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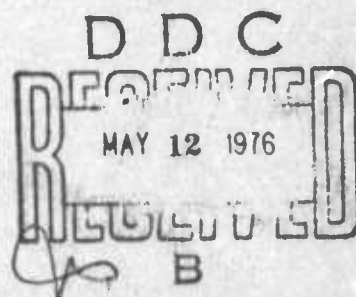# TECHNICAL REPORT NO. 74-16
S/P TRAVEL TIME RATIO IN CENTRAL ASIA

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NOVEMBER 1974

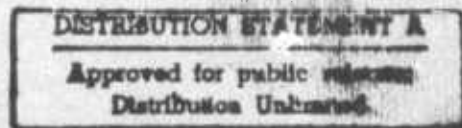ANNUAL REPORT FOR PERIOD 1 OCTOBER 1973 – 30 JUNE 1974

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TELEDYNE GEOTECH

S/P TRAVEL TIME RATIO IN CENTRAL ASIA

by

Jack G. Swanson

ABSTRACT

The S/P travel time ratio for intermediate depth Hindu-Kush earthquakes and shallow earthquakes in the Hindu-Kush, Pamir, and Tien Shan regions is investigated, using S and P arrival times at 6 World Wide Standard Seismograph Network stations and 19 other close-in stations.

For intermediate depth earthquakes, station mean values of the ratio average 1.78, ranging from 1.76 to 1.81. The ratio increases slowly with increasing distance over the range 4.5 to 13 degrees and increases rapidly with decreasing distance for distances less than 4.5 degrees. Variation of the ratio with focal depth is weak. The standard deviation of S/P origin time deviations from origin times based on locations restrained to pP depth is about 0.8 second, implying a standard deviation of S/P depth error, relative to pP depth, of about 8 km. S/P depths of 8 intermediate depth earthquakes, relocated with origin time restrained to the value determined from close-in P and S arrival times and regional mean S/P travel time ratios, were all within 7 km of the pP depths.

For shallow earthquakes, station mean values of the S/P travel time ratio average 1.78, ranging from 1.75 to 1.83. For the distance range 6.5 to 14 degrees, variation of the ratio with distance is weak, and for distances less than 6.5 degrees the ratio increases with decreasing distance. The S/P travel time ratio increases with increasing focal depth, the depth dependence being stronger at closer distances. The standard deviation of S/P origin time deviations from pP origin time is about 1.2 second for shallow earthquakes, implying a standard deviation of S/P depth error, relative to pP depth, of about 9 km. S/P depths for 12 of 15 shallow earthquakes relocated with origin time restrained to the value determined from S and P arrival times and regional mean S/P travel time ratios were within 9 km of the pP depths.

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TECHNICAL REPORT NO. 74-16

S/P TRAVEL TIME RATIO IN CENTRAL ASIA

by

Jack G. Swanson

Sponsored by

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REPORT SUMMARY

Estimation of focal depths for earthquakes occurring in the Hindu-Kush, Pamir, Tien Shan region of central Asia has been studied through development of refined S/P travel time ratios from Wadati graph analysis of data for nearby stations. A mean of 1.78 was determined for the ratio; however, the value of the ratio varies systematically with epicentral distance and focal depth, ranging from 1.75 to 1.83. Relative to depths based on the pP phase, the standard deviation of depths estimated from S/P ratios is 9 km for shallow earthquakes and 7 km for intermediate depth earthquakes.

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S/P TRAVEL TIME RATIO IN CENTRAL ASIA

1. INTRODUCTION

This report constitutes the annual report on work accomplished from
01 October 1973 through 30 June 1974, on the investigation of the use
of close-in P and S arrivals to determine focal depth of seismic events
in central Asia. An empirical calibration of the S/P travel time ratio
for intermediate depth earthquakes in the Hindu-Kush source and shallow
earthquakes in the Hindu-Kush, Pamir, and Tien-Shan regions observed at
stations within 14 degrees of the source is presented. The report
includes an evaluation of the importance of depth and distance depend-
ence of the S/P travel time ratio.

In section 2, the basic background of the methods used is briefly discussed.
The use of the ratio of S to P travel times to determine origin time and
depth of focus, together with the calibration of close-in stations, is
presented. The use of Wadati graphs (Wadati, 1933, Kisslinger and Engdahl,
1973) to determine variations in the ratio of P to S velocity with depth
and distance is also described. The data used in the study are described
in section 3. In section 4, the calibration of close-in stations for the
S/P travel time ratio is described and in section 5, the distance and
depth dependence of the S/P travel time ratio is discussed. Results of
applying the technique to locate an independent set of earthquakes are
described in section 6.

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2.   BACKGROUND

The modified Geiger method (Macelwane and Sohon, 1932) commonly used to locate earthquakes yields more accurate focal depths if origin times are known independently of the P arrival times used to make the location (Evernden, 1969, Swanson, 1969, 1971, Kisslinger and Engdahl, 1973). An origin time [T(S/P)] can be computed from S and P arrival times at a single station if the ratio of S to P travel times is known for the path from hypocenter to station.

$$T(S/P) = P - (S-P)/r \qquad\qquad (1)$$

$$\text{where } r \equiv (\tau_s/\tau_p) - 1$$

$$\tau_s \equiv S \text{ travel time}$$

$$\tau_p \equiv P \text{ travel time}$$

$$S \equiv S \text{ arrival time}$$

$$P \equiv P \text{ arrival time}$$

$$T(S/P) \equiv \text{origin time estimated by the S/P technique}$$

Depth is then estimated by a routine location procedure with origin time restrained to T(S/P).

To calibrate a station for a region, the travel time ratio is determined for a set of events whose origin times are known to high accuracy. For earthquakes, the origin time from a location with depth restrained to the value determined from pP-P intervals and/or other depth phase information is normally used. Then r may be obtained from:

$$r = (S-P)/[P-T(pP)] \qquad\qquad (2)$$

$$\text{where } T(pP) \equiv \text{origin time from location with depth}$$
$$\text{restrained to pP depth}$$

An estimate of the error in depth which results from an error in the estimate of the origin time may be made by means of hypocenter control factors (Veith and Van Leer, 1970). The depth control factor for a given station is defined as the change in depth estimate resulting from a one second residual at the station. For the ideal case of a symmetrical net, so there is no interaction between epicenter and depth estimates, the depth control factor for station i is given by

$$(\text{depth control factor})_i = \frac{(\partial t/\partial h)_i}{\sum_i (\partial t/\partial h)_i^2}$$

-2-

The change in depth (dh) is given by

$$dh = \frac{\sum\limits_{i}(\partial t/\partial h)_i u_i}{\sum\limits_{i}(\partial t/\partial h)_i^2}$$

where $u_i \equiv$ travel time residual at station i

If origin time is restrained to an erroneous value ($T' = T + \delta T$), then

$$dh' = \frac{\sum\limits_{i}(\partial t/\partial h)_i\ (u_i - \delta T)}{\sum\limits_{i}(\partial t/\partial h)_i^2}$$

or

$$dh' = dh + \frac{\sum\limits_{i}(\partial t/\partial h)_i}{\sum\limits_{i}(\partial t/\partial h)_i^2}\ (-\delta T)$$

Therefore, the error in depth (δh) resulting from an error in origin time (δT) is given by

$$\delta h = \frac{\sum\limits_{i}(\partial t/\partial h)_i}{\sum\limits_{i}(\partial t/\partial h)_i^2}\ (-\delta T)$$

As a rule of thumb, for a good network of stations (Swanson, 1969):

$$\delta h \simeq \frac{-\ \delta T}{(\delta t/\partial h)_{\overline{\Delta},h}} \tag{3}$$

where $\overline{\Delta} \equiv$ mean distance of locating net.

An estimate of the error in origin time due to an error in r may be obtained from a simple differentiation of equation 1. It is

$$\delta T = \frac{S - P}{r^2}\ \delta r \tag{4}$$

-3-

where $\delta T \equiv$ origin time error

$\delta r \equiv$ error in r

For typical values of r (about 0.78), a 1 second origin time error will arise from a 3 percent error in r for a station near a distance of 2 degrees (S-P ≈ 25 seconds). If the station distance is about 9 degrees (S-P ≈ 100 seconds), a 1 second error will arise from an error of only 0.8 percent in r. Thus, the required accuracy in r for a specified origin time accuracy increases rapidly with increasing distance. This analysis assumes that the S-P interval is known without error. In practice, the arrival time of the S phase may be quite uncertain either because of difficulty in timing the start of the phase or because of misidentification of the phase.

Because the S/P velocity ratios may vary from layer to layer within the crust and vary in general in the mantle, the observed S/P travel time ratios must also vary in accordance with the velocity structures traversed by the ray paths. It is expected, therefore, that the S/P travel time ratios will vary with epicentral distance and focal depth. If S and P arrival times are available at several close-in stations, Wadati graph analysis (Kisslinger and Engdahl, 1973, Wadati, 1933), where S-P time is plotted as a function of P travel time, may be used to determine the variation of S/P with depth and an estimate of the effect on r can be determined.

Considering Wadati graphs for shallow earthquakes, if the structure of the region can be approximated by a horizontal layering with constant P and S velocities in each layer, the Wadati graph slope (ρ) should be constant for each layer. The P travel time intercept (τ) should be a piecewise linear function of focal depth with the parameters of the function τ(h) depending on the layer in which the earthquake focus lies. The intercept, τ, will be zero only if the ratio of P to S velocity is constant along the path from hypocenter to station (Kisslinger and Engdahl, 1973). Regional variation of crustal and upper mantle velocities or variation of crustal thickness will, of course, complicate the analysis and reduce the reliability of results.

For each segment of the Wadati graph,

$$S - T_o = a_s + \frac{\Delta}{v_s} \tag{5}$$

$$P - T_o = a_p + \frac{\Delta}{v_p}$$

-4-

where $T_0 \equiv$ origin time

a_s and $a_p \equiv$ S and P travel time curve intercepts, respectively

$\Delta \equiv$ distance, and

v_s and $v_p \equiv$ respective P and S velocities at the ray bottom.

Then

$$S-P = [a_s - a_p \, (\rho + 1)] + \rho \, (P-T_0)$$

where $\rho \equiv v_p/v_s - 1$, the Wadati graph slope

or

$$S-P = \rho \, [P - (T_0 + \tau)] \tag{6}$$

where $\tau = - \dfrac{1}{\rho} [a_s - a_p \, (\rho + 1)]$, the $P-T_0$ intercept.

For intermediate depth earthquakes, P and S travel times are approximately linear at distances near the inflection point of the travel time curves. Kaila (1969) and Kaila, Krishna, and Narain (1969) estimated P and S velocities as a function of focal depth for earthquakes in the Hindu-Kush intermediate depth source, using time-distance plots for distances near the inflection point. Because the ray parameter changes very slowly over this range of distance, the ray parameter may be estimated from the slope of the travel time curve in this region. From Bullen (1963, p. 109),

$$P = \frac{R \sin i}{v} \tag{7}$$

where $p \equiv$ ray parameter and the slope of the travel time curve

$R \equiv$ distance from the center of the earth to any point on a ray path

$i \equiv$ the angle of incidence of the ray path at that point, and

$v \equiv$ either P or S velocity

The ray which arrives at the inflection point leaves the source horizontally so that $\sin i = 1$. If the depth is known from depth phases, the S and P velocities may be determined for the source depth. Noting that near the inflection point, the slope of the travel time curves is given by (7) instead of $1/v$, equations 5 become

$$S-T_0 = a_s + p_s \Delta$$

$$P-T_0 = a_p + p_p \Delta$$

-5-

so that

$$\rho = p_s/p_p - 1$$

For either shallow or intermediate earthquakes, the S/P travel time ratio (r) may be determined from equations 2 and 6.

$$r = \rho[1 - \tau/(P-T_o)] \qquad (8)$$

This equation describes the change in r to be expected as a function of P-T$_o$ and hence, distance. Because both τ and ρ are functions of focal depth, r can also be expected to vary with depth. Thus, the accuracy of origin times and resultant focal depths estimated by the S/P travel time technique will be limited by the sensitivity of ρ and τ to changes in focal depth.

-6-

3. DATA

P and S arrival times from 82 shallow (focal depth less than 50 km) and 41 intermediate depth (focal depth 85 - 290 km) earthquakes in the Hindu-Kush, Pamir, and Tien Shan regions recorded at 6 World Wide Standard Seismograph Network (WWSSN) stations and 21 other close-in stations were used as calibration data in this study. The calibration earthquakes occurred between 1964 and 1971. All had body wave magnitudes of 4.4 or greater and had previously been relocated with preliminary source-region/station time (SRST) corrections (Veith, 1973) with focal depth restrained to the value determined from pP-P intervals. These locations are considered to be the most reliable locations available for the calibration earthquakes. An additional 15 shallow and 8 intermediate depth earthquakes that occurred between 1968 and 1972 were used to test the accuracy of depths computed using the S/P travel time ratio. Locations of the calibration earthquakes and the test earthquakes are shown in figure 1, together with station locations that fall within the boundaries of the map. Boundaries of subareas defined for use in the analysis are also shown on figure 1. Table 1 lists the dates, origin times, and locations of the calibration earthquakes, ordered by subarea and by increasing focal depth within each subarea. Table 2 gives station codes, locations, and elevations of stations whose data were used in the study. In this table, WWSSN stations are indicated with an asterisk.

P and S arrival times at the 6 WWSSN stations were reviewed from film reproductions of their seismograms. Both P and S times were read from short-period seismograms whenever possible. In many cases, it was necessary to read the S arrival time from the long-period seismograms. Times were read to the nearest 0.1 second from the short-period seismograms and to the nearest 0.5 second from the long-period seismograms. P and S arrival times at the other close-in stations were taken from the bulletin of the International Seismological Centre (ISC) and the tri-monthly bulletin of the Moscow Academy of Sciences. In cases where times from the two bulletins disagreed for Russian stations, the arrival times were taken from the Moscow bulletin.

LEGEND

○ 0 < H ≤ 50
□ 50 < H ≤ 100
△ 100 < H ≤ 150
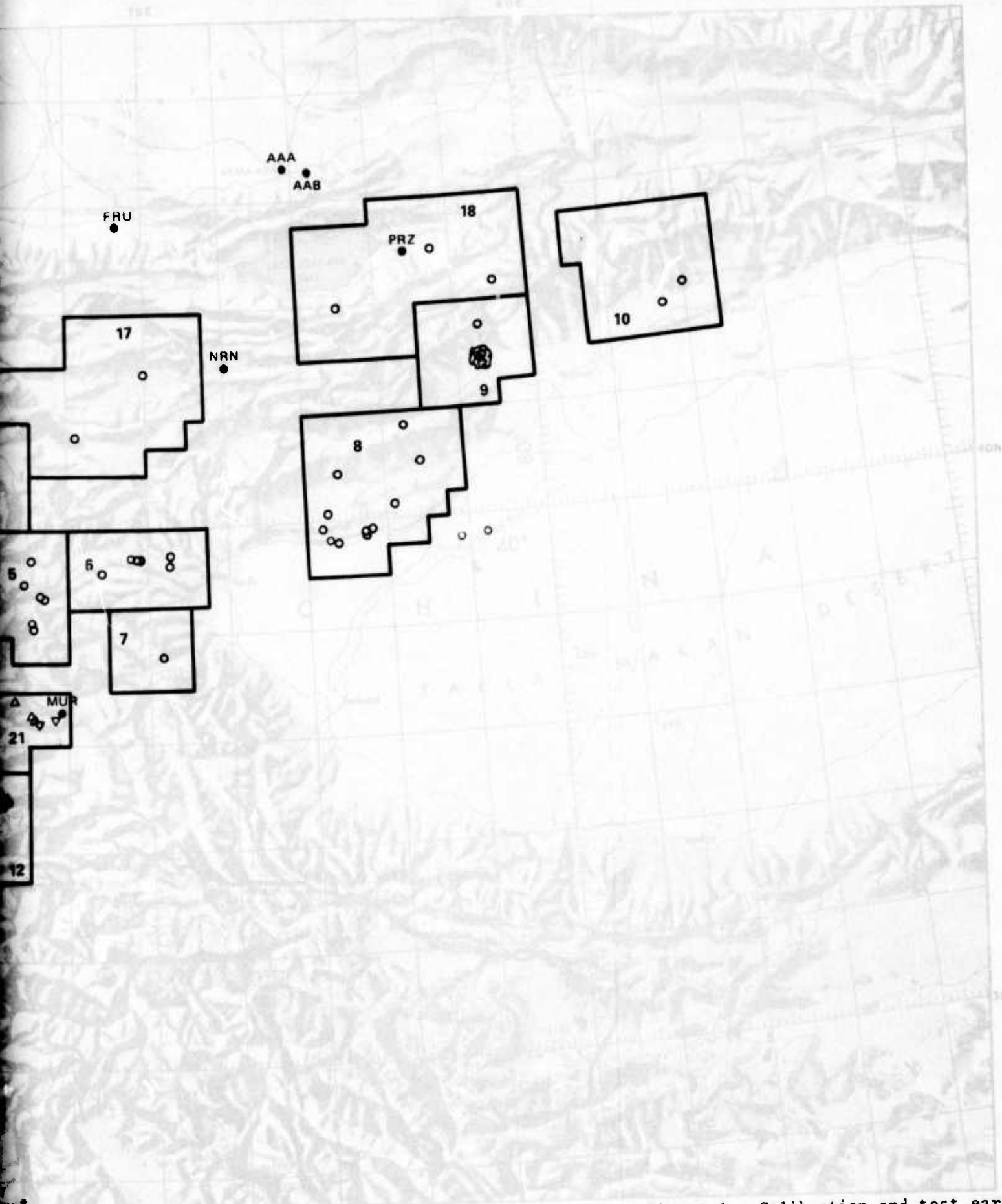▽ 150 < H ≤ 250
◇ 250 < H

