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SHORT-PERIOD EARTHQUAKE CODA SHAPE AS A FUNCTION OF GEOLOGY AND SYSTEM RESPONSE

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7 October 1975

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Measurements of short-period records from 33 earthquakes show that some Long Range Seismic Measurement (LRSM) stations have high levels of coda as compared to maximum motion, and that reverberation between successive coda maxima is less at stations overlying a low Q mantle than at those overlying a high Q mantle. The differences are 0.1-0.2, and 0.1 magnitude units respectively. For times greater than 1 or 2 minutes into the coda, minimal coda levels are typically 0.3 magnitude units less than the maxima. Comparison

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SHORT-PERIOD EARTHQUAKE CODA SHAPE AS A FUNCTION OF GEOLOGY AND SYSTEM RESPONSE

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ABSTRACT

Measurements of short-period records from 33 earthquakes show that some Long Range Seismic Measurement (LRSM) stations have high levels of coda as compared to maximum motion, and that reverberation between successive coda maxima is less at stations overlying a low Q mantle than at those overlying a high Q mantle. The differences are 0.1-0.2, and 0.1 magnitude units respectively. For times greater than 1 or 2 minutes into the coda, minimal coda levels are typically 0.3 magnitude units less than the maxima. Comparison with work by Filson shows that use of the maximum coda representation could lead to a 0.2 m_b underestimation of the detection capability for mixed events for times greater than 2 minutes. There seems to be no difference in coda shape measurements made on data recorded at WWSSN or LRSM systems.

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INTRODUCTION

The hide-in-earthquake (HIE) evasion technique has been briefly discussed in congressional testimony by Lukasik (1971) and in the literature by Blandford et al. (1971), Fink et al. (1971), Blandford and Husted (1973), Filson (1973), and Jeppsson (1975). To use the HIE technique, the evader waits for a large earthquake and then detonates his test, relying on the seismic noise from the earthquake to conceal the signal from the explosion.

In each of the studies cited above, it was necessary to estimate the earthquake coda shape in order to calculate the probability of the maximum of an explosion signal rising above the coda of the earthquake at any time after the arrival of the earthquake signal. The most exhaustive studies of earthquake codas have been those carried out at the Seismic Data Analysis Center (SDAC): Cohen et al. (1972), Sweetser et al. (1973), Cohen and

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Lukasik, S., 1971, In Hearings on Status of current technology to identify seismic events as natural or man-made, before the Joint Committee on Atomic Energy of the Congress of the United States, October 1971. GPO No. 69-648.

Blandford, R. R., T. J. Cohen, and H. L. Husted, 1971, Opportunities for foreign nations to hide an underground nuclear test in an earthquake, Seismic Data Laboratory Report No. 283, Teledyne Geotech, Alexandria, Virginia.

Fink, D. R., L. R. Miamidian, and W. Myers, 1971, Seismic Network Studies (U) CLASSIFIED, LOG GAC 7157, General Atronics Magnavox, Philadelphia, Pennsylvania.

Blandford, R. R. and H. L. Husted, 1973, Extension of Hide-In-Earthquake (HIE) technique to include probability of detection (U) CLASSIFIED, Seismic Data Laboratory Report No. 303, Teledyne Geotech, Alexandria, Virginia.

Filson, J. R., 1973, On estimating the effect of Asian earthquake codas to the explosion detection capability of LASA, Technical Report 1973-29, Lincoln Laboratory, Massachusetts Institute of Technology.

Jeppsson, Ingvar, 1975, Evasion by hiding in earthquake, FOA Rapport C 20043-T1, Forsvarets Forskningsanstalt, Stockholm, Sweden.

Cohen, T. J., E. T. Sweetser, and T. J. Dutterer, 1972, P and PKP coda decay characteristics for earthquakes, Seismic Data Laboratory Report No. 301, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I., T. J. Cohen, and M. F. Tillman, 1973, Average P and PKP codas for earthquakes, Seismic Data Laboratory Report No. 305, Teledyne Geotech, Alexandria, Virginia.

Sweetser (1973), Sweetser and Cohen (1973), Sweetser and Cohen (1974). These workers chose to parameterize the coda by film measurements of the maximum amplitude near 1 Hz in consecutive time intervals. The time intervals chosen were 0-5, 5-10 and every 10 seconds out to 1 minute and then at 1-minute intervals to the point where the coda returned to background noise levels. The SDAC studies have fairly well covered the distance range from 10°-180° and have treated the problem of false alarms as a function of mixed-event detection threshold. Sweetser and Blandford (1973) obtained distance-amplitude relations for $\Delta > 90°$ so that these coda shapes could be properly scaled with distance. This study also made it possible to discuss counterevasion possibilities offered by the earthquake core-shadow zone and by the explosion PKP caustic.

Fink et al. (1971) and Jeppsson (1975), the latter using data from Hagfors in Sweden (HFS), published coda shapes which fall off much more rapidly than those of Cohen and Sweetser. To some extent this appears to be a matter of data selection. The small samples of Fink et al. and of Jeppsson seem to have overemphasized the rapidly decaying signals which are often observed. Also, Fink et al. and Jeppsson applied "smoothing" procedures which tend to eliminate the "false alarms" in the coda, but which are not applied to the mixed event.

The results of these authors do, however, suggest a problem which is difficult to treat without an elaborate analyst detection experiment similar to the ones performed by Jeppsson and by Filson (1973) in which they buried explosion signals in earthquake coda. Cohen and Sweetser's coda-measurement technique is based on the hypothesis that an analyst cannot detect an arrival without an excessive false alarm rate unless the arrival is an appreciable fraction of the maximum in the time intervals which they selected. It seems

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Cohen, T. J. and E. I. Sweetser, 1973, False alarm probabilities for mixed events, SDAC-TR-73-8, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1973, Average P and PKP codas for earthquakes (103°-118°), SDAC-TR-73-10, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1974, Average P and PKP codas for earthquakes (118°-180°), SDAC-TR-74-19, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and R. R. Blandford, 1973, Seismic distance-amplitude relations for short-period P, P_{diff}, PP and compressional core phases for $\Delta > 90°$, SDAC-TR-73-9, Teledyne Geotech, Alexandria, Virginia.

possible that between the maxima in the coda which are separated by 1 minute or more; there might be 10-second intervals of substantially lower amplitude; as such, a signal which might otherwise be masked could be detected with a low false-alarm rate if it arrived in this time interval. In this study we estimate that the maximum size of such an effect is 0.3 magnitude units.

Filson's (1973) results for Kurile "explosions" in Kurile earthquakes can be interpreted to support the coda measurement concepts of Cohen and Sweetser for the first one or two minutes. Figure 1 gives the number of explosions, set off at 20-second intervals from the start of the earthquake coda, which are undetected by the LASA-SAAC detection algorithm. The dashed line has been drawn by us to give the median number of explosions (length of hiding time) as a function of the difference between the earthquake and explosion magnitudes. Filson's single-station false alarm rate (2 out of 34 earthquakes) is comparable to the 1 in 10 established by Cohen and Sweetser (1973) for a signal to coda detection ratio of 1.5 and is a reasonable rate for network operations if detection and location by 3-4 stations is required; see Cohen and Sweetser (1973).

We see that for a magnitude difference of 0.5 m_b, the median number of explosions hidden is 5, which for the 20-second intervals used by Filson corresponds to 100 seconds or approximately 2 minutes. This result is consistent with the median Kamchatka-Kuriles coda shapes determined by Cohen and Sweetser, which typically fall 0.7 m_b units in 2 minutes, and for which a signal/coda ratio of 1.5 is required for detection. These results are, however, inconsistent with coda shapes which fall a full magnitude unit or more in 2 minutes as determined by Jeppsson. As mentioned above, it appears that Jeppsson has a biased sample of codas. It is, of course, possible that HFS has simpler coda shapes than LASA or the WWSSN stations used by Cohen and Sweetser. At four minutes after first motion Filson's figure gives $\sim$1.0 m_b units, about the same result as given by Cohen and Sweetser. However, Cohen and Sweetser require a 1.5 signal-to-coda ratio for detection. This suggests that for large times, automatic detection can reliably detect $\log_{10}(1.5)=0.2$ m_b below the levels reported by Cohen and Sweetser.

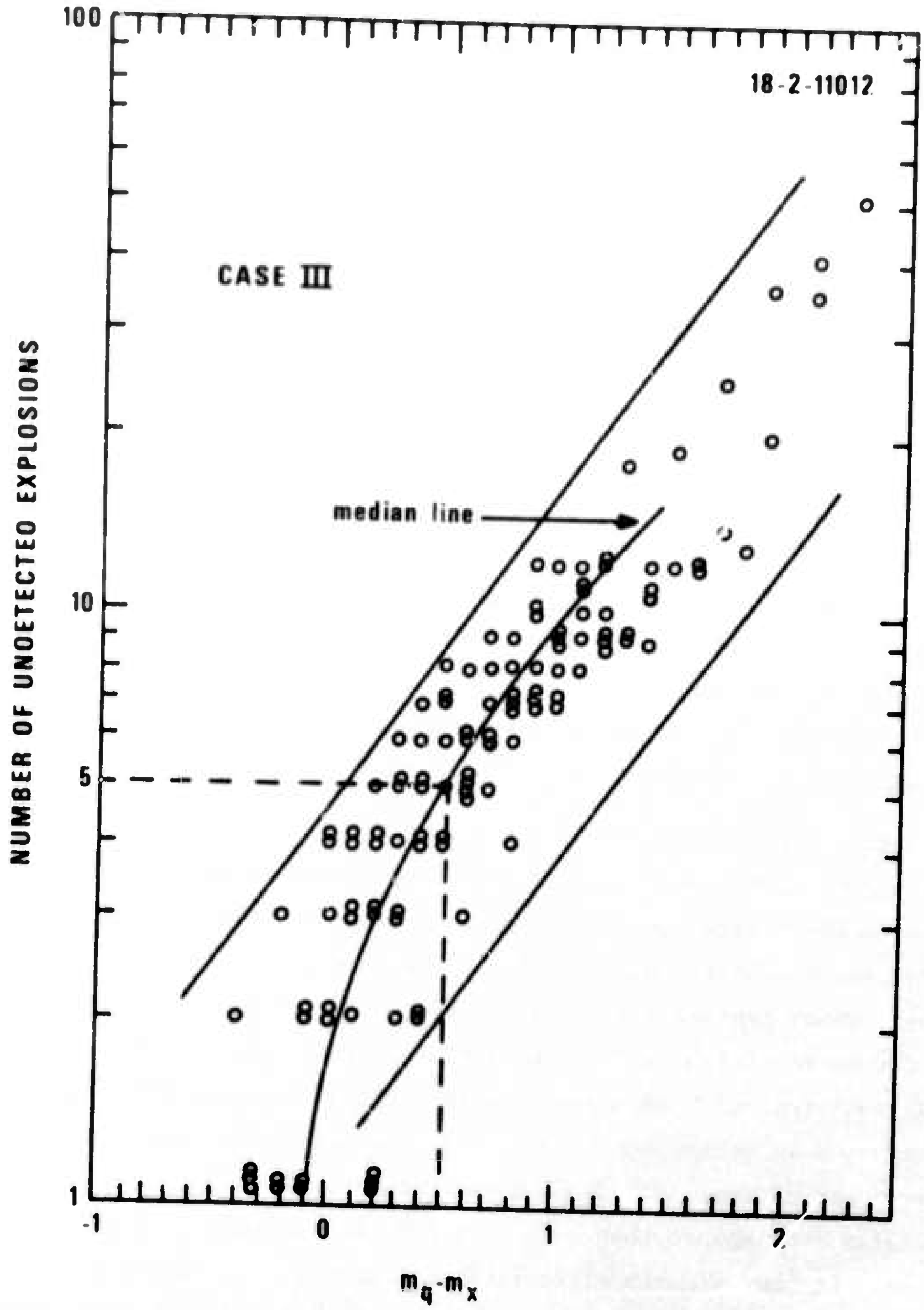

Figure 1. Hypothetical Kuriles explosions undetected on the LASA beam aimed at the Kurile Islands due to Kurile Islands earthquakes. From Filson (1973).

