightened or loosened and may or may not result in movement and an earthquake.

15. The depth at which a fault must be located in order to be affected by changes in effective stresses is dependent, in part, on the pore pressure in the rocks.

16. Shallow weathered zones subjected to relatively lower hydrostatic pressures and deep zones having essentially zero void space are both less likely to generate earthquakes than intermediate zones. The intermediate zone will exhibit hydrostatic pressures greater than those in the overlying weathered zone as well as significantly more void space than that in deep zones. Thus, the zone of concern is in an intermediate depth between the zone of weathering and above the zone effectively sealing the rock mass. This zone of induced seismicity may be difficult to specify in some cases but it would include only shallow focus earthquakes (less than 50 km deep). The depth of principal concern would most likely be within a few kilometres of the surface, but this probably depends upon both the depth and size of the reservoir.

PART III: MICROSEISMIC MONITORING

Purpose of Monitoring

17\. One purpose of microseismic monitoring is to describe the background seismicity in a limited area proximal to a particular project site. The monitoring program may be general in nature with the intent of defining background seismicity throughout a given area or it may be directed toward analyzing a particular fault which is suspected of being active.

18\. Microseismic monitoring of sites intended for purposes other than injection wells or reservoirs (such as nuclear power plants) may, under appropriate circumstances, provide some insight into anticipated levels of seismicity which could affect the design of a particular project. However, this is beyond the scope of this report. Ordinarily, the purpose of microseismic monitoring of injection wells and reservoir sites is to permit comparisons to be made between the seismicity before, during, and after injection or reservoir filling. This comparison will define the extent (if any) to which either fluid injection or reservoir filling is affecting the local seismicity and thus the possibility of producing a damaging earthquake. Having made this comparison, the decision can be made as to the need for regulating or even discontinuing injection or filling.

19\. The regional geology and historical seismicity are bases for the placement of instruments and the assessment of the microseismic records.

Instrument Placement

20\. The placement pattern of a number of seismometers at a site is called an array. For general monitoring programs the seismometers should be more or less evenly spaced around the site of the proposed injection well or around the reservoir. The spacing of seismometers is dependent upon the size of the monitored area. Injection well sites should be instrumented within approximately 1 km of the well, whereas reservoirs may require larger distances between seismometers. Uniform distribution and spacing of instruments assures uniform coverage of the area and may also permit accurate definition of earthquake source. The determination of source and the relative movements along a fault requires three instruments.

21. The considerations addressed above should also be analyzed when monitoring geologic faults. In some situations, however, additional requirements may be necessary. These stem from the need to distinguish between the levels of seismicity along the fault versus the general background seismicity. Thus, a level of seismicity which is higher along a fault, for example, than in the surrounding general area gives credence to the idea that the fault is indeed a source for earthquakes. The need to resolve details such as these requires that the geophone or seismometer array be sufficient in number and arrangement to distinguish between earthquake sources. Regardless of the reason for installing instruments, the number installed must be sufficient to permit fault-plane solutions for origin of the earthquakes to be obtained.

22. Ideally, instrument locations should be based upon the epicentral locations and focal depths of the expected earthquakes. Focal depths may best be determined by instruments located within one focal depth of the epicenter. However, instruments placed at greater than one focal depth may be used to determine earthquake epicenters.* Epicentral or focal distances may be determined by measuring the difference in arrival times between the first-arrival s-wave and the first-arrival p-wave. This time is multiplied by a factor, often 8 km/sec, to yield the approximate epicentral or focal distance.

23. The empirical factor, 8 km/sec, is based upon a presumed V_p/V_s ratio of 1.75 and can be used if the actual p- and s-wave velocities are not known. For more precise locations the actual velocities must be measured. This can be done by conducting controlled

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* Personal communication, Dr. Robert L. Wesson, USGS.

seismic profiling at the site. Another approach to identify seismic velocities is to monitor local quarry or construction blasting (see PART V: METHODS OF DATA ANALYSIS).

24. Instruments should be protected from theft and vandalism and located at obscure sites where there is insignificant influence from highways, power lines, and construction or industrial operations such as manufacturing, quarrying, or mining. These considerations must be balanced with those of the geology and seismology. Instruments should also be securely placed on a firm foundation such as rock or at least on a concrete pad to insure coupling between the seismometer and the subsurface.

Instrumentation[6]

25. The instrumentation system used in microseismic monitoring programs consists basically of the following components:

a. Seismometer or geophone and amplification subsystem.
b. Telemetry subsystem.
c. Recorder.
d. Power source.
e. Chronometer.

Other components may be required depending upon the type of monitoring program. Schematics of common instrumentation systems are shown in Figures 5, 6, and 10.

26. Monitoring methods are distinguished on the basis of where the input data are recorded. In one, the on-site method, data are recorded at the site on some form of chart recorder contained with or near the seismometer or geophone. In the other, the remote method, the data from an array of several seismometers or geophones are telemetered to a remote location where the data are subsequently recorded.

27. The choice of which system to use at a particular site is dependent upon requirements or purposes of the monitoring program and the funding available. Arrays consisting of several seismometers lend

themselves to remote recording as this method would eliminate the need for several recorders. However, remote recording is expensive and would have to be balanced against the costs of on-site recording. Another practical consideration is the need of periodically changing the tape at each geophone or seismometer in on-site recording systems.

28. The desired sensitivity of the system may be dependent upon the known or anticipated regional seismicity, although the ability to detect and resolve events having magnitudes of zero or less may often be necessary.

Seismometers, geophones, and amplification subsystem

29. In most microseismic monitoring the anticipated events are small in magnitude ($M \approx 0$) and are expected to occur near the site. For this situation a short-period (0.5-1.0 sec), vertical component, velocity transducer type of geophone is adequate. Such a system will also record the beginning of large nearby events but will go off-scale due to the high magnification required for the small events. Large earthquakes are recorded by different types of instruments, i.e., strong-motion accelerographs.

30. The geophone itself is a subsystem consisting of a coil or pendulum suspended in a magnetic field. Both the pendulum and the transducer exhibit natural frequencies which together define the natural frequency of the geophone. The response frequency of the entire system depends upon this frequency and the response frequency of the amplifier, the frequency of the telemetry line (if used), and if a galvanometer is used for recording, the galvanometer frequency.

Telemetry

31. The telemetry subsystem used for remote recording consists of a component which multiplexes, modulates, or joins incoming signals and distributes them by frequency to the telephone lines, the telephone lines themselves, and at the recording end, a discriminator or demodulator which separates the incoming signals. The multiplexing unit may be contained at the site with the geophone or it may be placed in a central location with respect to the other geophones in the array. In

either case landwires or radio links must extend from each geophone site to a central location where the telephone net is entered.

Recording

32. The recording of incoming signals consists of record printing and record storage. For on-site recording systems this phase consists only of a galvanometer and some form of recorder. Remote recording systems, on the other hand, may consist of signal recording on magnetic tape as well as a visual printout. The visual recording system in either the on-site or remote method may utilize smoked paper, light-sensitive paper, photography, or ink-type recording devices.

Power source

33. A d-c power source is required at each geophone site. Automobile or motorcycle batteries are convenient and adequate sources of power. Solar power cells may be used to charge batteries. Also, air cells may be used to provide power to the seismometer and telemetry systems for periods up to one year.

Chronometry

34. The need for accurate measurement of arrival times requires that each on-site recording station contain a calibrated chronometer or a clock-radio tuned to WWVB. Arrays that are recorded remotely require a chronometry subsystem at the recording location. Timing calibrations should be made daily to maintain timing accuracy to within 0.1 sec. Timing accuracy is most important for small aperture arrays such as those around injection wells where seismic travel times are very short.

Costs

35. The major costs of implementing, maintaining, and analyzing the data from a monitoring program generally depend upon the costs of instrument purchase (if required), the method selected for recording data, i.e., on-site or remote, complexity of installation, and the time required to service geophone sites and analyze the records.

36. Telemetry may contribute appreciably to the total cost of a project. Telemetry costs are dependent upon the distances over which

signals are transmitted, the availability of FTS versus commercial lines, the number of relaying stations between the site and the recording location, as well as other variables. Cost rates are project dependent and specific rates for a project must be obtained from the telephone company. Cost breakdowns are given for most projects (PART IV) and a cost summary is given below. Current costs may be 40 to 50 percent higher than earlier project costs given in summary due to inflation. In order to minimize the monitoring costs, the CE has, in certain instances, recommended the initial installation of one unit in the most strategic location possible. If seismic events are then detected, a temporary array of other instruments could quickly be brought into the site. This procedure has the advantage that many instruments with their corresponding increased costs are not tied up for months or years without furnishing beneficial data.

Installation	Estimated Average Annual Cost
Chatfield and Bear Creek Reservoirs	$33,000*
Childress Injection Well	35,000
Libby Reservoir	31,360
Dworshak Reservoir	16,000
Warm Springs Reservoir	37,900
New Melones Reservoir	34,300
Paintsville Reservoir	18,000*
Tocks Island	62,000
Dickey-Lincoln School	N/A
Clark Hill Reservoir	N/A
Carters Reservoir	N/A
Richard B. Russell Reservoir	N/A

Mean $33,445/yr

* For unfinished projects the annual costs are based upon five years of monitoring.

PART IV: MONITORED CE PROJECTS

General

37. Currently, ten damsites and one injection well have been monitored for microearthquake activity. These sites, locations of which are shown in Figure 1, include New Melones, Warm Springs, Libby, Dworshak, Chatfield, Bear Creek, Paintsville, Cochiti, Tocks Island, and Dickey-Lincoln School Reservoirs, and the Childress injection well. Carters and Clark Hill Reservoirs were monitored by academic institutions in cooperation with the CE, and monitoring has been proposed for Richard B. Russell Reservoir. Reservoirs at which microearthquake instrumentation has been installed are listed in Table 1, together with height of dam and reservoir volume. Most of the installations were made because of unusual geologic or environmental features at the sites.

38. The current monitoring programs have been contracted to either the United States Geological Survey (USGS) or to local academic institutions. In one case (Paintsville), the CE District performed the monitoring itself. Also, in one instance (Libby), the CE District plans to take over the program initiated by another organization. The CE has generally found it expeditious to contract this type of work to organizations having expertise in this field and which may be located near the site being studied. There is an obvious cost advantage when the contracted organization is located near the site. This stems from reduced field and travel costs as well as a possible reduction in the cost of telemetering data from the site to the recording location if this is nearby. This advantage, however, may be offset if instrument purchase was included in the contract.

39. The USGS and certain academic institutions also possess an advantage in that they may already operate a seismic net in or near the area of interest. Thus, the data from the site net may be enhanced by information provided by the existing seismic network.

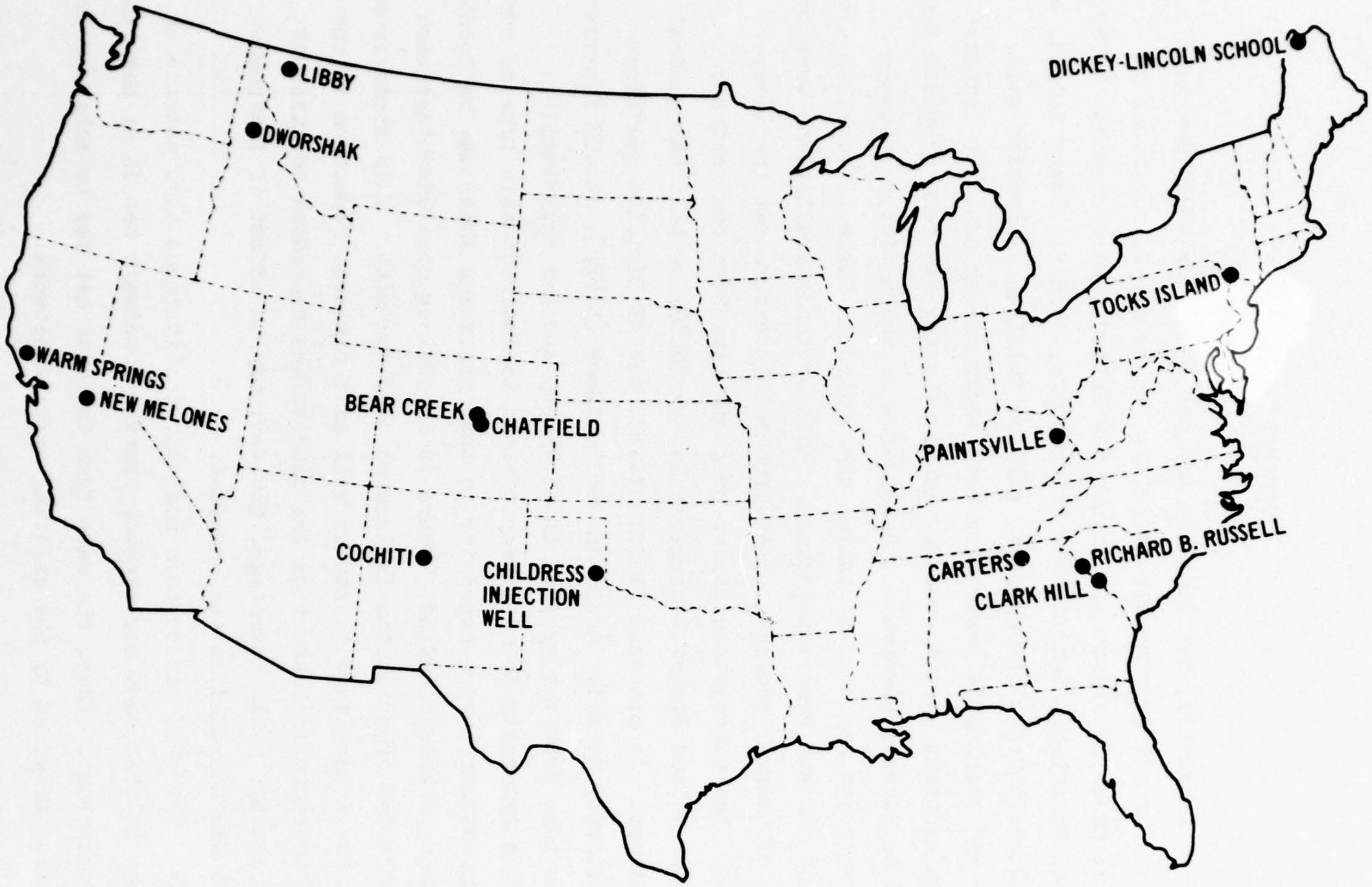

Figure 1. Locations of monitored CE installations

Table 1

CE Reservoirs with Microearthquake Monitoring for Induced Seismicity[1]

Dam	Use*	State	River	Dam Height m	Reservoir Capacity m³ × 10⁶ Max	Reservoir Capacity m³ × 10⁶ Normal	Reservoir Capacity m³ × 10⁶ Min	Reservoir Filling Date Started	Reservoir Filling Date Completed
Bear Creek**	FC	Colorado	Bear Creek	54.71	67.84	34.54	2.47	--	--
Carters	FC, P	Georgia	Coosawatee	136.25	583.43	465.01	226.96	1974	1975
Chatfield	FC	Colorado	South Platte	44.81	437.88	289.86	29.60	1973	--
Clark Hill	FC, P	Georgia-South Carolina	Savannah	60.96	3577.03	3095.98	1807.02	1951	1953
Cochiti	FC	New Mexico	Rio Grande	76.50	893.05	59.21	59.21	1975	1976
Dickey**	FC, P	Maine	St. John	102.11	9497.64	8017.49	5920.61	--	--
Lincoln School**	FC, P	Maine	St. John	25.91	107.31	--	34.54	--	--
Dworshak	FC, P	Idaho	Clearwater	218.54	4393.58	4277.64	1790.98	1971	1973
Libby	FC, P	Montana	Kootenai	112.78	7165.17	2260.93	1079.28	1972	1972
New Melones**	FC, P	California	Stanislaus	190.50	2960.30	382.37	382.37	--	--
Paintsville**	FC	Kentucky	Paint Creek	48.77	90.04	50.57	4.93	--	--
Richard B. Russell**	FC, P	Georgia-South Carolina	Savannah	55.44	1265.53	1201.39	1108.88	--	--
Tocks Island†	FC, P	Pennsylvania-New Jersey	Delaware	48.77	1042.27	642.63	118.41	--	--
Warm Springs**	FC	California	Dry Creek	97.23	469.95	302.20	24.67	--	--

* FC = flood control; P = power.

** Under construction.

† Discontinued project.

40. The remaining portion of this report deals with specific aspects of microearthquake monitoring at CE installations. This information was obtained from final reports, summaries, progress reports provided by contractors, letters and memoranda from CE offices, and, in a few cases, formal publications.

Chatfield and Bear Creek Reservoirs, Colorado

41. The Omaha District of the Missouri River Division, Corps of Engineers, initiated a microseismic monitoring program at Chatfield Reservoir, located southwest of Denver, Colorado, in the spring of 1973. The project was contracted to the Colorado School of Mines (CSM). Dr. Maurice W. Major of the CSM Department of Geophysics is the principal investigator. Monitoring at Bear Creek Reservoir was begun by CSM in January 1976. The purposes of the monitoring are to provide data for the seismic risk evaluation of both dams, to record earthquake activity (if present), and to permit comparisons to be made of pre- and post-filling seismicity. The geology at these sites is given below.

Geology of Bear Creek Dam and vicinity

42. Bear Creek Dam and Lake are located at the western edge of the Great Plains near Morrison, Colorado, at the foot of the Rocky Mountains. The sedimentary section extending below the dam consists of sandstone and shale beds totaling more than 13,000 ft* in thickness. These beds range in age from Pennsylvanian to Early Tertiary, and they overlie a basement of Precambrian igneous and metamorphic rock (Figures 2 and 3). The dam is on the eastern edge of a zone of monoclinal folding that trends N 25° W along the front. West of this zone of monoclinal folding, the Precambrian rocks are exposed in the mountain terrain.

43. A dominant structural feature of the region is the southeastwardly trending Golden fault. The mountainous region to the west has been elevated along this fault structure (Figure 3) and the monoclinal

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

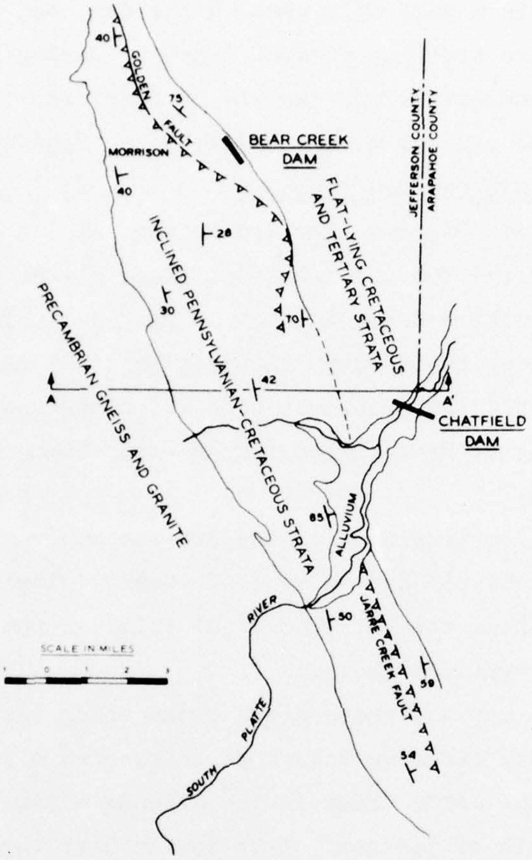

Figure 2. Geology at Chatfield Dam

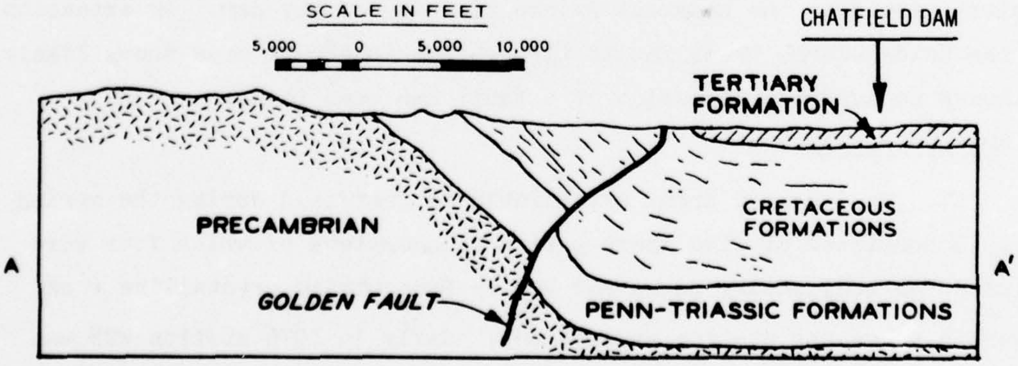

Figure 3. Geologic cross section showing Golden fault

dip of strata is another manifestation of the uplifting. The Golden fault passes within a half mile west of the dam, and other faulted or disturbed zones are probably present nearby. Geological evidence suggests major movement before the end of Paleocene time on the Golden fault and the last sign of movement was in the Pleistocene.[8]

Geology of Chatfield Dam and vicinity

44. Chatfield Dam and Lake are located at the western edge of the Great Plains near the foot of the Front Range of the Rocky Mountains. The sedimentary section below the dam is gently dipping sandstone and shale beds of Pennsylvanian through Early Tertiary age and has a thickness of about 13,000 ft.[9] The basement upon which the sedimentary rocks rest is composed mostly of Precambrian igneous and metamorphic rocks (Figures 2 and 3).