○ CALIBRATION EVENTS
○ TEST EVENTS
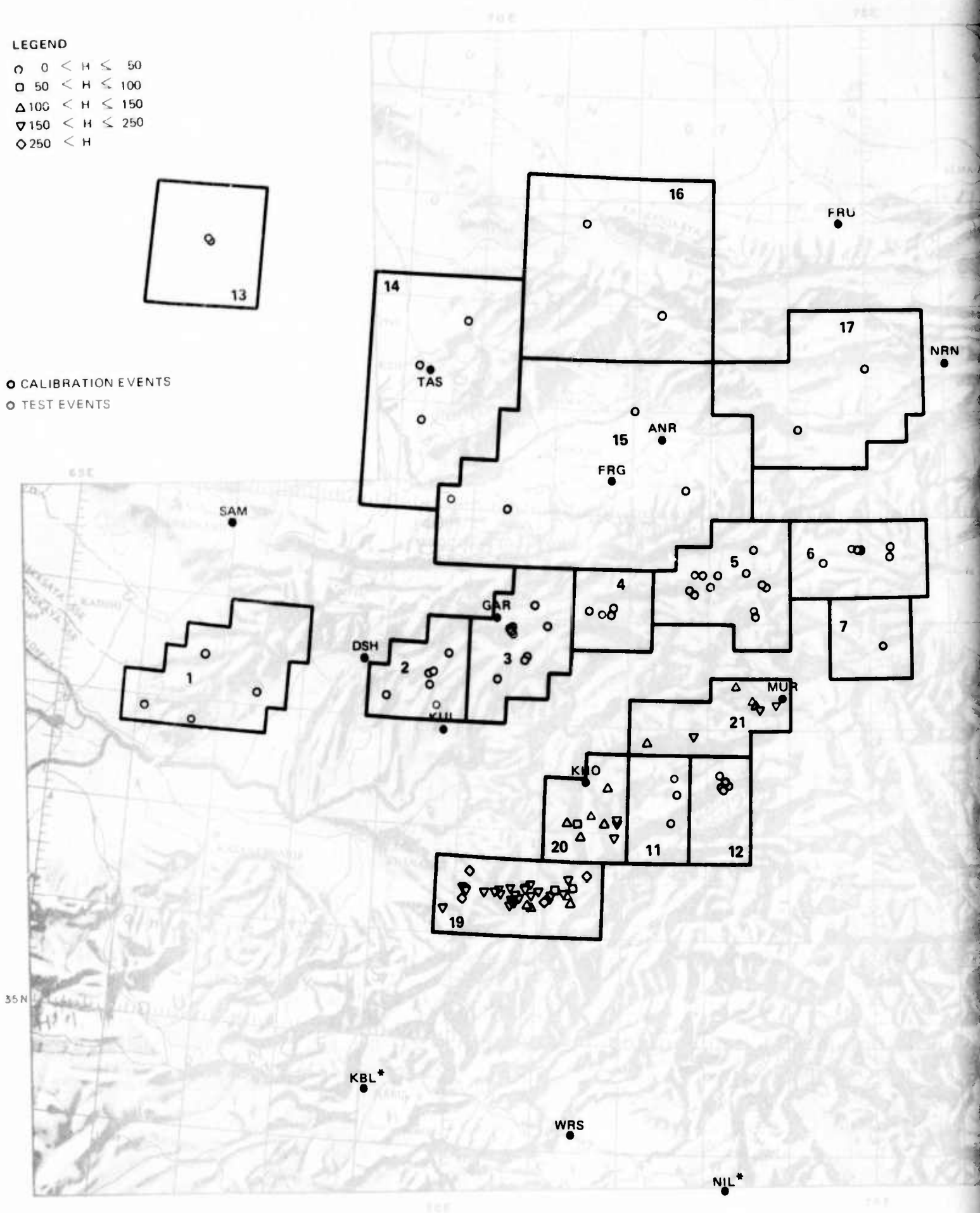
Figure 1. Calibration and test earthquakes

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Table 1. Calibration Earthquakes

SUBAREA	YR	DATE MO	DA	ORIGIN TIME HR:MIN:SEC	NORTH LATITUDE DEGREES	EAST LONGITUDE DEGREES	h(pP) km	m_b
1	66	12	22	12:29:59.8	37.93	66.11	10	4.7
	68	07	08	13:14:33.7	38.18	67.47	30	5.1
	71	11	18	07:31:36.1	38.37	66.72	35	5.2
2	71	05	27	00:30:26.0	38.22	69.02	7	4.8
	69	01	21	14:37:13.4	38.40	69.58	7	4.8
	69	09	20	14:07:55.4	38.50	69.63	8	5.1
	71	10	01	16:27:47.3	38.67	69.79	10	4.9
	66	08	10	22:05:39.4	38.45	69.58	14	5.2
3	66	04	11	16:42:53.1	38.94	70.59	3	4.7
	71	01	13	21:52:31.0	38.98	71.00	10	4.8
	66	04	14	21:06:17.6	38.91	70.58	14	5.1
	67	01	14	10:59:25.7	39.15	70.84	14	4.5
	67	09	08	05:23:43.4	38.45	70.42	15	4.2
	69	03	22	04:52:37.6	38.93	70.56	23	5.2
	64	10	25	22:56:09.4	38.64	70.75	24	4.8
	64	10	24	06:51:00.7	38.67	70.76	25	5.2
4	70	10	09	13:48:52.1	39.13	71.51	19	5.0
	69	03	27	19:37:45.3	39.15	71.82	19	5.0
	69	03	27	11:19:30.2	39.09	71.80	20	4.9
5	67	05	11	14:50:59.8	39.38	73.73	8	6.0
	66	01	28	08:52:04.2	39.37	73.02	11	5.1
	69	08	28	03:58:36.8	39.13	73.61	11	5.2
	71	07	24	11:43:38.7	39.53	73.14	12	5.5
	67	01	05	10:08:01.3	39.33	72.75	13	5.1
	67	05	20	08:47:20.4	39.32	72.81	14	4.7
	69	09	28	18:53:26.5	39.51	73.48	14	4.9
	64	02	13	13:53:20.4	39.49	72.91	24	5.3
	70	02	08	10:12:43.2	39.74	73.56	28	4.9
	67	05	12	05:21:11.1	39.41	73.68	30	5.0
6	69	09	16	21:19:28.6	39.72	74.92	14	4.8
	67	10	13	03:24:47.1	39.61	74.42	16	4.5
	70	03	29	03:48:49.3	39.67	75.27	23	4.9
	67	02	02	07:37:57.8	39.77	75.28	32	5.5
	69	09	14	14:46:24.0	39.71	74.87	35	5.1
7	69	09	27	16:56:25.8	38.80	75.08	8	4.9
8	70	07	29	05:50:57.9	39.93	77.77	4	5.3
	69	07	20	04:34:14.4	39.93	77.83	5	4.9
	70	06	12	16:00:01.0	40.88	78.26	5	4.8
	71	07	26	01:48:33.2	39.95	77.20	8	5.8
	71	07	27	12:48:33.3	39.82	77.39	9	4.9
	67	05	27	01:42:48.2	40.08	77.27	13	5.0
	66	05	12	11:42:47.3	40.13	78.12	14	4.5
	68	09	12	15:36:54.2	39.87	77.70	21	4.9
	65	03	21	15:09:17.2	40.54	78.43	25	4.9
	64	06	27	02:28:58.7	40.45	77.42	26	5.1
9	71	06	19	17:23:01.1	41.46	79.26	4	5.2
	69	02	11	22:08:53.0	41.42	79.36	5	5.8
	71	06	15	07:39:36.1	41.38	79.30	8	5.6
	71	06	15	22:04:11.9	41.41	79.29	8	5.6
	70	10	17	05:33:15.4	41.59	79.34	10	4.8

Table 1. Calibration Earthquakes (cont'd.)

SUBAREA	YR	MO	DA	ORIGIN TIME HR:MIN:SEC	NORTH LATITUDE DEGREES	EAST LONGITUDE DEGREES	h(pP) km	m_b
	69	02	12	00:22:36.5	41.46	79.36	10	4.9
	71	03	23	20:47:16.3	41.40	79.31	11	6.0
	71	03	24	21:01:55.7	41.39	79.30	11	5.3
	71	06	15	23:17:32.9	41.48	79.23	11	4.9
	71	06	16	10:56:38.9	41.47	79.24	11	5.0
	71	06	16	13:46:51.2	41.47	79.23	11	5.1
	71	03	24	20:54:30.4	41.39	79.28	12	5.3
	65	05	04	08:34:45.0	41.75	79.27	19	5.4
10	70	11	29	02:03:38.4	41.77	81.69	13	4.8
	67	04	27	23:15:21.8	41.96	81.96	13	5.0
11	68	09	15	14:16:56.0	37.14	72.56	14	4.8
	67	04	24	08:51:11.6	37.41	72.63	15	5.2
12	68	10	19	07:01:30.9	37.51	73.26	6	5.1
	65	02	02	15:56:50.5	37.51	73.20	6	5.3
	68	10	30	04:07:23.2	37.46	73.21	10	5.1
	65	04	10	14:11:21.9	37.59	73.16	10	4.9
	68	10	19	02:33:26.4	37.48	73.17	12	5.0
13	68	03	14	02:08:36.5	42.38	66.37	13	5.3
	68	03	13	22:38:38.4	42.36	66.38	13	5.1
14	65	03	17	13:14:18.2	40.84	69.28	13	5.0
	66	04	25	23:22:52.9	41.35	69.22	13	4.9
	65	07	26	00:38:36.2	41.81	69.82	17	4.7
15	66	04	30	13:41:10.4	41.02	72.02	7	5.0
	70	12	30	09:35:26.6	40.28	72.68	15	4.8
	69	12	09	13:41:08.9	40.05	70.45	18	4.8
16	71	10	28	13:30:58.3	41.89	72.32	11	5.4
	71	05	10	14:51:47.2	42.79	71.33	16	5.6
17	66	07	16	19:43:26.7	40.86	74.12	7	4.7
	65	09	25	15:47:58.4	41.44	75.00	12	5.2
18	70	06	05	04:53:06.9	42.48	78.74	7	5.9
	65	10	18	10:21:48.0	41.97	77.50	15	5.1
	67	09	28	02:53:51.5	42.15	79.51	32	5.5
19	71	10	14	21:55:55.2	36.51	71.26	86	5.0
	67	12	17	00:25:19.2	36.52	71.41	97	5.6
	64	12	24	01:08:38.9	36.32	70.94	140	5.2
	70	01	08	21:19:14.4	36.35	70.91	146	4.9
	71	06	22	06:30:03.3	36.29	69.87	167	5.0
	70	06	11	17:40:53.9	36.47	70.99	195	5.1
	70	11	29	08:53:25.1	36.58	71.36	200	4.8
	69	09	12	05:08:04.3	36.42	70.91	201	4.9
	70	12	26	07:58:44.4	36.46	70.89	204	4.4
	66	08	16	02:16:22.9	36.42	70.79	208	5.5
	71	08	04	01:59:06.3	36.44	70.73	214	4.9
	71	08	04	00:24:39.9	36.42	70.73	215	5.6
	70	07	21	01:18:08.0	36.46	70.36	215	5.1
	66	03	31	23:38:04.3	36.40	70.71	216	5.4
	64	11	16	04:47:29.9	36.44	70.54	222	5.1
	67	05	08	18:48:08.0	36.47	70.13	223	4.8
	66	06	06	07:46:18.6	36.39	71.11	225	6.2
	65	03	14	15:53:09.7	36.38	70.70	225	6.4

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Table 1. Calibration Earthquakes (cont'd.)

SUBAREA	YR	MO	DA	ORIGIN TIME HR:MIN:SEC	NORTH LATITUDE DEGREES	EAST LONGITUDE DEGREES	h(pP) km	m_b
	70	01	26	16:38:34.1	36.46	70.50	228	4.6
19	66	06	04	05:11:58.6	36.35	70.69	228	5.4
	65	09	14	18:57:30.7	36.50	70.14	228	4.6
	70	09	14	16:.1:19.3	36.45	70.15	229	4.8
	69	09	04	02:57:22.1	36.51	70.85	231	4.7
	69	10	28	18:45:13.5	36.51	70.86	234	5.0
	65	10	06	15:35:09.5	36.49	70.11	235	5.0
	65	07	24	17:57:44.8	36.44	71.15	238	4.7
	65	11	16	01:03:58.9	36.38	71.09	252	5.1
	70	09	04	13:12:03.7	36.64	70.17	280	4.7
	67	01	25	01:50:22.2	36.63	71.57	289	5.7
20	70	09	05	19:26:27.3	37.13	71.42	100	5.0
	67	08	12	22:54:39.4	37.11	71.33	101	5.1
	70	11	13	17:30:08.9	37.00	71.54	116	5.1
	65	04	10	21:21:29.4	37.44	71.80	124	4.9
	67	11	07	19:57:28.6	37.12	71.77	128	5.0
	68	05	08	22:45:10.9	37.17	71.91	161	4.9
	71	10	15	16:22:15.3	36.99	71.89	165	4.9
	64	06	06	08:05:59.8	37.13	71.92	171	4.8
21	68	09	27	10:37:58.9	37.88	72.26	124	5.3
	64	03	23	13:40:31.1	38.25	73.61	150	5.2
	71	03	18	19:12:46.4	38.22	73.64	153	4.9
	64	03	16	03:28:17.0	37.95	72.81	161	5.0

Table 2. Station Locations

STATION	Code	NORTH LATITUDE DEG	MIN	SEC	EAST LONGITUDE DEG	MIN	SEC	ELEVATION METERS
Alma-Ata, Kazakh SSR	AAA	43	16	18.0	76	56	48.0	800
Talgar, Kazakh SSR	AAB	43	16	00.0	77	23	00.0	850
Andizhan, Uzbek SSR	ANR	40	45	18.0	72	21	36.0	494
Ashkhabad, Turkmen SSR	ASH	37	57	00.0	58	21	00.0	220
Dehra Dun, India	DDI	30	19	00.0	78	02	00.0	682
Dushambe, Tadzhik SSR	DSH	38	33	30.0	68	46	30.0	817
Fergana, Uzbek SSR	FRG	40	23	00.0	71	47	00.0	600
Frunze, Kirgiz SSR	FRU	42	50	00.0	74	37	00.0	655
Garm, Tadzhik SSR	GAR	39	00	00.0	70	19	00.0	1300
Karachi, Pakistan	KAR	24	56	00.0	67	08	36.0	34
Kizyl-Arvat, Turkmen SSR	KAT	39	12	00.0	56	16	00.0	90
Kabul, Afghanistan	KBL*	34	32	27.0	69	02	35.4	1920
Khorog, Tadzhik SSR	KHO	37	29	00.0	71	32	00.0	1850
Kulyab, Tadzhik SSR	KUL	37	54	00.0	69	45	00.0	605
Lahore, Pakistan	LAH*	31	33	00.0	74	20	00.0	210
Mangla, Pakistan	MNL	33	08	50.0	73	45	00.0	436
Meshed, Iran	MSH*	36	18	40.0	59	35	16.0	987
Murgab, Tadzhik SSR	MUR	38	22	00.0	73	56	00.0	3800
New Delhi, India	NDI*	28	41	00.0	77	13	00.0	207
Nilore, Pakistan	NIL*	33	39	00.0	73	15	06.0	536
Naryn, Kirgiz SSR	NRN	41	26	00.0	76	00	00.0	2849
Przhevalsk, Kirgiz SSR	PRZ	42	29	00.0	78	24	00.0	1599
Quetta, Pakistan	QUE*	30	11	18.0	66	57	00.0	1721
Samarkand, Uzbek SSR	SAM	39	40	24.0	66	59	24.0	704
Semipalatinsk, Kazakh SSR	SEM	50	24	00.0	80	15	00.0	209
Tashkent, Tadzhik SSR	TAS	41	19	30.0	69	17	42.0	470
Warsak, Pakistan	WRS	34	09	00.0	71	25	00.0	343

*WWSSN station

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4. CALIBRATION OF CLOSE-IN STATIONS

For each calibration earthquake, the S/P travel time ratio r was computed from equation 2 for each station that recorded both P and S from the earthquake. Contoured values of r for the WWSSN stations whose data were reviewed are shown in figures 2 through 7 for the shallow calibration earthquakes. Data for the unreviewed stations were too erratic to contour smoothly. Therefore, to aid in investigating regional variation of the travel time ratio, the area of shallow earthquakes was divided into 18 subareas and the area of intermediate depth earthquakes was divided into 3 subareas for further analysis. The subareas are outlined on figures 1-7. Each station's mean r and number of observations for each subarea are listed in table 3.

