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Coda-Wave Anomalies in Small Earthquakes Before Three Large Earthquakes in the Kuril-Kamchatka Area

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The slope of the coda envelope has been studied as a function of time for small local earthquakes that occurred within the precursory areas of three Kuril-Kamchatka earthquakes with $M_{LH} \sim 8$. This parameter has been found to increase significantly 1 to 1.5 years prior to a large earthquake in all three cases. A change in the apparent frequency of coda waves during the anomalous period has also been detected. It is shown that the slope anomalies are most probably due to increased S-wave attenuation.

This paper is a sequel to an earlier paper [1] where we demonstrated the existence of precursory anomalies in a coda envelope before the large (M_{LH} = 7.8) Ust'-Kamchatsk earthquake of 1971. This paper is concerned with testing for similar effects before a number of large earthquakes, as well as for anomalies in the frequency content of the coda. We show that precursory variations in the envelope shape are typical of large Kuril-Kamchatka earthquakes and obtain estimates for the time and amplitude parameters that characterize this phenomenon. We also demonstrate the existence of precursory variations in coda frequency content. We further show that the anomalies were probably caused by absorption changes in the medium.

METHODS OF INVESTIGATING THE ENVELOPE SHAPE

We shall follow the successful method of retrospective analysis of the coda envelope (the second of those described in [1]) which can be summed up as follows. One chooses regional seismic stations, at distances of 150 to 200 km from the future epicenter, and an epicentral area that can well be expected to cover the future source (about 200 km in diameter). The data base consists of records of small earthquakes occurring within this area. The seismogram to be measured must have a well-recorded "tail" of scattered waves (coda). In specific terms, this means a minimum duration of 70 s from the time $t_S + 2(t_S - t_P)$ to the instant when the coda amplitude is as low as twice that of the microseisms. This record length is later divided into intervals of 10 s whose end points are given by $t_i = t_o + n \cdot 10$ where t_o is the origin time of the shock and n is an integer. A rationale for this choice is given in [1].

The double amplitude 2 $A_i(t_i)$ is then measured in each interval; the results obtained for the three components at a station are used in further calculations. Each record is characterized by the parameter α, representing the deviation of the envelope decay rated log A(t)/dt from the mean. This parameter is calculated for the vertical component and for the geometrical mean amplitude of the two horizontal components. A limited set of records is first used to obtain a mean regional envelope of the coda [1], denoted as log $A_{mean}(t)$. The parameter α is then determined as a constant in the linear regression equation

$$\log A_{obs(erved)} - \log A_{mean}(t) = \alpha t + b$$

The parameter b characterizes the record level; it is in fact a magnitude determined from the coda.

Each record of a small earthquake gives an estimate of α; the estimates are plotted as a function of calendar time (in years). Below we give individual plots ("Z") for Z-components and average plots ("H") for the two horizontal components. The averaging is legitimate, since we have shown that no significant differences exist between the two horizontal components of one station [1]. Plots for different components and stations exhibit simultaneous anomalies observed against a mean background level. This is slightly different for different components and stations, slowly changing with time. Nevertheless we thought it advisable to average the data over different stations and components in the usual manner, thus enhancing the anomalies.

We now discuss some details of the method. Since in our case, the epicentral areas are marine, a T-phase is sometimes superimposed on the scattered waves (see [1]), an example based on our data is given in [5, p. 60]. Such cases were generally excluded from consideration when visually inspecting the records; however some of them may have remained undetected, producing biased results. Systematic changes in epicenter distribution within the future source area may well cause a systematic variation in α, and thus produce a spurious anomaly; we were therefore careful to use epicenters that were spread evenly enough over the source area. This is particularly important during anomalous periods. The parameter α was also found to depend on the earthquake energy class, K, but only if it was low enough. Consequently, we imposed a lower K threshold on the data. Since attenuation in the upper Earth is depth-dependent, the hypocenters of small earthquakes should be less than 80 km deep.

It was practically impossible to obtain complete initial data; we did not make any purposeful selection of data, all material available and suitable for processing within the period under study was used.

RESULTS FOR INDIVIDUAL COMPONENTS AND STATIONS FOR THREE LARGE EARTHQUAKES

In this section we present factual information relating to the anomalies in coda waves observed prior to three large earthquakes within the Kuril-Kamchatka area: the 1971 Ust'-Kamchatsk earthquake with $M_{LH} = 7.8$; the 1978 Iturup earthquake sequence with $M_{LH,max} = 8.0$; and the 1963 Urup earthquake with $M_{LH} = 8.1$. These are three of the six large ($M_{LH} \sim 8$) shallow earthquakes that occurred within the Kuril-Kamchatka area during the period of detailed seismological observations. Technical difficulties have prevented us from obtaining sufficient data on the 1969 and 1973 Shikotan earthquakes with $M_{LH} = 8.2$ and $M_{LH} = 7.9$. Also, there is a 1-year gap in the Urup data. Records relating to the Iturup earthquake of November 6, 1958 with $M_{LH} = 8.2$ could not be utilized because of changes made in the equipment parameters in an early period of observations. The 1971 Petropavlovsk earthquake with $M_{LH} = 7.3$, $H = 120$ km was also studied but, since no anomalies, precursory or any other, have been discovered,

TABLE I
Parameters of large earthquakes

Date	Time			Coordinates, deg.		H, km	M_{LH}
	hour	min	s	Lat. N	Long. E		
	1971 Ust'-Kamchatsk earthquake						
Dec. 15, 1971	0.8	29	54.0	55.9	163.4	20-30	7.8
	1978 Iturup earthquake sequence						
March 23, 1978	00	30	58.0	43.7	149.3	40	7.6
March 23, 1978	03	15	23.0	43.9	148.9	40	7.8
March 24, 1978	19	47	50.0	43.9	149.1	39	8.0
	1963 Urup earthquake						
Nov. 13, 1963	05	17	57.0	44.6	149.5	60	8.1

we have not included the results in this paper as intermediate-depth earthquakes may have some specific features.