45. Six kilometres west of the dam the major part of the section surfaces as a relatively narrow zone of steeply dipping beds that trend N 25° W. Beyond this zone of monoclinal folding, the Precambrian rocks are exposed at elevations above.

46. Faults cut the sedimentary rocks along the monoclinal zone. The southeastwardly trending Golden fault reaches a point 10 km northwest of the dam, and the Jarre Creek fault[9] extends along the same trend from a point 16 km south of the dam. Both faults have throws of thousands of feet. Quaternary movement is said to have occurred on the Golden fault.[8] Numerous old faults trend northwest through the Precambrian rocks from the front of the mountains[7] and suggest that there are other inactive faults limited to the basement in the vicinity of the dam. An extension of the Golden-Jarre Creek faults through the reservoir area seems likely although no surface expression of a fault has been found.

Seismic networks[9]

47. The seismic array established at Chatfield during the spring of 1973 consisted of five short-period seismometers of which four were situated on sedimentary rocks and one on Precambrian crystalline rock. Figure 4 shows the station arrangement. Early in 1976 station WTN was dropped from the Chatfield network and two additional stations were

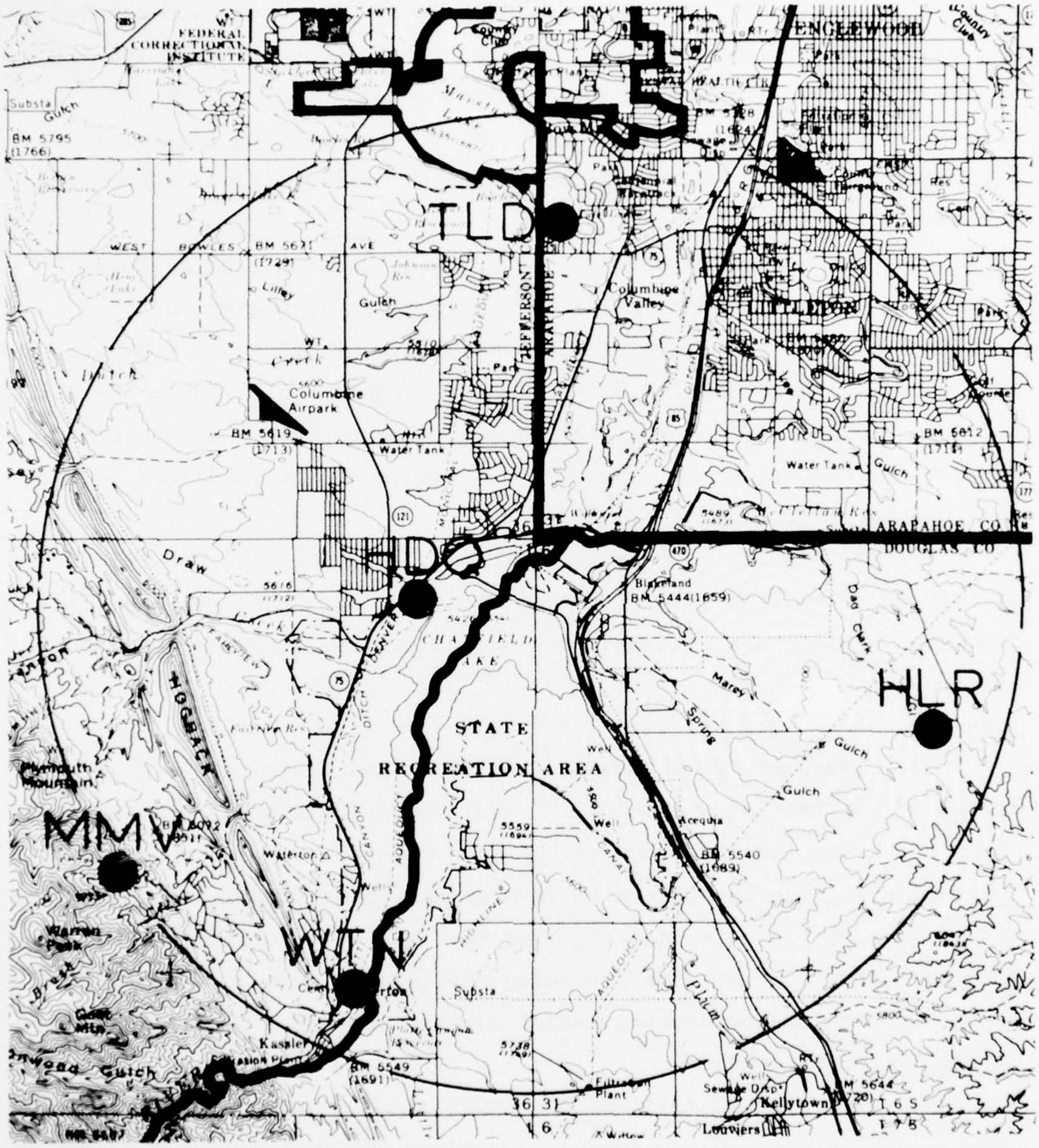

Figure 4. Microseismic array at Chatfield and Bear Creek sites[8]

located in the vicinity of Bear Creek Reservoir. These stations are complemented by the existing worldwide standard seismic station (GOL) located at Bergen Park and an additional short-period station located in the CSM Geophysics Department at Golden, Colorado. Recording and chronometry are performed in the Geophysics Department on the CSM campus. Two telephone links connect the arrays with the recording equipment at CSM and ground lines connect the seismometer stations to the telephone links.

48. The instrumentation at each station consists of a short-period vertical component, velocity transducer seismometer adjusted to 1 Hz, an amplifier having a damping resistance of 7600 ohms which is 83 percent of critical damping for a natural frequency of 1 Hz, a 12-volt d-c power source to the amplifier, and a voltage-controlled oscillator (VCO) which modulates the signals and connects to the landlines. These instruments are diagrammed in Figure 5.

49. At the recording station in the CSM Geophysics Department the signals received from the telephone line are demodulated and signals from each station are recorded on film. Figure 6 illustrates these instruments.

Costs

50. Purchase of instruments, salaries and certain maintenance costs, telemetry, and operation of recording systems are significant costs of the monitoring program. The two telephone lines (which are intermediate grade as opposed to data grade) cost approximately $300 per month. The recording system requires that the film be changed each day. Film and other supplies for recording may cost as much as $100 per month. The estimated average annual cost is $33,000.*

Seismic velocity studies

51. Velocity modeling of the upper crust in the general area of the reservoirs had been conducted in earlier CSM studies and was not a part of this contract.

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* Dr. Maurice Major, personal communication, Jul 1976.

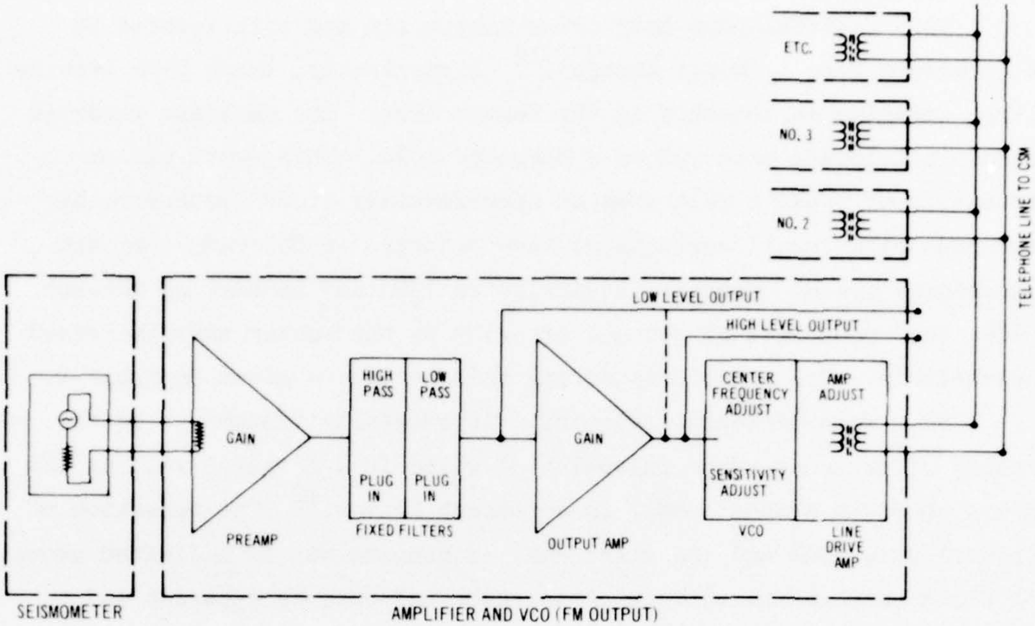

Figure 5. Field instruments at Chatfield and Bear Creek[8]

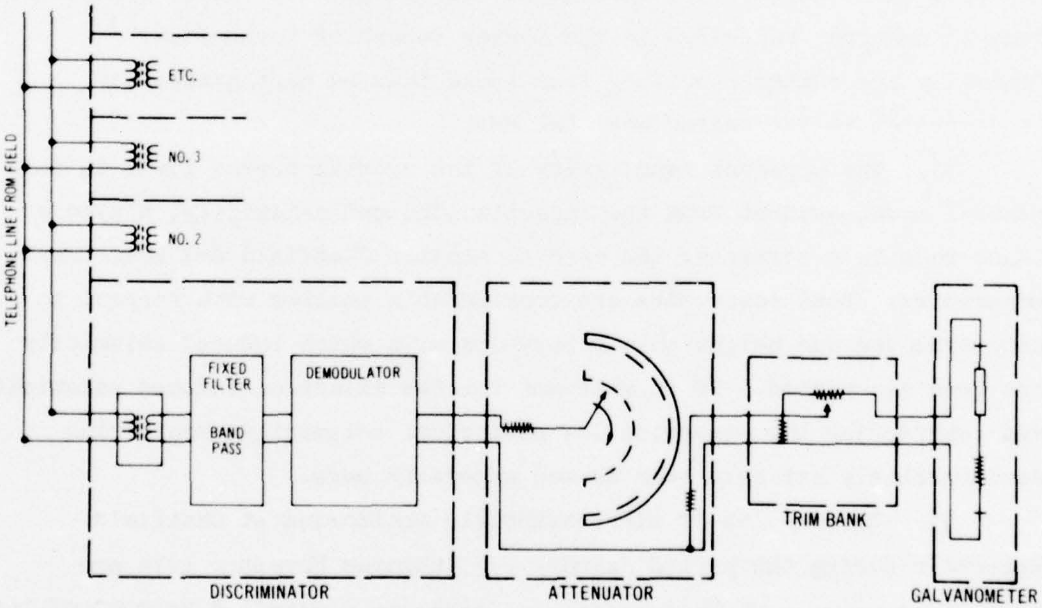

Figure 6. Receiving and recording instruments, Chatfield and Bear Creek[8]

Regional[10] and site[9] seismicity

52. Chatfield and Bear Creek Reservoirs are both located in Algermissen Zone 1 (minor damage).[11] Historically, there have been no large damaging earthquakes in the Denver area. The earliest reported event in Colorado occurred on 7 November 1882. This event had an intensity of V and a felt area of approximately 11,000 square miles. Numerous other small earthquakes have occurred in Colorado over the succeeding years. However, beginning in 1962 and continuing through 1970, the occurrence of seismic activity in the Denver area increased appreciably. The seismicity during this period is given in Table 2.

53. This increased seismicity is generally thought to be the result of the subsurface injection of waste in a disposal well at the Rocky Mountain Arsenal (RMA) in northeast Denver.[12] The cessation of injection in 1968 and the withdrawal or pumping out of a limited amount of fluid resulted in an initial decrease and then an apparent end to significant earthquake activity in the area. The damage produced by these earthquakes was not great compared to other United States events. However, the 9 August 1967 earthquake (the largest in Denver's history) damaged numerous buildings in the Denver suburb of Northglenn.[13] Generally the damage resulting from these induced earthquakes was concentrated in the region near the RMA.

54. The apparent sensitivity of the crustal stress field in this general area, evident from the injection-induced seismicity, played a major role in determining the need to monitor Chatfield and Bear Creek Reservoirs. Both reservoirs are considerably smaller with respect to pool area and dam height than reservoirs with which induced seismicity has been associated. If it were not for the injection-induced seismicity, and considering the otherwise low historical seismicity, monitoring would probably not have been deemed necessary here.

55. The results of microearthquake monitoring at Chatfield Reservoir during the period January 1973 through November 1974 are summarized by Fassett.[9] Fassett also presents a detailed account of the instrumentation, the sensitivity of the instruments in detecting microearthquakes, as well as information on the overall program. During

TABLE 2

SEISMICITY IN THE DENVER, COLORADO, AREA DURING 1962-1970

Date	Location	Magnitude
18 Jun 1962	Dupont	---
6 Aug 1962	Dupont	---
4 Dec 1962	Northeast of Denver	3.5
5 Dec 1962	North Central Colorado	4.0
2 Jul 1963	Northern Colorado	4.6
16 Feb 1965	Denver	4.9
18 Jul 1965	Denver	4.6
31 Jul 1965	Denver	4.6
13 Sep 1965	Denver	4.5
14 Sep 1965	Denver	4.7
29 Sep 1965	Denver	4.7
20 Nov 1965	Denver	4.5
4 Jan 1966	Denver	5.0
14 Nov 1966	Denver	4.3
10 Apr 1967	Denver-Commerce City	4.8
27 Apr 1967	Denver	4.4
9 Aug 1967	Denver (Derby Event)	5.3
15 Nov 1967	Denver	3.7
26 Nov 1967	Denver	5.2
15 Jul 1968	North Central Colorado	3.4
23 May 1969	Commerce City	3.3
23 May 1970	Commerce City	3.2

nearly two years of monitoring, representing pre-filling conditions, no natural seismic events could be positively identified. However, numerous explosions and other activities of man were recorded.

56. A conservation pool has not yet been established at Chatfield, and Bear Creek is still under construction. Thus, post-filling monitoring has not yet been performed. To date the pre-filling monitoring has revealed no positively identifiable earthquakes; however, six possible earthquakes have been detected.*

Childress Injection Well, Texas

57. The Tulsa District, Southwestern Division, conducted deep-well injection studies in Salt Area XIII, located in the northwestern quarter of Childress County, Texas, during the period 1970 through 1975. Microseismic monitoring of the injection area was conducted by the USGS during this same period. Salt Area XIII comprises the lower drainage area of Jonah Creek (see Figure 7), which is a tributary of the Prairie Dog Town Fork of the Red River. Saline seeps and springs in Salt Area XIII contribute an average chloride load of approximately 420 tons per day (of total chloride) to Lake Texoma downstream on the Red River. The purpose of the overall project was to test the feasibility of subsurface brine collection and deep-well injection of natural saline flows. The objective of the microseismic monitoring program was to determine pre- and post-injection seismicity in the vicinity of the well site.[14]

Site geology[14]

58. The surface geology in the area containing the injection well and the collection system consists of the Permian Blaine formation. This unit includes interbedded shale, siltstone, sandstone, gypsum, and dolomite. The Blaine as well as other younger Permian rocks is the principal source of the natural salinity in the area. The total stratigraphic section at the well site consists of approximately 8000 ft of

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* Personal communication from Dr. Maurice W. Major, July 1976.

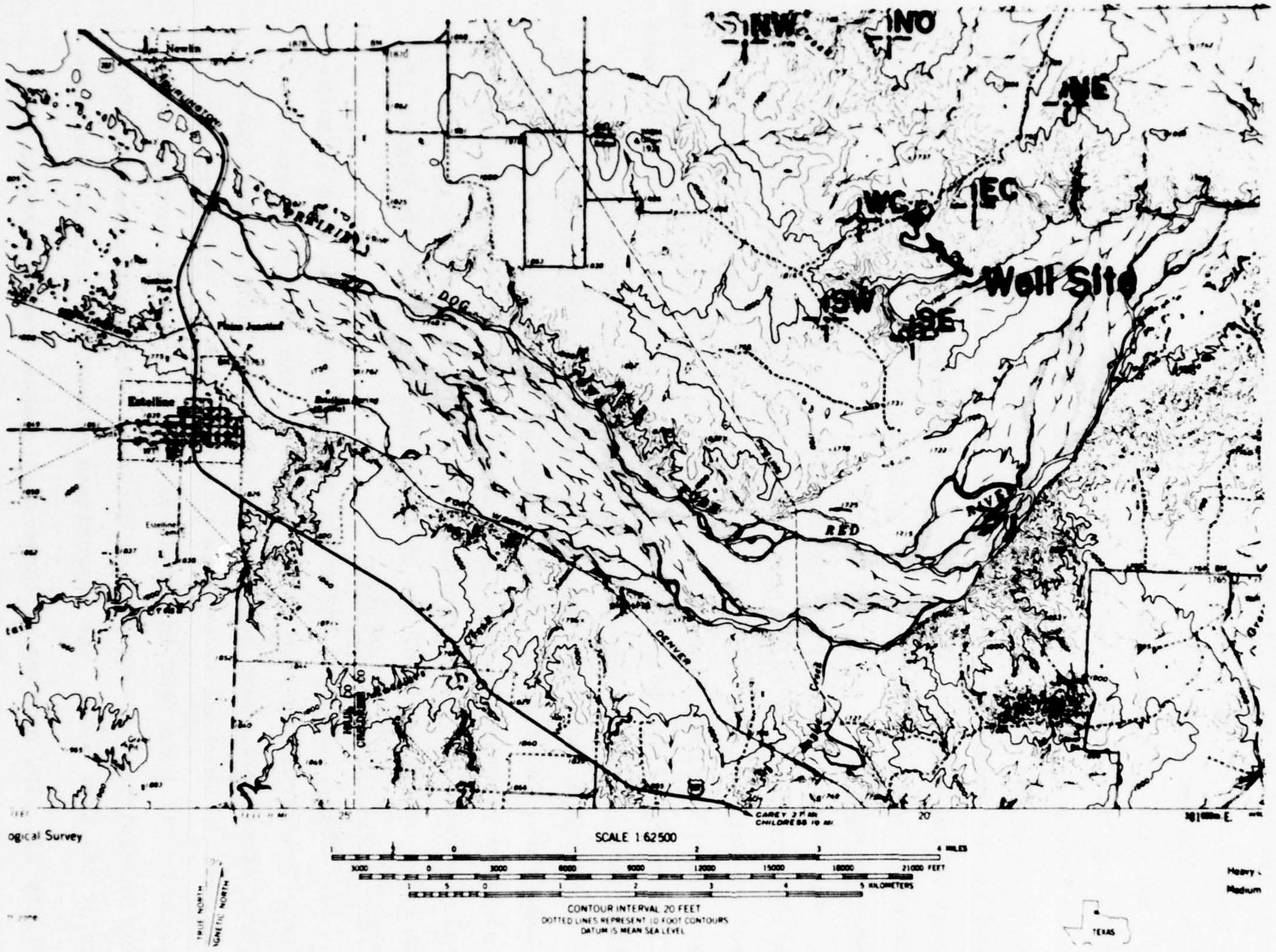

Figure 7. Site location and microseismic array at Childress, Texas injection well

sedimentary rocks ranging in age from Permian to Cambrian (see stratigraphic section shown in Figure 8). The brines were injected into the carbonate rocks of the Lower Ordovician, Ellenburger Group at depths between 6500 and 7840 ft.

