PL-TR-91-2001
Environmental Research Papers, No.1076

Seismic Recordings in the Northeastern United States of the Shagan River Nuclear Test of 14 September 1988

AD-A240 791

James C. Battis
John J. Cipar

7 January 1991

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

91-11349

GEOPHYSICS DIRECTORATE OF
PHILLIPS LABORATORY
AIR FORCE SYSTEMS COMMAND
HANSCOM AIR FORCE BASE, MA 01731

91 24 006

"This technical report has been reviewed and is approved for publication"

JAMES F. LEWKOWICZ, Chief
Solid Earth Geophysics Branch

DONALD H. ECKHARDT, Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify GL/IMA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2 REPORT DATE	3 REPORT TYPE AND DATES COVERED
	7 January 1991	Scientific, Final (1 Oct. 88 to 30 Sep. 89)

4. TITLE AND SUBTITLE

Seismic Recordings in the Northeastern United States of the Shagan River Nuclear Test of 14 September 1988

5. FUNDING NUMBERS

PE62101F
PR7600 TA09 WU08

6 AUTHOR(S)

James C. Battis and John J. Cipar

7 PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Phillips Laboratory (LWH)
Hanscom AFB, MA 01731-5000

8 PERFORMING ORGANIZATION REPORT NUMBER

PL-TR-91-2001
ERP, No. 1076

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited.

12b DISTRIBUTION CODE

13 ABSTRACT (Maximum 200 words)

On 14 September, the USSR conducted an announced nuclear test as part of the US-USSR Joint Verification Experiment (JVE) called for in the protocols of the Threshold Test Ban Treaty of 1974. The test, code named SHAGAN, was detonated at the Shagan River test area in eastern Kazakh SSR. For this nuclear test, a small-aperture array in New Hampshire and a small five station network located in the Adirondack Mountains of New York State were operated by GL. The following report describes the data taken during this experiment and preliminary analysis of the arrival time and magnitude estimates from the data. The results of this analysis are consistent with those from previous studies.

14 SUBJECT TERMS	15. NUMBER OF PAGES
Key words. Seismology, Nuclear tests, Crustal structure, Seismic arrays, Northeastern United States.	48
	16 PRICE CODE

17 SECURITY CLASSIFICATION OF REPORT	18 SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	S.A.R.

NSN 7540-01 280-5500

Standard Form 298 (rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

Contents

Illustrations

Tables

Acknowledgements

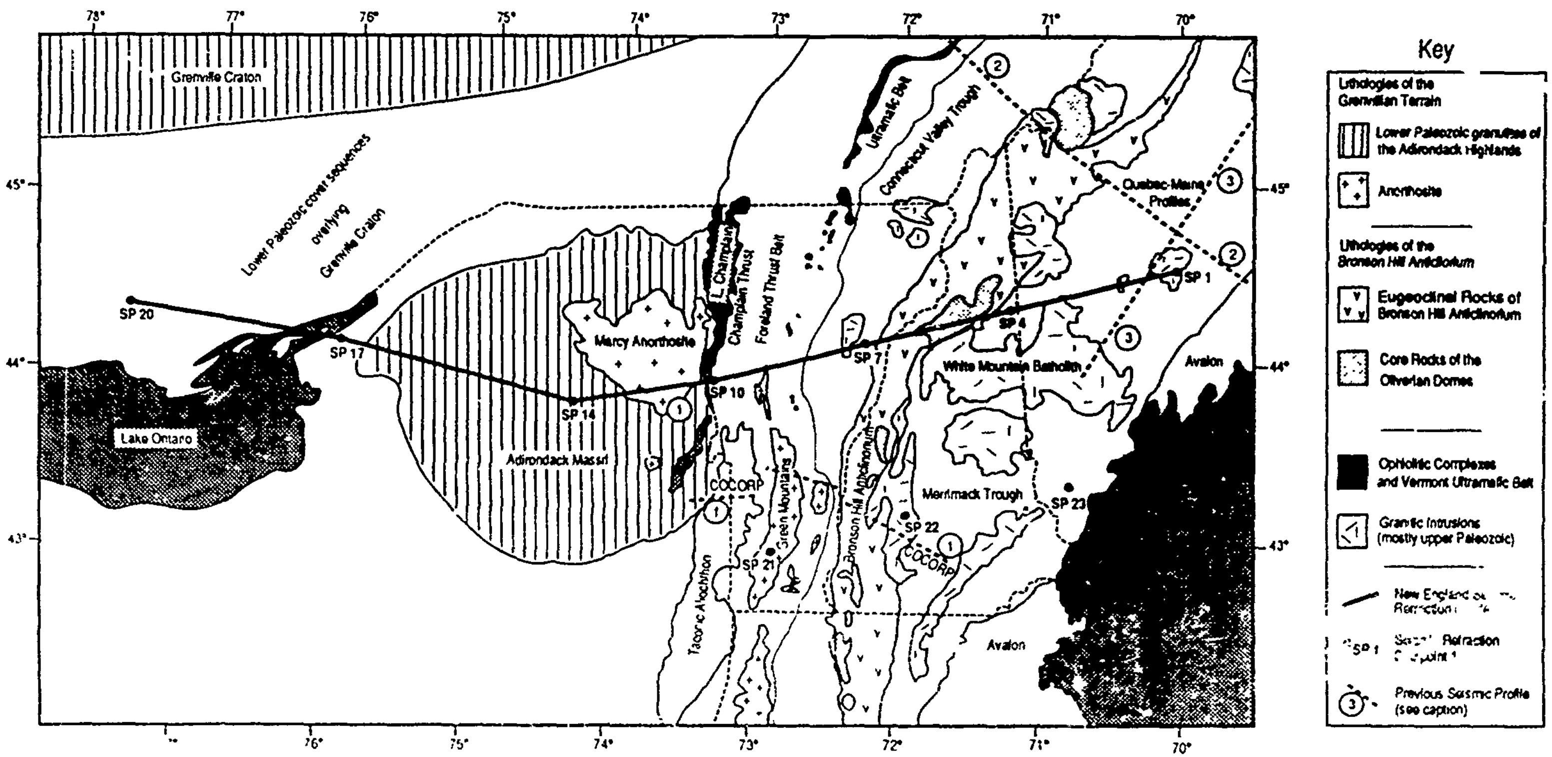
The authors express their appreciation to the many people who provided assistance to this effort particularly in supporting the field efforts required to obtain the data. These include Joseph Blaney and Christopher Center of the Weston Observatory of Boston College, Capt Lloyd Rainey and Sgt Joe Craig of the Geophysics Laboratory (GL) and Dr Anton Dainty, a National Research Council Research Associate at GL for assisting in the set-up and operation of the North Haverhill array. We also acknowledge the community and people of North Haverhill, New Hampshire for allowing access to the Dean Memorial Airport site. The authors also thank Stephen Mangino, Janet Johnston, Henry Ossing and Katharine Kadinsky-Cade of GL, and Al Leverette and Kent Anderson of the Air Force Weapons Laboratory for assistance in the field. Katharine Kadinsky-Cade critically reviewed the manuscript.

Seismic Recordings in the Northeastern United States of the Shagan River Nuclear Test of 14 September 1988

1. INTRODUCTION

In early September 1988 the Solid Earth Geophysics Branch of the Geophysics Laboratory Earth Sciences Division was preparing to support a major crustal refraction survey transecting New England and New York, and continuing into Ontario, Canada. This experiment, the Ontario-New York-New England Seismic Refraction Experiment (nicknamed NY-NEX; *Battis*, 1990; *Mangino and Cipar*, 1990) was conducted jointly by the Geophysics Laboratory (GL), the US Geological Survey (USGS), and the Geological Survey of Canada (GSC). The generalized geology of the region and the shot lines of this experiment are shown in Figure 1. During this experiment GL conducted two separate field operations. The first of these was a 25-station network of three-component seismic recorders whose locations were varied throughout the experiment. The second operation was a 16-element, small-aperture seismic array located in the Connecticut River Valley at North Haverhill, New Hampshire.

(Received for Publication 7 January 1991)



New England Seismic Refraction / Wide Angle Reflection Profile

Geology simplified after Hatcher, 1975, and McLeland and Isachsen 1986

Figure 1. A Generalized Geologic Map of the Northeastern United States and Adjacent Canada Showing the Shot Lines of the Ontario-New York-New England Seismic Refraction Survey (after Luetgert and Hughes, 1989).

On 14 September, the USSR conducted an announced nuclear test as part of the US-USSR Joint Verification Experiment (JVE) called for in the protocols of the Threshold Test Ban Treaty of 1974. The test, code named SHAGAN, was detonated at the Shagan River test area in eastern Kazakh SSR (Figure 2). Table 1 gives the USGS origin time, location, and magnitudes along with coordinates and distances to stations used in this study. This event provided an opportunity to test and calibrate the GL field equipment prior to the crustal refraction experiment. For this nuclear test, the small-aperture array in New Hampshire and a five-station network located in the Adirondack Mountains of New York State were operated by GL. This report describes the data taken during this shot and some preliminary analysis of the data.

2. THE NEW HAMPSHIRE SMALL-APERTURE ARRAY

The Soviet nuclear test on 14 September 1988 was recorded by a small-aperture seismic array that had been installed by GL at North Haverhill, New Hampshire to support the Ontario-New York-New England Seismic Refraction Experiment. The primary purpose of the array was to examine high frequency (> 5 Hz) seismic propagation at regional distances during the Ontario-New York-New England Seismic Refraction Experiment. The configuration of the array was, therefore, not optimal for observing a teleseismic event such as the SHAGAN nuclear test. However, as a result of the relative quiet of the site and the level of noise suppression achieved through array processing, the North Haverhill array provided relatively high quality seismic recordings of this event. Due to the limited recording time available on the configured system the data from this event consisted primarily of the body wave phases.

2.1 Geological and Geophysical Setting

The GL seismic array was located on the property of a small municipal airport in the town of North Haverhill, New Hampshire (Figure 3). The latitude and longitude of the array, referenced to the vertex of the arms of the array, was measured to be 44.079°N and 72.009°W. An elevation of 177 meters above mean sea level was determined from the USGS 15" topographic sheets for this area. Geophysically, the site is of interest as it lies near the contact line between the ancient North American and European or African plates. Arrivals at the array from the east are basically traveling in the alien crust while those from the west travel through the original North American plate, as defined by the limits of Grenville formations.

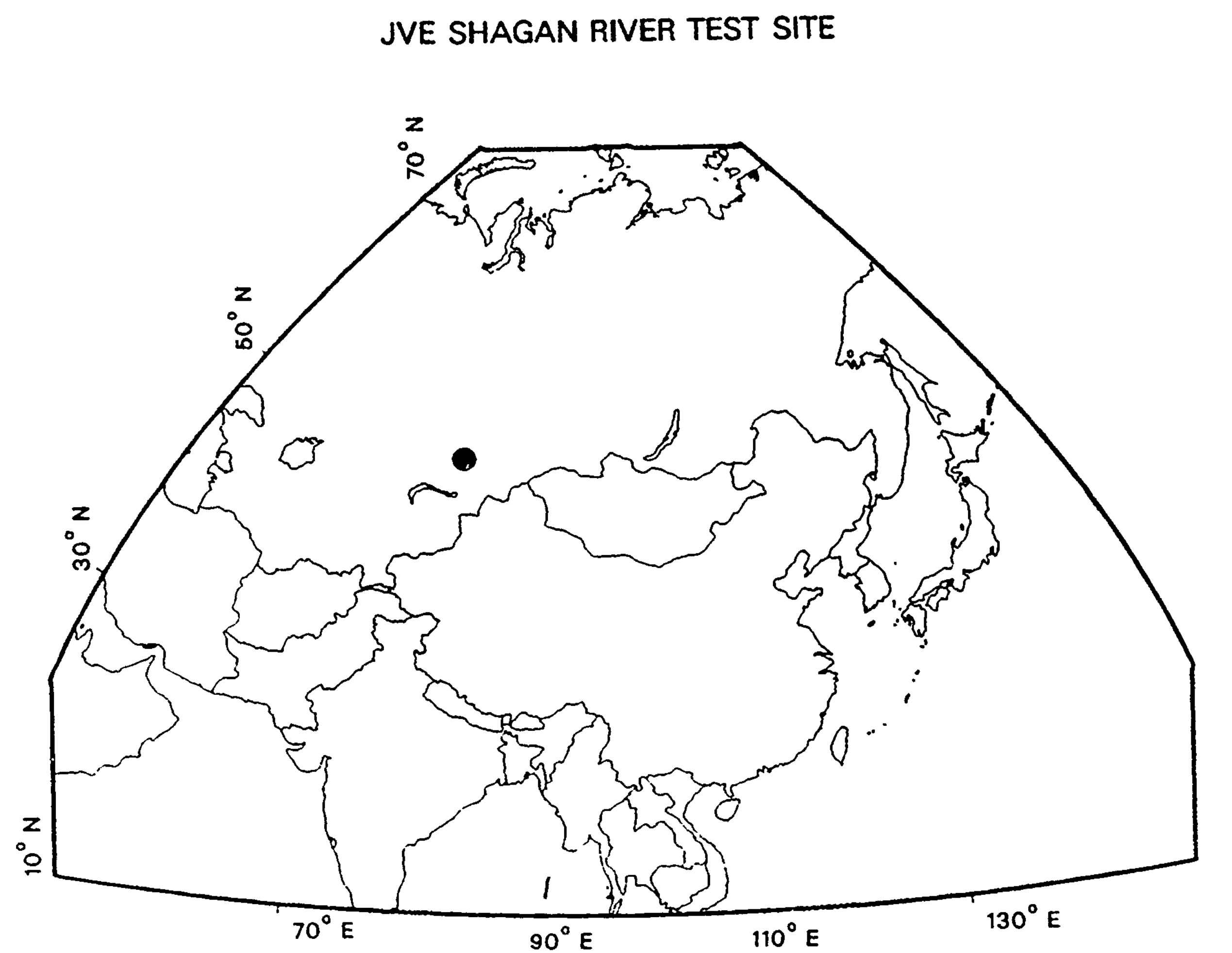


Figure 2. The Location of the Joint Verification Experiment Nuclear Test of 14 September 1988 at the Shagan River Test Site in the Soviet Union.

Table 1. Event and Station Information.

