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A Study of Seismicity and Earthquake Hazard in Northern Alabama and Adjacent Parts of Tennessee and Georgia

Annual Report
May 1982 -- August 1983

Prepared by A. M. Dainty, L. T. Long, J. Liow/GIT

Georgia Institute of Technology

Geological Survey of Alabama

Prepared for
U.S. Nuclear Regulatory
Commission

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SUMMARY

The Georgia Tech-Geological Survey of Alabama Seismic Network has been in operation in Alabama since April 1981 and in southeast Tennessee since April 1982. During this time 83 events have been located. In Alabama, the distribution of epicenters generally confirms trends noted in historical studies, namely a broad northeast-southwest trend and a north-south trend. In southeast Tennessee, four trends running approximately east-west were noted. No interpretation of these trends are made at this time. Few focal depths have been obtained; those that have lie between 9 and 15 km in the Greenville basement below the Paleozoic Valley Ridge sediments. Cumulative frequency-magnitude plots using m_b(Lg) estimated from duration indicate a slope of 0.65 in southern Tennessee; this is consistent with the Alabama data. A tendency of events to occur in pairs closely spaced in time (within one day) and space was noted. A preliminary determination of crustal structure in Alabama is presented in Appendix 1. The average crustal velocities observed are 6.15 km/sec for P waves and 3.55 km/sec for S waves with an average crustal thickness of 35 km. We have not yet found conclusive evidence of a high velocity layer in the crust.

INTRODUCTION

The Southern Applachian Seismic Zone extends the length of the Appalachian Mountains from Virginia to Alabama (Bollinger, 1973; Figure 1). The School of Geophysical Sciences, Georgia Institute of Technology has operated a seismic array under this contract in the northern Alabama portion of the Zone since April 1981 (stations BKA, HGA, HVA, MLA, OCA, TDA, TSA; Figure 2). A second set of stations (CBT, DCT, RCT, RHT, TLT; Figure 2) has been deployed in southeastern Tennessee and became operational in April 1982. This report covers the results obtained from these two arrays, which together constitute the Georgia Tech Geological Survey of Alabama (GT-GSA) Seismic Network. Other stations in Figure 2 are also operated by the School of Geophysical Scinces, Georgia Institute of Technology and were used in the location of many of the earthquakes discussed in this report.

The original motivation for setting up this array was to monitor seismicity in the Southern Appalachian Seismic Zone as originally delineated by Bollinger (1973) on the basis of historical seismicity. The rationale was that more accurate locations of earthquakes could be obtained than with historical data, and possibly focal mechanisms as well. The more accurate locations could more accurately delineate trends that might give a clue as to the cause of seismicity--historical epicenters are only accurate to ± 10 km under the best of circumstances, and in the often sparsely populated area of this study the error can be much larger. Errors in location are formally ± 1 km in much of this study, and at worst ± 5 km. Focal depths and focal mechanisms may be obtained from array studies; this represents new information that cannot be determined by historical studies.

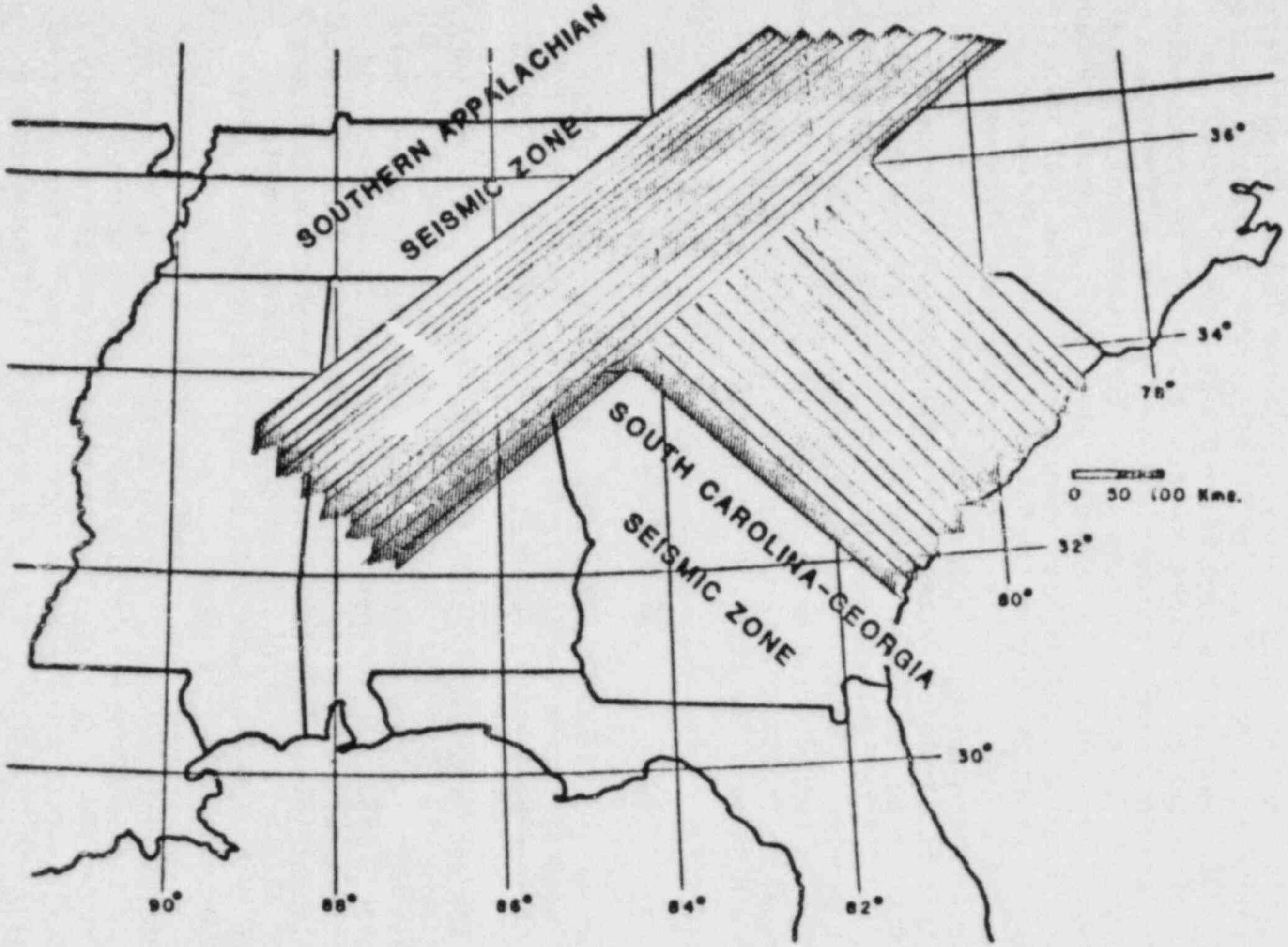

Figure 1. Seismic Zones in the Southeastern United States (after Bollinger, 1973, and Steigert, 1982).

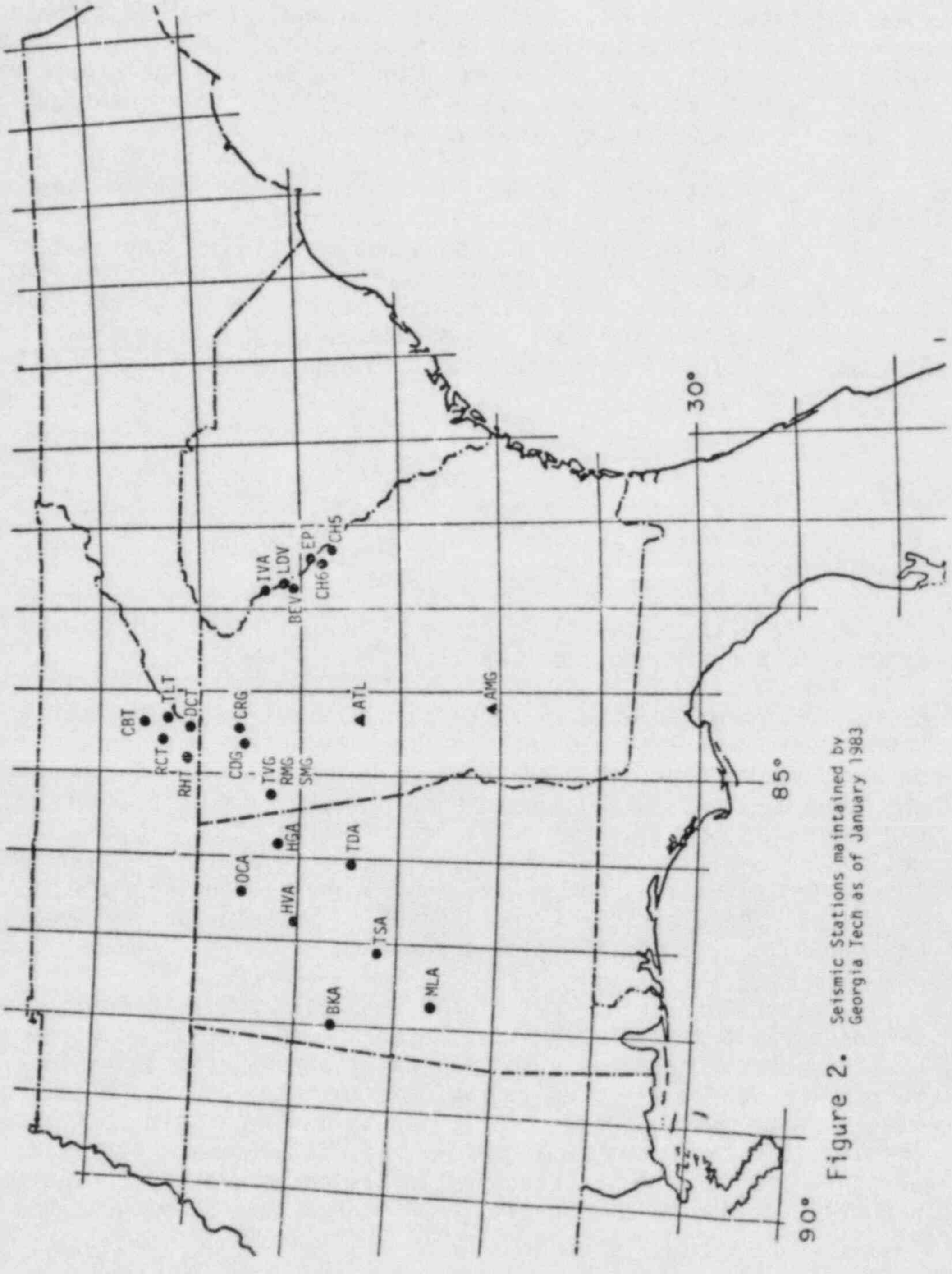

Figure 2. Seismic Stations maintained by Georgia Tech as of January 1983

The principal question that must be addressed in array studies conducted over a short period of time (about 2 1/2 years in this case) is the relationship of the inevitably rather small ($m_b(Lg)_{Dur} \leq 3.5$) events detected in such a small time span and larger, less frequent events of importance in the analysis of seismic hazard. In the main, we shall assume that a one to one relationship exists; i.e. there are no seismic "gaps", either temporal or spatial. At present the data does not permit us to make any other assumptions.

An important factor in determining the accuracy of epicenter location is the velocity model of the earth used. Appendix I is the text of a presentation made to the annual meeting of the Eastern Section, Seismological Society of America, on September 19, 1983. We intend to carry out a similar seismological study in southeast Tennessee, and then relocate all events using these two crustal models. The sensitivity of the crustal model to depth determination is being investigated in detail.

EPICENTERS

Introduction

Figure 3 shows the 83 epicenters located in the study area by the network in the time period 1 April 1981 to 31 August 1983. Information about the epicenters is given in Table 1. In this report, we are primarily concerned with epicenters in Alabama and southeastern Tennessee. In addition to these epicenters, there was a notable sequence of earthquakes near Macon, GA between December 1982 and June 1983, with the largest event having a magnitude $m_b(Lg)_{Dur}$ of 3.5. There were also two events in Columbus, GA on 31 October 1982 of magnitude 3 and 3.1, as well as several small events in the general vicinity of the Clark Hill Reservoir in the Savannah River, the border between Georgia and South Carolina. The vicinity of the Richard B. Russell Dam and impoundment has shown no evidence of seismic activity.

Earthquakes were distinguished from quarry blasts on the basis of the appearance of surface waves, location and time of occurrence. Distinguishing characteristics of quarry blast seismograms include a relatively weak S wave, well developed surface wave train due to the near surface source, occasionally an air wave, and similarity to previous blasts in the same quarry. We will discuss earthquakes in northern Alabama and southeastern Tennessee separately, since the network stations were installed at different times in these two areas.