59. The site area lies on the southwest flank of the Wichita-Amarillo uplift, an uplifted igneous basement complex exposed in the Wichita Mountains of Oklahoma and extending to the northwest in the subsurface of the Texas Panhandle. No surface-cutting faults have been mapped in the general region of the injection well. However, faults are present in the basement complex and also in the older parts of the sedimentary section. These basement faults are shown in Figure 9.

Seismic network[15]

60. The seismic network operated by the USGS from July 1970 to June 1975 consisted of eight seismometer stations situated about the injection well (Figure 7). The equipment at each station included a short-period vertical component seismometer, amplifier, voltage-controlled oscillator (VCO), and battery. The frequency-modulated signal from each station was carried by landline to a central point where the signals were multiplexed and transmitted by telephone to the recording station at Menlo Park, California. Upon arrival at Menlo Park, the incoming signals were recorded on magnetic tape prior to discrimination (or signal unsorting). After discrimination, the signals were recorded on 16-mm film. A schematic of the instrumentation is shown in Figure 10.

Regional[10] and site[16] seismicity

61. The Jonah Creek injection well is located in Zone 1 (minor damage) of Algermissen's seismic zonation of the United States. No historic earthquakes have occurred in Childress County, Texas; however, earthquakes in Oklahoma as well as in other parts of the Texas Panhandle have, no doubt, been felt in Childress County. Several earthquakes having intensities of V to VI have occurred within approximately 100 miles of the test site. The approximate epicenter locations are given in Figure 11. The sources of these earthquakes are believed to be buried structures on the Wichita-Amarillo uplift.

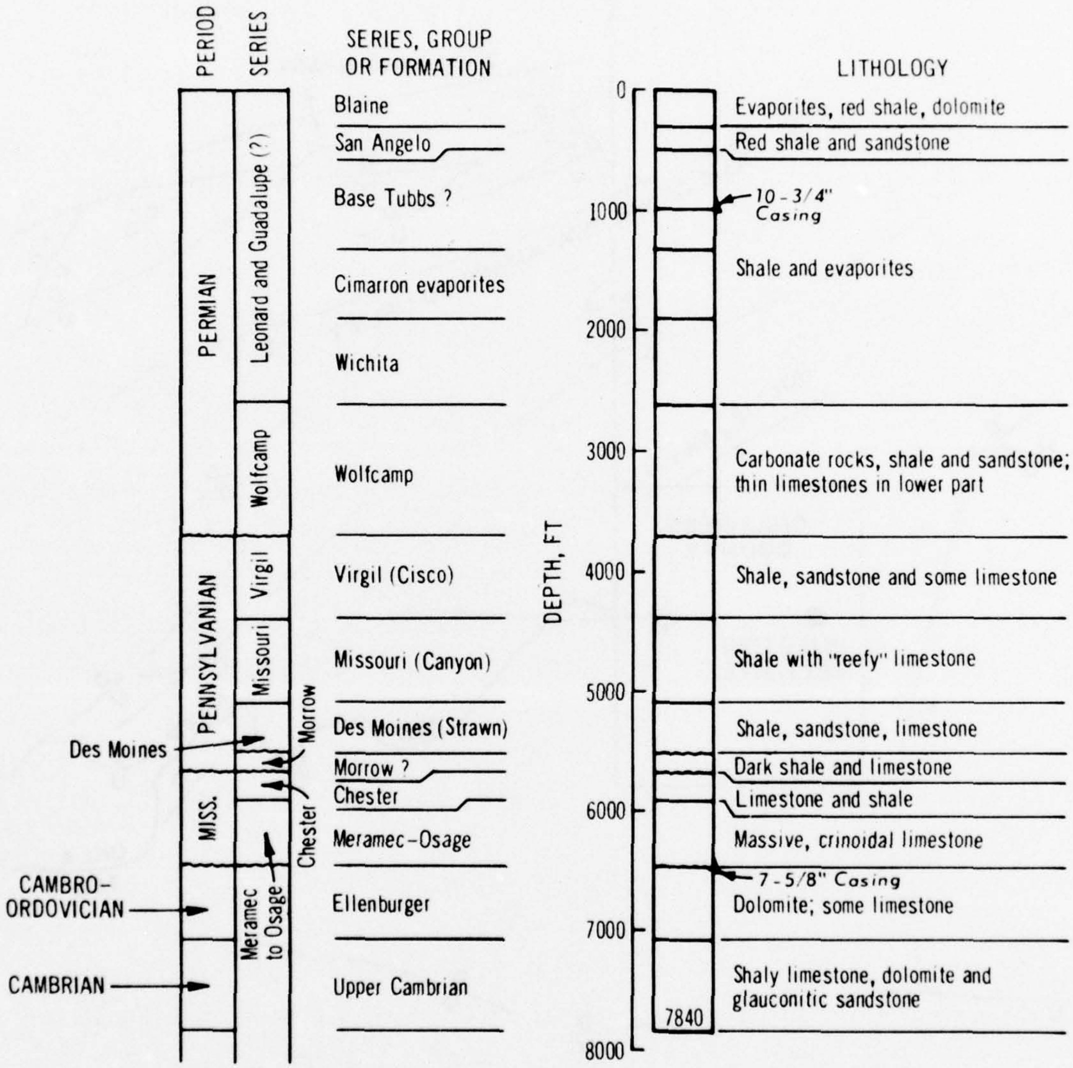

Figure 8. Stratigraphic section at Childress, Texas injection well

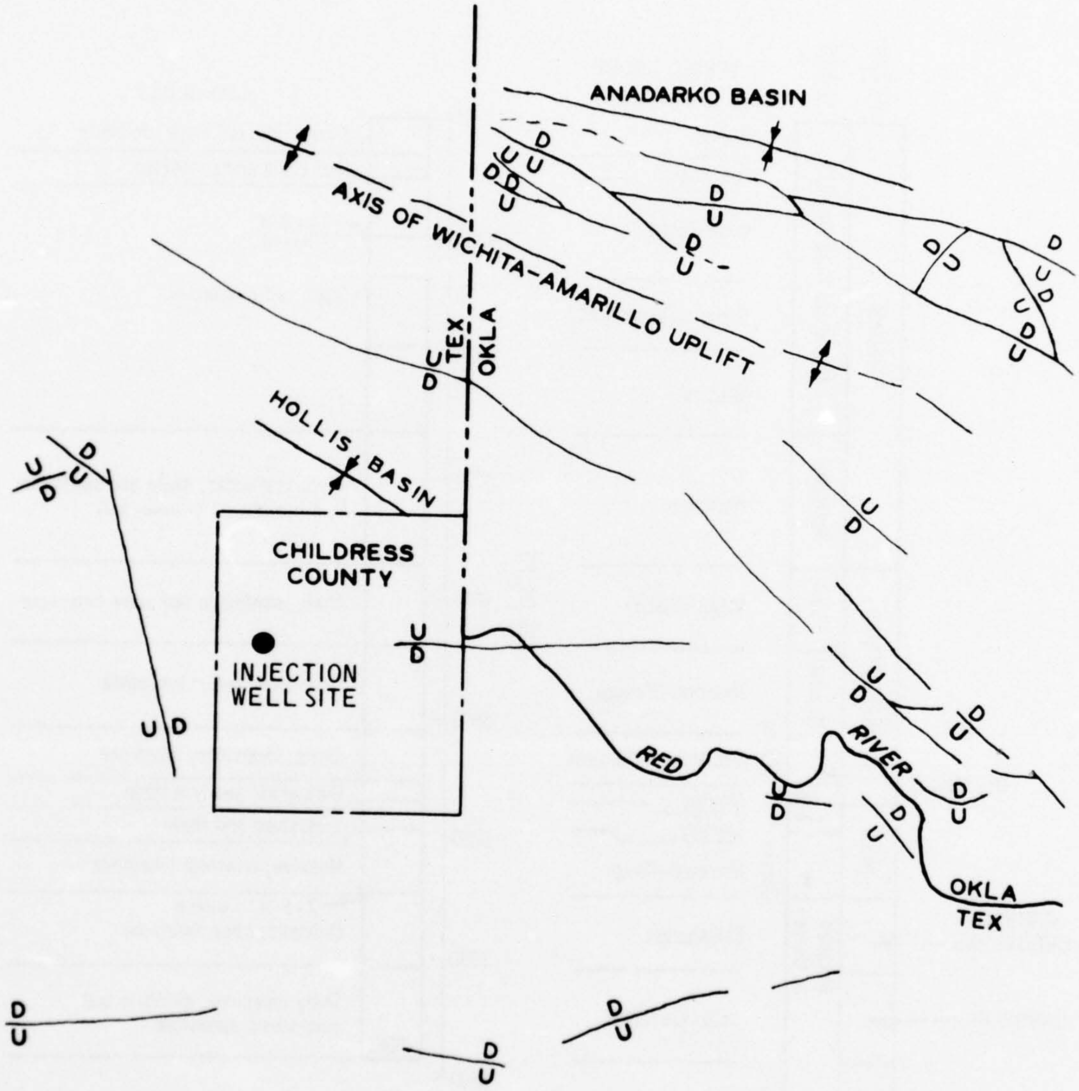

Figure 9. Regional basement faults in vicinity of Childress, Texas site

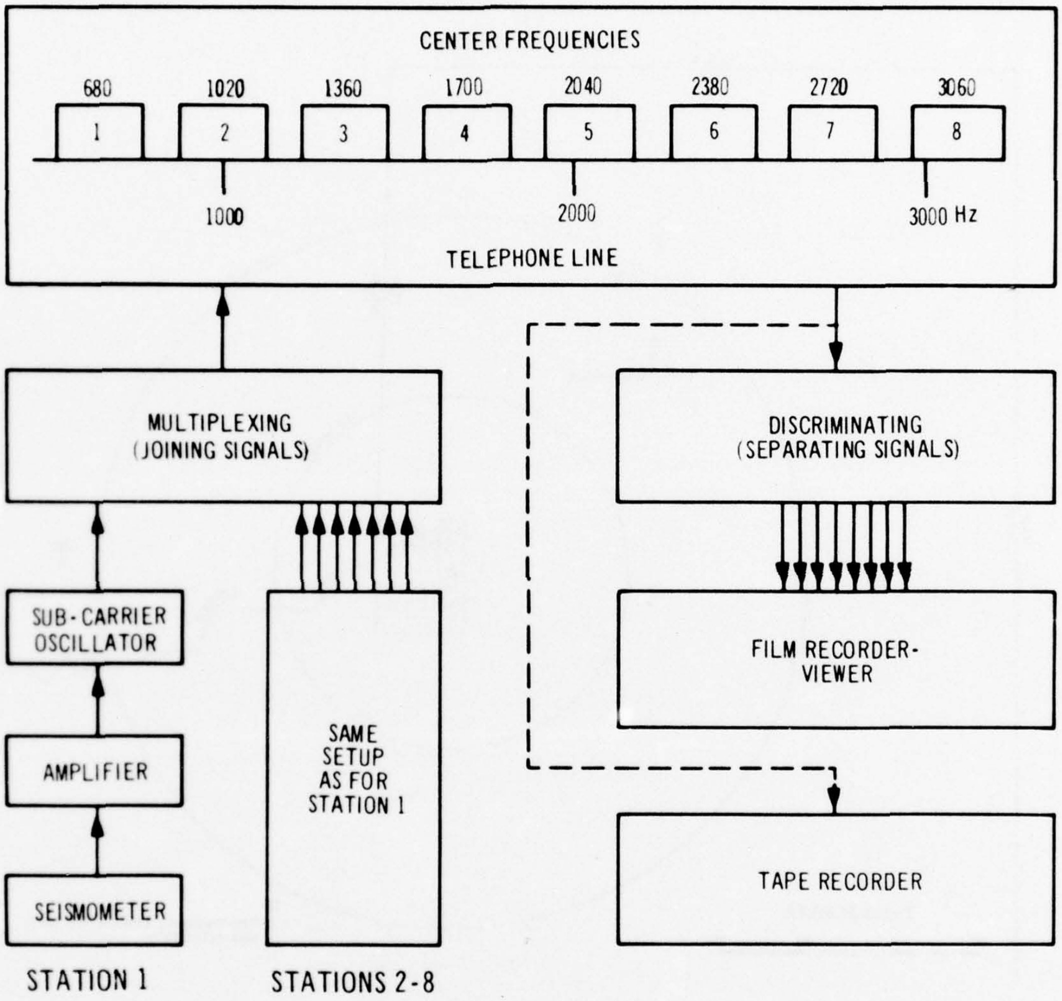

Figure 10. Seismic telemetry system for Childress, Texas, injection well[14]

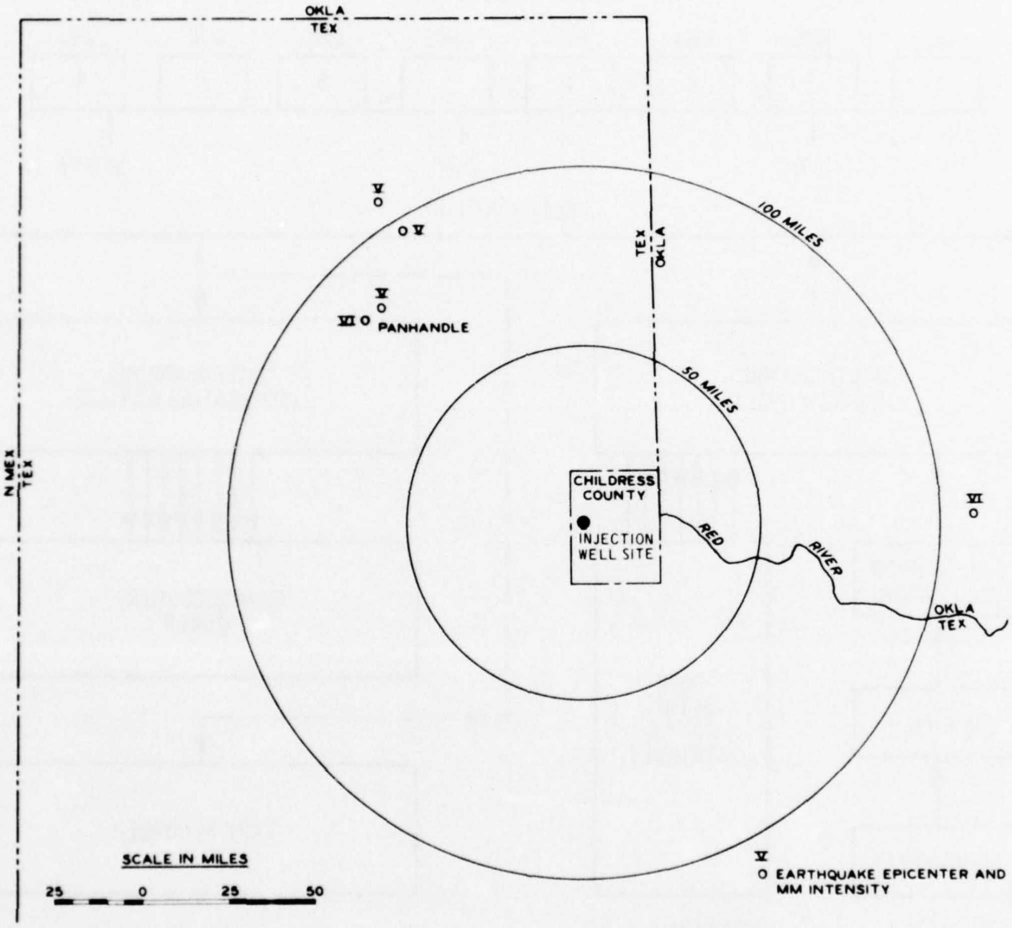

Figure 11. Historical earthquakes within 125 miles of Childress injection well.

62. During the period of seismic monitoring, several earthquakes originating in the Oklahoma City area as well as some from Missouri were recorded. Also, an earthquake (M = 4.5) was recorded from Perrytown, Texas, 225 km from the injection site. The monitoring thus indicated that the region was relatively aseismic and that the injection, which was begun in February 1974, had no effect on the local seismicity. On the basis of the absence of local seismicity, the USGS recommended that monitoring be discontinued.

Seismic velocity model

63. Regional, crustal seismic velocity measurements were not performed as a part of this project.

Costs[16]

64. The following are the approximate costs for monitoring the Childress site:

First year:	
Equipment	
Remote equipment, 7 @ $750	$ 5,200
Discriminators, 7 @ $450	3,200
Seismometers, 7 @ $275	1,900
Develocorder	11,000
Miscellaneous	1,000
	$22,300
Salaries	2,200
Installation expenses	2,200
Technical and administrative support	9,300
Total	$36,000
Second through next to last year:	
Salaries	$ 6,000
Telemetry	15,000
Maintenance	2,000
Computer time	800
Technical and administrative support	10,200
Total	$34,000/yr

65. Costs for the last year were approximately the same as those for the second year except for additional cost of $5,000 for equipment dismantling and report preparation.

Libby and Dworshak Reservoirs, Montana and Idaho

66. The University of Montana has conducted seismic monitoring at Libby Reservoir in Montana (Seattle District, CE) and Dworshak Reservoir in Idaho (Walla Walla District, CE) since 1971.* This effort was supported in terms of instrumentation and finances by the USGS for the period 1971 to 1973. The principal investigators are Drs. Gary W. Crosby and Anthony Qamar, both of the Department of Geology, University of Montana. Beginning in 1973 this work was funded by the above-mentioned CE Districts. The contract for monitoring Dworshak Reservoir was terminated in December 1975 and CE support for Libby Reservoir was terminated in the fall of 1976.** The objectives of this monitoring program were (a) to provide close-in monitoring of all seismic activity; (b) to compare pre-filling and post-filling seismicity; and (c) to relate local seismicity to regional seismicity. The site geology at Libby and Dworshak Reservoirs is given below.

Geology of Libby Dam and vicinity[17]

67. Practically all of the rocks in this region are slightly to moderately metamorphosed sedimentary rocks of the Precambrian Belt Series consisting of quartzite, argillite, and argillaceous limestone. The four specific units recognized locally within the Belt Series are the Prichard Formation, Ravalli Group, Wallace Formation, and Missoula Group. These beds are arranged in broad open folds with axes trending N 30° W. The section in Figure 12 crosses normal to this trend and reveals the fold structure from a point south of Libby and 16 miles

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* Prior to 1971 the CE had monitored the areas with Benioff-type seismometers.

** Monitoring is expected to continue at Libby and will be conducted by CE personnel.

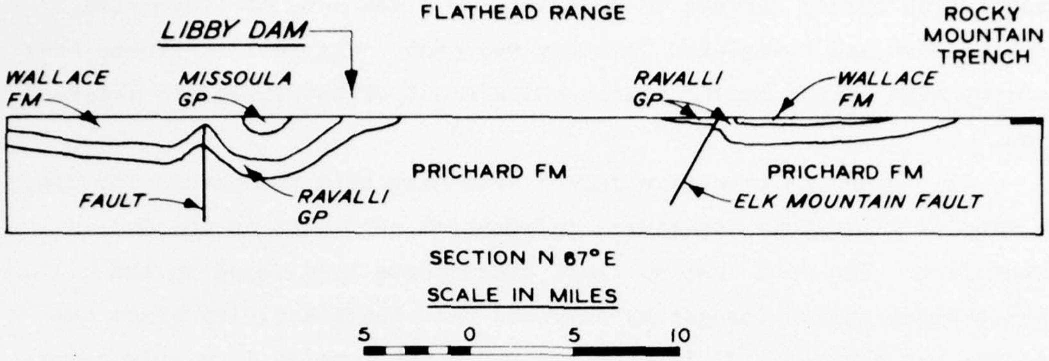

Figure 12. Geologic cross section, Libby site

southwest of the dam to a point southeast of Stryker and 33 miles northeast of the dam. Bedding dips usually range from horizontal to about 70°, but within 2 miles of the dam they are about $40 \pm 10^{\circ}$.