Date		Origin Time		Latitude	Longitude	Depth	m_b	m_s	Location
Sept. 14, 1988		258d 3h 59m 57.400s		49.833N	78.808E	0.0	6.1	4.5	Eastern Kazakh. USSR
Station		**Latitude (deg)**	**Longitude (deg)**	**Elevation (meters)**	**Delta (deg)**	**Distance (km)**	**Azimuth (deg)**	**Back Azimuth (deg)**	**Location**
NHNH	AFGL	44.079N	72.009W	177.00	83.063	9221.55	339.33	18.49	North Haverhill, NH
1125	AFGL	43.934N	74.812W	548.61	83.816	9304.98	341.22	16.77	AFGL NY-NEX Sta.
1126	AFGL	43.942N	74.759W	556.23	83.797	9302.86	341.18	16.81	AFGL NY-NEX Sta.
1128	AFGL	43.962N	74.659W	560.80	83.757	9298.46	341.12	16.87	AFGL NY-NEX Sta.
1130	AFGL	43.986N	74.550W	585.19	83.710	9293.30	341.05	16.94	AFGL NY-NEX Sta.
1131	AFGL	44.000N	74.490W	508.99	83.685	9290.44	341.01	16.97	AFGL NY-NEX Sta.
CTR	LDGO	43.874N	74.460W	585.00	83.798	9303.10	340.96	16.99	Castle Rock, NY
ECO	LDGO	43.971N	74.224W		83.656	9287.27	340.82	17.14	Ecological Ctr., NY
GNF	LDGO	43.915N	74.229W		83.711	9293.36	340.81	17.13	Goodnow Flow, NY
HBVT	LDGO	44.362N	73.065W	1130.00	83.031	9217.94	340.14	17.86	Hinesburg, VT
MDV	LDGO	43.999N	73.181W	134.00	83.402	9259.19	340.11	17.77	Middlebury, VT
MIV	LDGO	44.075N	73.534W		83.408	9259.78	340.38	17.56	Mineville, NY
MSNY	LDGO	44.[illegible]83N	74.862W	51.72	82.821	9194.45	341.56	16.78	Massena, NY
NWC	LDGO	43.845N	74.150W	563.00	83.760	9298.89	340.73	17.18	N. Woods Club, NY
PGY	LDGO	43.708N	74.045W		83.869	9310.96	340.62	17.24	Peter Gray Mtn, NY
PTN	LDGO	44.572N	74.983W	238.00	83.240	9240.92	341.52	16.69	Potsdam, NY
WNY	LDGO	44.391N	73.859W	598.00	83.177	9234.05	340.69	17.37	Wilmington, NY

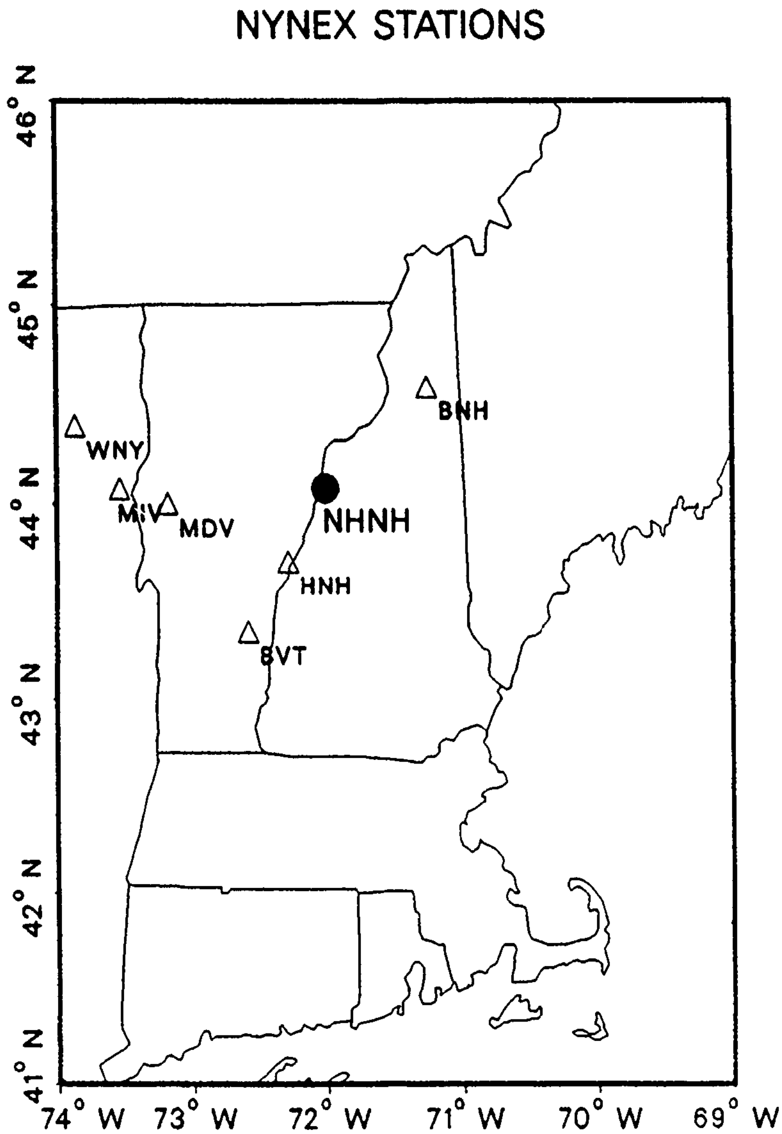


Figure 3. Location of the GL North Haverhill, New Hampshire Small-Aperture Array Also Showing Selected Stations of the New England Seismic Network. Stations MDV and WYN are shown for orientation of this plot with Figure 11.

This site is within the Connecticut River Valley and just west of the White Mountain plutons (Figures 1 and 4). The array lies between the Foster Hill sole fault on the east and the Ammonoosuc fault on the west, both of which trend north-northeast in the area of the array (*Moench*, 1989). The Ammonoosuc fault is taken to be the western boundary of the Bronson Hill anticlinorium, an island arc complex associated with the overthrusting of the oceanic plates during the closing of the proto-Atlantic ocean. This event occurred about 440 million years ago, during the middle Ordovician. The site is at the northern end of the Piermont Allochthon which appears to have been transported to its present location during the Acadian orogeny and before the emplacement of the Devonian New Hampshire Plutonic Series. The array was located just outside of the mapped southern boundary of the French Pond pluton from this series. Underlaying the site and extending well to the south is a turbidite sequence of interbedded metasandstones and phyllites, part of the allochthon. Both the allochthon and the plutonic intrusions are typical of continental convergence zones (*Dewey*, 1977) as has been hypothesized as causes of the Acadian orogeny.

In a comprehensive 3-D study of the crust under the Northeastern US, *Taylor and Toksöz* (1979) found distinct evidence for crustal thickening between central Vermont and central Maine. That study indicated the thickest crust runs along the Connecticut River Valley from the Massachusetts border to somewhat north of the array site. They estimated a crustal thickness of approximately 41 km along this belt. It was hypothesized that this region took the main brunt of the continental collision during the Acadian orogeny. Further, an anomalous, low-velocity upper mantle, extending at least to 200 km, was also indicated for central New Hampshire from their study. This deep seated feature is correlated with the Bronson Hill Anticlinorium (Figure 1 and Figure 4), an island arc complex associated with subduction of oceanic lithosphere during the Early Devonian.

Luetgert and Hughes (1989), based on data taken during the Ontario-New York-New England Seismic Experiment data, also found a thickened crust in the vicinity of the GL array. Beneath the array the crustal thickness was estimated to be approximately 40 km, close to the maximum value along the examined transect. In general, they found the crust deepened from about 34 km in central Maine to about 41 km approximately 60 km to the west of the array. They also found pronounced lower P-wave velocities in the upper crust, at depths less than 20 km, in the vicinity of the array as compared to the structure observed further to the west under western Vermont and eastern New York.

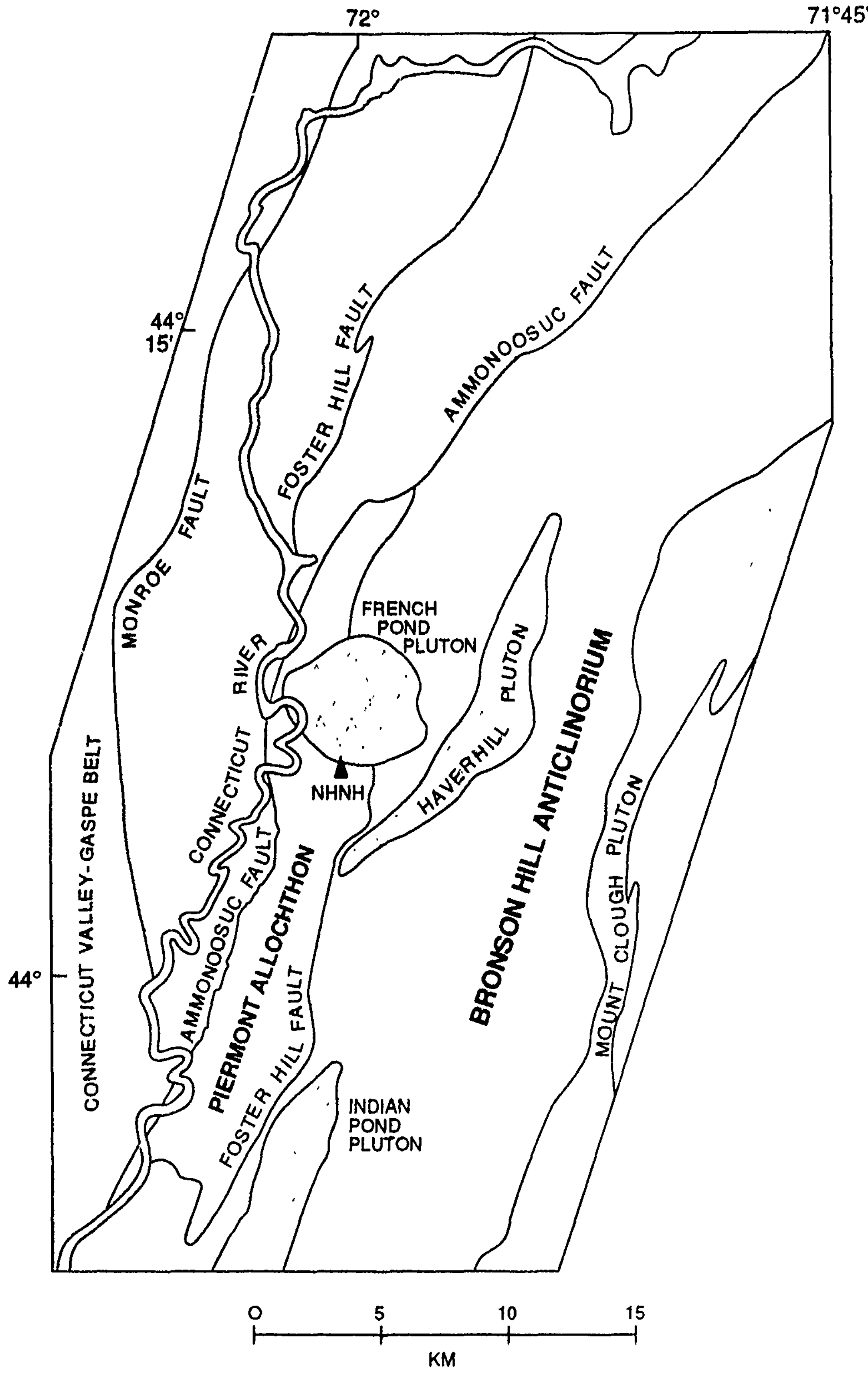


Figure 4. Simplified Geologic Map of the Region Near the North Haverhill, New Hampshire Small-Aperture Array. (After Moench, 1989).

2.2 Array Configuration

The configuration of the North Haverhill array on 14 September, 1988 is shown in Figure 5. This layout was dictated both by the main purpose of the array, namely the study of high frequency propagation during the Ontario-New York-New England Seismic Experiment, and by the available open land at the site. On 14 September the array consisted of 14 vertical Electro-Tech EV-17 one second vertical seismometers and 2 EV-17-H horizontal units. The vertical instruments were laid out along two arms having azimuths of 351° 59' and 290° 34'. The northerly arm was 448.0 meters long while the westerly arm was 341.4 meters long. In addition, one vertical instrument was located midway between the arms 69.4 meters from the vertex of the array. The two horizontal seismometers were collocated at the vertex of the array and oriented to true North and West, respectively. The position of each sensor, relative to the vertex of the array is given in Table 2 along with the associated system parameters.

Data from the array were digitally recorded by the GL developed Geophysical Data Acquisition System (GDAS), an upgraded version of the data acquisition system described by *von Glahn* (1980) and *Blaney* (1990). The GDAS sampled the array at the rate of 100 samples per second per channel. A 6-pole Butterworth anti-aliasing filter with a corner frequency of 34.3 Hz and a nominal system gain of 2022 were applied to the analog signals before digitization. System responses were obtained *in-situ* by application of a known current to the calibration coils of the seismometers. Estimates of the full system response, due to the instrument, electronics, and signal conditioning, were obtained by minimizing the least squared error between the observed calibration pulses and simulated pulses derived from theoretical models of the system. A typical system response function, in this case for the vertical seismometer at the vertex of the array, channel 7, is shown in Figure 6.

Time references for tagging sampled data were obtained from an internal clock in the GDAS. Timing errors for this clock were determined by comparing clock pulses with the output signal of a Geostationary Operational Environmental Satellite (GOES) receiver. At the time of the JVE shot, the GDAS internal clock was found to be 32.25 msecs late relative to the GOES time signal. In addition, it was later found that the GDAS sampling software introduced a 205 msec advance on the time tag. In other words, data tagged as being taken at t_0 sec were actually taken at t_0 + 0.205 sec. Thus, times taken from the GDAS files for SHAGAN must be increased by a total of 237 msec for full correction to Universal Time.