Other questions which have arisen with respect to coda measurements will also be treated in this report. It is conceivable that stations in different tectonic settings could have different coda shapes. For example, signals received at a station on thick sediments might be expected to have long reverberation times while stations on granite might have rapidly-decaying codas. One might also suspect that stations above low-Q regions of the mantle would have upper-mantle reverberations damped out so that in the times between arrivals of major phases, the coda levels would be low.

One might also question whether the analysts measuring the codas have been successful in measuring, on the WWSSN short-period systems, amplitudes for periods close to 1.0 Hz. It seems possible that the coda shapes could differ if measured on LRSM systems, which peak at shorter periods. We shall investigate this question in this report.

The problem of regionalization, picking out areas where coda shapes offer little opportunities for evasion by HIE or shot arrays, has recently been discussed with respect to LASA recordings of Kamchatka data by Blandford and Clark (1975).

Blandford, R. R. and D. Clark, 1975, Variability of seismic waveforms at LASA from small subregions of Kamchatka, SDAC-TR-75-12, Teledyne Geotech, Alexandria, Virginia.

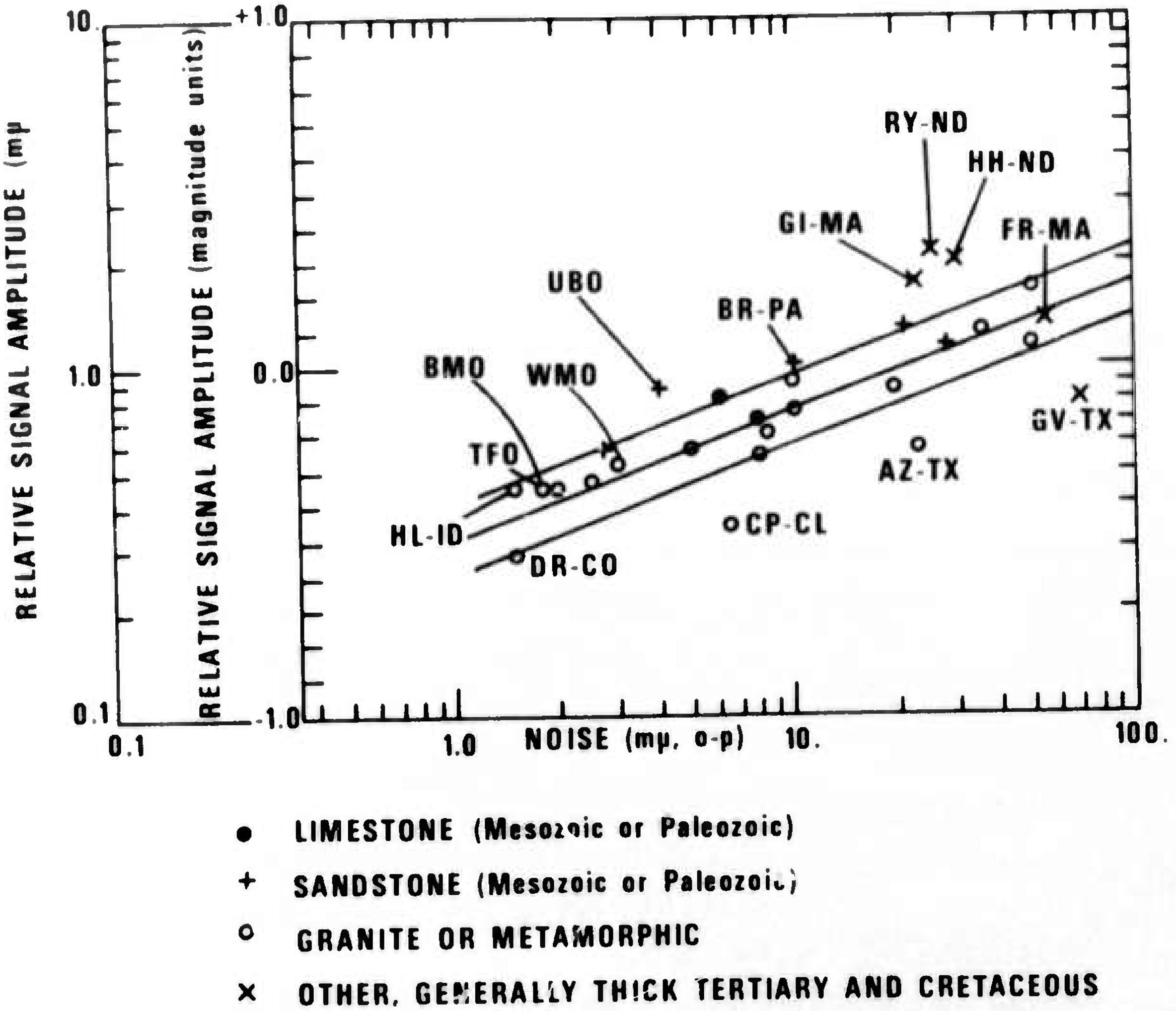

Figure 2. Relative signal amplitude (BRPA 1.0) versus noise. From Evernden and Clark (1970b).

DATA SELECTION

Table I lists the stations which provided data for this report. They were selected after reference to Figure 2, taken from Evernden and Clark (1970b). Stations at the extremes of the plotted distribution were selected together with station BRPA, Evernden and Clark's reference station, located at 0.0 relative signal amplitude and 10 mμ noise level. Stations PIWY, PI2WY and TFO were also included. Note that PIWY and PI2WY, although close to each other geographically are located on substantially different types of rock.

Table II gives the events examined in the study. The first seven events were taken from Table Ib of Evernden and Clark (1970a). Only seven events were chosen for an initial study since we required that signals had to be readable at PIWY, the reference station, and at several of the other stations of interest. Further we required that the events chosen could not be too close or too far from the United States in order that the signals would arrive at all the stations of interest in the teleseismic distance range.

After performing preliminary studies with the first seven events in Table II, we found that more data were required. We decided to make an intensive investigation of stations BRPA, CPCL, PIWY, PI2WY, and RYND. Station TFO was selected as a reference since it was in operation continuously during the operation of all the other stations, and since both high- and low-gain films at TFO made almost all events readable at this station. All National Earthquake Information Service (NEIS) events in the following categories were examined for the time interval 1 January 1963 - 31 December 1965: Alaska, the Aleutian Islands, and South and Central America (Seismic Regions 1, 6, 8), $m_b \geq 5.6$; and the Kurile Islands (Seismic Region 19), $m_b \geq 5.3$. Since all but one of the initial seven events were deep, we required that the new events selected have depths $\leq$ 70 km. The requirement that the event be readable, and in the teleseismic P range at TFO and at one other station, then permitted the selection of the remaining 26 events in Table II.

Evernden, J. F. and D. Clark, 1970b, Study of teleseismic P...II amplitude data, Phys. Earth Planet. Interiors, 4, 24-31.

Evernden, J. F. and D. Clark, 1970a, Study of teleseismic P...I travel-time data, Phys. Earth Planet. Interiors, 4, 1-23.

TABLE I

Station Information

STATION DESIGNATOR	LOCATION	LATITUDE Deg Min Sec	LONGITUDE Deg Min Sec	ELEVATION (Meters)	DATES OF OPERATION (Inclusive)	GEOLOGY
AZ-TX	Amarillo, Texas	35 25 48 N	101 55 50 W	988	28 Aug 63 - 06 Mar 64	Dolomite (Palaeozoic)
BR-PA	Berlin, Pennsylvania	39 55 27 N	78 50 41 W	665	30 Dec 62 - 23 Jul 65	Sandstone (Palaeozoic)
CP-CL	Campo, California	32 43 44 N	116 22 16 W	1189	10 Oct 61 - 01 Mar 64	Granite
DR-CO	Durango, Colorado	37 27 53 N	107 47 00 W	2225	01 Oct 61 - 30 Dec 64	Granite
FR-MA	Forsyth, Montana	46 06 00 N	106 26 25 W	823	07 Jul 63 - 05 Aug 64	Sediment (Tertiary)
GI-MA	Glendive, Montana	47 11 34 N	104 13 10 W	732	17 Jul 63 - 05 Aug 64	Sediment (Tertiary)
GV-TX	Grapevine, Texas	32 53 09 N	96 59 54 W	152	02 Jun 62 - 31 Dec 65	Sediment (Tertiary)
HH-ND	Hannah, North Dakota	48 56 53 N	98 41 33 W	488	22 Jul 63 - 05 Aug 64	Shale (Mesozoic)
HL-ID	Hailey, Idaho	43 38 50 N	114 15 02 W	1890	14 Oct 61 - 07 Mar 64	Metamorphic (Granite)
KM-CL	Kramer, California	34 52 52 N	117 15 24 W	853	14 Jan 64 - 21 Mar 64	Dolomite (Palaeozoic)
PI-WY	Pinedale, Wyoming	42 27 10 N	109 32 55 W	2170	22 Jan 64 - 29 Apr 64	Sandstone (Tertiary)
PI2WY	Pinedale, Wyoming	42 46 02 N	109 33 43 W	2195	01 Mar 65 - 26 Apr 65	Granite (Pre-Cambrian)
RY-ND	Ryder, North Dakota	48 05 50 N	101 29 40 W	640	22 Jul 63 - 22 Mar 65	Sediment (Tertiary)
SK-TX	Shamrock, Texas	35 04 58 N	100 21 50 W	671	19 Aug 63 - 06 Mar 64	Sediment (Palaeozoic)
TFO	Tonto Forest, Arizona	34 16 04 N	111 16 13 W	1609	14 Jul 62 - 28 Feb 75	Granite

TABLE IIa

Events Analyzed
(Evernden and Clark, Part I Table 1b)