68. Two major faults are well established in the region. One fault passes a point 5 miles west of the dam in following the crest of an anticline. A parallel fault may continue the trend to the southeast from a position within 2 miles of the dam and generally along Fisher River.

69. The Elk Mountain fault is a major, well-defined thrust passing through a point 18 miles northeast of the dam (see Figure 12). In Design Memorandum No. 5, Libby Dam Project,[17] the fault is described as a zone of gouge and intensely sheared rock several hundred feet wide that strikes N 10° W and dips 65° W. No evidence of recent fault activity was found during investigations for the Libby Project.

Geology of Dworshak Dam and vicinity[18]

70. Rock types underlying the drainage basin are of considerable variety and complexity largely because of the intricate intrusive relationship of Mesozoic granitic types to similar-appearing metamorphosed Precambrian Belt Series sedimentary rocks. The highly metamorphosed rocks are known as the Orofino series and have been simply

classified as granitic gneiss though several gneissic types are recognized. The upland surface is underlain by a sequence of flat-lying basalt flows and associated Tertiary sediments (Figure 13). These beds outcrop high on the canyon flanks but are out of the immediate reservoir area.

71. Since no extensive marker beds have been recognized for use in mapping geological structure, information on faults at the dam is incomplete. The fact that no fault traces have been found on the basalt-based upland topography suggests that fault activity since the Miocene has been negligible. On the whole, the gneiss is highly competent; field compressional wave velocities are on the order of 15,000 fps.

Seismic networks

72. The initial seismic networks or arrays at both Libby and Dworshak Reservoirs (Figure 14) each consisted of eight seismometers, variable-control oscillator (VCO), batteries, and circuitry for interfacing with the telephone system. Also, five stations at Dworshak required the use of radio links to tie remote stations to the telephone system. During the summer of 1974 the number of stations at both reservoirs was reduced to four. The data from the seismometers in the networks were transmitted by commercial telephone to the University of Montana campus at Missoula where, after discrimination and demodulation, the data were recorded on film. The University of Montana operates a worldwide standard seismic station at Missoula which complemented the data from the arrays. Chronometry and hypocenter determinations were performed at Missoula.

73. Monitoring at Libby was begun in-house by the Seattle District in the fall of 1976. The operation consists of three stations rather than the existing four and all stations will maximize the use of radio telemetry to the damsite.

Costs

74. The cost for the monitoring period, 1 July 1975 to 30 June 1976, at Libby Reservoir is given below:

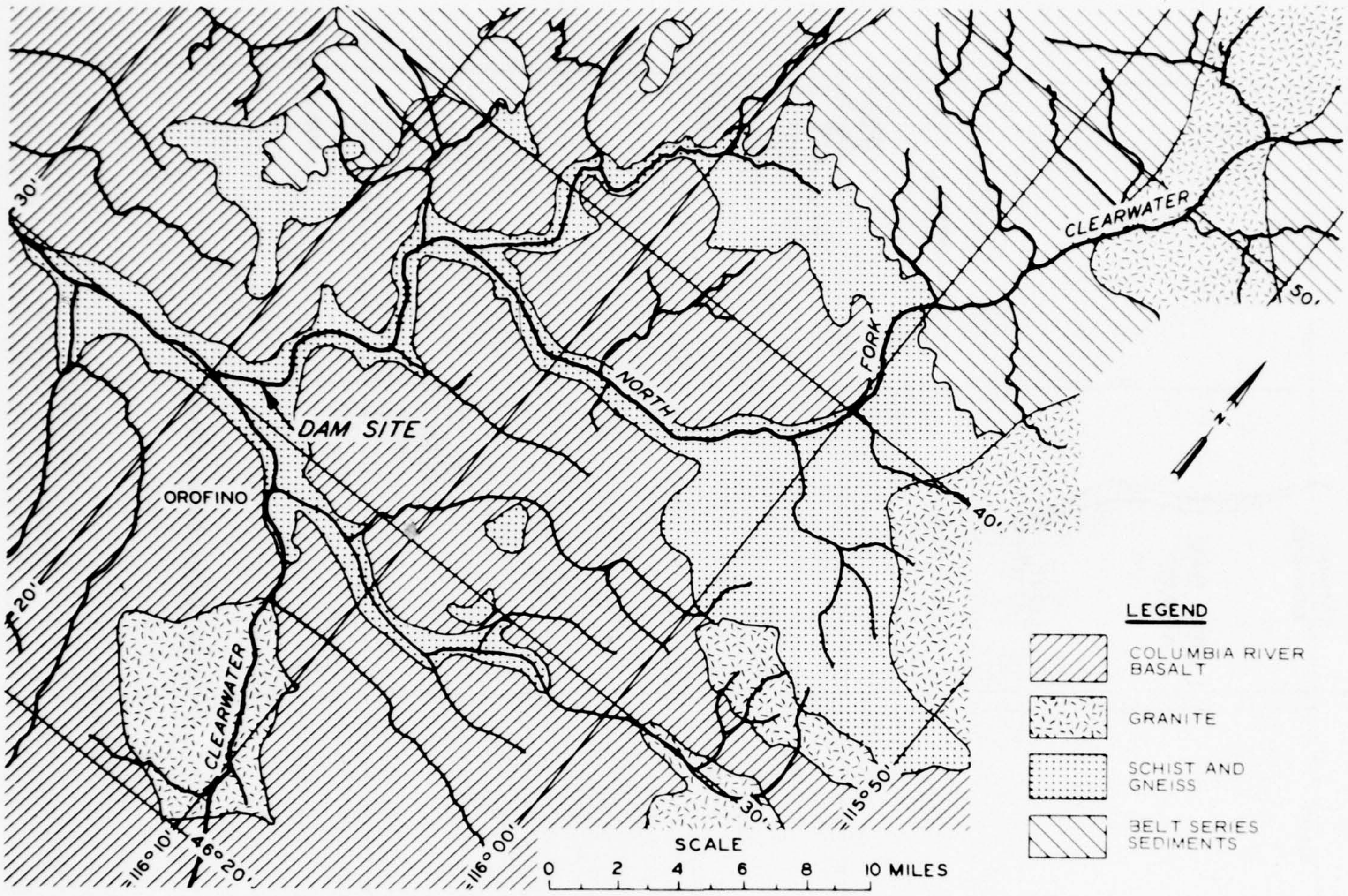

Figure 13. Regional geology, Dworshak site

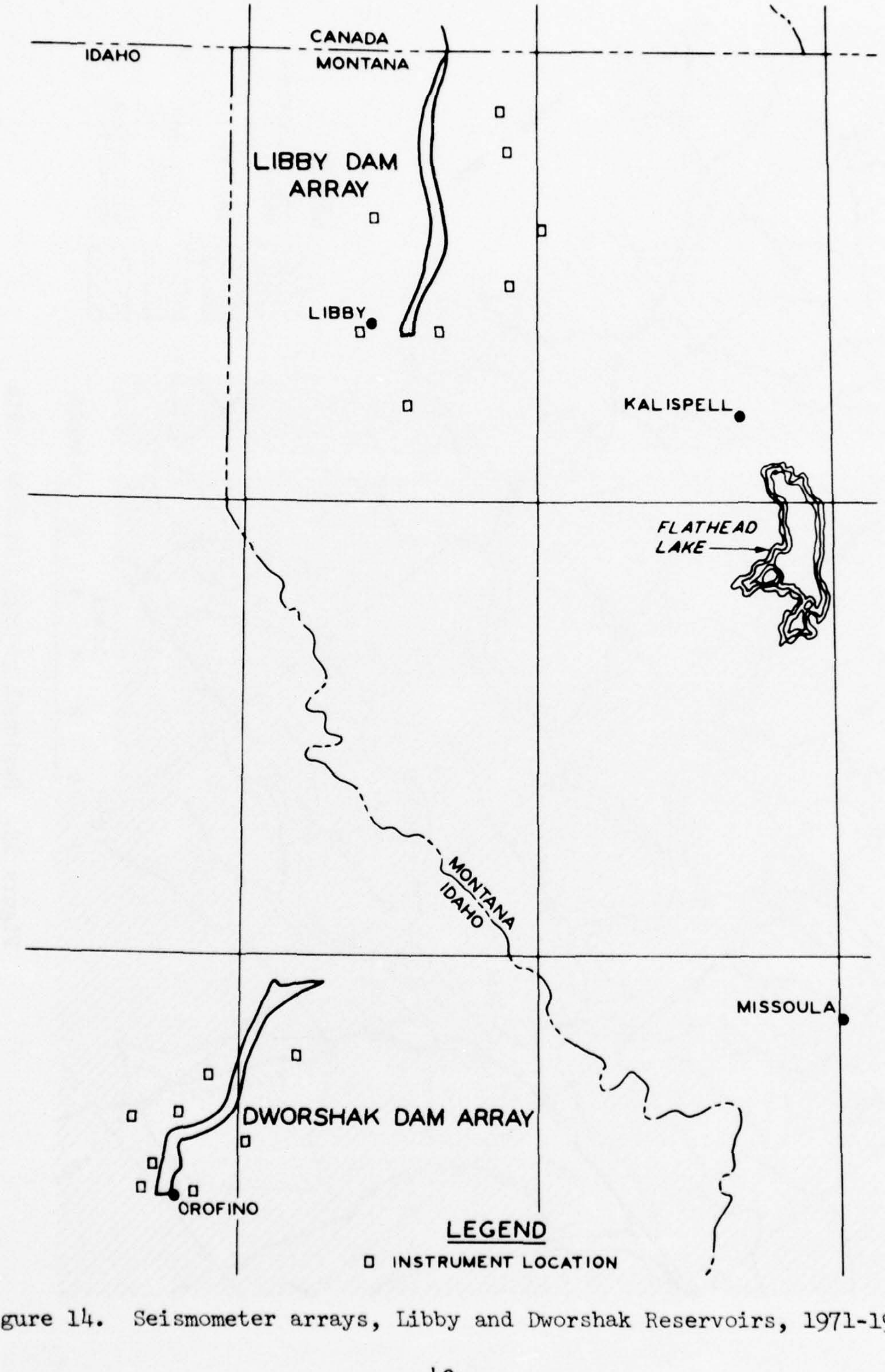

Figure 14. Seismometer arrays, Libby and Dworshak Reservoirs, 1971-1974

University of Montana Contract

Salaries and fringe benefits	$ 6,045
Operational costs (materials, supplies, and services	
Telephone line rental, 12 months @ $540	6,480
Long distance calls	50
Develocorder supplies, 12 months @ $50	600
Repair costs	200
Batteries	470
Reproduction	50
VCO replacement	165
Discriminator replacement	160
	$ 8,175
Travel	791
Indirect costs	3,349
TOTAL	$18,360

75. Additional costs included the analysis and review of data by the CE. This amounted to approximately $13,000.

76. The cost for monitoring Dworshak Reservoir for two years was $31,943.

Seismic velocity model

77. The University of Montana has conducted numerous seismic surveys in both reservoir areas. These surveys consisted of measuring arrival times from mine, quarry, and road construction blasting. This work has resulted in the development of a crustal model for the area and the determination of seismic velocities. These previous studies were not a part of the contracted monitoring program. However, they contributed to the determination of hypocenters for events detected during monitoring.

Regional[10] and site seismicity

78. Both Libby and Dworshak Reservoirs are located in Zone 2 (moderate damage) of Algermissen's seismic zonation of the United States and lie appreciably outside of the Intermountain Seismic Belt (Zone 3,

major damage). Although as previously stated no active faults are known at either site, the general area has experienced several rather large earthquakes and numerous small ones.

79. Major earthquakes include the 27 June 1925 event near Helena, Montana. This earthquake had an epicentral MM intensity of VIII and a magnitude of 6.75. The shaking caused damage in the epicentral area and the felt area covered 310,000 square miles. The largest known earthquake in this general area was the 17 August 1959 event near Hebgen Lake, Montana. This earthquake exhibited an intensity of X and a magnitude of 7.1. The shock was felt over 600,000 square miles, caused considerable damage, and resulted in the loss of 28 lives. The low regional population density and late settlement of this area have resulted in a rather incomplete definition of the regional seismicity. The historic seismicity of the general region is shown in Figure 15.

80. Numerous local events were registered at both arrays. The two arrays have averaged approximately three events per day; however, it is believed that half of them may have been caused by blasting. Among the bona fide earthquakes registered were several from the Yellowstone area. Some of these were magnitude 3 to 3.9. The period of monitoring has covered both pre- and post-filling of the reservoir, and there has been no indication to date that the filling of either reservoir has resulted in a change in the seismicity of the region. Figure 16 shows a plot of earthquake events per month versus pool elevation at Libby Reservoir. There does not appear to be any correlation between seismicity and pool level during this period. The data obtained illustrate the importance of long pre-filling monitoring; if monitoring had started in late 1971, the conclusion could have been drawn that reservoir filling caused increased seismic activity.

Paintsville Project, Kentucky

81. The Paintsville Project consists of a proposed rockfill dam with central clay core in eastern Kentucky (see Figure 17). The reservoir area has exhibited no historical seismic activity and the Paint

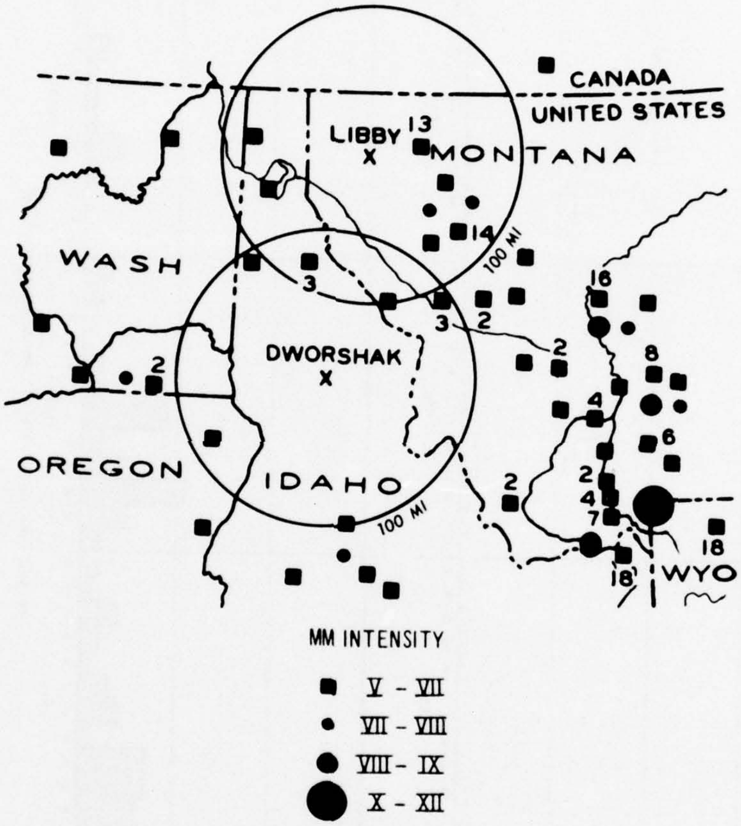

Figure 15. Regional historic seismicity at Libby and Dworshak reservoirs

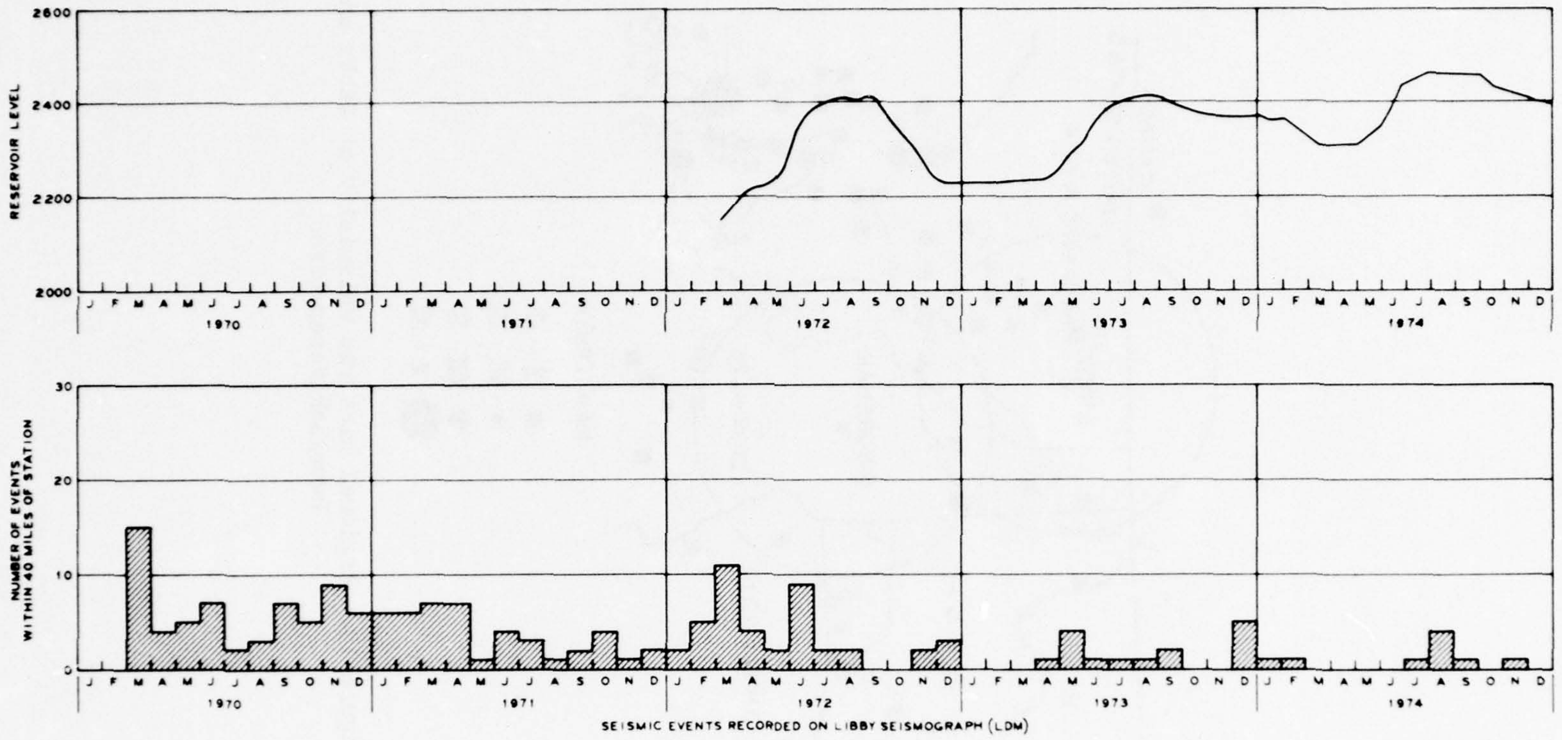

Figure 16. Plot of seismic events versus reservoir level, Libby Reservoir

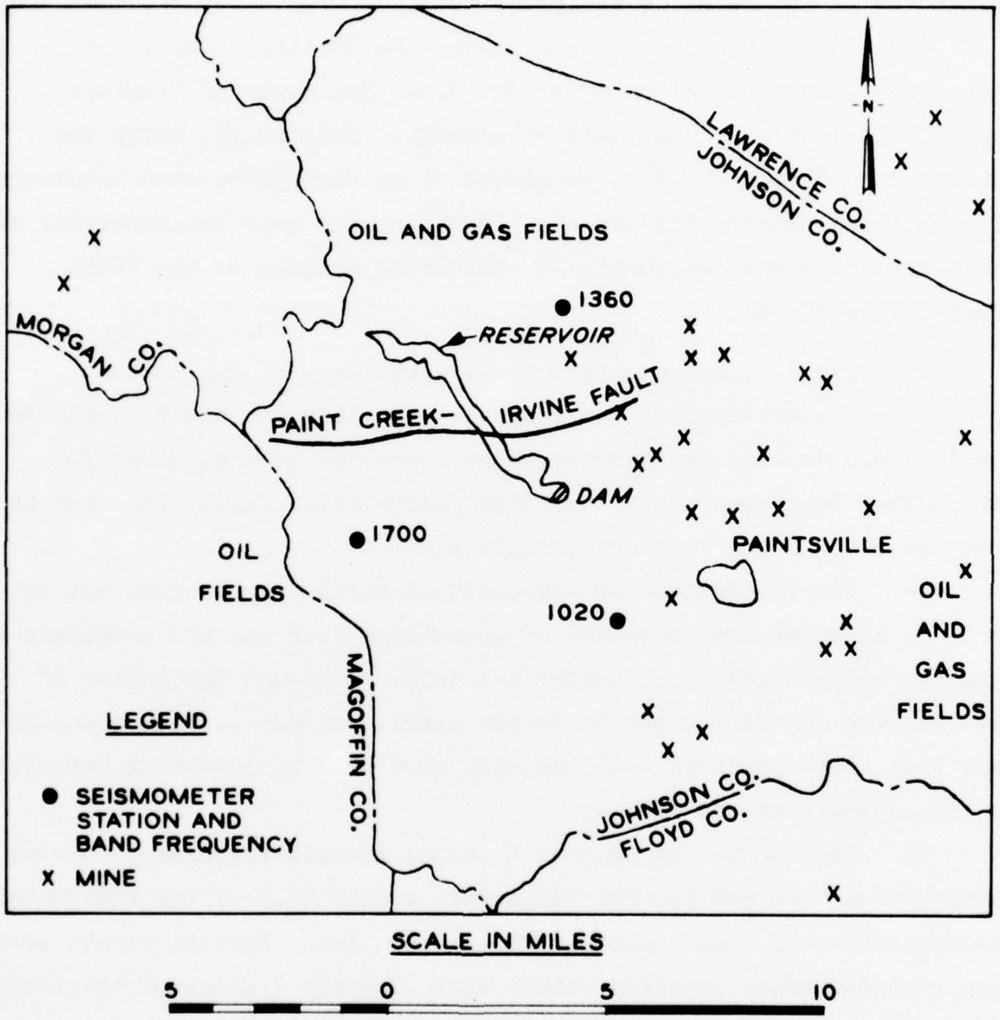

Figure 17. Location map of Paintsville Reservoir showing seismometer stations and Paint Creek-Irvine fault

Creek-Irvine fault near the site is not considered to be active (see paragraph 92). Even so, opponents of the reservoir alleged that the Paint Creek-Irvine fault may pose an earthquake hazard to the dam. The allegations generally suggested that the proposed reservoir might induce seismicity at the Paint Creek-Irvine fault.