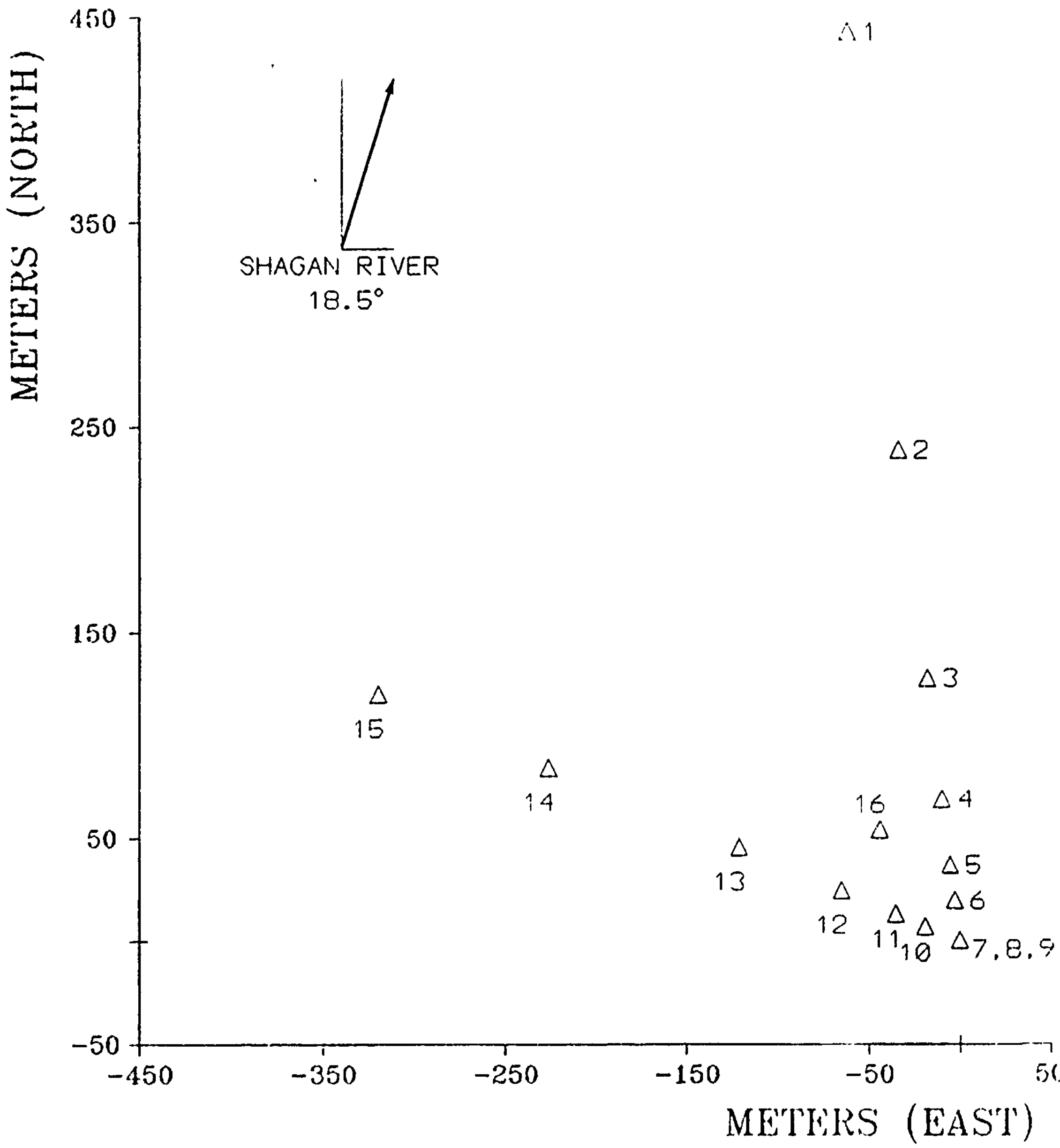


Figure 5. Configuration of the North Haverhill, New Hampshire Small-Aperture Array on 14 September 1988, the Day of the Shagan River Nuclear Test.

Table 2. North Haverhill Seismic Array System Parameters.

Sensor	East (meters)	North (meters)	Elevation (meters)	Frequency (Hz)	Damping	Sensitivity 10^6 V/(m/s)
1-V	−62.5	443.6	170.4	0.932	0.698	1.1004
2-V	−33.7	239.0	172.1	0.966	0.647	1.1251
3-V	−18.1	128.2	173.6	1.008	0.618	1.0757
4-V	−9.7	68.8	174.4	0.931	0.662	1.0703
5-V	−5.2	36.9	174.9	0.951	0.713	1.1641
6-V	−2.8	19.8	175.3	0.937	0.673	1.1327
7-V	0.0	0.0	175.5	0.936	0.737	1.1327
8-N	0.0	0.0	175.5	1.004	0.642	1.1880
9-W	0.0	0.0	175.5	0.981	0.639	1.2189
10-V	−18.7	7.0	175.3	0.975	0.625	1.1018
11-V	−34.9	13.1	174.8	0.951	0.704	1.1021
12-V	−65.1	24.4	174.2	0.936	0.726	1.1279
13-V	−121.3	45.5	173.1	0.938	0.718	1.1225
14-V	−226.0	84.8	169.4	0.924	0.747	1.1507
15-V	−319.7	119.9	163.3	0.923	0.694	1.1321
16-V	−43.9	53.8	174.2	0.922	0.655	1.1082

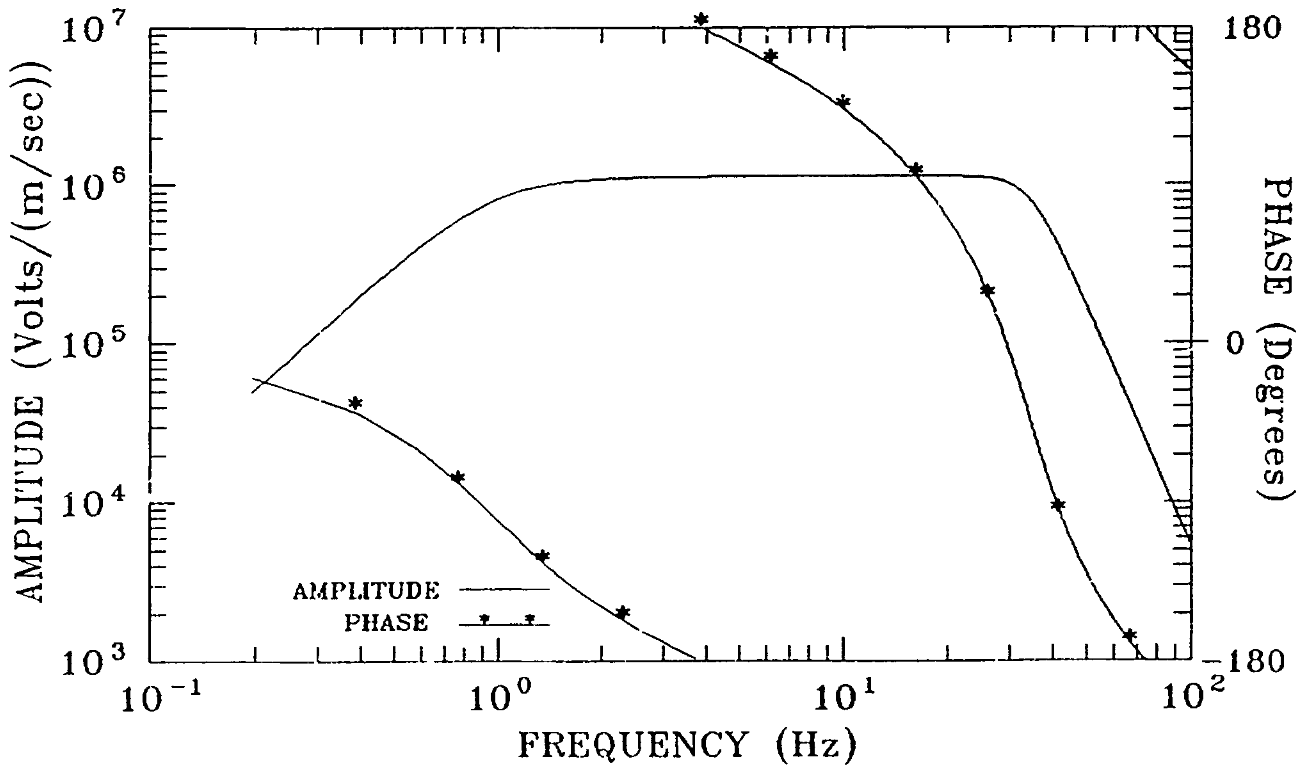


Figure 6. A Typical System Response Curve for a Vertical Element of the North Haverhill Array on 14 September 1988, in This Case for Sensor 7, the Vertical Element at the Vertex of the Array.

2.3 The New Hampshire Recordings

At 04:10 UT on 14 September 1988, the North Haverhill array was turned on and data were recorded for approximately the next 30 minutes, the maximum capacity of the recording system at 100 samples per second per channel. During the observation window wind conditions at the array were gusty with moderate wind speeds. These winds produced substantially higher rms noise levels at the extremities of the array than at the vertex due to the induced motions in wind breaks bordering the site. This problem was particularly pronounced at sensor 1, the northern most seismometer in the array.

Figure 7 shows the ground velocity traces from the three instruments at the vertex of the array for a 100 second window around the P-wave arrival time. The plot shows channel 7, a vertical sensor, channel 8, north-south, and channel 9, west-east. In addition, the vertical stack for the array, excluding channels 8 and 9, is displayed as the bottom trace. The vertical line at 26.7 seconds into the record indicates the picked first arrival time at the array. Figure 8 shows equivalent traces for a 100 second window around the expected S-wave arrival. In this figure the vertical line is placed at the predicted S-wave arrival time based on the Jeffreys-Bullen Tables (*Jeffreys and Bullen*, 1967). Time labels for these figures have been corrected by the required 237 msec. It should further be noted that the time tics are relative to the beginning of the displayed data file as given in the lower left hand corner of the figure. The true ground motions were evaluated over a pass band of 0.3 to 30.0 Hz. As should be expected for an explosive source, the S-wave window does not show any pronounced arrivals. There are, however, indications of several weak arrivals in the window. The maximum amplitudes in this window are at less than one-fifth of the those during the P-arrival from this event.

Figure 9 a, b, and shows the power spectra for channels 7, 8, and 9, respectively, estimated from a 5.12 second window starting just before the P-wave first arrival. The dashed lines in these plots are noise spectra taken just prior to the first arrival. The spectrum for channel 7, a vertical sensor, is typical of all vertical channels below approximately 5.0 Hz. It is apparent from these figures that, as should be expected for a teleseismic event, the power in the P-wave is primarily in a band below 4.0 Hz. At frequencies higher than 5.0 Hz there appears to be little signal power and the spectrum is dominated by locally generated noise. This could also be seen in a rapid decline in signal coherence across the array at frequencies greater than 4.0 Hz. The shoulder in these spectra at 0.4 Hz is the result of a high-pass filter applied during instrument response correction.

FK-spectra calculated for the first P-arrival and for several frequencies below 4 Hz all indicate a near vertical arrival as shown in Figure 10. The spectra are essentially duplicates of the theoretical array beamform. They do, however, show substantial variation in apparent azimuth estimates. The inability of the array to discriminate apparent azimuth was not unexpected due to the small-aperture of the array and relatively steep angle of incidence of the signal.

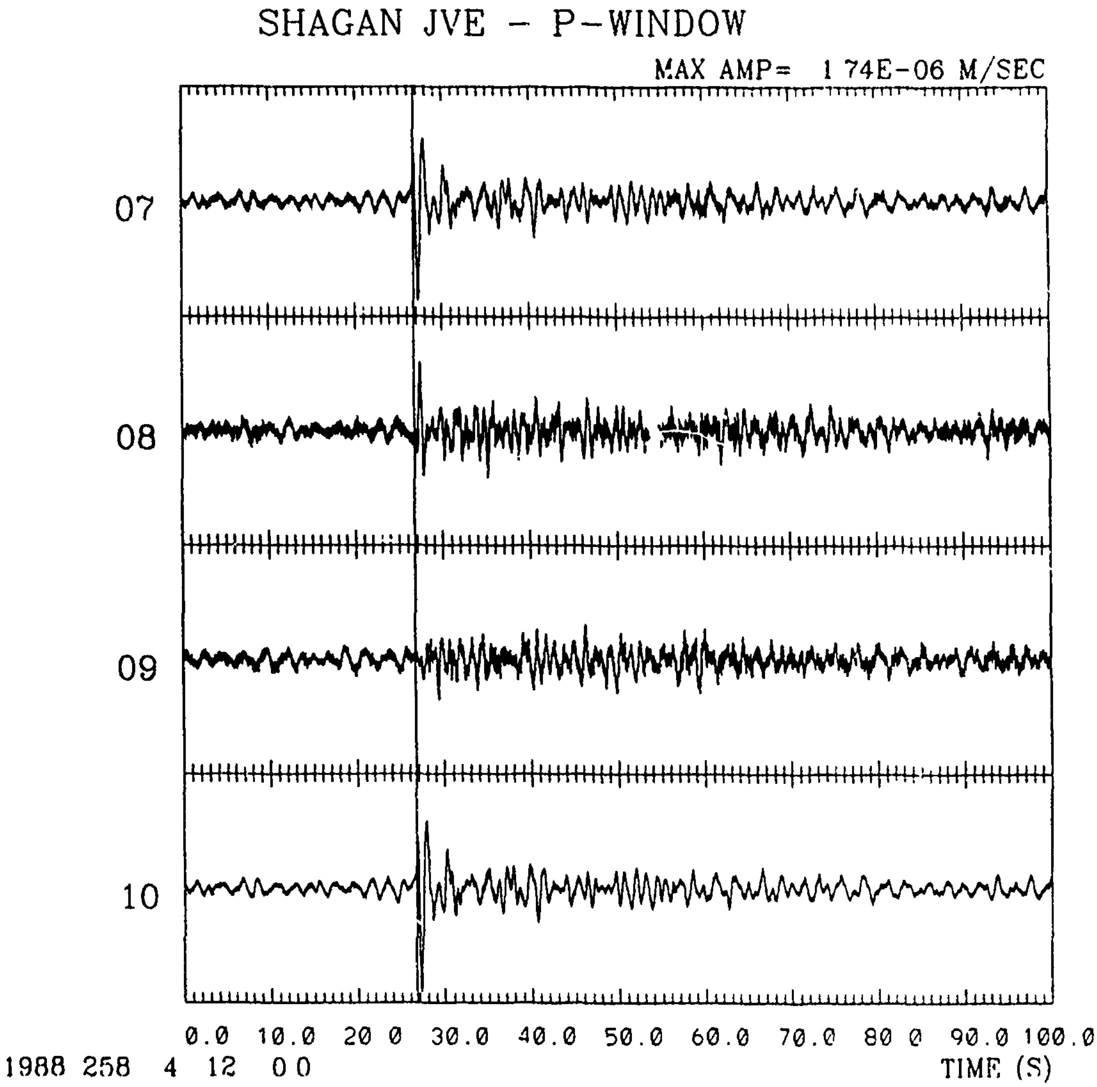


Figure 7. True Ground Velocity Time Traces for a Window Around the P-Wave Arrival for Channels 7, 8 and 9, Vertical, North-South and West-East Sensors, Respectively, and with the Vertical Stack of the Vertical Elements of the Array Displayed as the Bottom Trace. The line at 26.7 sec indicates the picked first arrival time.