The 1971 Ust-'Kamchatsk earthquake. We have reported our previous work on coda anomalies prior to this earthquake [1], but we have since extended the period of study (1966 to 1977 instead of 1966 to 1974) and utilized more data. Figure 1 shows the source region, the epicentral area, and the seismic stations used: Krutoberegovo (KB), Kronoki (KRN), Klyuchi (KL), and Bering (BRN). The stations have three-component VEGIK-GB4 instruments with a photographic recorder; the free period is 1.2 s. Earthquakes with $K_{S1.2}^{F68} \geqslant 9.5$† have been used. Greater coverage for the period 1966-1974 was achieved by including events with relatively low-quality photographic recordings, as well as three-component seismograms with only some of the components being fit for measurement. Data coverage relative to the catalog was about 50 percent in [1]; it is about 70 percent in this paper, the total number of events being about 280 (about 2000 records). The average number of amplitude measurements per record was 10 to 15, with a minimum of 7.

† $K_{S1.2}^{F68}$ is Fedotov's S-wave energy class scale [7].

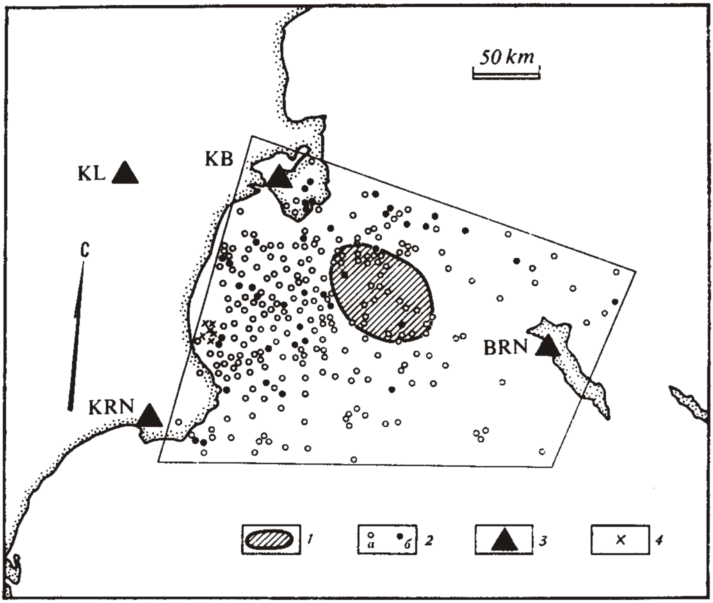

FIGURE 1 Ust'-Kamchatsk earthquake of December 15, 1971, M_{LH} = 7.8: 1 – source region; 2 – epicenters of small earthquakes used (a), the same for the year 1971 (b): 3 – seismic stations; 4 – epicenters of events that generated T-phases recorded at BRN.

The parameter α from H and Z components is plotted in Figure 2. The arrows indicate the time of a large earthquake (1971). Most of the plots show negative anomalies (the coda decay rate is greater than normal) in 1971 through 1973. Particularly clear anomalies occur on Z-components at stations KB, KRN, BRN. This is rather remarkable, since the H plots present results from average two components, which procedure was to have decreased random noise, producing clearer anomalies compared with the Z component. Relatively weaker anomalies are observed at the Klyuchi station, the farthest from the epicenter (200 km). No anomaly was recorded at distances of about 400 km (stations Shipunskiĭ and Petropavlovsk are not shown).

The 1978 Iturup earthquake sequence. Data on the Iturup sequence and the Urup earthquake of 1963 were obtained from recordings made at the South Kuril stations Shikotan (SKT) and Kuril'sk (KUR) by VEGIK-GB4 seismographs whose free period was 0.7 s. South Kuril earthquakes are routinely assigned energy class $K_{S0.7}^{S67}$ according to the