82. In response to these charges, the Huntington District contracted a geophysical study to Dr. G. A. Bollinger of Virginia Polytechnic Institute and State University. This study, which was completed in September 1973, consisted of an earthquake risk investigation of the proposed site and the general region near the reservoir area and a reconnaissance microseismic monitoring program on the Paint Creek-Irvine fault.

83. The earthquake hazard study supported the Huntington District's contention that the reservoir area had not experienced strong shaking from distant earthquakes, that there had been no historic earthquakes generated along the Paint Creek-Irvine fault, and that the area exhibited a low level of seismic risk.

84. The reconnaissance microseismic monitoring program was one month in duration and consisted of operations from one and sometimes two strategically located seismometer stations. Although the number of stations was not sufficient to locate exact epicenters, the consultant felt that these stations could provide some data on low-level seismicity in the vicinity of the faults.

85. The monitoring program detected microearthquakes occurring at rates between one and two per day within a half mile of the instrument. The magnitudes of these events were zero or less. Several events were also recorded which occurred within approximately 7 miles of the instrument. This occurrence rate for the close-in events is not known to be either typical or atypical for eastern Kentucky.

86. Several swarms of microearthquakes were also recorded following periods of rainfall. The magnitudes of these events ranged from -1/2 to 0. The origins of these events were not known; however, Bollinger offered the following possible explanations:

a. "Tiny movements along the Paint Creek-Irvine fault."*

b. "Slumping of exposed rock outcrops on the sides of Paint Creek Valley."

c. "Local bedrock response to gravity loading by creep action of a saturated soil overburden."

d. "Involvement with water flooding process at a nearby oilfield."

87. This monitoring program thus raised certain interpretive questions regarding the nature of the site seismicity, namely the significance of measured background seismicity with respect to the fault as a source and the interpretation of the earthquake swarms. These questions may be due to the short duration of monitoring and to the use of only one or two instruments at a given time.

88. Therefore, Bollinger recommended that the Huntington District install a continuous-recording seismograph system at the site to monitor the local seismicity through all stages of construction. Accordingly, the District established a three-station seismometer array at the fault area during the summer of 1975 (see paragraph 94).

Geology of Paintsville Dam and vicinity[19]

89. Paintsville Dam is in the Cumberland Plateau physiographic province, locally known as the Eastern Kentucky coal field or Eastern Kentucky Mountains. This region has a maturely dissected, irregular high-level surface characterized by narrow winding ridges and dissected by deep, steep-sided valleys. All flat land is virtually confined to the flood plains and valley bottoms which border the rivers and larger tributaries.

90. Flat-lying sedimentary beds of two formations, the Middle Pennsylvanian Breathitt and the Lower Pennsylvanian Lee, comprise the bedrock of the drainage basin. The combined thickness of the two formations is approximately 1200 ft. The upper formation, the Breathitt, consists of interbedded shale, sandstone, siltstone, and coal, with

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* These possible movements would have been within 1/2 km of the surface, thus not indicating any significant earthquake-producing activity on the fault.

shale being the dominant rock type. The members of the Breathitt formation are inconsistent, gradational, and variable. Included thin limestones and marine shales indicate short periods of invasion and recession by shallow seas, and the coal beds are an indication of swampy lowlands. The Breathitt formation extends to the hilltops throughout the entire basin.

91. The lower formation, the Lee, is of the Pottsville series, and consists of several massive sandstone and conglomerate members and interbedded shale and thin coal seams. This formation is from 400 to 500 ft thick.

92. Structurally, Paint Creek basin lies on the eastern flank of the Paint Creek uplift. The axis of this broad regional structure trends north-south and crosses the headwater of Paint Creek. The uplift is accompanied by several local faults and folds of an east-west orientation, some of which culminate in domes. The most prominent of these structures is the Irvine-Paint Creek fault, which dips toward the south at approximately 85° and has a maximum stratigraphic displacement of about 180 ft. The fault is visible on the outcrop in many places. Near the community of Fishtrap, approximately 2.5 miles from the dam, about 50 ft of the Lee formation is exposed on the up-throw side of the fault against Breathitt beds.

93. Another prominent feature is the Paintsville anticline, which extends from the head of Pigeon Creek to the eastern edge of Paintsville. The axis of this anticline trends almost due east-west and appears to plunge toward the east.

Seismic network*

94. The instrument array shown in Figure 17 was designed to monitor both ambient seismicity beyond the fault and the seismicity on the fault. Each station consists of a short-period, vertical component seismometer and amplifier. Signals are carried from each station by buried and elevated hard wire to the telephone lines where the unmixed

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* This and following sections were based on information provided by Mr. John Bertram, Chief, Geology Section, Huntington District.

signals are carried to a regional telephone office. Signal modulation is performed at the telephone office and the mixed signals are transmitted by telephone lines and microwave relay to the Huntington District Office where they are discriminated and recorded on a heat-sensitive continuous recorder. Data analysis is performed at the District office and epicentral locations are determined there by computer.

95. Generally, this first year of monitoring has been one of debugging the instrumentation and refining the operation. The lengths of hard wire posed some problems due to the inducement of stray currents in the longer stretches, especially the buried portions. The hard wire sections, which varied in length from 2400 to 7400 ft, will be reduced by judiciously moving the instrument stations closer to the telephone lines. This is intended to reduce this problem. Also, lightning-induced currents have disrupted service at two stations. This will be corrected by placing lightning arresters in each system. Instrumentation problems such as these have resulted in only 40 days of monitoring by all three stations. However, one or two stations were recording during most of the first year.

Costs

96. The approximate costs of the monitoring program are given below:

First year:

Instrumentation	$25,500
Telemetry, @ $128 a month	1,540
Maintenance and supplies (mainly batteries and recording paper)	1,185
Salaries	3,500
Equipment calibration by manufacturer	850
Installation of buried cable	7,500
Test equipment	2,050
Computer time (2 hr/month)	1,000
Consultant fees	2,500
TOTAL	$45,625

Second and subsequent years (estimate):

Telemetry	$ 1,540
Maintenance and supplies	1,185
Salaries	3,500
Equipment calibration by manufacturer	850
Computer time	1,000
Consultant fees	2,500
TOTAL	$10,575

Seismic velocity model

97. The development of a seismic velocity model by seismic profiling was not conducted in this study. This was not believed to be necessary due to the existing detailed knowledge of the local stratigraphy and lithology and the uniformity of the geologic section.

Regional[10] and site seismicity

98. The proposed Paintsville Reservoir is in Zone 1 (minor damage) of Algermissen's seismic zonation of the United States. Bollinger identified seven historic earthquakes which have occurred within a radius of 100 miles of the site. The intensities of four of these earthquakes are unknown; the intensities of the other three varied from IV to VI. The closest earthquakes were two events of unknown intensity which occurred near Catlettsburg, about 45 miles northeast, in 1883. As previously mentioned, there was no identifiable relationship between the regional historic earthquakes and the Paintsville-Irvine fault.

99. The site seismicity as deduced from Bollinger's initial survey was discussed briefly in paragraphs 85 and 86. The Huntington District array has detected long-duration events occurring beyond the site area and also some local short-duration events which may be microearthquakes. The nearness of the site to numerous quarries and mines (see Figure 17), however, suggests that some, at least of the local events, may result from blasting.

Tocks Island Project, Pennsylvania and New Jersey

100. The Tocks Island project[20] consisted of a proposed* dam and reservoir on the Delaware River approximately 18 miles south of Dingman's Ferry, Pennsylvania. The Philadelphia District contracted the seismic investigations to the Lamont-Doherty Geological Observatory at Columbia University which conducted microseismic monitoring at the site for approximately two years beginning in 1972. Professor Lynn R. Sykes and Dr. Marc L. Sbar were the principal investigators. Upon termination of the contract in 1974, three of the original five stations were dismantled and the remaining stations continued to be operated by Lamont-Doherty.

Site geology

101. Generally, the bedrock geology at the site consists of folded Paleozoic rocks of the central Appalachian structural belt (see Figure 18). Faults at and near the site are also Paleozoic in age and were produced during orogenic cycles which culminated in the Appalachian Orogeny. The youngest faults occur to the southeast and south and are boundary faults of the Triassic basins. There are no known active faults in the general area of the site.

Seismic network

102. The monitoring array consisted of five short-period vertical component seismometer stations positioned along the Delaware River in Pennsylvania and New Jersey. Figure 19 shows the station locations. A pre-existing station at Ogdensburg, New Jersey, operated by Lamont-Doherty provided additional control.** The locations of the five stations were determined on the basis of providing the densest coverage of the deeper portions of the proposed reservoir (Nos. 1-3) and providing control for identifying earthquake epicenters. Signals from each station

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* This project was cancelled in 1975.

** Lamont-Doherty operates a regional seismic net in the northeastern United States.

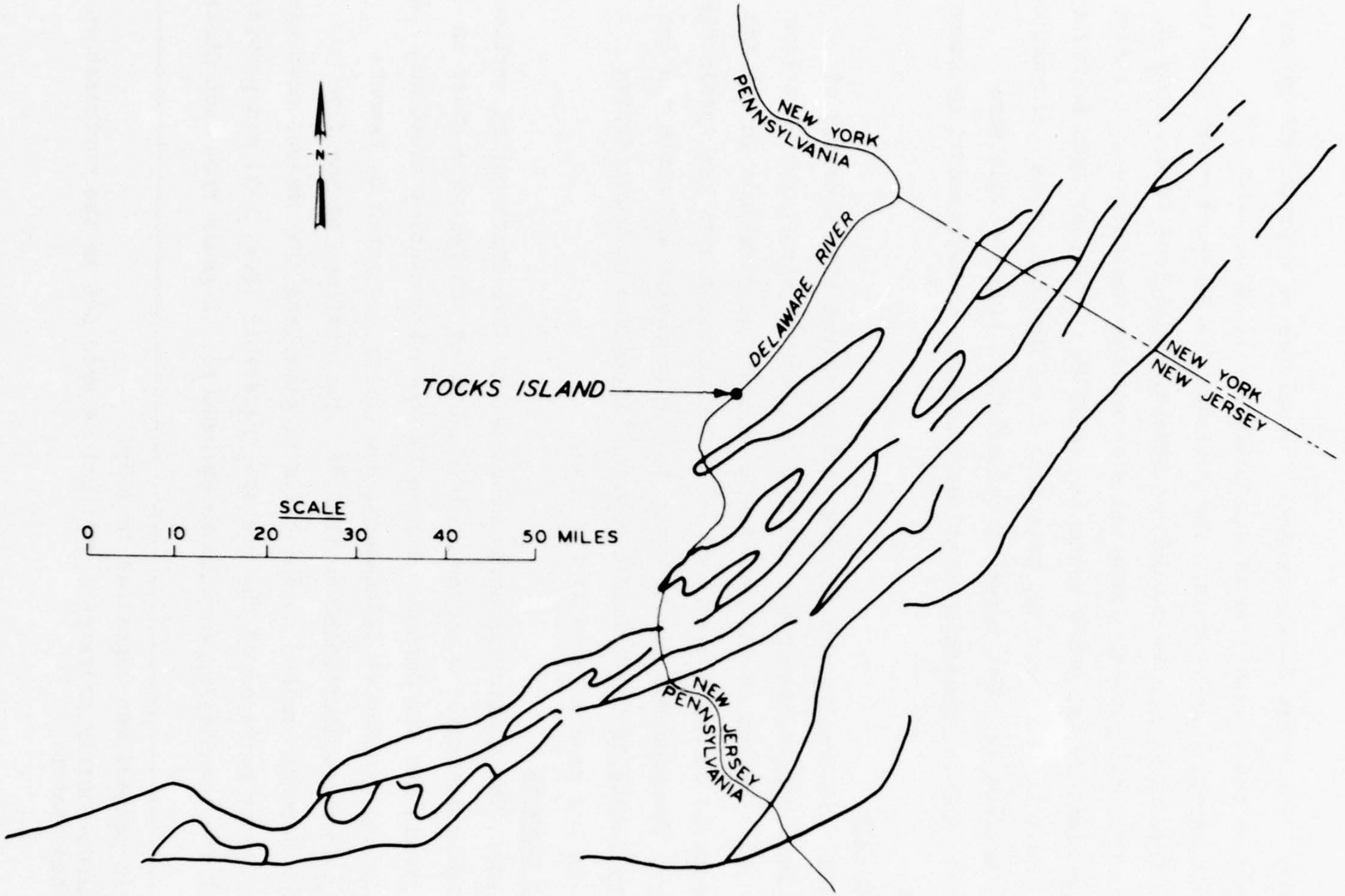

Figure 18. Regional faulting in the Tocks Island Reservoir area

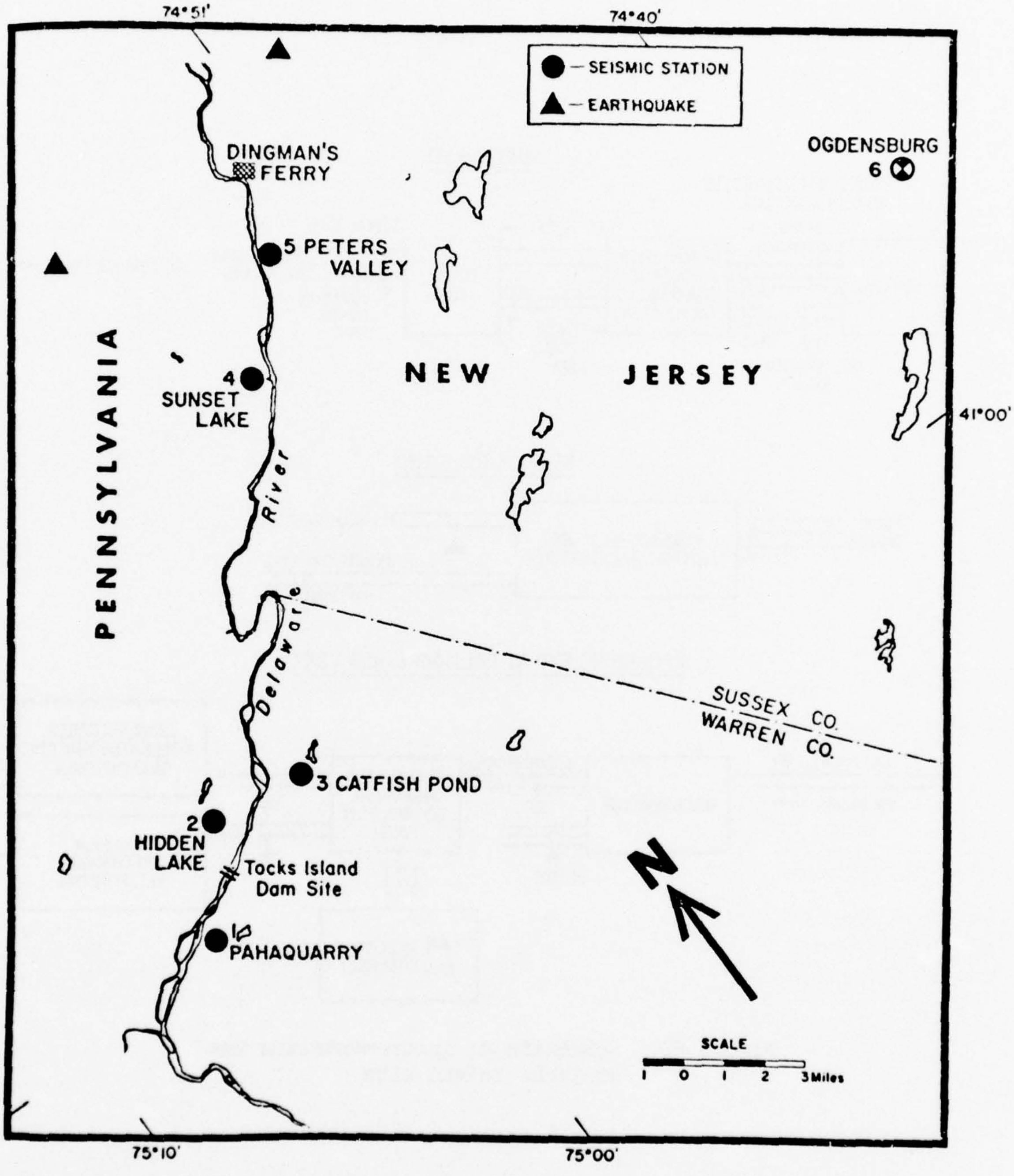

Figure 19. Seismic array, Tocks Island Project

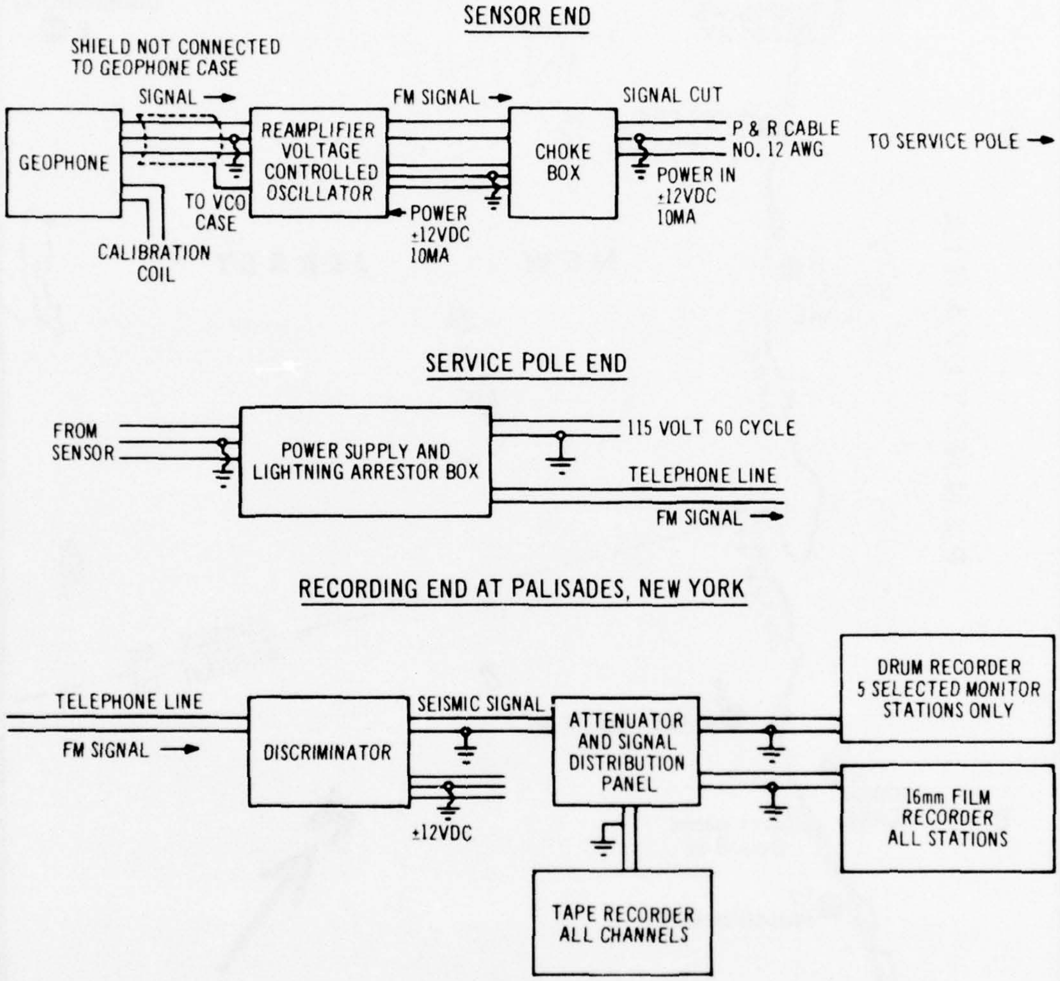

Figure 20. Schematic of instrumentation used at Tocks Island site

were transmitted by telephone to Lamont-Doherty where the data were recorded on magnetic tape and 16-mm film. Figure 20 shows a schematic diagram of the instrumentation used at this project.