To examine the consistency of the calibration, origin time deviations from the pP values were computed for each calibration earthquake for each station which had two or more observations in the appropriate subarea:

$$\delta T_{ij} = [P - T(pP)]_{ij} - (S-P)_{ij}/\overline{r}_{ik} \qquad (9)$$

where $\delta T_{ij} \equiv$ origin time deviation for
station i and event j

$\overline{r}_{ik} \equiv$ mean r for station i and
subarea k

Event (E_j) and station (S_i) mean origin time deviations were computed by taking the appropriate mean of equation (9):

$$E_j = \frac{1}{I_j} \sum_{i=1}^{I_j} \delta T_{ij} \qquad (10)$$

where $I_j \equiv$ number of stations with an origin time
estimate for event j

$$S_i = \frac{1}{J_i} \sum_{j=1}^{J_i} \delta T_{ij} \qquad (11)$$

where $J_i \equiv$ number of events for which station i has
an origin time estimate

Values of S_i and the standard deviation of origin time deviations about S_i for each station are given in table 4, separately, for shallow and intermediate depth calibration earthquakes.

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The standard deviations are plotted as a function of the mean station distance in figure 8. While the data are scattered, there is a definite trend of increasing standard deviation with distance. This trend reflects the lack of increasing accuracy in the S/P travel time ratio with distance as expressed in equation 4. The maximum accuracy in the ratio is apparently reached near 6-8 degrees. Beyond this distance, the standard deviation of the origin time estimates increases in proportion to increasing S-P time. It reflects an average maximum accuracy of the S/P travel time ratio of 1.5 percent. The reviewed data from the WWSSN stations are much more consistent than the bulletin data. But even these data show an increasing trend with distance. They reflect an average maximum accuracy in the S/P travel time ratio of 0.9 percent. These results strongly suggest that T(S/P) estimates should be obtained from weighted data which will adjust for the differences in the accuracy of the origin time estimates from the individual stations.

Table 5 gives the mean and standard deviation of E_j for shallow and intermediate depth calibration earthquakes. The statistics on E_j are given for two cases: first using only events having origin time estimates from 5 or more stations, and second, using only reviewed data and requiring that each event have origin time estimates from 2 or more stations. The reliability of depth estimates to expect when locating earthquakes in this region with origin time restrained to the value determined from close-in S and P arrival times and the subarea S/P travel time ratios may be estimated from the standard deviation of origin time errors (deviations from the pP values) in table 5, by means of the approximate relation (3). Assuming a depth derivative at the mean distance ($\bar{\Delta} \approx 50°$) of the locating network of about -0.14 sec/km for shallow earthquakes and about -0.10 sec/km for intermediate depth earthquakes, the standard deviation of depth error (deviation from the pP depth) would be about 9 km for shallow earthquakes and about 8 km for intermediate depth earthquakes.

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LEGEND

○ 0 < H ≤ 50
◻ 50 < H ≤ 100
△ 100 < H ≤ 150
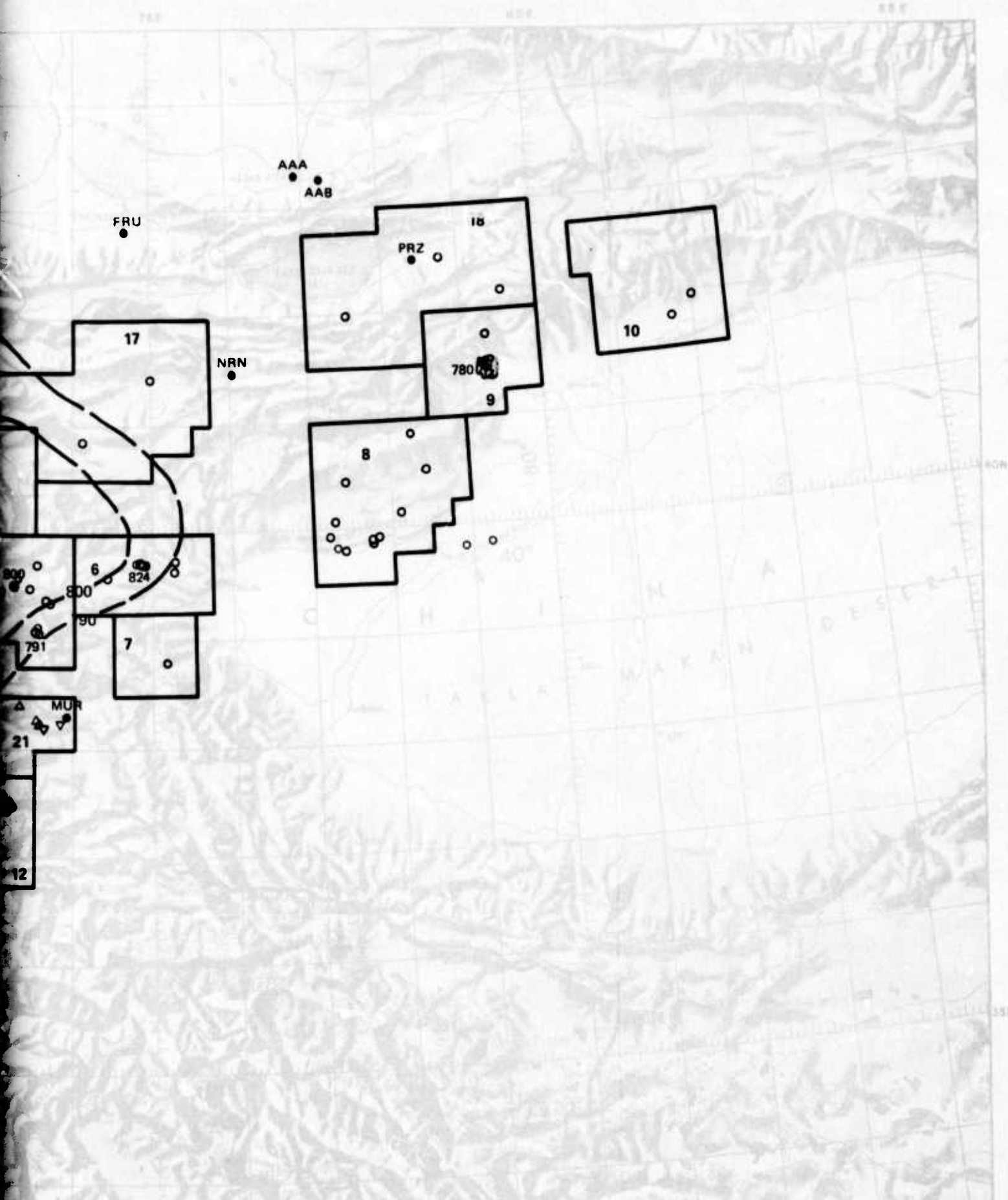▽ 150 < H ≤ 250
⬦ 250 < H

⊙ CALIBRATION EVENTS
○ TEST EVENTS
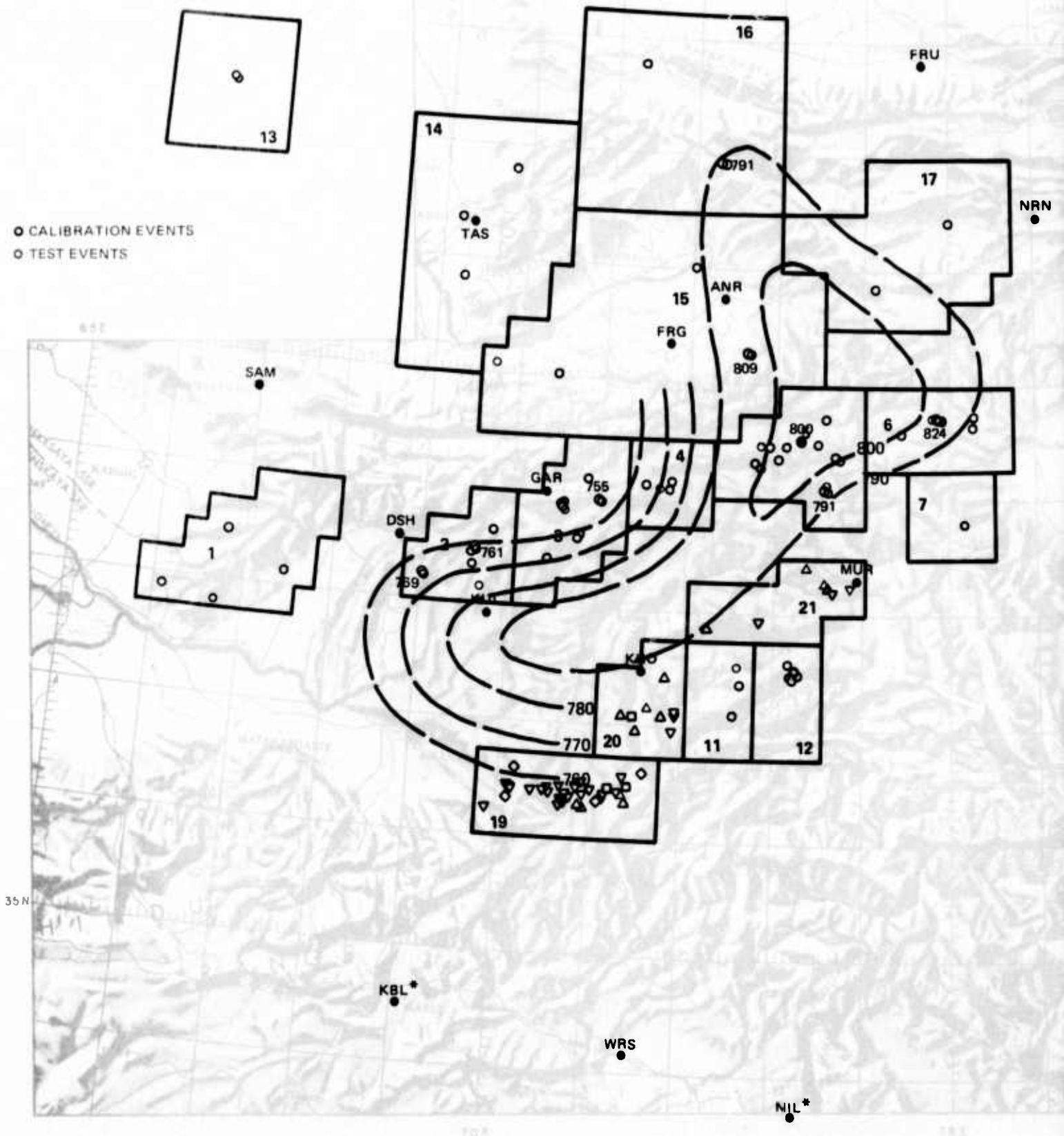
Figure 2.   S/P travel time ratio for KBL

-17/18-

TR 74-16

LEGEND

○ 0 < H ≤ 50
□ 50 < H ≤ 100
△ 100 < H ≤ 150
▽ 150 < H ≤ 250
◇ 250 < H

● CALIBRATION EVENTS
○ TEST EVENTS
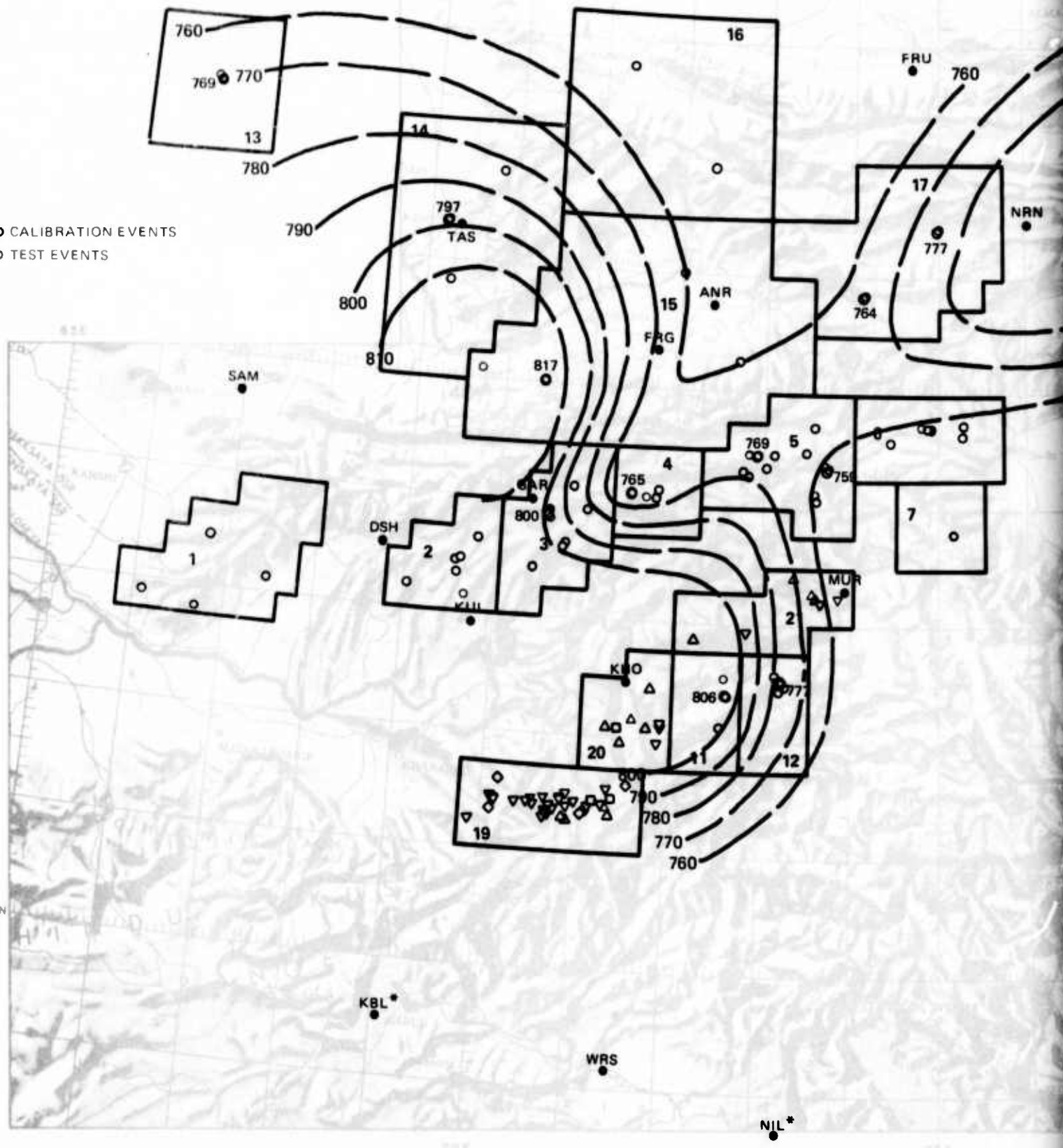
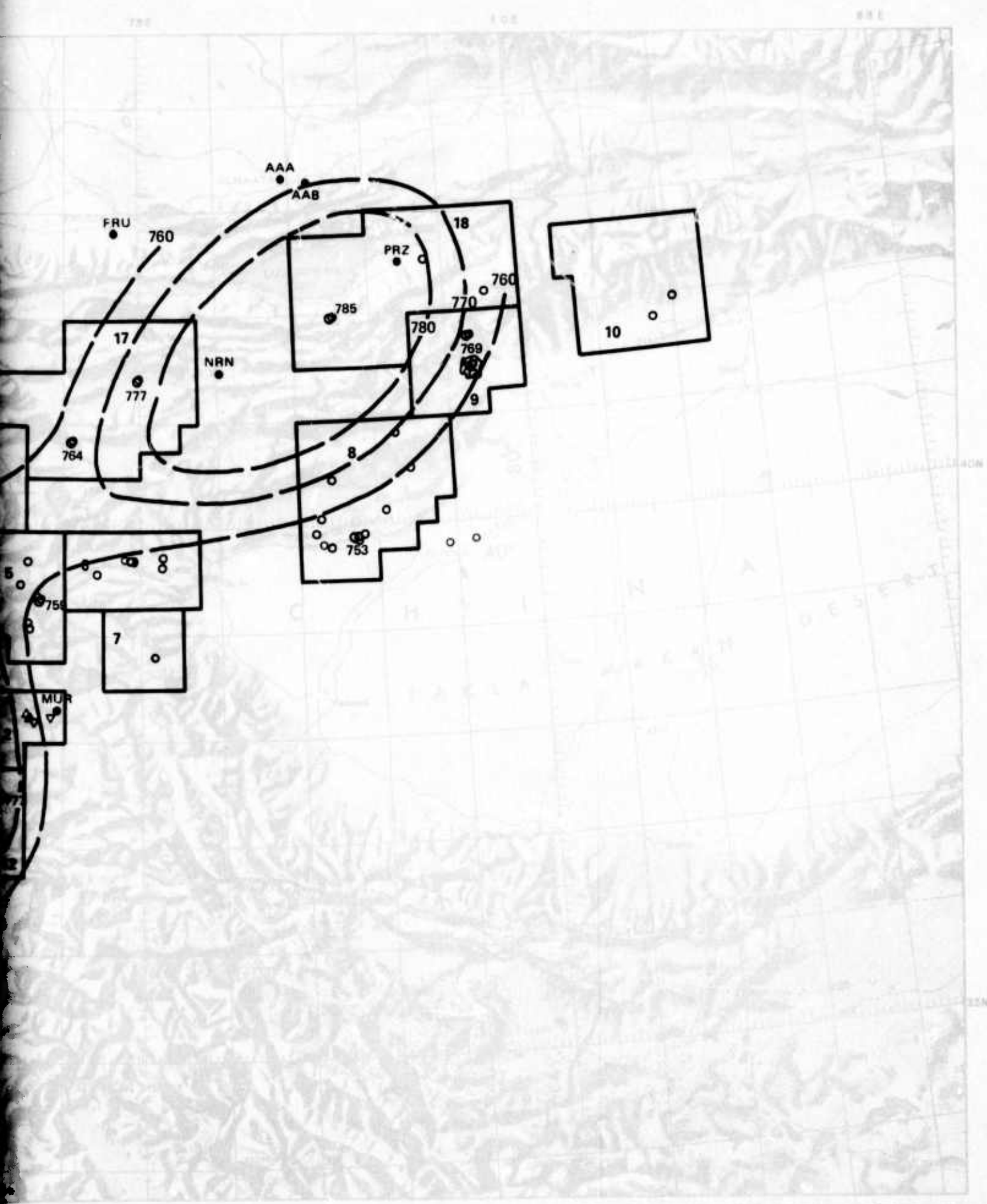Figure 3. S/P travel time ratio for LAH