TABLE 1b EVENT NUMBER	DATE	ORIGIN TIME Hr Min Sec	LATITUDE Deg Min Sec	LONGITUDE Deg Min Sec	DEPTH (km)	NOAA m_b	AREA LOCATION	AZ-TX	BR-PA	CP-CL	DR-CO	FR-MA	GI-MA	GV-TX	HH-ND	HL-ID	KM-CL	PI-WY	RY-ND	SK-TX	TFO
53	26 Jan 64	09 09 36.3	16 14 48 S	71 29 30 W	116	6.1	Peru	58.9°		64.8°	63.4°	69.6°	69.6°	54.6°	69.2°	71.2°		68.1°	69.4°		62.8°
7	01 Feb 64	01 47 53.4	51 45 24 N	170 59 42 W	45	5.2	Fox Islands	50.6°	61.0°	43.4°	45.7°	41.4°				38.0°		41.6°			45.6°
64	06 Feb 64	04 35 56.8	6 43 18 N	73 13 30 W	140	5.0	Colombia				43.9°	48.6°	48.3°			51.4°		47.9°		37.7°	44.6°
14	08 Feb 64	11 17 48.5	52 13 24 N	175 30 00 E	94	5.4	Rat Islands		67.8°	51.8°	53.8°	49.0°	49.6°		51.4°	46.0°		49.5°	50.5°	59.7°	53.9°
50	16 Mar 64	08 44 34.1	44 46 36 N	147 02 18 E	148	5.7	Kuril Islands		86.2°		74.1°	68.8°	69.2°		70.5°		70.2°	69.6°	69.8°		74.2°
20	18 Mar 64	04 37 27.1	52 33 00 N	153 40 12 E	440	5.6	Sea of Okhotsk		77.3°		66.0°		60.6°	75.1°	61.8°			61.4°			66.5°
62	22 Mar 64	07 05 41.3	5 34 42 S	76 56 18 W	147	5.1	Northern Peru		45.2°		51.4°	57.6°	57.7°	42.6°	57.4°			56.1°			51.0°

TABLE IIb

Events Analyzed

EVENT NO.	DATE	ORIGIN TIME Hr Min Sec	LATITUDE (Degrees)	LONGITUDE (Degrees)	DEPTH (km)	NOAA m_b	AREA LOCATION	TFO	BR-PA	CP-CL	PI-WY	PI2WY	RY-ND
1	10 May 63	22 22 42.7	2.1S	77.6W	30	5.8	Peru-Ecuador Border	48.2°	42.0°	50.5°			
2	22 May 63	13 56 47.5	48.[illegible]	154.8E	54	6.4	Kurile Islands	67.3°	79.5°	65.3°			
3	26 Jun 63	17 42 42.2	7.0N	82.3W	34	6.0	South of Panama	38.2°	33.1°	40.7°			
4	28 Jun 63	21 55 36.8	46.7N	153.3E	12	6.2	Kurile Islands	69.1°	81.7°	67.0°			
5	29 Aug 63	15 30 31.4	7.1S	81.6W	23	6.1	Off Coast of Northern Peru	50.0°	47.1°	51.8°			57.9°
6	03 Nov 63	03 10 12.7	3.5S	77.8W	33	6.0	Peru-Ecuador Border	49.2°	43.4°	51.4°			55.6°
7	05 Feb 64	11 30 15.7	36.5N	141.0E	46	5.4	Near East Coast of Honshu, Japan	82.4°		80.0°	78.2°		
8	22 Feb 64	17 50 56.2	48.5N	154.9E	60	5.3	Kurile Islands	67.3°			62.7°		
9	31 Mar 64	00 14 11.7	45.3N	151.0E	60	5.3	Kurile Islands	71.2°	81.5°		66.7°		67.2°
10	08 Apr 64	10 58 09.1	45.8N	150.8E	40	5.5	Kurile Islands	71.1°	84.3°		66.5°		66.9°
11	18 Apr 64	05 27 44.6	45.5N	151.1E	33	5.3	Kurile Islands	71.0°			66.6°		
12	07 May 64	07 58 14.3	40.4N	139.0E	33	6.2	Near West Coast of Honshu, Japan	81.2°	92.6°				76.6°
13	07 May 64	20 12 49.3	40.5N	139.0E	33	5.9	Near West Coast of Honshu, Japan	81.1°	92.5°				
14	24 Jul 64	06 50 52.8	46.9N	153.9E	33	5.9	Kurile Islands	68.7°	81.3°				64.6°
15	24 Jul 64	08 12 40.0	47.2N	153.8E	33	5.9	Kurile Islands	68.6°	81.1°				64.5°
16	24 Jul 64	17 02 49.2	47.1N	153.6E	33	5.8	Kurile Islands	68.7°	81.2°				64.6°
17	25 Jul 64	19 31 07.0	27.9S	70.9W	26	6.1	Near Coast of Northern Chile	73.0°	68.2°				80.8°
18	30 Jul 64	05 16 03.3	11.1N	86.2W	42	5.7	Near Coast of Nicaragua	32.5°	29.5°				39.1°
19	08 Aug 64	15 45 10.9	12.5N	87.8W	63	5.8	Near Coast of Nicaragua	30.5°	28.5°				37.4°
20	22 Mar 65	22 56 26.5	31.9S	71.5W	46	6.0	Near Coast of Central Chile	76.0°	72.1°			82.1°	84.4°
21	28 Mar 65	13 22 57.6	55.1N	162.1E	33	5.9	Near East Coast of Kamchatka	60.7°	71.7°			55.5°	
22	29 Mar 65	10 47 37.6	40.8N	142.8E	33	6.1	Near East Coast of Honshu, Japan	78.7°	90.8°			74.2°	
23	30 Mar 65	[illegible] 34.1	41.0N	142.7E	32	5.7	Hokkaido, Japan Region	78.6°				74.1°	
24	06 Apr 65	03 31 59.7	36.1N	139.6E	69	5.7	Honshu, Japan	83.5°				79.3°	
25	15 Apr 65	23 41 58.8	34.9N	138.0E	36	5.6	Near South Coast of Honshu, Japan	85.3°				81.1°	
26	20 Apr 65	06 50 [illegible]7.6	54.6N	161.4E	33	5.3	Near East Coast of Kamchatka	61.2°				56.1°	

SHORT-PERIOD CODA SHAPE DIFFERENCES
AS A FUNCTION OF GEOLOGY

Table III gives the Table IIb event maximum-amplitude coda data used in this report for stations PIWY, PI2WY, TFO, and BRPA. The data are reported as the $\log_{10}$ of the coda percentage of maximum motion.

Differences in coda shape are determined by calculating the differences in the logarithms at two stations for a set of common events, and by averaging the differences over the events. When this had been accomplished, inspection of the data at times beyond 30 seconds revealed that one cannot usually reject the hypothesis that the mean difference is constant with time. Therefore, in Table IV we summarize coda shape differences between station pairs averaged over events. The first number reported is the average difference in the first 10 seconds, and the second number is the average difference after 30 seconds. The averaging after 30 seconds is carried out to times T_{all} such that both stations are still reporting for all events. This avoids biasing the averages with slowly decaying events which continue to be detected for long times.

In the first part of Table IV, utilizing the preliminary seven events from Evernden and Clark (1970a), PIWY is the reference station; in the second part, TFO is the reference station. Examination of both parts of Table IV shows that station PIWY, but not PI2WY, is in a class by itself in having coda on the order of 0.2 magnitude units larger than the other stations. Stations HLID is 0.1 magnitude units lower, FRMA and DRCO somewhat lower still. There is no obvious correlation with region or type of station bedrock, and we therefore have no explanation for the observed facts. It seems possible, however, that structural complexities may break up the initial pulse at PIWY so that the remaining signal seems larger by comparison.

In Figure 3 we see the short-period vertical waveforms for the 16 March 1964 event at PIWY and BRPA; we can see directly that the coda decays more slowly at PIWY.