Costs

103. The total cost of this project including instrumentation, maintenance, telemetry, salaries, and administrative expenses was $124,000 for two years.

Seismic velocity model

104. Seismic profiling was not included as a portion of this project.

Regional[10] and site[20] seismicity

105. The Tocks Island Project was located in Zone 1 (minor damage) of Algermissen's seismic zonation of the United States. The historic earthquake activity (shown in Figure 21) in this area has not been extensive and there have been no large damage-producing earthquakes

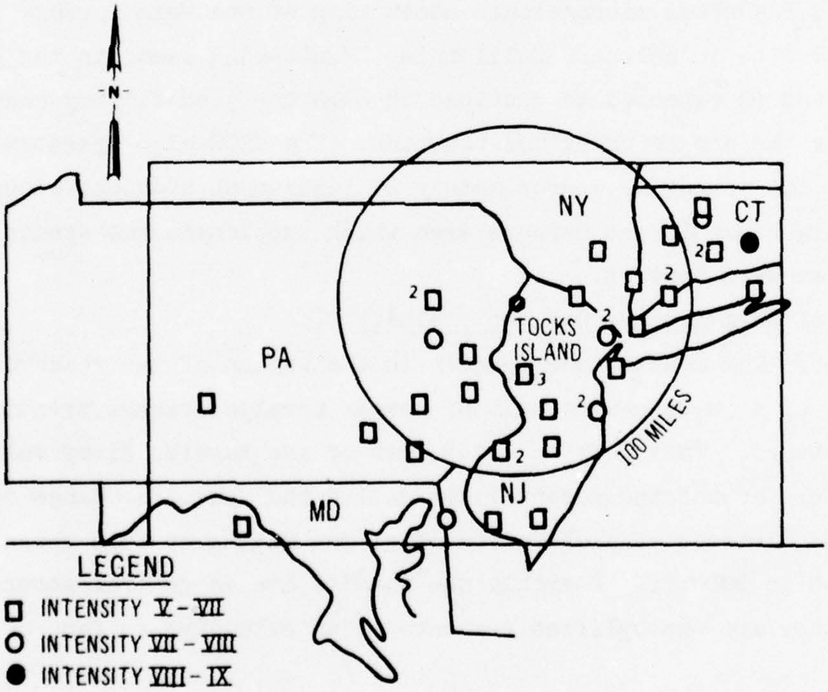

Figure 21. Earthquakes activity in the vicinity of Tocks Island Reservoir

within a radius of 100 miles of the site. However, there have been approximately 25 events occurring within this radius which had intensities of V to VIII. A local magnitude 3.4 event was reported to have occurred within 20 miles of the site and near Stroudsburg, Pennsylvania. This occurrence is considered questionable by Sbar.

106. Two years of monitoring at Tocks Island revealed very light microearthquake activity. Three possible microearthquakes were detected within approximately 30 miles of the site. These questionable events exhibited magnitudes of 0 to 1. Numerous quarry and other blasting was recorded by the net. Sbar concluded that the Tocks Island site was the least seismic of any area within the Lamont-Doherty regional net.

Warm Springs Reservoir, California

107. The USGS has, under contract with the San Francisco District, conducted microseismic monitoring at the Warm Springs Reservoir site in northern California. Monitoring began in the summer of 1975 and is expected to continue through the post-filling phase. Currently the dam is under construction. The USGS also operates other networks consisting of approximately 20 instrument stations along the Healdsburg Fault in the Geysers area which supplement the special network at Warm Springs.

Geology of Warm Springs Dam and vicinity[21]

108. The mountainous terrain in the region of the reservoir consists of a 50-mile-wide belt of nearly parallel ranges trending northwestward. That portion lying west of the Russian River valley and immediately around the reservoir is called the Mendocino Range or Mendocino Plateau. The elevation of ridges making up this range varies from 1200 to 3000 ft. Commonly the summits are in general accordance as though they are the uplifted remnants of an extensive surface of low relief.

109. Bedrocks are principally of the Cretaceous-Jurassic Great Valley and Franciscan assemblages which are in contact at the dam along the Dry Creek fault zone (Figure 22). Franciscan rocks south of this

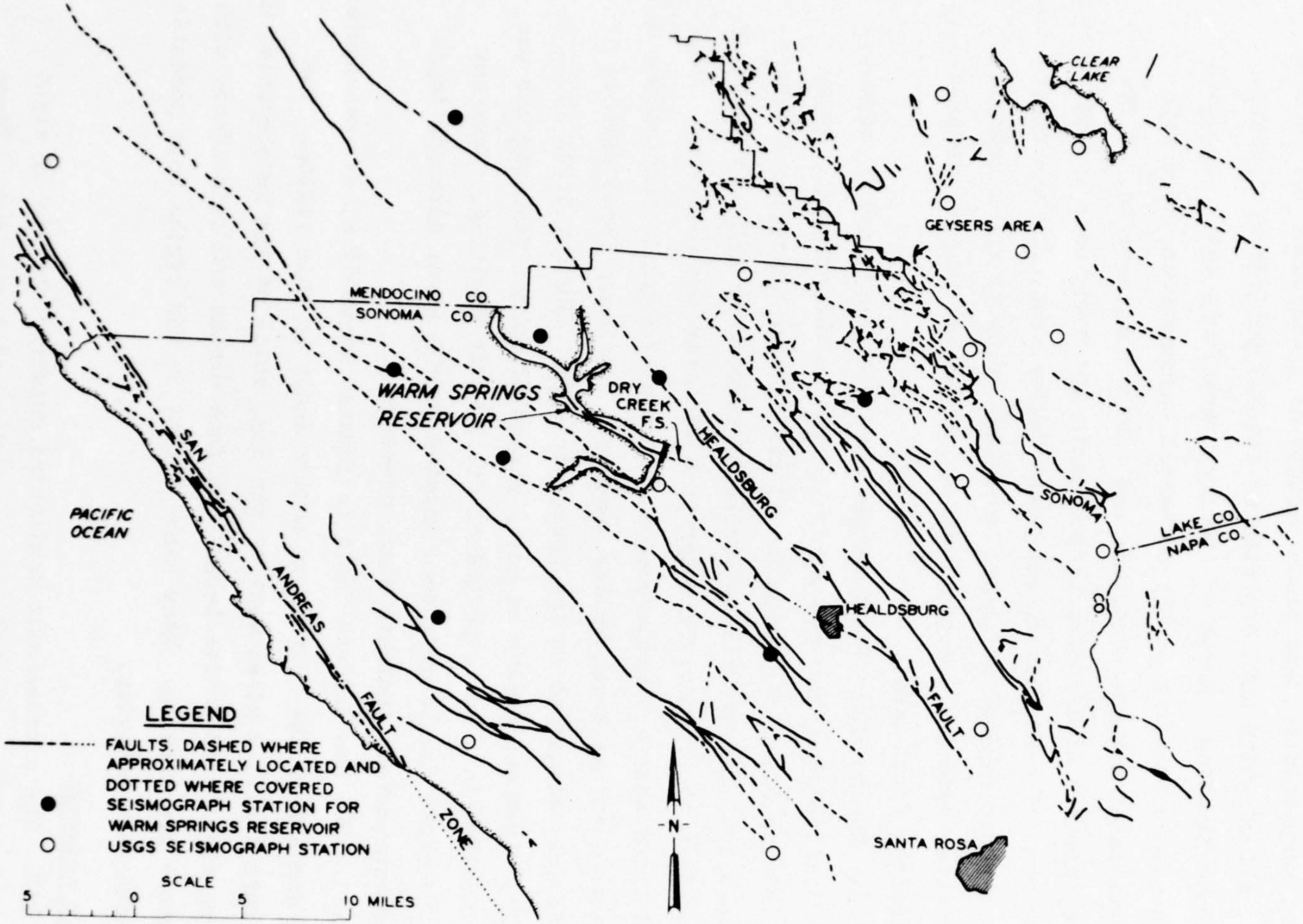

Figure 22. Surface faulting and seismometer station locations, Warm Springs Reservoir

fault consist of a heterogeneous assemblage of sandstone (graywackes) and interbedded shale, altered volcanic rocks (greenstones), ultramafic rocks and serpentinite, and minor amounts of glaucophane and related schists, all of which have experienced several periods of intense folding and faulting. North of the Dry Creek fault zone, the Great Valley sequence consists mainly of bedded carbonaceous shale with intraformational arkosic sandstone and cobble conglomerate. A few scattered patches of Tertiary conglomerate are found near and downstream from the dam. The Franciscan and Great Valley sequences are regarded as largely contemporaneous offshore, deepwater deposits and nearshore, shallow-water deposits, respectively. The two are usually separated by serpentinized fault zones.

110. The northern Coast Ranges have been subjected to repeated crustal disturbances from pre-Jurassic time to the present. Major faults (Figure 22) form boundaries of rift blocks hundreds of square miles in area. The prevailing strike of bedding is slightly north of east and dips are commonly greater than 45^o near the reservoir. Well-defined folds have not been recognized except for minor contortions and crenulations in the Great Valley sequence. At least three periods of faulting are recognized in the reservoir area. The Dry Creek fault zone probably originated during an early period of normal faulting and was later involved in a later period of strike-slip faulting. Very few branch or cross faults have been located in the area, although topographic expressions indicate their presence.

111. The San Andreas fault is located about 18 miles west-southwest of the dam and is the only known active fault in this region. The Healdsburg fault, 2 miles west of the dam, while of the same system, has not been considered active because surface breaks and coincidence with epicenters are lacking. Many other faults in the region have potential for earthquake activity.

Seismic network

112. The microseismic monitoring network consists of eight seismograph stations positioned around the reservoir area. These stations and portions of the Healdsburg and Geysers networks are shown

in Figure 22. The station instrumentation, telemetry, and recording equipment are similar to the instrumentation and equipment used at New Melones. All stations are connected by radio links. As at New Melones, recording and data reduction are performed by the USGS at Menlo Park, Calfornia.

<u>Costs</u>

113. The approximate anticipated and actual costs of the Warm Springs monitoring program are given below:

Installation:	
<u>Equipment</u>	
Seismometers, 10 @ $320	$ 3,200
Amplifier/VCO unit, 10 @ $350	3,500
Radio links, if used, 7 @ $1,000	7,000
Discriminators, 10 @ $150	1,500
Develocorder, 1/2 @ $14,000	7,000
Tape recorder (prorated)	1,500
Miscellaneous	4,000
	$27,700
<u>Salaries</u>	3,800
<u>Installation</u>	2,800
<u>Technical and Administrative Support</u>	6,500
TOTAL	$40,800
Operational years:	
<u>Salaries</u>	$ 9,000
<u>Telemetry, 12 months @ $315/month</u>	3,800
<u>Maintenance</u>	3,200
<u>Computer Time</u>	800
<u>Data Processing</u>	1,200
<u>Technical and Administrative Support</u>	7,300
TOTAL	$25,300/yr

114. The final year of monitoring is expected to cost an additional $5,000 to cover report preparation and the dismantling of equipment. The seismic velocity survey cost approximately $20,000.

Seismic velocity model

115. The determination of crustal seismic velocities was conducted in August of 1976 and was similar to that for New Melones.

Regional[10] and site seismicity

116. Warm Springs Reservoir is located in Zone 4 (great damage) of Algermissen's seismic zonation of the United States. Although no large historic earthquakes have occurred at the site, there have been numerous severe and damage-producing earthquakes within approximately 50 miles of the site. The regional seismicity with respect to earthquakes exhibiting MM intensity of VII or greater is shown in Figure 23. Generally, the loci of earthquake events are centered along the San Andreas fault zone to the southwest and the Healdsburg fault to the northeast. The Geysers area to the northeast is also a center for earthquake activity.

117. The Warm Springs network and the pre-existing USGS network have detected numerous small earthquakes in the general area. Between 1 January 1974 and 17 August 1975, 293 events having magnitudes of 0.60 to 3.51 have been recorded. The majority of this activity occurred along the Healdsburg fault north of Santa Rosa and in the Geysers area south of Clear Lake. A magnitude 1.91 event occurred approximately 5 km southeast of Warm Springs at a focal depth of 0.92 km on 19 September 1974. This event, although imperfectly located, has been the nearest to the reservoir site.

New Melones Reservoir

118. The USGS has conducted microseismic monitoring at New Melones Reservoir for the Sacramento District, since 20 January 1972. The objectives of the monitoring were to evaluate the seismic history of the reservoir and vicinity before, during, and after filling.

Geology of New Melones Dam and vicinity

119. New Melones Dam and Lake are located in the steep-sided canyon cut in the lower Sierra Nevada foothills by the Stanislaus River.

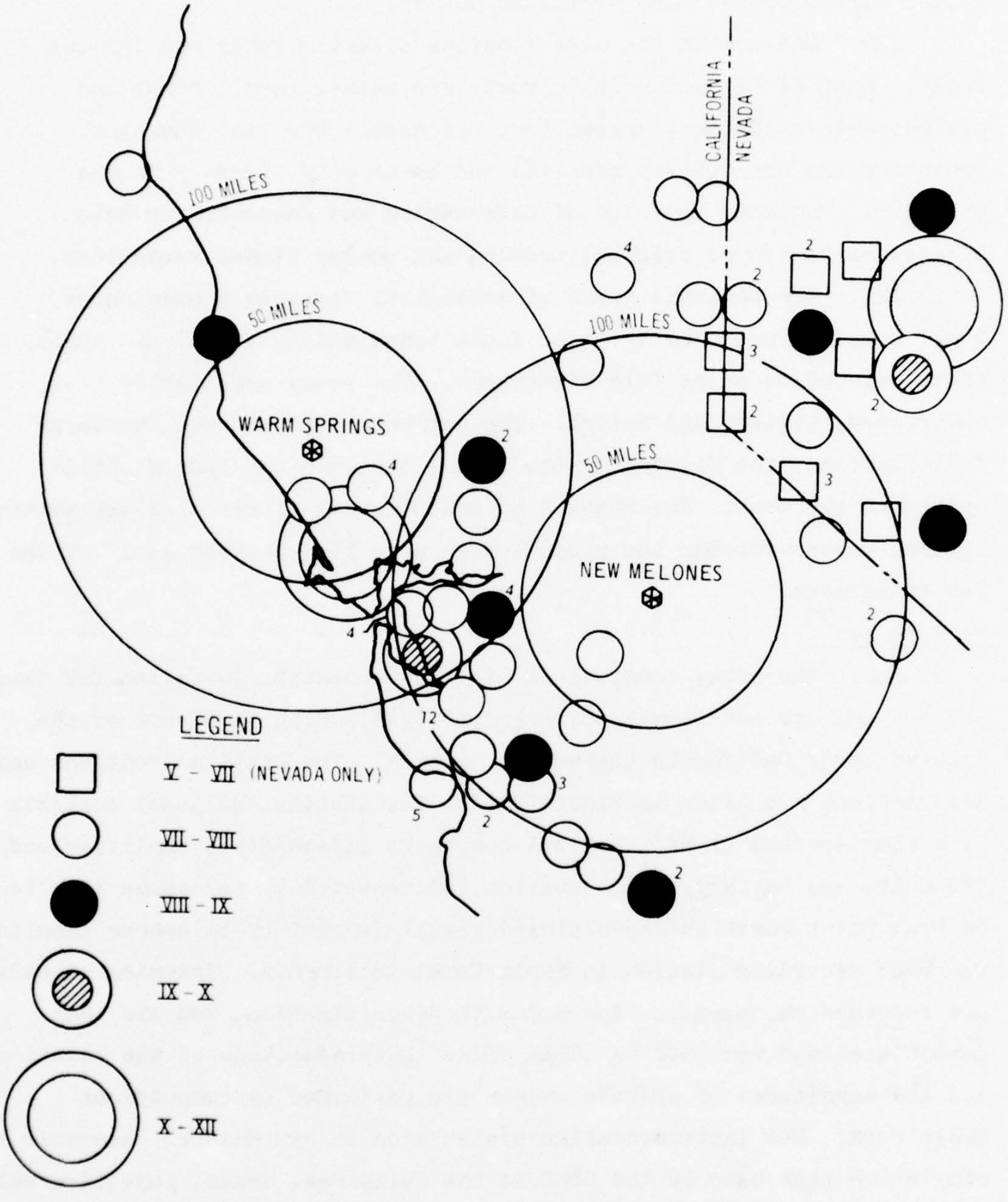

Figure 23. Regional seismicity, New Melones and Warm Springs Reservoirs

Canyon sides descend as steeply as 45° from about elevation 1500 ft msl to the narrow bottom near elevation 500 ft.[22]

120. Bedrock in the area consists of metamorphic and igneous rocks. Most of the metamorphic rocks are meta-volcanic rocks and slates; meta-sandstone, serpentine, and marble are less abundant. The igneous rocks are chiefly granitic and occur only sparsely in the vicinity. Repeated episodes of deformation and metamorphism have blurred or destroyed original bedding and compositional variations.

121. The regional grain of geological features trends about N 45° W and is produced by major fault zones and by lithologic variations related to major fold structures. The rocks are tightly compressed, tilted, and folded. The dam area lies between two large fault systems, the Melones system on the east and the Bear Mountain system on the west. The Bostick Mountain fault, a branch of the western system, passes through the project area near the upstream limit of the dam embankment.

Seismic net[23]

122. The array consists of eight seismographs installed for this project and one additional seismograph* (JAS) which is a part of the University of California (Berkeley) network. The station locations and designations are given in Figure 24.** The station equipment consists of a short-period (1 Hz) vertical component seismometer, amplifier and VCO unit, and battery. Each station is connected by telephone line to a central point where the multiplexed signal is sent by telephone line to the USGS recording station in Menlo Park, California. Incoming signals are recorded on magnetic tape prior to discrimination, and are then demodulated and recorded on 16-mm film. Determinations of the locations and the magnitudes of seismic events are performed by computer at Menlo Park. The instrumentation system used at New Melones Reservoir is similar to that used by the USGS at the Childress, Texas, injection well (see paragraph 60).

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* A 14-kg Benioff vertical seismometer.