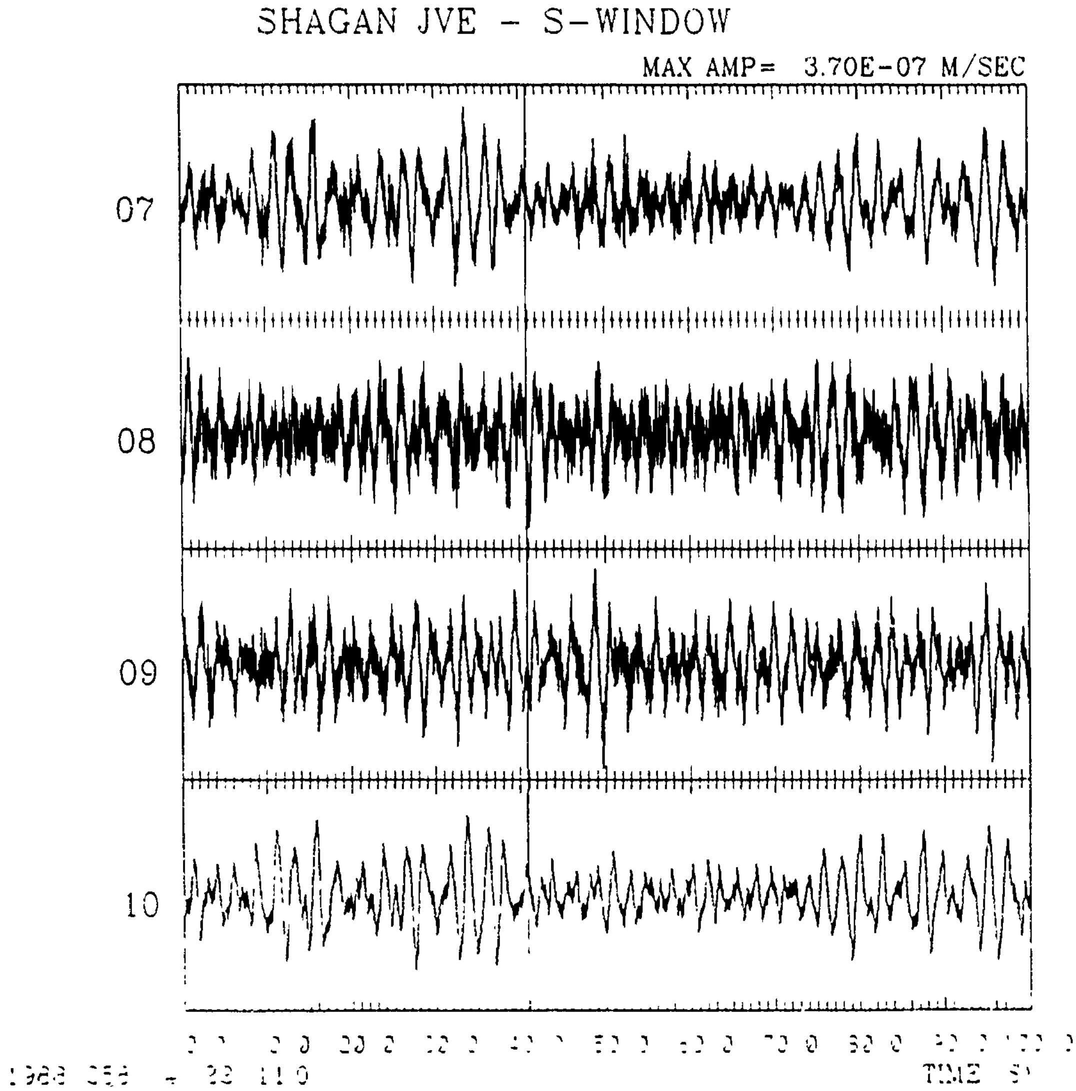
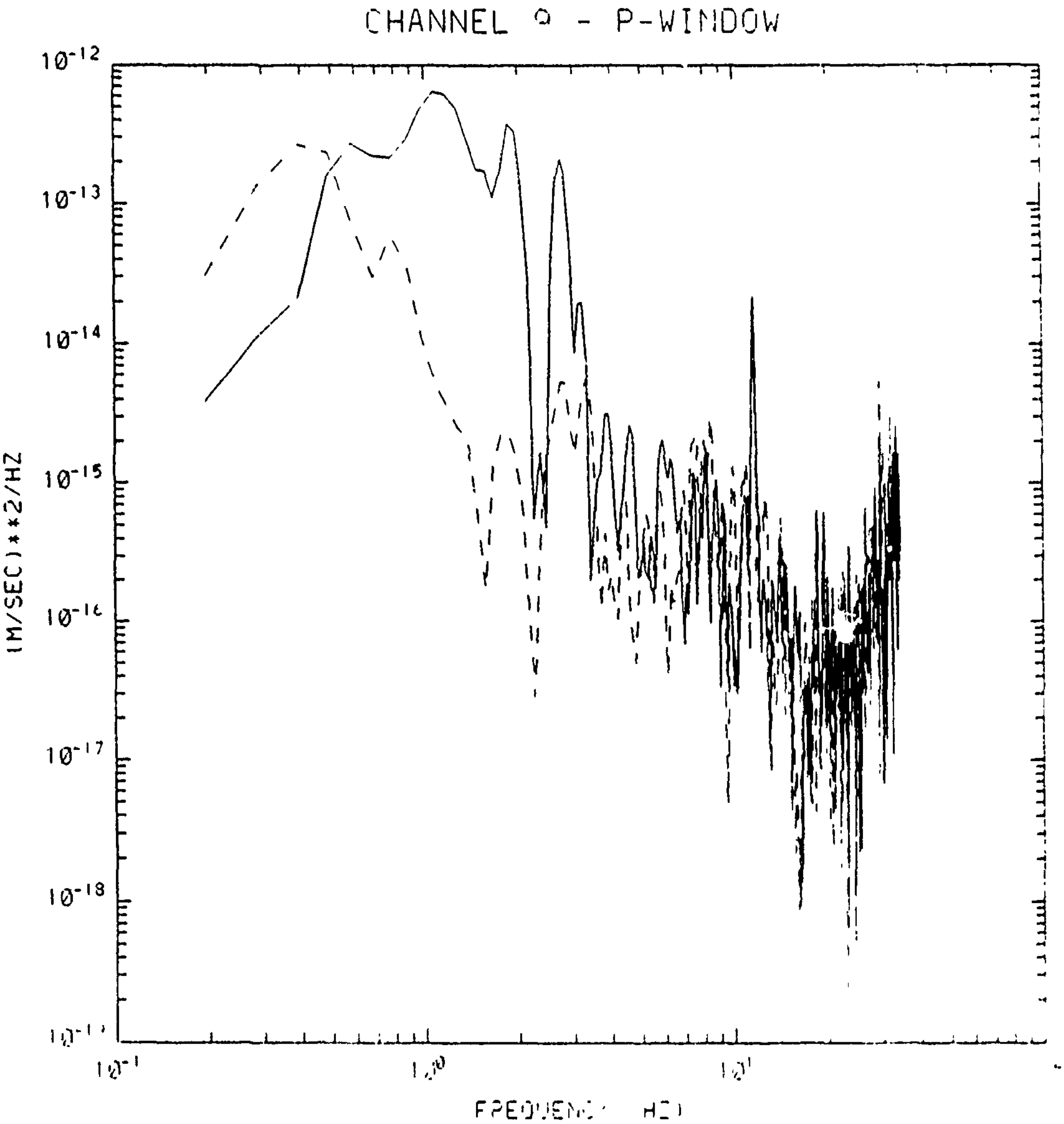
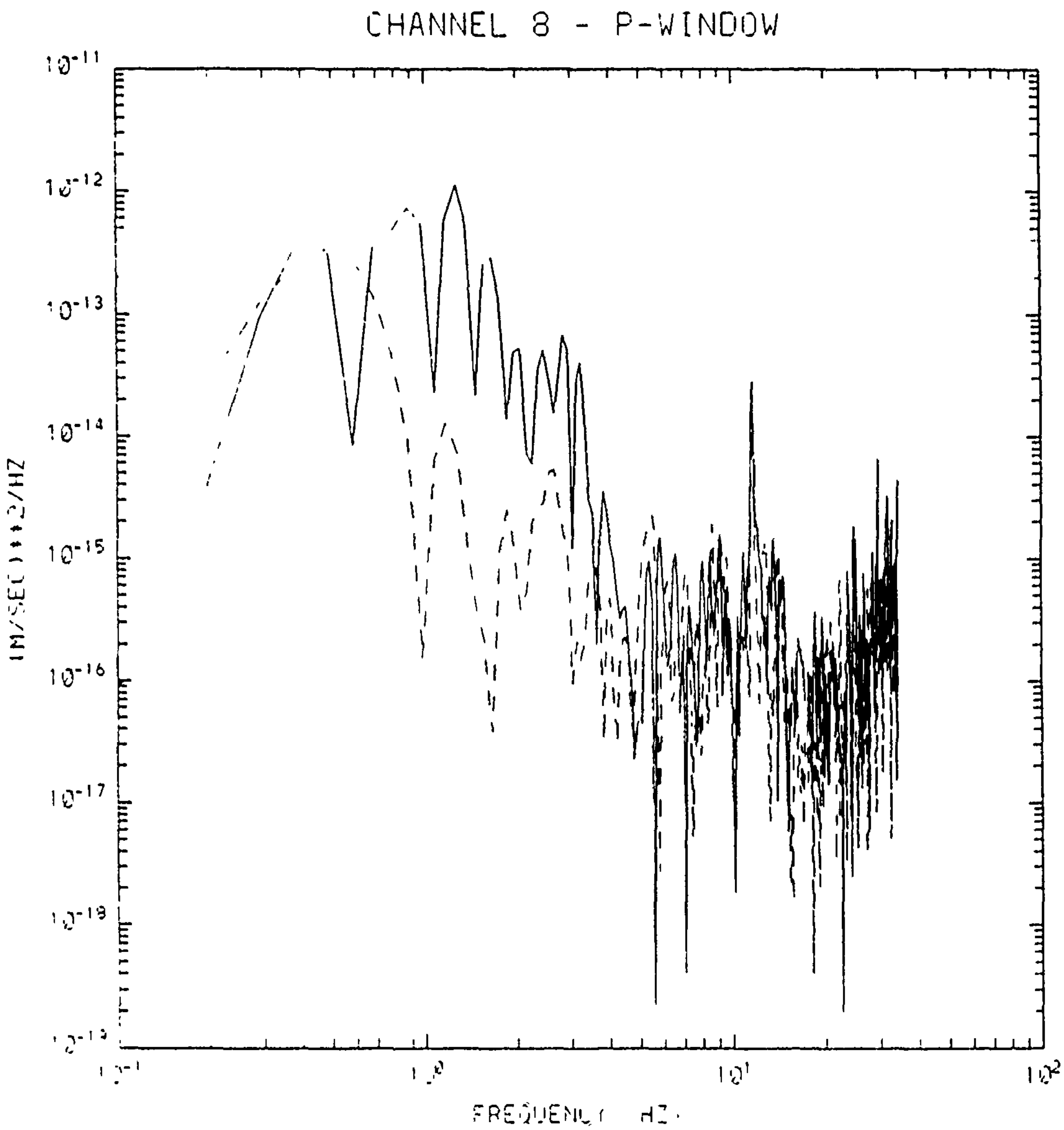


Figure 8. True Ground Velocity Time Traces for a Window Around the S-Wave Arrival for Channels 7, 8 and 9, Vertical, North-South and West-East Sensors, Respectively, and a Vertical Stack of the Array Vertical Sensor Elements at the Bottom. The vertical line is the predicted S-wave arrival time based on the Jeffreys-Bullen tables (1967).

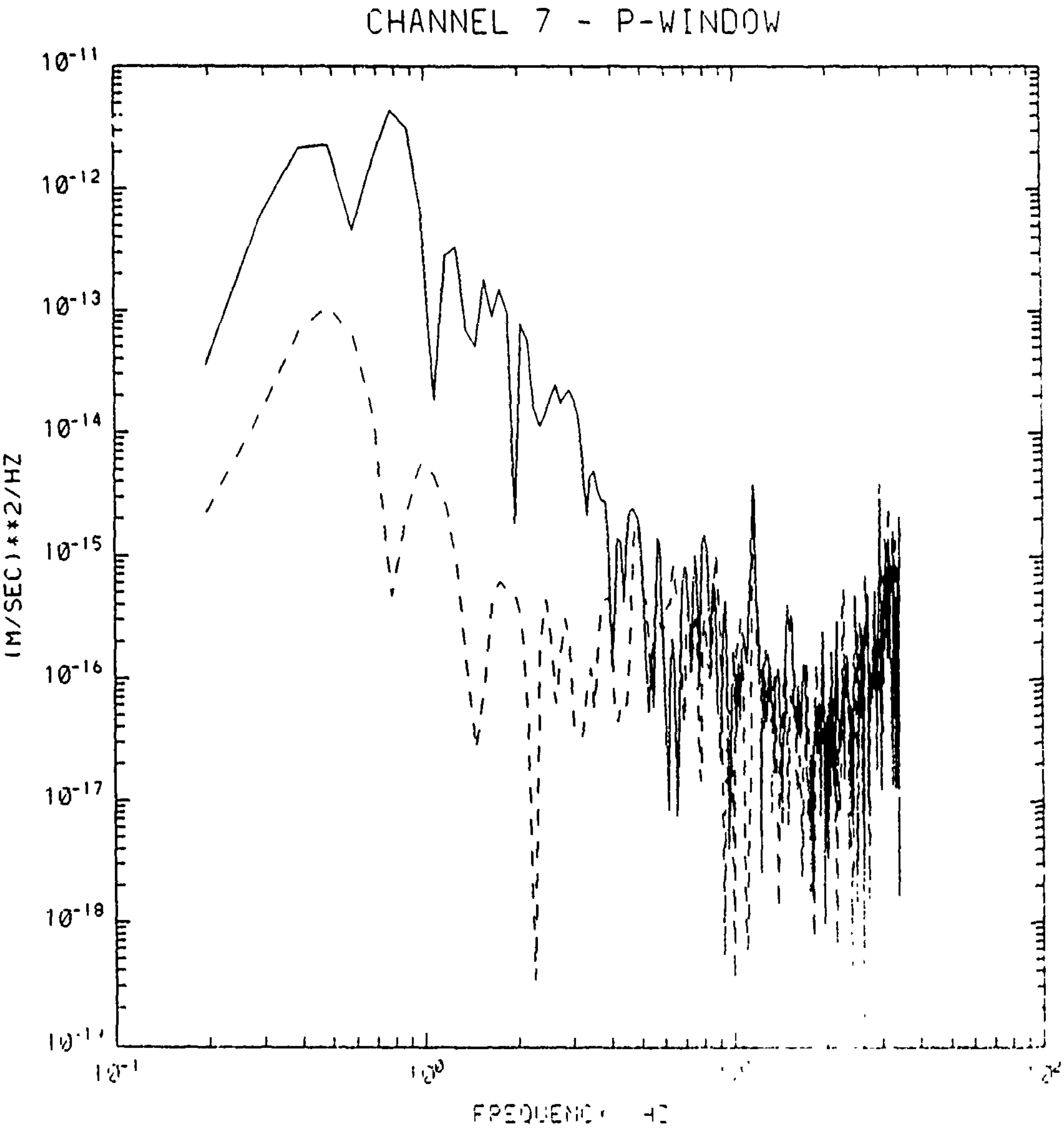


9a

Figure 9. Power Spectra Estimated from (a) Channel 7, (b) Channel 8, and (c) Channel 9 for a Window of 5.12 Sec Starting with the First Arrival of the P-Wave. The dashed lines are noise spectra based on similar windows taken just prior to the first arrival time.