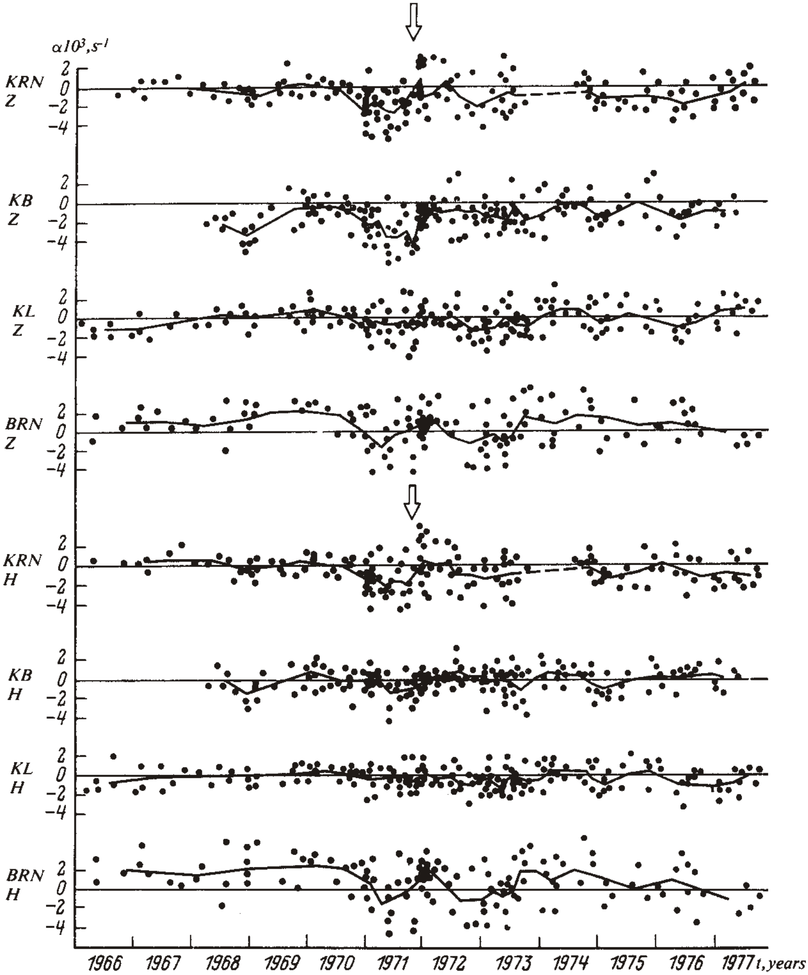

FIGURE 2 The parameter α for small earthquakes as a function of time within the Ust'-Kamchatsk earthquake area for different stations and record components. Negative values of α indicate a more rapid decay of the coda. The lines connect the centers of mass between sets of 8 data points moved in step of 4. Arrows indicate the instant of a large earthquake.

Solov'ev scale; this is "heavier" than $K_{S1.2}^{F68}$ by unity within our range of K; therefore for the lower threshold value we chose $K_{S0.7}^{S67} = 9$ (the bulletins give integer values of $K_{S0.7}^{S67}$). The map (Figure 3) shows the source region of the 1978 sequence (drawn for this paper from bulletin data), the epicentral area, and the seismic stations SKT and KUR.

The mean envelope log $A_{mean}(t)$ for the South Kurils was obtained by the standard techniques [1] using about 60 recordings. This mean was then used to compute α for a total of about 200 events (about 600

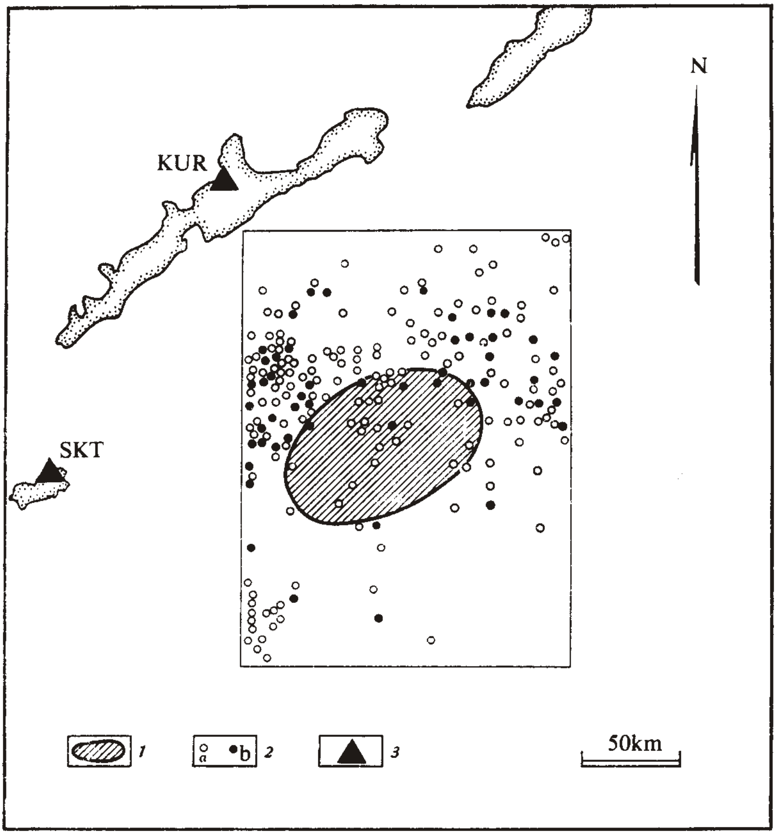

FIGURE 3 Iturup earthquake sequence of March 1978, $M_{LH\,max} = 8.0$: 1 – source region of large earthquakes; 2 – epicenters of earthquakes used (a), the same from January 1, 1977 through March 15, 1978 (b); 3 – seismic stations.

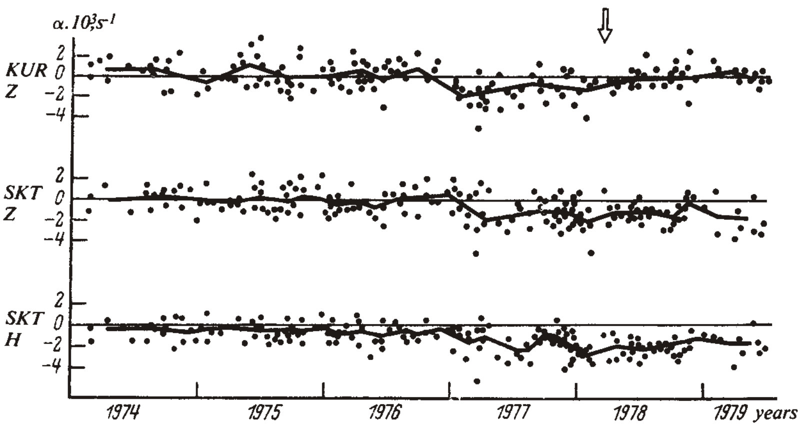

FIGURE 4 The parameter α for small earthquakes within the Iturup sequence epicentral area as a function of time. For symbols see Figure 2.

recordings) that occurred in 1974-1979. The method of computation was that described above. KUR has a single Z component, hence only three plots in Figure 4. All plots indicate negative anomalies in 1977-1978, the scatter of data points being close to that for the Kamchatka data.

The 1963 Urup earthquake. This is of particular interest because, being close to other events in magnitude, it has an appreciably greater seismic moment. The SKT data for the period 1959 to 1965 were used, with a gap from October, 1960 to December, 1962. The computational procedure and the limitations of the method were similar to those for the Iturup sequence of 1978. Figure 5 shows the 1963 source region as identified in [6], the epicentral area, and the seismic station SKT. A negative anomaly in 1963-1964 is clearly visible in the plots (Figure 6). About 60 events (approximately 150 recordings) were used.

