Microseismic Monitoring for Evidence of Geothermal Heat in the Capital District of New York

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MICROSEISMIC MONITORING FOR EVIDENCE OF GEOTHERMAL HEAT IN THE CAPITAL DISTRICT OF NEW YORK

Final Report
Phases I-III

Prepared for

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ABSTRACT

The seismic monitoring work of the geothermal project was initiated for the purpose of determining more exactly the relationship between seismicity and the postulated geothermal and related activity in the Albany-Saratoga Springs area in upstate New York.

The seismic monitoring aspect of this work consisted of setting up and operating a network of seven seismograph stations within and around the study area capable of detecting and locating small earthquakes. To supplement the evidence from present day seismic activity, a list of all known historical and early instrumental earthquakes was compiled and improved from original sources for a larger region centered on the study area. Additional field work was done to determine seismic velocities of P and S phases by special recording of quarry blasts. The velocity results were used both as an aid to improve earthquake locations based on computer programs and to make inferences about the existence of temperature anomalies, and hence geothermal potential, at depths beneath the study area. Finally, the level in the continuous background earth vibration, microseisms, was measured throughout the study area to test a possibility that a relationship may exist at the surface between the level in microseisms and the geothermal or related activity. The observed seismic activity within the study area, although considerably higher (two to three times) than inferred from the historical and early instrumental data, is still not only low for a potential geothermal area but appears to be related to coherent regional tectonic stresses and not to the proposed more localized geothermal activity reflected in the mineralized, CO_2 rich spring discharge.

The evidence for the geothermal activity from other seismic characteristics, like large anomalies in microseismic level and velocities, also are negative. However, the seismic velocity data, so far, are neither abundant nor sufficiently precise to eliminate temperature anomalies on a more limited scale and further work on this aspect could be of value.

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SUMMARY

A systematic monitoring of seismic activity, based on a special network of seismograph stations, was carried out in several stages as part of the geothermal project from May 1979 through October 1982 for an area centered on the well known, CO_2 charged, mineral springs near Saratoga Springs, N.Y. The study area for the purpose of seismic monitoring extends approximately from 42.5^{o}N to 43.5^{o}N latitude and from 73.0^{o}W to 74.5^{o}W longitude. The results show that the seismic activity, although about two to three times higher, when normalized to a unit area and time as well as size, than could be inferred from the compiled data for all known historical and early instrumental earthquakes, is low compared to many active geothermal areas of the world. Of the 39 earthquakes ranging in size from M_c = - 0.3 to M_c = 2.8 that could be located with various degrees of precision, 19 events occurred in a form of two swarms during May, 1980 near Glens Falls and on February 8, 1982 near Thompsons Lake. Because of their widely scattered distribution and systematic focal mechanisms, all of these events, including the two swarms, appear to be related to the regional tectonic stresses acting coherently over a wide area and not to the more localized postulated geothermal activity. The suggestion that CO_2 rich, mineralized spring activity near the surface may be related to degasing from an extensive intrusion of hot or molten mantle material into the lower crust in some form, appears to be ruled out by the observation that both the amplitudes and velocities of P and S phases passing beneath the study area are normal and not unusually attenuated or slow as would be expected if substantial temperature anomalies existed. This information is based on special recording of quarry blasts and a few larger earthquakes. Unfortunately, the available velocity data are too limited and not sufficiently accurate to detect more subtle temperature anomalies. For example, a velocity anomaly of 2% to 3% over a wide area (50 km) or 10% to 15% over a limited area (10 km) could not be detected. More precise

work on the attenuation and velocities of seismic phases is recommended as the most promising and productive direction to follow in any future study of this problem. Further study of seismicity, on the other hand, because of its apparent nature and very low rate, does not look promising. Finally, a direct search for geothermal activity at the surface based on unusually high levels in continuous background earth vibrations (microseisms) proved unsuccessful because, in addition to the geothermal effect, there are large variations in microseisms related to differences in the nature and thickness of material immediately beneath the seismometer (solid rock, loose or solid soil, etc.). Such microseisms are generated by variations in meteorological (wind, rain, thunderstorm, etc.) and especially cultural (traffic, pumps, transformers, etc.) activity within the study area.

Section 1

INTRODUCTION

The presence of seismic activity, particularly microearthquake swarms, is well known in highly active geothermal areas (1). Such microearthquake activity may result either directly from stress readjustments caused by hot or molten rock in or near the ascent path of an intrusion, or indirectly along more distant faults in the area from regional stress variations or both. It also is known that in very active volcanic and geothermal areas continuous earth vibrations (microseisms) are considerably higher in amplitude than in normal non-volcanic areas (2). Finally, such geothermal areas may show abnormal velocities and attenuation of seismic waves within the crust and upper mantle because of the temperature anomalies associated with them (3). Thus, seismic techniques may be used as a reconnaissance tool to help locate and to evaluate the geothermal potential of an area.

A recent suggestion by Young and Putman (4) that the well known carbonated (CO_2-charged) "mineral" springs of Saratoga Springs and nearby areas of New York may be related to thermally generated CO_2-derived at depth has one implication in that this area may be "volcanic" either in its beginning or dying stages if an intrusion of hot rock is present. In this case considerable geothermal potential could be present and seismic monitoring is suggested as a useful prospecting tool here. For this purpose a special seismic monitoring network was conceived, designed and implemented with the idea of determining more accurately the seismicity within the area between 42.5°N and 43.5°N latitude and 73.0°W and 74.5°W longitude, centered on Saratoga Springs. (This area will be referred to as the "study area" in this report.) More specifically, an effort was made to determine the following parameters of the seismicity: (1) level of seismic activity, (2) location, depth and size of detected earthquakes, and (3) if possible, the nature of any relationship between seismicity and the CO_2-charged mineral spring activity. In short, an attempt was made to test the hypothesis that both the springs at the surface and earthquakes at depth may be related in some way to a postulated intrusion of hot or molten mantle material into the crust at greater depths.

The location of all earthquakes detected by the seismic network was done through a complex mathematical procedure carried out by computer programs. The procedure requires a knowledge of the seismic velocity model of the area, i.e. velocity of seismic phases (P and S) as a function of depth. Because this information was not available for the study area at the start of the geothermal project considerable effort was made throughout the project to determine the seismic velocity structure using special quarry blasts and several well determined earthquakes. Any event whose origin time and location are known accurately can be used, as will be described later, to determine such a velocity model. Both the location and origin time of any quarry blast can be determined directly and with considerable accuracy using special instruments and a simple field procedure. Fortunately, numerous quarry blasts are set off in the study area during the mining of limestone and considerable effort in instrumentation and field work was devoted to this aspect of the geothermal project.

It is well known that velocities and attenuation of seismic phases (P and S) depend not only on the composition and pressure conditions of rocks but also on their temperature (5, 6). Seismic velocities decrease and attenuation increases with increasing temperature. For this reason, the velocities as determined from quarry blasts for the purpose of earthquake location and the observed attenuation of seismic waves can be used more directly to infer temperature conditions beneath the study area. Because the temperature effect on seismic velocities is not very large (5), the velocities have to be known very accurately in order to detect small temperature anomalies. This method, however, is not limited to shallow depths but is equally valid at great depths where more direct geological and geochemical techniques do not apply.

In addition to monitoring the present day seismic activity a comprehensive effort was made, as part of this study, to compile a catalog of historical and earlier instrumental earthquakes for the study area and adjacent regions in order to have as complete a picture of the seismicity of the area as possible. For historical earthquakes this effort included, in addition to compiling data from already published catalogs, going back to original historical sources like old newspapers, diaries, special publications, etc. to improve the completeness of the available catalog.

Section 2

NETWORK HISTORY

The seismic monitoring work of the geothermal project evolved through several stages, with one long interruption, in the course of the study. The seismic network also went through several changes in instrumentation and station location. For this reason, its history will be reviewed and presented briefly through maps and tables.

While the main seismic monitoring network of the geothermal project was being planned and the main equipment being placed on order, a small network, consisting of three stations, was set up by the New York State Geological Survey (NYSGS) during May 1979 just south of Lake George to do preliminary study of seismic activity in the northern part of the study area (Table 2-1, Figures 2-1 and 5-3). The equipment consisted of special portable, smoked-paper recorders already owned by the NYSGS. This equipment will be described in more detail later. The network was operating, with a minor change in the location of one station (COP), as part of the geothermal project for about one year when two of these stations (LGE, COP) were discontinued (Table 2-1, Fig. 5-3). They were discontinued at that time because no local station operators could be found to replace the ones who resigned and not because it was decided that these stations were no longer needed. This network and this stage of the geothermal project will be called Phase I in this report.

Meanwhile, during the fall and winter of 1979-80 additional equipment was ordered, modified, assembled, tested and calibrated. This equipment was specially designed and purchased for the continuation of the geothermal project. It had ink recording and consisted of equipment (to be described later) sufficient

Table 2-1

SEISMIC MONITORING NETWORK OF THE NYS GEOLOGICAL SURVEY
(using smoked-paper recorders, May 1979 - May 1980)
(Phase I of the geothermal project)

Station Code	Location Lat(°N)	Long(°W)	Dates of Operation From	To
ACC	43.3542	73.6545	05/03/79	09/22/80
COP(a)	43.4337	73.5545	05/03/79	11/28/79
COP(b)	43.4315	73.5574	11/28/79	06/11/80
LGE	43.4330	73.6885	05/03/79	05/22/80

See Figures 2-1 and 5-3 for location of Stations.

for five stations with duplicates of several critical parts as backup. The equipment was deployed, starting in March 1980 (Table 2-2), into a larger network of eight stations by incorporating the initial three smoked-paper recording stations of Phase I (Fig. 2-1). After the two of the three smoked-paper stations were discontinued (May-June, 1980) a network of six stations (one smoked-paper, five ink recorders) operated until September 1980. This stage of network operation will be called Phase II in this report. (Note, this phase of the project was referred to as Phase I in several earlier reports.)

The operation of the geothermal seismic network was interrupted from September 1980 till October 1981. It was then restarted with several changes in station locations and one station addition (Table 2-3, Figure 2-2). Station MBR of Phase II was moved to FMC because FMC was quieter and because a decision was made to improve the detection capability in the western part of the study area. The equipment for THP of Phase II was moved only slightly west to BDR because no reliable person was available to change records at THP and because of earlier amplifier problems due to electromagnetic radiation interference. In

Table 2-2

SEISMIC MONITORING NETWORK OF THE GEOTHERMAL PROJECT FROM APRIL 1980 THROUGH SEPTEMBER 1980 (PHASE II)

Station Code	Locality	Latitude Deg(N)	Longitude Deg(W)	Elevation (Meters)	Maximum Gain (at 12 HZ)	Dates of Operation	Station Operator
COM	Colfax Mountain Washington Co.	43.0910	73.3915	314	1,050,000	April 10- Sept. 5, 1980	Dan Molloy
MBR	Malden Bridge Columbia Co.	42.4661	73.5719	146	190,000- 360,000	April 13- Sept. 5, 1980	Art Bernett
MCG	Mount McGregor Saratoga Co.	43.2031	73.7489	323	663,000- 1,326,000	April 7- Sept. 5, 1980	Dan Heffner
RPI	Rensselaer Polytechnic Institute Troy	42.7314	73.6664	131	550,000	March 27- Sept. 5, 1980	Bill May Pete Angerani
THP	Thacher State Park Albany Co.	42.6472	74.0064	354	1,170,000	March 18- Sept. 5, 1980	Tom Schoffeild John Jamnback
ACC	Adirondack Community College Warren Co.	43.3542	73.6545	98	320,000- 640,000	May 1979- Sept. 1980	Anson Piper