** Reflects repositioning of four stations in 1976 in order to better monitor the major fault systems.

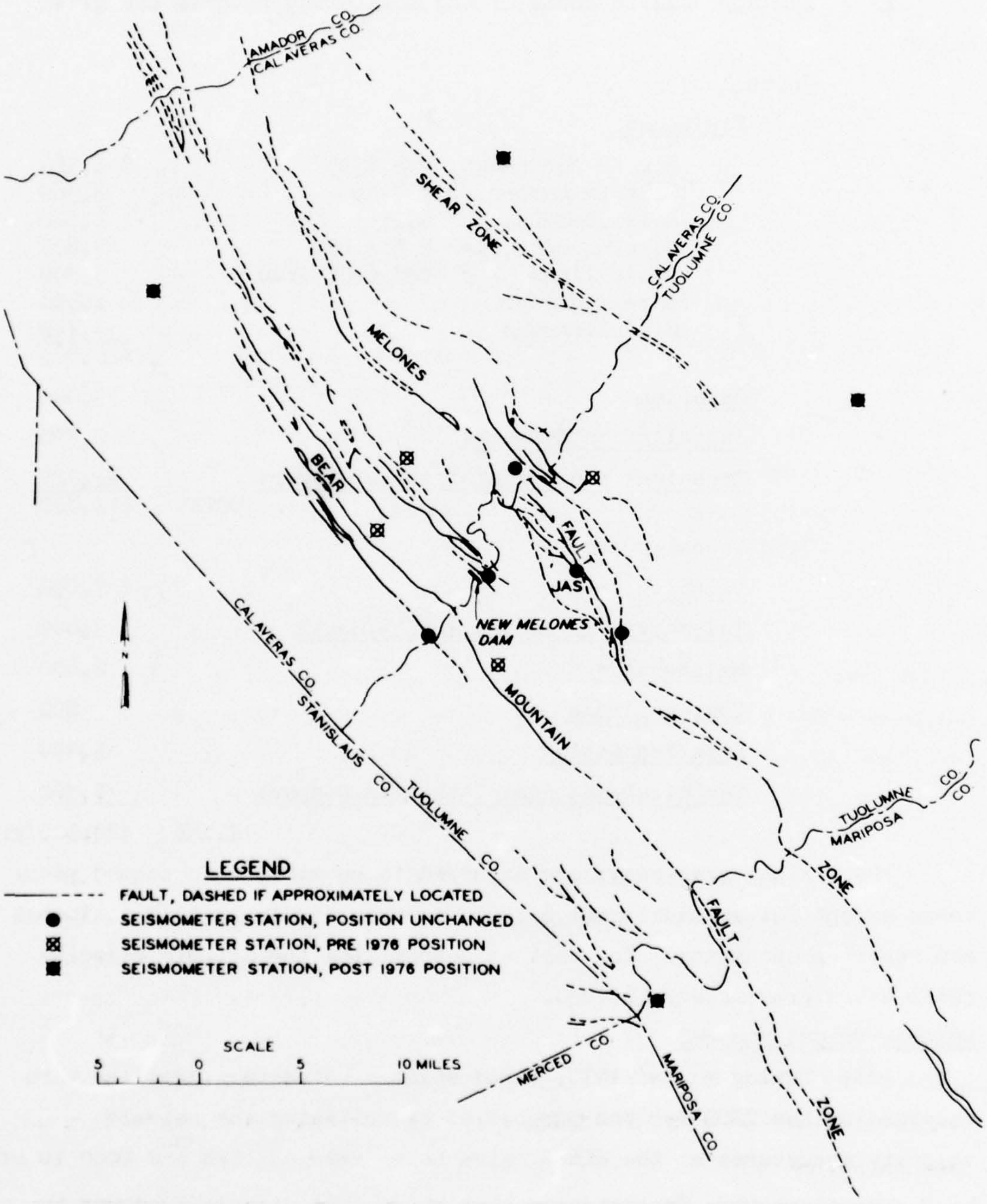

Figure 24. Surface faulting and seismometer stations, New Melones Reservoir area, California

Costs

123. The approximate costs of the monitoring program are given below:

Installation:	
Equipment	
Remote Equipment, 8 @ $795	$ 6,360
Discriminators, 8 @ $445	3,560
Seismometers, 8 @ $325	2,600
Develocorder, 1/2 @ $11,650	5,825
Radio links, 4 @ $820 (not used)	3,300
Tape recorder	1,500
Miscellaneous	3,740
	$26,885
Salaries	3,000
Installation Expenses	2,700
Technical and Administrative Support	11,215
TOTAL	$43,800
Operational years:	
Salaries	$ 7,000
Telemetry, 12 months @ $315/month	3,800
Maintenance	2,400
Computer Time	800
Data Processing	1,200
Technical and Administrative Support	5,300
TOTAL	$20,500/yr

124. Final year costs are expected to be similar to second year costs except for an additional $5,000 to cover dismantling of equipment and report preparation. The cost of determining the seismic velocity model was approximately $20,000.

Seismic velocity model

125. During May of 1972, three seismic refraction profiles were recorded by the USGS for the purpose of establishing the seismic velocity structures at the site. Five holes were drilled and 2000 lb of high explosives were detonated in each hole. The signals produced by these detonations were recorded on the station seismographs and on 26

portable temporary seismic units. The analysis of these explosions as well as those from two quarry blasts permitted the determination of seismic velocities in the upper crustal layers.

Regional[10] and site[23] seismicity

126. The New Melones Reservoir is located in Zone 3 (major damage) of Algermissen's seismic zonation map of the United States. This suggests that the site is situated in a relatively active seismic area. However, there have been no serious, damage-producing earthquakes within approximately 50 miles of the site in historic times. Two earthquakes having intensities of VII to VIII have occurred to the southwest of the site at distances of 40 to 50 miles away. Within 100 miles of the site there have been numerous large, damage-producing earthquakes. The regional seismicity with regard to earthquakes having intensities greater than V for Nevada and greater than VII for California is shown in Figure 23.

127. The current seismic monitoring program, which has been in effect for over three years and which has covered pre-filling conditions, has not detected any earthquakes within approximately 30 km of the site. However, distant events originating along the San Andreas fault zone and other earthquakes in central California and in Nevada have been detected. Also, numerous blasts and explosions have been recorded. It would seem that the site is relatively aseismic with respect to microearthquakes as it is with respect to larger events. Filling of the reservoir is expected to begin in 1977 or 1978 and monitoring will continue through this phase.

Cochiti Reservoir

128. Cochiti Reservoir is located in seismic Zone 2 on the Rio Grande River approximately 42 miles upstream from Albuquerque, New Mexico. The USGS is currently conducting studies on the Rio Grande Rift Zone and is operating an array of 13 seismometers in the vicinity of Jémez Caldera located approximately 20 miles northwest of the dam. One

high-gain, short-period vertical component instrument in this array is located at the dam and another instrument is located on Tetilla Peak approximately 5 miles east of the dam. Although this program was not designed to monitor reservoir-related events, the two nearby instruments which can detect magnitude 0 to magnitude 1 earthquakes will be able to provide some coverage of the reservoir. The reservoir is currently being filled.

Dickey-Lincoln School Project

129. The Dickey-Lincoln School Project consists of two proposed dams on the St. John River in northwest Maine. The earthquake hazard and seismological investigation at these sites did not reveal any active faults nor any macroearthquake activity in the immediate vicinity of the sites although there were numerous actual and postulated faults of Paleozoic age in the area. The investigation concluded that the area of most interest was the more active St. Lawrence Valley seismic belt located approximately 45 miles to the northwest (Figure 25)[24]. The St. Lawrence Valley area is in Zone 3 (major damage) of Algermissen's seismic zonation of the United States. This zone, according to Algermissen, also extends into the project area.

130. Currently the New England Division (NED) is developing a program of microseismic monitoring of the site area.* Weston Observatory, Boston College, under contract to the NED, has established one short-period seismometer station at Allagash, Maine. Three more stations were scheduled to be added during the summer of 1976. If considerable microearthquake activity is detected, the four-instrument net will be supplemented at a later date by five additional instruments. Monitoring is expected to continue through the post-filling stages of both reservoirs.

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* Personal communication, Mr. Edward Blackey, New England Division.

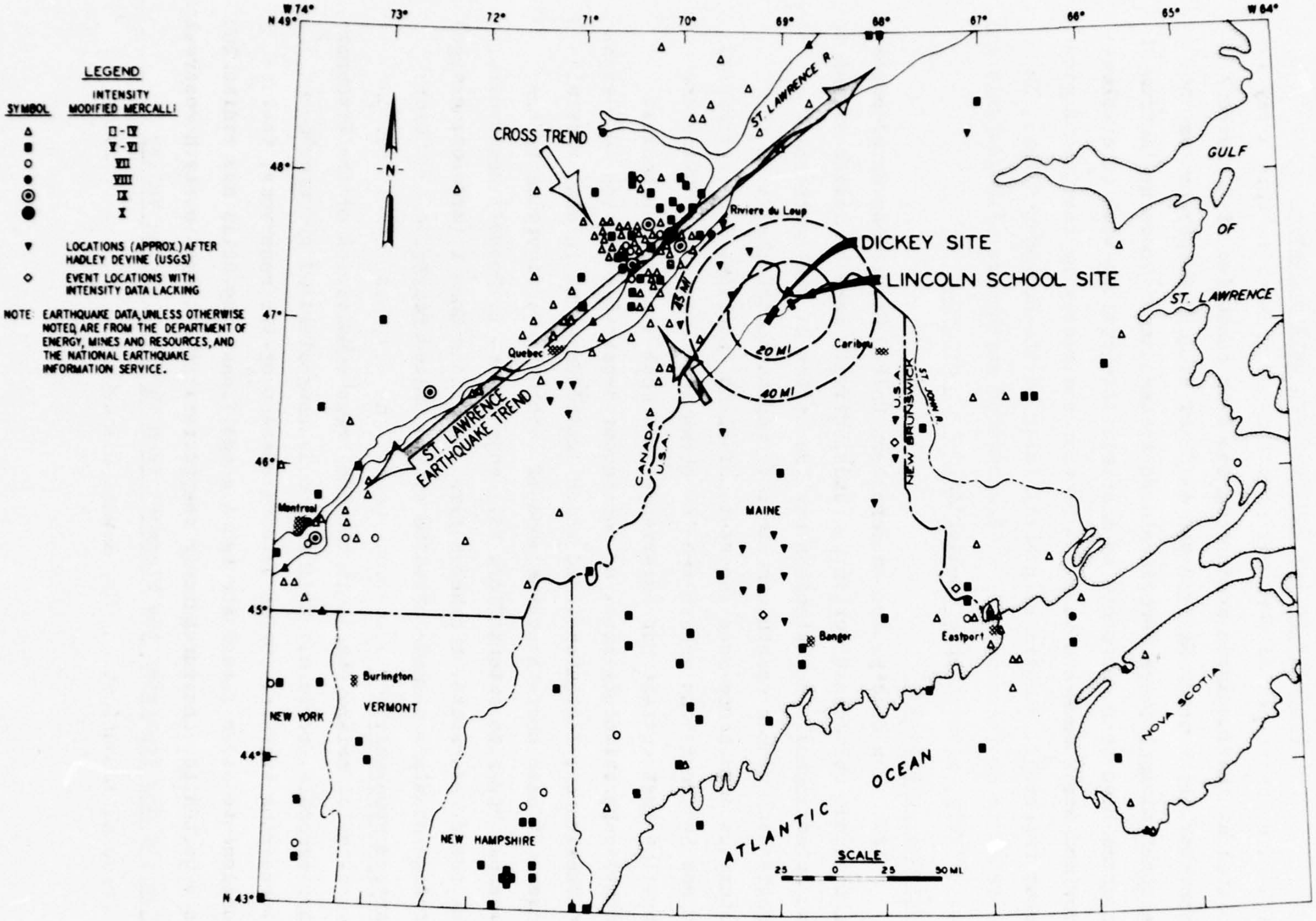

Figure 25. Historic earthquakes in northern New England and adjacent parts of Canada: 1638 to 1975

Projects in the Southeastern United States

131. Microseismic monitoring has been conducted at Carters Reservoir in northern Georgia and at Clark Hill Reservoir on the Savannah River between Georgia and South Carolina. These monitoring programs have been performed by academic institutions with CE cooperation and assistance but were not sponsored directly by the CE. A proposed reservoir, Richard B. Russell (also on the Savannah River), is expected to be the object of a CE-sponsored earthquake risk analysis and, most likely, microseismic monitoring.

Regional seismicity[10]

132. Regionally, the southeastern United States has experienced significant earthquake activity. This activity more or less conforms to two broad zones. One extends along the strike of the southern Appalachian Mountains and the other is normal to the strike of the mountains and encompasses the state of South Carolina. The seismicity in the southern Appalachian area is shown in Figure 26.[25] The South Carolina seismic belt has experienced the most intense earthquake activity in the southeast. Of particular importance was the 1886 event in Charleston, South Carolina, which exhibited an MM intensity of X. Figure 26 also shows a narrow zone of earthquake activity along the Savannah River near both Clark Hill and Richard B. Russell Reservoirs. The three reservoirs of concern here are all in Zone 2 (moderate damage) of Algermissen's seismic zonation of the United States.

Carters Reservoir[26]

133. Carters Dam is in the Dahlonega subdivision of the Piedmont physiographic province. This region is characterized by rugged, mountainous terrain. Prior to construction of the reservoir, the Coosawattee River flowed through a gorge flanked by hills and ridges 300 to 700 ft high. An irregularly shaped escarpment immediately downstream from the dam separates the Piedmont from the Appalachian Valley

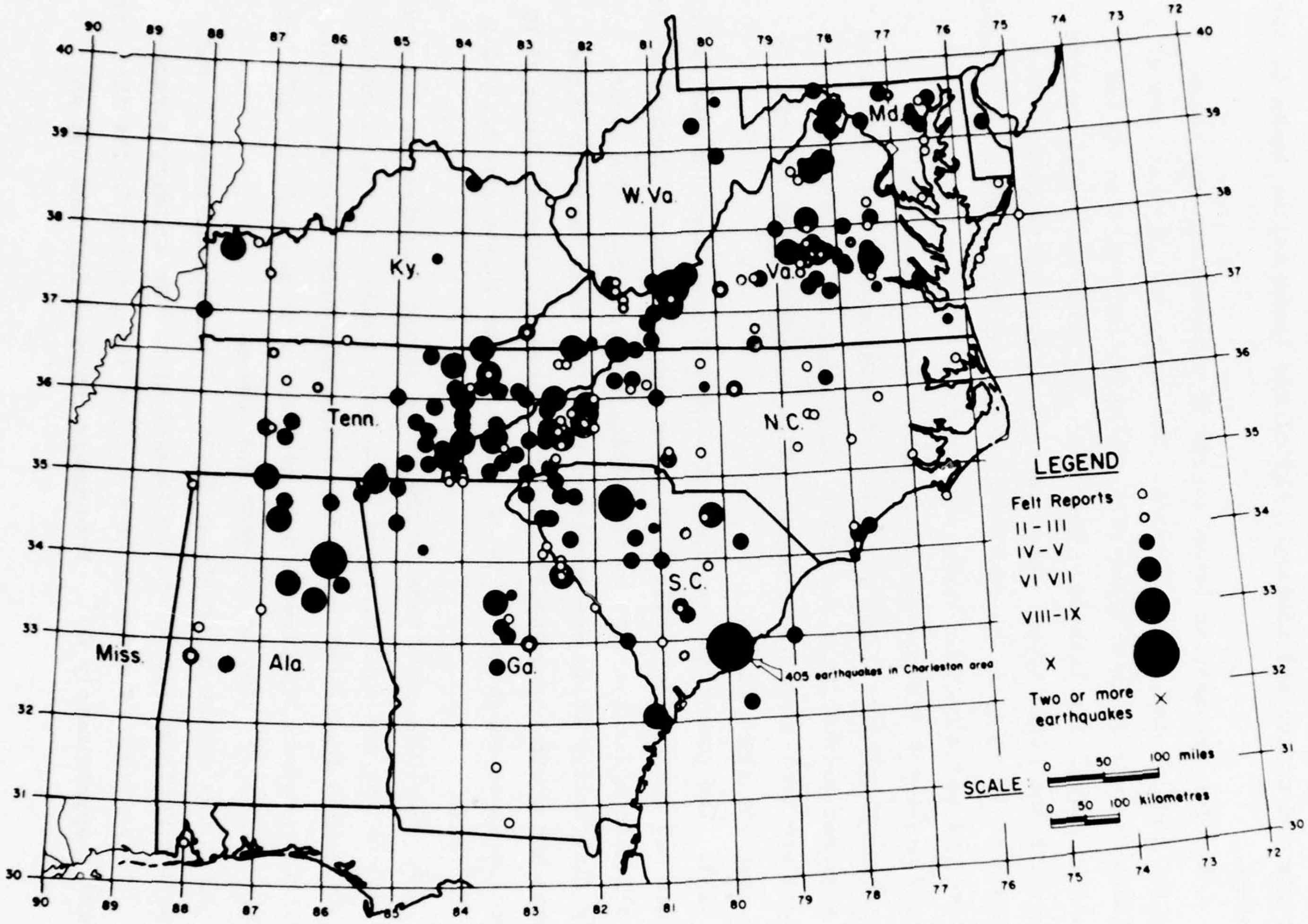

Figure 26. Southern Appalachian seismicity 1754-1971 (after Bollinger, 1975[25])

province. This escarpment is the result of faulting and differential erosion along the contact between hard crystalline rocks around the reservoir and softer sedimentary rocks of the broad valley lands to the southeast.

134. The Precambrian Ocoee series of meta-sedimentary rocks underlies the dam and reservoir area. The Ocoee is composed here of a continuous series of rock types with quartzite and phyllite as end members and argillite between. Quartzite predominates but it is interbedded with the other types. Individual beds vary in thickness from laminae size to 50 ft. The quartzites vary from conglomeratic to highly argillaceous and micaceous types but are mostly very hard, quartzose, slightly micaceous, medium-grained, massive rocks with excellent engineering properties. The phyllites are moderately hard rocks that have a characteristic wavy foliation and silky sheen on fracture surfaces and semi-slabby fracturing. High concentrations of phyllite occur near indicated faults.

135. The Conasauga formation of Cambrian age underlies the Valley province and consists of shale with a few limestone beds. Topography is controlled to a large extent by the geologic structure. The lower, nearly flat valley areas are developed upon the shale, and the higher plateaus and north-to-northeast trending ridges are generally capped by harder limestone which has resisted erosion. The strata generally dip 40 to 70° east.

136. Geologic structure in the Ocoee series is extremely complex. Lithologic units are discontinuous along both strike and dip directions. Numerous healed faults and overturned folds have been observed on outcrops. The general dip direction is eastwardly at about 20 to 30°, but variations from 10° west to 65° east are common.

137. One of the major thrust faults of the southeastern United States, the Cartersville fault, is located along the boundary escarpment. It is a zone of movement or a maze of interlacing faults that dip eastwardly approximately 60°. Presumably the zone flattens out at

depth. The rock within this zone is a distorted hybrid type formed by mixing and intermingling of the Ocoee and the underlying Conasauga formation as shearing took place.

138. The thickness of soil overburden is quite variable due to the variety of topography. Near the dam the valley walls have retained little residual soil except near the base and near the upper limits where as much as 20 ft of silty clay and disintegrated rock is present. Near Globe site, 5 miles upstream from the dam, soil is much thicker though the valley is narrower. As much as 70 ft of residual soil was found there by drilling. Generally the soil overburden is thickened in the Valley province to the west; at the reregulation dam location about 2 miles downstream from Carters Dam, overburden soils average about 18 ft in thickness and consist of micaceous clayey silts and lean clays with some strata of fine silty sands. A thin silty-clayey-gravel layer overlies the top of the rock.

139. Professor L. T. Long of Georgia Institute of Technology (GIT) is currently conducting microseismic monitoring at Carters.* The purpose of the monitoring is to detect and identify earthquakes which might be foreshocks for a larger earthquake. The instrumentation includes a short-period vertical component seismometer positioned near the visitors' center at the dam. A helical drum recorder is located in the visitors' center and records Monday through Friday of each week. A WWVB radio receiver provides universal time. Seismograms are mailed weekly to GIT where they are examined. Of special interest are events located within approximately 15 km of the reservoir since these events would, most likely, be indicative of stress conditions in the reservoir area. Although events beyond 15 km have been detected, no earthquakes have been recorded at distances less than 15 km. In the event that close-in activity is detected, GIT would supplement the existing station with three to five additional geophones.