Epicenters in Northern Alabama

As can be seen from Figure 3, only a small number of earthquakes were located in northern Alabama during the reporting period. The small number of events relative to southeastern Tennessee is even more striking considering that network stations have been deployed in north

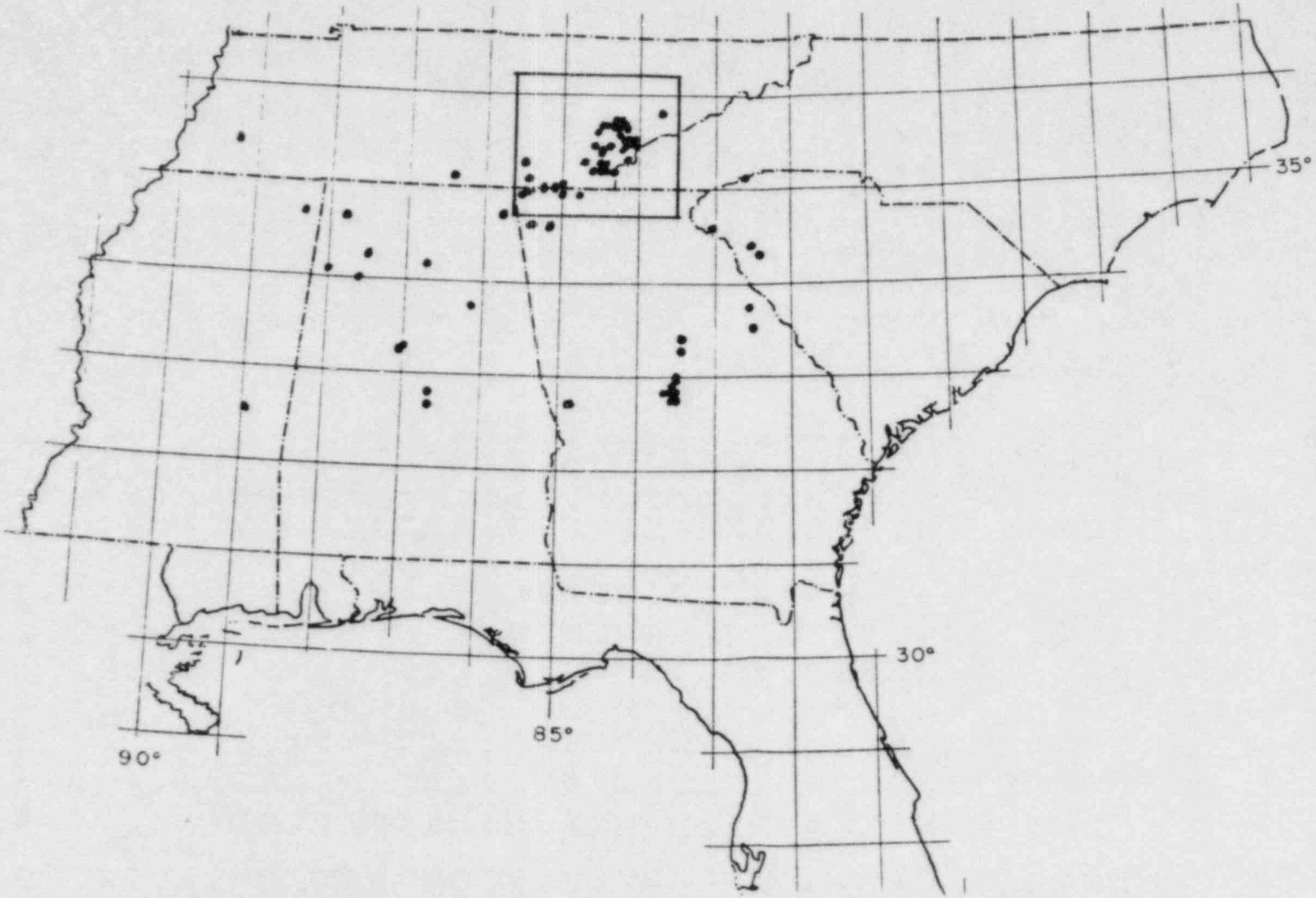

Figure 3. Epicenter Locations, April 1981 - September 1983.

Table 1. Events located by GT-GSA network, 1 April 1981 - 31 August 1983

Date (m/d/yr)	Time (UT)	Latitude	Longitude	Depth (km)	m_b	Location
05/07/81	09:58:44	34°13'38"N	86°44'43"W	0*	2.8	Hanceville, AL
08/26/81	04:05:32.6	34°6'14"	87°59'22"	0*	2.4	Hamilton, AL
09/04/81	17:21:43.8	34°38'43"	85°8'21"	0*	3.2	AL-GA border
09/28/81	18:03:34	34°36'24"	85°23'39"	0*	2.9	AL-GA border
12/09/81	03:29:35.8	33°18'20"	87°3'53"	0*	2.9	Tannehill State Park
12/13/81	09:42:29.5	35°15'35"	85°30'36"	0*	1.8	GA-TN-AL border
12/23/81	16:10:11.7	34°45'6"	85°46'54"	0*	2.4	GA-AL border
01/02/82	02:00:26.1	35°6'41"	86°22'51"	0*	3.4	Fayetteville, TN
02/05/82	10:59:07	32°40'43"	86°37'22"	0*	2.5	Montgomery, AL
02/05/82	14:17:26	32°48'58"	86°35'46"	0*	2.4	Montgomery, AL
02/23/82	09:19:07.9	34°36'50"	85°27'31"	0*	2.5	AL-GA border
05/05/82	15:28:16	35°40'0"	84°28'48"	0*	1.9	Sweetwater, TN
05/12/82	01:21:51.8	34°54'2"	85°1'19"	9	2.9	Ringgold, GA
05/12/82	04:58:3	34°13'31"	87°30'22"	0*	2.3	Haleyville, AL
05/17/82	03:54:13.4	35°43'23"	84°19'16"	15	1.0	Sweetwater, TN
05/20/82	07:12:8.5	35°0'39"	85°7'25"	0*	1.7	Chattanooga, TN
05/26/82	07:42:43.2	34°58'37"	85°14'45"	13.5	2.0	Chattanooga, TN
05/30/82	07:12:0	35°40'55"	84°12'23"	0*	1.7	Sweetwater, TN
06/07/82	03:28:48.8	34°53'49"	84°50'34"	12	0.6	Beaverdale, GA
06/17/82	21:09:37.1	35°12'13"	84°24'44"	0*	1.5	Servilla, TN
07/08/82	05:18:50.6	35°28'17"	84°7'0"	0*	1.4	Citico Beach, TN
09/05/82	10:11:9.2	35°12'10"	84°31'15"	0*	3.2	Reliance, TN
09/24/82	21:57:42	35°40'7"	84°15'11"	0*	3.2	Greenback, TN
09/24/82	22:19:16.5	35°40'13"	84°16'56"	0*	3.5	Greenback, TN
09/24/82[1]	22:54:11.8	35°39'40"	84°13'35"	11	1.5	Greenback, TN
10/09/82	18:09:53.7	35°8'53"	84°41'7"	0*	1.8	Benton, TN
10/31/82	03:07:36.7	32°40'17"	84°52'22"	0*	3.0	Columbus, GA
10/31/82	03:12:12.2	32°38'38"	84°53'37"	0*	3.1	Columbus, GA
11/08/82	09:56:10.6	35°11'20"	84°20'9"	0*	1.8	Farner, TN
11/20/82	03:30:44.7	35°13'14"	84°45'1"	0*	1.1	Fairview, TN
11/23/82	04:51:0.1	35°4'1"	85°26'44"	0*	2.0	Walden Ridge, TN
11/29/82	10:52:9.1	33°43'0"	86°8'17"	0*	1.5	Ohatchee, AL
12/01/82	13:39:45	35°15'10"	84°26'46"	0*	2.4	Servilla, TN
12/14/82	06:35:9.6	35°18'8"	84°7'48"	0*	3.0	Coker Creek, TN
12/15/82	02:27:59.4	35°44'13"	84°13'0"	0*	2.6	Greenback, TN
12/21/82	05:30:46.2	32°47'57"	83°31'7"	0*	2.7	Macon, GA
01/05/83	23:05:56.5	34°1'3"	87°37°14"	0*	2.4	Gold Mine, AL
01/08/83	22:30:37	34°54'55"	85°31'34"	0*	2.3	Trenton, GA
01/16/83	19:28:13.9	32°47'27"	83°31'41"	0*	2.6	Macon, GA
01/17/83	02:06:6.9	32°44'43"	83°31'25"	0*	2.8	Macon, GA
01/17/83	03:34:20.3	32°45'44"	83°31'18"	0*	2.6	Macon, GA
01/18/83	05:09:12.1	35°35'20"	84°17'29"	0*	n.a	Vonore, TN
01/18/83	11:06:10.4	32°51'56"	83°32'44"	0*	n.a	Macon, GA
01/20/83	08:15:8.1	32°50'40"	83°34'44"	0*	2.9	Macon, GA.
01/26/83	11:30:55.5	35°26'37"	84°8'58"	0*	2.1	Tellico Plains, TN
01/26/83	12:32:7.6	32°50'58"	83°32'5"	0*	n.a	Macon, GA

Date (m/d/yr)	Time (UT)	Latitude	Longitude	Depth (km)	m_b	Location
01/26/83	14:07:44.7	32°51'10"	83°35'17"	0*	3.5	Macon, GA
01/26/83	14:17:39.8	32°49'23"	83°33'6"	0*	n.a	Macon, GA
01/29/83	04:55:37.8	32°53'30"	83°33'7"	0*	3.0	Macon, GA
01/29/83	05:04:21.5	32°48'2"	83°30'44"	0*	2.5	Macon, GA.
01/31/83	23:04:8.6	34°57'44"	85°30'42"	0*	2.1	AL-TN-GA border
01/31/83	23:41:1.1	34°18'2"	82°25'12"	0*	2.7	Honea Path, SC
02/05/83	13:08:18.2	34°41'43"	88°19'55"	0*	3.0	AL-MS-TN border
02/11/83	01:15:37.8	35°3'53"	84°59'16"	0*	2.2	Blue Springs, TN
02/23/83	08:51:32.2	35°24'13"	89°11'59"	0*	3.4	Boliver, TN
02/27/83	23:52:17.3	35°27'16"	84°34'46"	0*	2.1	Madisonville, TN
03/04/83	14:03:28.1	35°35'13"	84°18'30"	0*	2.6	Sweetwater, TN
03/11/83	22:29:40.3	35°13'58"	84°28'41"	0*	2.3	Servilla, TN
03/13/83	03:53:13.3	35°27'28"	84°23'41"	0*	2.0	Madisonville, TN
03/16/83	09:13:51.6	35°12'37"	84°33'40"	0*	2.8	Reliance, TN
03/25/83	02:47:12.8	35°9'25"	82°40'52"	0*	3.3	SC-NC border
03/30/83	11:52:14.1	35°24'41"	84°30'27"	0*	2.1	Athens, TN
04/05/83	00:41:21	33°10'9"	86°59'23"	0*	2.9	Marvel, AL
04/05/83	03:17:59.2	35°32'22"	84°10'14"	0*	2.2	Tellico Plains, TN
04/16/83	07:26:43.4	35°24'32"	84°11'32"	0*	2.2	Belltown, TN
05/16/83	06:50:23.5	35°32'23"	84°3'26"	0*	2.1	Tellico Plains, TN
05/25/83	10:46:6.7	35°41'57"	84°27'20"	0*	2.1	Sweetwater, TN
05/26/83	12:30:2	35°39'6"	84°15'2"	0*	2.8	Greenback, TN
05/30/83	07:14:3.9	32°32'8"	88°57'7"	0*	2.7	Quitman, MS
06/17/83	04:11:8.8	32°21'45"	83°28'6"	0*	2.5	Eatonton, GA
06/17/83	11:23:15	33°16'10"	83°27'27"	0*	2.5	Eatonton, GA
06/22/83	05:53:25.5	35°36'52"	84°39'4"	0*	2.0	Sweetwater, TN
06/26/83	17:34:2.8	35°24'0"	84°18'15"	0*	2.1	Tellico Plains, TN
07/02/83	06:46:28.6	35°38'31"	84°8'39"	0*	2.2	Greenback, TN
07/07/83	07:06:42.9	34°35'55"	83°4'2"	0*	2.7	Hartwell Reservoir, SC
07/08/83	19:29:5.5	35°31'39"	84°8'1"	0*	3.2	Tellico Plains, TN
07/09/83[2]	03:28:46.9	35°31'16"	84°6'36"	0*	1.5	Tellico Plains, TN
07/09/83[2]	09:57:48	35°27'10"	84°2'44"	0*	1.7	Tellico Plains, TN
07/12/83	20:46:15.9	33°30'25"	82°37'31"	0*	n.a	Clark Hill Reservoir, SC
07/15/83	19:32:56.7	35°29'5"	84°7'10"	0*	2.8	Tellico Plains, TN
07/20/83	17:30:19.4	33°46'4"	82°34'28"	0*	n.a	Clark Hill Reservoir, SC
07/22/83	18:36:6.1	34°23'4"	82°37'52"	0*	n.a	Richard B. Russell Dam, SC
08/28/83	10:44:3	34°38'52"	87°46'35"	0*	2.7	Florence, AL

Notes

* Deptn fixed

[1] Aftershock. Other aftershocks were recorded on station CBT at the following time (to the nearest minute):
On 09/24/82 at 22:24, 22:29, 22:34, 22:46, 22:47, 23:05.
On 09/25/82 at 4:41, 5:20, 6:28, 10:24.
On 09/27/82 at 7:49.

[2] Aftershock

Alabama since the beginning of the reporting period, whereas the southeastern Tennessee stations were not deployed until April 1982, a year later. To alleviate the problems caused by the small sample, we will also use historical events occurring between 1886 and 1957 and events located instrumentally in the period 1957 to 1981 before the installation of the network. These events are given in Steigert (1982).

Figure 4 shows the events located by the network together with events taken from Steigert. On the whole, new trends other than those reported by Steigert are not apparent on the map--indeed, the network epicenters suggest that the zone may be more diffuse than the earlier data indicated. For example, there are several recent epicenters in the northwest corner of the state, but no earlier epicenters. Similarly, there are events near Montgomery, AL (between 32° and 33°N latitude and 86° and 87°W longitude) that have no earlier counterparts.

Four trends are marked on Figure 4 and labelled by Arabic numerals. Trends 1 and 2 are discussed by Steigert (1982)--trend 1 is the Southern Appalachian Seismic Zone, and trend 2 is a north-south trending zone identified by Steigert, in part using historical earthquakes in central Tennessee not shown on Figure 4. Trend 1 is a diffuse trend, if anything made more diffuse by the data given in this report. Trend 2 shows less scatter of epicenters about the trend line, and it is possible that the two events near Montgomery, AL are on this trend.