See Figure 2-1 for location of stations

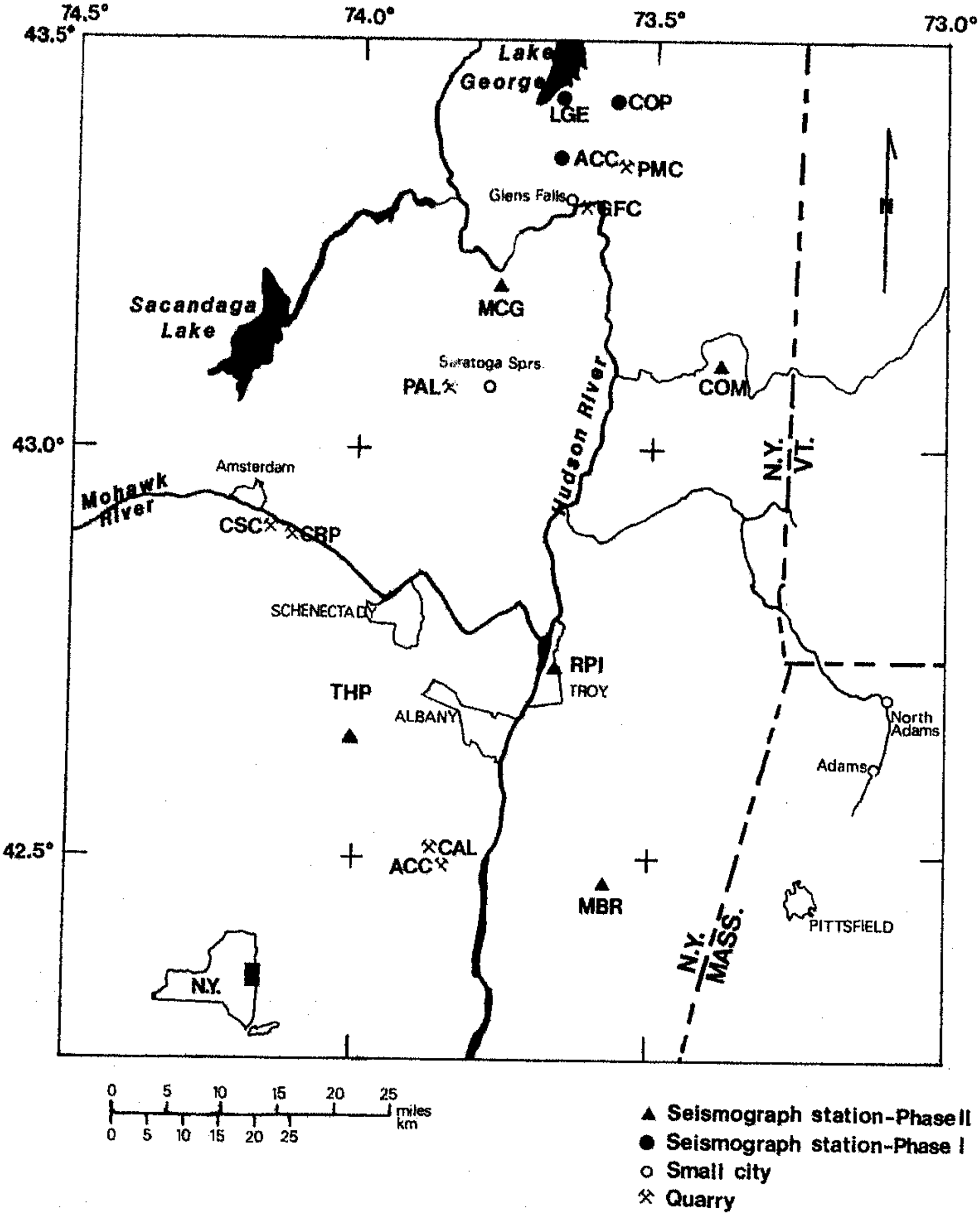

Figure 2-1. Location of the geothermal project seismic stations from May 1979 to September 1980 (Phase I and II).

addition, a special station was added to this network at the Cultural Education Center (CEC) of the Empire State Plaza in Albany. The equipment consisted of a special long-period seismometer owned by the NYSGS and the backup ink recorder amplifier and clock acquired during Phase II. Because of high-frequency earth noise due to the cultural activity within the city, this station was specially designed to record only long-period signal from larger and/or more distant events. This arrangement lasted till the end of October 1982 when the seismic monitoring effort of the geothermal project came to an end and will be referred to as Phase III. (Note, this phase of the project was called Phase II in the proposal.)

Soon after Phase III of the geothermal project was restarted by the NYSGS, and completely independent of NYSGS, Woodward-Clyde Associated deployed a seismic network in the mid-Hudson regions sponsored by the Empire State Electric Energy Research Corporation (ESEERCO). Six of its stations were located within and near the geothermal project study area (Table 2-4, Fig. 2-2). One of its stations STWA, was especially conveniently located, southeast of Saratoga Springs, where no quiet location and satisfactory operator could be found for a geothermal network station. The ESEERCO network could make measurements there because its seismometer signals are fed directly into telephone lines and recorded elsewhere, so there is no need for an on-site operator. However, this station proved noisy.

In addition to the six ESEERCO stations (four letter codes), several of the stations of the North East Seismic Network (NESN) also are close to the geothermal project study area (Table 2-4, Fig. 2-2, three letter codes). The station WND is part of the subnetwork of NESN being operated by the Lamont-Doherty Geological Observatory of the Columbia University and stations LNX and IVT are part of the subnetwork of NESN being operated by the Weston Seismological Observatory of Boston College. The NES network is being sponsored and funded jointly by the Nuclear Regulatory Commission (NRC) and the U.S. Geological

TABLE 2-3

SEISMIC MONITORING NETWORK OF THE GEOTHERMAL PROJECT FROM OCTOBER 1981 THROUGH OCTOBER 1982 (PHASE III)[a/]

Station Code	Locality	Latitude Deg(N)	Longitude Deg(W)	Elevation (Meters)	Maximum Gain (10-15HZ)	Dates of Operation	Type of Recording	Station Operator
BDR	Beaver Dam Road	42.6398	74.0284	415	900K	Nov. 6, '81 Oct. 30, '82	ink on paper	Douglas Fraser
RPI	Rensselaer Polytechnic Institute	42.7314	73.6664	131	800K	Oct. 30, '81	ink on paper	Luanne Wheeler
FMC	Fulton-Montgomery Community Coll.	42.9839	74.2955	226	300K	Nov. 19, '81 Oct. 30, '82	ink on paper	Walter Smith Robert Kormordick
COM	Colfax Mountain Washington Co.	43.0910	73.3915	335	1500K	Nov. 2, '81 Oct. 30, '82	ink on paper	Dan Molloy
MCG	Mount McGregor Saratoga Co.	43.2032	73.7470	323	850K	Nov. 4, '81 Oct. 30, '82	ink on paper	Dan Heffner
CEC	Cultural Education Center, Albany	42.6481	73.7627	52	1K[b/] (LP)	Jan. 5, '82 Oct. 30, '82	ink on paper	Karen Bosher
ACC	Adirondack Community Coll.	43.3542	73.6545	98	350K	Dec. 2, '81 Oct. 30, '82	smoked paper	Anson Piper

a/See Figure 2-2 for location of Stations
b/Special long-period (LP) response from 5 sec. to 200 sec.

TABLE 2-4

ADDITIONAL SEISMOGRAPH STATIONS WITHIN AND AROUND THE STUDY AREA

Station Code	Locality[a/]	Latitude Deg(N)	Longitude Deg(W)	Elevation (Meters)	Operator
GERM	Germantown	42.1570	73.8113	-	W. Clyde[b/]
WND	Windham	42.3375	74.1525	602	LDGO[c/]
LNX	Lenox, Mass.	42.3389	73.2724	345	West.[d/]
BERL	Berlin	42.6913	73.3913	-	W. Clyde
ROTD	Rotterdam	42.7508	74.0872	-	W. Clyde
STWA	Stillwater	42.9620	73.6773	104	W. Clyde
CAMB	Cambridge	43.0488	73.2967	287	W. Clyde
GLOV	Gloversville	43.0895	74.3320	296	W. Clyde
IVT	Ira, Vermont	43.5521	73.0533	295	West.

a/See Figure 2-2 for location of stations.
b/W. Clyde = Woodward-Clyde Consultants, P.O. Box #290, 201 Willowbrook Blvd., Wayne, NJ 07470.
c/LDGO = Lamont-Doherty Geological Observatory, Palisades, NY 10964
d/West. = Weston Observatory, Department of Geology and Geophysics, Boston College, Weston, Mass. 02193.

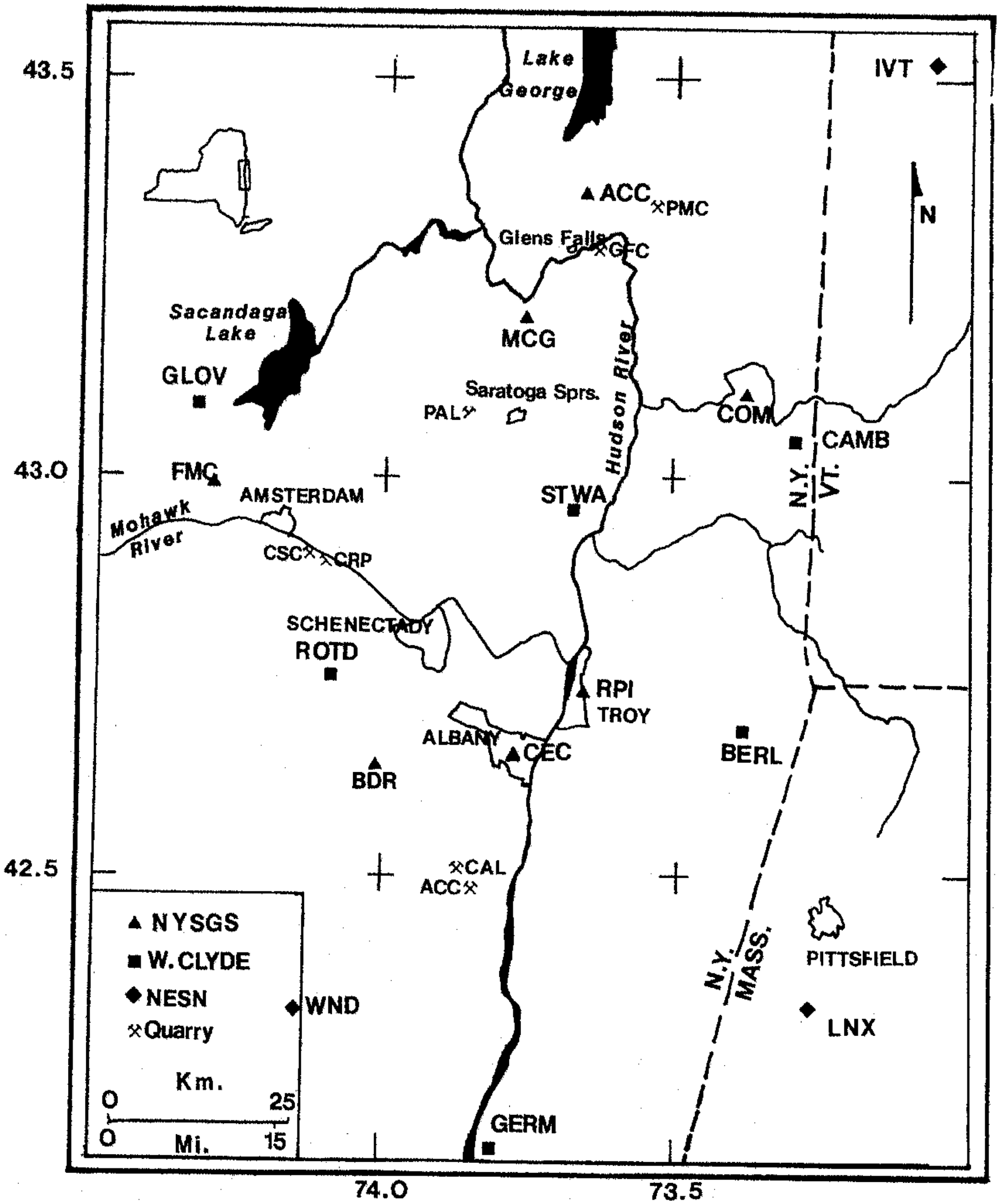

Figure 2-2. Location of the geothermal project and other network seismic stations from November 1981 to November 1982 (Phase III).