TABLE III

PIWY, PI2WY, TFO and BRPA Coda Data

Date	NOAA m_b	Δ°	Event No. from Table IIb	0-5	5-10	10-20	20-30	30-40	40-50	50-60	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
PIWY, PI2WY CODA																									
05 Feb 64	5.4	78.2°	7	1.46	1.42	2.00	1.94	1.78	1.99	1.68	1.90	1.74	1.56	1.56											
22 Feb 64	5.3	62.7°	8	2.00	1.69	1.69	1.71	1.71	1.76	1.53	1.46	1.38	1.30												
31 Mar 64	5.3	66.7°	9	1.74	1.58	1.92	1.84	2.00	1.96	1.95	1.85	1.84	1.61	1.52	1.45	1.38									
08 Apr 64	5.5	66.5°	10	1.86	1.61	1.91	1.95	1.85	1.89	1.92	2.00	1.66	1.62	1.64	1.46	1.41	1.23	1.36	1.41	1.46	1.41	1.23			
18 Apr 64	5.3	66.6°	11	1.65	1.81	1.95	1.91	2.00	1.86	1.91	1.79	1.58	1.58	1.52	1.38										
22 Mar 65	6.0	84.4°	20	1.75	1.58	2.00	1.82	1.86	1.76	1.79	1.78	1.48	1.34	1.20	1.00	1.15	.95	1.00	.95	.108	1.00	1.00			
28 Mar 65	5.9	55.5°	21	2.00	1.97	1.67	1.60	1.61	1.57	1.51	1.54	1.26	.95	.85	.90	.78	.95	.85	.70						
29 Mar 65	6.1	74.2°	22	1.81	1.69	2.00	1.80	1.76	1.73	1.66	1.60	1.30	1.45	1.08	1.11	.90	.85	.85	1.00	1.11	1.08	.90	.95	.85	.78
30 Mar 65	5.7	74.1°	23	1.48	1.48	2.00	1.65	1.74	1.62	1.59	1.52	1.32	1.18												
06 Apr 65	5.7	79.3°	24	2.00	1.91	1.76	1.72	1.57	1.46	1.61	1.49	1.28	1.23	1.08											
19 Apr 65	5.6	81.1°	25	1.49	1.75	2.00	1.88	1.73	1.60	1.81	1.62	1.30	1.38	1.26	1.18	1.11	1.32	1.08							
20 Apr 65	5.3	56.1°	26	2.00	1.56	1.77	1.59	1.67	1.49	1.36	1.48	1.20	1.15	.95											
TFO CODA																									
10 May 63	5.8	48.2°	1	1.59	1.95	2.00	1.86	1.89	1.94	1.90	1.84	1.72	1.65	1.57	1.40	1.30	1.28	1.20	1.23	1.11	1.08	.85	.85	.90	.78
22 May 63	6.4	67.3°	2	2.00	1.52	1.71	1.38	1.40	1.26	1.38	1.26	1.08	.95	.70	.60	.48	.60	.48	.30						
26 Jun 63	6.0	38.2°	3	1.99	2.00	1.54	1.48	1.40	1.36	1.36	1.34	1.30	.90	.70	.60	.70	.60	.48	.30	.30	.30				
28 Jun 63	6.2	69.1°	4	1.63	1.73	2.00	1.88	1.75	1.69	1.76	1.57	1.59	1.43	1.18	1.18	.85	.85	.60	1.04	.95	.95	.85	.70	.78	.78
29 Aug 63	6.1	50.0°	5	2.00	1.86	1.88	1.61	1.67	1.52	1.60	1.75	1.40	1.00	.85	.95	.85	1.00	.60	.78	.85	.60				
03 Nov 63	6.0	49.2°	6	2.00	1.94	1.92	1.65	1.61	1.59	1.71	1.77	1.52	1.34	1.23	1.32	1.11	.90	.90	.90	.78	.78	.78	.78	.60	.60
05 Feb 64	5.4	82.4°	7	1.38	1.20	2.00	1.73	1.63	1.72	1.52	1.65	1.28	1.08	1.04											
22 Feb 64	5.3	67.3°	8	2.00	1.42	1.98	1.45	1.32	1.36	1.23	1.36	1.11	1.11												
31 Mar 64	5.3	71.2°	9	1.52	1.77	2.00	1.88	1.68	1.64	1.52	1.62	1.54	1.28	1.11	.90	.78									
08 Apr 64	5.5	71.1°	10	1.97	1.54	1.78	1.97	1.78	1.75	2.00	1.86	1.62	1.51	1.15	1.26	1.04	1.08	.95	1.23	1.18	.95	1.00			
18 Apr 64	5.3	71.0°	11	1.84	1.76	2.00	1.90	1.67	1.74	1.61	1.57	1.43	1.26												
07 May 64	6.2	81.2°	12	1.70	2.00	1.72	1.82	1.42	1.49	1.26	1.43	1.00	1.41	1.00	.95	.78	.60	.60	.60	.70	.48	.48	.48	.48	.30
07 May 64	5.9	81.1°	13	2.00	1.75	1.89	1.68	1.60	1.56	1.42	1.43	1.18	1.42	1.00	.78	.78	.70								
24 Jul 64	5.9	68.7°	14	1.70	1.91	2.00	1.85	1.58	1.72	1.79	1.62	1.46	1.34	1.00	.90	1.04	.95	.85							
24 Jul 64	5.9	68.6°	15	1.62	1.54	2.00	1.73	1.70	1.49	1.64	1.73	1.61	1.32	1.18	1.18	1.08	1.11								
24 Jul 64	5.8	68.7°	16	1.89	2.00	1.74	1.74	1.64	1.70	1.72	1.79	1.56	1.32	1.20	1.04										
25 Jul 64	6.1	73.0°	17	2.00	1.97	1.93	1.92	1.89	1.75	1.76	1.75	1.64	1.64	1.26	1.26	1.15	1.18	.95	1.08	1.00					
30 Jul 64	5.7	32.5°	18	1.54	1.36	2.00	1.38	1.71	1.36	1.28	1.52	1.66	1.30	1.00	.85	1.11	.85	.60	.78	.78	.78	.60			
08 Aug 64	5.8	30.5°	19	1.90	1.72	1.63	1.68	1.63	1.62	1.72	1.80	1.48	2.00	1.34	1.23	1.80	1.26	1.08	1.08	1.40	1.28	1.20	1.04		
22 Mar 65	6.0	76.0°	20	1.98	1.56	2.00	1.89	1.66	1.83	1.60	1.56	1.34	1.54	1.32	1.04	1.15	,90	1.04	.85	.95	.95	.78			
28 Mar 65	5.9	60.7°	21	2.00	1.52	1.95	1.76	1.69	1.65	1.54	1.61	1.36	1.15	.95	.95	.70									
29 Mar 65	6.1	78.7°	22	1.64	1.57	2.00	1.73	1.66	1.77	1.51	1.70	1.38	1.32	1.18	1.08	1.00	.95	.85	.95	1.11	.85				
30 Mar 65	5.7	78.6°	23	1.42	1.66	2.00	1.61	1.68	1.60	1.60	1.56	1.45	1.48	1.30											
06 Apr 65	5.7	83.5°	24	2.00	1.62	1.62	1.63	1.45	1.28	1.18	1.08	.90	.90	.78											
19 Apr 65	5.6	85.3°	25	1.49	1.43	1.86	1.86	2.00	1.76	1.66	1.63	1.28	1.36	1.11	.95										
20 Apr 65	5.3	61.2°	26	2.00	1.57	1.99	1.71	1.64	1.59	1.43	1.46	1.30													
BRPA CODA																									
10 May 63	5.8	42.0°	1	1.46	1.94	1.83	2.00	1.90	1.63	1.63	1.64	1.51	1.28	1.34	1.15	1.11	1.04	1.11	.85						
22 May 63	6.4	79.5°	2	2.00	1.78	1.62	1.38	1.23	1.23	1.30	1.15	1.04	1.11	.95	1.00	.85	.70	.78	.70						
26 Jun 63	6.0	33.1°	3	2.00	1.56	1.72	1.49	1.26	1.23	1.15	1.20	1.08	.95	.95	.85	.85	.78								
28 Jun 63	6.2	81.7°	4	1.81	1.90	2.00	1.99	2.00	1.90	1.85	1.71	1.32	1.42	1.30	1.26	1.04	1.20	1.11	1.00	1.00	1.00				
03 Nov 63	6.0	43.4°	6	1.89	1.94	2.00	1.60	1.46	1.51	1.63	1.45	1.34	1.11	.90	.90	1.18	.95	.85	.78	.70	.78	.70	.78	.85	.60
31 Mar 64	5.3	81.5°	9	1.68	1.52	1.92	1.93	2.00	1.64	1.87	1.75	1.72	1.57												
08 Apr 64	5.5	84.3°	10	2.00	1.61	1.74	1.90	1.72	1.77	1.78	1.68	1.60	1.58	1.53	1.53										
07 May 64	6.2	92.6°	12	1.76	1.92	2.00	1.84	1.66	1.70	1.59	1.66	1.36	1.41	1.49	1.28	1.30	1.30	1.23	1.15	1.20	1.20	1.15	1.26	1.20	1.04
07 May 64	5.9	92.5°	13	2.00	1.79	1.92	1.81	1.71	1.62	1.62	1.43	1.34	1.42	1.49	1.34	1.20									
24 Jul 64	5.9	81.3°	14	2.00	1.94	1.91	1.75	1.85	1.81	1.71	1.64	1.51	1.40	1.45	1.30	1.26									
24 Jul 64	5.9	81.1°	15	1.74	1.85	2.00	1.92	1.85	1.75	1.72	1.69	1.42	1.38	1.51	1.23	1.26	1.20								
24 Jul 64	5.8	81.2°	16	1.63	1.99	1.98	[illegible]	1.72	1.84	1.86	1.77	1.56	1.59	1.45											
25 Jul 64	6.1	68.2°	17	2.00	1.76	1.62	[illegible]	1.53	1.71	1.64	1.56	1.45	1.18	1.08	.85										
30 Jul 64	5.7	29.5°	18	1.88	1.49	2.00	1.65	1.42	1.15	1.18	1.23	1.04	1.00	.85	.85	.70	.70	.60	.60	.60	.48				
08 Aug 64	5.8	28.5°	19	1.90	1.52	1.60	1.63	1.63	1.74	2.00	1.82	1.53	1.46	1.38	1.38	1.34									
22 Mar 65	6.0	72.1°	20	1.80	1.70	2.00	1.83	1.68	1.57	1.46	1.52	1.34	1.18	1.11	1.04	1.04	.90	1.00	1.04	.95	.90				
28 Mar 65	5.9	71.7°	21	2.00	1.45	1.75	1.76	1.64	1.73	1.64	1.68	1.53	1.45	1.51	1.45										
29 Mar 65	6.1	90.8°	22	1.84	1.63	2.00	1.67	1.76	1.75	1.62	1.70	1.45	1.62	1.40	1.45	1.28	1.40	1.34	1.34	1.28					

TABLE IV

Summary Table of Coda Shape Differences

Station	$\overline{Max}$(station) - $\overline{Max}$(PIWY)	
	(0→10)sec	(30→T_{all})sec
RYND	.06	-.21±.05
FRMA	.01	-.13±.03
GIMA	.05	-.27±.03
HLID	.03	-.09±.02
BRPA	-.08	-.23±.01
TFO	-.01	-.15±.02
GVTX	-.02	-.15±.004
DRCO	-.02	-.11±.01
CPCL	+.01	-.17±.02
HHND	-.09	-.26±.04
	$\overline{Max}$(station) - $\overline{Max}$(TFO)	
CPCL	.00	+.05±.01
BRPA	.02	-.05±.01
RYND	.09	-.04±.02
PIWY	.04	.24±.03
PI2WY	+.07	.04±.05

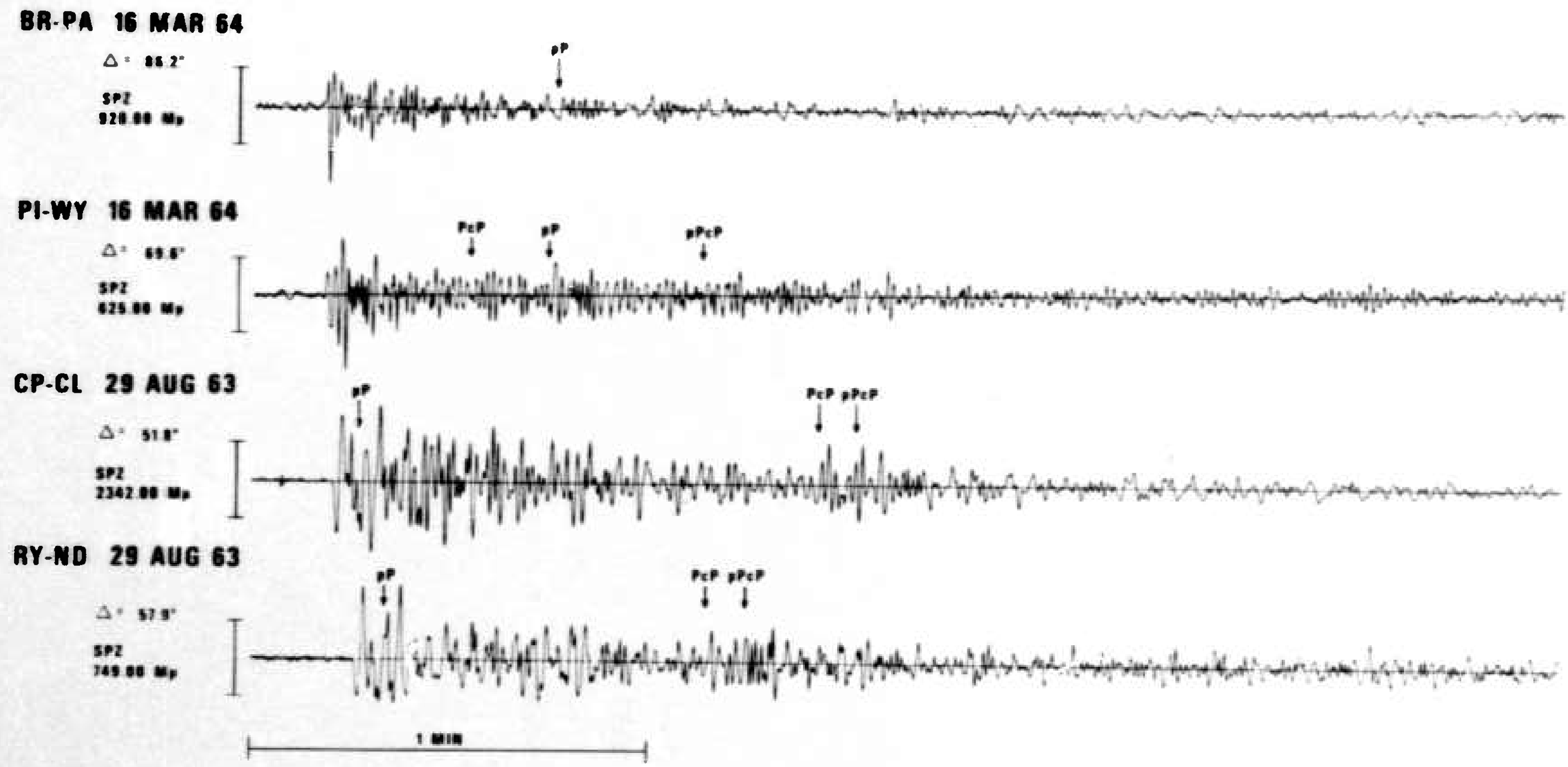

Figure 3. Short-period vertical waveforms of the 16 March 1964 event at PIWY and BRPA and of the 29 August 1963 event at CPCL and RYND.