9b


CHANNEL 7 - P-WINDOW
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
(M/SEC)**2/HZ
10^-1
10^0
FREQUENCY HZ

9c

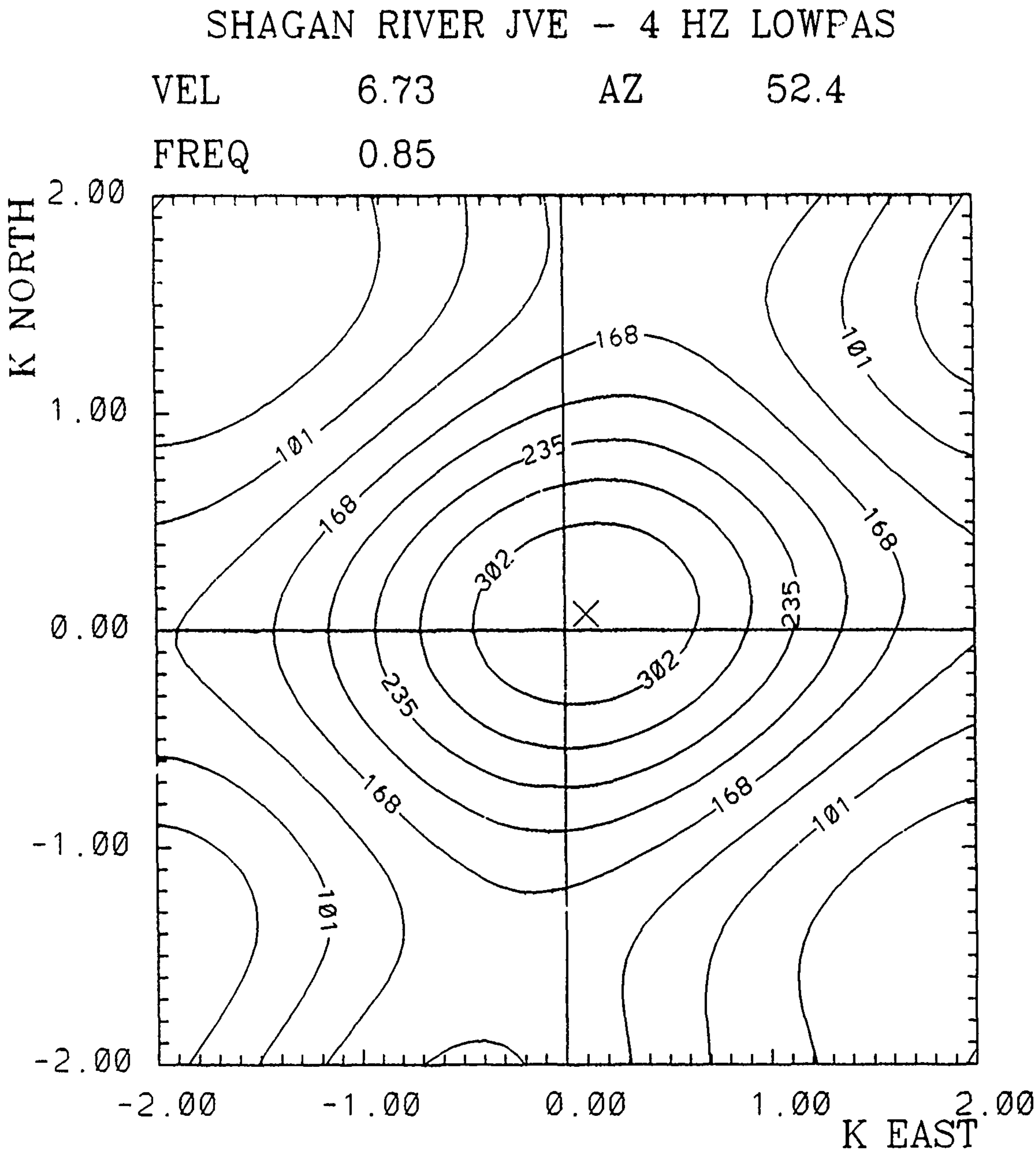


Figure 10. FK-Spectrum from the first 5.12 Seconds of the P-Wave at a Frequency of 0.85 Hz, Near the Peak Frequency of the SHAGAN Event at the North Haverhill Array.

3. THE ADIRONDACK ARRAY

A five station array was set up in the Long Lake, New York, area of the Adirondack Mountains to record the Shagan River explosion. These stations comprised part of deployment 1 of the Ontario-New York-New England Seismic Refraction Experiment (*Mangino and Cipar*, 1990). Deployment 1 extended from Long Lake to Lorraine, New York, with the purpose of studying the crustal structure of the central Adirondack Mountains. Five profile stations in the Long Lake area were installed in time to record the SHAGAN shot (Table 1). Time limitations and difficult access for most of the profile precluded installing additional stations.

3.1 Geological and Geophysical Setting

The Adirondack Mountains are an extension of the Proterozoic (1.2-1.0 by) Grenville Province of the Canadian Shield. The mountains form a nearly circular dome, roughly 200km in diameter. They are surrounded by nearly undeformed Paleozoic sedimentary rocks on the north, west, and south; to the east are the highly deformed and metamorphosed Paleozoic Appalachian Mountains. The Adirondack array stations were located in the Highlands region, approximately 46 km southwest of Mount Marcy, the highest mountain peak of the Adirondacks. In the immediate vicinity of Long Lake, the rocks are mangerite-syenite-quartz syenite and hornblende gneiss covered by a thin veneer of soil (*Whitney et al*, 1989). Mount Marcy and the other High Peaks are underlain by the Marcy metanorthosite. The rocks of the Highlands were metamorphosed to granulite facies during Proterozoic times, indicating burial at deep levels within the crust. Geobarometry and geothermometry indicate maximum temperatures and pressures of 710-760 degrees C and 7.4-7.6 kilobars in the area of the array. (many studies summarized in *Whitney et al.*, 1989). The metamorphic pressure and temperature of the Adirondack rocks are appropriate for depths of 25-30 km in the continental crust. Since the depth to the Moho is presently about 35 km (*Katz*, 1955), this implies that the crust was thickened to 60-65 km, double its present value, during the regional metamorphic event. A modern analogue to the Proterozoic Adirondacks are the Himalaya Mountains (*Dewey and Burke*, 1973).

While the rocks of the Adirondacks are ancient, the present elevations may be youthful. *Isachsen* (1975) reports 3.7 mm/year uplift in the center of the Adirondack dome, although systematic errors in leveling make this estimate somewhat suspect (*Isachsen*, 1985). *Whitney et al.* (1989, p. 26-27), however, cite several other lines of evidence to support recent doming in the Adirondacks and speculate that the uplift is caused by crustal expansion over a hotspot.

Taylor and Toksöz (1982) suggest, based on early work, that the crust under the Adirondacks consists of a thin 6.1 km/sec layer overlying 6.4 to 6.6 km/sec material that extends to the crust-mantle boundary (Moho) at 35 km depth. *Mangino and Cipar* (1989) measure apparent velocities for Pg to be 6.5 km/sec, Pn to be 8.05 km/sec, and no coherent reflection from the crust-mantle boundary. The latter observation suggests a transitional

Moho. A transitional Moho is also indicated by analysis of teleseismic receiver functions by *Owens* (1987) who infers that the crust is up to 50 km thick beneath station RSNY in the northern Adirondacks. *Owens* (1987) demonstrates considerable complexity in the crustal S-wave structure including strong lateral variations in velocity. Seismic reflection data obtained by COCORP (*Brown et al.*, 1983) reveal that the upper 12 km of the crust is acoustically transparent suggesting a considerable thickness of homogeneous material. Just east of the GL station array, a series of strong, discontinuous, sub-parallel reflectors are observed in the 10 to 20 km depth range. Farther east, below the Marcy Massif, the COCORP data image a wedge of extremely strong reflectors dipping westward (the Tawahus complex). The Tawahus structure also produces strong reflections on the NY-NEX refraction data (*J. Luetgert*, pers. comm.). The COCORP sections indicate scattered reflections from the Moho suggesting a crustal thickness of 33 to 35 km.

3.2 Array Configuration

Five sites (station numbers 1125, 1126, 1129, 1130, and 1131) were occupied during the SHAGAN explosion (Figure 11; Table 1). At each station, Terra Technology DCS-302 digital cassette seismographs were used to record signals from a three-component set of Geospace HS-10-1B 1-Hz seismometers. At stations 1125 and 1130, a second DCS-302 recorded signals from a three-component set of Kinemetrics SV/SH-1 5-second seismometers. The HS-10-1B and SV/SH-1 sensors were installed on aluminum baseplates which have machined indentations for the seismometer feet, allowing precise alignment and orientation. Horizontal seismometers were aligned to within 2 degrees of magnetic north.

Each seismograph system (sensor plus recorder) was calibrated by driving the seismometer calibration coil with a known current and recording the main coil output on cassette tape. The calibration pulse was fit in a least-squares sense to the equation for a damped pendulum (*Mitchell and Landisman*, 1969). Seismometer constants are given in Table 3.

Station timing was done by initially setting the internal clock of each recorder to universal time (UTC) via a GOES satellite clock. After the experiment, the internal clock drift was measured by re-comparing the clock to GOES and interpolating to the event time. For several stations, WWVB radio receivers provided continuous time correction data. Whenever possible, the WWVB corrections are used. Table 3 gives the measured time correction with the notation "GOES" or "WWVB" indicating how the correction was measured.

The recorders employ a 12-bit data word and automatic gain ranging to provide 126 dB of dynamic range. For the SHAGAN experiment, gain ranging was not needed and the nominal digitizing factor is 2.4414 microvolts/count. A five-pole Butterworth anti-aliasing filter with a corner frequency of 30 Hz is applied to the signal which is sampled at 100 samples per second.

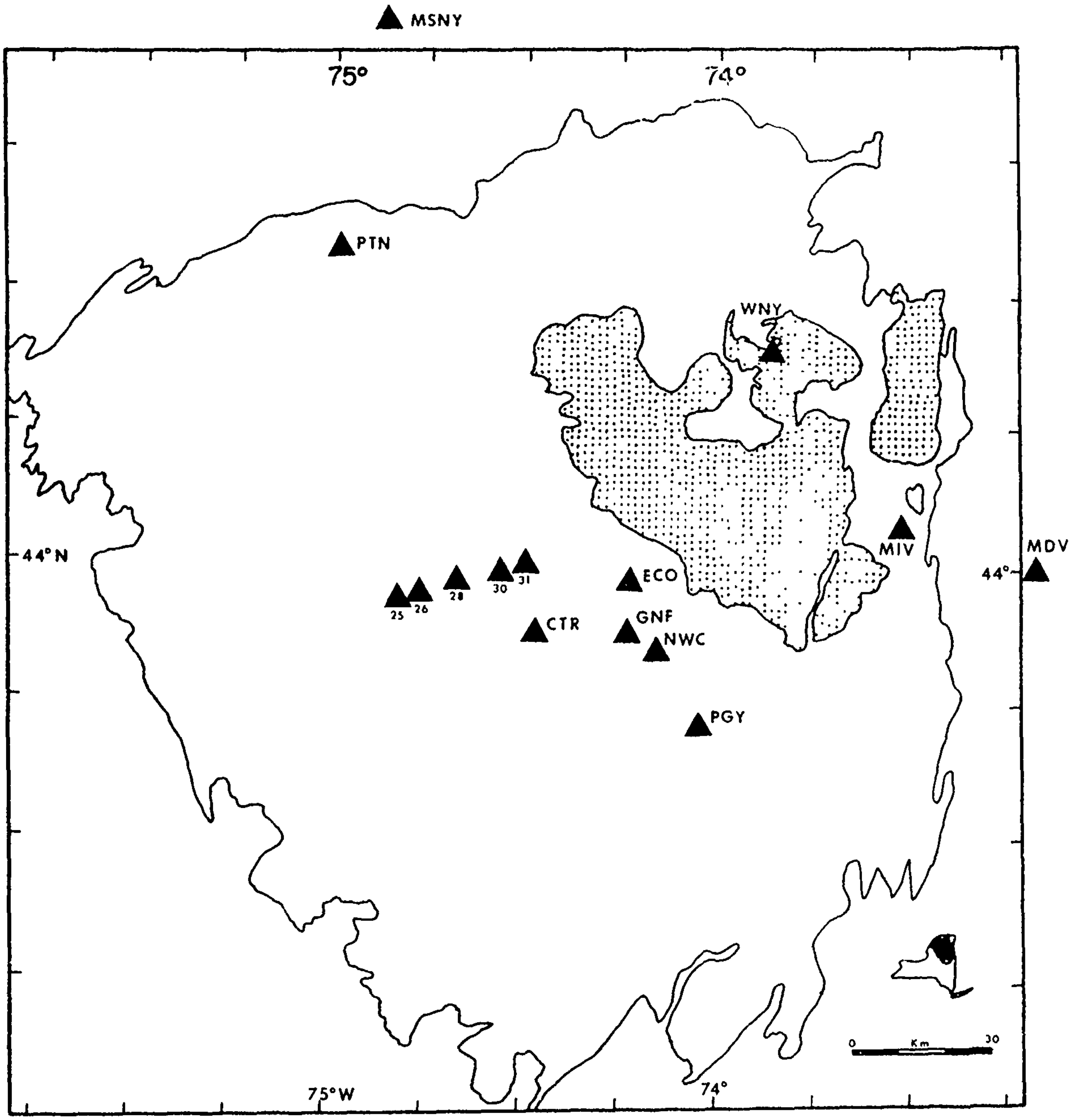


Figure 11. Seismic Stations in the Adirondack Mountains, New York. The GL Adirondack, Array are the numbered stations at approximately 44°N, 74.5-75°W. Other stations are maintained by Lamont-Doherty Geological Observatory. The solid line indicates the limit of Pre-Cambrian outcrops of the Adirondack dome. The stippled area is the outcrop of Marcy anorthosite.

Table 3. Seismometer Constants for the Adirondack Array.