Survey (USGS) with some contributions from various states. By exchanging data among these network operators it was possible to monitor the geothermal project study area more extensively and more effectively during most of Phase III than earlier.

Section 3

INSTRUMENTS AND FIELD PROCEDURES

SEISMIC NETWORK

The instruments used during Phase I for the three stations LGE, COP and ACC, (Table 2-1, Figure 5-3) consisted of special portable, smoked-paper recorders developed by W. F. Sprengnether Instruments Company of St. Louis, Missouri (Model MEQ-800) for quick field installations where AC power is not available. The record preparation and changing procedure for these instruments, however, is messy and time consuming and is not well suited to long-term operation. These instruments, however, were already available at the NYSGS, acquired earlier for a different project, and could be deployed on short notice. During Phases II and III only one of these units (ACC) was used as a permanent station because only one person was available who was willing to operate this instrument on a longer term basis. The other two units were later used to record quarry blasts, an application for which these instruments are much better suited.

All other stations under NYSGS operation during Phases II and III consisted of seismic equipment especially designed and purchased for the geothermal project (Tables 2-2 and 2-3). They use ink recorders that are simple to operate, can be installed relatively fast and are suitable for long-term operation. The equipment was modified, assembled and calibrated at the NYSGS. Table 3-1 lists all major components, their original manufacturer's serial numbers and other pertinent information on all major equipment not owned by the NYSGS. For additional information on the amplifiers and recorders (Swiss equipment) see Wieland and Mitronovas (7).

Table 3-1

GENERAL INFORMATION AND SERIAL NOS. OF MAJOR SEISMIC EQUIPMENT SPECIALLY ORDERED FOR THE GEOTHERMAL PROJECT

Description	Vendor	Qty.	Manufacturer Serial No.	ERDA Property Tax No.	Current Location 10/82	Current Condition 10/82
Mark Products Geophones w/ Pressure case and Rectangular Base Model #1-158[a]	W.F. Sprengnether Instrument Co.	5	S-0 5877-1	DOE-32	ACC	Working
			S-0 5877-2	DOE-33	MCG	"
			S-0 5877-3	DOE-34	BDR	"
			S-0 5877-4	DOE-35	RPI	"
			S-0 5877-4	DOE-36	COM	"
Amplifier & Filter Units Model No. ST LPV 763[b]	Gunar Streckeisen & Company Switzerland	6	7914-1	DOE-12	FMC	Working
			7914-2	DOE-24	MCG	"
			7914-3	DOE-08	BDR	"
			7914-4	DOE-16	RPI	"
			7914-5	DOE-20	COM	"
			7914-6	DOE-04	CEC	"
Ink Recorders Without Pen Moters With 12 S.P. Pens Model #HAE-LP1/30	Gunar Streckeisen & Company	6	914-1	DOE-10	FMC	Working
			914-2	DOE-22	MCG	"
			914-3	DOE-02	CEC	"
			914-4	DOE-14	RPI	"
			914-5	DOE-18	COM	"
			914-6	DOE-06	BDR	"
Pen Moters Model #T4-150B[c]	MFE Corporation	6	82540	DOE-05	BDR	Working
			82541	DOE-09	FMC	"
			82542	DOE-21	MCG	"
			82543	DOE-01	CEC	"
			82544	DOE-13	RPI	"
			82545	DOE-17	COM	"
Digital Timing System, Model #TS-400	W.F. Sprengnether	6	7413	DOE-07	BDR	Working
			7414	DOE-15	RPI	"
			7415	DOE-19	COM	"
			7416	DOE-03	CEC	"
			7417	DOE-11	FMC	"
			7418	DOE-25	CEC	Under Repair
Standard Time Receiver	Caringella Electronics	6	-None-	DOE-26	CEC	Under Repair
			"	DOE-27	"	Under Repair
			"	DOE-28	"	Working
			"	DOE-29	"	"
			"	DOE-30	"	"
			"	DOE-31	"	"

a/ Special calibration of seismometers, (5) calibration data sheets.
b/ (5) portable calibrators purchased from W. F. Sprengnether Instrument Co. have been installed in and become a part of the amplifier and filter units.
c/ now an integral part of the ink recorders.

Each station was cared for by a person who either lived or worked near that station. Their names during Phases II and III are listed in Tables 2-2 and 2-3, respectively. The duties consisted of changing paper records daily (or, in a few cases, every other day on weekends or holidays), maintaining the equipment and reporting equipment problems to the NYSGS in Albany. Most problems were corrected on the following day. Blank paper records were prepared in Albany and delivered to each station at least once every two weeks at which time the registered records were picked up and brought back to Albany for analysis at the NYSGS.

During each station visit, the station clock was checked and resyncronized with the help of a master clock. The master clock was synchronized in Albany just before each trip to the field stations using time signal from a special shortwave radio receiver superimposed on a fast sweep (200 mm/sec) oscilloscope. Such a procedure made it possible to adjust the master clock to within ± 0.001 sec of true (atomic clock) time. At each field station this clock was used to check and resynchronize the station clock using fast record speed (5 mm/sec) to within ± 0.01 sec. This procedure, given the stability of the Sprengnether TS-400 clocks, made it possible to determine the arrival time of a sharp seismic signal to within ± 0.05 sec of true time anywhere on a seismogram at the normal record speed of 2 mm/sec. On most records the accuracy in time determinations was limited only by the accuracy in "reading" the signal on a seismogram with the help of a fine ruler under a magnifying glass.

Figure 3-1 shows the ground amplification as a function of frequency of ground motion (frequency response) for the station RPI. Except for CEC, the relative frequency response is similar to all other stations, including the smoked-paper recorders. Only the absolute gain is different because it is limited by the background noise (microseisms) level. The shape of this curve (filter characteristics) was chosen to optimize the signal-to-noise ratio based on the experience of the frequency content of microseisms and the expected signal from earthquakes and quarry blasts. The background noise at this frequency (5-20 hz) is caused mainly by meteorological factors like wind, rain, thunderstorms and by cultural (man-related) activity like traffic, pumps, generators, transformers, etc. The level of such microrecordings at any location depends critically, and in a complex way, on the intensity of the above factors, on distance from the source to the station, and on the nature of material (solid rock, hard soil, loose soil, etc.) where the seismometer is placed. Tables 2-2 and 2-3 show common gains, or range in gains because of changes in meteorological factors, at the peak of the frequency response curve (10-15 hz) for each station. Because of the very high cultural noise level at high frequencies at CEC, this station was designed to respond only to low frequencies (long periods) in ground motion. Such response is useful to record larger events without the pen going off scale (strong motion).

In general, the equipment performed as well as can be expected under actual operating conditions throughout the geothermal project. The few problems encountered and corrected during the installation and operation of the network during Phases II and III were related to simple operator mistakes, excessive humidity during summer months, and strong radiation of electromagnetic energy from unknown sources at two stations (THP, MCG). The operator mistakes involved problems like a failure to change records on time or to clean ink clogged pens as soon as the problem developed. At several stations where the recording equipment was located in a basement (MBR, RPI, CEC) excessive humidity during summer months resulted in soggy recording paper where ink could "spread" producing unsatisfactory records. A change to a special recording paper during Phase III reduced this problem considerably. The problem of strong electromagnetic radiation that interfered with the proper operation of the sensitive electronic amplifier at THP during Phase II and at MCG during Phase III was more serious and time consuming to diagnose and solve. This was because the problem at both

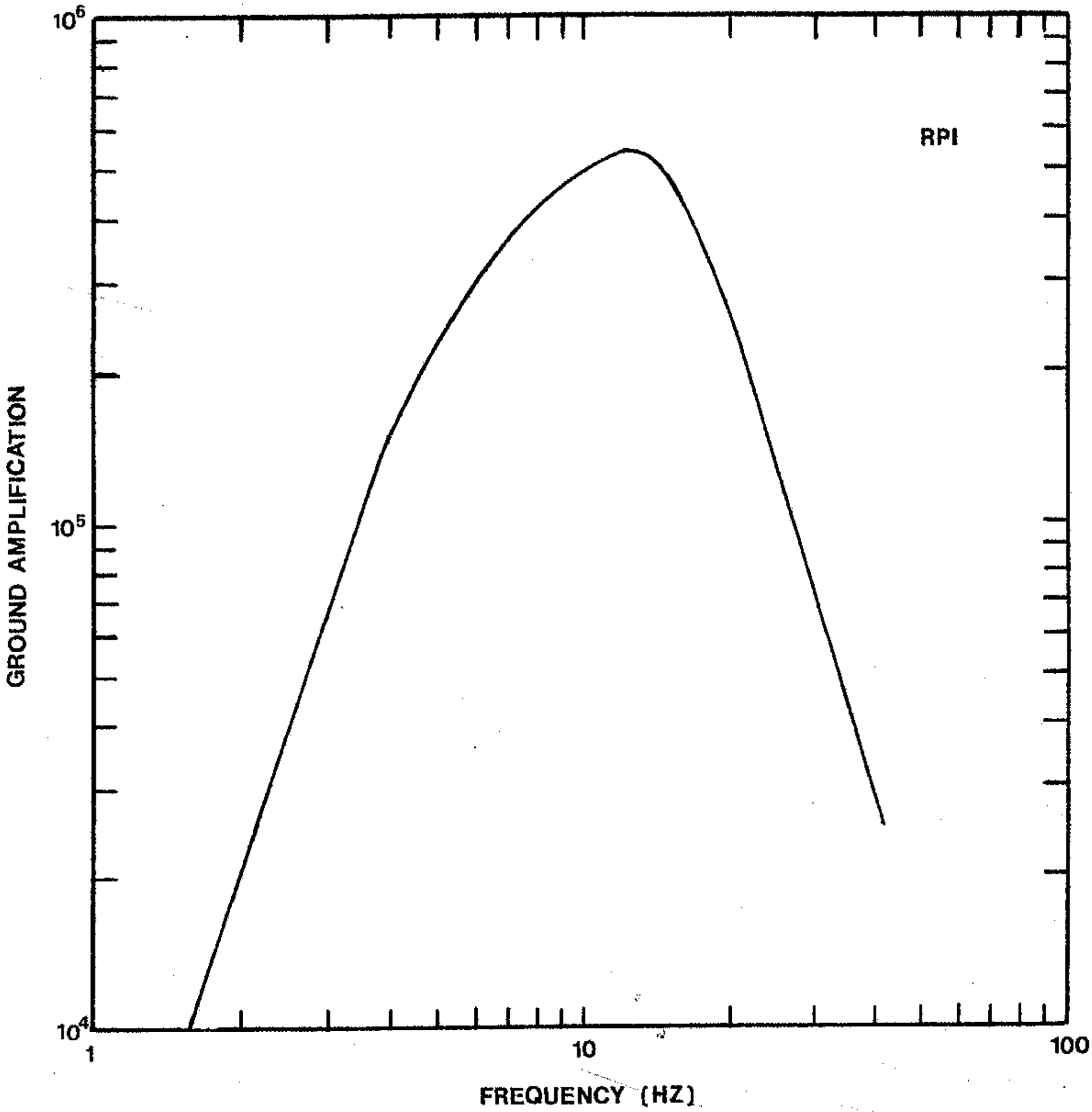

Figure 3-1. Ground amplification as a function of frequency for the RPI seismograph station.

locations was intermittent in nature and, therefore, was difficult to diagnose correctly and promptly.

The loss of recording time because of various problems discussed above and due to equipment failure is estimated to be less than 5 percent of the total operating time of the geothermal networks. To date, there have been no mechanical failures of any kind with the equipment from Switzerland (amplifiers and ink recorders). The smoked-paper recorders (MEQ-800) had several problems with drum- and penmotor-driven motors. This represents normal wear and tear of such equipment. Several failures of the short-wave time receivers (Caringella STR-1) and crystal clocks (Sprengnether TS-400), however, were related to faults in original design of this equipment.