ANALYSIS OF AVERAGED ANOMALIES

It is advisable to average data over different stations and components in order to identify typical features of the anomalies and to be able to

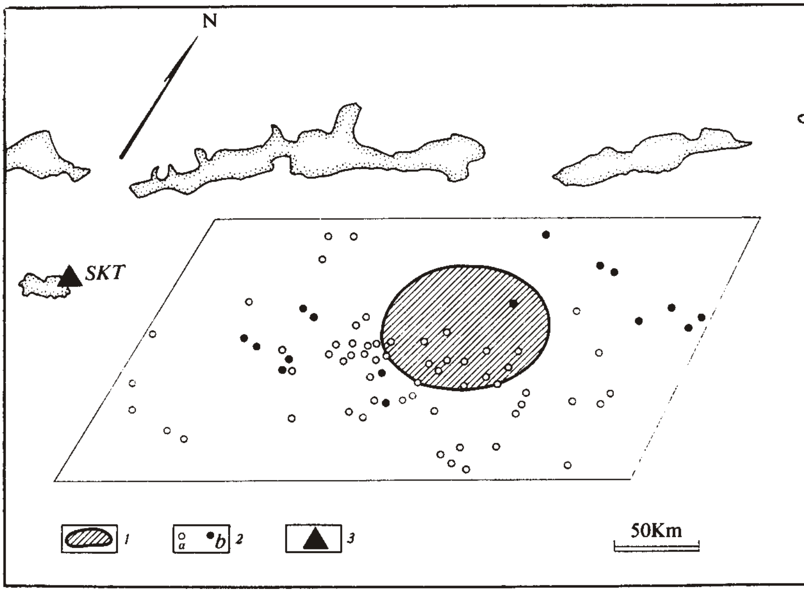

FIGURE 5 Urup earthquake of October 13, 1963, $M_{LH} = 8.1$: 1 – source region; 2 – epicenters of small earthquakes used (a), the same for the year 1963 (b); 3 – seismic stations.

carry out significance testing. Figure 7 shows averaged α values measured on all the components we have used for the three large earthquakes. The number of components averaged, N_{comp}, was 12, 4, and 3 respectively (or less than this, if some of the components were missing).

We are here interested mostly in the "prognostic" part of the anomalies. "Normal" and "anomalous" periods have been identified for the portions of the plots preceding large earthquakes. For these we have computed estimates of the mean and standard deviation (Table 2).

We proceed to discuss problems that arise in connection with significance testing. The distribution of α is close to Gaussian during the normal period and is different from it during the anomalous period. It has a flat top, thus approximating the rectangular, or uniform, distribution. This may indicate a mixture of several Gaussian distributions with different means, μ, i.e., an absence of true homogeneity of data during the anomalous period. The scatter appears to be greater during the anomalous period.

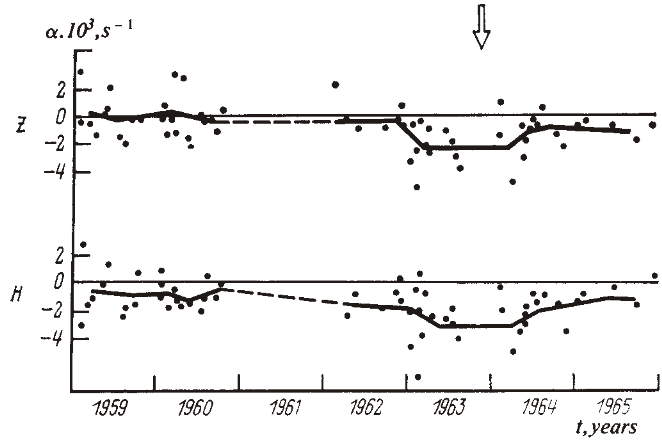

FIGURE 6 The parameter α for small earthquakes within the Urup earthquake area as a function of time based on SKT data. For symbols see Figure 2.

Mathematical statistics offers nonparametric methods (the sign test, etc.) in the case of non-Gaussian (other than) distributions. We have, however, assumed it permissible to use tests based on the hypothesis of normality. The significance of the difference between μ_{norm} and μ_{anom} was testing using the normal test statistic

$$d = \frac{\mu_{\text{norm}} - \mu_{\text{anom}}}{\left(\dfrac{\sigma^2_{\text{norm}}}{N_{\text{norm}}} + \dfrac{\sigma^2_{\text{anom}}}{N_{\text{anom}}}\right)^{1/2}},$$

where μ_{norm} and μ_{anom} were replaced by their estimates, which may usually be done with $N > 30$. The value corresponding to a significance level of 1 percent is $d = 2.57$; hence the difference is amply significant at this level in the first two cases under consideration (see Table II). In the third case the sample size is small, thus a nonparametric test had to be used. We enter the data in a 2×2 contingency table using the threshold value $\alpha = \alpha_{\text{crit}} = -0.2 \cdot 10^{-3}$

	$\alpha > \alpha_{\text{crit}}$	$\alpha < \alpha_{\text{crit}}$	Σ
Normal	29	4	33
Anomalous	0	9	9
Σ	29	13	42