SHORT-PERIOD REVERBERATION DIFFERENCES BETWEEN STATIONS

In the Introduction we discussed the possibility that detections might be made in short, quiet, 10-second intervals between the large maxima in each minute of the coda. To examine this possibility we examined each of the second set of events (the latter 26) in Table II at stations TFO, PIWY, PI2WY, BRPA, CPCL, and RYND in the following way. The coda intervals 0-20, 20-40, 40-60 seconds, and every minute thereafter were examined to find the 10-second interval with the smallest maximum. The $\log_{10}$ of this maximum in percent was then recorded as the minimum coda level for the time interval. The technique is illustrated in Figure 4. The complete minimum coda level data derived in this manner are given in Table V for stations PIWY, PI2WY, TFO, and BRPA.

The minimum coda-level values were then subtracted from the maximum in the interval and the differences tabulated as (max-min) for each time interval, event, and station. Using TFO as a reference and for a given station, say PIWY, we than averaged $(\text{max-min})_{PIWY} - (\text{max-min})_{TFO}$ over all event pairs for all times. By choosing paired events we attempted to suppress the effects of varying epicentral distance. The results, together with their standard deviations, are given in Table VI. By examining the differences for $t \geq 1$ minute, so long as data is available for every event, we find some indication that there are two sets of stations: averaged for all events TFO and CPCL have equal values of (max-min) and PIWY, PI2WY, BRPA, and RYND have values .06 to .13 magnitude units smaller. The differences are not large enough to reject the hypothesis that the difference is zero. However, the sign of the difference is in agreement with the idea that a low-Q mantle will reduce reverberation. The data are rather sparse for PIWY and PI2WY, and one cannot reject the hypothesis that there is no significant difference between them. In Figure 3 we see waveforms of the 29 August 1963 event at CPCL and RYND which explicitly illustrate the fact that CPCL is relatively quieter between maxima than is RYND. There seems to be little effect due to type of station bedrock.

To investigate whether there is a variation in the quantity (max-min) as a function of distance, we have grouped CPCL and TFO together and PIWY,

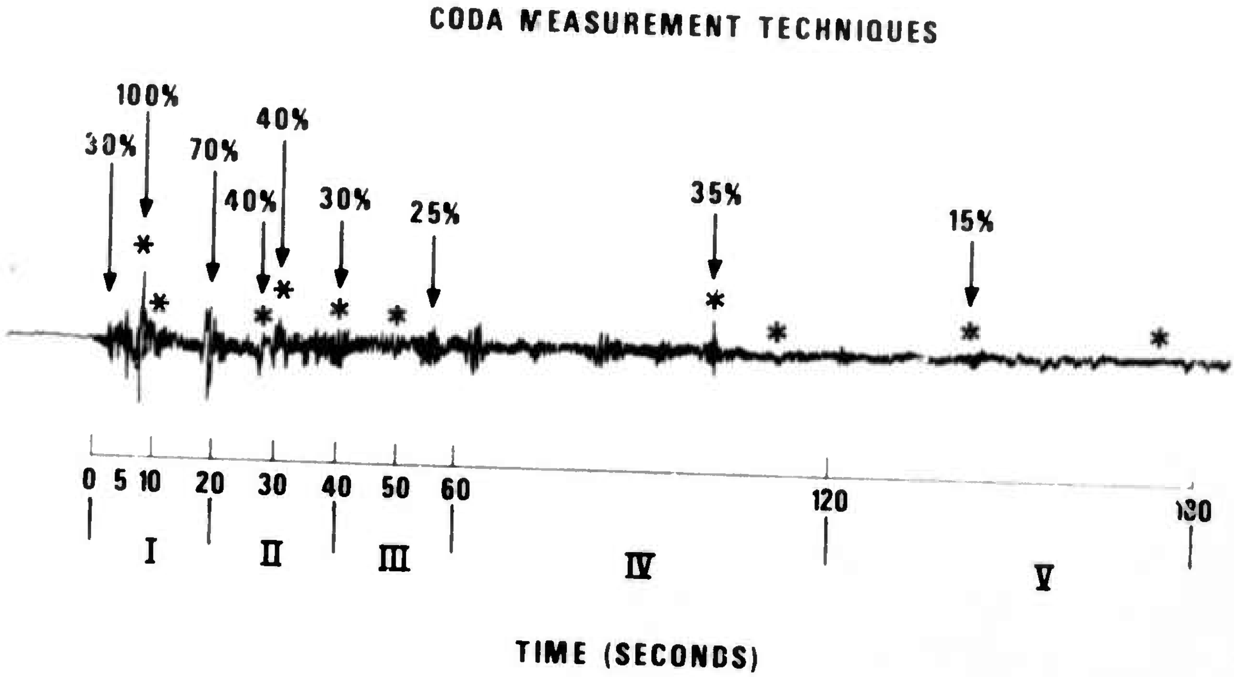

Figure 4. Schematic illustration of method of measuring minimum short-period coda levels. Arrows indicate peak-to-peak values selected as maximum coda levels in the time windows selected by Cohen and Sweetser. Intervals for (maximum-minimum) determinations are indicated by vertical lines. Asterisks indicate the maximum in each interval and the peak-to-peak value selected as the coda minimum in the interval. Note that in interval I the maximum is about three times the minimum, while in interval II they are about the same.

TABLE V

Minimum 10-Second Coda Levels for P1WY, P12WY, TFO, BRPA

DATE	NOAA m_b	Δ°	Event No. from Table IIb	0-20	20-40	40-60	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14
P1WY(P12WY)																			
05 Feb 64	5.4	78.2°	7	.54	.24	.34	.33	.46	.30	.33									
22 Feb 64	5.3	62.7°	8	.31	.02	.27	.26	.23											
31 Mar 64	5.3	66.7°	9	.25	.16	.03	.27	.30	.19	.20	.22								
08 Apr 64	5.5	66.5°	10	.29	.10	.03	.34	.20	.26	.30									
18 Apr 64	5.3	66.6°	11	.14	.09	.19	.21	.12	.30										
22 Mar 65	6.0	84.4°	20	.41	.04	.03	.30	.44	.24	.25	.15	.37	.25	.40	.35				
28 Mar 65	5.9	55.5°	21	.33	.05	.17	.34	.36	.10	.07	.30								
29 Mar 65	6.1	74.2°	22	.19	.19	.37	.40	.19	.50	.23	.26	.20	.15	.15					
30 Mar 65	5.7	74.1°	23	.52	.16	.04	.22	.14											
06 Apr 65	5.7	79.3°	24	.24	.16	.19	.45	.24	.19										
19 Apr 65	5.6	81.1°	25	.28	.24	.21	.36	.22	.18	.18									
20 Apr 65	5.3	56.1°	26	.28	.03	.19	.33	.20											
TFO																			
10 May 63	5.8	48.2°	1	.05	.08	.04	.23	.23	.25	.39	.29	.35	.43	.42	.45	.41	.30	.15	
22 May 63	6.4	67.3°	2	.45	.02	.23	.36	.04	.35	.10	.30								
26 Jun 63	6.0	38.2°	3	.47	.14	.13	.34	.52	.42	.22	.30	.40	.30						
28 Jun 63	6.2	69.1°	4	.28	.16	.07	.39	.55	.35	.28	.30	.15							
29 Aug 63	6.1	50.0°	5	.14	.06	.08	.47	.45	.40	.37	.47	.55	.52	.12	.48	.55			
03 Nov 63	6.0	49.2°	6	.21	.04	.12	.47	.37	.39	.33	.54	.41	.12	.12	.30	.30	.30	.48	.48
05 Feb 64	5.4	82.4°	7	.62	.10	.20	.70	.38	.04	.19									
22 Feb 64	5.3	67.3°	8	.49	.13	.08	.32	.07											
31 Mar 64	5.3	71.2°	9	.23	.22	.12	.42	.64	.33										
08 Apr 64	5.5	71.1°	10	.37	.19	.25	.50	.34	.33	.20	.56								
18 Apr 64	5.3	71.0°	11	.16	.23	.13	.37	.28											
07 May 64	6.2	81.2°	12	.09	.42	.23	.48	.10	.46	.30	.65	.48	.30	.60	.60	.40	.48	.48	.48
07 May 64	5.9	81.1°	13	.12	.10	.18	.43	.33	.52	.40	.18	.30							
24 Jul 64	5.9	68.7°	14	.09	.33	.07	.22	.35	.44	.22	.12								
24 Jul 64	5.9	68.6°	15	.38	.27	.02	.62	.38	.42	.40	.28								
24 Jul 64	5.8	68.7°	16	.26	.10	.13	.47	.56	.17	.42	.26								
25 Jul 64	6.1	73.0°	17	.08	.03	.09	.16	.32	.46	.26	.31	.30							
30 Jul 64	5.7	32.5°	18	.47	.35	.10	.37	.76	.35	.40	.25	.63	.37	.12					
08 Aug 64	5.8	30.5°	19	.36	.10	.20	.44	.18	.82	.44	.33	.95	.31	.30					
22 Mar 65	6.0	76.0°	20	.44	.22	.23	.14	.23	.46	.42	.34	.45	.20	.44					
28 Mar 65	5.9	60.7°	21	.43	.07	.29	.38	.41	.25	.35	.10								
29 Mar 65	6.1	78.7°	22	.37	.14	.34	.40	.68	.42	.40	.30	.52	.47	.55	.47	.63	.25		
30 Mar 65	5.7	78.6°	23	.34	.08	.00	.41	[illegible]											
06 Apr 65	5.7	83.5°	24	.38	.18	.10	.23	.30	.42										
19 Apr 65	5.6	85.3°	25	.37	.14	.11	.43	.43	.46	.21									
20 Apr 65	5.3	61.2°	26	.02	.07	.16	.26	.30											
BRPA																			
10 May 63	5.8	42.0°	1	.13	.19	.03	.16	.31	.17	.39	.25	.16	.19	.33	.15				
22 May 63	6.4	79.5°	2	.52	.18	.10	.25	.26	.41	.25									
26 Jun 63	6.0	33.1°	3	.31	.23	.19	.35	.30	.17	.17									
28 Jun 63	6.2	81.7°	4	.10	.15	.17	.41	.28	.38	.35	.41								
03 Nov 63	6.0	43.4°	6	.06	.07	.12	.34	.44	.33	.20	.30	.58	.35						
31 Mar 64	5.3	81.5°	9	.40	.09	.26	.21												
08 Apr 64	5.5	84.3°	10	.39	.25	.01	.26												
07 May 64	6.2	92.6°	12	.08	.19	.11	.34	.18	.26	.38	.28								
07 May 64	5.9	92.5°	13	.08	.23	.10	.17	.14											
24 Jul 64	5.9	81.3°	14	.09	.13	.11	.32	.25											
24 Jul 64	5.9	81.1°	15	.15	.08	.04	.33	.27	.20	.31									
24 Jul 64	5.8	81.2°	16	.01	.32	.20	.35												
25 Jul 64	6.1	68.[illegible]°	17	.40	.18	.07	.26	.34	.23	.13									
30 Jul 64	5.7	29.5°	18	.37	.37	.03	.23	.34	.30	.25	.25	.22							
08 Aug 64	5.8	28.5°	19	.38	.05	.26	.48	.23	.26	.10	.30	.26							
22 Mar 65	6.0	72.1°	20	.30	.19	.12	.24	.23	.18	.21	.26	.26							
28 Mar 65	5.9	71.7°	21	.27	.12	.09	.30	.15											
29 Mar 65	6.1	90.8°	22	.37	.13	.13	.32												