QUARRY BLASTS

The origin time of a quarry shot was determined by placing a special portable seismograph as close to the blast area as the safety of equipment permits, which is usually within 50 m. A convenient instrument for this purpose was found to be the portable smoked-paper recorder (Sprengnether MEQ-800). This instrument was first modified by replacing the original slower drum and penmotor drive motors with faster ones to increase the recording speed from the normal 2 mm/sec to 10 mm/sec and by decreasing its gain to very low value. With the faster drum speed it is possible to determine the blast time to within $\pm$ 0.01 sec after making a small ($\sim$ 0.01 sec) allowance for the travel time of the seismic signal from the shot point to the seismometer.

The location of each shot was determined directly by identifying and matching visually the earth's topography and other features with topography on a large-scale topographic map. Using the standard 7½ minute quadrangle topographic maps published by the U.S. Department of the Interior (Geological Survey) at a scale of 1 to 24,000, it is possible, in most cases, to estimate the true location of the shot to within 100 m.

During Phases I and II only one portable instrument was deployed at a quarry just before shot time. At greater distances the blast was recorded by the permanent stations of the geothermal and other networks. The observed travel times to such stations, from a source for which both its location and origin time are known, constituted the basic data for seismic velocity determination. The exact location and origin time were determined in this manner only for selected larger blasts in order to obtain useful travel time data from greater distances.

During Phase III two additional modified portable instruments were usually deployed at some distance from a quarry to supplement the permanent stations, because in most cases the nearest permanent stations were at considerable distance from the quarries. This was possible because blasting usually was done at noon or later, so that sufficient time was available in the morning to deploy two temporary stations at various distances from the quarry, in addition to a third one at the quarry, before shot time. If extra time was available, a special trip to one of the permanent stations was made to increase its recording speed to maximum (5 mm/sec) and check the station clock using a master clock.

Section 4

DATA ANALYSIS

EARTHQUAKE DATA

1) Historical and Instrumental Before 1980

Information on historical earthquakes within the study area was compiled from several sources. Pomeroy and Fakundiny (8) made a compilation based on earlier catalogs of all historical and early instrumental earthquakes for New York State and adjacent regions up to 1975. This catalog has recently been corrected and updated by Mitronovas and Nottis (9) and Nottis (10). In the present study, effort was made to go to the original sources like old newspapers, diaries, special publications, etc. to improve the catalog for the study area by adding obscure events originally overlooked or by eliminating others that turned out not to be earthquakes. The most common information on the size of historical earthquakes is in the form of maximum intensity (I_0), based on the standard Modified Mercalli (MM) scale (11), and can be related to magnitude.

Information on instrumental earthquakes from 1974 through 1979 comes from the annual Regional Seismicity Bulletins of the Lamont-Doherty Network (12). The size of the instrumental earthquakes, as reported in these bulletins, is in the form of "body wave" magnitude (M_bL_g) as modified by Lamont-Doherty of Nuttli's (13) original proposal for eastern North America. Based on the more recent instrumental events for which both I_0 and M could be determined, the approximate relationship between them is of the form $I_0 = 0.70 + 1.2$ M (14).

2) Geothermal Seismic Network Since 1979

Since the start of the geothermal project in 1979 our information on seismic activity within the study area is based on direct monitoring by a seismic network. Since then our catalog of earthquakes for this area is not only much more complete but also extends to much smaller earthquakes than before. The following general procedure was used in data analysis from detecting to locating seismic events.

Smoked-paper and ink records (seismograms) were "read" manually using a fine ruler under a magnifying glass to determine the arrival time of all visible seismic phases. The arrival time for phases with sharp onsets could be determined to within ± 0.05 sec from original records with drum speed of 2 mm/sec, which is the normal speed. Seismic phases were read for all events that could be identified on three or more stations because that is the minimum number of stations required for a successful location. Most events can be identified at a glance whether they are local or distant from certain characteristics of their phases as they appear on a seismogram. The difference in the arrival time of P and S phases is one such important characteristic. No further analysis was done on the phases from distant events (earthquakes or quarry blasts). All local events were checked with the logs of all known quarry operators, or calling them directly, to determine which ones could be man-made blasts or natural earthquakes. Except for special work on a number of such blasts for the purpose of velocity studies, to be described below, no further analysis was done on them as part of the geothermal project.

The arrival times of phases (P and S) from all remaining local events were then used in a digital computer program to determine origin time, location and depth for these events. During Phase III, data from the additional seismograph stations, operated by other networks (Table 2-4), were used whenever available to supplement the geothermal network data. Two different computer programs were used for locating the events. They were selected, modified and adapted especially for this study, taking into account the size and the geometry of the network as well as the seismic velocities appropriate for different parts of the study area. One of the programs is quite simple and is best suited for very small events, those recorded by only a few nearby stations. The other program is a more sophisticated, general purpose program (15) better suited for larger events recorded over a wider area.

After a preliminary location of all such events, another attempt was made to check those events that happen to fall near known or suspected quarries and at suspicious times to see if they might be quarry blasts. Additional quaries in and around the study area were discovered this way and events related to their activity were eliminated from the list of possible earthquakes.

The size (magnitude) of all earthquakes since 1979, as detected by the geothermal network, has been determined using a new method for calculating magnitudes (16). This method is based on the duration (coda length) of the seismogram and not on the amplitude of such phases, as used in all previous methods. The main and important advantage of this coda-length magnitude (Mc) is that it can be applied to very small events, those recorded only by local stations, as well as larger events. The minimum distance requirement for the Nuttli magnitude, M_bL_g, for example, is about 50 km (13), while there are no minimum distance requirements for Mc. In other words, an event has to be large enough to be recorded by stations at distances greater than 50 km before an M_bL_g can be calculated, because amplitudes at smaller distances do not reliably represent the size of an event.

QUARRY BLAST DATA

Table 4-1 presents, in a chronological order, all the quarry blasts for which origin times and locations have been determined during the geothermal project using the special field techniques described earlier. Locations are believed to be accurate to within 100 m and origin times to within 0.01 sec in each case. The 39 shots cover seven different quarries. Their general distribution within the study area is shown in Figures 2-1, 2-2 and 5-3.

The smoked-paper records from the temporary portable instruments, especially modified and deployed to record selected quarry blasts, were analyzed (read) in the same manner as described earlier for the permanent stations, using a fine ruler under a magnifying glass. Because of the higher drum speed (10 mm/sec) all quarry blast phases with sharp onsets could be read to within ± 0.01/sec, instead of the normal ± 0.05 sec that is possible from the seismograms of the permanent stations with normal drum speed (2 mm/sec). In addition to being recorded by the temporary stations and the permanent stations of the geothermal and other networks at local and intermediate distances, several of the largest quarry blasts were also recorded by the more distant stations up to 250 km away.

The travel times from all such stations were used to determine the seismic velocity model on a local and regional scale. Because both distances and travel times of P and S phases can be determined directly and accurately, such information can be used to infer the seismic velocity structures using standard refraction techniques (17). In this method it is assumed that the earth can be represented by a number of nearly horizontal layers, that within each layer the seismic velocities are constant, and that each deeper layer has higher velocities than the one above. The data are first presented in the form of travel time as a function of distance plots for both P and S phases. From such travel-time plots it is possible to estimate both the P and S velocities and thickness of each layer.

Table 4-1

CHRONOLOGICAL LIST OF QUARRY BLASTS FOR WHICH ACCURATE LOCATION AND ORIGIN TIME HAVE BEEN DETERMINED

DATE Y M D	TIME(EST) H M S	LOCATION LAT(°N)	LONG(°W)	QUARRY CODE[a]
79 07 17	14:37:24.97	43.3494	73.5691	PMC
79 10 02	15:31:49.54	43.3507	73.5716	PMC
79 11 16	15:49:24.20	43.3029	73.6127	GFC
79 11 29	11:58:19.57	43.303	73.617	GFC
80 01 24	15:49:47.12	43.3030	73.6206	GFC
80 07 16	10:33:02.05	42.4861	73.8389	ACC
80 08 13	12:31:21.36	42.4920	73.8420	ACC
81 08 18	12:16:10.6	42.4994	73.8409	ACC
81 09 10	12:30:44.22	42.4879	73.8409	ACC
81 10 09	12:16:46.55	42.5006	73.8421	ACC
81 10 16	13:29:33.30	42.4851	73.8254	ACC
81 10 30	15:48:57.45	42.5205	73.8619	CAL
81 11 19	12:24:53.6	43.0798	73.8395	PAL
81 11 19	13:27:57.55	42.5017	73.8400	ACC
81 11 19	17:46:35.16	42.9919	74.1397	CSC
81 11 25	12:24:15.09	42.5235	73.8613	CAL
82 04 20	12:22:20.48	42.5205	73.8626	CAL
82 04 27	11:24:51.05	42.9027	74.1152	CRP
82 05 11	12:31:20.18	42.5017	73.8419	ACC
82 05 12	15:11:02.22	42.5171	73.8623	CAL
82 05 19	11:29:37.36	42.5013	73.8424	ACC
82 05 19	11:50:35.14	42.5240	73.8604	CAL
82 05 21	12:29:20.02	42.4918	73.8416	ACC
82 05 25	11:42:47.80	42.9027	74.1152	CRP
82 05 27	11:18:59.90	42.9111	74.1410	CSC
82 06 11	13:14:34.06	42.4976	73.8402	ACC
82 06 18	11:14:37.26	42.5206	73.8624	CAL
82 06 25	12:57:43.22	42.9021	74.1158	CRP
82 07 01	12:01:23.68	42.4840	73.8245	ACC
82 07 01	15:09:46.27	42.5150	73.8610	CAL
82 07 07	12:30:20.82	42.5006	73.8421	ACC
82 07 16	11:03:34.575	42.9028	74.1152	CRP
82 07 26	11:06:39.36	42.9110	74.1404	CSC
82 07 27	10:01:42.28	42.5239	73.8604	CAL
82 08 16	13:51:03.325	43.0781	73.8400	PAL
82 09 07	10:59:19.38	42.9023	74.1149	CRP
82 09 09	12:47:27.51	42.5239	73.8604	CAL
82 09 13	15:34:59.47	43.0780	73.8398	PAL
82 09 22	12:13:37.10	42.9112	74.1401	CSC

a/ ACC Atlantic Cement Company, Inc., P.O. Box #3, Ravena, NY 12143
CAL Callanan Industries, Inc., South Bethlehem, NY 12161
CRP Crushed Rock Products, RD #2, Amsterdam, NY 12010
CSC Cushing Stone Company, P.A. Box #1019, Schenectady, NY 12301
GFC Glens Falls Cement Division, The Flintkote Company, P.O. Box #440, 313 Lower Warren St., Glens Falls, NY 12801
PAL Pallette Stone Corporation, Washington St., Saratoga Springs, NY 12866
PMC Peckham Materials Corp., 419 Vaughn Rd., P.O. Box #310, Hudson Falls, NY 12839

See Figures 2-1, 2-2, and 5-3 for location of quarries.

Section 5

RESULTS

SEISMIC VELOCITY STRUCTURE

A computer program needs a model for seismic velocities as a function of depth in order to determine origin time, location and depth of an earthquake detected by a seismic network. The closer the resemblance of the velocity model to actual velocities in the earth, the more accurate will be the resulting solution, other factors being constant. Before presenting the earthquake results, therefore, the seismic velocity model, based on quarry blast data, will be presented and discussed.

Table 5-1 summarizes the parameters for the seismic velocity model as determined from the available data. The earth's crust within the study area can be represented reasonably well by three layers. The range in both the thickness and velocities for layer 1, as shown, reflect both the errors in data analysis as well as true regional variation in these parameters, where most of the "scatter" is due to real regional variations in layer 1 (Paleozoic sediments). Large variations in the thickness and velocities within the top layer are responsible for most of the uncertainties in thickness and velocities of the lower layers.