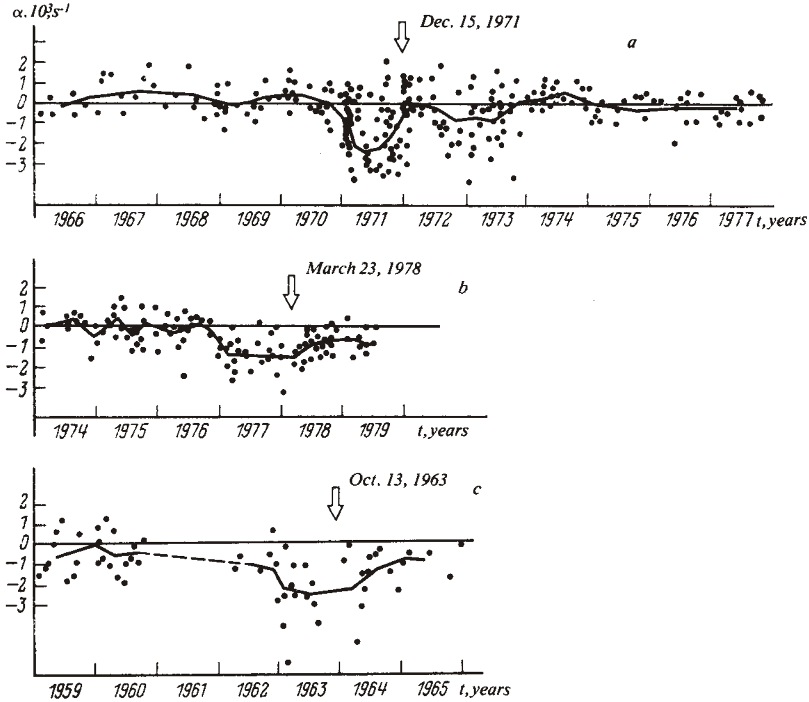

FIGURE 7 The parameter α for small earthquakes as a function of time after averaging over different stations and components: a – Ust'-Kamchatsk, 1971; b – Iturup sequence, 1978; c – Urup, 1963. For symbols see Figure 2.

We get $\mathscr{X}^2 = 25.5$ for one degree of freedom, rejecting the null hypothesis at a 1 percent level of significance. We are thus entitled to conclude that the anomalies are highly significant, hence undoubtedly real.

It is also of interest that the variance of α increased during the anomalous period. The F-test rejects the null hypothesis at a 5 percent level only in the first case, although this conclusion cannot be quite correct under a distribution that is not normal. In the two other cases the increase is not significant by the F-test. However, we still believe it to be real.

It is important to know how many "anomalous points" are needed to call a "significant alarm". The answer depends on how many components and stations are available, a rough estimate being given by

TABLE II
Characteristics of precursory anomalies

Earthquake	Period	Time interval	N	$\mu \cdot 10^3$	$\sigma \cdot 10^3$	$\sigma_0 \cdot 10^3$	d	F	$F_{0.05}$
1	Normal	Jan. 1, 1966- Dec. 31, 1970	61	0.15	0.8	0.10	7.43	4.0	1.82
	Anomalous	Jan. 1, 1971- Dec. 14, 1971 (11 months)	66	−1.5	1.6	0.20			
	Anomalous after the event	Dec. 6, 1971- Jan. 1, 1974 24 months)							
1	Normal	Jan. 1, 1974- Dec. 31, 1976	52	−0.1	0.75	0.10	6.35	1.44	1.74
	Anomalous	Jan. 1, 1977- March 15, 1978 (14 months)	26	−1.4	0.9	0.18			
	Anomalous after the event	March 25, 1978- July 1, 1979 (15 months)							
3	Normal	Jan. 1, 1959- Dec. 31, 1962	19	−0.7	1.1	0.20	3.78	1.92	2.04
	Anomalous	Jan. 1, 1963- Oct. 12, 1963 (9 months)	13	−2.5	1.5	0.41			
	Anomalous after the event	Oct. 14, 1963- March 1, 1965 (15 months)							

Note: N is the number of events used; μ is the mean of α; σ is standard deviation; σ_0 is the standard deviation of μ; d is the normal test statistic ($d_{0.05} = 1.96$); F is the F-statistic; $F_{0.05}$ is the upper 5 percent critical value for F-test.

$$\frac{\mu_{\text{anom}}}{\sqrt{\dfrac{\sigma_{\text{anom}}}{N_K n}}} = d_{\text{crit}}$$

where N_c is the number of components, n is the number of "anomalous" earthquakes, d_{crit} is the critical value chosen. When $N_c = 6$, we obtain the result that about 20 "anomalous" earthquakes are required to "call an alarm", if we set a significance level of 0.9 ($d = 1.63$).

The duration of a precursory anomaly was determined visually, the onset being fairly distinct in all three cases. The resulting estimates are given in Table II. The variation of α within the anomalous periods is small; in particular, there is no conspicuous "bay". The curves look as if α jumped to a lower constant value and remained there. However, the variance increase as compared with the normal period indicates that the phenomenon is in fact much more complex. A large earthquake is followed by a relatively slow return of α back to the "normal" value. The "normal level" was reached only for the Ust'-Kamchatsk earthquake; in the two other cases the length of our time series is insufficient to bring this out clearly.

The return motion is monotonic for the two Kuril earthquakes, while the Ust'-Kamchatsk curve is not, showing as it does another dip in 1973. Generally, the duration of an anomaly following a large earthquake is largely a matter of conventional definition (see Table II).

The two "spurious" anomalies in the Ust'-Kamchatsk plot, in 1969 and 1973, are not classified here as false alarms. The former (based on KB data) had occurred prior to the Ozernovsk earthquake of November 22, 1969 with $M_{LH} = 7.7$ whose epicenter was situated 150 km north of this station. It can probably be included as number four in our list of precursory anomalies. The 1973 anomaly appears at several stations but is much too close to the occurrence time of the 1971 earthquake and should be regarded as a "tail" of the 1971 anomaly. Apart from these irregularities, the parameter α is more or less stable during the "normal period".