Two other, much shorter possible trends, 3 and 4, are also shown on Figure 4. These trends will be discussed in the next section, since they seem to fit more closely the style of seismicity found in southeastern Tennessee. Trend 4 in Figure 4 corresponds to trend 4 in Figure 6. Trend 3 would be a similar trend to the south of the trends shown on Figure 6. As can be seen from Figure 4, trends 3 and 4 are rather speculative.

Epicenters in Southeastern Tennessee

Epicenters in southeastern Tennessee plotted on Figure 3 are shown at a larger scale in Figure 5. To allow assessment of trends discussed in this section, no other information is presented in Figure 5 except for the position of the town of Maryville, site of previous seismic activity (Bollinger *et al.*, 1976). The epicenters in Figure 5 cover the period 1 May 1982 to 31 August 1983.

The most notable feature of Figure 5 is the non-random distribution of the epicenters. There is a broad trend from southwest to northeast, the trend of the Southern Appalachian Seismic Zone. Another broad trend running from southeast to northwest, the South Carolina-Georgia Seismic Zone (Bollinger, 1973; Figure 1), intersects the Southern Appalachian Seismic Zone in this general area, but no southeast-northwest trend is evident on Figure 5. Within the broad trend of the Southern Appalachian Seismic Zone, however, there appear to be about four approximately east-west trends, about 50-75 km long and about 10 km wide.

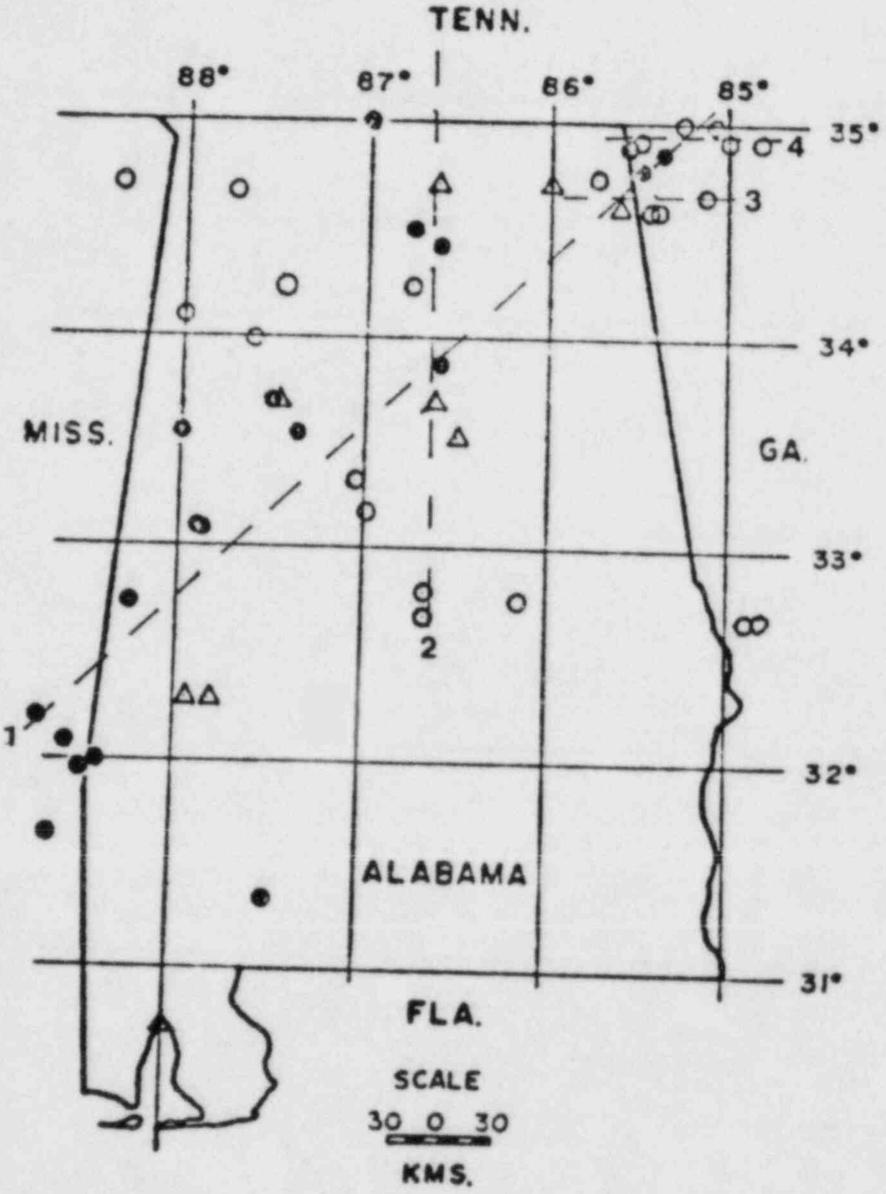

Figure 4. Epicenter locations and trends, Alabama. Trends discussed in text. Open triangle, historical epicenters, 1886-1956. Solid circles, instrumental epicenters, 1957-1981. Open circles, instrumental epicenters (this report), April 1981 - September 1983.

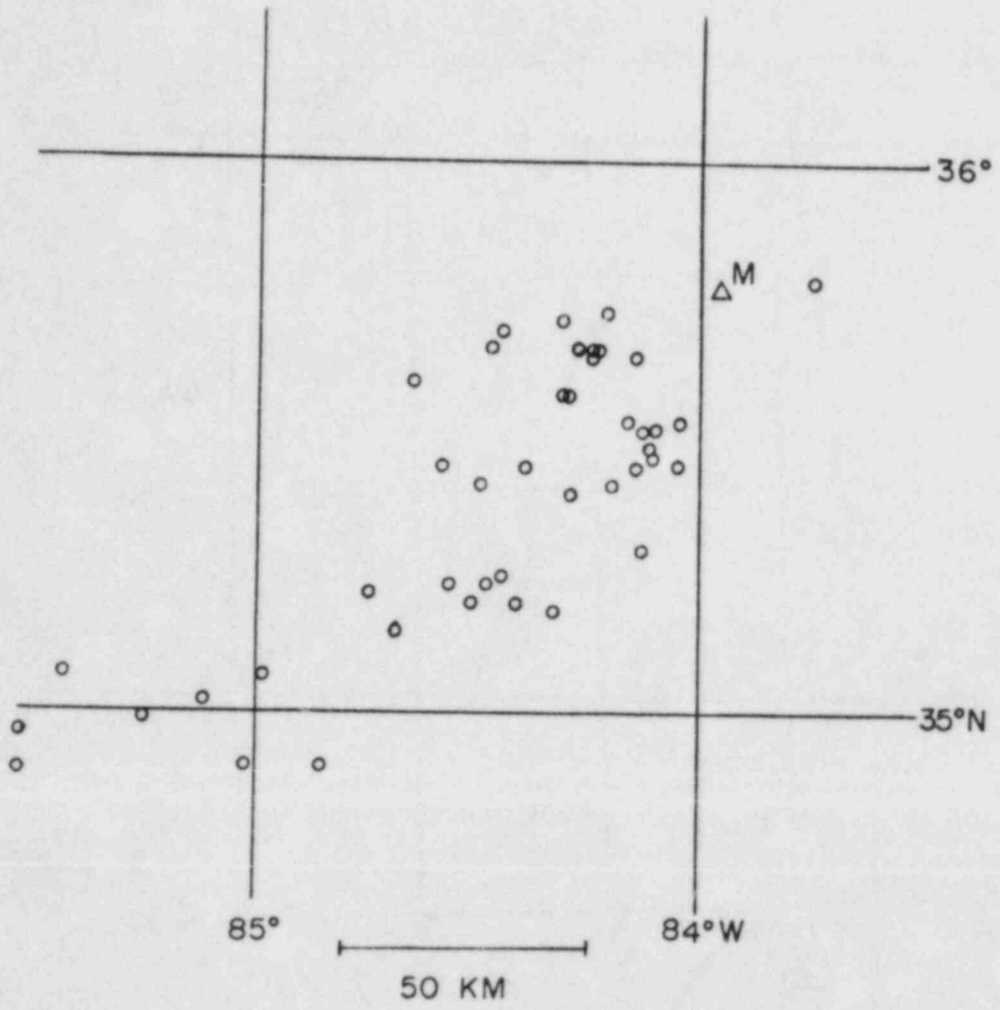

Figure 5. Epicenter locations, southeast Tennessee, April 1982 - September 1983. Open triangle labeled M, town of Maryville, Tennessee.

To examine these trends further, the epicenters are replotted on Figure 6 with the five network stations shown and the focal mechanisms that are available. The trends are numbered 1 to 4 in Arabic numerals; as discussed previously, trend 4 on Figure 6 corresponds to trend 4 on Figure 4, and there may be another east-west trend south of it. Trend 1 contains events near Greenback, TN, Sweetwater, TN, and Maryville, TN. Trend 2 includes events near Tellico Plains, TN, trend 3 events near Servilla, TN and Reliance, TN, and trend 4 events near Chattanooga, TN. None of the trends seem to correlate with topographic features except trend 3, which follows (approximately) the course of the Hiawassee River. The trends all crosscut the Paleozoic Appalachian trend, which runs southwest-northeast.

In assessing the significance of these trends, some estimate of the accuracy of epicenter location is needed. Formal errors are provided by the location program and indicate that epicenters are generally known to within about ± 1 km. However, there are two problems concerning the calculation of errors. One is the lack of depth control due to lack of stations with an epicentral distance equal to or less than the focal depth of the epicenter. Another is the absence of a velocity model for the area. To attempt to analyze these difficulties, we have looked at independent estimates of epicenters for earthquakes and aftershocks (there are two examples in Table 1), and also at quarry blast locations. These studies suggest that errors may be as large as ± 5 km in some cases.

With this accuracy of location, the width (10 km) of trends 1-4 are about the scatter of the data--the trends could be much narrower. The trends are about as long, or somewhat longer, than the trend reported by Bollinger and Wheeler (1980) in Giles County, VA. Bollinger and Wheeler have interpreted the Giles County trend as a fault. We note, however, that the focal mechanisms shown in Figure 6 do not show noticeably consistent trends of faulting or nodal planes. At present, we make no interpretation of trends 1-4 pending further investigation.

FOCAL DEPTHS, MAGNITUDES AND PAIR EVENTS

Very few focal depths have been determined to date because of insufficient numbers of close stations. A commonly used rule of thumb is that at least one station should be within one focal depth of the epicenter, but many studies indicate that even this rule is inadequate if the velocity structure is not well known. We intend to carefully analyze the velocity structure in our area and then attempt to see which events can be reliably located in depth by any means available. Initially we attempted to determine depths in southeast Tennessee (Table 1), but decided to wait until more accurate information was available. Such depths as were determined are in the 9-15 km range, placing the hypocenters in the (Grenville) basement below the Paleozoic Valley and Ridge sediment.

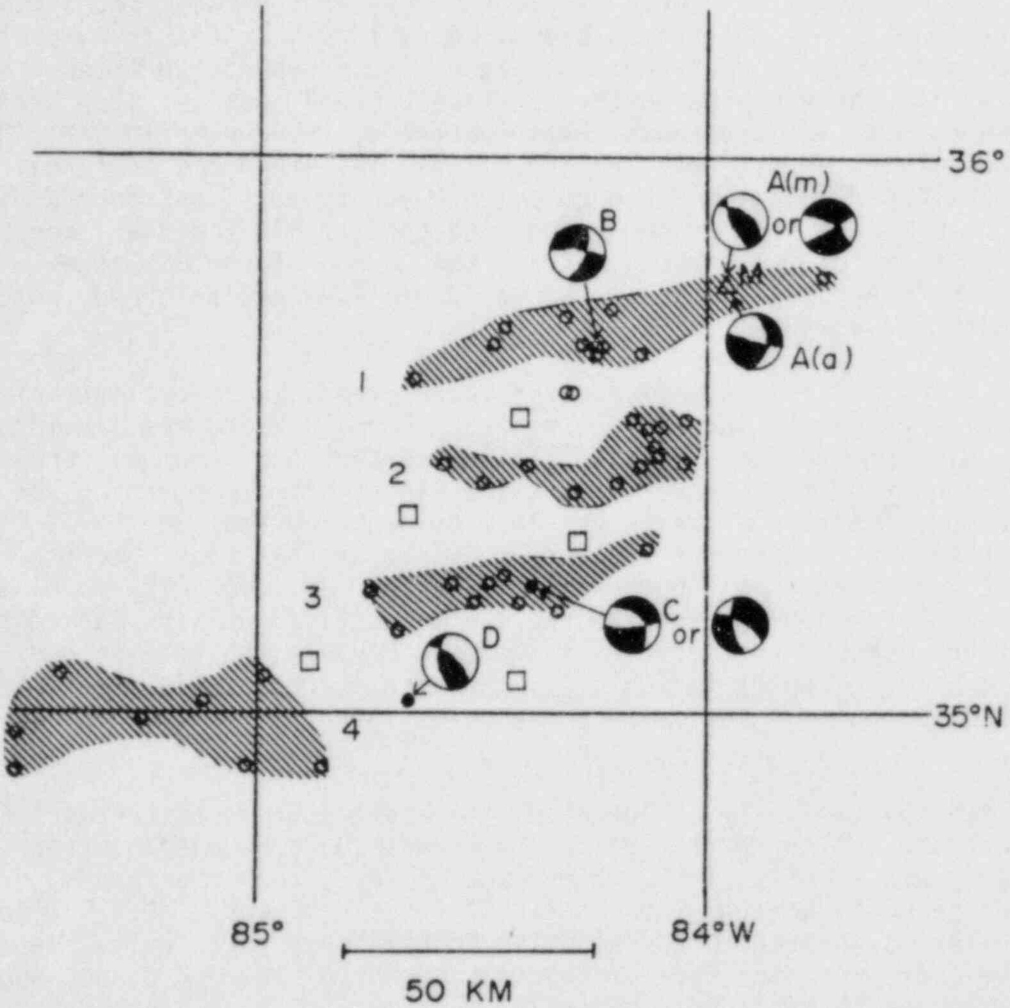

Figure 6. Epicenter locations (April 1982 - September 1983), trends and focal mechanisms, southeast Tennessee. Open circles, epicenters, April 1982 - September 1983 (this report). Open squares, station locations (see Figure 2). Open triangle, town of Maryville, Tennessee. Solid circles, additional epicenters for focal mechanisms. Trends discussed in text. Focal mechanisms: A, Bollinger _et al_. (1976) (m - mainshock, a - aftershocks). B, Reinbold and Cornwell (1983). C, Long _et al_. (1980). D, Guinn (1977).