The available surface and subsurface geological and tectonic data (18) indicate that the contact between the Paleozoic sediments (layer 1) and the Precambrian basement (layer 2) in general dips a few degrees to the south. The thickness of layer 1 increases from zero in the north, underneath stations LGE and COP where the Precambrian basement of the Adirondack uplift is exposed at the surface, to about 5 km in the south underneath stations THP and BDR (Figs. 1

Table 5-1

SUMMARY OF THE SEISMIC VELOCITY STRUCTURE FOR THE STUDY AREA

LAYER	THICKNESS (km)	V_p (km/sec)	V_s (km/sec)
1. Paleozoic sediments	0 - 5	4.00 - 5.60	2.30 - 3.25
2. Pre-Cambrian Basement	12 ± 3	6.00 ± 0.20	3.45 ± 0.25
3. Lower Crust	20 ± 5	6.70 ± 0.10	3.80 ± 0.15

and 2). Layer 1 is composed of a complex sequence of thin sedimentary layers of shales, siltstones, sandstones and limestones deposited during lower Paleozoic time (18). The P and S velocities depend critically on the rock type, ranging from about 4.0 km/sec and 2.3 km/sec for shale to about 5.6 km/sec and 3.3 km/sec for limestone, respectively. For a given rock type (composition) the seismic velocities also depend, to a smaller degree, on their temperature and pressure conditions.

There is no direct geological information concerning either the dip of the contact between layer 2 and layer 3 (refractor) or the nature of layer 3. The dip of a refractor, based on refraction data above, can be determined accurately only from a "reversed" profile shooting (17). Because both the seismic velocity and depth to an interface depend on the dip of such a refractor, their true values cannot be determined without "reversed" profiling. The available quarry blast data, unfortunately, is not "reversed." However, because the range in the observed velocities for layer 3 is quite small, it suggests that this contact is horizontal or nearly so. This conclusion and its implications are still preliminary.

Although the seismic velocity model, as presented in Table 5-1, is generalized and approximate, it is of considerable usefulness for earthquake location purpose, when taken together with other information available from quarry blasts. For example, by locating a known quarry shot using a computer program and noting the direction and distance of "mislocation," it is possible to find station "corrections" that "pull" the solution closer to its true location. Such station "corrections" also improve location of any earthquake in the general area of such a quarry. Other problems, in addition to uncertainties in the seismic velocity model, contribute to errors in earthquake locations based on computer solutions. Such problems are: (1) insufficient or poor distribution of recording stations, (2) misidentification of seismic phases on a seismogram, and (3) errors in reading the phases. In the analysis of many seismic events it is one or more of these unavoidable problems, and not errors in the velocity model, that limit the accuracy of a computer location.

SEISMICITY

Historical and Instrumental Before 1980

A list of all known historical and pre-geothermal network instrumental earthquakes for the area between latitude 42°N and 44°N and longitude 73°W to 75°W is presented in Table 5-2 and their distribution is shown in Figure 5-1. This area includes the study area and adjacent regions to show a broader view of past seismic activity. The earliest event recorded in this area occurred in 1775. It is believed that before 1850 the available historical record is complete only for earthquakes I_0 = VI (M = 4.0) and larger for this area (14). An unknown number of smaller earthquakes before 1850 were either not felt or not reported and do not appear on this list. The "completeness" of this catalog extends to include smaller events with increasing reliability after 1850, but probably at a slow and uneven rate.

Only since 1970, does the instrumental record of earthquakes become more complete than direct reports by the public of felt earthquakes for this area. Between 1970 and 1980 the available instrumental record for the area is

Table 5-2

INFORMATION ON ALL KNOWN HISTORICAL AND INSTRUMENTAL EARTHQUAKES WITHIN AND AROUND THE STUDY AREA UP TO 1980

DATE	ORIGIN TIME(EST)	LOCALITY[a]	LATITUDE DEG.(N)	LONGITUDE DEG.(W)	MAXIMUM[b] INTENSITY(I^o)	MAGNITUDE
Jul. 6, 1775	10:55 -	Lake George	43.50	73.90	V	-
Jul. 6, 1775	18:51 -	Lake George	43.50	73.90	IV	-
Jul. 6, 1775	19:41 -	Lake George	43.50	73.90	IV	-
Jan. 16, 1840	20:00 -	Herkimer	43.00	75.00	VI	-
Jan. 11, 1847	23:30 -	Albany	42.60	73.80	III-IV	-
July 9, 1847	"AM"	Glens Falls	43.40	73.70	III	-
Dec. 17, 1855	14:00 -	Warren Co.	43.50	73.80	IV	-
May 11, 1877	10:02 -	Schoharie	42.60	74.40	IV	-
Dec. 28, 1878	21:32 -	Schoharie	42.70	74.30	III-IV	-
Mar. 18, 1881	21:30 -	Schenectady	42.80	73.90	IV	-
Apr. 2, 1882	06:30:07	Amsterdam	42.90	74.20	III	-
Apr. 2, 1882	08:10 -	Amsterdam	42.90	74.20	IV	-
Aug. 10, 1889	08:40 -	Warrensburg	43.50	73.80	V	-
May 25, 1890	17:10 -	Little Falls	43.00	74.80	V	-
Dec. 17, 1894	03:00 -	Coeymans	42.48	73.80	IV-V	-
Jan. 5, 1916	08:56 -	Chestertown	43.60	73.70	V	-
Feb. 2, 1916	23:25 -	Mohawk Valley	42.80	73.90	V-VI	-
Nov. 1, 1916	21:30 -	Glens Falls	43.40	73.60	V	-
Oct. 1, 1917	21:30 -	Glens Falls	43.30	73.70	III	-
Apr. 20, 1931	14:54 -	Warrensburg	43.50	73.80	VII	4.7
Oct. 29, 1933	-	St. Johnsville	43.00	74.70	IV	-
Apr. 13, 1938	01:00 -		43.17	73.12	II	-
Oct. 21, 1939	03:59:33	Glens Falls	43.30	73.30	II	-
Apr. 11, 1940	20:58 -	St. Johnsville	42.80	74.60	II	-
Oct. 2, 1942	17:29:31	Albany	42.60	73.80	-	3.0
Aug. 24, 1952	19:07 -	Johnstown	43.00	74.50	V	-
Mar. 31, 1953	02:50 -		43.70	73.00	III	-
Jul. 1, 1963	14:59:12	Albany	42.60	73.80	-	3.3
May 23, 1971	01:24:27	Blue Mtn. Lake	43.90	74.48	V	4.1
May 23, 1971	04:29:59	Blue Mtn. Lake	43.93	74.47	V	3.8
Jun. 20, 1971	21:48:31	Blue Mtn. Lake	43.90	74.48	IV	3.4
Jul. 10, 1971	03:15:01	Blue Mtn. Lake	43.91	74.44	V	3.6
Dec. 20, 1971	06:44 -	Blue Mtn. Lake	43.90	74.60	-	2.0
Mar. 15, 1972	07:10 -	Old Forge	43.70	74.70	-	2.6
June 16, 1972	04:01:58	Schenectady	42.80	73.90	-	2.0
Mar. 6, 1973	23:05:56	Blue Mtn. Lake	43.81	74.45	-	1.9
Mar. 21, 1873	22:10:30	Blue Mtn. Lake	43.89	74.42	-	-
June 11, 1973	05:08:31	Newcomb	43.95	73.98	-	-
July 15, 1973	03:30 -	Blue Mtn. Lake	43.90	74.40	-	3.4
July 15, 1973	05:32 -	Blue Mtn. Lake	43.90	74.40	-	-
Oct. 21, 1973	04:25:45	Blue Mtn. Lake	43.82	74.45	-	2.2
Sep. 11, 1974	15:54:13	Blue Mtn. Lake	43.83	74.19	-	2.2
Sep. 15, 1974	09:01:17	Schoon Lake	43.89	73.92	-	1.7
Sep. 18, 1974	01:23:09	Lake George	43.40	73.80	-	2.5
Nov. 19, 1974	04:23:28	Stony Creek	43.50	74.00	-	2.3
Jan. 27, 1975	05:40:10	Near Vt. Border	43.78	73.36	-	1.7
June 22, 1975	06:30:26	Old Forge	43.65	74.99	-	1.9
Aug. 3, 1975	23:58:22	Blue Mtn. Lake	43.87	74.15	-	2.1
Sep. 11, 1975	11:54:58	Raquette Lake	43.89	74.66	-	1.6
Sep. 23, 1975	10:11:16	Raquette Lake	43.90	74.65	-	1.6
Nov. 3, 1975	15:54:55	Raquette Lake	43.87	74.64	-	3.9
Nov. 3, 1975	16:06:40	Raquette Lake	43.89	74.65	-	-
Nov. 5, 1975	06:53:11	Raquette Lake	43.89	74.65	-	-
Nov. 17, 1975	17:36:41	Raquette Lake	43.90	74.64	-	-
Nov. 18, 1975	16:00:13	Raquette Lake	43.89	74.64	-	-
May 9, 1976	08:56:03	Raquette Lake	43.88	74.65	-	1.0
May 9, 1976	22:19 -	Raquette Lake	43.88	74.65	-	-
Aug. 19, 1976	10:47:53	Raquette Lake	43.89	74.64	-	-
Aug. 21, 1976	09:00:12	Raquette Lake	43.89	74.66	-	-
Sep. 17, 1976	20:15:23	Blue Mtn. Lake	43.82	74.20	-	1.6
Nov. 5, 1976	13:07:48	Raquette Lake	43.79	74.59	-	-
Apr. 5, 1978	09:45:49	Newcomb	43.85	74.24	-	2.6
Nov. 7, 1979	21:58:44	Blue Mtn. Lake	43.88	74.50	-	-
Nov. 28, 1979	21:58:44	Blue Mtn. Lake	43.79	74.49	-	2.5

a/See Figure 5-1
b/MM-Modifier Mercalli Intensity Scale

believed to be complete only for events $I_0 \geq IV$ ($M > 2.5$). Figure 5-2 shows the distribution of the available instrumental earthquakes for the northeastern part of North America.

Geothermal Network

Most of the local events detected by the geothermal network since 1979 turned out to be quarry blasts. There are over 15 known active quarries within and around the study area that have contributed to the list of recorded blasts. Most of the work in data analysis throughout the geothermal project consisted of identifying and separating such blasts from natural earthquakes. During Phases I and II of network operation only 14 events, out of a total of 115, turned out to be natural earthquakes, the rest being quarry blasts or suspected blasts. During Phase III only 25 events are earthquakes out of a total of about 170 local events. The information on the quarry blasts, except those already presented in Table 4-1 for which accurate locations and origin times have been determined, will not be presented or discussed further because they have no direct or relevant bearing on the conclusions of this study.

A list of all known earthquakes recorded during Phases I and II is presented in Table 5-3. This list consists of a few earthquakes widely scattered throughout the study area and a sequence of small events (seven) near Glens Falls that occurred during May 1980. Figure 5-3 shows the distribution of seven of the larger events that could be located. Additional events, believed to be part of this swarm, were too small to be recorded on at least three stations, especially after the stations LGE and COP were discontinued (Table 2-1) and so could not be located.