VARIATION OF APPARENT PERIOD IN CODA-WAVES

The available records of coda-waves were obtained from short-period seismographs. For reasons discussed in [1] these are relatively narrow-band recordings, the apparent period ranging between 0.8 and 1.8 s. We have accordingly hypothesized that variations in the envelope shape may be accompanied by those in coda frequency content. The data used for this study are associated with the Ust'-Kamchatsk earthquake (see Figure 1). A total of about 220 earthquakes recorded at four stations from 1967 through 1977 were utilized. The procedure was as follows. 50-s intervals were chosen (according to the criteria we have discussed) within a coda recording, and the number of positive peaks, n, was counted. The apparent frequency was then estimated as $\bar{f} = n/50$. The intervals were centered at instants 75, 125, . . ., 325 s as measured from origin time. The data for all components at each of the four stations for each year from 1968 through 1976 were averaged; the functions $\bar{f}(t)$ are

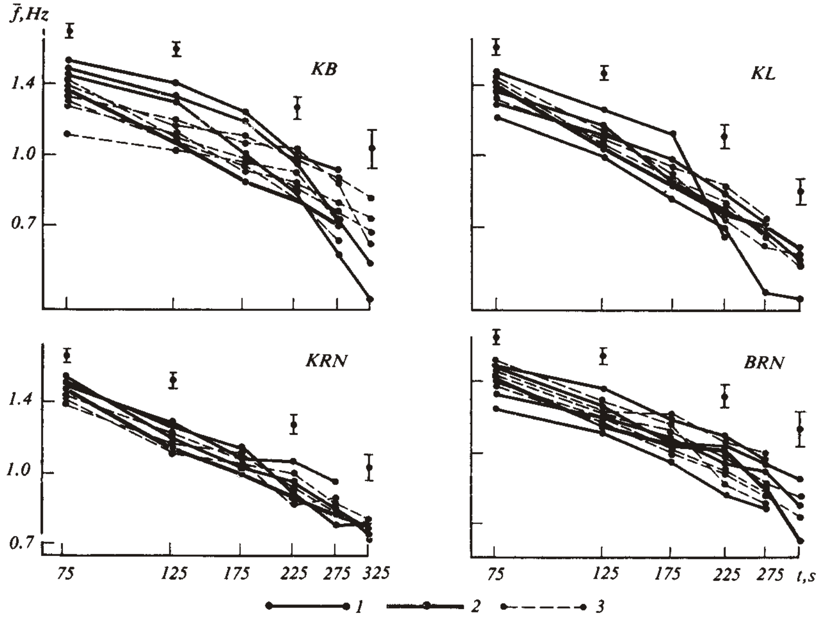

FIGURE 8 The apparent frequency of the coda, f, as a function of seismogram time for four seismic stations. 1 - mean annual values for 1967-1970; 2 - 1971; 3 - 1972-1976. Vertical bars show the ranges $\pm\sigma$ for the mean annual values $\overline{f}$ obtained by averaging annual σ^2 values.

given in Figure 8. The left-hand parts of the lines are based on a greater number of small earthquakes and consequently are more reliable than the right-hand parts.

It is seen from Figure 8 that the 1971 lines (the year when α was anomalous) are everywhere below the long-term average level. The lowest frequencies were recorded by station KB in 1971 before a strong shock, during aftershock activity following the 1971 earthquake, and in 1973; by station KRN, in 1970 and 1971; by KL, in 1968 and 1971; by BRN, in 1967, 1971, and 1973. Here again, the more pronounced anomalies occurred in 1971-1973.

Figure 9 shows the mean annual value of $\overline{f}$ as a function of time for t = 125 s; individual H and Z components are given for station KB in addition to the mean of all the three components. There is a well-

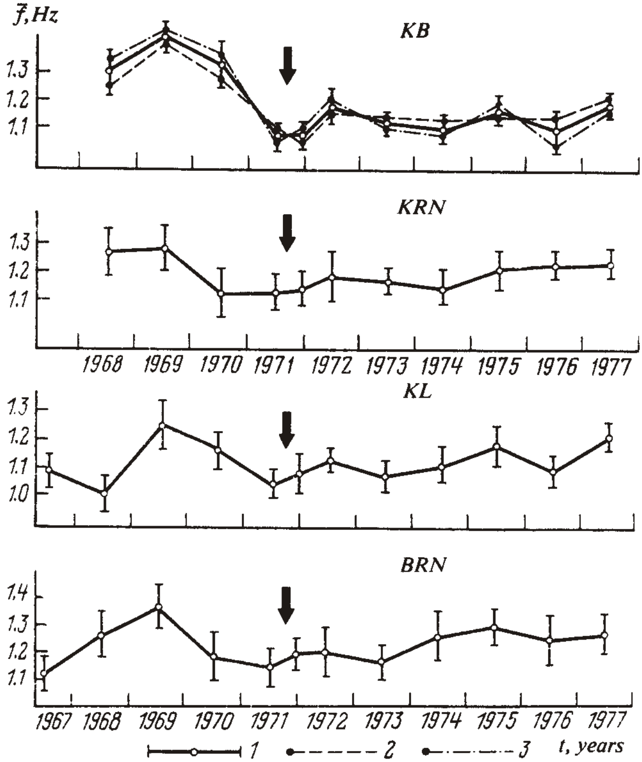

FIGURE 9 Mean annual apparent frequency $\overline{f}$ for the instant t = 125 s as recorded by four seismic stations. 1 – mean over all components; 2 – H component; 3 – Z component. Vertical bars indicate ± σ intervals. An "extra point" was obtained in 1971 from aftershocks of the Ust'-Kamchatsk earthquake, December 15-31, 1971.

pronounced drop in apparent frequency for KB and a less distinct one for KRN. No unambiguous anomaly was recorded at BRN and KL. Note that the KB curve is still below the pre-earthquake level 6 years after the event.

Thus, the apparent frequency shows some anomalous behavior most clearly at KB which is closest to the epicenter of the large earthquake. The anomalies are less stable and uniform, however, than those found for the envelope shape.