G 8607
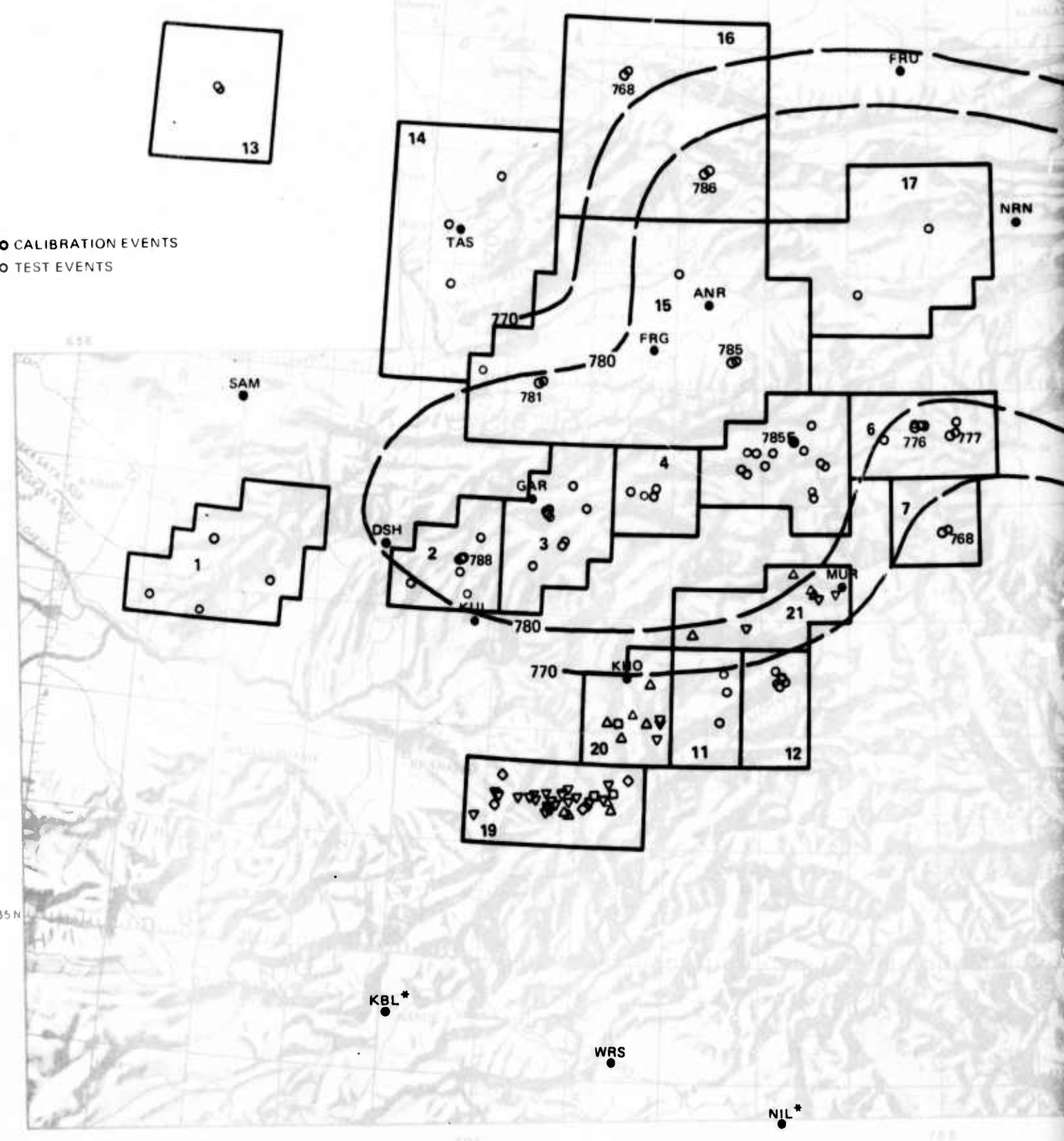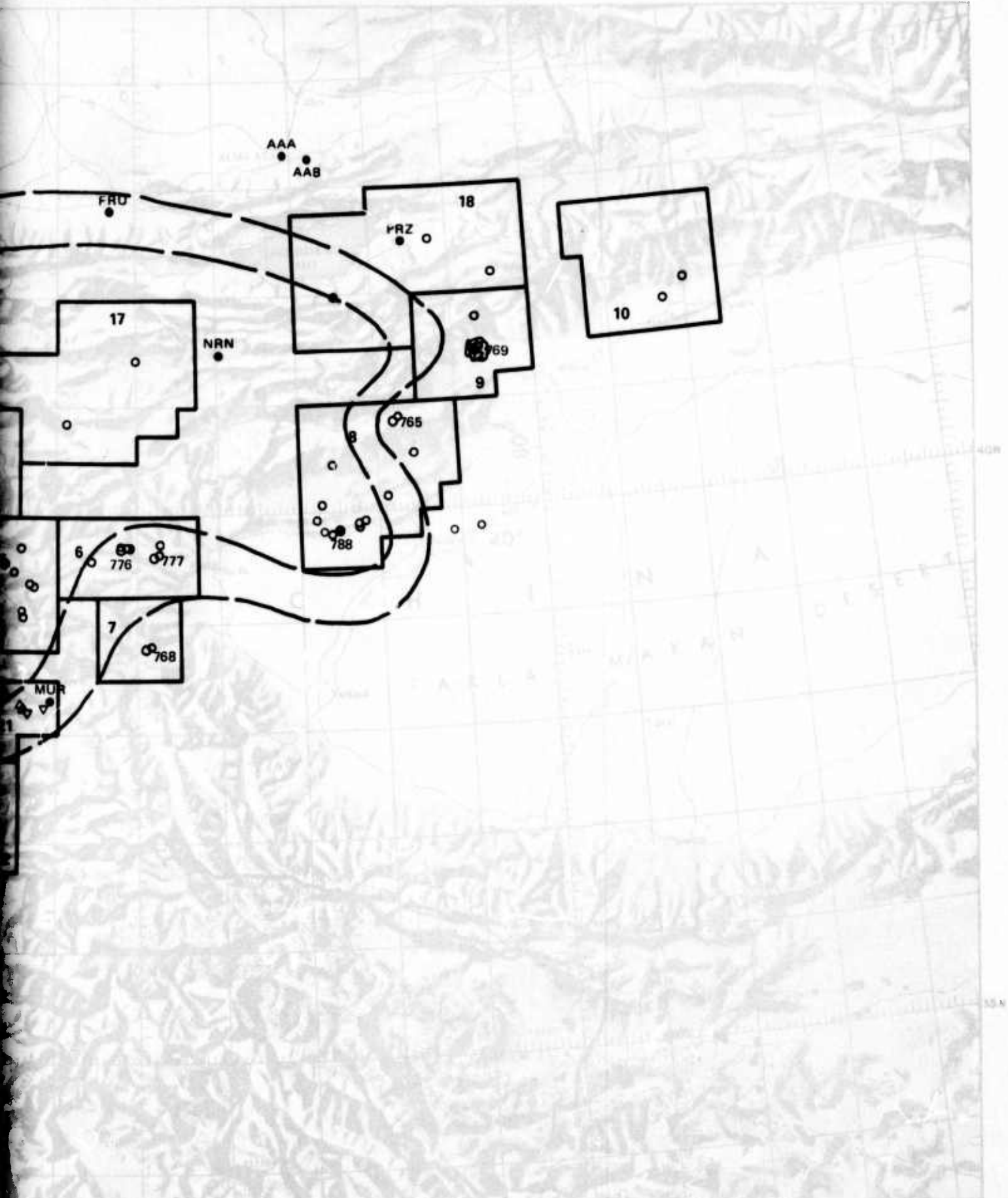
Figure 4. S/P travel time ratio for NIL

G 8608

TR 74-16

LEGEND

○ 0 < H ≤ 50
□ 50 < H ≤ 100
△ 100 < H ≤ 150
▽ 150 < H ≤ 250
◇ 250 < H

◉ CALIBRATION EVENTS
○ TEST EVENTS

Figure 5. S/P travel time ratio for MSH

G 8609

TR 74-16
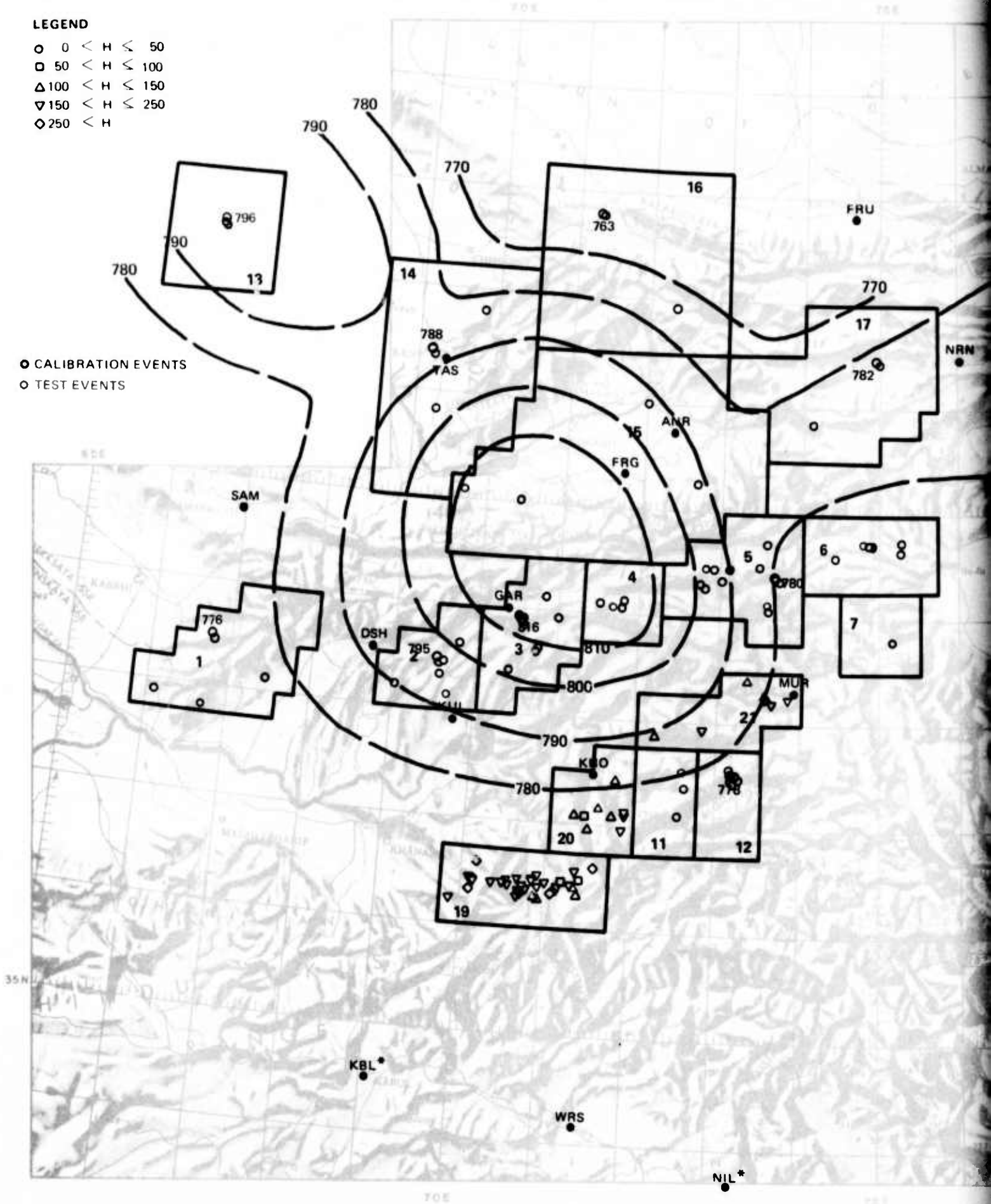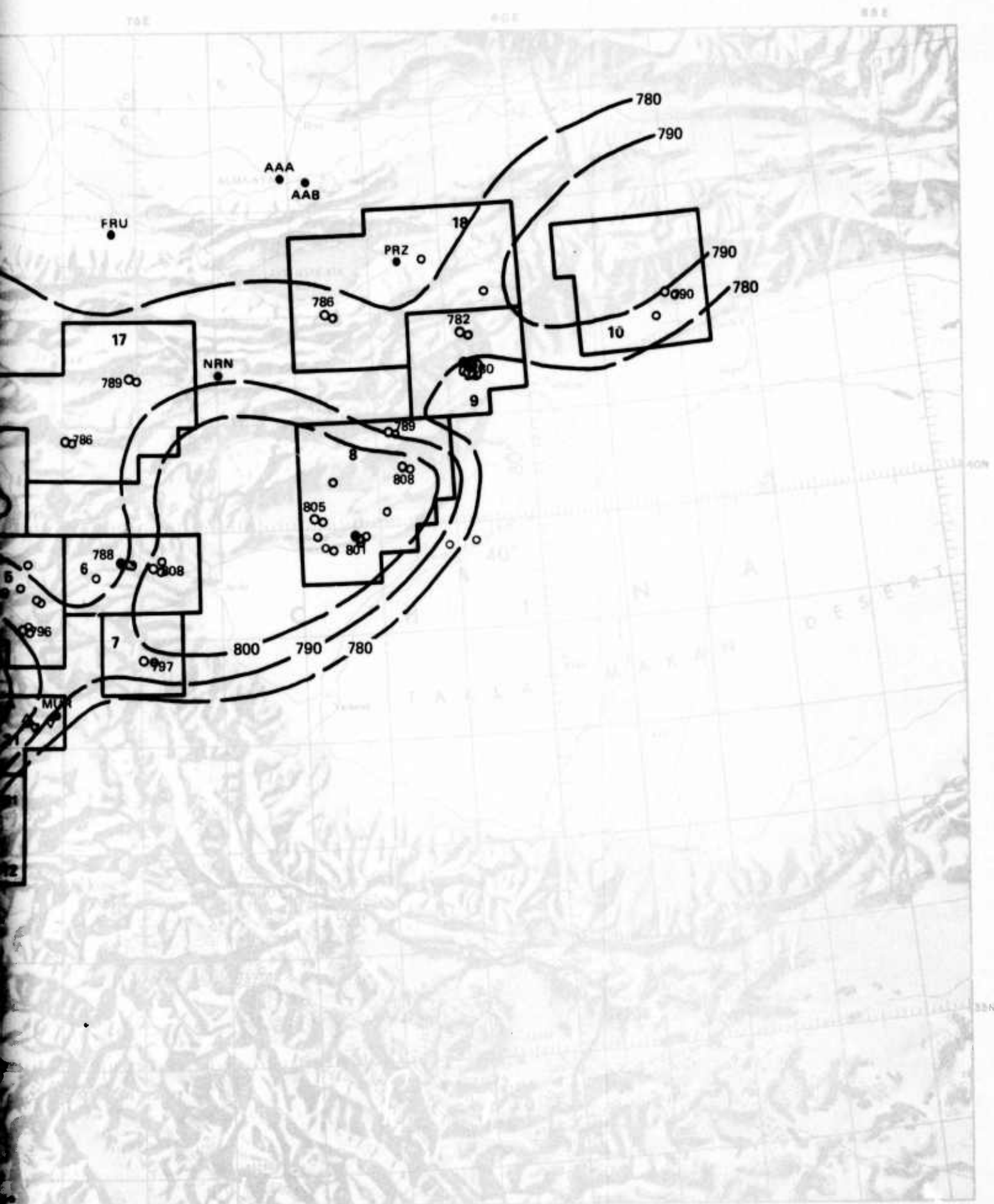
Figure 6. S/P travel time ratio for QUE

G 8610

LEGEND

○ 0 < H ≤ 50
◻ 50 < H ≤ 100
△ 100 < H ≤ 150
▽ 150 < H ≤ 250
◇ 250 < H

● CALIBRATION EVENTS
○ TEST EVENTS

Figure 7. S/P travel time ratio for NDI

TR 74-16

Table 3. Station subarea mean S/P travel time ratios
(mean r/no. of observations)