A list of all known earthquakes recorded during Phase III (Oct. 81 to Oct. 82) is presented in Table 5-4. The list includes another interesting sequence of deep, small earthquakes that occurred on February 8, 1982 near Thompson's Lake. By chance, this sequence took place almost underneath one of the stations of

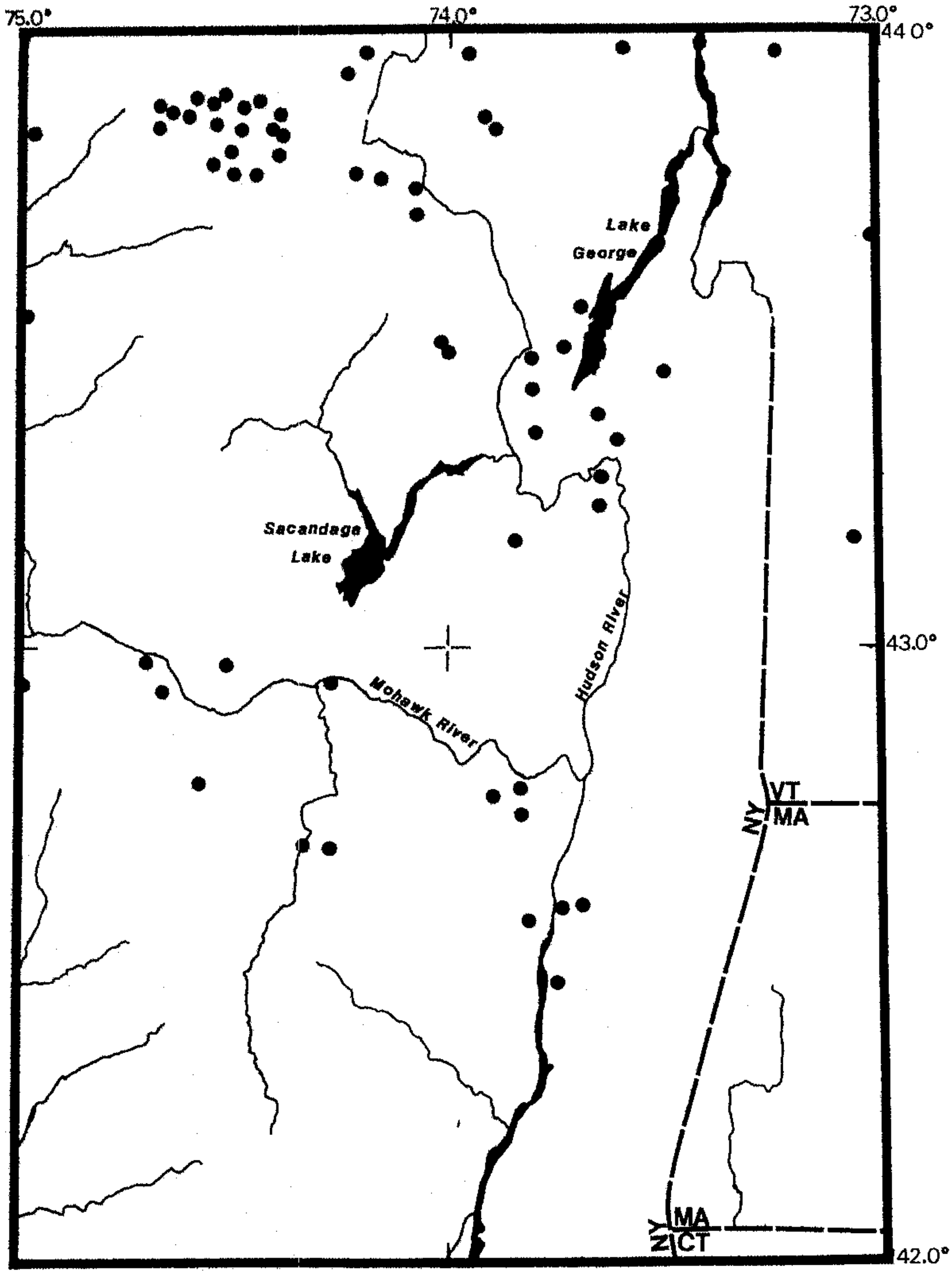

Figure 5-1. Location of all known historical and instrumental earthquakes within the study area and adjacent regions.

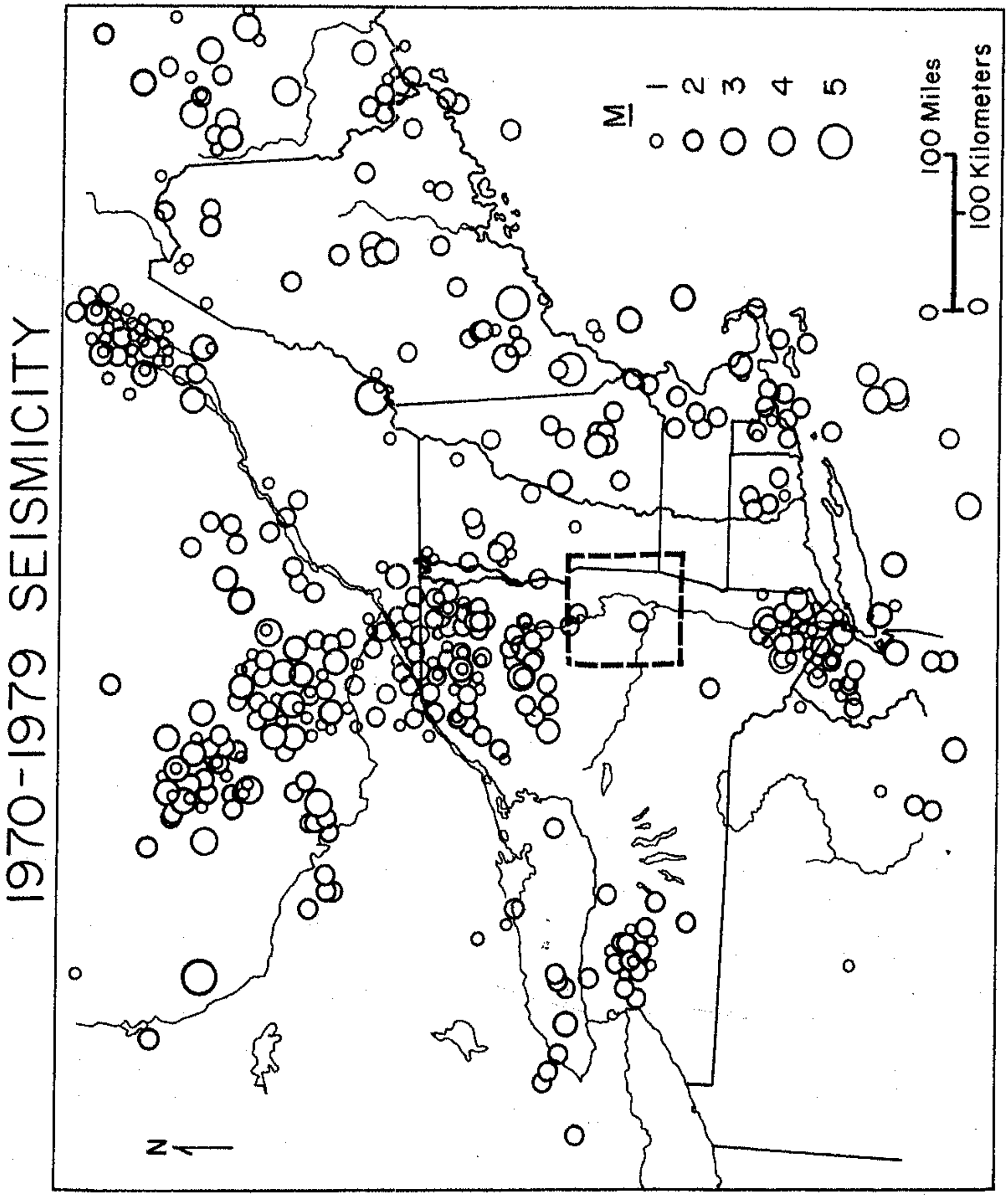

Figure 5-2. Location and size of instrumental earthquakes (1970-1979) for northeastern United States and adjacent Canada. (Redrawn from a compilation by the Lamont-Doherty Geological Observatory of Columbia University.)

the geothermal network, BDR. Also, because of good distribution of the other stations, especially of the geothermal and ESEERCO networks, both the depth and location could be determined exceptionally well for 9 of the events (19). Additional earthquakes assumed to be part of this swarm were too small to be located, being recorded only at BDR. Figure 5-4 shows the distribution of epicenters, with their estimated error bars to indicate the high precision, for 9 of these events. All depths, also well determined, are greater than 16 km (Table 5-4), which is unusual not only for the study area but for the whole of eastern North America (20).

The location of all earthquakes recorded during the geothermal project (Tables 5-3 and 5-4) is shown in Figure 5-5. The two special earthquake sequences of May 1980 near Glens Falls and February 8, 1982 near Thompson's Lake (near BDR) are marked by letters _a_ and _b_ respectively.

Table 5-3

INFORMATION ON EARTHQUAKES DETECTED AND LOCATED BY THE GEOTHERMAL PROJECT SEISMIC NETWORK FROM MAY, 1979 THROUGH SEPTEMBER, 1980 (PHASES I AND II)

DATE	ORIGIN TIME (EST)	LOCALITY	LATITUDE DEG.(N)	LONGITUDE DEG.(W)	DEPTH (km)	M_c
01/04/80*/	15:27:35.14	Whitehall	43.590	73.299	0.0	1.6
03/11/80	06:08:46.02	Athol	43.511	73.795	0.0	1.8
04/24/80	13:31:04.03	Lebanon Springs	42.499	73.425	0.0	1.7
05/05/80a/	07:18:54.42	Near Glens Falls	43.314	73.652	1.8	-0.2
05/05/80	16:11:13.27	Lake George	43.437	73.645	0.0	2.2
05/12/80a/	13:30:18.36	Near Glens Falls	43.328	73.650	5.6	0.2
05/13/80a/	07:36:13.37	Near Glens Falls	43.317	73.655	1.8	-0.2
05/13/80a/	13:35:37.62	Near Glens Falls	43.346	73.689	4.6	1.1
05/14/80a/	07:11:33.98	Near Glens Falls	43.314	73.660	0.5	-0.2
05/15/80a/	07:03:36.24	Near Glens Falls	43.320	73.650	2.1	-0.3
05/22/80a/	05:17:49.47	Near Glens Falls	43.347	73.683	4.7	0.5
05/29/80*/	14:04:58.08	Menands	42.698	73.709	0.0	1.5
06/06/80	12:40:07.67	New Lebanon	42.466	73.440	0.0	1.8
06/24/80	13:46:28.22	Halfmoon	42.835	73.714	0.0	1.0

*/Uncertain whether man-made or natural.
a/Earthquake sequence of 1980 near Glens Falls. See Figure 5-3.

Table 5-4

INFORMATION ON EARTHQUAKES DETECTED AND LOCATED BY THE GEOTHERMAL PROJECT SEISMIC NETWORK FROM OCTOBER, 1981 THROUGH OCTOBER, 1982 (PHASE III)

DATE	ORIGIN TIME (EST)	LOCALITY	LATITUDE DEG. (N)	LONGITUDE DEG. (W)	DEPTH (km)	M_c
12/41/81	13:30:38.21	Saratoga Springs	43.078	73.838	≤ 2	2.2
02/08/82	10:59:30.5	Thompsons Lake	Too Small To Locate		-	0.9
02/08/82	11:05:47.5	Thompsons Lake	42.630	74.042	17.5	1.8
02/08/82	11:07:26.6	Thompsons Lake	42.627	74.048	17.5	1.1
02/08/82	11:07:47.9	Thompsons Lake	42.627	74.038	17.3	1.1
02/08/82	11:08:36.5	Thompsons Lake	42.628	74.038	17.1	1.5
02/08/82	11:09:03.5	Thompsons Lake	42.630	74.048	17.9	1.8
02/08/82	11:11:27.8	Thompsons Lake	42.630	74.053	17.1	0.9
02/08/82	11:16:43.4	Thompsons Lake	42.629	74.041	17.4	2.6
02/08/82	11:44:36.2	Thompsons Lake	42.631	74.044	17.2	1.8
02/08/82	11:49:21.45	Thompsons Lake	42.626	74.046	16.4	1.8
02/08/82	12:57:12.45	Thompsons Lake	42.632	74.044	18.4	1.7
02/08/82	13:05:52.7	Thompsons Lake	Too Small To Locate		-	1.1
03/14/82	22:59:10.82	Mt. Marcy	44.0981	73.5307	0.1	1.6
05/03/82	06:09: -	Saratoga	Too Small To Locate		-	1.4
05/17/82	06:14:11:12	Saratoga	43.0877	73.8436	2.9	1.0
05/19/82	22:53: -	Near Glens Falls	Too Small To Locate		-	1.2
06/12/82	14:26: -	White Mans Mtn.	42.29	74.58	-	2.2
08/09/82	04:51:50.20	New Baltimore	42.4501	73.8186	2.61	1.7
08/10/82	19:41:22.80	Sacandaga	43.1997	74.1875	0.00	1.5
08/14/82	00:28:40.91	New Baltimore	42.4382	73.8176	5.17	1.6
08/31/82	05:17:57.94	Sacandaga	43.2026	74.1743	0.00	2.8
09/04/82	22:44:30.14	Sacandaga	43.2452	74.2610	15.59	2.0
10/06/82	22:57:04.20	Elsmere	42.6284	73.8507	2.72	1.3
10/10/82	04:45:40.00	Elsmere	42.6320	73.8446	3.00	1.6

[b]/A swarm of deep earthquakes near Thompsons Lake. See Figure 5-4.