We have determined magnitudes by measuring the total duration of the event and using the formula of Chaplin et al. (1980) derived for New England. This is a temporary measure until we derive our own magnitude scale. Since Chaplin et al.'s scale is tied to the teleseismic scale m_b (body-wave magnitude), the resulting magnitudes are $m_b(Lg)_{Dur}$. We present cumulative frequency against magnitude plots for southeast Tennessee (Figure 7, covering the period April 1982 - September 1983) and Alabama (Figure 8, covering the period April 1982 - September 1983, also includes some events near the Alabama border). The line on Figure 7 obeys the equation

$$\log_{10} N = 2.7 - 0.65\ m_b(Lg)_{Dur} \tag{1}$$

The failure of the points at low values of $m_b(Lg)_{Dur}$ to fit this line suggests that the capability of the array to detect and locate events in southeast Tennessee begins to degrade for events of magnitude 1.8 and less.

The points plotted on Figure 8 do not define a line with any accuracy. The line drawn was constrained to have a slope of -0.65, as in (1). This compares with a slope of -0.62 obtained by Steigert (1982) using earlier data. The line on Figure 8 obeys the equation

$$\log_{10} N = 2.6 - 0.65\ m_b(Lg)_{Dur} \tag{2}$$

This relation breaks down for magnitudes of 2.0 and less, indicating that this is the threshold for detection and location of events in this region.

One final comment may be made about the events listed in Table 1. Of the 83 events listed in Table 1, there are 10 "pair" events, defined as two events of comparable size occuring on the same day. These pairs are the events at Montgomery, AL on 02/05/82, the events at Greenback, TN on 09/24/82, the events at Columbus, GA on 10/31/82, the events at Macon, GA on 01/17/83 (other possibilities at Macon were not considered) and the events at Eatonton, GA on 06/17/83. Even if the Macon, GA events are not considered, this is a higher number of pairs than would be expected by chance. This mode of earthquake occurrence may be characteristic of the southeastern United States.

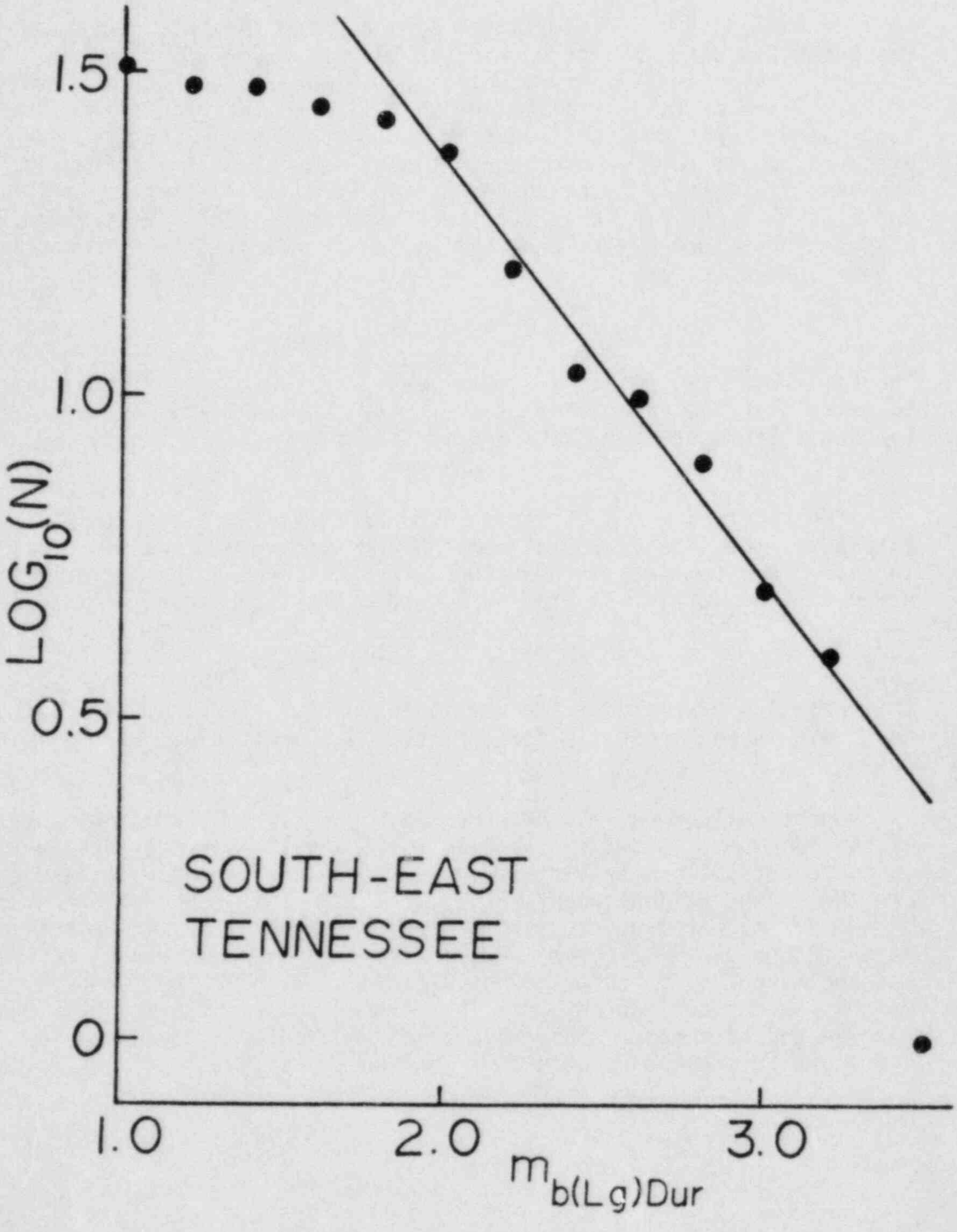

Figure 7. Cumulative frequency vs. magnitude, southeast Tennessee, April 1982 - September 1983. Line discussed in text.

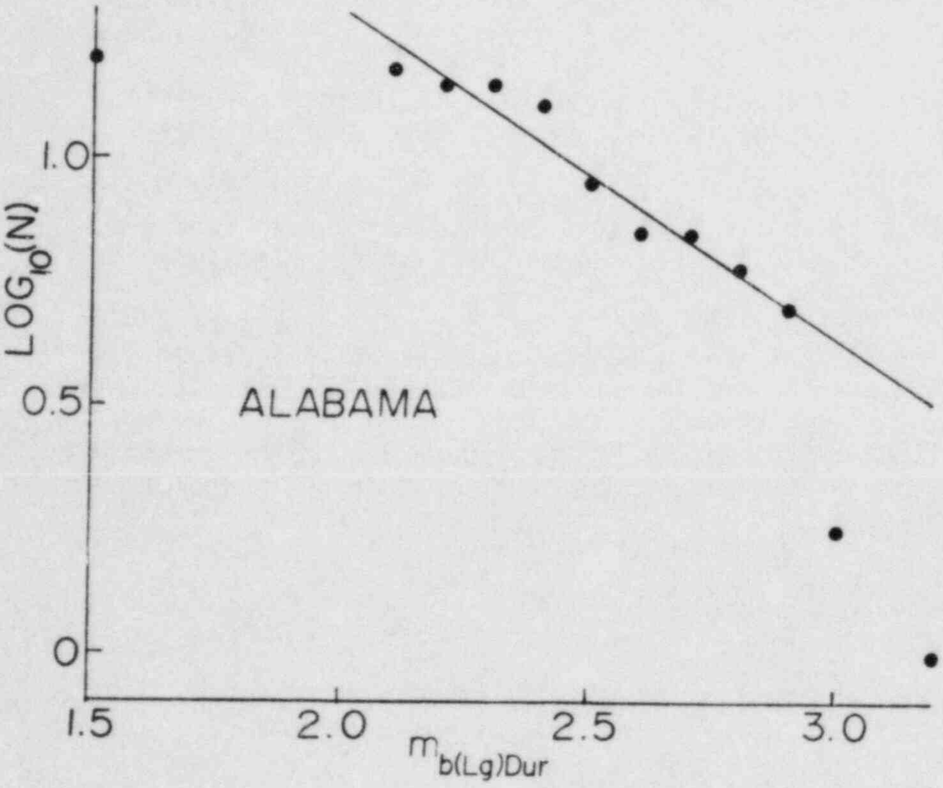

Figure 8. Cumulative frequency vs. magnitude, Alabama, April 1981 - September 1983. Line discussed in text.

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APPENDIX I

Velocity Structure of the Crust
in the Southern Appalachian Seismic Zone in Alabama

By

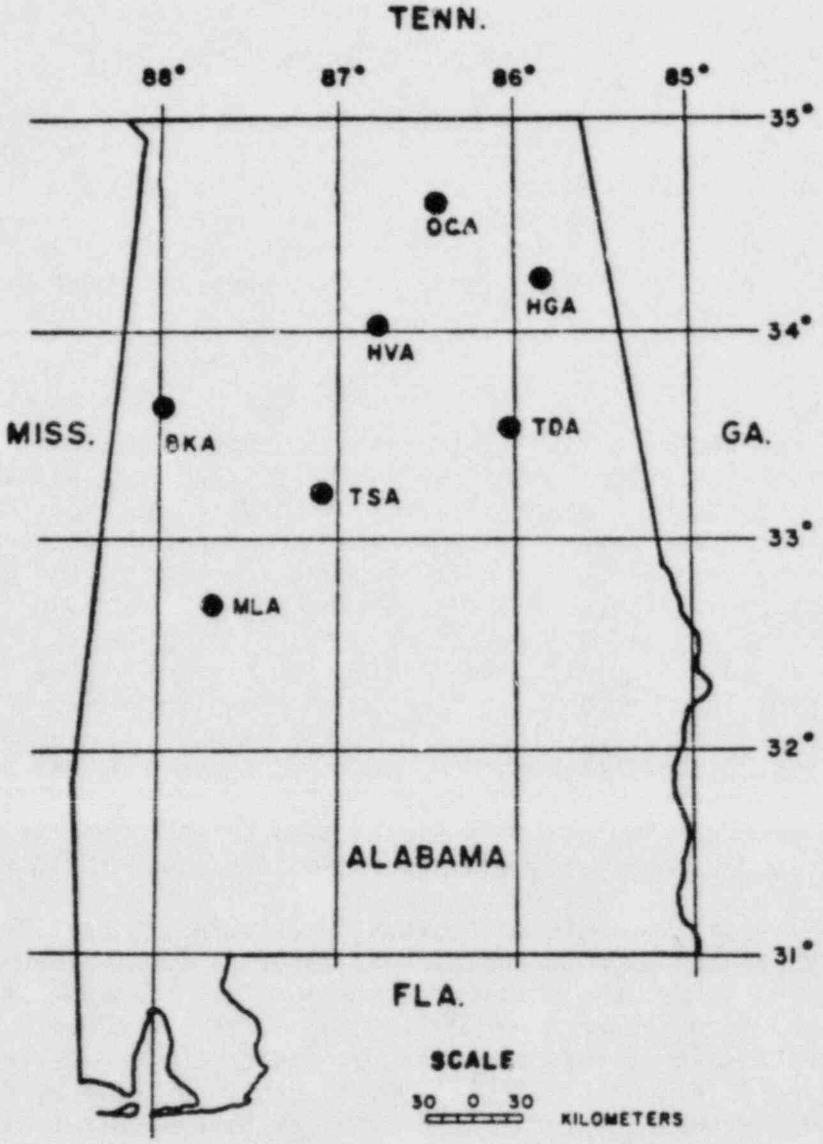
Jeih-San Liow, Leland Timothy Long, and Anton M. Dainty

Introduction

The southern Appalachian seismic zone is a 100 km wide diffuse zone of seismicity which enters the northeast corner of Alabama and extends southwest to the Alabama-Mississippi border. Most of the historical earthquakes defining this zone have been located on the basis of intensity data alone which may account for some of the diffusion. In Alabama, earthquakes of the southern Appalachian seismic zone occur in the Valley and Ridge province or its extension beneath the sediments of the Gulf coastal plain. The geological history of the Valley and Ridge province since Precambriam time is complex, including episodes of folding and thrust faulting during the Paleozoic. During the Tertiary and possibly continuing to the present, the region has been the focus of gentle uplifting or epeirogeny. While the area contains many faults, no earthquakes in the southern Appalachian seismic zone is known to be associated with ground breakage along an exposed fault trace.

A seismic network maintained by Georgia Tech and the Geological Survey of Alabama with Nuclear Regulatories Agency Support has been operating since 1980. This network consists of seven stations extending from the north-eastern corner of Alabama to the central west edge of the state (Figure I-1). The average spacing between stations is 100 km. The distribution of stations is designed to monitor the seismicity of the southwestern terminus of the southern Appalachian seismic zone and to provide more accurate locations for recently recorded events. A detailed description of the sites and individual station information is given in Annual Report No. 1 (Long, Dainty, and Steigert, 1980).