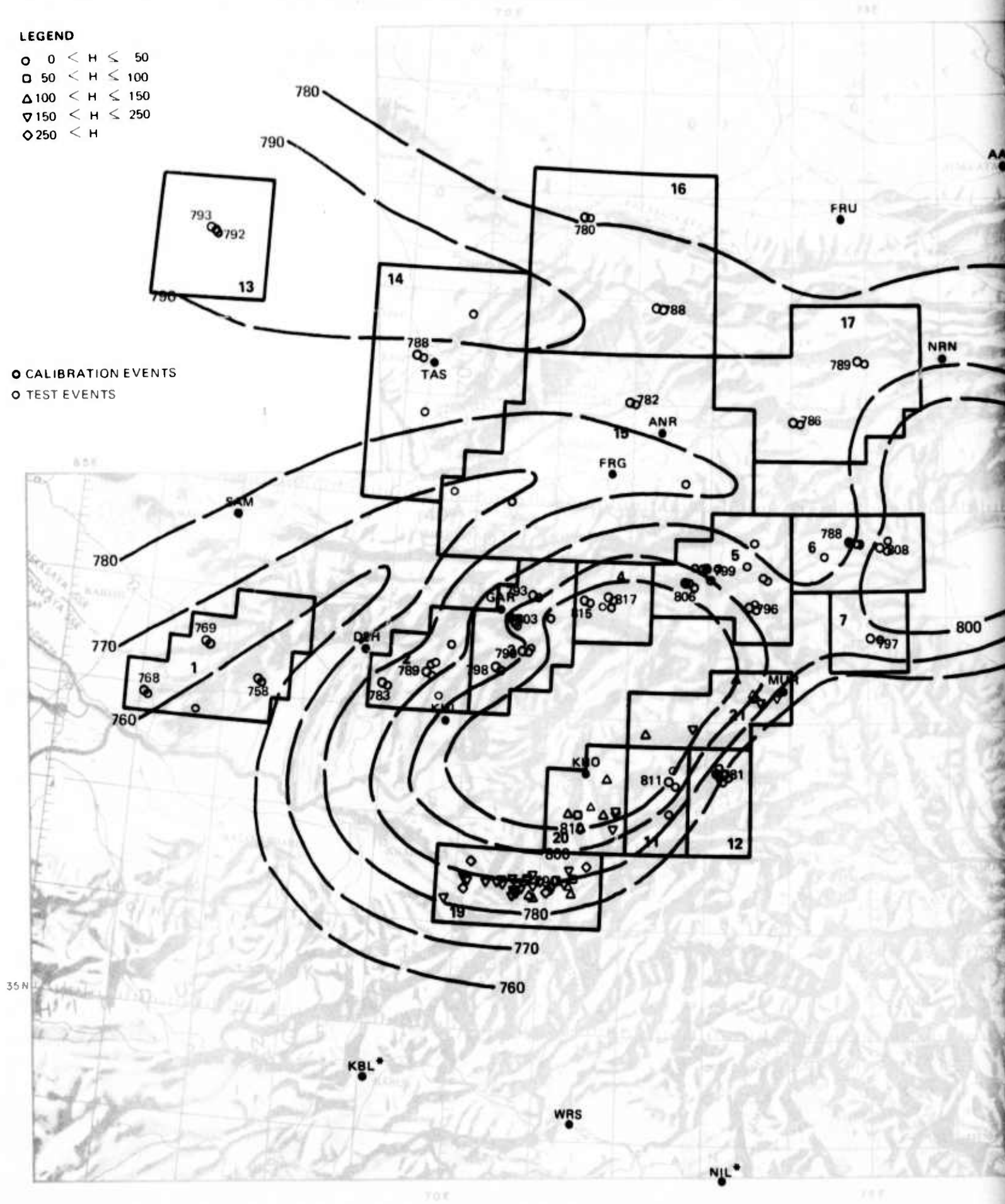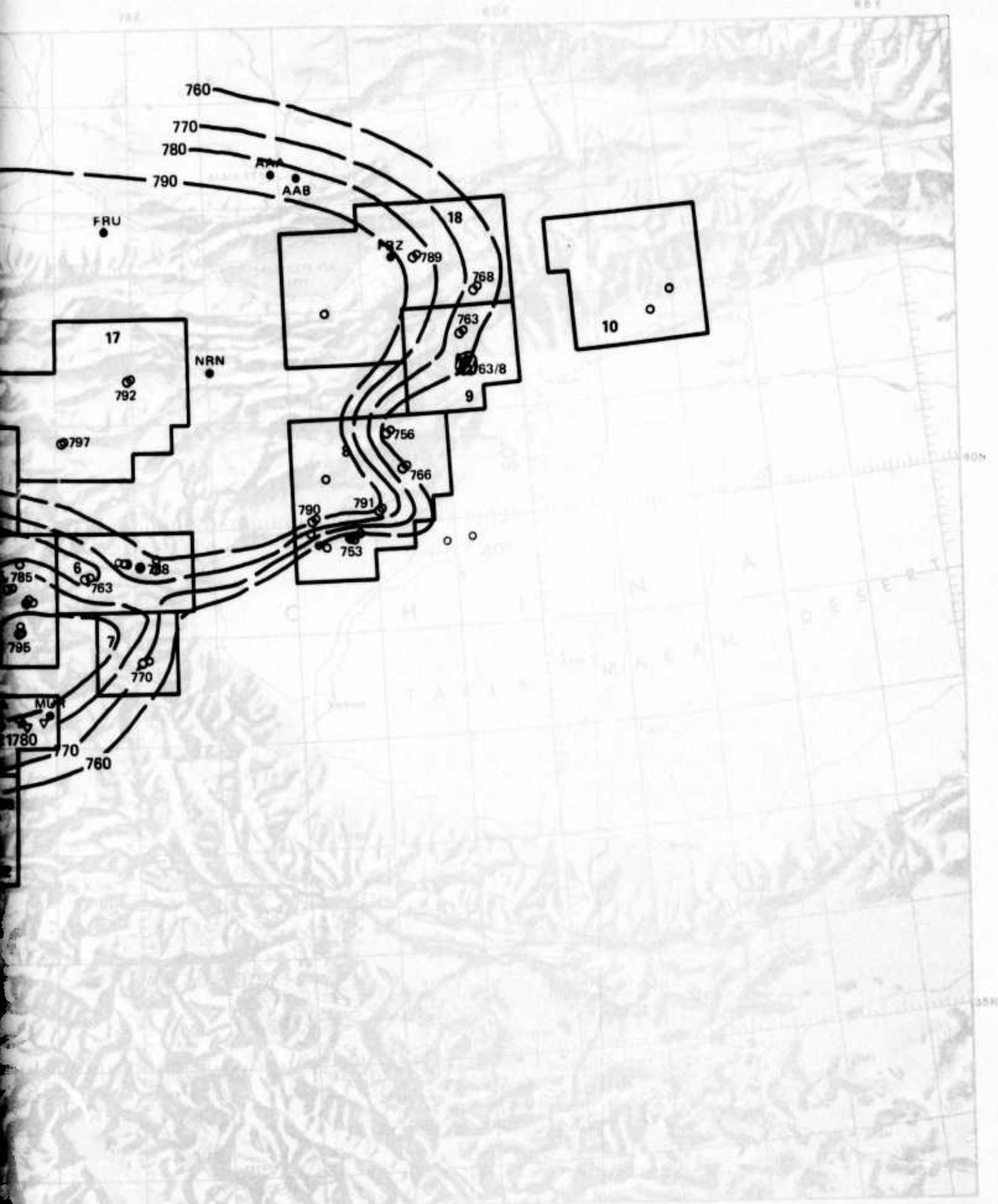| SUBAREA STATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	ALL	19	20	21	ALL
																			SHALLOW			INTERMEDIATE DEPTH	
AAA					.803/2			.846/2	.769/1									.895/1	.827/6	.787/12	.793/1		.787/13
AAB		.794/2		.763/1	.841/1	.662/1		.744/1	.764/7		.792/1	.788/3	.697/2	.764/3	.828/1	.825/1	.837/1		.768/13	.779/18	.767/6	.787/4	.778/28
ANR	.772/1		.766/6	.808/1		.842/3	.805/1					.779/3	.755/1	.762/1		.778/1			.783/24	.803/7	.792/3	.777/1	.797/11
ASH		.811/2			.796/2				.753/1		.780/1	.770/1		.762/1					.783/12	.779/11	.796/1	.779/2	.780/14
DDI			.820/2		.802/3	.806/1		.834/1			.764/1	.813/3		.743/1	.740/2	.788/2		.796/1	.794/11	.773/23	.800/8	.788/3	.781/34
OSH				.891/1				.796/2			.793/2	.800/2		.806/3			.831/1		.802/9	.779/6	.798/1	.810/2	.788/9
FRG	.801/1	.757/1	.815/1		.777/5	.784/2		.763/2	.753/3		.741/1	.754/3	.759/2		.736/2	.816/2	.845/1	.747/2	.770/36	.781/18	.774/5	.767/2	.779/25
FRU	.805/3	.723/2	.782/5	.746/2	.777/5	.784/2		.868/1	.753/3		.888/1	.774/3	.815/1	.778/2		.796/2	.787/1		.806/17	.771/18	.801/4	.824/3	.782/25
GAR	.802/2				.848/3				.729/1											.776/8	.766/1	.776/2	.775/9
KAR							.833/1				.760/2	.775/1	.736/1	.826/2	.736/1	.762/2	.836/1		.780/21	.789/9	.808/1		.789/12
KAT	.769/2	.760/2	.784/1		.792/3	.781/2									.794/1	.791/1			.780/12	.781/9			.781/9
KBL*		.765/2	.755/1		.797/3	.796/1		.757/1	.770/3			.859/1			.764/1	.732/1	.820/1	.719/1	.780/25	.802/25	.817/4	.791/1	.804/30
KHU	.756/2	.783/2			.794/5	.786/2	.797/1		.781/4		.794/2			.786/1		.871/1			.822/7	.807/14	.827/6	.834/1	.814/21
KUL	.815/1			.841/2				.800/1						.797/1	.817/1			.785/1	.779/14	.758/17	.763/5	.773/2	.760/24
LAH*		.726/1	.800/1	.765/1	.764/2	.752/3	.678/1	.753/1	.769/1		.806/1	.777/1	.769/1	.797/1	.753/1		.728/1		.749/15	.772/9	.747/3	.788/2	.766/12
MBL	.776/1	.726/1	.755/1		.783/2			.758/3	.790/2			.745/1	.746/1	.738/1	.763/1		.782/1	.793/1	.788/15	.788/11	.773/5	.777/2	.784/18
MSH*	.805/1	.795/1	.816/2		.780/3	.760/3	.770/1	.774/1	.763/9			.778/2	.796/1	.754/2	.763/1		.751/1	.852/1	.770/8	.766/4	.782/3		.773/7
MUR	.773/2	.78?/4	.778/5	.768/3	.778/7	.777/2	.761/1	.766/7	.769/5		.761/2	.758/4	.751/1	.777/2	.761/1		.794/2	.778/2	.773/56	.768/23	.768/7	.777/2	.768/32
NDI*		.78?/?	.778/3										.781/2	.754/2					.771/1	.782/5	.770/3		.777/8
NIL*					.78b/3	.777/2		.730/3	.769/5						.783/2	.777/1				.799/3	.782/2		.792/5
NRN								.769/4		.775/2		.800/1	.757/1		.799/1		.717/1		.770/10	.792/12	.807/2		.794/14
PRZ			.800/6				.797/1	.801/6	.780/6	.790/1		.731/3	.733/2		.784/2		.787/2	.786/1	.792/49	.789/21	.775/5	.778/2	.785/28
QUE*	.765/3	.736/2	.855/1	.816/2	.801/6	.794/3	.797/1		.814/1	.790/1	.811/1	.800/1	.757/1	.798/1	.782/1	.732/1			.792/12				
SAM	.769/1	.723/1	.770/1		.792/4	.801/3			.718/1	.774/1	.682/1	.771/2		.795/2	.776/1		.751/1	.765/2	.772/12	.756/6	.765/1		.757/7
SEM				.815/2	.777/2				.774/1	.774/1	.790/1				.831/1	.751/1			.793/31	.769/22	.774/7	.786/4	.772/33
TAS	.696/2	.819/1	.809/4		.802/6	.631/1		.820/2	.823/5		.740/1	.758/4					.800/1		.515/9	.779/6	.792/2	.739/2	.772/10
WRS	.823/1				.892/3	.750/2							.767/2										
Mean																			.783				.782

* WWSSN Stations

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Table 4. Station mean origin time deviations,
using subarea mean S/P ratios

STATION	SHALLOW EARTHQUAKES				INTERMEDIATE DEPTH EARTHQUAKES			
	NO. OF EVENTS	MEAN DISTANCE DEGREES	S_i SECS	ST DV SECS	NO. OF EVENTS	MEAN DISTANCE DEGREES	S_i SECS	ST DV SECS
AAA	4	3.36	+0.01	0.96	0			
AAB	7	3.47	+0.01	1.36	13	8.48	+0.07	4.84
ANR	19	2.85	-0.03	2.33	28	4.05	-0.02	1.50
ASH	9	10.57	-0.01	4.32	11	10.31	+0.06	2.53
DDI	5	10.12	+0.11	4.02	14	8.59	+0.01	1.61
DSH	11	4.32	+0.02	1.74	34	2.73	+0.03	1.73
FRG	5	2.57	+0.04	1.75	9	3.56	-0.01	0.88
FRU	33	4.36	+0.01	2.98	25	6.72	-0.02	1.51
GAR	14	3.87	+0.08	3.31	25	2.51	+0.03	2.38
KAR	0				9	12.08	+0.10	2.75
KAT	15	11.92	0.00	3.91	12	12.00	-0.08	3.04
KBL*	8	6.94	+0.05	0.73	9	2.31	+0.01	0.85
KHO	18	4.15	+0.02	1.52	30	1.18	-0.06	1.35
KUL	4	3.28	+0.04	2.77	21	1.73	+0.03	1.18
LAH*	4	8.97	+0.05	1.10	24	5.88	+0.15	1.55
MNL	11	6.90	+0.13	4.65	12	4.14	-0.02	1.53
MSH*	6	11.33	+0.10	1.25	18	9.43	+0.02	1.98
MUR	4	4.66	-0.07	2.43	7	2.72	+0.03	1.15
NDI*	55	11.88	-0.06	2.34	32	9.56	+0.06	1.34
NIL*	17	7.49	+0.02	1.69	8	3.58	+0.03	0.63
NRN	0				5	6.04	+0.01	1.22
PRZ	6	3.79	-0.09	1.28	14	8.36	-0.02	1.62
QUE*	43	11.40	+0.02	1.45	28	7.33	+0.03	1.64
SAM	7	4.96	-0.02	2.28	7	4.33	+0.03	2.04
SEM	8	11.43	+0.06	3.11	0			
TAS	27	4.38	0.00	3.38	33	4.83	+0.04	1.57
WRS	7	6.54	+0.02	0.97	10	2.94	+0.08	1.93
AVERAGES			+0.01 on 347 obs	2.59			+ .02 on 438 obs	1.88

*WWSSN Station

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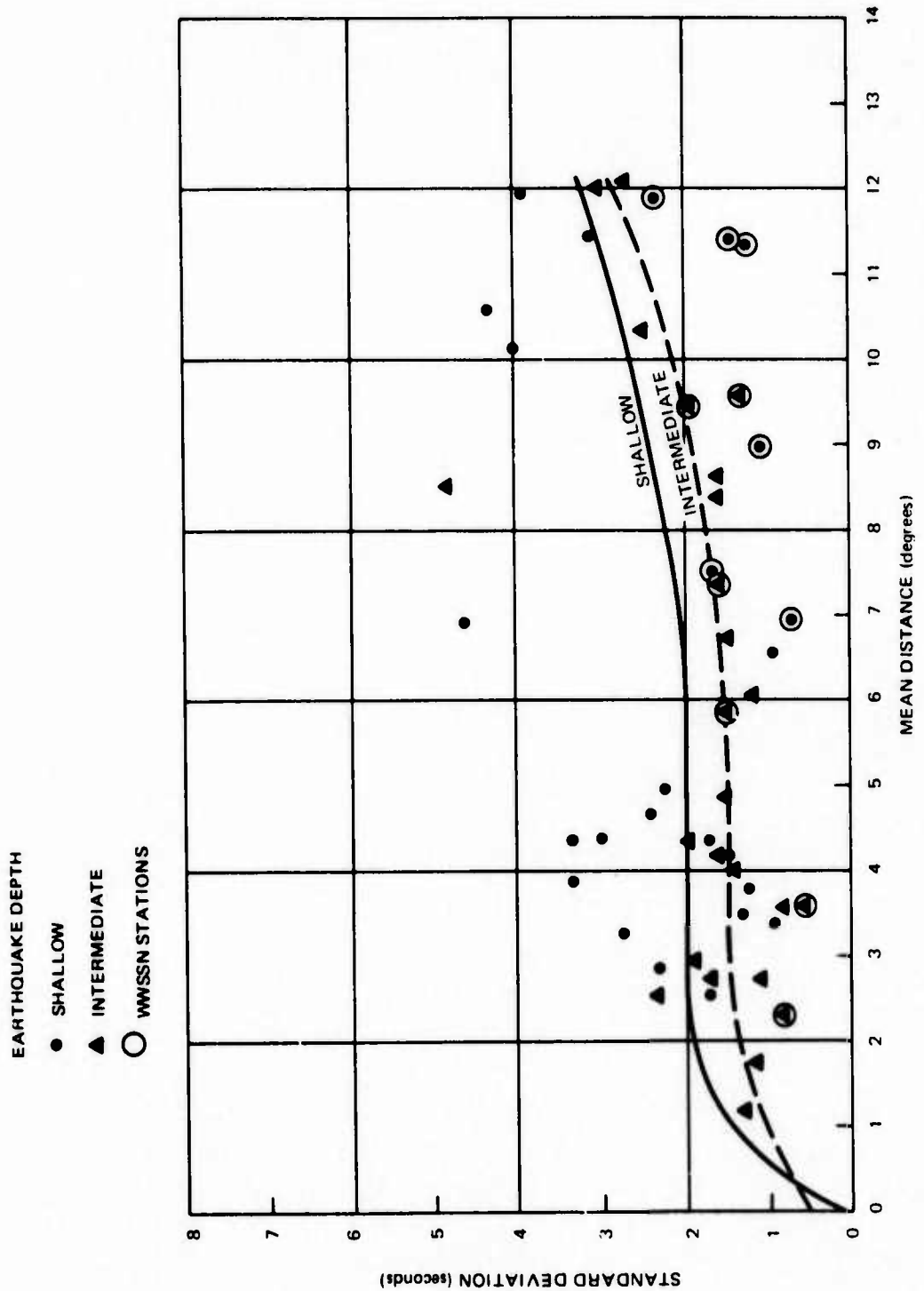
Figure 8. Standard deviations of origin time deviations vs. distance