PI2WY, BRPA, and RYND together and produced Table VII giving (max-min) averaged over all events for several distance ranges. Examinatior of graphs of these data leads to the conclusion that one cannot reject the hypothesis that there is no difference in the quantity (max-min) as a function of epicentral distance. We have, therefore, average (max-min) over all distance ranges and all events for the two groups and produced Figure 5. This suggests that there is little difference in (max-min) between the low-Q and high-Q stations until approximately a minute after the P arrival, whereupon the low-Q stations begin to have about 0.35 magnitude units quieter 10-second minima between 1-minute maxima, while the high-Q stations have minima only 0.25 magnitude units quieter. If CPCL and TFO are selected a-priori as low-Q stations, and if the others are high-Q, one can reject the hypothesis that (max-min) is the same for both groups for $t > 1.0$.

In the first 20 seconds of the coda there is a 10-second interval which is typically 0.3 m_b units quieter than the maximum in this time interval. This is only to be expected for a sharp arrival and is reflected in the fact that the smallest teleseismic coda level in the first 20 seconds of codas measured by Cohen et al. (1972) and Sweetser et al. (1973) is typically 60% of maximum.

In summary, on two counts the stations TFO and CPCL would be excellent for counterevasion. Not only are the later coda amplitudes smaller by about 0.2 m_b units than the amplitudes at some other stations, e.g. PIWY, but also the minuma between maxima are 0.1 magnitude units lower.

TABLE VI

$(\text{Maximum-Minimum})_{\text{Station}} - (\text{Maximum-Minimum})_{\text{TFO}}$, Mean Number of Observations and Standard Deviation

	0-20	20-40	40-60	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
CPCL												
No. of Observations	7	7	7	7	7	6	3	2	1	1	1	
Mean	-.00	+.03	.00	+.00	+.06	+.02	+.10	-.12	-.25	-.05	+.25	
Standard Deviation of Mean	.04	.04	.04	.05	.04	.08	.12	.21				
BRPA												
No. of Observations	18	18	18	18	14	11	11	7	5	2	1	1
Mean	-.04	+.01	-.04	-.08	-.08	-.17	-.07	-.09	-.26	-.00	-.09	-.30
Standard Deviation of Mean	.03	.03	.03	.03	.05	.05	.04	.06	.14	.24		
PIWY												
No. of Observations	5	5	5	5	5	3	2					
Mean	-.07	-.05	+.02	-.18	-.08	+.02	+.12					
Standard Deviation of Mean	.03	.05	.07	.05	.09	.12	.32					
PI2WY												
No. of Observations	7	7	7	7	7	5	4	3	2	2	2	
Mean	-.06	+.00	-.04	+.02	-.14	-.16	-.16	-.01	-.20	-.13	-.22	
Standard Deviation of Mean	.05	.03	.05	.05	.08	.06	.05	.11	.12	.18	.18	
RYND												
No. of Observations	12	12	12	12	8	6	3	3	2	1	1	
Mean	+.01	-.12	-.02	-.06	-.10	-.16	-.08	-.28	-.27	+.13	+.21	
Standard Deviation of Mean	.05	.04	.03	.05	.07	.02	.03	.05	.06			

TABLE VII

Summary (Maximum-Minimum) in Different Distance Ranges for Two Sets of Stations

		Seconds 0-20	20-40	40-60	Minutes 1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
TFO and CP-CL																
28°-42°	μ	.42	.180	.1825	.410	.4975	.530	.3533	.2933	.660	.3267	.210				
	σ	.0292	.0573	.0444	.0339	.1195	.1466	.0677	.0234	.1597	.0219	.0903				
42°-53°	μ	.1567	.100	.1067	.4267	.380	.3383	.380	.412	.4025	.385	.2575	.410	.420	.300	.315
	σ	.0269	.0318	.0186	.0581	.0479	.0255	.0724	.0711	.0541	.0902	.080	.0557	.0724	.000	.1655
53°-63°	μ	.225	.070	.225	.320	.355										
	σ	.2056	.000	.0652	.0602	.0552										
63°-62°	μ	.3055	.170	.1145	.400	.3518	.3278	.270	.3033							
	σ	.0449	.0275	.0230	.0343	.0573	.0402	.0503	.0583							
72°-79°	μ	.3075	.1175	.1650	.2775	.420	.4467	.360	.3167	.4233	.3350	.4950				
	σ	.0787	.0409	.0751	.0738	.0977	.0133	.0504	.0120	.0650	.1354	.0552				
79°-93°	μ	.380	.1667	.1383	.460	.350	.3783	.2960	.4150	.390						
	σ	.1019	.0533	.0330	.0615	.0624	.0706	.0427	.2357	.0903						
BR-PA, PI-WY(PI2WY) and RY-ND																
28°-42°	μ	.4240	.1860	.1240	.320	.3380	.230	.1733	.2750	.240						
	σ	.0531	.0548	.0460	.0545	.0355	.0303	.0434	.0251	.0201						
42°-53°	μ	.0950	.130	.0750	.250	.3750	.250	.2950	.2750	.3700	.270					
	σ	.0351	.0602	.0451	.0903	.0652	.0802	.0953	.0251	.2106	.0802					
53°-63°	μ	.2760	.0640	.1780	.340	.2640	.1333	.220	.2867							
	σ	.0574	.0150	.0319	.0255	.0427	.0203	.0765	.0297							
63°-72°	μ	.1950	.1060	.1070	.3160	.2086	.2467	.210								
	σ	.0363	.0294	.0290	.0363	.0346	.0167	.0494								
72°-79°	μ	.3560	.1640	.150	.290	.240	.340	.2350	.2567	.2033						
	σ	.0731	.0335	.0530	.0331	.0567	.0673	.0340	.0033	.0318						
79°-93°	μ	.2473	.1547	.1180	.3153	.2657	.2867	.280								
	σ	.0417	.0216	.0194	.0204	.0351	.0302	.0751								

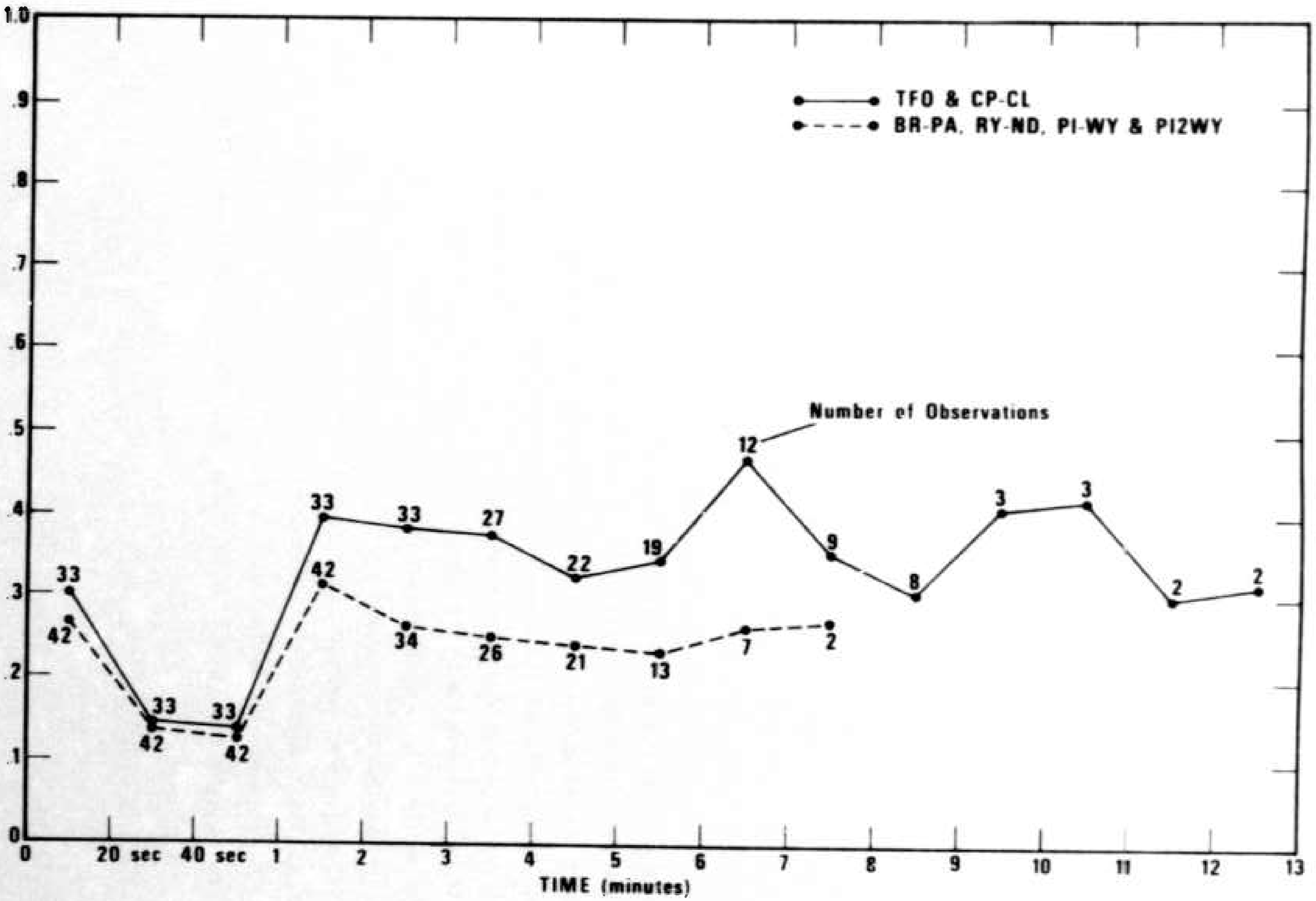

Figure 5. Mean value of (max-min) as a function of time for two groups of stations, TFO and CPCL, RYND, PIWY, PI2WY, and BRPA.