BAND-PASS FILTERING OF CODA RECORDS

The precursory envelope shape anomalies must have been due to some physical events. As mentioned in [1], these may be variations in the properties of the transmitting medium (scattering and/or absorption) or in the spectrum of the seismic source radiation. The latter effect is associated with changes in the mean signal frequency, the medium being "sounded" at a different wavelength. If the properties of the medium are frequency-dependent, they will exhibit apparent changes with time.

It is obviously of interest to understand the origin of coda envelope shape anomalies as there is an important qualitative difference between source and medium anomalies. We have tried to resolve this problem by utilizing band-pass filtered records of regional stations. With a narrow enough band-pass, the envelopes of filtered records will not be affected by the source spectrum, depending on the medium only (as usual, the source time function is assumed to be short).

TABLE III
Data on records used

No.	Date	Time			Coordinates deg.		H, km	K	Station	$\alpha\cdot10^3$
		hour	min	s	Lat. N	Long. E				
				"Normal" period						
1	Dec. 14, 1968	16	21	13.5	55.50	163.40	0	10.7	KB	+0.5
2	Jan. 1, 1969	10	33	45.0	55.80	163.50	5-10	10.6	KB	−1.7
3	April 26, 1969	11	39	13.5	55.85	162.50	20	10.3	KB[a]	0.0
4	Oct. 12, 1969	14	22	02.0	55.10	162.12	20	11.2	KB	−2.3
5	Feb. 14, 1970	05	12	59.0	55.90	163.06	0-5	10.7	KB	−1.6
6	Feb. 26, 1970	06	37	30.0	54.99	162.92	35	11.2	KRN[a]	−1.6
7	April 10, 1970	01	04	58.4	54.78	162.40	25	11.1	KRN	−0.8
8	April 12, 1970	17	38	56.5	55.39	163.21	5	10.7	KB	−0.3
				"Anomalous" period						
9	April 11, 1971	00	54	04.0	55.56	162.33	15	11.0	KB	−1.9
10	June 7, 1971	13	07	15.0	55.54	162.47	5	9.8	KB[b]	−5.2
11	June 10, 1971	08	37	20.0	55.72	162.15	20	10.3	KB[b]	−3.7
12	Aug. 19, 1971	09	28	51.8	55.55	162.46	60	10.3	KB	−4.0
13	Oct. 4, 1971	12	25	0.00	54.85	162.90	5-10	10.6	PRN	−3.5
14	Nov. 11, 1971	06	04	13.5	55.16	162.71	80	10.5	KB	−3.2

[a] The EW component was not digitized.
[b] The Z was not digitized.

We selected recordings made on vertical and horizontal components at KB and KRN during the normal and the anomalous periods. Unfortunately, very few records were suitable for digitization. The earthquakes we have used are listed in Table III, and the epicenters plotted in Figure 10. They cluster around two stations, KB and KRN, and were accordingly studied separately, using records obtained at the nearest station only. The records were digitized in the interval from $t_o + 2.5(t_S - t_P)$ or somewhat later (when the amplitudes were excessively large) to the instant when the coda level was twice that of the microseisms. Band-pass digital filtering was then performed using semi-octave filters with axial frequencies 0.75 and 1.5 Hz. The output was a smoothed (with a time constant of 5 s) mean-square amplitude, $\bar{A}(t)$. Individual plots of $\bar{A}(t)$ were averaged by shifting them vertically until they matched as much as possible. Figure 11 shows eight plots of log $\bar{A}(t)$ for two frequencies, two data sets, and two time periods of study. There is a pronounced increase in the slope for all four pairs during the anomalous

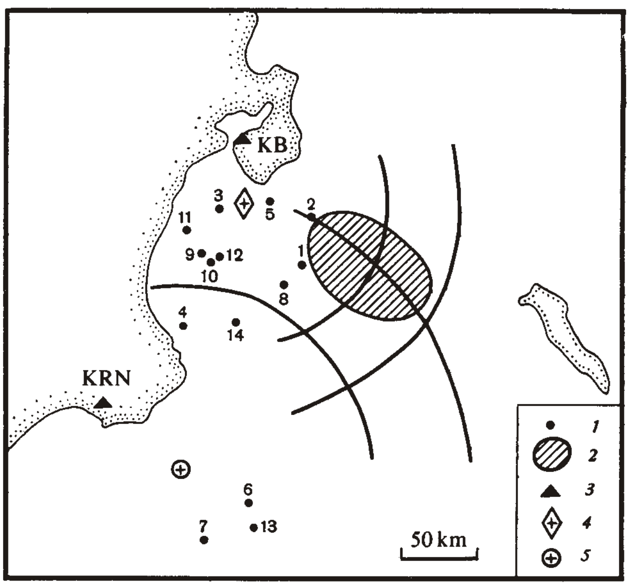

FIGURE 10 The study area: 1 - earthquake epicenters numbered according to Table III; 2 - epicentral area of the December 15, 1971, earthquake, M_{LH} = 7.8; 3 - seismic stations; 4 - the middle point of the "northern epicenters - station KB" area serving as the center for the arcs shown; 5 - the same for the southern epicenters and station KRN.