A few earthquakes and a great number of blasts have been detected and located since the network was established. The revised locations of earthquakes by the seismic net will contribute to the refinement of the extent and activity level of the southern Appalachian seismic zone. The many blasts can contribute to the understanding of the crustal structure and the ability to locate earthquakes precisely. The objective of this report is to present an analysis of the velocity structure of the crust in northern central Alabama.



SEISMIC STATIONS FOR GT-GSA NETWORK

Figure I-1. The Georgia Tech - Geological Survey of Alabama (GT-GSA) Seismic Network. Operation initiated in April 1981. Other seismic stations in Alabama are not shown.

Data Collection

A set of Alabama blasts detected by the Georgia Tech-Geological Survey of Alabama (GT-GSA) network from July 1981 to April 1983 were chosen for this report (Table I-1). These events were first examined carefully for their P-wave and S-wave arrival times, then located by an iterative-least square residual error technique (equivalent to HYPO71). The exact locations were unknown. Only those events with an error ellipse based on residual errors less than 10^2 km were used. Most of the blast sites were in the central portion of the array (Figure I-2) and concentrated within the triangle of stations HVA, BKA, and TSA, or the area between 33°N and 34°N and 87°W and 88°W.

A crustal velocity model with an average P-wave velocity of 6.12 km/sec and an average S-wave velocity of 3.55 km/sec was used in the location program and was based on a preliminary analysis of the data. Locations were based entirely on the direct P wave or S wave in the crust arriving at a distance of less than 220 km and greater than about 35 km.

Data Analysis

1. Travel Time Curve

The travel times for each event were plotted versus distance as shown in Figure I-3. The travel times show two straight lines for both the P wave and the S wave. The coverage for distances less than 40 km and beyond 150 km is equivalent to one travel time arrival every 4.0 km. The arrival time density over the rest of the travel time curve is one to two arrivals every km. The points at a distance of less than 40 km indicate a lower velocity surface layer. The surface layer consists primarily of Paleozoic sediments with varying low velocities.

A least squares regression was used to fit straight lines to the two curves. The velocities obtained are $V_p = 6.15 \pm 0.02$ km/sec and $V_s = 3.55 \pm 0.01$ km/sec. The standard deviation is 0.26 sec for the P travel-time curve and 0.31 sec for the S travel-time curve. There is no significant correlation of the error with distance.

2. Reduced Travel Time Curve

In order to observe the detailed variations of the travel time curve and relate them to velocity structure, reduced travel time curves were generated (Figures I-4 and I-5). At least 3 layers can be identified from these curves. Because of current lack of close in data, a first layer of $V_p = 5.57 \pm 0.01$ km/sec and $V_s = 3.16 \pm 0.01$ km/sec is determined by the points from zero up to 35 km distance. An ambiguity in origin time computation introduced in the location program could in effect allow lower first layer velocities. Though the points are

Table I-1. Origin times and locations of the blasts.

EVENT NO.	DATE	ORIGIN TIME	LATITUDE	LONGITUDE
1	81/07/11	17:46:48.75	34.0134	86.9967
2	81/07/11	18:00:11.58	33.9548	86.9671
3	81/09/17	14:18: 1.10	33.7163	87.1356
4	81/09/26	21:49:39.29	34.1098	87.7064
5	81/09/28	19:26:25.81	33.5857	86.4902
6	81/10/08	18:36:31.10	33.8464	87.3915
7	81/10/09	17:01:34.80	33.8185	87.3705
8	81/10/12	22:02:58.09	33.8146	87.0480
9	81/10/15	18:50: 1.42	33.7887	87.3090
10	81/10/16	14:30:57.34	33.8475	87.4288
11	81/10/20	14:52:17.71	33.6697	86.9687
12	82/10/02	15:19:44.08	33.8334	87.4010
13	82/10/27	18:51:19.98	33.8037	87.4307
14	82/11/01	19:54:31.54	33.8394	87.3848
15	82/11/08	19:44:48.59	33.8166	87.3556
16	82/11/10	21:05:24.60	33.7835	87.2728
17	82/11/15	18:30: 2.78	33.1987	87.0261
18	82/11/19	20:43:22.37	33.5841	87.0500
19	82/11/27	19:28:31.25	33.8581	87.3660
20	82/11/27	20:30:17.78	33.8349	87.3721
21	83/01/08	15:54: 4.19	33.9210	86.8757
22	83/01/09	20:27:15.57	33.5673	87.0658
23	83/02/07	18:25:15.36	33.8440	87.3575
24	83/02/17	17:35:33.12	33.7857	87.4320
25	83/02/19	16:21:24.55	33.9956	86.9940
26	83/02/25	21:03: 1.37	33.2032	86.9957
27	83/03/25	22:28:43.87	33.1821	87.0320
28	83/04/15	19:01:27.60	33.8468	87.4192
29	83/04/15	21:57:13.61	33.8667	87.4762
30	83/04/16	20:39:16.27	33.8245	87.4631

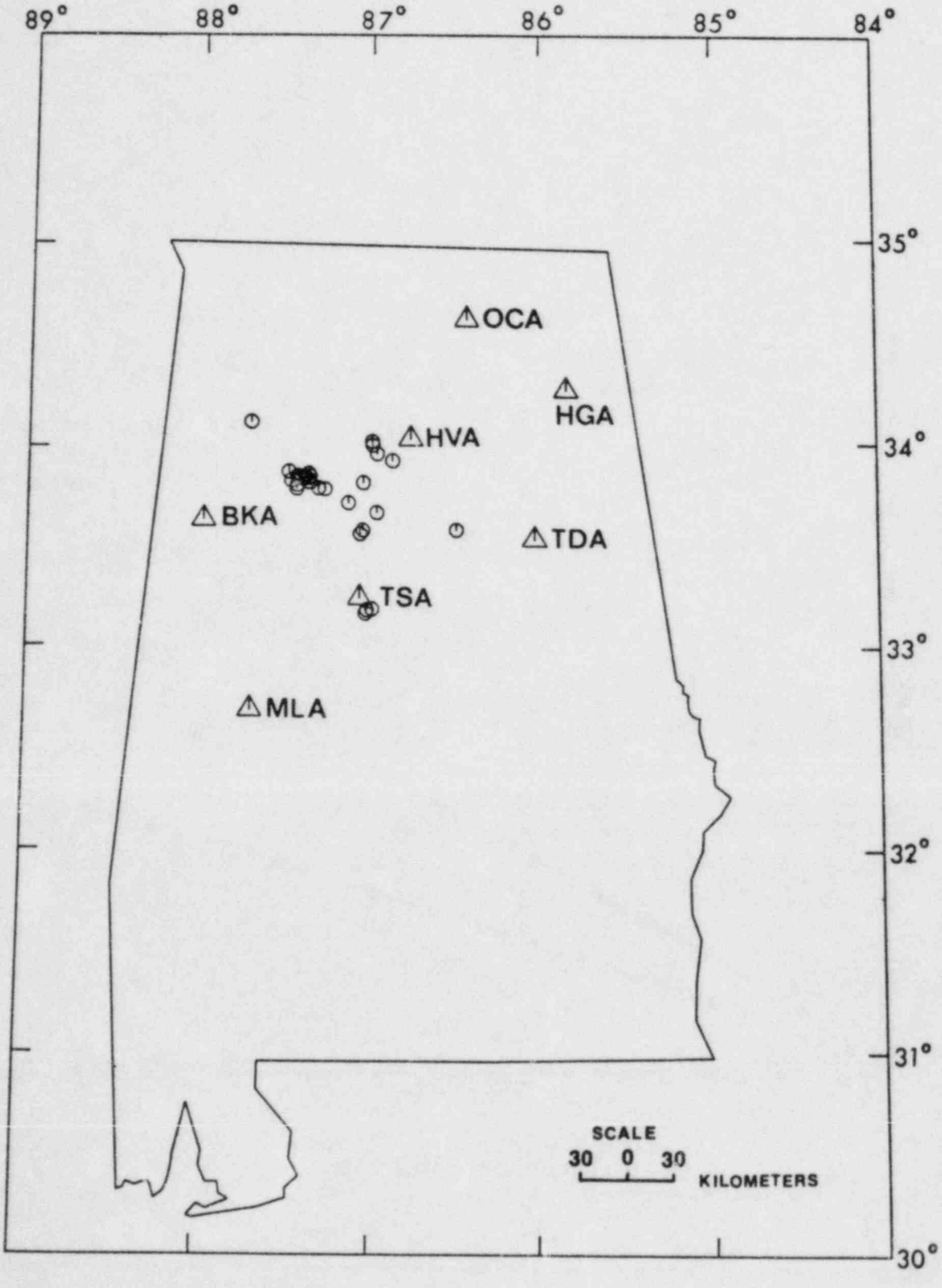


Figure I-2. Locations of the blasts

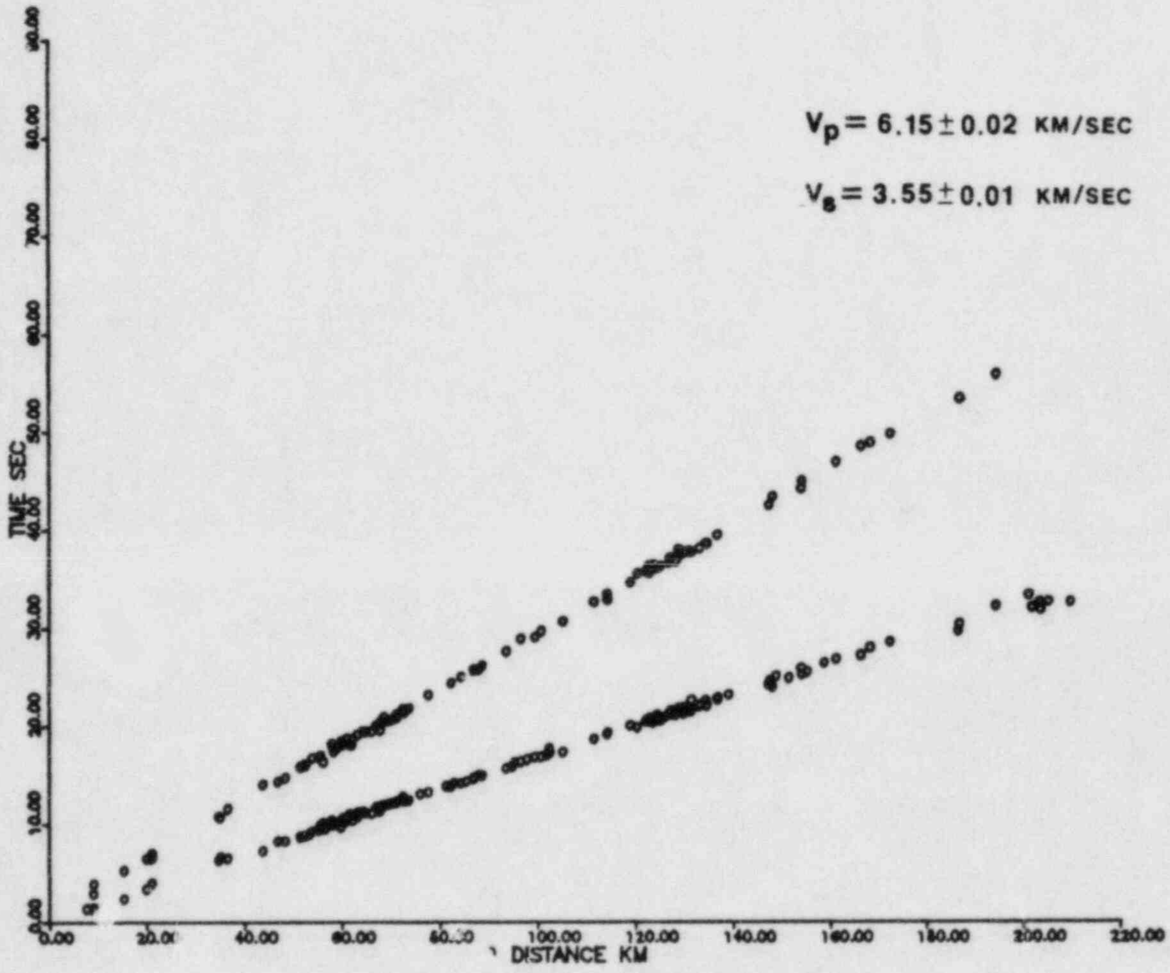


Figure I-3. Observed travel time curve.