Seismogram			Date	Starting Time d	h	m	s	Time Correction (Sec.)		Seismometer Orien. (Deg.)	Seismometer Sensitivity (Volts/m/sec)	Pendulum Period (Sec.)	Damping Ratio	Serial No.	Calib. Date	Polarity
1125	SHGN	MPN	14 SEP 88	258	4	11	55.000	0.0083	WWVB	-15.00	190.0000	5.000	0.695	236	0 JAN 88	1
""	""	MPE	14 SEP 88	258	4	11	55.000	0.0083	""	75.00	190.0000	5.000	0.695	247	0 JAN 88	1
""	""	MPZ	14 SEP 88	258	4	11	55.000	0.0083	""	-	190.0000	5.000	0.695	160	0 JAN 88	1
""	""	MPN	14 SEP 88	258	4	22	10.000	0.0156	""	-15.00	190.0000	5.000	0.695	236	0 JAN 88	1
""	""	MPE	14 SEP 88	258	4	22	10.000	0.0156	""	75.00	190.0000	5.000	0.695	247	0 JAN 88	1
""	""	MPZ	14 SEP 88	258	4	22	10.000	0.0156	""	-	190.0000	5.000	0.695	160	0 JAN 88	1
""	""	SPN	14 SEP 88	258	4	11	55.000	-0.0615	""	-15.00	590.0545	0.641	0.987	104540	13 SEP 88	1
""	""	SPE	14 SEP 88	258	4	11	55.000	-0.0615	""	75.00	542.9311	1.033	1.646	104548	13 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	11	55.000	-0.0615	""	-	442.2431	0.692	1.078	104556	13 SEP 88	1
""	""	SPN	14 SEP 88	258	4	22	10.000	-0.0693	""	-15.00	590.0545	0.641	0.987	104540	13 SEP 88	1
""	""	SPE	14 SEP 88	258	4	22	10.000	-0.0693	""	75.00	542.9311	1.033	1.646	104548	13 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	22	10.000	-0.0693	""	-	442.2431	0.692	1.078	104556	13 SEP 88	1
1126	""	SPN	14 SEP 88	258	4	11	55.000	-0.0322	GOES	-15.00	833.3716	0.976	1.260	104703	13 SEP 88	1
""	""	SPE	14 SEP 88	258	4	11	55.000	-0.0322	""	75.00	476.0570	1.005	1.227	104704	13 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	11	55.000	-0.0322	""	-	596.3226	0.673	0.842	104557	13 SEP 88	1
""	""	SPN	14 SEP 88	258	4	22	10.000	-0.0322	""	-15.00	833.3716	0.976	1.260	104703	13 SEP 88	1
""	""	SPE	14 SEP 88	258	4	22	10.000	-0.0322	""	75.00	476.0570	1.005	1.227	104704	13 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	22	10.000	-0.0322	""	-	596.3226	0.673	0.842	104557	13 SEP 88	1
1128	""	SPN	14 SEP 88	258	4	11	55.000	0.0000	""	-15.00	505.6474	0.902	1.454	104700	27 SEP 88	1
""	""	SPE	14 SEP 88	258	4	11	55.000	0.0000	""	75.00	694.0557	0.551	0.681	104705	8 MAR 88	1
""	""	SPZ	14 SEP 88	258	4	11	55.000	0.0000	""	-	624.0928	0.864	1.000	104688	8 MAR 88	1
""	""	SPN	14 SEP 88	258	4	22	10.000	0.0000	""	-15.00	505.6474	0.902	1.454	104700	27 SEP 88	1

Seismometer orientation is measured as degrees clockwise from geographic north

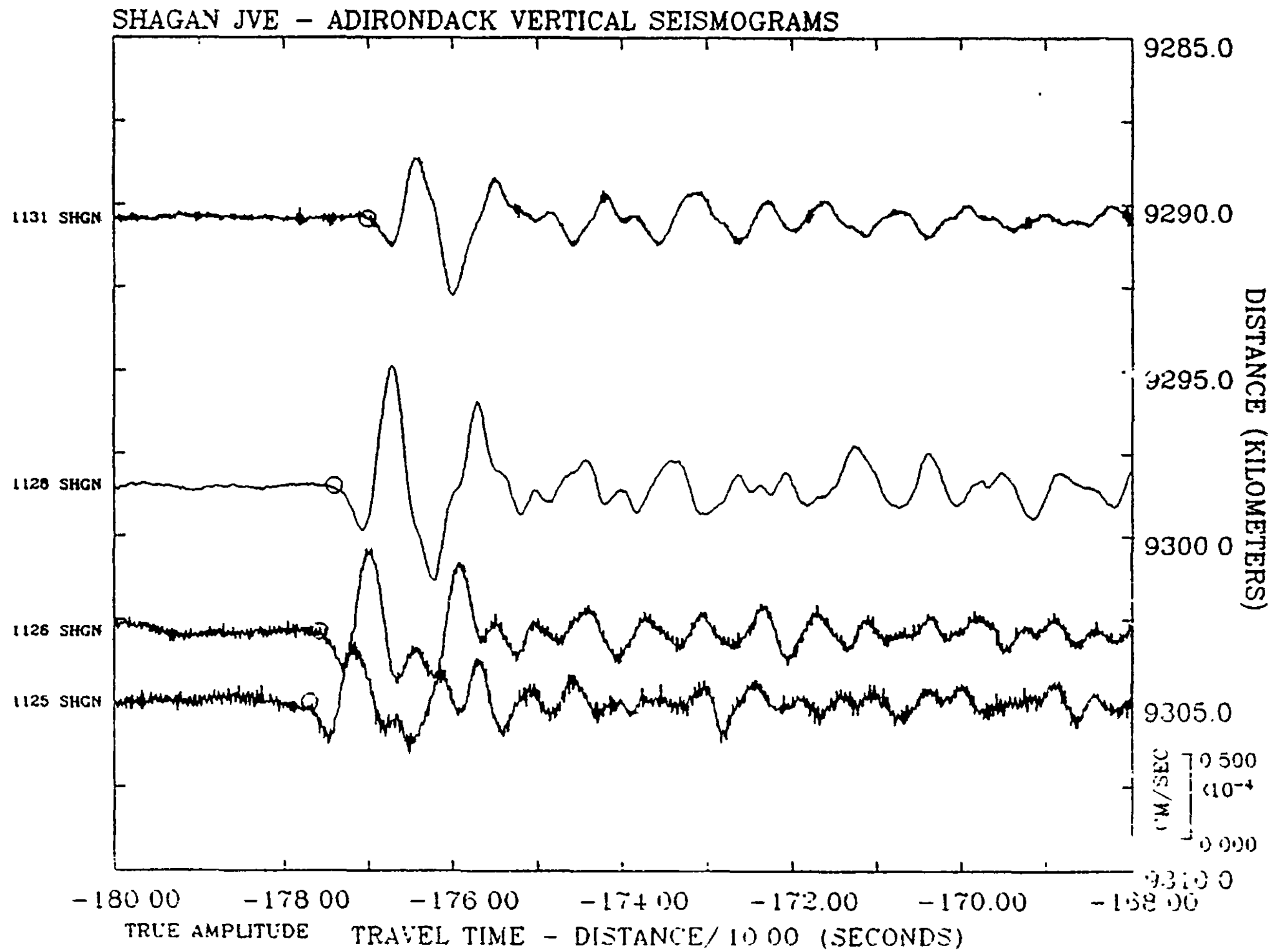
Table 3 (Cont.). Seismometer Constants for the Adirondack Array.

Seismogram			Date	Starting Time d	h	m	s	Time Correction (Sec.)		Seismometer Orien. (Deg.)	Seismometer Sensitivity (Volts/m/sec)	Pendulum Period (Sec.)	Damping Ratio	Serial No.	Calib. Date	Polarity
1128	SHGN	SPE	14 SEP 88	258	4	22	10.000	0.0000	GOES	75.00	694.0557	0.551	0.681	104705	8 MAR 88	1
""	""	SPZ	14 SEP 88	258	4	22	10.000	0.0000	""	–	624.0928	0.864	1.000	104688	8 MAR 88	1
1130	""	MPN	14 SEP 88	258	4	11	55.000	0.0000	""	–15.00	190.0000	5.000	0.695	231	0 JAN 88	1
""	""	MPE	14 SEP 88	258	4	11	55.000	0.0000	""	75.00	190.0000	5.000	0.695	248	0 JAN 88	1
""	""	MPZ	14 SEP 88	258	4	11	55.000	0.0000	""	–	190.0000	5.000	0.695	167	0 JAN 88	1
""	""	MPN	14 SEP 88	258	4	22	10.000	0.0000	""	–15.00	190.0000	5.000	0.695	231	0 JAN 88	1
""	""	MPE	14 SEP 88	258	4	22	10.000	0.0000	""	75.00	190.0000	5.000	0.695	248	0 JAN 88	1
""	""	MPZ	14 SEP 88	258	4	22	10.000	0.0000	""	–	190.0000	5.000	0.695	167	0 JAN 88	1
""	""	SPN	14 SEP 88	258	4	11	55.000	0.0497	""	–15.00	743.4758	1.024	1.293	104547	27 SEP 88	1
""	""	SPE	14 SEP 88	258	4	11	55.000	0.0497	""	75.00	706.5759	0.938	1.117	104544	27 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	11	55.000	0.0497	""	–	697.1599	1.007	1.238	104553	27 SEP 88	1
""	""	SPN	14 SEP 88	258	4	22	10.000	0.0497	""	–15.00	743.4758	1.024	1.293	104547	27 SEP 88	1
""	""	SPE	14 SEP 88	258	4	22	10.000	0.0497	""	75.00	706.5759	0.938	1.117	104544	27 SEP 88	1
""	""	SPZ	14 SEP 88	258	4	22	10.000	0.0497	""	–	697.1599	1.007	1.238	104553	27 SEP 88	1
1131	""	SPN	14 SEP 88	258	4	11	55.000	–0.3457	WWVB	–15.00	707.9183	0.750	0.885	104543	5 APR 88	1
""	""	SPE	14 SEP 88	258	4	11	55.000	–0.3457	""	75.00	696.1515	1.041	1.315	104701	8 MAR 88	1
""	""	SPZ	14 SEP 88	258	4	11	55.000	–0.3457	""	–	835.2012	0.680	0.900	104554	8 MAR 88	1
""	""	SPN	14 SEP 88	258	4	22	10.000	–0.3691	""	–15.00	707.9183	0.750	0.885	104543	5 APR 88	1
""	""	SPE	14 SEP 88	258	4	22	10.000	–0.3691	""	75.00	696.1515	1.041	1.315	104701	8 MAR 88	1
""	""	SPZ	14 SEP 88	258	4	22	10.000	–0.3691	""	–	835.2012	0.680	0.900	104554	8 MAR 88	1

Seismometer orientation is measured as degrees clockwise from geographic north

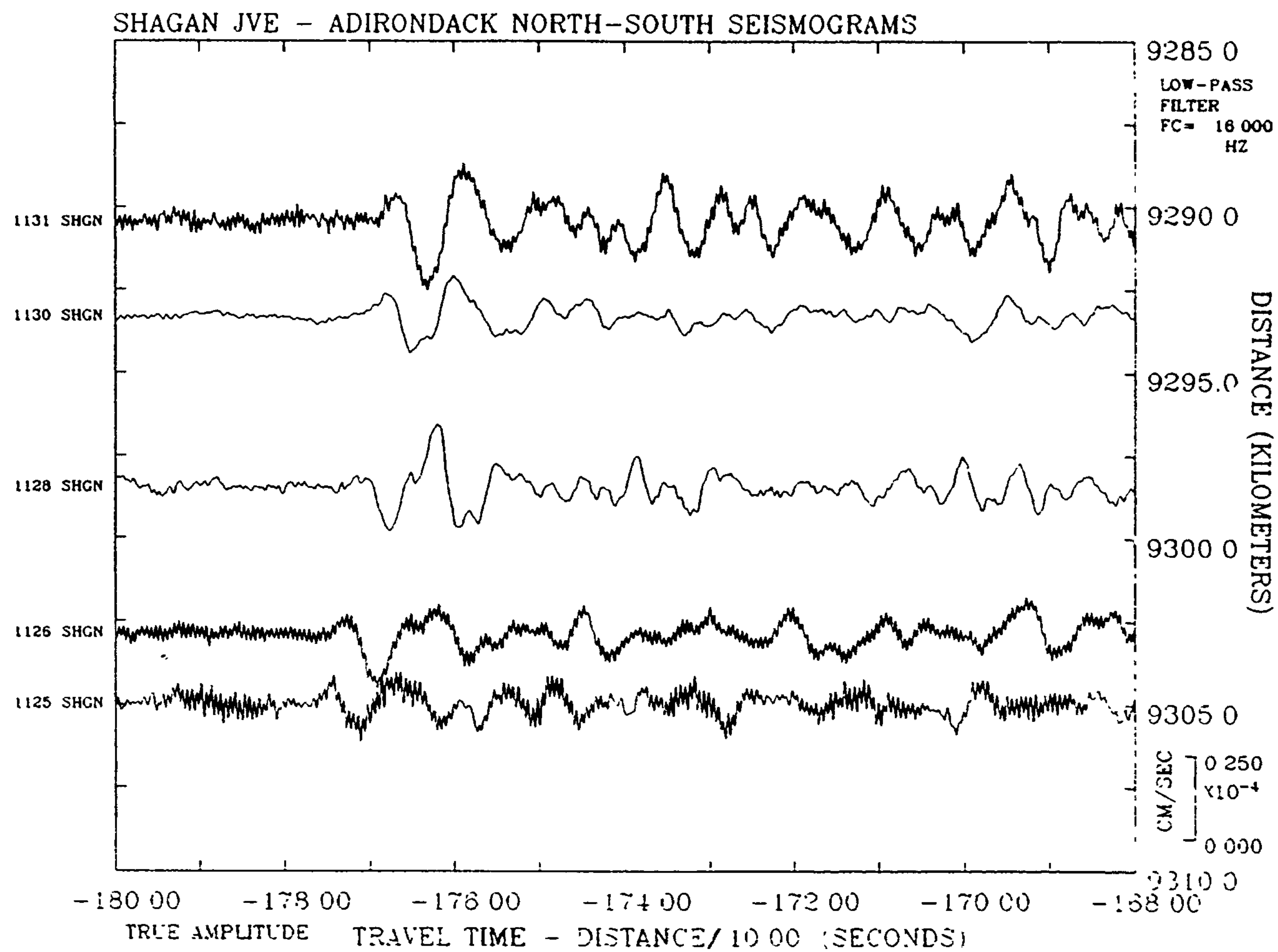
3.3 Adirondack Recordings

Figures 12 a,b,c show the P-wave portion of the short-period seismograms in record section format. These figures show pendulum velocity in cm/sec uncorrected for instrument response which means that the polarities are opposite the true ground motion. For an explosion P-wave arriving with a 17 degree station-to-source azimuth, the expected first motion is south, west, and up, opposite to the polarities shown in Figure 12 a,b,c. The short-period horizontal records are low-pass filtered below 16 Hz to remove ambient noise probably due to wind moving trees. The short-period vertical records are unfiltered. The short-period vertical channel at station 1130 and the east-west channel at station 1125 did not work. The 5-second seismometer records are shown in Figures 13 a,b. It is clear that the north-south channel at station 1130 is mis-identified (top trace labelled MPN on Figure 13b) and is, in fact, the vertical component. It is probable that the bottom trace (labelled MPZ) is the north-south component since it has larger amplitude as predicted by the source-station geometry. Note that the trace labelled MPE has reversed polarity. All mid-period seismograms were band-pass filtered between 0.4 and 16 Hz to remove microseismic and cultural noise. No S-wave signals stand out above the noise on either the short- or mid-period systems.