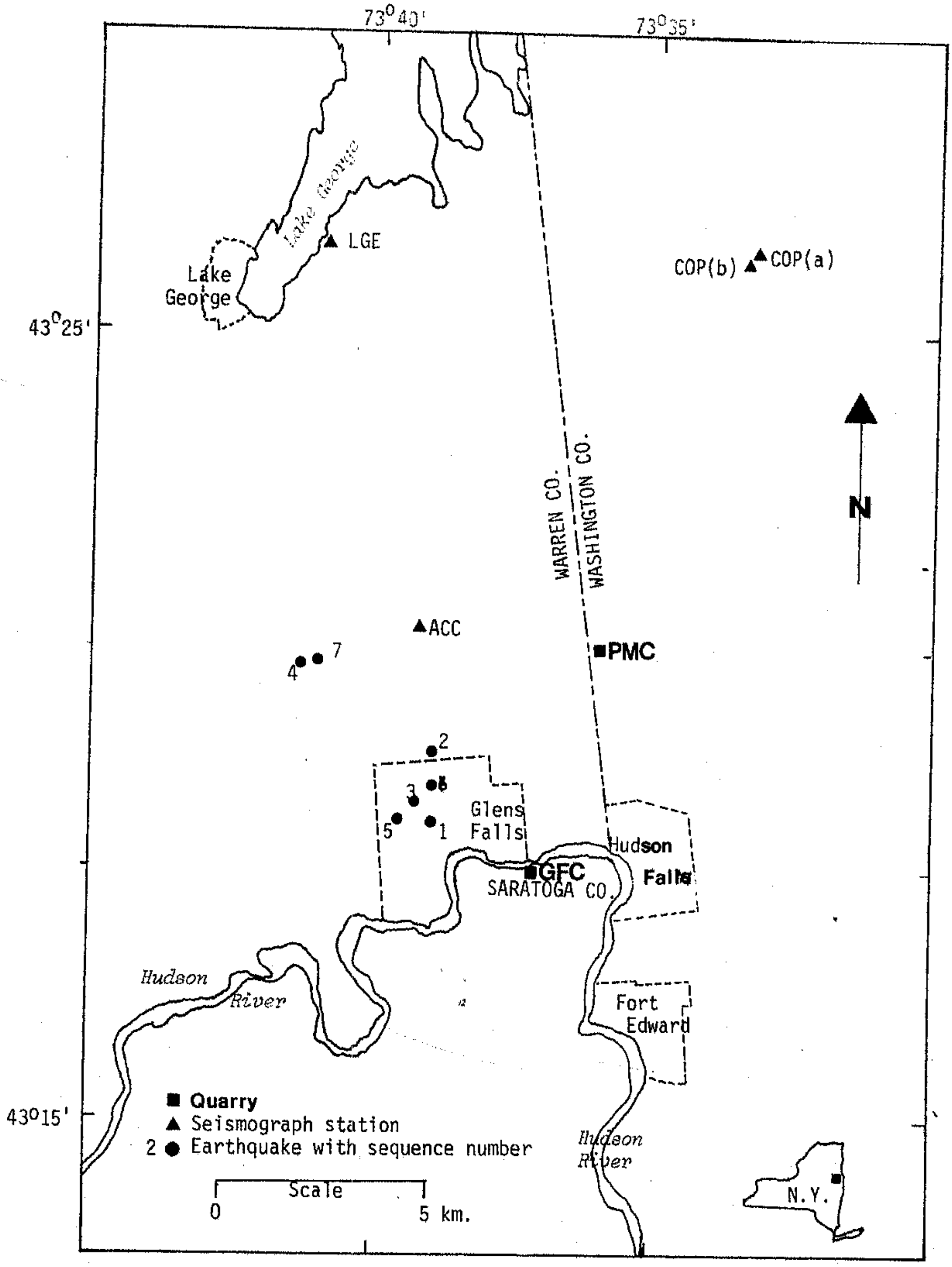

Figure 5-3. Location of the geothermal project smoked-paper recording stations (triangles) from May 1979 to June 1980 (Phase I) and the distribution of the earthquake swarm (dots) of May 1980 (numbers refer to chronological sequence of event occurrence).

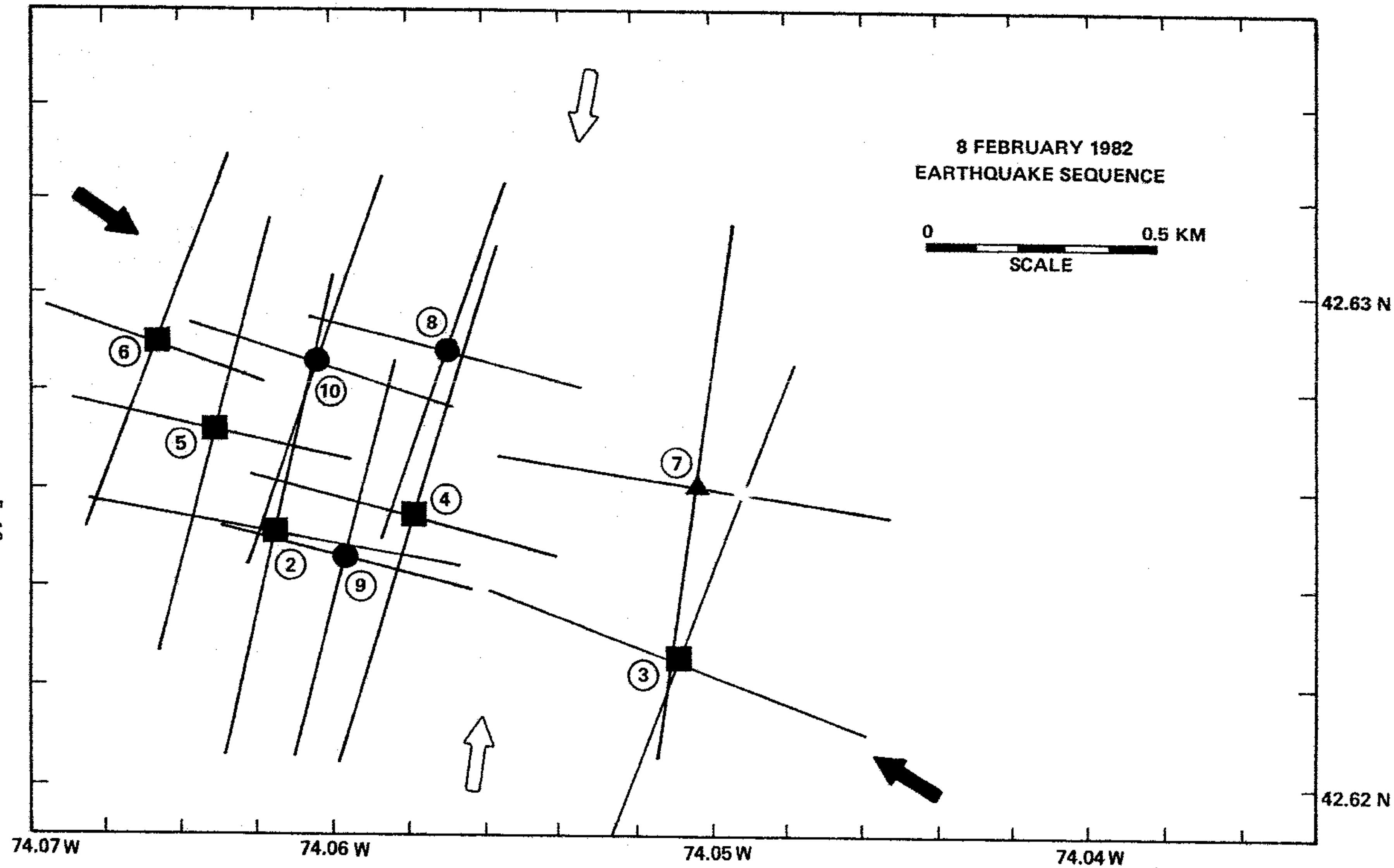

Fig. 5-4. Epicentral distribution of the earthquake swarm of February 8, 1982 near Thompsons Lake. (Lines indicate estimated location errors; numbers refer to chronological sequence of event occurrence - squares are foreshocks, triangle is mainshock, circles are aftershocks; large open and filled arrows indicate strike of nodal planes referring to the focal mechanisms solutions.)

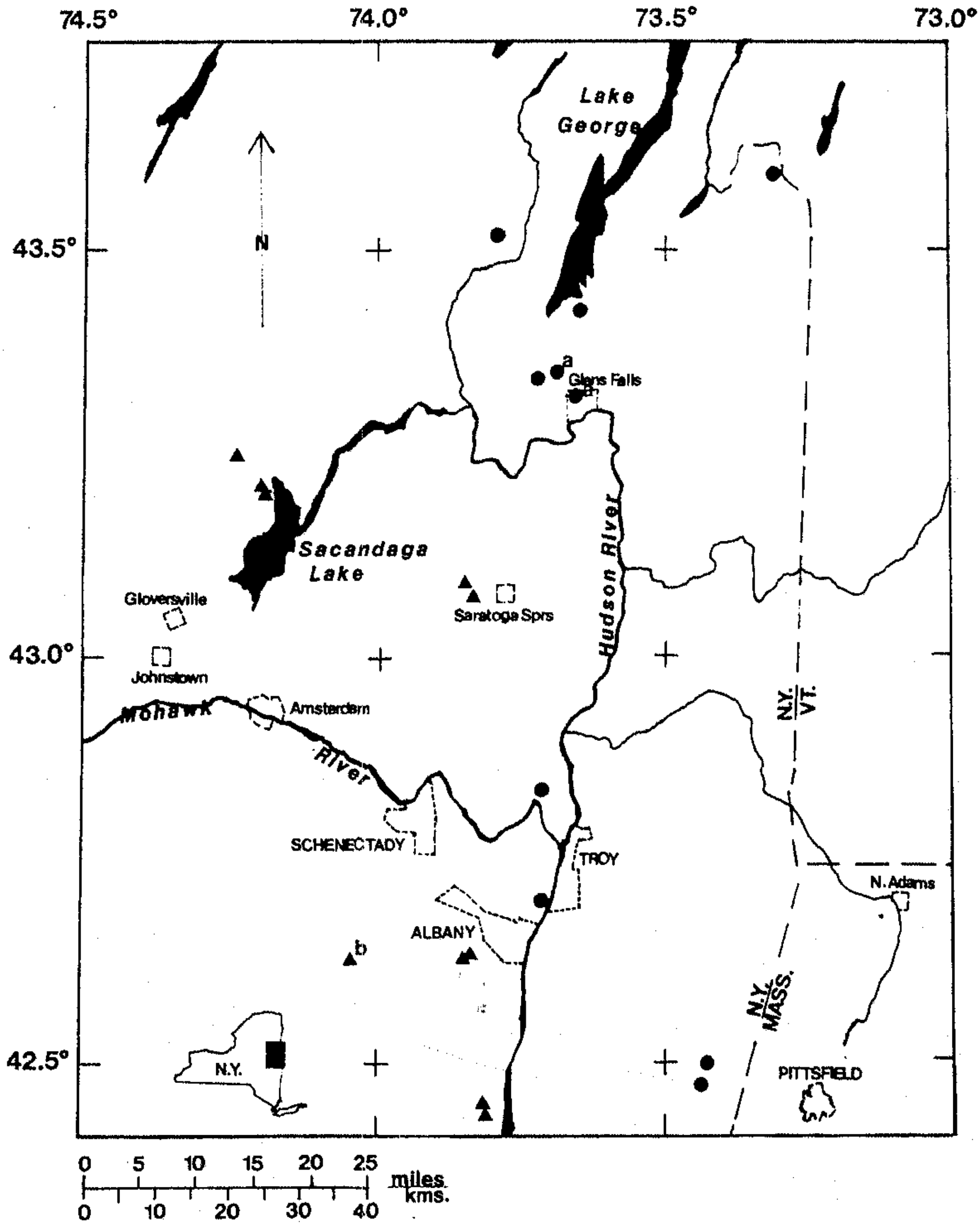

Figure 5-5. Epicenters of all earthquakes detected and located by the geothermal project seismic network: (circles) during Phase I and II, (triangles) during Phase III. Location of earthquake swarm of May 1980 (a), swarm of February 8, 1982 (b).