G 8612

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Table 5. Event mean origin time deviations, using subarea mean S/P ratios

SOURCE DEPTH	NETWORK TYPE	NUMBER EVENTS	E_{ij} MEAN (SEC)	E_{ij} ST.DV. (SEC)
Shallow	All stations (5 or more)	35	0.00	1.19
	Reviewed stations only (2 or more)	43	+0.16	1.28
Intermediate depth	All stations (5 or more)	41	+0.12	0.75
	Reviewed stations only (2 or more)	35	+0.05	0.95

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5. DISTANCE AND DEPTH DEPENDENCE OF THE S/P TRAVEL TIME RATIO

5.1 SHALLOW EARTHQUAKES

For the shallow calibration earthquakes, Wadati graph analysis was carried out separately for two distance ranges, less than or equal to 6.5 degrees and 6.5 to 14.0 degrees. This division into two distance ranges was based on inspection of empirical P and S travel time curves for the region, which showed a clear change in apparent velocity at about 6.5 degrees. The two branches of the travel time curves are interpreted as Pn and Sn for the less than 6.5 degree branch and as mantle P and S for the 6.5 to 14 degree branch. Reliable estimates of Wadati graph parameters could not be obtained for individual events because too few stations within either distance range recorded both P and S for any single event. Therefore, data from earthquakes of similar depth were combined and least squares estimates of the Wadati graph slope (ρ) and P-T intercept (τ) were determined for each of 7 depth ranges. This procedure is valid if the pP depths are valid, the velocity structure is fairly uniform laterally throughout the region, and the Wadati graph parameters do not change too rapidly with depth.

Wadati graph parameter estimates for the shallow earthquakes are listed in table 6 and are shown in figure 9 as a function of focal depth for each of the two distance ranges. One standard error limits are shown for both slope and intercept values. Although there is some evidence of depth dependence of the Wadati graph slope, especially in the 20 to 30 km depth range, there is no statistically significant difference in the slopes at the 95% confidence level. Therefore, a weighted mean value of slope was determined from all depths in each of the distance ranges. The τ intercept values obtained with the slopes restrained to the weighted mean value for each distance range are also included in table 6 and plotted on figure 9. Statistically, there is no difference in the slopes between the two distance ranges but there is a difference in the τ intercepts. The depth dependence of the τ intercept is clearly evident for both distance ranges on figure 9, the intercept decreasing with increasing depth. Linear least squares estimates of the intercept-depth relations for the two distance ranges, with Wadati graph slope restrained, are shown on the figure and listed in table 7.

Table 6. Shallow Wadati graph parameters, by depth

DEPTH(km)	0-5	6-10	11-15	16-20	21-25	26-30	31-35
NO. EVENTS	6	21	32	8	7	4	4

EPICENTRAL DISTANCE $\leq 6.5°$

	0-5	6-10	11-15	16-20	21-25	26-30	31-35
MEAN DEPTH(km)	3.3	8.3	13.1	17.6	23.7	28.7	33.6
NO. OBSER.	3	62	95	26	17	17	11
$\hat{\rho}$	---	.758	.756	.760	.815	.845	.781
STANDARD ERROR($\hat{\rho}$)	---	.017	.016	.031	.049	.052	.042
$\hat{\tau}$ (SECS)	---	-1.43	-1.85	-2.10	+0.50	+3.56	-1.88
STANDARD ERROR($\hat{\tau}$)	---	1.30	1.13	1.94	3.21	3.67	3.26

$\overline{\rho} = 0.764$

		6-10	11-15	16-20	21-25	26-30	31-35
$\hat{\tau}(\rho=.764)$(SECS)		-0.90	-1.18	-1.80	-3.20	-2.63	-3.33
STANDARD ERROR($\hat{\tau}$)		0.46	0.40	1.69	1.21	1.21	1.16

EPICENTRAL DISTANCE $6.5° - 14.0°$

	0-5	6-10	11-15	16-20	21-25	26-30	31-35
MEAN DEPTH(km)	4.2	8.1	13.0	17.9	23.5	29.3	33.7
NO. OBSER.	22	61	104	23	18	6	9
$\hat{\rho}$	.782	.792	.781	.771	.810	.758	.784
STANDARD ERROR($\hat{\rho}$)	.022	.014	.010	.024	.033	.037	.026
$\hat{\tau}$ (SECS)	+1.04	+2.35	-0.34	-0.76	+2.89	-4.55	+0.21
STANDARD ERROR($\hat{\tau}$)	4.08	2.48	1.78	4.32	5.43	5.52	4.49

$\overline{\rho} = 0.784$

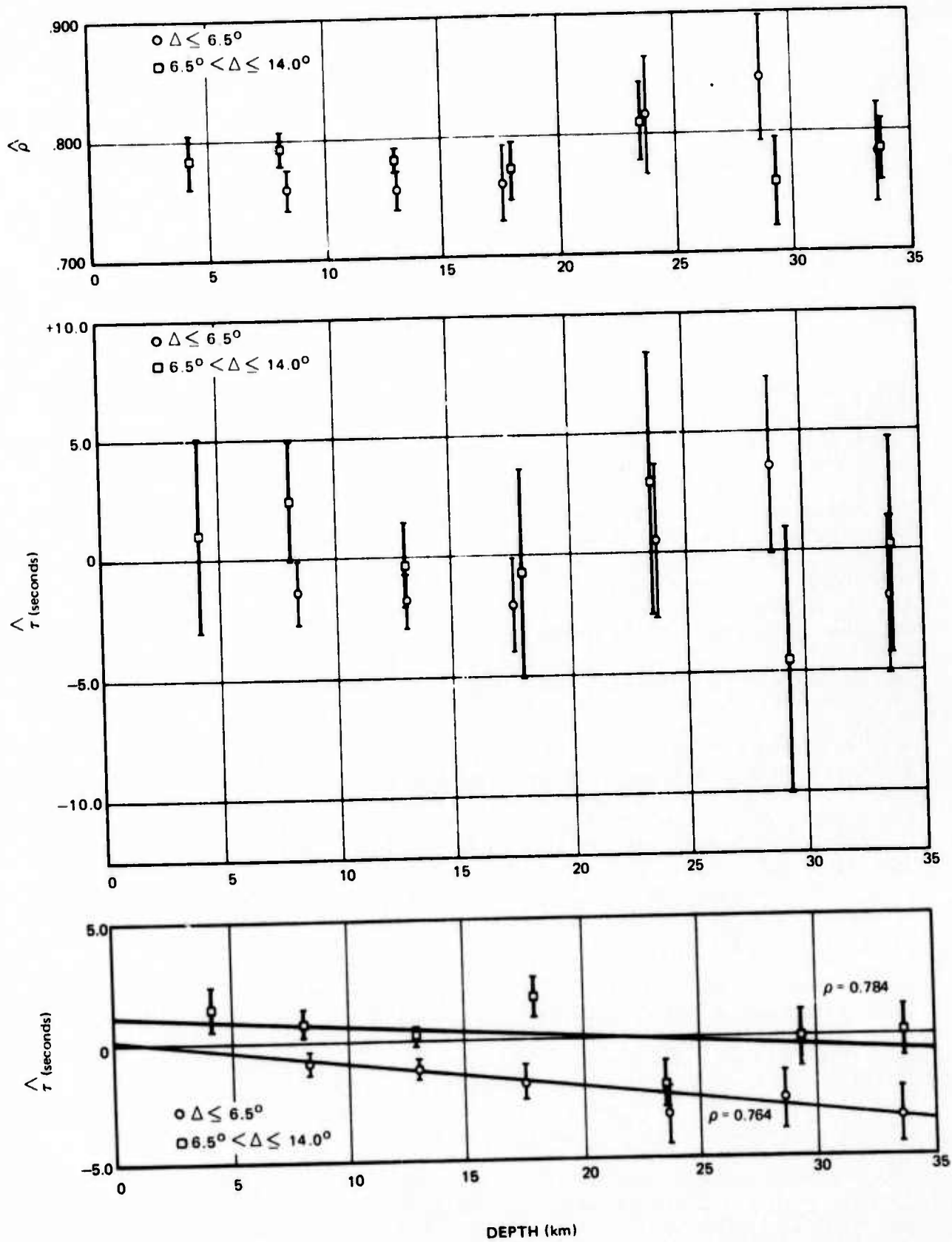|	0-5	6-10	11-15	16-20	21-25	26-30	31-35
$\hat{\tau}(\rho=.784)$(SECS)	+1.41	+0.77	+0.20	+1.76	-1.92	-0.12	+0.15
STANDARD ERROR($\hat{\tau}$)	0.94	0.58	0.41	0.83	0.94	1.20	1.04

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Figure 9. Shallow Wadati graph parameter

Table 7.   Mean Wadati graph parameters
for shallow earthquakes

DISTANCE RANGE DEGREES	ρ	τ (h) (SECS)
< 6.5	0.764	+0.10 - 0.106h
6.5 - 14.0	0.784	+1.14 - 0.051h

h = focal depth in km

Using the Wadati graph parameters from table 7, the S/P travel time ratio
r, computed with equation 8, is shown in figure 10 as a function of focal
depth for selected distances. Also shown in the figure is the depth
distribution of the station observations. The figure shows that r varies
rather strongly with increasing depth for distances less than 6.5 degrees.
The variation ranges from more than 12 percent at distances less than 2
degrees to about 5 percent near 6 degrees. The depth variation of r is
small beyond 6.5 degrees; decreasing slowly from about 1.5 percent near
6.5 degrees to less than 1.0 percent beyond 14 degrees. The depth distri-
bution of earthquakes suggests that the values of r should be the most
reliable in the 5 to 25 km depth range.

The dependence of r on focal depth will limit the accuracy of origin times
computed with the S/P technique for shallow earthquakes in central Asia.
For example, if r values for a depth of 20 km were used to compute S/P
origin times of an earthquake with a focal depth of either 0 or 40 km,
the error in origin time based on S and P arrival times at distances less
than 6.5 degrees would be about 2 seconds and the origin time error for
distances greater than 6.5 degrees would be about 1 second. Corresponding
depth errors, from approximate relation (3), would be about 15 km if only
data from distances less than 6.5 degrees were used and about 10 km if
only data from distances greater than 6.5 degrees were used. The direction
of depth error for both the surface and the 40 km earthquake would be
toward the 20 km depth.

Figure 11 shows the variation of r with distance for selected depths, again
using parameter values from table 7 in equation 8. Also shown is the dis-
tance distribution of station observations. The figure shows a strong
variation of r with distance for the deeper crustal earthquakes at distances
less than 6.5 degrees. There is practically no distance dependency beyond
this distance. The large number of observations suggests that the distance
variations should be valid, particularly between about 1 and 12 degrees.

The dependency of r on distance may also limit the accuracy of origin times
computed with the S/P technique. The problem will be the most severe for
deep crustal earthquakes at stations within 3 or 4 degrees. For example,
if the subarea values of r represent averaged distance effects and there
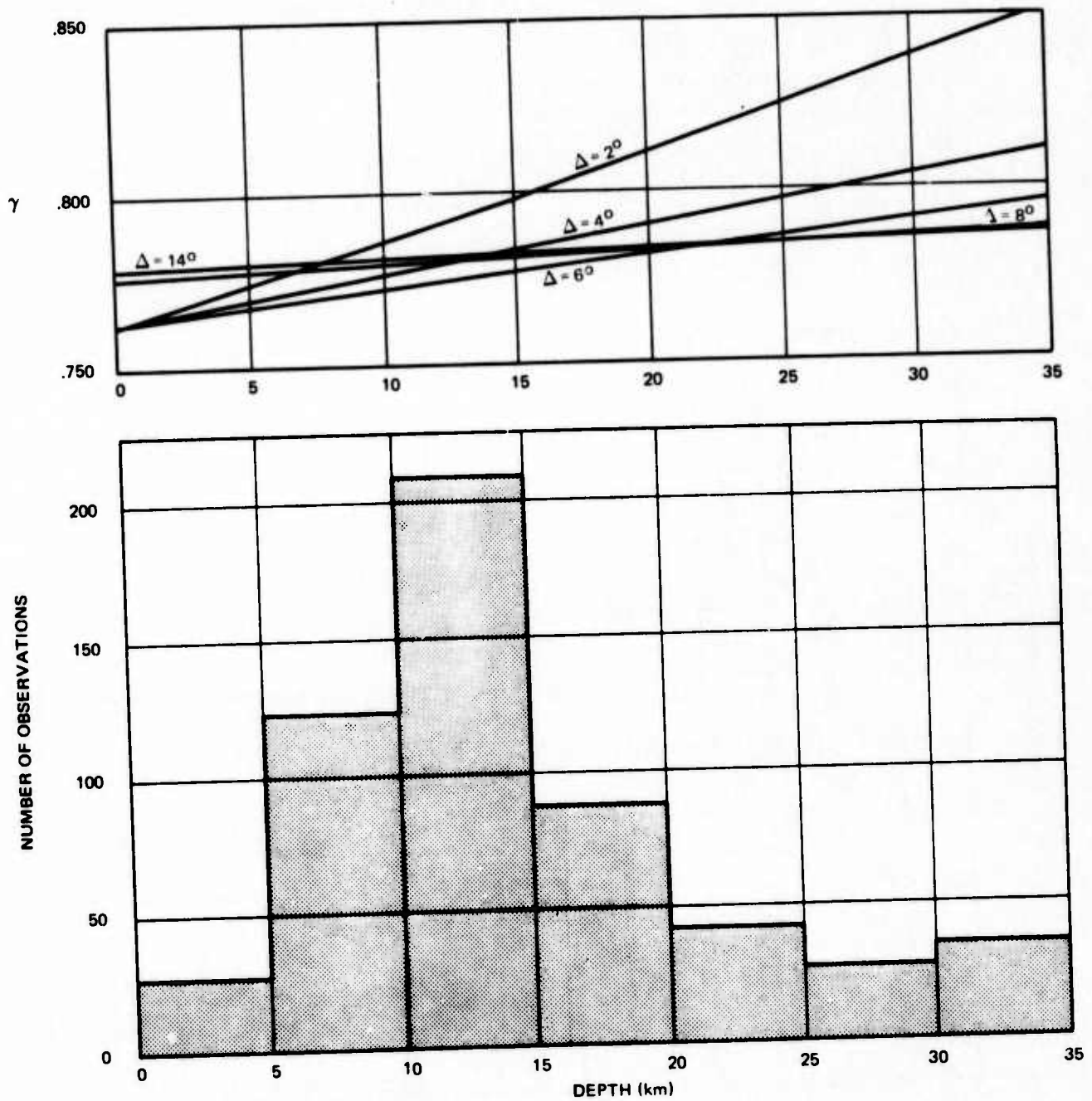is a maximum distance range within the subarea of 2 degrees, a 35 km event