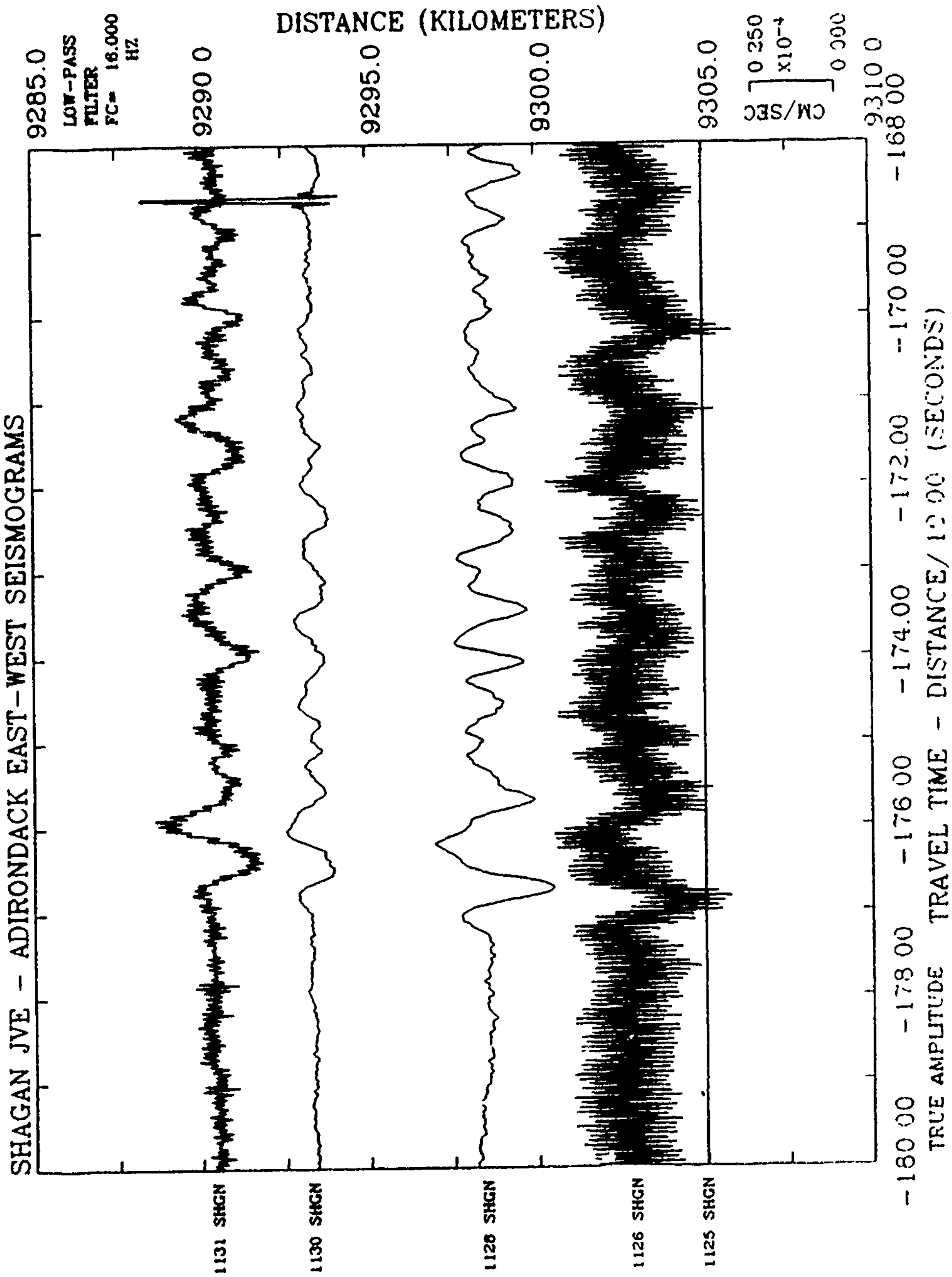
12a

Figure 12. Short-Period Seismograms of the SHAGAN Explosion Recorded by the Adirondack Array. Seismograms are plotted in record-section format at true amplitude (scale shown at lower right). Figures a, b, and c are the vertical, north-south, and east-west components, respectively. See text for further discussion.



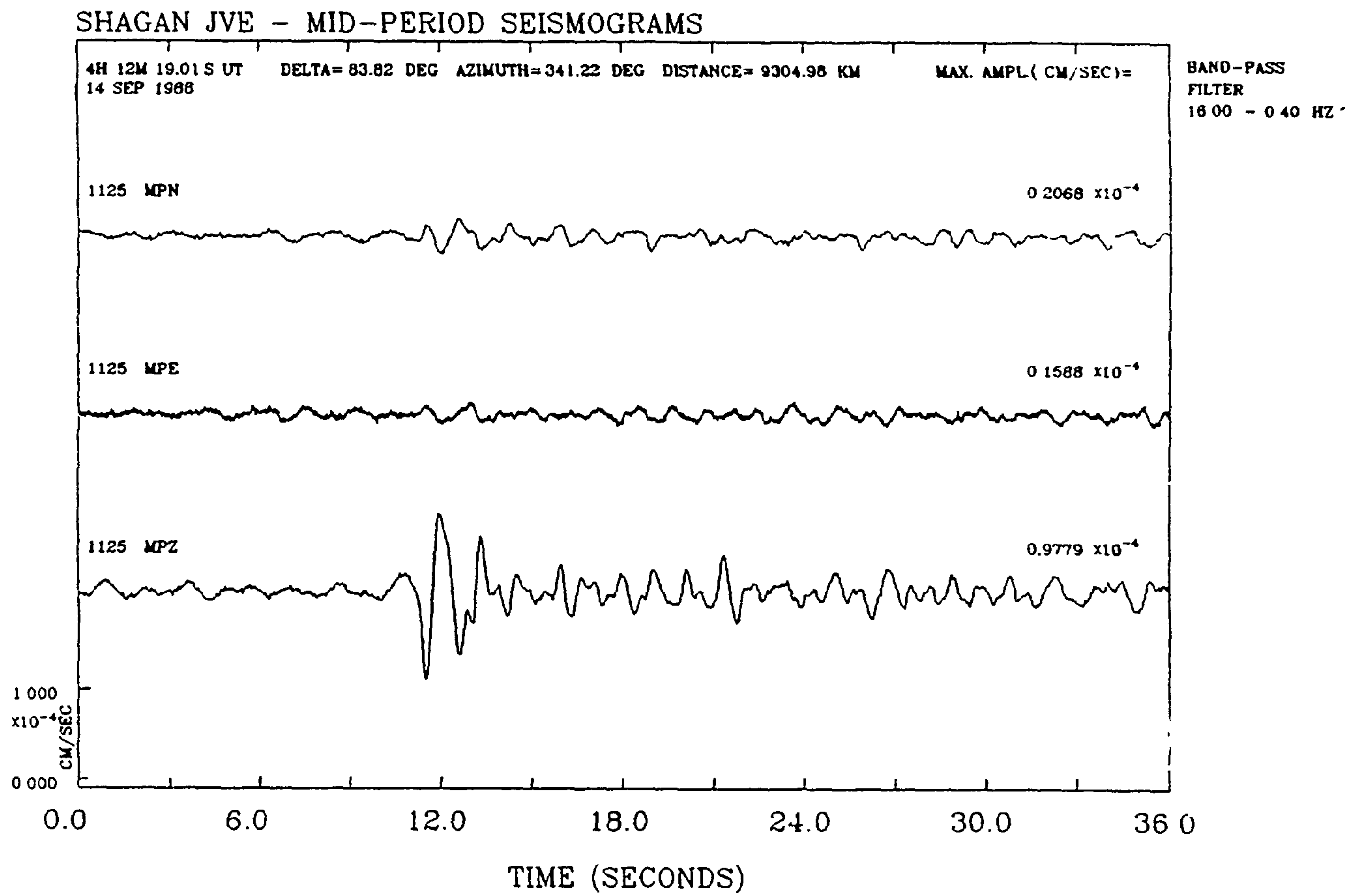
SHAGAN JVE - ADIRONDACK NORTH-SOUTH SEISMOGRAMS
1131 SHGN
1130 SHGN
1128 SHGN
1126 SHGN
1125 SHGN
9285 0
9290 0
9295.0
9300 0
9305 0
9310 0
LOW-PASS
FILTER
FC= 16 000
HZ
DISTANCE (KILOMETERS)
CM/SEC
0 250
X10⁻⁴
0 000
-180 00
-178 00
-176 00
-174 00
-172 00
-170 00
-168 00
TRUE AMPLITUDE
TRAVEL TIME - DISTANCE/ 10 00 (SECONDS)

12b



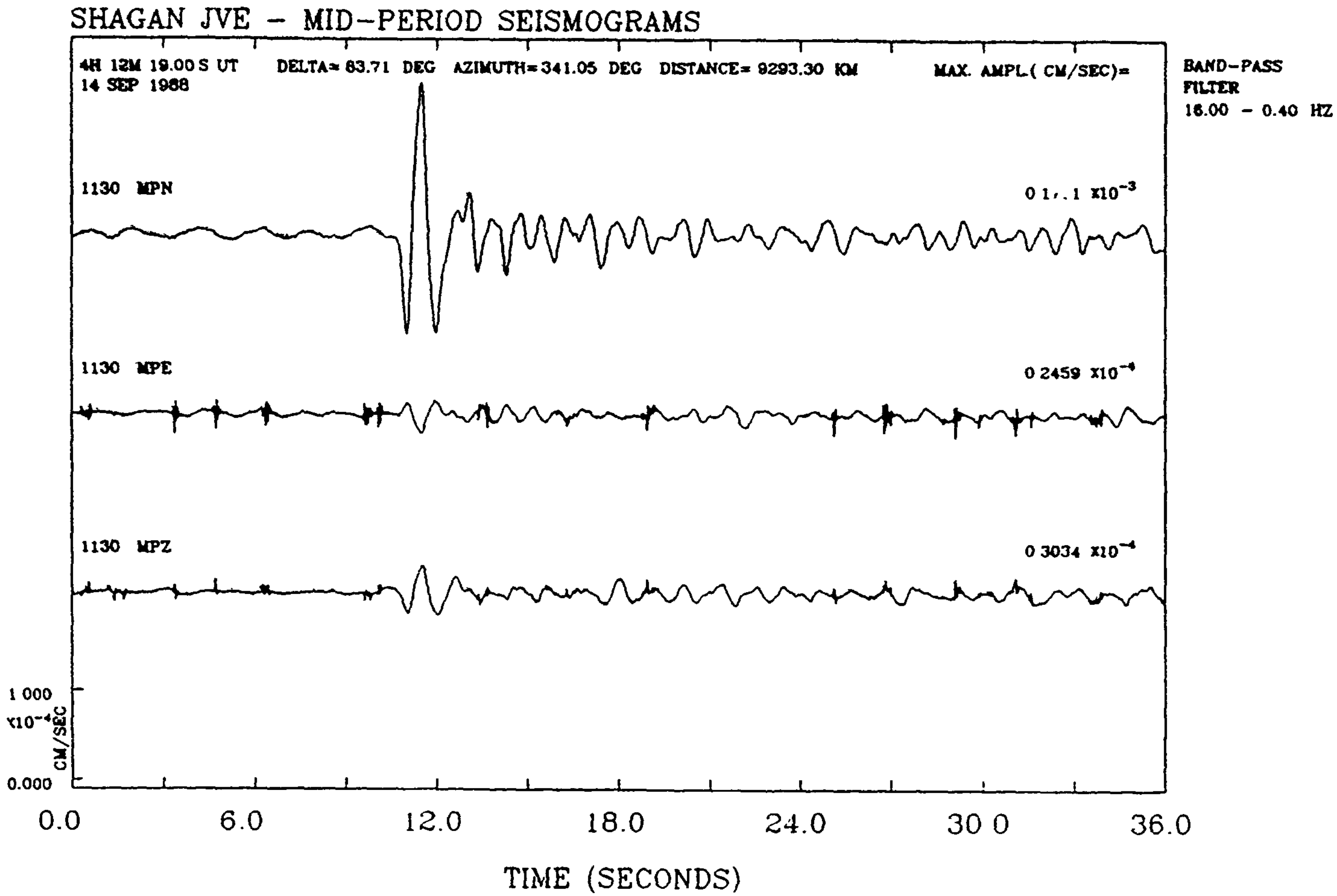
SHAGAN JVE - ADIRONDACK EAST-WEST SEISMOGRAMS
DISTANCE (KILOMETERS)
9285.0
9290 0
9295.0
9300.0
9305.0
9310 0
LOW-PASS FILTER FC= 16.000 HZ
CM/SEC
0 250
X10⁻⁴
0 000
-168 00
-170 00
-172.00
-174.00
-176 00
-178 00
-180 00
TRUE AMPLITUDE
TRAVEL TIME - DISTANCE/ 12 00 (SECONDS)
1131 SHGN
1130 SHGN
1128 SHGN
1126 SHGN
1125 SHGN

12c



13a

Figure 13. Mid-Period Records of the SHAGAN Explosion Recorded at (a) Station 1125, and (b) Station 1130. Seismograms are plotted at true amplitude (scale at lower left). See text for further discussion.


SHAGAN JVE - MID-PERIOD SEISMOGRAMS
4H 12M 19.00 S UT
14 SEP 1988
DELTA= 83.71 DEG AZIMUTH=341.05 DEG DISTANCE= 9293.30 KM
MAX. AMPL.(CM/SEC)=
BAND-PASS
FILTER
16.00 - 0.40 HZ
1130 MPN
1130 MPE
0 2459 X10⁻⁴
1130 MPZ
0 3034 X10⁻⁴
1 000
X10⁻⁴
CM/SEC
0.000
0.0
6.0
12.0
18.0
24.0
30 0
36.0
TIME (SECONDS)

13b

4. P-WAVE ARRIVAL TIMES

4.1 New Hampshire Array

The Shagan River test site is located at a distance of 83.1° from the North Haverhill array on an azimuth of 18.5°, as shown in Figure 5. Based on the Jeffreys-Bullen and Herrin Seismological Tables the expected P-wave transit and first arrival times for the North Haverhill array are given in Table 4 (*Jeffreys and Bullen*, 1967; and *Herrin*, 1968). This table also lists the observed transit and arrival times at the North Haverhill site. The predicted times are all based on the USGS origin time of 03:59:57.4 UT and the observed arrival time has been fully corrected to UT. It is apparent that the P-arrival at North Haverhill is significantly delayed relative to these standard travel-time tables.

P-wave relative residuals, computed from the mean residual from arrivals at 16 stations of the New England Seismic Network operated by Weston Observatory of Boston College, show that the North Haverhill array has the largest relative P-residual in the New England region, 0.61 sec (*Ebel*, 1990; *Ebel, et al.*, 1989). Although *Ebel, et al.* (1989) did not find any particular pattern in the distribution of relative residuals over the ensemble of New England network stations, it is observed that network stations located nearest to the array, specifically Berlin (BNH) and Hanover (HNH) in New Hampshire, and Baltimore (BVT) in Vermont also show significant P-delays. At these sites, however, the delays are of lesser magnitude being of 0.22, 0.41, and 0.44 sec, respectively. The locations of these stations with respect to the New Hampshire array are shown in Figure 3.

These results are in accord with the crustal thickening and low-velocity mantle along this segment of the Connecticut River Valley previously proposed by *Taylor and Toksöz* (1979) on the basis of extensive teleseismic travel time residual studies in this region and by *Luetgert and Hughes* (1989) based on refraction work from the Ontario- New York-New England Refraction Experiment.

4.2 Adirondack Array

The Shagan River test site is located at an epicentral distance between 82 and 84 degrees from the Adirondack array at a station-to-source azimuth of 16 to 19 degrees. Observed arrival times and transit times based on the USGS PDE origin time are listed in Table 4. Readings from permanent stations operated by Lamont-Doherty Geological Observatory (LDGO) are also included (*Russell Such*, pers. comm.). Transit times and residuals have been calculated for the Jeffreys-Bullen Tables and the Herrin Tables (*Jeffreys and Bullen*, 1967; *Herrin*, 1968). The observed travel times are in good agreement with the Jeffrey-Bullen Tables, but about 2 sec late compared to Herrin. *Dziewonski and Anderson* (1981) point out that the J-B Tables are about 2 seconds slow compared to nuclear test travel times. For this particular event, however, the J-B Tables predict the arrival times to within 0.30 sec.