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* Dr. L. T. Long, personal communication.

Clark Hill Reservoir

140. Clark Hill Dam is on the Savannah River near the southeastern margin of the Piedmont Plateau region of Georgia and South Carolina. Topography of the reservoir area is typical of the eastern Piedmont. The drainage pattern is dendritic and streams have reached a mature stage in the erosion cycle. Summits of the broad, rather flat-topped ridges between stream valleys are remnants of an old erosional surface into which the valleys have been incised. The high-level surface has a general elevation of about 500 ft above sea level near the dam and slopes gently to the southeast. All streams are still degrading their courses; stream gradients are rather steep; shoals and rapids are common; flood plains are developed only along the main trunk streams and are mostly very narrow, an exception being in the vicinity of Augusta, starting some 15 miles southeast of the dam.[27]

141. The reservoir area is entirely underlain by crystalline rocks of igneous or metamorphic character. At the dam the formation is the Carolina gneiss, which in the vicinity is a rather coarsely crystalline biotite granite gneiss generally regarded as upper Precambrian to Cambrian in age. Intrusive into the gneiss are several stocks of younger, even-textured, medium-grained biotite granite. One of these intrusives forms the left abutment of the dam.

142. Four miles upstream from the dam, near the mouth of Little River, a fault (?) contact of the Carolina gneiss crosses in a northeasterly direction. Beyond this contact a 15-mile-wide belt of meta-volcanic and meta-sedimentary rocks trends northeastward across the region. These younger formations, known in the past as the Little Creek series, are dominated by argillite though a variety of graywacke, agglomerate and tuff types, and volcanic flows are included. The age has been bracketed in the interval Ordovician to Mississippian.[27] South from a point about 12 miles southeast of the dam, relatively weak rocks and lightly consolidated sediments of Cretaceous and Eocene age overlap and cover the old, hard crystalline formations. As a result of dynamic metamorphism, the older rocks have been completely recrystallized and a generally parallel orientation of the mineral constituents

has developed distinct cleavage and foliation. The regional strike of the foliation is northeast and the regional dip is to the southeast at a high angle. Folding has been so complex, however, that the attitude in any given exposure may vary widely. Minor faulting is evident in outcrops but the only known major fault is the one believed to separate the Carolina gneiss from the Little Creek series. One fault near Augusta is suspected of having had movement in the Holocene.[28]

143. Residual soils in the region are red to gray stiff, sandy clays and sandy silts. The top 10 ft of soil tends to be red, clayey, and less pervious than the soil below. Grain size increases downward to gray clayey sand with angular fragments just above bedrock. The total soil thickness is usually about 25 ft. Similarly the valley alluvium measures about 20 ft and consists of sand and silt with minor lenses of gravel and pockets of clay.

144. Clark Hill Reservoir has been monitored at various times by GIT under the direction of Professor Long and by Professor Pradeep Talwani of the University of South Carolina (USC). Both investigators have reported microearthquake activity in the vicinity of the reservoir and have studied the relationship between the frequency of earthquakes and the water level in the reservoir. These special monitoring programs have been supplemented by data derived from the permanent seismic net operated by the USGS and USC in South Carolina.

145. Denman, a student of Long, conducted microseismic monitoring between September 1973 and April 1974. Eleven stations were operated for approximately 95 days. Most of the monitoring was with a single station although three stations were operated simultaneously for a short period. Approximately 11 events were recorded; however, no positive relationship could be made between the seismicity and the water level in the reservoir.[29]

146. Talwani and his students have studied the seismicity in the vicinity of Clark Hill Reservoir since the occurrence of the magnitude 4.3 event nearby on 2 August 1974.[30] Immediately following this earthquake three portable seismometers were placed in the epicentral

area. This was followed by monitoring with a single instrument for several months. In 1975 the region was monitored for over a week in March with three to five seismometers and for about seven weeks in the summer of 1975. During this monitoring period over 1000 events were detected. One instrument is currently in operation in the epicentral area.

147. March of 1975 was a particularly rainy month and as a consequence the water level in the reservoir rose over 5 ft. The seismometer net was installed shortly after a period of heavy rainfall and while the water level in the reservoir was rising. The earthquake frequency also increased while the pool was filling. The earthquake activity appeared to slacken as the reservoir filling leveled off, then lowered somewhat. Talwani, based upon this evidence, suggested that there was a possible direct relationship between the frequency of earthquakes and the pool elevation.[31]

148. Definitive direct relationships are, however, very difficult to formulate without a solid baseline from which to make comparisons. Conclusions such as Long's and Talwani's, as logical as they may be, suffer from the defect of not knowing what the background seismicity was for a period of time prior to the construction of the reservoir. Furthermore, monitoring durations of weeks or even months do not provide a statistically broad period of time for analyzing earthquake events.

Richard B. Russell Reservoir[32]

149. This proposed reservoir is to be built on the Savannah River approximately 30 miles upstream of Clark Hill Reservoir and 25 miles downstream of Hartwell Reservoir. Although the microseismicity near the Richard B. Russell and Hartwell sites has not been studied in detail, Figure 26 does indicate the occurrence of historic earthquakes in this region. The extent to which the Richard B. Russell site has been affected by filling of Hartwell and Clark Hill Reservoirs is unknown. The nearness to two pre-existing reservoirs is an additional complication to determining baseline seismicity at the site. The earthquake risk analysis proposed for Richard B. Russell will consider this relationship as well as other aspects of the regional and site seismicity.

PART V: METHODS OF DATA ANALYSIS

Introduction

150. Having studied the local geology and seismicity and installed, calibrated, and de-bugged an instrument array, the organization sponsoring the monitoring (or the contractor) is faced with the problem of reviewing and analyzing the recorded data and arriving at conclusions from the data which are pertinent to the installation being monitored. Depending upon the amount of seismicity and the data processing capability, this may become a sizeable task.

151. The required information to be determined from the seismograph records includes the identification of actual earthquakes (as distinguished from man-made effects), epicentral and focal locations, and magnitudes for all natural events. Upon determining this information, the data must be listed, plotted on maps and charts, and grouped in such a manner that one can compare variations in seismicity with time or so that one can compare levels of seismicity with either rates or durations of either injection or filling.

Seismograph Analysis

152. The examination of the seismograph records is the first step in data analysis. This examination consists principally of identifying earthquake events. Quarry blasts or other man-produced explosions may complicate this step in the analysis, but these events can usually be rapidly identified by several techniques. These include the wavetrain, but of more importance are the times of occurrence and the arrival times of the events. Knowledge of blasting sites and the usual time of blasting, as in a mine or quarry for example, will simplify this portion of the study.

153. The determination of first arrival times for the p-wave (which arrives first) and the s-wave is the next step in the analysis. The chronometer is coupled to the recorder and these time intervals are shown as tick marks on the film or paper record. S-wave arrivals are somewhat more difficult to pick as this event is often obscured by the p-waves. In Part III it was mentioned that the time difference between these first arrivals multiplied by 8 km/sec yielded the distance to the earthquake focus.* This may be used for epicenter determination in the absence of detailed information on crustal velocities.

Focus and Magnitude Determination

154. Computer programs exist which permit the rapid determination of earthquake magnitude, epicenter, and focal depth for instrument arrays such as those which have been described in this report. HYPO 71, a program in use by the USGS, is one system available.[33] This program is readily adaptable to most computers and is used by the USGS on IBM 370 and CDC 70-600 systems.**

155. Briefly, HYPO 71 operates in the following way. Input data programmed in the computer include the latitude, longitude, and elevation of all seismometer stations in the net and information on

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* The value, 8 km/sec, is based upon two assumptions: first, that Poisson's ratio is approximately 0.25 (this yields a V_p/V_s ratio of 1.73); secondly, that V_p is around 5.8 km/sec. These values are useful for hard, crystalline rocks but may be inaccurate for sediments, soil, or sedimentary rocks. The actual value of the factor is:

$$\frac{V_p}{\left(\frac{V_p}{V_s} - 1\right)}$$

and can be measured by calibrating with quarry blasts or by seismic profiling.

** Personal communication, Mr. Rick Lester, USGS, July 1976.

the crustal seismic velocities in the area of interest. Input data derived from the seismograph records and which are punched on cards include the p- and s-wave first arrival times for hypocenter determination and the duration of the p-wave from the time of its first arrival until its amplitude drops to less than 1 cm. This duration is used to determine magnitude.

156. The computer calculates and prints out the epicentral locations by latitude and longitude, focal depths, magnitude, and time of event, as well as an indication of the relative reliability of the output data.

Analysis of Seismicity

157. The events located during the monitoring program should be plotted on a geologic map of the site. This permits rapid observations to be made on any spatial relationships between the seismicity and known geologic structures, and also points out anomalous seismic areas which may suggest unknown faults.

158. The study of the local seismicity should not necessarily be limited to the area within a 10- to 15-km radius of the reservoir or well but should also include listing and plotting events beyond this radius. These more distant events provide baseline data for the following situations.

- a. When monitoring faults near the site prior to filling or injection, there is a need to know the background seismicity beyond the fault in order to determine the significance of events at the fault.
- b. During the monitoring of reservoir filling or the injection of fluids, the seismicity beyond the site as well as pre-filling or pre-injection seismicity provides baseline information with which the post-filling or post-injection seismicity may be compared.

159. Thus, the variation in concentration of seismic events at various distances from the site may be a method of determining differences between seismicity at the site versus beyond.

160. The example given in Figure 27 illustrates a monitored reservoir with plots of earthquake epicenters detected during pre-filling monitoring. There are no known structures which could be considered an earthquake source.

161. Considering the example given in Figure 27 one might question the significance of the events close-in to the reservoir site with respect to more distant events.

162. The statistical significance of these close-in events may be calculated by various techniques.[34] One such method, the t-test, was used to evaluate this example. These calculations revealed that there is little likelihood of any significant difference in close-in versus distant seismicity. This is also more or less evident from merely observing the data. Thus one concludes that the reservoir site is not atypical.

163. Figure 28 shows the same reservoir and the hypothetical seismicity during the post-filling phase. Comparison with the data in Figure 27 reveals an increase in the number of distant and close-in events as well as an increase in earthquake magnitude of close-in events. Having established in the first example that the reservoir area is not particularly different from the area beyond, we may now inquire as to the significance of the seismicity in the shaded area versus the regional pattern determined by pre-filling monitoring. This may be accomplished by statistical comparison of the events in the shaded area after filling with the total of events detected during the pre-filling phase. Statistical analysis using the t-test suggests that there has been a significant increase in the level of seismicity in the close-in zone.

164. Another approach to the problem of comparing levels of seismicity is the use of graphs. Plots of earthquake magnitude versus time provide valuable insight into the time dependency of activity and permit comparisons of seismic levels during various monitoring phases to be easily made. For example, if several of the larger events shown in Figure 28 (post-filling) occurred in a relatively short time period after filling, there would be added evidence for induced seismicity.

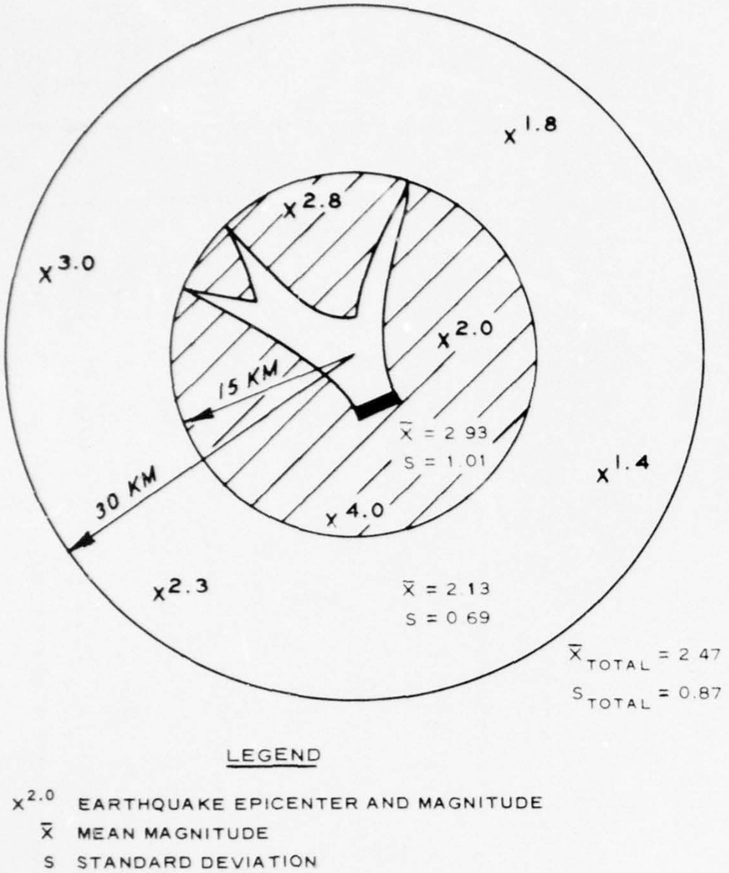

Figure 27. Close-in and distant seismicity during a conceptual pre-filling phase of one-year duration

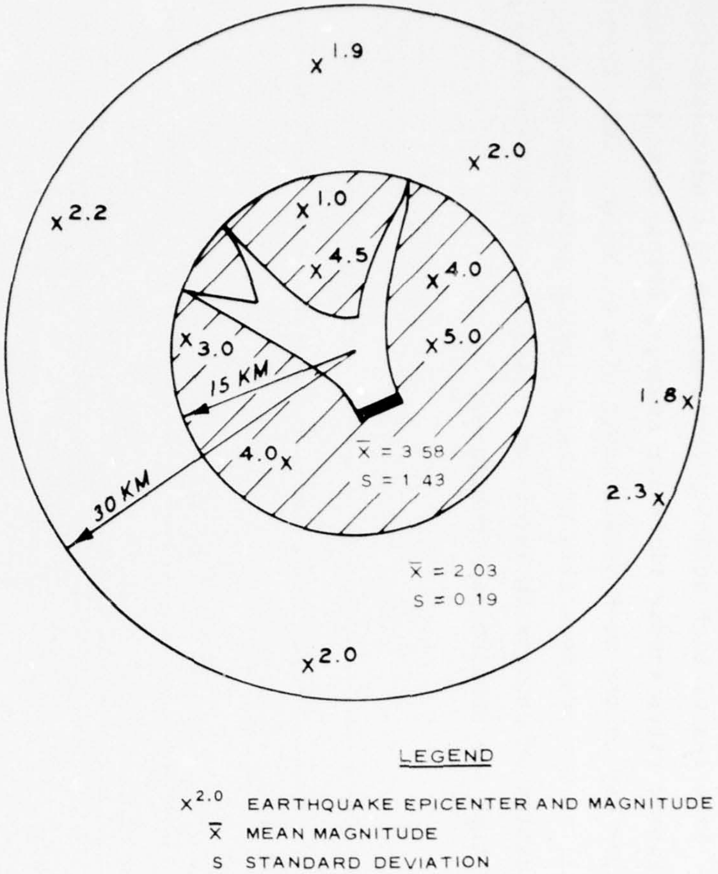

Figure 28. Close-in and distant seismicity during a conceptual post-filling phase of one-year duration

165. In areas of high activity there may be some advantage in plotting seismic rates versus time—for example, events over a particular magnitude per day or per week versus month of monitoring. This type of plot as well as the one described in the preceding paragraph permits rapid evaluation of changes in levels of seismicity and is more easily visualized than the statistical techniques.

PART VI: SUMMARY AND CONCLUSIONS

166. The CE has conducted or is currently conducting microseismic monitoring at nine reservoirs (New Melones, Warm Springs, Libby, Dworshak, Chatfield, Bear Creek, Paintsville, Tocks Island, and Dickey-Lincoln School) and one injection well site (Childress, Texas). Two reservoirs (Carters and Clark Hill) have been monitored by academic institutions with CE cooperation, and monitoring has been proposed for one reservoir (Richard B. Russell). Monitoring has been conducted at Cochiti Reservoir by the USGS as a part of one of their programs. Although instruments have not in all cases been installed prior to construction, the purposes of these monitoring programs have been to investigate the local background seismicity and to compare the seismicity after reservoir filling or fluid injection with that prior to filling or injection. The monitoring has been conducted under contract by the USGS at three sites (New Melones, Warm Springs, and Childress), and by academic institutions under contract at six sites (Libby, Dworshak, Chatfield, Bear Creek, Tocks Island and Dickey-Lincoln School). The CE District has conducted the monitoring in-house at one site (Paintsville) and another District is expected to take over operations from a contractor at another site (Libby).

167. These contracted and in-house programs have involved monitoring with arrays consisting of three to eight short-period, vertical component seismometers and necessary amplification and modulation equipment for long-distance telemetry of detected signals to a central demodulating and recording center (usually to the contractor's office or the District office) where the data are analyzed.

168. To date there have been no unequivocal indications that either reservoir filling or fluid injection at CE projects has produced any change in the level of seismicity at the monitored sites. There is a suggestion, however, that there may be a relationship between reservoir pool level and small-magnitude seismicity at Clark Hill

Reservoir along the Georgia-South Carolina border. The evidence for a direct causal relationship is not definitive, however, and this will be addressed during the seismic risk study at the Richard B. Russell site upstream from Clark Hill.

169. These monitoring projects have generally shown that a long pre-filling baseline must be determined in order to avoid erroneous conclusions.

PART VII: RECOMMENDATIONS

170. The following recommendations are based upon CE and others' experience with microseismic monitoring at various installations situated in geologically and seismologically diverse areas. The recommendations include considerations of earthquake risk studies, instrument type and placement, duration of monitoring, and data analysis.

Seismic Risk Analysis

171. Decisions affecting the design of the total monitoring program must be based upon knowledge of the local geology, particularly the structure and tectonics, and the seismicity of the area of concern. This will provide detailed information on the activity of local faults and yield some data on expected levels of background seismicity as well as ground motion input to the overall project design. In some cases it may be helpful to initiate a limited monitoring program at the outset of the seismic analysis in order to provide input data. Whether or not this is done would probably depend upon the prior knowledge of the site. However, short-duration and/or vaguely planned monitoring programs will not provide meaningful data due to the statistically short monitoring period and the limited number of instruments which would be installed in such a scheme.

Duration of Monitoring

172. The time of monitoring must be of sufficient duration to encompass pre-, during-, and post-filling or injection phases in order to permit comparisons to be made of the respective levels of seismicity. Furthermore, the time for monitoring a particular phase should be of such a length that a statistical sampling of the ambient or possible induced seismicity can be taken. This would mean a minimum of a year

for pre-filling or injection phases and possibly three years for post-filling or injection, depending upon the level of ambient seismicity at the site.

Number of Instruments

173. Since instrument number as well as arrangement affects the quality of the data with respect to hypocenter location, earthquake source, and earthquake magnitude definition, it is necessary to employ a minimum of three or four instruments. Four has an advantage in that the above data can still be determined if one instrument is not operable. One instrument may be used, however, for initial or preliminary monitoring if measures are taken to add supplemental instruments in the event that microearthquake activity is detected.

Location of Instruments

174. Instrument sites should be based upon the following guidelines:

a. Locate away from industrial operations if possible.

b. Position array such that selected instruments are near or at structures of interest with the remaining instruments positioned around the site to measure ambient or background seismicity.

c. Instrument spacing and arrangement should provide east-west and north-south control for the accurate determination of hypocenters.

Instrumentation System

175. Off-the-shelf commercial packages and components are available. The choice of models and types of specific components depends mainly upon the sensitivity required and the number of channels operated. The system should detect close-in events having a magnitude of one or

zero. The location and type of recording system are dependent upon the location of the project with respect to available facilities. These decisions must be based upon a study of relative costs. Generally, there is no preferred or "best" method for all sites for designing the instrumentation system.

Data Analysis

176. Magnitude, focal depth, and epicentral location must be determined for each recorded natural event. This can be done using available computer programs. Focal mechanism studies should be conducted for selected events. Epicenters of recorded earthquakes should be plotted on maps and the levels of seismicity detected at various distances from the project site should be analyzed either visually or statistically in order to understand relationships (if any) between seismicity at the site and that away from the site. The number of earthquake events per day, week, or month within a selected radius of the site should be plotted versus time on a graph in order to show relative levels of seismicity during various phases of operation.

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APPENDIX A: MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

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