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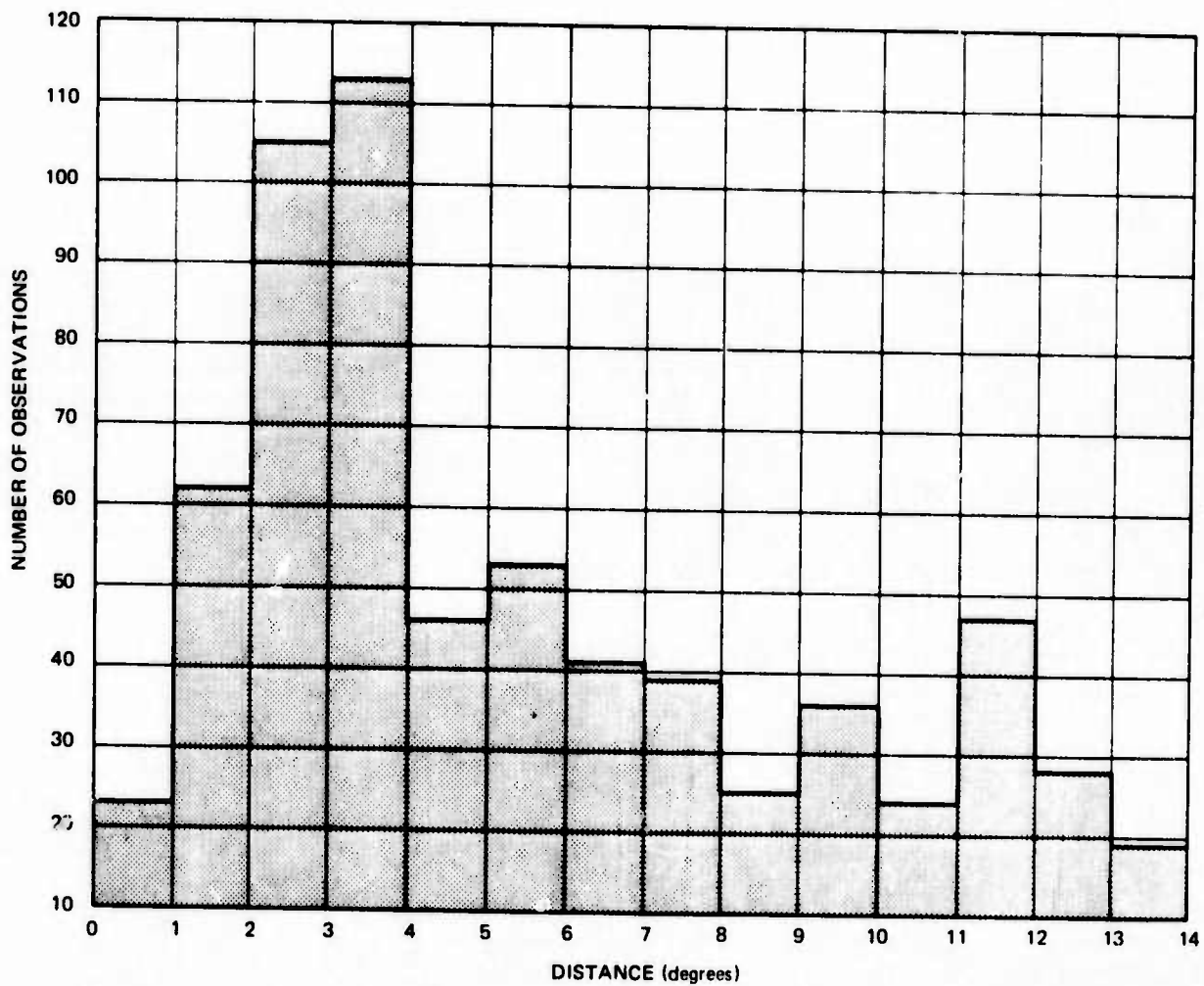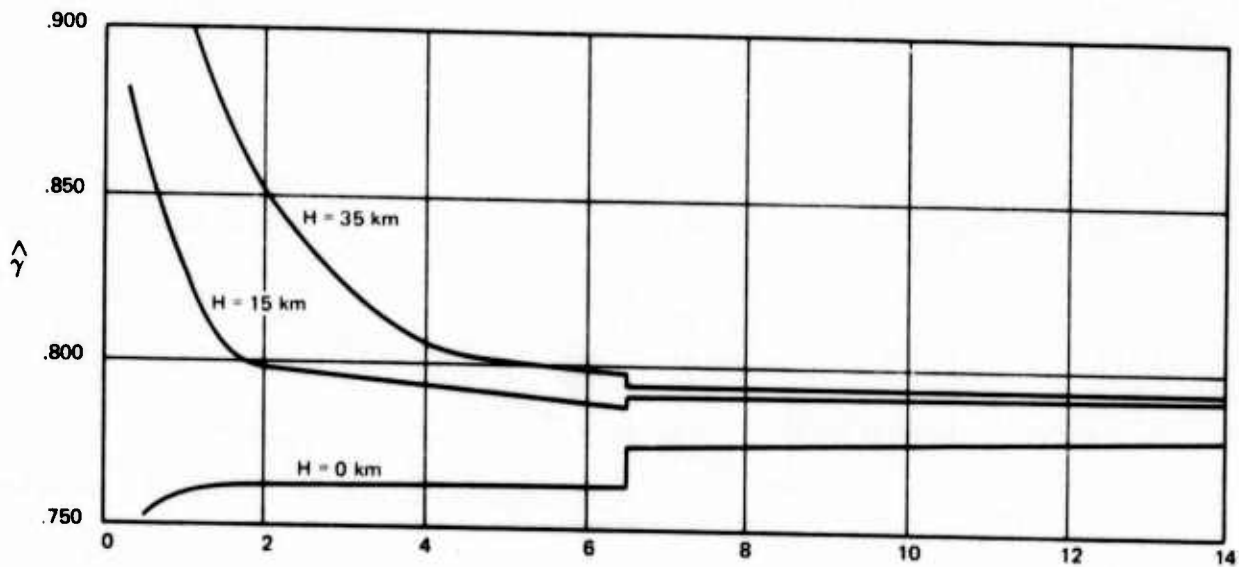Figure 10. Variation of S/P travel time ratio with focal depth, shallow earthquakes

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Figure 11. Variation of S/P travel time ratio with distance, shallow earthquakes

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may have an origin time error of 2.5 seconds from the S/P technique, based
only on data at less than 6.5 degrees. Similarily a 15 km earthquake may
have an origin time error of about 0.5 second. These correspond to depth
errors of less than 20 and 5 km, respectively. However, these estimates
assume that all close-in stations are in the same direction from the hypo-
center. If the close-in stations are distributed about the hypocenter, as
they generally are in the Hindu-Kush region, the distance effects on depth
estimates from this technique tend to cancel and reduce the error in the
origin time estimate. Similar sources would have essertially no origin
time errors from stations beyond 6.5 degrees.

5.2   INTERMEDIATE EARTHQUAKES

A distance range of 4.5 to 13.0 degrees was selected for Wadati graph
analysis of the intermediate depth calibration earthquakes, based on results
reported by Kaila, and others (1969) on S and P travel times from Hindu-Kush
earthquakes. This assured that the assumption of a linear relation between
S-P and P-T was valid. Data from earthquakes of similar depth were combined
and least squares estimates of the Wadati graph parameters were determined
for each of 10 depth ranges.

The Wadati graph for intermediate depth earthquakes should not be linear
at distances less than about 4.5 degrees. However, because almost half
the data fall in this distance range, it is of interest to determine if
S and P arrival times at stations in this distance range can be used to
compute accurate origin times using the slope and intercept determined from
Wadat: graph analysis. Such analysis should also aid in investigating
sensitivity of the S/P travel time ratio to changes in focal depth and
epicentral distance over this distance range. Therefore, linear Wadati
graph parameters were also estimated for each of 10 depth ranges using
only arrivals at distances less than 4.5 degrees.

Table 8 lists the Wadati graph parameters estimated for the 10 depth ranges
and the two distance ranges, less than 4.5 degrees and 4.5 to 13.0 degrees.
Figure 12 shows the Wadati graph slopes and τ intercepts, with plus or minus
one standard error limits, as a function of pP depth for the two distance
ranges. Once again there is a suggestion of a change in slope, this time
near 175 km, but there are no statistical differences in the slopes for any
of the various depth ranges in either distance range. However, there is a
significant difference in the slope between the two distance ranges. A
weighted mean value of ρ was determined for all depths for each distance
range. The resultant τ intercepts for each depth range obtained with the
mean values are also given in table 8 and plotted on figure 12. No signifi-
cant depth dependency occurs for either depth range. The mean value of the
τ intercept is also given in table 8.

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Table 8. Intermediate depth Wadati graph parameters, by depth

DEPTH(km)	86-101	116-128	140-153	161-171	195-204	208-216	222-225	228-238	252	280-289
NO. EVENTS	4	4	4	5	4	5	4	8	1	2

Epicentral distance < 4.5°

MEAN DEPTH(km)	95.4	123.3	148.0	163.9	200.1	213.7	223.8	231.8	252.0	282.3
NO. OBSER.	20	22	16	28	18	23	16	44	7	8
$\hat{\rho}$	.724	.714	.709	.685	.749	.704	.754	.735	.756	.746
STANDARD ERROR($\hat{\rho}$)	.032	.026	.040	.023	.034	.029	.030	.016	.040	.032
$\hat{\tau}$ (SECS)	-2.43	-4.08	-4.82	-6.13	-1.56	-4.02	-0.97	-2.80	-1.57	-1.12
STANDARD ERROR($\hat{\tau}$)	1.82	1.32	1.96	1.18	1.88	1.50	1.51	0.86	2.28	2.06

$\overline{\rho}$ = 0.725 $\overline{\tau}$ = -3.19

$\hat{\tau}(\rho=.725)$ (SECS)	-1.92	-3.39	-3.79	-3.55	-3.17	-2.65	-2.71	-3.43	-3.74	-2.76
STANDARD ERROR($\hat{\tau}$)	0.65	0.49	0.55	0.41	0.59	0.42	0.41	0.24	0.58	0.49

Epicentral distance 4.5° - 13.0°

MEAN DEPTH(km)	98.1	123.6	146.6	164.3	199.6	213.6	223.2	231.3	252.0	284.2
NO. OBSER.	19	21	24	25	19	43	19	53	6	17
$\hat{\rho}$	.795	.797	.778	.769	.798	.793	.781	.787	.821	.805
STANDARD ERROR($\hat{\rho}$)	.015	.016	.016	.013	.019	.012	.015	.011	.038	.018
$\hat{\tau}$ (SECS)	+2.56	+2.24	-0.37	-0.88	+2.51	+2.10	+0.97	+0.54	+5.21	+3.33
STANDARD ERROR($\hat{\tau}$)	1.78	2.15	2.10	1.69	2.42	1.55	1.80	1.34	4.84	2.27

$\overline{\rho}$ = 0.788 $\overline{\tau}$ = +1.27

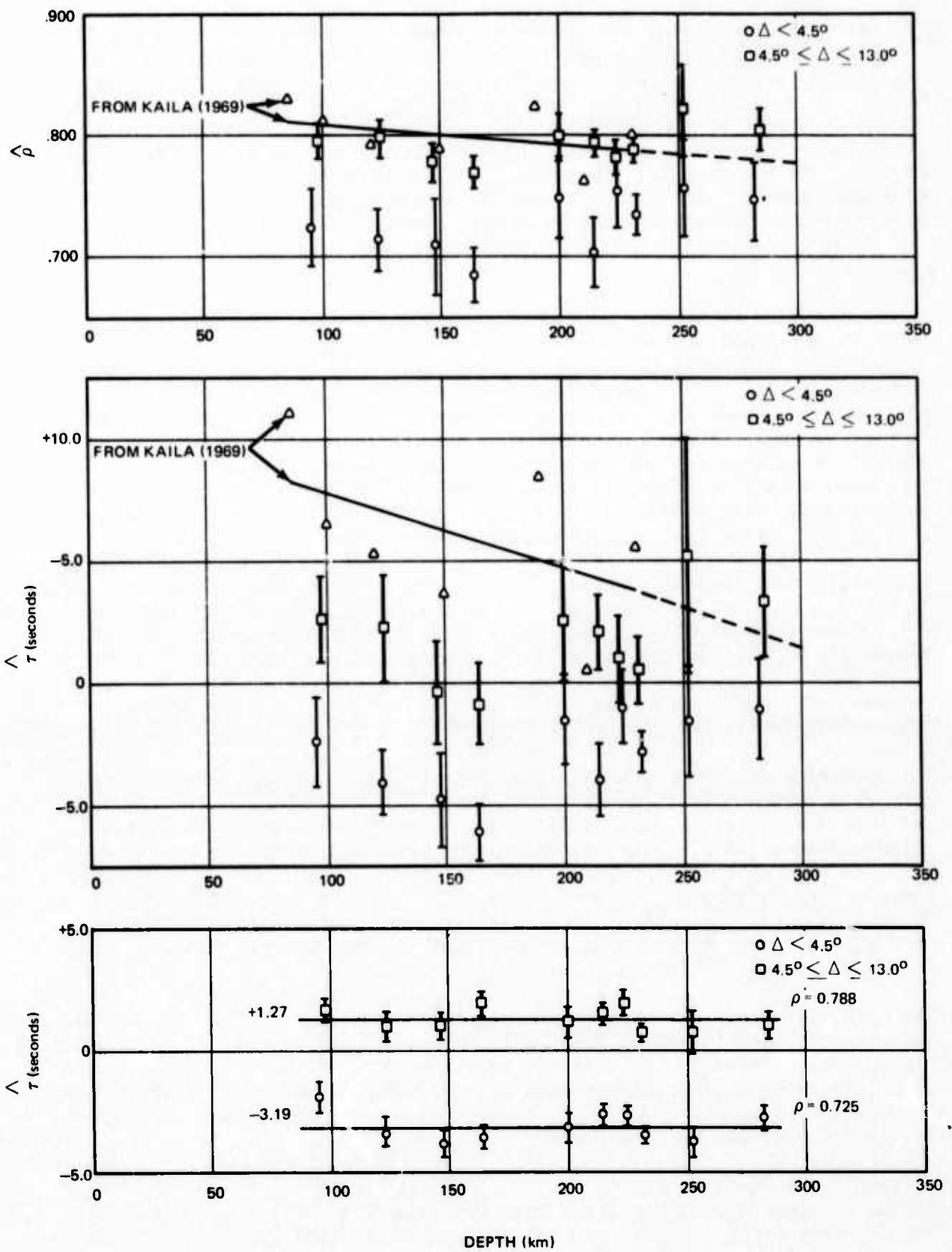|										
$\hat{\tau}(\rho=.788)$ (SECS)	+1.65	+0.97	+0.99	+1.87	+1.14	+1.47	+1.89	+0.71	+0.74	+1.02
STANDARD ERROR($\hat{\tau}$)	0.45	0.64	0.64	0.51	0.62	0.42	0.51	0.35	0.92	0.59

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Figure 12.   Intermediate depth Wadati graph parameters

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For comparison purposes, the values of ρ and τ computed from the P and S velocity values reported by Kaila, and others (1969) for the Hindu-Kush region are plotted on figure 12. Also plotted are the smooth curves of ρ and τ as functions of h(pP) computed from Kaila's linear velocity-depth functions. Most of the difference between Kaila's intercept values and the intercept values determined in the present study can be accounted for by the different P travel times used. Jeffreys-Bullen (1958) travel times (JB) were used in Kaila's study and the Herrin (1968) travel times in the present study. Locations made with Herrin times yield origin times which are about 2.5 seconds later, on the average, than locations made with JB times.

The travel time ratio r, computed with equation 8 using the intermediate depth Wadati graph parameters from table 8, is shown as a function of depth for selected distances in figure 13. The ratio (r) decreases with increasing depth; this is the opposite of the depth effect observed for shallow earthquakes (figure 10). The greatest variation of r with depth, about 14 percent, occurs between 100 and 300 km for a station directly over the source. At 2 degrees, this variation is about 2 percent and beyond 4 degrees, it is less than 0.4 percent. The depth distribution of station observations, also shown on figure 13, suggests that the depth variation of r is well controlled over the distance range from 100 to 300 km.

The origin time errors resulting from the use of an average value of r for either a 100 or 300 km source may now be estimated for stations inside of 4.5 degrees. There is no error for stations beyond 4.5 degrees. The errors are about 1 second for a 100 km source and only about -0.5 second for a 300 km source. These correspond to -10 and +4 km depth errors, respectively; the 100 km source will locate near 90 km and the 300 km source will locate near 305 km.

The variation of the S/P travel time ratio with distance for the intermediate depth earthquakes is shown in figure 14. The distance dependency is greatest for the shallower depths. Once again, this is opposite to the effects observed for shallow earthquakes (figure 11) where the distance variation was greatest for the deepest crustal events. This suggests that the distance variation of r must reach a maximum at a depth somewhere between about 40 and 100 km. The distance distribution of observations also shown on figure 14 suggests that the estimates of r should be good between about 1 and 12 degrees.

The possible origin time errors due to distance effects for 100 and 300 km sources using stations at distances less than 4.5 degrees are about 1.5 and 0.5 seconds, respectively. The corresponding depth errors are about 15 and 5 km. As with the shallow earthquakes, the effects from individual stations of a network which is distributed about the source tend to cancel each other and reduce the size of these errors.