Table 4. Predicted and Observed P-Phase Transit Times.

	Observed		Jeffrey-Bullen		Herrin		
Station	Arrival Time	Transit Time	Transit Time	Residual (sec)	Transit Time	Residual (sec)	m_b
NHNH	04h 12m 26.7s	12m 29.3s	12m 28.7s	+0.60	12m 26.80s	+2.50	6.23
1125	30.20	32.80	32.56	+0.24	30.00	+2.03	5.77
1126	30.11	32.71	32.46	+0.25	30.37	+2.08	5.79
1128	29.85	32.45	32.26	+0.29	30.58	+2.13	6.10
1131	29.44	32.04	31.89	+0.15	30.67	+2.13	5.83
MSNY	24.79	27.39	27.47	−0.08	25.56	+1.83	–
HBVT	26.09	28.69	28.56	+0.13	26.65	+2.04	–
WNY	26.52	29.12	29.30	[illegible]	27.40	+1.72	–
PTN	27.27	29.87	29.62	+0.25	27.72	+2.15	–
MIV	28.01	30.61	30.48	+0.13	28.59	+2.02	–
MDV	28.03	30.63	30.45	+0.18	28.56	+2.07	–
ECO	29.45	32.05	31.75	+0.30	29.86	+2.19	–
GNF	29.41	32.01	32.03	−0.02	30.14	+1.87	–
NWC	29.61	32.21	32.28	−0.07	30.39	+1.82	–
CTR	30.23	32.83	32.47	+0.36	30.58	+2.25	–
PGY	30.41	33.01	32.83	+0.18	30.94	+2.07	–

The average residual of 0.14 sec for the Adirondacks was computed for stations within the Pre-Cambrian outcrop boundary on Figure 11. The difference of the residuals between the North Haverhill and Adirondack arrays (0.47 seconds) is in good agreement with the results of *Taylor and Toksöz* (1979) who measure a 0.5 second difference between the central Adirondacks and the New Hampshire-Vermont border region. Crustal models derived from NY-NEX data (*Luetgert and Hughes*, 1990) indicate a 0.23 second difference between the vertical travel time through the crust of the Adirondacks compared to the Appalachians. Thus, approximately 0.2 seconds of the 0.4 to 0.5 second difference must be accounted for in the upper mantle, as suggested by *Taylor and Toksöz* (1979).

The Adirondack station residuals listed in Table 4 suggest that the Marcy anorthosite and the underlying Tawahus complex is a high velocity feature, as suggested by *Owens* (1987). Figure 11 shows the surface outcrop of the anorthosite body and local seismic stations. With the exception of ECO and CTR, stations in or near the anorthosite have large negative residuals indicating high velocities beneath the stations. Farther away, the residuals drop to lower (but still negative) values. Note that the GL stations show an increase in residual going east: station 1131 is about 0.08 seconds faster than 1125. Since P waves at delta of 83 degrees have an incidence angle of 16 degrees, these observations suggest that one edge of the Tawahus complex lies approximately 5 km east of station 1126.

Travel time data from the SHAGAN explosion can be used to estimate the teleseismic ray parameter. Figure 14 shows the travel times to the Adirondack stations plotted versus distance. The least-squares straight line is also shown. The slope of the line (5.33 sec/deg) is an estimate of ray parameter that ignores second-order terms (*Johnson*, 1967). This estimate compares to 5.09 sec/deg at 83.5 deg listed in the Herrin Tables for a discrepancy of 0.24 sec/deg. The second-order terms would contribute only 0.05 sec/deg to the discrepancy. A 2-4 degree regional dip to the Moho under the array would produce roughly a 0.2 sec/deg change in the ray parameter measurement. Thus a moderate regional variation in crustal thickness could account for this discrepancy. Clearly, additional data are required to confirm this observation.

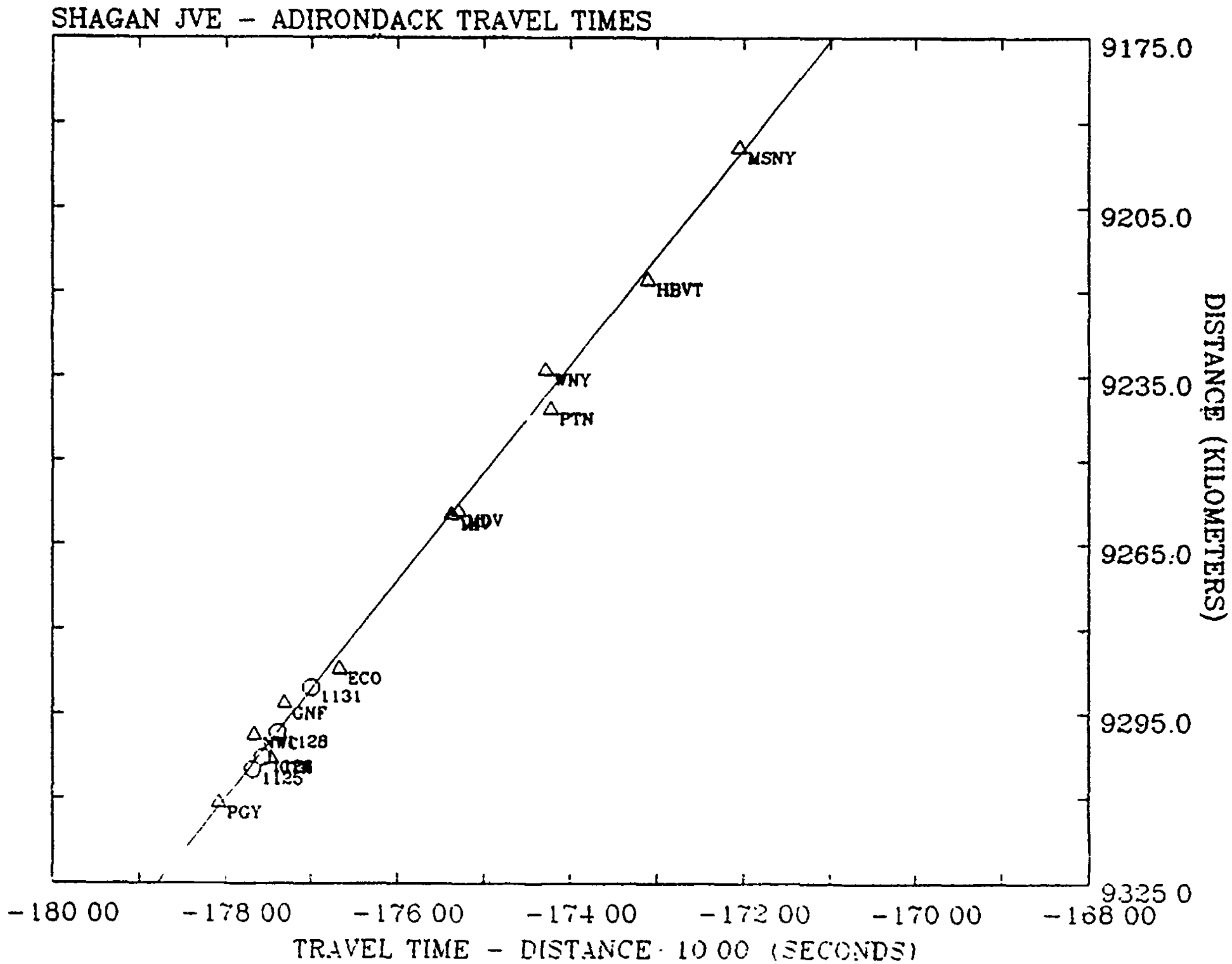


Figure 14. Travel Times of the SHAGAN Explosion Observed in the Adirondacks at GL Stations (Circles) and LDGO Stations (Triangles). Line represents best fit straight line to the observations.

5. MAGNITUDE ESTIMATION

Body-wave magnitude, m_b, estimates for the Shagan River JVE were made from the North Haverhill array vertical stack and for each vertical sensor separately (*Richter*, 1958). The initial attempt at magnitude estimation resulted in estimates ranging from m_b = 6.21 to 6.31. After reanalysis of the data it was determined that the apparent variation in signal amplitude was largely the result of high frequency noise riding on top of the teleseismic signal. A low-pass filter with a corner at 5 Hz was applied to the data and the magnitudes were recalculated. After filtering, the m_b estimates for the array elements were found to have a slightly lower variance, with estimates ranging from m_b = 6.19 to 6.26. Variance in the filtered magnitude estimates can easily be explained from expected inaccuracies in system calibration. The mean, m_b = 6.23, for the array is slightly more than 0.1 magnitude unit of the USGS assigned value of 6.1.

The array magnitude is also higher than the New England network average value of m_b = 5.95 reported by *Ebel, et al.* (1989), but is well inside the range of the New England network site estimates of m_b = 5.59 to 6.51. It is interesting to note that while there is a consistency in travel time residuals between the array and network stations BNH, HNH, and BVT, it does not carry over to the magnitude estimates. In fact, stations HNH and BVT were among the lowest magnitude estimates in the New England network at m_b = 5.59 while BNH had the highest estimate at m_b = 6.51.

Magnitudes for the Adirondack array were calculated from instrument-corrected displacement seismograms and are listed in Table 4. The average m_b is 5.87, below the North Haverhill array value, the USGS determination, and the New England network average, yet still well within the range of these estimates.

6. CONCLUSIONS

Observations of the Soviet SHAGAN nuclear test were made at a 16-element high-frequency array in North Haverhill, New Hampshire, and on a five-station array in the central Adirondack Mountains, New York. Travel times to the stations are in good agreement with travel times predicted by the Jeffrey-Bullen Tables and are about 2 seconds late compared to the Herrin Tables. Relative residuals indicate a 0.5 second difference between the pre-Cambrian Adirondacks and the Paleozoic Appalachian orogenic zone, with the Adirondacks being faster. About 0.23 second of the difference can be accounted for by faster crustal velocities in the Adirondacks. The remainder must be due to velocity differences in the upper mantle. Residuals at Adirondack stations reflect the presence of the high-velocity Tawahus complex beneath the Marcy anorthosite of the Adirondack Highlands. Body wave magnitudes range from 5.87 (the average for the Adirondack array) to 6.23 (the mean for the North Haverhill array), well within the scatter of other observations in the northeastern United States.

References

Battis, J.C. (1990) *Data Report for the 1988 Ontario-New York-New England Seismic Refraction Experiment: Small-Aperture Array*, AFGL-TR-90-0178, Hanscom AFB, MA. ADA235845

Blaney, J.P. (1990) *GDAS Hardware System Definition*, in preparation, Boston College, Boston, MA.

Brown, L., Ando, C., Klemperer, S., Oliver, J., Kaufman, S., Czuchra, B., Walsh, T., and Isachsen, Y.W. (1983) Adirondack-Appalachian crustal structure: The COCORP Northeast Traverse, *Bull. Geol. Soc. Am.*, **94**:1173-1184.

Dewey, J.F. (1977) Suture zone complexities: A review, *Tectonophysics*, **40**:53-67.

Dewey, J.F., and Burke, K.C.A. (1973) Tibetan, Variscan and Precambrian basement reactivation: Products of Continental Collision, *Jour. Geol.*, **81**:683-692.

Dziewonski, A. M., and D. L. Anderson (1981) Preliminary reference Earth model (PREM), *Phys. Earth Planet. Int.*, **25**:297-356.

Ebel, J.E. (1990), personal communications, Weston Observatory, Boston College.

Ebel, J.E., Kafka, A.L., and Zhiping, T. (1989) Analysis of m_b variations in New England from the Joint Verification Experiment (JVE) Explosions, *Eos*, **70**:1188.

Herrin, E., ed. (1968) 1968 Seismological Tables for *P* Phases, E. Herrin, ed., *Bull. Seism. Soc. Am.*, **58**:1193-1241.

Isachsen, Y.W. (1975) Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity, *Tectonophysics*, **29**:169-181.

Isachsen, Y. W. (1985) Structural and tectonic studies in New York State, *US Nuclear Regulatory Comm. Report NUREG/CR-3178*, 74p.

Jeffreys, H., and Bullen, K.E. (1967) *Seismological Tables*, British Association for the Advancement of Science, Smith & Ritchie Ltd., Edinburgh, UK.

Johnson, L. R. (1967) Array measurements of P velocities in the upper mantle, *Jour. Geophys. Res.*, **72**:6309-6326.

Katz, S. (1955) Seismic study of crustal structure in Pennsylvania and New York, *Bull. Seism. Soc. Am.*, **45**:303-325.

Luetgert, J. (1990), personal communications, USGS, Menlo Park, CA.

Luetgert, J., and Hughes, S. (1989) *Technical Report on initial processing and analysis of seismic refraction data collected in the 1988 New York-New England Experiment (NYNEX)*, USGS, Menlo Park, CA.

Mangino, S., and Cipar, J.J. (1990) *Data Report for the 1988 Ontario-New York-New England Seismic Refraction Experiment: GL Three Component Profiles*, AFGL-TR-90-0039, Hanscom AFB, MA. ADA221898

Mitchell, B.J., and Landisman, M. (1969) Electromagnetic seismograph constants by least-squares inversion, *Bull. Seism. Soc. Am.*, **59**:1335-1348.

Moench, R.H. (1989) Metamorphic stratigraphy and structure of the Connecticut Valley area, Littleton to Piermont, New Hampshire in *A Transect Through the New England Appalachians*, J.B. Lyons, and W.A. Bothner, ed., American Geophysical Union, Field Trip Guidebook T162, Washington, D.C.

Owens, T.J. (1987) Crustal structure of the Adirondacks determined from broadband teleseismic waveform modeling, *Jour. Geophys. Res.*, **92**:6391-6402.

Richter, C.F. (1958) *Elementary Seismology*, W.H. Freeman and Co., San Francisco.

Such, R. (1990) personal communications, Lamont-Doherty Geological Observatory, Columbia University.

Taylor, S.R., and Toksöz, M.N. (1979) Three-dimensional crust and upper mantle structure of the Northeastern United States, *J. Geophys. Res.*, **84**:7627-7644.

Taylor, S.R., and Toksöz, M.N. (1982) Crust and upper-mantle velocity structure in the Appalachian orogenic belt: implications for tectonic evolution, *Bull. Geol. Soc. Am.*, **93**:315-329.

von Glahn, P.G. (1980) *The Air Force Geophysics Laboratory Standalone Data Acquisition System: A Functional Description*, AFGL Report No. AFGL-TR-80-0317, Hanscom AFB, MA.ADA100253

Whitney, P. R., Bohlen, S.R., Carl, J.D., deLorraine, W., Isachsen, Y.W., McLelland, J. Olmstead, F., and Valley, J.W. (1989) *The Adirondack Mountains - A Section of Deep Proterozoic Crust*, Field Trip Guidebook T164, 28th International Geological Congress, American Geophysical Union, Washington, DC, 63p.