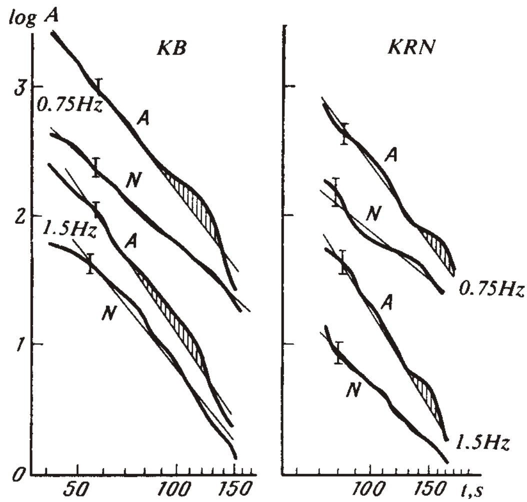

FIGURE 11 Smoothed and averaged $\bar{A}(t)$ curves for stations KB and KRN, frequencies 0.75 and 1.5 Hz, normal (N) and anomalous (A) periods. The curves are approximated visually by straight lines, "humps" are shaded for times greater than 85 and 130 s for stations KB and KRN respectively. Vertical bars indicate $\pm\sigma$ ranges for the estimated curves. The curves were shifted vertically.

period. The difference in the mean slope for the most reliable pair of log $\bar{A}(t)$ curves (station KB, 1.5 Hz) amounts to $-1.6 \times 10^{-3}s^{-1}$. If we attribute this to increased absorption, then formula (32) from [1] with $f_a = 1.5$ Hz and $Q_{norm} = 250$ will give an absorption increase of about 20 percent. The same value is obtained when the mean α for the anomalous period is substituted, viz., $\alpha = -0.002$ (Table II).‡

The fact that the variations in the slope of the coda envelope persisted through the filtering procedure indicates that variations in the source spectrum cannot have caused envelope shape anomalies. A similar conclusion can be drawn from an analysis of anomalies in the apparent frequency. A steeper envelope slope indicates an increase in the effective absorption of the medium. If the properties of the medium are unchanged, this must imply a greater frequency of the source radiation,

‡ Formula (32) in [1] is valid, but the mean frequency f_a and $d\alpha/dQ$ are wrong. The estimate of changes in Q (about 20 percent) is correct in [1]. We have used here the correct values $f_a = 1.2$ Hz and $d\alpha/dQ = 2.7 \times 10^{-5}$, getting ~20 percent again.

so that the apparent coda frequency must increase too, whereas the observations point to its decrease.

Of great interest is the appearance of "humps" during the anomalous period (shaded portion of Figure 11). The reality of these is hard to prove in a rigorous manner, but simple tests seem to demonstrate that they were not caused by random effects. The presence of "humps" may indicate that a powerful local scattering "spot" was created during the anomalous period. This possibility has been discussed theoretically in [4]. In the framework of the single-scattering model the "spot" will produce a "hump" over periods of about twice the travel time from the "spot" to the station-source area. The distance to the "spot", r, is given as

$$r = \tau/2\, V_S$$

where τ is time delay and V_S is S-wave velocity. Assuming V_S = 3.5 km/s and τ = 85 and 130 s (these are the values for KB and KRN), we obtain r = 150 and 230 km. However, it follows from [2] that the waves are usually scattered twice. Accordingly, the "sounding distance" will be less by a factor of about 1.5 and the estimates for r will be 100 and 150 km.

Figure 10 shows possible locations for the "spot" (another set of locations may lie west of the station). Judging by these locations, the local diffracting "spot" may be close to the source region of the future earthquake.

THE NATURE OF PRECURSORY ANOMALIES

The use of band-pass filtering enabled us to eliminate variations in the source spectrum as a possible cause of the coda envelope anomalies. We proceed therefore to discuss the effects of scattering. It should be noted that changes in the mean turbidity of the medium leave the shape of the coda envelope unchanged (only the level will be affected). For this reason increases in the envelope slope can only have been associated with spatially inhomogeneous and rather specific changes in scatterer density. However, since the effect occurred at several stations at once, this explanation appears to be doubtful. Most likely, the α anomalies are associated with increased effective absorption of S-waves at 0.6-2 Hz. The increase is about 20 percent. The size of the anomalous absorption region is about 100-200 km.

We should like to mention that the author of [3] estimated Q_S in the Kamchatka Bay area on the assumption that it was proportional to the apparent frequency of S-waves from local earthquakes. This rather peculiar method of estimation gave results that are directly opposite to ours, viz., an anomalous increase of Q_S prior to the 1971 Ust'-Kamchatsk earthquake. Since our respective techniques have nothing in common, we do not see how the results can be mutually contradictory.

The inference about a local scattering spot within the source region is less reliable than that concerning absorption variations. It is based on a limited amount of data relating to a single large earthquake and should for the time being be considered tentative.

The frequency anomalies of the coda are les pronounced than the envelope shape anomalies. They may also have been caused by absorption variations, though it is difficult to estimate theoretically how an absorption change can affect the apparent frequency. The time offsets between the curves for different stations in Figure 9 and the qualitative differences between the α curves (there is a return to the initial value after the event) and the $\bar{f}$ curves (there is no such return) suggest that the variation of $\bar{f}$ can also be due to causes other than absorption changes. It has been found [9] that events with m_b = 4-5 which occurred within the 1971 earthquake precursory area emitted abnormally low-frequency P-waves. Therefore, the temporal variation of $\bar{f}$ may be due to changes in the source regions of smaller earthquakes. This, however contradicts the fact that no anomaly was observed at BRN. The nature of $\bar{f}$ anomalies remains an open question.

CONCLUSION

The principal result of the present study has been the detection of a precursory increase in the slope of the coda envelope prior to three large Kuril-Kamchatka earthquakes. The precursor is relatively uniform: α abruptly drops from zero to about $-(0.0015\text{-}0.0025)$ approximately a year before the shock, remaining at this level up to the origin time. After the earthquake the parameter α returns to zero within a year or two. The precursory anomaly is highly significant according to statistical tests and can be detected from data obtained in 2-4 months (provided there is no pronounced seismic quiescence).

One should note an abrupt precursory change and the absence of any distinct bay appearance. It is worth recalling in this connection that the temporal variations of the coda envelope observed in California were also abrupt (a change occurring over a month or so, based on an observation period of about a year) [8].

The use of spectral analysis has provided additional evidence in support of our earlier conclusion [1] to the effect that a probable cause of the anomaly was an absorption increase of about 20 percent.

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