Section 6

DISCUSSION

It is well known (14) that in all seismic areas the number of observed earthquakes increases rapidly with decreasing size. For New York State, this relationship is approximately 3.5 to 4 times more events for one unit decrease in I_o and it appears to be constant in space and time (14). The 39 events of Tables 5-3 and 5-4, when normalized to a unit area, time and size, represent a level of seismic activity that is at least 5 times higher than the average for all of New York State from 1970 to 1980. Even when corrected for the two earthquake swarms of May 1980 and February 8, 1982 that contributed 19 of the 39 events, the activity within the study area is still 2 to 3 times higher than the average for the total state. On the other hand, the impression from Figure 5-2 is that the seismic activity within the study area is considerably lower than average. The reason for this is not completely clear. It is possible, but not likely, that seismic activity for the study area, or any other region this size ($\sim 10^4$ km^2), instead of being nearly constant with time, has large short-term fluctuations and that it was unusually high during the geothermal project (1979-1982). It is more likely that, given the past distribution of the statewide seismic network (12), the study area has been very poorly monitored before the geothermal project. As a result, it appears that the data presented in Figure 5-2 do not give a true picture of seismic activity throughout the State. Because of the uneven distribution of the statewide seismic network, the incompleteness in these data has strong regional dependence.

Based on a much better monitoring effort as a result of the geothermal project, the seismic activity within the study area, although considerably higher than previously believed, still appears to be unusually low for a potential geothermal area. The few observed earthquakes appear to be widely scattered throughout the study area in a random fashion (Figure 5-5). No unusual concentration of seismic activity has been detected in the center of the study area, north of Schenectady and south of Glens Falls where most of the CO_2 rich, mineralized spring activity is known to occur. In fact, when taken together with historical data (Figure 5-1) a case can be made that the area around Saratoga Springs, instead of being more active as expected, may actually be less active seismically than the surrounding areas. Bollinger and Gilbert (21) report such an unexpected relationship for the well known Hot Springs, Virginia area. Their data are even more pronounced than that of Figure 5-1, and the anomalously low seismic activity is well expressed in terms of historical as well as present instrumental data. If this is real for other such areas within eastern North America, there is as yet no obvious physical explanation.

There is no positive evidence that the observed seismicity, including the two swarms, within the study area is related in some way to the postulated geothermal activity. In fact, limited evidence is consistent with a suggestion that this activity is part of the normal regional tectonic seismicity resulting from coherent horizontal NE-SW tectonic compression extending from the Adirondack Mts. south along the Appalachian Mts. into Tennessee (20). For example, the focal mechanism solution of the deep swarm of February 8, 1982 near Thompsons Lake (19) is consistent with such regional tectonic compression in the NE-SW direction (Figure 5-4). Unfortunately, such data are not available for other shallower earthquakes in this area because all of them were too small and did not record over a wide enough area for such analysis. The earthquake swarm of May 1980 occurred to the northwest of Glens Falls (Figure 4-1), at some distance from the well known mineral springs to the southeast and southwest (4, 22). Finally, all other earthquakes seem to scatter at random throughout the study area, instead of being concentrated in a few spots (Figure 5-5).

Such a distribution is more consistent with a regional tectonic, rather than a geothermal process.

Given the tentative conclusion that all or most of the earthquakes are tectonic in origin, a relationship between earthquakes and geologic faults should exist. The exact nature of the relationship between the known or inferred faults as mapped at the surface (22), and the location of earthquakes is difficult to evaluate from the available evidence for several reasons. Given the typical errors in earthquake location ($\pm$ 2 to 3 km in epicenter, $\pm$ 3 to 5 km in depth) there usually are several faults within such an error ellipse. The problem is made more difficult by the fact that usually neither the dip of a fault at the surface nor its change with depth are known sufficiently well to predict where such a fault may be at a given depth. Finally, the total number of earthquakes with reliable locations available for such a correlation is very small.

There has never been any directly observed evidence in the form of a fresh break and displacement along a fault at the surface in this area, or anywhere in the State, to indicate which fault was responsible for a given earthquake. Because of the lack of such evidence there is no direct proof that earthquakes in eastern North America are directly associated with surface mapped faults. For example, it is difficult to believe that the February 8, 1982 sequence of deep earthquakes ($h > 16$ km) near Thompsons Lake had anything to do with the few surface faults in that area (22). These deeper earthquakes, as well as other shallower events, could result from motion along faults that have no surface expression, motion along faults at depth which do not reach the surface, or from fresh rock fractures at depth.

Work on determining seismic velocities during the geothermal project using quarry blasts initially was undertaken to improve earthquake locations. However, such results also can be used to test more directly the suggestion that the study area, or part of it, is underlain by abnormally hot upper mantle or lower crust and that this is the ultimate cause for the unusual mineralized spring activity and the source of the geothermal energy at shallow depths. The fact that seismic velocities decrease and their attenuation increases with increasing temperature has been widely used in recent years to study geothermal areas based on seismic techniques (6). The results of Taylor and Toksoz (23) and Fletcher and others (24) for the northeastern United States, using teleseismic P-waves, suggest that no major travel time anomalies exist to indicate large temperature anomalies in the upper mantle and lower crust here like those found under the Yellowstone National Park (25), the Coso and Geyser-Clear Lake geothermal areas of California (26, 27), and Hawaii (28). The results for the northeastern U.S. (23, 24), however, were based on a few stations distributed over a large area. No seismic stations in or close to our study area were available for these studies.

The seismic velocities for the lower crust (Table 5-1) have special relevance in testing the hypothesis that hot upper mantle material may be intruding the lower crust. Compared to other regions of the earth (29), the velocities of 6.70 km/sec for P and 3.80 km/sec for S phases represent normal conditions at such depths ($\sim$ 20 km) within the crust. These data, therefore, preclude any substantial temperature anomaly extending over a large region beneath the study area at such depths. However, as was pointed out in Section 5, these velocities were determined on the assumption that the interface between layer 2 and 3 is horizontal. At present, unfortunately, there are insufficient data to test this assumption. Also, there are insufficient teleseismic P-wave data at present to test the above results using vertical, in addition to horizontal, propagating waves. In general, given the precision and amouht of relevant data, it is estimated that a velocity anomaly at depth of 2% to 3% over an area of the order of 50 km or an anomaly of 10% to 15% over an area of less than 10 km could not be detected in this study. The velocity results at shallower depths (Table 5-1) are harder to interpret in this context because such velocities are known to vary considerably for reasons other than temperature (29).

In the process of occupying many temporary locations with portable smoked-paper recorders throughout the study area for the purpose of searching for potential quiet sites for permanent stations of the geothermal seismic network and for recording numerous quarry blasts (Table 4-1), relevant data were obtained to test the suggestion that abnormally high background earth motion (microseisms) may be associated with a geothermal system or its related activity (CO_2 release). The results show that there are large differences in the ground noise level from place to place, by a factor of up to 100. In general, the lowest noise levels were found on solid rock outcrops, away from human habitation and human related (cultural) activity. The highest noise levels were found on thick, loose sediments near lakes and within river valleys. In addition to cultural contributions to the microseismic level, meteorological factors like wind, rain, thunderstorms, etc. also are important, but more variable, sources of background noise. The time variation in the background noise due to meteorological factors is much more pronounced on thick loose soil than on solid rock. In addition, the cultural contribution also is greatest on loose, alluvial sediments near lakes and in river valleys because that is where the human activity is preferrentially concentrated.

The observed variations in the background noise level showed no systematic and coherent patterns on a regional extent. That is, no evidence was found anywhere to indicate that the relationship between the microseismic level and the geological, meteorological and cultural factors was different than normally expected in a non-geothermal region. For example, no anomalous area was found that had high noise level on solid bedrock that could not be explained in terms of obvious meteorological or cultural factors and that such noise level decreased systematically from any points consistent with an internal source like geothermal and related activity. In short, it appears that if the relationship between geothermal activity in any form and higher than normal microseismic level exists, such a "signal" is swamped by the meteorological and especially the cultural factors.

Section 7

CONCLUSIONS AND RECOMMENDATIONS

The northern part of the study area, between Glens Falls and Lake George, was monitored using three seismograph stations for one year from May 1979 through May 1980 (Phase I - Table 2-1, Figures 2-1 and 5-3). The total study area (here defined as from 42.5^{o}N to 43.5^{o}N latitude and from 73.0^{o}W to 74.5^{o}W longitude) was monitored at first using six seismograph stations from April 1980 to September 1980 (Phase II - Table 2-2, Figure 2-1), and then using 16 stations from October 1981 through October 1982 (Phase III - Tables 2-3 and 2-4, Figure 2-2).

A total of 39 earthquakes, ranging in size from Mc = -0.3 to Mc = 2.8 (Tables 5-3 and 5-4), were located within the study area with various degrees of precision during the geothermal project (Phases I-III). Nineteen of these events occurred in the form of two earthquake swarms during May, 1980 near Glens Falls (Table 5-3, Figure 5-3) and on February 8, 1982 near Thompsons Lake (Table 5-4, Figure 5-4). The other events appear to be distributed throughout the study area in a random way.

The distribution of all known historical (Figure 5-1) and instrumental (Figure 5-2) earthquakes prior to 1980, suggests that seismic activity within the study area is significantly below the average for all of New York State. That the actual seismic activity, as detected by the geothermal seismic network, turns out to be about 2 to 3 times higher than the average for the total state, probably means that, until the geothermal project, the seismicity in the study area was poorly monitored and considerably underestimated. Nevertheless, the observed level of activity is low for a possible geothermal area. In fact, the limited available evidence about this seismicity, including the two swarms, in the form of its distribution and focal mechanism solutions when compared to larger historical and instrumental earthquakes over a wider area, suggests that it probably is in response to regional tectonic stresses acting coherently over a wide area and not to the observed local geothermal or related activity.

The seismic velocity model for the study area based on data from 39 quarry shots (Table 4-1) and a few larger earthquakes, originally was determined as an aid to improve the location of earthquakes. The seismic velocities, because of their dependence on temperature, can be used directly to indicate the presence or absence of temperature anomalies at depth. The limited results in a form of normal velocities of P and S seismic phases suggest no significantly high temperature anomalies of great extent within the crust under the study area. To detect more subtle temperature anomalies over a more limited region requires more precise knowledge of seismic velocities as a function of region and depth for which the available data are not yet sufficient. For example, a velocity anomaly of 2% to 3% over a wide area (50 km) or 10% to 15% over a limited area (less than 10 km) could not be resolved from the available data.

A method based on systematic and coherent variation in the level of the background earth vibrations (microseisms) was found to be unsuccessful as a prospecting tool for locating geothermal heat or related activity. The available data show that variations in microseisms due to meteorological (wind, rain, thunderstorms, etc.) and cultural (traffic, pumps, transformers, etc) factors are extremely large and are sensitive to differences in geological conditions (solid rock, hard soils, loose soil, etc.) in the immediate vicinity of a seismometer. If the level in the background noise also depends on geothermal or related activity it is being effectively covered up by the meteorological and especially the cultural factors.

Based on the above conclusions and inferences it is suggested that further monitoring of the seismicity within the study area over a short time will not help locate geothermal heat because the seismic activity is relatively low and probably not directly related to mineral spring or geothermal activity. Only through a much longer survey is there hope to improve substantially our understanding of the nature and relationship of seismicity to other geophysical or tectonic processes in this area.

Section 8

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