To examine the consistency of origin time estimates using the Wadati graph parameters, and to compare these with the subarea average value results, station mean origin time deviations (S_{zi}) were computed for both the shallow

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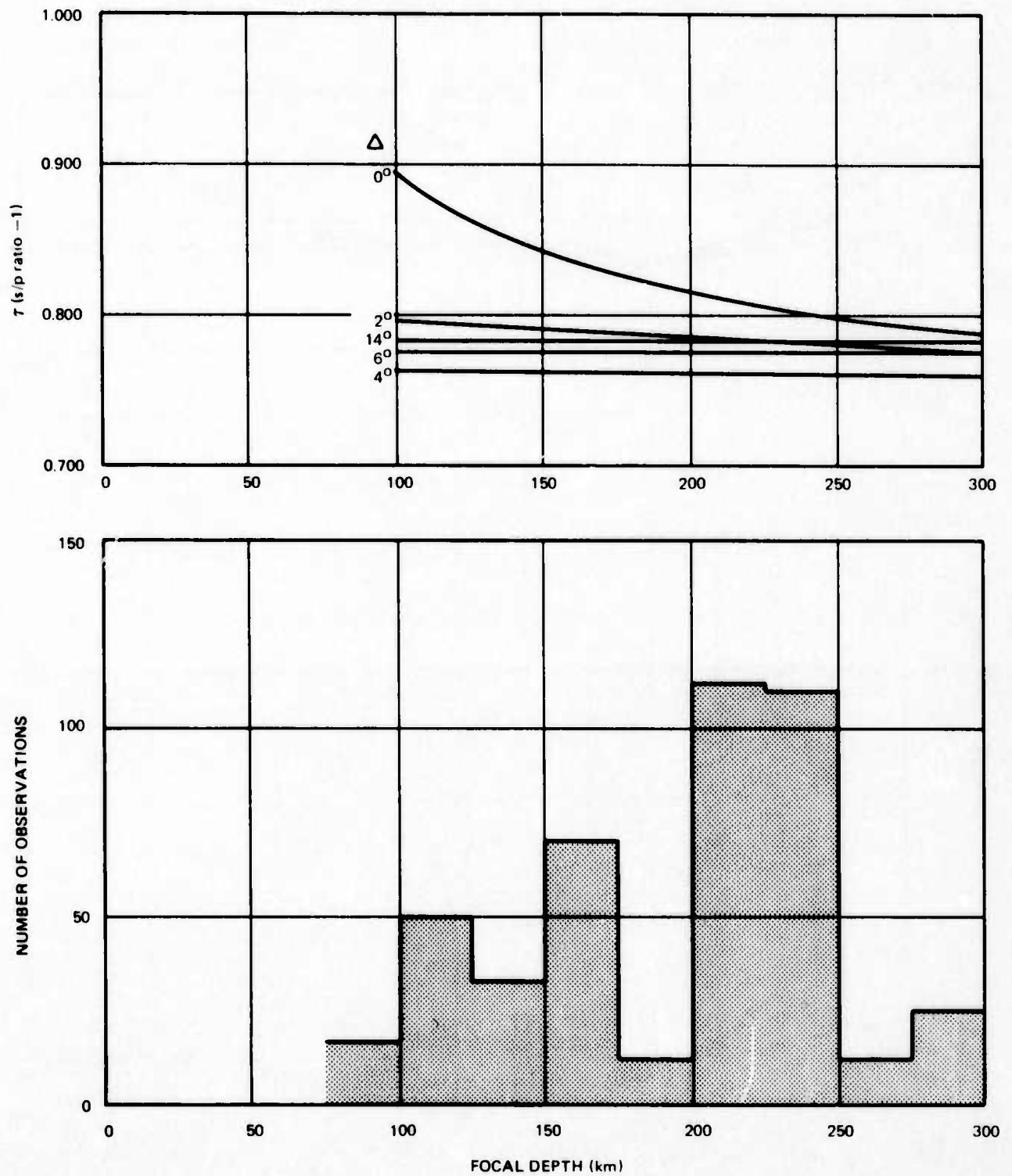
Figure 13. Variation of S/P travel-time ratio with focal depth;
intermediate depth earthquakes

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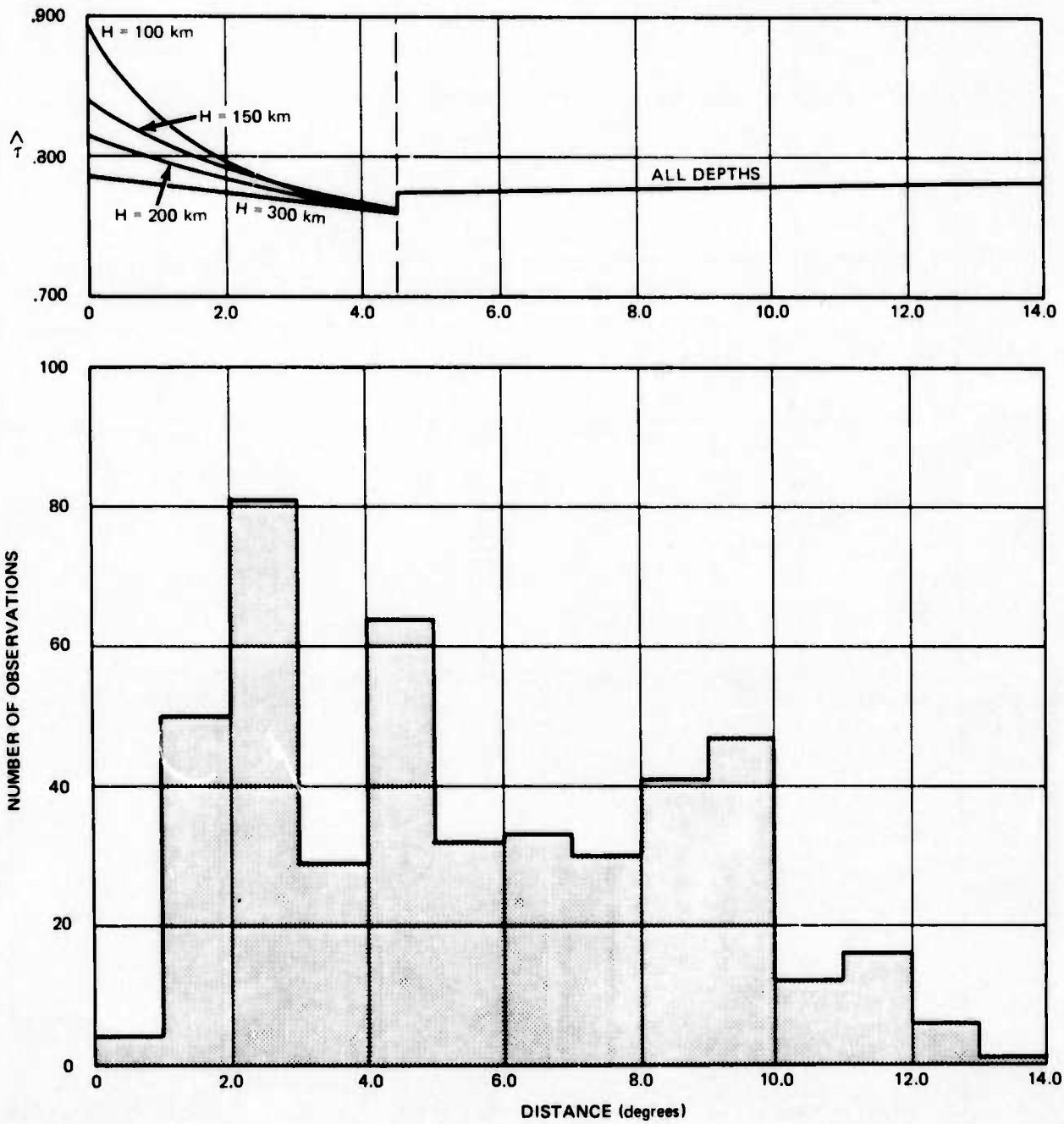
Figure 14. Variation of S/P travel time ratio with distance, intermediate depth earthquakes

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and intermediate depth calibration earthquakes from

$$S_{zi} = \frac{1}{J_i} \sum_{j=1}^{J_i} \{[P-T(pP)]_{ij} - \tau_k(h_j) - (S-P)_{ij}/\rho_k\} \qquad (12)$$

where $i \equiv$ station index

$j \equiv$ event index

$k \equiv$ distance range index

$\left.\begin{matrix} \rho_k \\ \\ \tau_k \end{matrix}\right\}$ Wadati graph parameters

For the shallow earthquakes, the mean Wadati graph parameters listed in table 7 were used to compute the station mean origin time deviations. For the intermediate depth earthquakes, the mean Wadati graph parameters in table 8 were used. Resulting station mean origin time deviations are listed in table 9. These values are consistently larger with larger standard deviations than the corresponding values given in table 4. This should be expected because the Wadati graph parameters describe the average effects from all shallow or all intermediate depth sources to all stations while the subarea average values are average effects from a small region to each particular station.

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Table 9. Station mean origin time deviations, using mean Wadati graph parameters

STATION	SHALLOW EARTHQUAKES				INTERMEDIATE DEPTH EARTHQUAKES			
	NO. OF EVENTS	MEAN DISTANCE DEG.	S_{zi} SECS.	ST.DV. SECS.	NO. OF EVENTS	MEAN DISTANCE DEG.	S_{zi} SECS.	ST.DV. SECS.
AAA	6	3.36	-1.80	2.10	0			
AAB	13	3.47	+0.60	3.56	13	8.48	-1.11	4.84
ANR	24	2.85	+0.80	3.32	28	4.05	-0.74	1.59
ASH	12	10.57	-0.27	4.76	11	10.31	-2.86	2.95
DDI	11	10.12	-2.13	5.77	14	8.59	-0.09	1.74
DSH	14	4.32	-0.90	2.69	34	2.73	0.00	1.95
FRG	9	2.57	-1.04	1.83	9	3.56	-1.22	0.95
FRU	36	4.30	+1.24	4.36	25	6.72	-0.19	1.54
GAR	17	3.87	-0.60	4.67	25	2.51	+0.26	2.57
KAR	0				9	12.08	+2.33	3.64
KAT	21	11.92	+0.04	7.08	12	12.00	-1.40	3.49
KBL*	12	6.94	-0.40	2.15	9	2.31	+0.14	0.98
KHO	25	4.06	0.66	2.84	30	1.18	+0.08	1.34
KUL	7	3.28	-2.29	3.56	21	1.73	-0.66	1.41
LAH*	14	8.97	+0.35	3.03	24	5.88	+1.78	1.50
MNL	15	6.90	+3.73	4.62	12	4.14	+0.31	2.94
MSH*	15	11.33	-1.00	2.74	18	9.43	-0.56	2.27
MUR	8	4.66	+0.52	3.96	7	2.72	+0.41	1.18
NDI	56	11.88	+1.65	3.03	32	9.56	+1.99	1.36
NIL*	19	7.30	+0.14	2.48	8	3.58	-0.82	0.69
NRN	0				5	6.04	-1.76	1.61
PRZ	10	3.79	+0.88	2.77	14	8.36	-2.17	1.79
QUE*	49	11.40	-1.97	2.55	28	7.33	-0.89	1.82
SAM	14	4.93	-0.74	4.90	7	4.33	+2.38	3.12
SEM	12	11.43	+1.55	4.25	0			
TAS	31	4.38	-1.22	4.43	33	4.83	+0.09	1.75
WRS	9	6.54	-3.17	6.64	10	2.94	+1.08	3.09

* WWSSN station

6. RELOCATION OF TEST EARTHQUAKES

Eight intermediate depth and 15 shallow earthquakes for which focal depth had been established from depth phase information were relocated with origin time restrained to the value determined from S and P arrival times and the station regional mean travel time ratios (table 3). None of the test earthquakes were used to calibrate the stations for the S/P travel time ratio. Locations of the test events are shown in figure 1. Table 10 lists the test earthquake epicenters, pP depth (h(pP)), and S/P depth (h(S/P)). S/P depths of all intermediate depth test earthquakes were within 7 km of h(pP). S/P depths of all but three of the shallow test earthquakes were within 9 km of h(pP). For the 12 April 1972 earthquake in subarea 1, with a S/P depth error of -27 km, the S/P origin time estimates for individual stations were inconsistent; the standard deviation of S/P origin time estimates being 4.8 seconds. Therefore, the large S/P depth error for this earthquake probably should not be considered a failure of the S/P technique. The S/P origin time estimate for the 28 August 1969 earthquake in subarea 5, with an S/P depth error of -11 km, was based on S and P arrival times at only two stations, although the origin time estimates for the two stations agreed well with each other. For the 11 February 1972 earthquake in subarea 8, with an S/P depth error of +24 km, S and P arrival times at 6 stations were available and the consistency of the S/P origin time estimates for the individual stations was fair; the standard deviation of S/P origin time estimates being 1.8 seconds. Reliability of the pP depth estimate for this earthquake is considered fair. If the pP depth estimate of 15 km is accepted for this earthquake, the S/P depth estimate of 39 km must be considered a failure of the S/P depth estimation technique. However, in view of the consistency of the individual S/P origin time estimates for this earthquake, the possibility of an error in the pP depth estimate cannot be discounted.

Table 10. Test earthquake relocations

SUBAREA	DATE	NORTH LATITUDE	EAST LONGITUDE	h(pP)	h(S/P)
		SHALLOW EARTHQUAKES			
1	12 Apr 72	37.83	66.71	27	0*
2	30 May 72	38.18	69.73	6	0*
3	10 Feb 71	38.85	70.61	11	20
4	18 Apr 71	39.09	71.75	22	18
5	27 Apr 71	39.48	72.91	16	17
5	28 Aug 69	39.23	73.68	11	0*
6	14 Sep 69	39.75	74.83	34	32
8	15 Jan 72	39.79	79.30	5	0*
8	15 Jan 72	39.77	78.99	8	0*
8	11 Feb 72	39.85	77.30	15	39
9	23 Mar 71	41.45	79.28	14	22
9	16 Jun 71	41.48	79.29	12	13
11	23 Apr 70	37.55	72.68	8	17
12	19 Oct 68	37.56	73.24	7	2
15	17 Mar 72	40.07	69.71	5	3

*orbit

SUBAREA	DATE	NORTH LATITUDE	EAST LONGITUDE	h(pP)	h(S/P)
		INTERMEDIATE DEPTH EARTHQUAKES			
19	20 Jan 72	36.38	70.70	224	225
19	22 Feb 72	36.46	70.51	220	215
19	29 May 72	36.51	70.77	235	235
19	20 Jun 72	36.38	71.41	121	125
20	24 Nov 69	37.19	71.66	127	127
21	05 Feb 72	38.37	73.64	143	136
21	04 Mar 72	38.31	73.94	149	145
21	05 Apr 72	38.39	73.41	129	128

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7. CONCLUSIONS AND RECOMMENDATIONS

The S/P travel time ratio technique of computing focal depth will yield accurate depth estimates and thus identify Hindu-Kush intermediate depth earthquakes if reliable S and P arrival times at stations within 13 degrees of the epicenter are available. Variation with distance of the S/P travel time ratio for intermediate depth earthquakes is weak over the distance range 4.5 to 13 degrees. For distance less than 4.5 degrees, the S/P travel time ratio increases rapidly with decreasing distance. The effects of this variation tend to cancel for a distributed network of close-in stations. The depth dependence of the S/P travel time ratio is weak for distances greater than 4.5 degrees and can be neglected for identification purposes. Even at distances less than 4.5 degrees, the effects of the changing value of r will not prevent a valid identification of the source.

For shallow earthquakes in the Hindu-Kush, Pamir, and Tien Shan regions, variation of the S/P travel time ratio with distance is weak over the distance range 6.5 to 14 degrees. For distances less than 6.5 degrees, the S/P travel time ratio increases with decreasing distance. These effects also tend to cancel for a distributed network of close-in stations. The S/P travel time ratio for shallow earthquakes in this region varies with focal depth, the depth dependence of the ratio being stronger at closer distances. The S/P travel time ratio technique is useful for estimating focal depth of shallow central Asia earthquakes, although its capability for identifying shallow earthquakes is limited by depth dependence of the ratio and uncertainty in observed arrival times, especially the S arrival time, together with the very shallow depths of most shallow earthquakes in this region.

We recommend that other regions of special interest, for which adequate close-in P and S data are available, be calibrated for the S/P travel time ratio for close-in stations. Other depth refinement techniques, in particular, the technique employing source-region/station time (SRST) corrections (Veith, 1973) should also be applied. The two techniques should be employed together to increase the resolution of the focal depth by the close-in stations.

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The S/P travel time ratio for intermediate depth Hindu-Kush earthquakes and shallow earthquakes in the Hindu-Kush, Pamir, and Tien Shan regions is investigated, using S and P arrival times at 6 World Wide Standard Seismograph Network stations and 19 other close-in stations.

For intermediate depth earthquakes, station mean values of the ratio average 1.78, ranging from 1.76 to 1.81. The ratio increases slowly with increasing

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20. distance over the range 4.5 to 13 degrees and increases rapidly with decreasing distance for distances less than 4.5 degrees. Variation of the ratio with focal depth is weak. The standard deviation of S/P origin time deviations from origin times based on locations restrained to pP depth is about 0.8 second, implying a standard deviation of S/P depth error, relative to pP depth, of about 8 km. S/P depths of 8 intermediate depth earthquakes, relocated with origin time restrained to the value determined from close-in P and S arrival times and regional mean S/P travel time ratios, were all within 7 km of the pP depths.

For shallow earthquakes, station mean values of the S/P travel time ratio average 1.78, ranging from 1.75 to 1.83. For the distance range 6.5 to 14 degrees, variation of the ratio with distance is weak, and for distances less than 6.5 degrees the ratio increases with decreasing distance. The S/P travel time ratio increases with increasing focal depth, the depth dependence being stronger at closer distances. The standard deviation of S/P origin time deviations from pP origin time is about 1.2 second for shallow earthquakes, implying a standard deviation of S/P depth error, relative to pP depth, of about 9 km. S/P depths for 12 of 15 shallow earthquakes relocated with origin time restrained to the value determined from S and P arrival times and regional mean S/P travel time ratios were within 9 km of the pP depths.