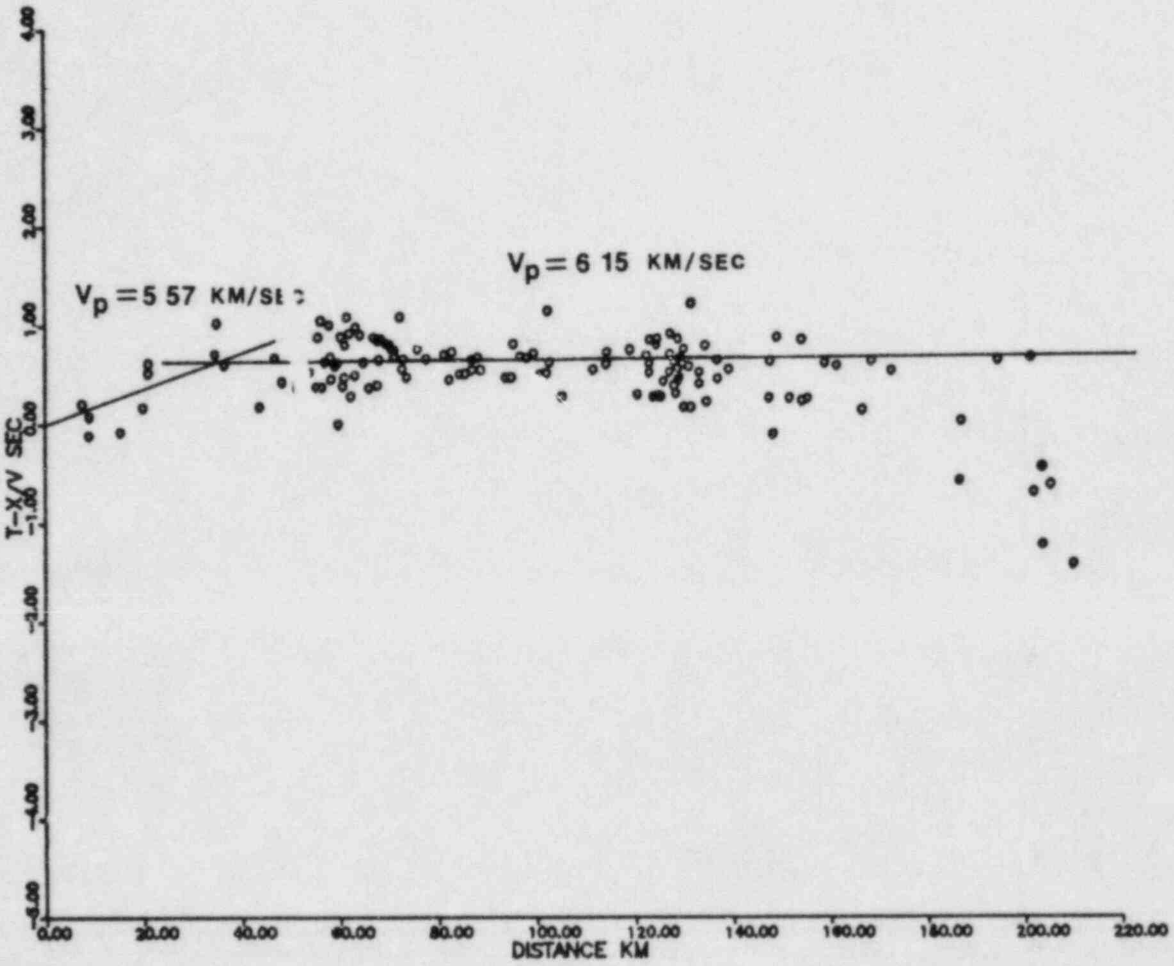


Figure I-4. Reduced travel time curve of P wave.

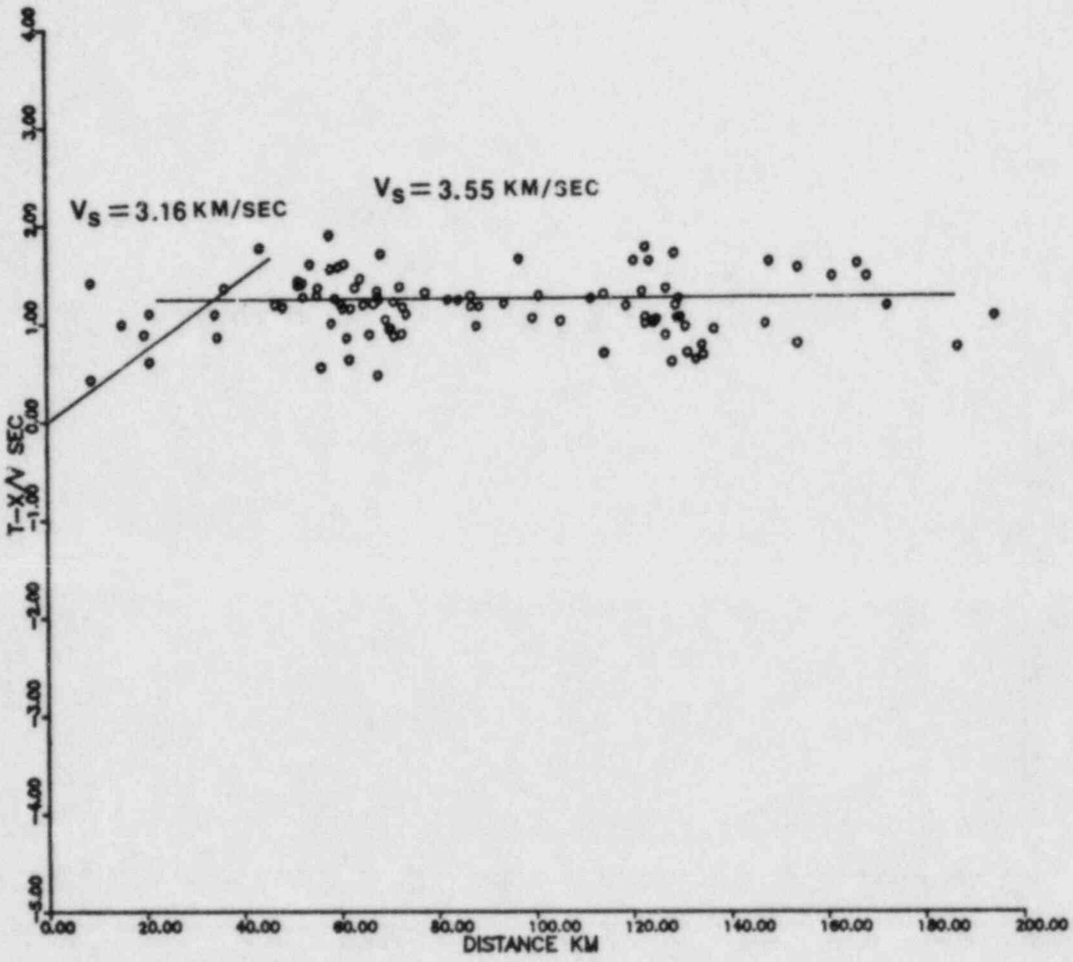


Figure I-5. Reduced travel time curve of S wave.

limited and scattered, a change of slope at 35 km is clear. From 35 km to 160 km, the data points for the S wave are more scattered than that of the P wave, but both trends go horizontally, which indicate the uniformity of the velocities within this range (V_p = 6.15 km/sec and V_s = 3.55 km/sec). For those few data points over 160 km, the decrease of slope indicates the existence of a higher velocity layer at depth. This increase in velocity is related to the lower crust and/or the Moho discontinuity. The study of the Pn phase was not an immediate objective of this report.

From the crossover at 35 km and the P-wave velocities of the sedimentary layer and the crust, an approximate thickness of sedimentary layer is estimated to be 4.0 km (12,000 ft). The 4.0 km depth agrees with the basement map of North America (Flawn et al., 1967), which shows the depth of basement rock in northern central Alabama to be between 4 and 5 km (12,000 and 16,000 feet), but may not be consistent with recent data from wells. The depth to basement will be considered in more detail in future studies.

3. Station Corrections

The mean residuals of P-wave arrivals at each station were obtained from the relocation of each event. The residuals for each event are listed in Table I-2. The largest mean residuals are -0.149 sec for HGA and +0.100 sec for HVA. The remaining are less than our reading error, estimated to be ±0.1 sec, therefore the station corrections are insignificant; however, we applied these to the data for subsequent analysis. The standard deviation of the residuals about the travel time curve is 0.25 sec.

4. Azimuthal Variation

An azimuthal variation of P-wave velocity is studied in this section using the travel time residuals. The average station corrections, though considered small, are subtracted from each residual to remove any possible station bias in the azimuthal distribution.

The reduced P wave residuals (Table I-3) are plotted versus azimuth of direction of propagation (Figure I-6). To reduce the scatter, we take an average of those points over 22.5 degree increments, and thus reduce the whole set of data to 16 points (Figure I-7). A north-south variation of residuals is observed. The average residual is -0.14 second at an azimuth of zero (north), increases gradually to 0.13 second at 180° (south). Though the residuals variation is small, the residuals still imply a trend of azimuthal variation of the P-wave velocity. Applying a Fast Fourier Transform (FFT) to these 16 points (Figure I-8), the highest peak appears at one cycle, which again supports the north-south variation of the velocity. The amplitude for two cycles is small indicating that the effect of anisotropy, if present, is less than the measuring uncertainty of 0.1 sec.

Table I-2. Residuals of P wave for each event in seconds. For station locations, see Figure I-1.

EVENT NO	TSA	TDA	HVA	HGA	OCA	MLA	BKA
1			0.081		-0.068	-0.004	
2			-0.201		0.102	0.238	
3	-0.133		-0.127		0.153		
4	-0.047		-0.034	-0.098	0.146		
5	0.057		-0.183		0.006		
6		-0.028	-0.095		0.002	-0.005	
7	0.292	-0.301	0.320		-0.331	-0.084	
8	0.353	0.126	0.475		-0.319	0.034	
9	-0.069		-0.184		0.090		
10	-0.102	0.182	0.338		-0.334	0.051	
11	0.115	-0.033	-0.376				
12	0.175	0.611	-0.288	-0.365	0.256	-0.222	0.067
13	0.249		-0.201	-0.367	0.257	0.200	-0.215
14	0.125		-0.176		0.252	-0.136	
15	-0.175		0.026	-0.728	-0.087	0.305	
16	0.523		-0.030		-0.304	-0.173	
17	0.070	-0.080	-0.107	-0.032	-0.484	0.157	
18	0.054	0.232	0.326	-0.384		0.129	-0.066
19	0.514		-0.107	0.014		-0.444	0.238
20	0.231		-0.570	0.258		-0.047	0.052
21	0.192		-0.364	0.563	0.075		
22	0.159	0.096	0.439		-0.443		
23	0.183	0.027	0.123	-0.351			
24	0.281	-0.202	0.311				-0.230
25	-0.130	0.030	0.119				
26	-0.090	0.084	-0.113				
27	-0.284	-0.081			0.003	0.122	
28	-0.017	-0.090	0.417		-0.325	-0.176	0.483
29	0.088	-0.153	0.084		0.072		-0.196
30	0.083	-0.065			0.096		-0.207

Table I-3. Reduced residuals of P wave for each event in seconds. For station locations, see Figure I-1.

EVENT NO	TSA	TDA	HVA	HGA	OCA	MLA	BKA
1			0.084		-0.014	-0.001	
2			-0.198		0.156	0.241	
3	-0.233		-0.124		0.207		
4	-0.147		-0.031	0.051	0.200		
5	-0.043		-0.180		0.060		
6		-0.049	-0.092		0.056	-0.002	
7	0.192	-0.322	0.323		-0.277	-0.081	
8	0.253	0.105	0.478		-0.265	0.037	
9	-0.169		-0.181		0.144		
10	-0.202	0.161	0.341		-0.280	0.054	
11	0.015	-0.054	-0.373				
12	0.075	0.590	-0.285	-0.216	0.310	-0.219	0.075
13	0.149		-0.198	-0.218	0.311	0.203	-0.207
14	0.025		-0.173		0.306	-0.133	
15	-0.275		0.029	-0.579	-0.033	0.308	
16	0.423		-0.027		-0.250	-0.170	
17	-0.030	-0.101	-0.104	0.117	-0.430	0.160	
18	-0.046	0.211	0.329	-0.235		0.132	-0.058
19	0.414		-0.104	0.163		-0.441	0.246
20	0.131		-0.567	0.407		-0.044	0.060
21	0.092		-0.361	0.712	0.129		
22	0.059	0.075	0.442		-0.389		
23	0.093	0.006	0.126	-0.202			
24	0.181	-0.223	0.314				-0.222
25	-0.230	0.009	0.122				
26	-0.190	0.063	-0.110				
27	-0.384	-0.102			0.057	0.125	
28	-0.117	-0.111	0.420		-0.271	-0.173	0.491
29	-0.012	-0.174	0.087		0.126		-0.188
30	-0.017	-0.086			0.150		-0.199

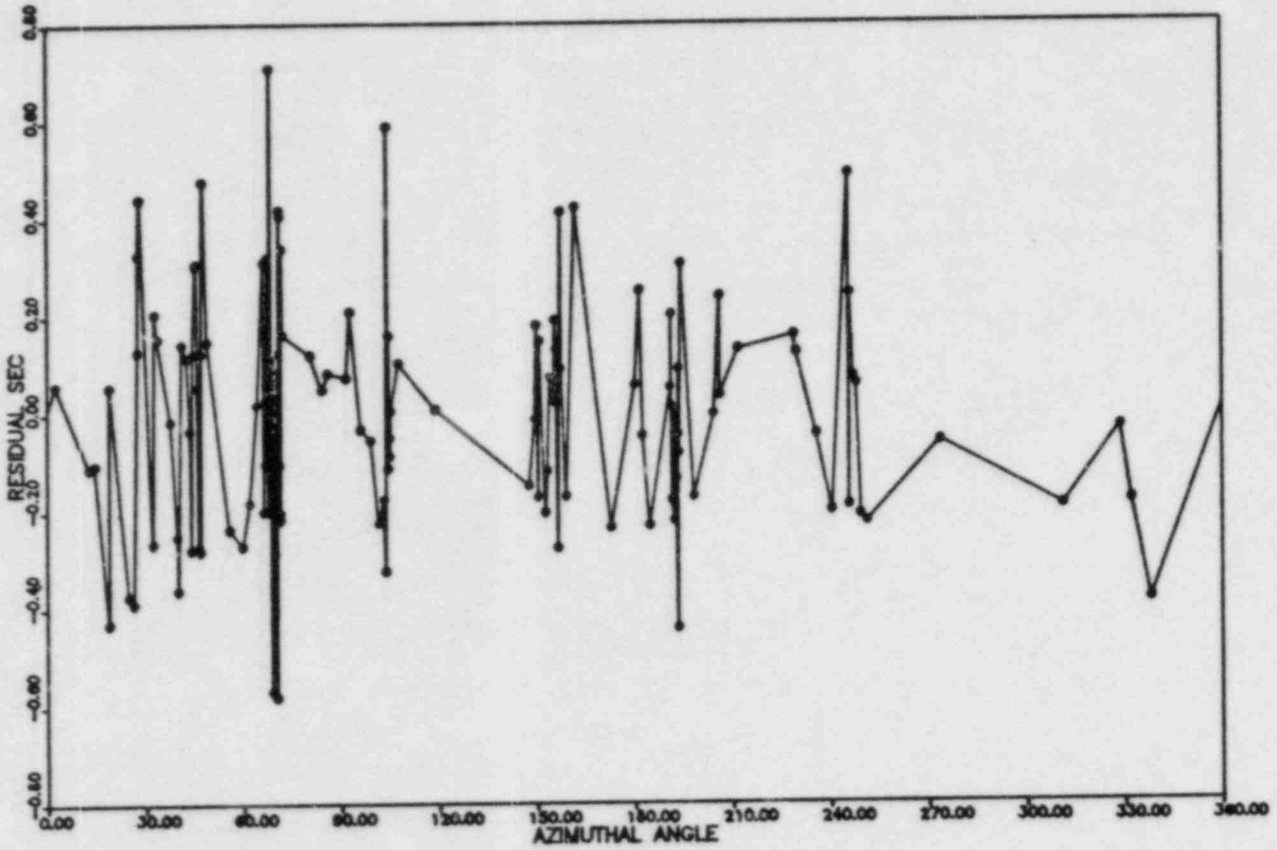


Figure I-6. Reduced P-wave residuals versus azimuth of direction of propagation.