CODA SHAPE DIFFERENCES FOR WWSSN AND LRSM STATIONS

It seems possible that the differing responses of the short-period WWSSN and LRSM systems, Figure 6, could result in different coda shapes, despite the fact that during analysis an effort is made to pick coda amplitudes with periods near 1 Hz. In order to check this hypothesis, events whose coda were measured at WWSSN stations in the United States and Canada, which were reported by Cohen et al. (1972) and by Sweetser et al. (1973), and which were at least 2 minutes long, were also read at nearby LRSM stations. We required that the distances to the two stations of a pair be in the same distance range. The set of distance ranges was established by Cohen et al. (1972) to ensure that PP and PcP would fall in the same time window for all distances in the range. Many events were not usable because the gain at the appropriate LRSM station was either too high or too low. The resulting set of stations used is given in Table VIII, the events used are listed in Table IX, and the individual $\log_{10}$ (percentage) differences are given in Table X. Three different averages over events were taken, and are given at the bottom of Table X: an average over all event-station differences, an average over all event-station differences in the distance range 84°-98°, and an average of the longest duration event-station data set for each event. In each case we found the LRSM long-time coda to be .05-.1 magnitude units larger than the WWSSN. At first glance the difference, although operationally unimportant, seems statistically significant since it is so stable with time. However, we must reflect that due to the normalization to maximum amplitude the long-time values will have a bias. For example, if the coda are identical, except that the maximum of one is larger than the other, then there will be no difference at the maximum, and a bias everywhere else. Thus the consistent mean difference with respect to time reflects a difference at the maxima, and since .05-.1 magnitude differences are well within the range of the calculated standard deviations of the mean for a single time interval, one cannot reject the hypothesis of no difference between LRSM and WWSSN measurements.

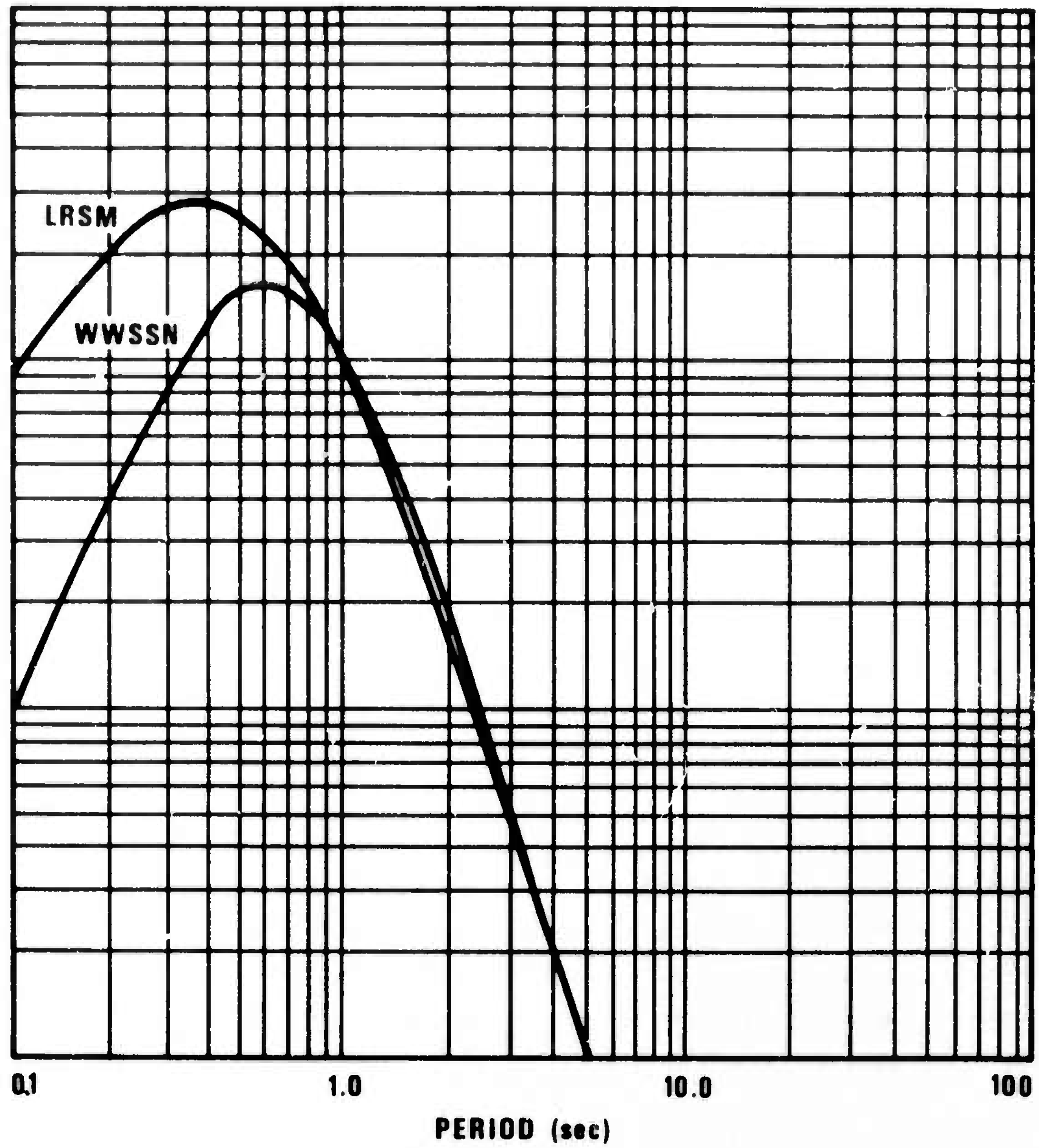

Figure 6. WWSSN and LRSM short-period system responses.

TABLE VIII

Station Information

STATION DESIGNATOR	LOCATION	LATITUDE Deg	Min	Sec		LONGITUDE Deg	Min	Sec		ELEVATION (Meters)
BOZ	Bozeman, Montana	45	36	00	N	111	38	00	W	1575
BR-PA	Berlin, Pennsylvania	39	55	27	N	78	50	41	W	665
CMC	Coppermine, N.W.T., Canada	67	50	00	N	115	05	00	W	31
DAL	Dallas, Texas	32	50	46	N	96	47	02	W	187
DH-NY	Delhi, New York	42	14	39	N	74	53	18	W	652
FO-TX	Fort Stockton, Texas	30	54	06	N	102	41	52	W	880
FR-MA	Forsyth, Montana	46	06	00	N	106	26	25	W	823
GI-MA	Glendive, Montana	47	11	34	N	104	13	10	W	732
GV-TX	Grapevine, Texas	32	53	09	N	96	59	54	W	152
HE-TX	Hempstead, Texas	30	11	59	N	96	05	31	W	67
HL-ID	Hailey, Idaho	43	38	50	N	114	15	02	W	1890
HL2ID	Hailey, Idaho	43	33	40	N	114	25	08	W	1829
HN-ME	Houlton, Maine	46	09	43	N	67	59	09	W	213
JE-LA	Jena, Louisiana	31	47	05	N	92	00	55	W	46
LS-NH	Lisbon, New Hempshire	44	14	18	N	71	55	21	W	287
NP-NT	Mould Bay, Canada	76	15	08	N	119	22	18	W	59
PG-BC	Prince George, B.C., Canada	53	59	50	N	122	31	23	W	914
RG-SD	Redig, South Dakota	45	12	59	N	103	32	05	W	945
WES	Weston, Massachusetts	42	23	05	N	71	19	20	W	60

TABLE IX

Events Analyzed

EVENT NO.	DATE	ORIGIN TIME Hr Min Sec	LATITUDE (Degrees)	LONGITUDE (Degrees)	DEPTH (km)	NOAA m_b	AREA LOCATION
1	20 Jan 64	17 08 37.4	20.7S	169.9E	141	6.7	Loyalty Islands Region
2	06 Feb 64	13 07 25.2	55.7N	155.8W	33	6.8	Kodiak Island Region
3	07 May 64	07 58 14.3	40.4N	139.0E	33	6.2	Off Coast of Northern Honshu, Japan
4	31 May 64	00 40 36.4	43.5N	146.8E	48	6.3	Kurile Islands
5	16 Jun 64	04 01 44.3	38.0N	139.1E	57	6.1	Near West Coast of Honshu, Japan
6	05 Jul 64	03 14 33.3	60.8N	144.9W	30	5.0	Alaska
7	18 Aug 64	04 44 58.0	26.4S	71.5W	8	6.4	Off Coast of Northern Chile
8	29 Mar 65	10 47 37.6	40.8N	142.8E	33	6.1	Near East Coast of Honshu, Japan
9	18 Nov 65	21 58 12.4	53.9N	160.7E	12	6.0	Near East Coast of Kamchatka
10	09 Dec 65	06 07 48.6	17.3N	100.0W	57	6.0	Guerrero, Mexico
11	15 Dec 65	23 05 20.7	7.5N	82.2W	15	6.0	South of Panama
12	05 Feb 66	16 16 01.0	50.2N	155.1E	98	5.8	Kurile Islands
14	22 Apr 66	23 27 20.3	57.5N	152.1W	22	5.9	Kodiak Island Region
15	29 Apr 67	03 55 20.8	51.4N	178.3W	50	6.0	Andreanof Islands, Aleutian Islands
16	03 Oct 67	18 16 03.2	10.9N	85.9W	21	5.8	Costa Rica
17	28 Dec 67	06 26 15.8	44.2N	128.8W	33	5.4	Off Coast of Oregon

TABLE X

Log_{10} Percentage Differences, LRSM-WWSSN, Together with Means and Standard Deviations of the Mean