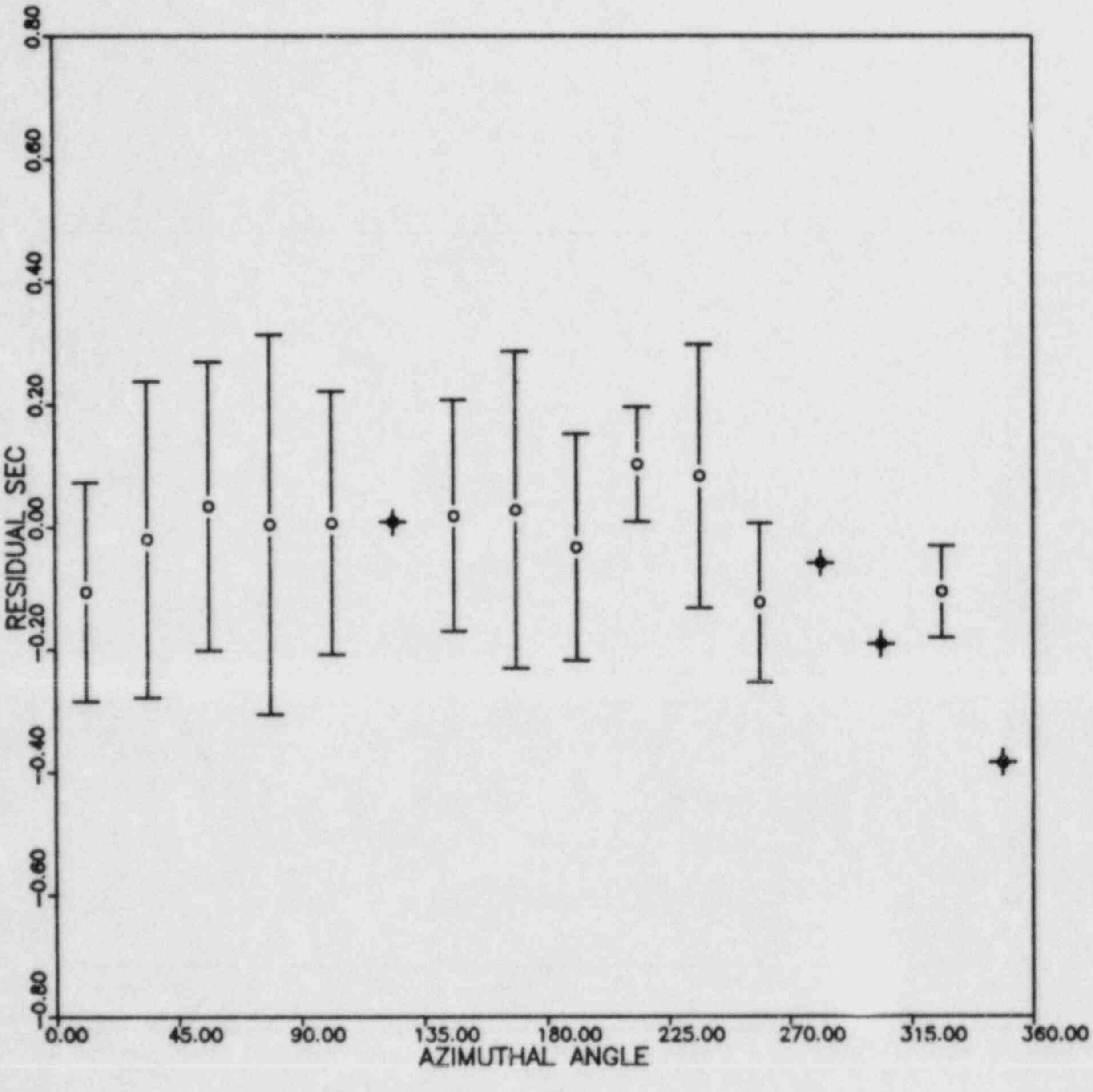


Figure I-7. Reduced P-wave residuals average every 22.5 versus azimuth.

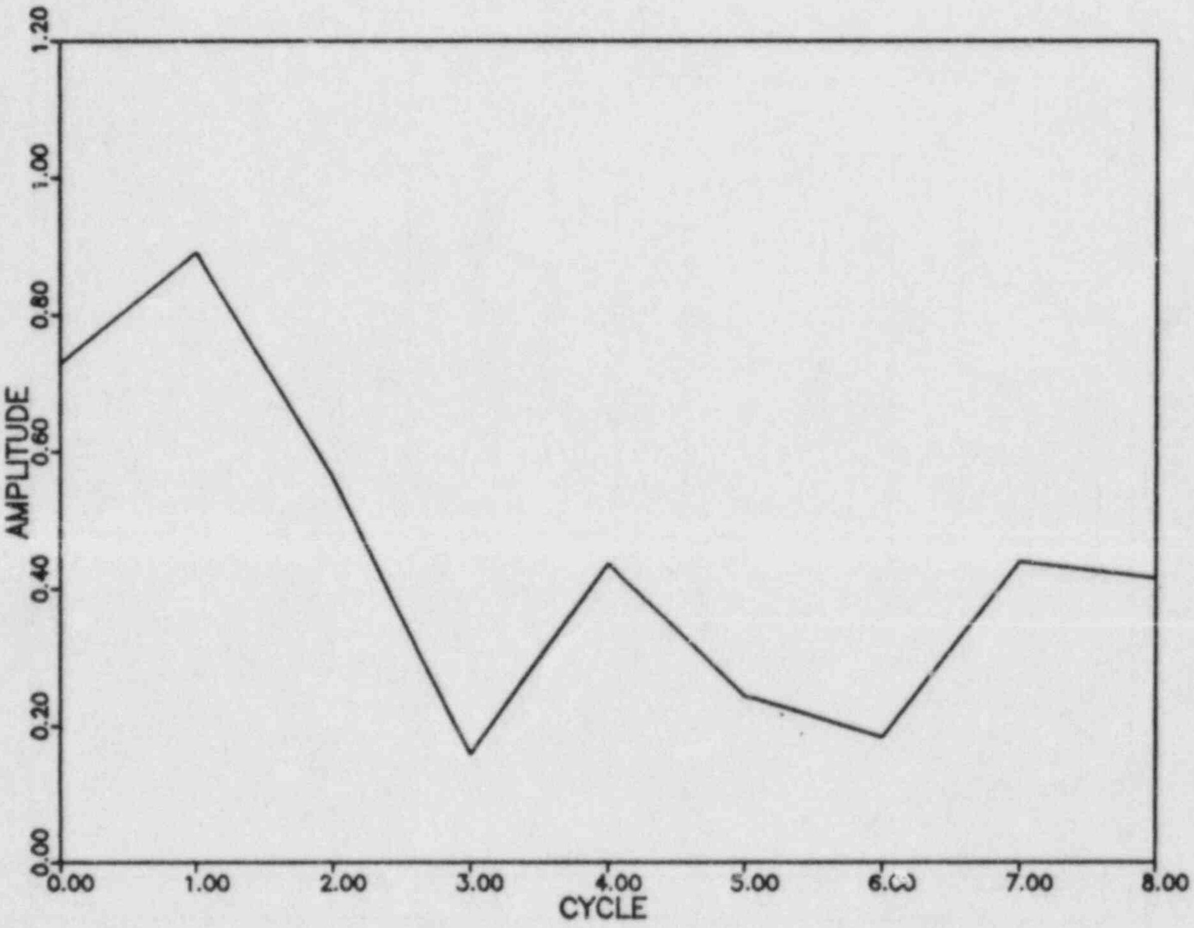


Figure I-8. Reduced P-wave residuals after FFT.

5. Crustal Structure and Depth of Penetration

Our data show good arrivals from the upper crust (velocity 6.15 km/sec). At 160 km, the data (Figure I-4) show some evidence for the Moho arrival. The data allow two possible models of the crust for northern central Alabama. Both models show a 4-km deep Paleozoic sedimentary layer of average P-wave velocity 5.57 km/sec overlying the upper crust. The first model has an upper crust continuously varying P-wave velocity extending down to 35 km. The gradient of the P-wave velocity in the crust is 0.01 sec^{-1}. The Moho discontinuity is given at depth of 35 km with an average P-wave velocity of 8.10 km/sec underneath (Figure I-9). The theoretical reduced travel time curve is superimposed on the observed travel time data (Figure I-10). The second model is similar to the first model except a hypothetical lower crustal layer of higher velocity is inserted at a depth of 20 km and extends down to the Moho discontinuity at 35 km deep (Figure I-11). The model assumes a maximum thickness allowed by the data which show no first arrivals from this layer. Figure I-12 shows the theoretical reduced travel time curve superimposed on the observed travel time data. Several other models have been tried, but either a shallower lower crustal layer or a shallower Moho discontinuity will show a crossover at a horizontal distance of less than 160 km on the travel time curve. This does not fit the observed travel time data, on which a crossover at 160 km is shown.

From the theoretical travel time curve, a maximum depth of penetration of rays can be calculated by using Wiechert-Herglotz-Bateman integration. For a ray that travels 160 km in horizontal distance, the depth of penetration is 10 km. The result is the same for both kinds of models. Because the velocity structure of the lower crust is not defined by this data, we need P-wave arrivals at greater distance and Pn-wave arrivals.

Discussion and Conclusions

The southern Appalachian seismic zone terminates in central Alabama and extends beneath the sediments of the Gulf Coastal Plain. The velocity structure is uniform in this area. No major discontinuity in seismic velocity is found except the sediment-basement boundary. An average of 12,000 feet of sediments is confirmed by seismic data. Surface waves are seen on several stations, especially OCA; this also suggests a considerable thick layer of sediments.

Station corrections are not necessary for each station. The azimuthal variation of P wave travel time can be explained by thickening of the sediments toward the south. No anisotropy was observed in the crust.

The data allow two possible crustal models for northern central Alabama. The first layer, consisting of Paleozoic sediments, is 4 km thick with a P-wave velocity of 5.57 km/sec or lower and a S-wave

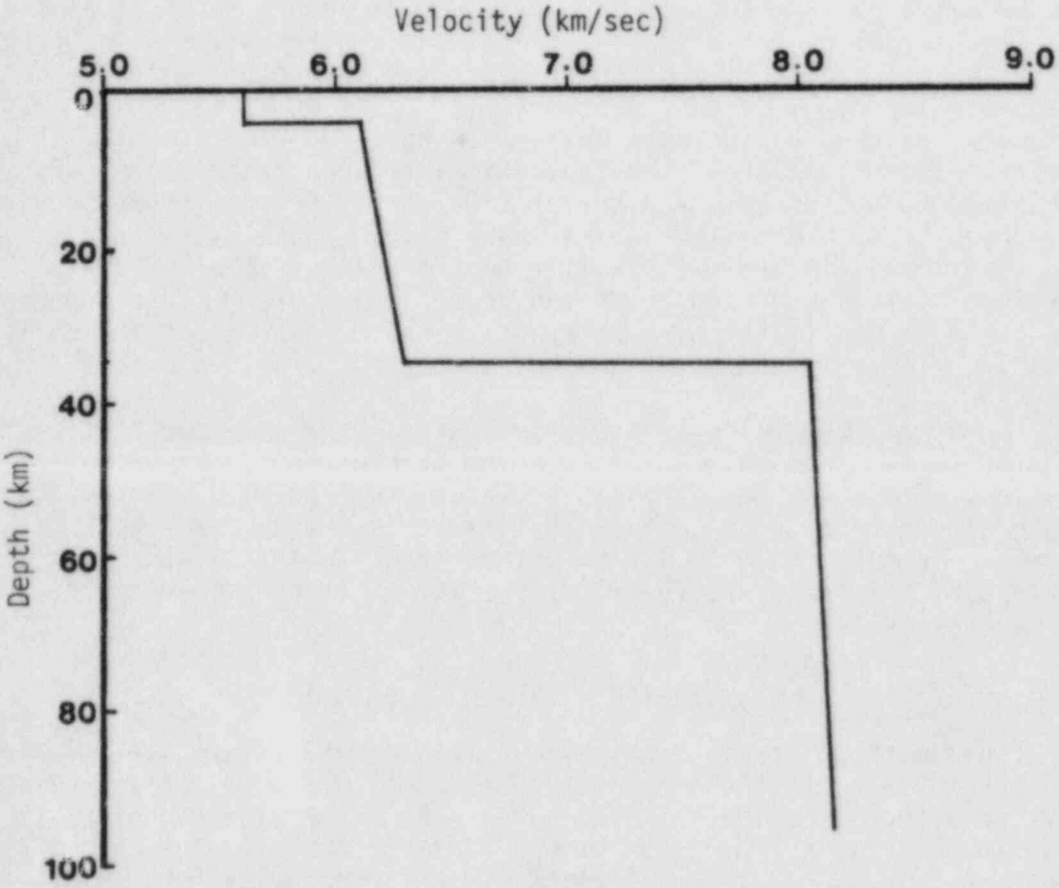


Figure I-9. Crustal model 1.

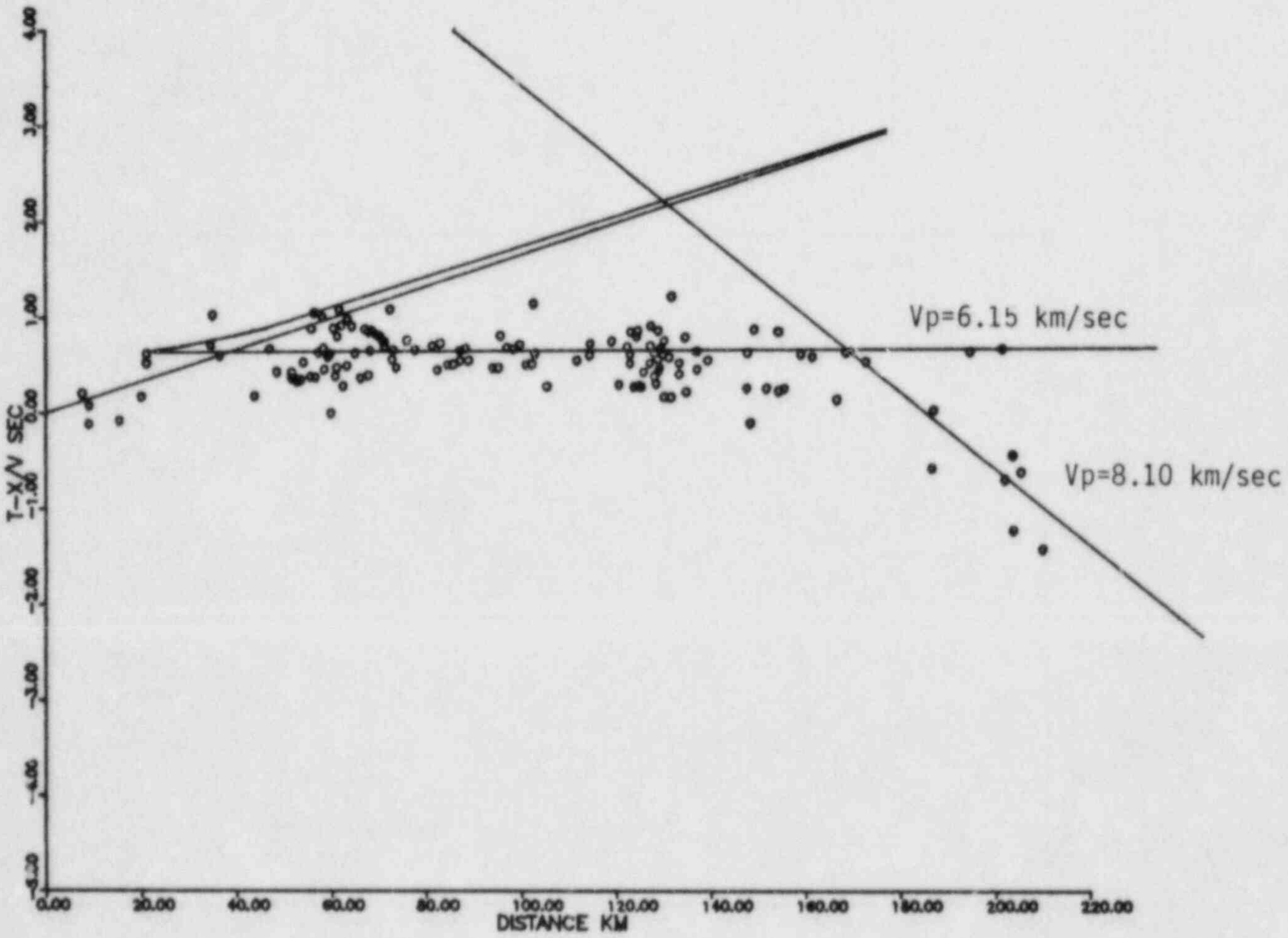


Figure I-10. Calculated travel time curve based on model 1. This is the preferred model from our data.

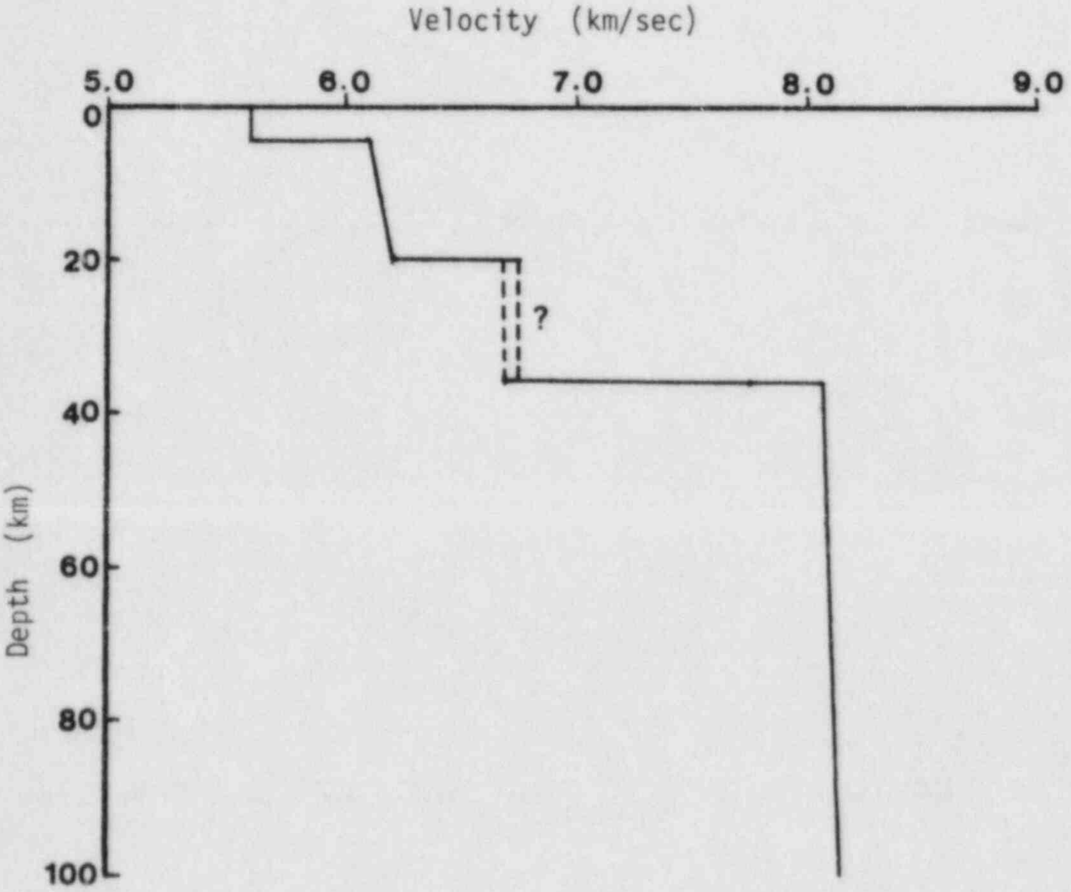


Figure I-11. Crustal model 2.

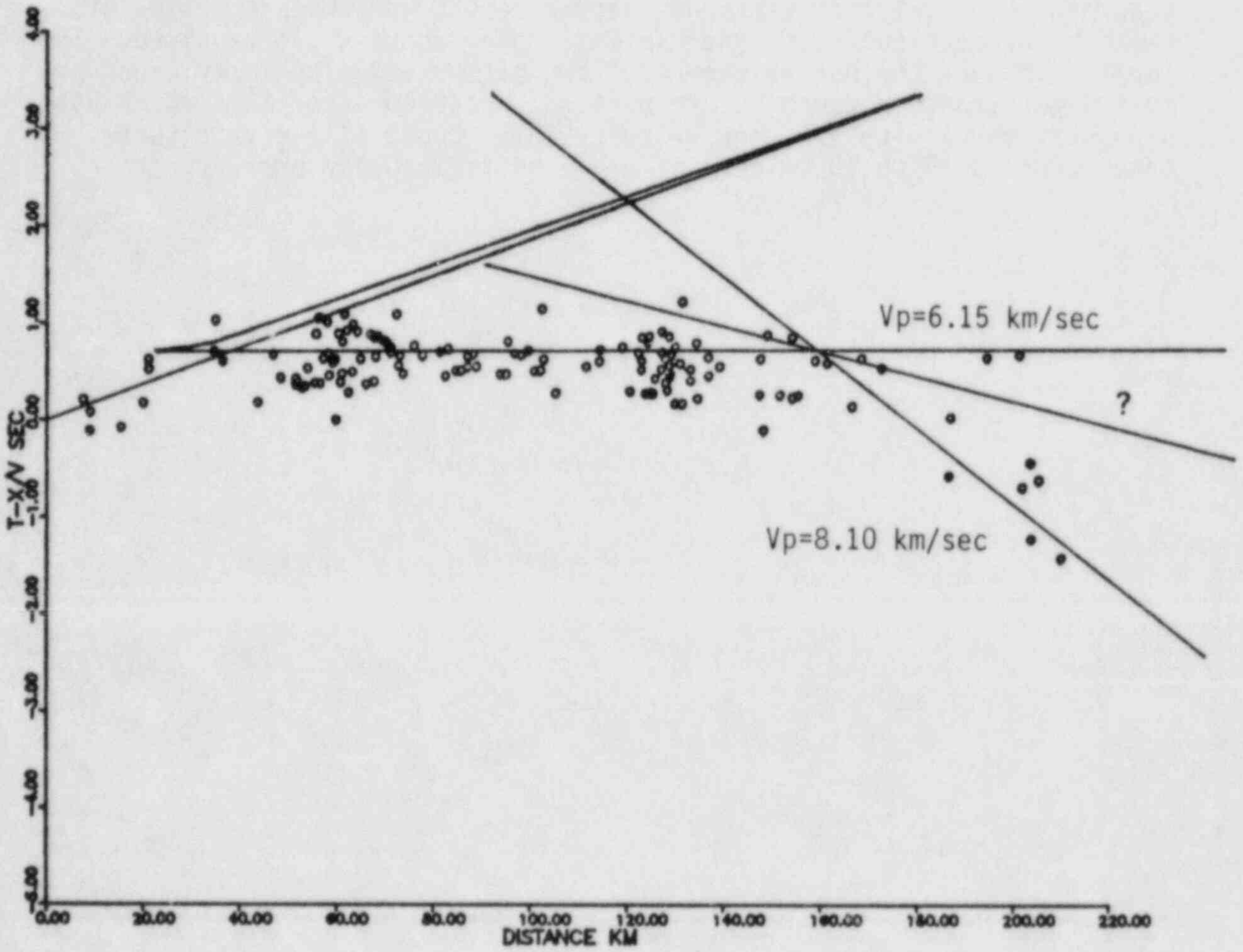


Figure I-12. Calculated travel time curve based on model 2. The 6.70 km/sec layer is inserted to find the minimum depth of its existence, but it is not confirmed from our data.

velocity of 3.16 km/sec. The second layer begins at 4 km depth with a linearly varying P-wave velocity. This is the major part of the upper crust. The average P-wave velocity and S-wave velocity are 6.15 km/sec and 3.55 km/sec for this layer. The Moho discontinuity is at least 35 km deep. A layer with higher P-wave velocity in the lower crust, though it has been observed in some other places in the southeastern United States (Tatel *et al.*,1953; Steinhart and Meyer, 1961; Borcherdt and Roller, 1966), cannot be confirmed from our travel time data. If it exists, the depth of this layer will not be shallower than 20 km. To determine how velocity varies at deeper depths and the properties of the Moho discontinuity, further seismic observatories are required. The implications of the non-existence of the higher velocity lower crust are most significant in depth determination. Location algorithms which use a crustal model with a higher velocity lower crust will give a false convergence at 5 to 15 km deep if no layer is actually present.

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The Georgia Tech-Geological Survey of Alabama Seismic Network has been in operation in Alabama since April 1981 and in southeast Tennessee since April 1982. During this time 83 events have been located. In Alabama, the distribution of epicenters generally confirms a broad northeast-southwest trend and a north-south trend. In southeast Tennessee, four trends running approximately east-west were noted. Few focal depths have been obtained; those that have lie between 9 and 15 km in the Greenville basement below the Paleozoic Valley Ridge sediments. Cumulative frequency-magnitude plots using m_b(Lg) estimated from duration indicate a slope of 0.65 in southern Tennessee; this is consistent with the Alabama data. Events tend to be closely paired in space and time (within one day). A preliminary determination of crustal structure in Alabama is presented in Appendix 1. The average crustal velocities observed are 6.15 km/sec for P waves and 3.55 km/sec for S waves with an average crustal thickness of 35 km. Conclusive evidence of a high velocity layer in the crust has not yet been found.

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