EVENT NO.	WORLD-WIDE STATION	Δ°	LRSM STATION	Δ°	DISTANCE INTERVALS	0-5	5-10	10-20	20-30	30-40	40-50	50-60	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
1	BOZ	96.8°	HL-ID	94.3°	84°-98°	.0	+.36	+.25	+.28	+.18	+.21	+.06	+.22	-.10	+.11	+.05	+.10	+.20									
2	DAL	46.4°	GV-TX	46.2°	42°-53°	-.26	-.17	+.02	-.16	-.31	-.25	-.22	+.07	-.08	-.28												
2	DAL	46.4°	HE-TX	49.2°	42°-53°	-.09	-.11	+.02	-.14	-.30	-.15	-.06	-.10	-.25	-.26	-.49	-.19										
2	DAL	46.4°	JE-LA	49.8°	42°-53°	-.22	-.15	+.02	-.30	-.36	-.25	-.23	-.08	-.38	-.32												
2*	WES	53.6°	HN-ME	52.6°	53°-56°	-.46	-.17	+.12	-.02	-.28	-.07	-.09	-.19	-.11	-.20												
2*	WES	53.6°	DH-NY	51.8°	53°-56°	-.50	-.30	-.09	-.19	-.14	+.02	-.02	+.08	-.12	-.02												
2*	WES	53.6°	BR-PA	51.3°	53°-56°	-.49	-.04	-.19	-.15	-.22	-.05	+.02	+.02	.0	-.04												
3	DAL	90.7°	GV-TX	90.6°	84°-98°	-.07	.0	-.04	+.09	-.03	-.17	-.02	+.14	-.08	-.11	-.18	-.12										
3	DAL	90.7°	JE-LA	94.1°	84°-98°	+.29	.0	+.24	+.40	+.16	+.21	+.36	+.25	+.28	+.27	+.56	+.40	+.41									
3	WES	93.1°	BR-PA	92.9°	84°-98°	-.18	-.09	+.19	+.04	-.02	-.07	-.08	+.07	+.02	-.24	-.09	-.16	-.08	-.06	.0							
3	WES	93.1°	DH-NY	92.2°	84°-98°	+.07	-.09	+.09	-.11	-.04	-.02	-.17	-.39	+.04	-.38	-.50	-.30	-.38									
3	WES	93.1°	LS-NH	91.3°	84°-98°	-.15	-.17	+.19	+.05	+.22	-.11	-.06	+.02	+.06	-.17	-.13	-.08	-.17	-.26								
3	WES	93.1°	HN-ME	90.5°	84°-98°	+.02	-.03	+.19	-.06	-.19	-.40	-.22	-.18	-.30	-.26	-.34	-.39	-.38	-.48								
4	WES	87.9°	DH-NY	86.8°	84°-98°	.0	+.16	-.07	+.07	+.21	+.46	.0	+.04	+.25	+.14	+.08	+.10	.0	+.12	.0							
4	WES	87.9°	LS-NH	86.1°	84°-98°	.0	+.39	+.11	+.18	+.48	+.66	+.35	+.52	+.60	+.40	+.41	+.35	+.35	+.37	+.42	+.55	+.30	+.47	+.22	+.30	+.18	
5	WES	95.3°	BR-PA	95.0°	84°-98°	+.20	-.08	-.10	.0	+.30	+.08	+.17	+.20	+.46	+.41	+.14	+.23	+.25	+.36	+.33	+.38	+.25	+.51	+.17	+.15	+.26	+.12
5	WES	95.3°	DH-NY	94.3°	84°-98°	+.10	-.17	-.04	.0	+.09	-.10	.0	+.09	-.05	-.10	-.23	-.37	-.13	-.20	-.37							
5	WES	95.3°	HN-ME	92.8°	84°-98°	-.03	-.20	-.26	.0	+.06	+.22	+.26	.0	+.09	+.46	.0	-.15	-.05	-.20	-.15	-.10	+.08	.0	-.30	-.10	-.30	
6	BOZ	24.7°	HL2ID	25.1°	24°-26°	-.07	+.22	-.13	-.23	+.09	+.07	+.15	-.12	-.06	-.09	-.33											
6**	BOZ	24.7°	FR-MA	26.7°	24°-29°	-.03	-.10	+.15	+.07	+.08	+.12	+.16	+.05	+.08													
6**	BOZ	24.7°	GI-MA	27.0°	24°-29°	.0	+.21	+.15	+.19	+.32	+.34	+.29	+.20	+.08													
7	WES	68.4°	DH-NY	68.4°	67°-72°	.0	+.27	-.33	+.06	-.20	-.06	-.28	+.05	-.07	-.22	-.40	-.35										
7	WES	68.4°	LS-NH	70.3°	67°-72°	.0	+.36	-.12	+.28	+.05	+.03	-.20	+.12	-.07	-.10	-.22	-.25										
7	WES	68.4°	HN-ME	72.3°	67°-72°	.0	+.36	-.10	+.22	+.22	+.13	-.07	+.23	+.11	+.04	-.10											
7	DAL	63.6°	GV-TX	63.8°	63°-67°	.0	+.09	-.16	-.14	-.05	+.12	-.13	-.20	-.40	-.48	-.60	-.48										
8	DAL	88.4°	FO-TX	86.5°	84°-98°	-.07	-.01	.0	+.28	+.25	-.13	+.16	+.03	-.14	-.14												
8	BOZ	71.3°	HL2ID	71.0°	67°-72°	-.10	-.06	.0	-.08	+.27	+.06	+.08	+.13	+.16	+.07	+.42	+.22	+.20	+.15								
9	CMC	39.8°	NP-NT	39.2°	31°-42°	.0	+.17	+.06	+.22	+.07	+.19	+.43	+.16	+.09	.0	-.10	+.51	.0									
10	WES	35.0°	HN-ME	39.2°	31°-42°	.0	+.08	-.11	+.17	+.22	+.25	+.04	+.37	+.25	-.02	-.14	.0	-.15	+.07								
11	WES	36.1°	HN-ME	40.4°	31°-42°	+.03	-.10	+.10	-.02	-.10	+.07	-.08	-.46	-.19	-.11												
12	WES	79.3°	HN-ME	77.0°	72°-79°	.0	-.30	-.12	-.33	-.16	-.28	-.40	-.30	-.41	-.48												
12	BOZ	58.7°	RG-SD	63.1°	59°-63°	.0	+.51	+.34	+.30	+.31	+.24	+.26	+.02	+.05	+.08												
14	WES	51.0°	HN-ME	49.9°	42°-53°	+.13	.0	+.11	-.04	+.26	-.19	+.11	+.02	+.30	+.15	.0											
15	CMC	34.1°	NP-NT	33.5°	31°-42°	+.14	+.49	+.17	+.18	+.34	+.22	+.15	-.17	.0	-.09	-.22											
16	WES	33.9°	HN-ME	38.3°	31°-42°	.0	-.07	+.04	-.01	+.07	+.06	+.13	-.04	-.15	-.18	-.16	-.26	-.07	-.40								
17	BOZ	12.3°	PG-BC	10.6°	10°-14°	-.28	+.07	+.29	+.29	+.47	+.27	+.18	+.39														

* PF changes from 1-2 minutes to 2-3 minutes
** PcP changes from 30 to 40 seconds

TOTALS for Comparison of World-Wide Stations to LRSM Stations (all distance ranges)

		0-5	5-10	10-20	20-30	30-40	40-50	50-60	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
Mean	84°-98°	+.0138	+.0054	+.0577	+.0938	+.1285	+.0646	+.0623	+.0777	+.0869	+.0300	-.0192	-.0325	+.0018	-.0438	+.0383	+.2767	+.2100	+.3267	+.0300	+.1167	+.0467	+.12
Standard Deviation of Mean		.0360	.0523	.0431	.0414	.0486	.0787	.0515	.0600	.0696	.0789	.0863	.0775	.0817	.1074	.1205	.1949	.0667	.1639	.1658	.1168	.1751	
Mean	ALL	-.0561	+.0369	+.0275	+.0386	+.0644	+.0481	+.0286	+.0350	-.0011	-.0645	-.1071	-.0595	.0000	-.0482	+.0383							
Standard Deviation of Mean		.0289	.0362	.0263	.0304	.0375	.0364	.0325	.0344	.0379	.0408	.0589	.0641	.0619	.0865	.1205							
Mean - LARGEST CODA PER EVENT		-.0138	+.0775	+.0344	+.0356	+.1231	+.0869	+.0594	+.0588	+.0433	-.0367	-.0700	+.0450	+.0875	+.0817	+.2500	+.4650	+.2750	+.4900	+.1950	+.2250	+.2200	+.12
Standard Deviation of Mean		.0295	.0549	.0406	.0447	.0584	.0558	.0521	[illegible]	.0704	.0623	.0768	.0898	.0651	.1180	.1278	.0852	.0251	.0201	.0251	.0752	.0401	

SUMMARY

We have found evidence that there are a few stations, e.g. PIWY (but not PI2WY, only 20-30 km distant) and HLID which have relative asymptotic coda amplitudes 0.1-0.2 magnitude units larger than other stations. A possible explanation for this is that the single sharp first arrival is broken up for these stations, perhaps by complicated tectonic structures,

There seem to be differences in the degree of reverberation between stations in high-Q and low-Q tectonic regions. The quiet periods between coda maxima at times greater than 1-2 minutes into the coda are 0.1 m_b quieter at the low-Q stations. This is in qualitative agreement with what one would expect if some of this reverberation were generated in the upper mantle and had to pass once or twice through the low-velocity channel.

The above results suggest the counter-HIE stations should be located in low-Q regions where the tectonic structure is simple.

Beyond 1 minute into the coda, the minimum 10-second interval maximum is about 0.3 magnitude units below the maximum in the surrounding minute. This might suggest that the coda published by the Cohen and Sweetser overestimate the hiding potential of earthquake coda for times greater than 1 minute by some amount less than 0.3 magnitude units. Comparison with the work of Filson (1973) suggests that the coda of Cohen and Sweetser are accurate up to 2 minutes, but that then the detectibility of a mixed signal is indeed underestimated by about 0.2 m_b units.

Both the results of Filson (1973) and this study find slower coda decay in the first minute than did Jeppsson (1975) and Fink et al. (1971) who apparently selected a biased sample of rapidly decaying coda.

There seems to be no difference in coda estimates made using WWSSN or LRSM records.

REFERENCES

Blandford, R. R., T. J. Cohen, and H. L. Husted, 1971, Opportunities for foreign nations to hide an underground nuclear test in an earthquake, Seismic Data Laboratory Report No. 283, Teledyne Geotech, Alexandria, Virginia.

Blandford, R. R. and H. L. Husted, 1973, Extension of Hide-in-Earthquakes (HIE) technique to include probability of detection (U) CLASSIFIED, Seismic Data Laboratory Report No. 303, Teledyne Geotech, Alexandria, Virginia.

Blandford, R. R. and D. Clark, 1975, Variability of seismic waveforms at LASA from small subregions of Kamchatka, SDAC-TR-75-12, Teledyne Geotech, Alexandria, Virginia.

Cohen, T. J., E. I. Sweetser, and T. J. Dutterer, 1972, P and PKP coda decay characteristics for earthquakes, Seismic Data Laboratory Report No. 301, Teledyne Geotech, Alexandria, Virginia.

Cohen, T. J. and E. I. Sweetser, 1973, False alarm probabilities for mixed events, SDAC-TR-73-8, Teledyne Geotech, Alexandria, Virginia.

Evernden, J. F. and D. Clark, 1970a, Study of teleseismic P...I travel-time data, Phys. Earth Planet. Interiors, 4, 1-23.

Evernden, J. F. and D. Clark, 1970b, Study of teleseismic P...II amplitude data, Phys. Earth Planet. Interiors, 4, 24-31.

Filson, J. R., 1973, On estimating the effect of Asian earthquake codas to the explosion detection capability of LASA, Technical Report 1973-29, Lincoln Laboratory, Massachusetts Institute of Technology.

Fink, D. R., L. R. Miamidian, and W. Myers, 1971, Seismic Network studies (U) CLASSIFIED, LOG GAC 7157, General Atronics Magnavox, Philadelphia, Pennsylvania.

Jeppsson, Ingvar, 1975, Evasion by hiding in earthquake, FCA Rapport C 20043-T1, Forsvarets Forskningsanstalt, Stockholm, Sweden.

REFERENCES (Continued)

Lukasik, S., 1971, In Hearings on Status of current technology to identify seismic events as natural or man-made, before the Joint Committee on Atomic Energy of the Congress of the United States, October 1971. GPO No. 69-648.

Sweetser, E. I. and R. R. Blandford, 1973, Seismic distance-amplitude relations for short-period P, P_{diff}, PP and compressional core phases for $\Delta > 90°$, SDAC-TR-73-9, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1973, Average P and PKP codas for earthquakes (103°-118°), SDAC-TR-73-10, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I., T. J. Cohen, and M. F. Tillman, 1973, Average P and PKP codas for earthquakes, Seismic Data Laboratory Report No. 305, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1974, Average P and PKP codas for earthquakes (118°-180°), SDAC-TR-74-19, Teledyne Geotech, Alexandria, Virginia.