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# CODA-BASED ENERGY CLASSIFICATION OF NEAR KAMCHATKA EARTHQUAKES

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The coda envelope shape of Kamchatka earthquakes has been tested for stability. The correlation between coda level $2A_{100}$ and S.A. Fedotov's energy class has been used to develop a technique for the energy classification of local Kamchatka earthquakes. Corrections for the site effect and the depth of focus have been computed. The relative uncertainty of energy class estimates based on coda observations ranges between 0.1 and 0.5.

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## Introduction

One of the major parameters of the earthquake source is the energy it radiates. The seismic energy of near earthquakes is usually determined using "direct" waves. It has recently been found however that the tail portion of earthquake records or coda waves can also be used for this purpose /1, 8, 9, 12, 14, 15/. Following the lines of /9/, we suggest a regional $K_c$ scale for energy classification of Kamchatka earthquakes based on the amplitude level of the coda envelope. Instead of using absolute calibration for our scale, we "tied" it by way of correlation to the Fedotov $K_{S1,2}^{F68}$ scale which is the standard one for Kamchatka /10/.

## Method of New Classification

To work out this classification we used earthquake records obtained at the regional Kamchatka seismograph network (Fig.1) with the conventional instruments: a VEGIK or SM-3 seismometer with $T_S$=1.2 and a GB-IV galvanometer with $T_g$=0.07 s. The magnification range was between 3,000 and 10,000. The flat portion of the frequency response curve ranged within 1-10 Hz. The drum speed of 120 mm/min permitted the identification of motions of as short period as T=0.2 s.

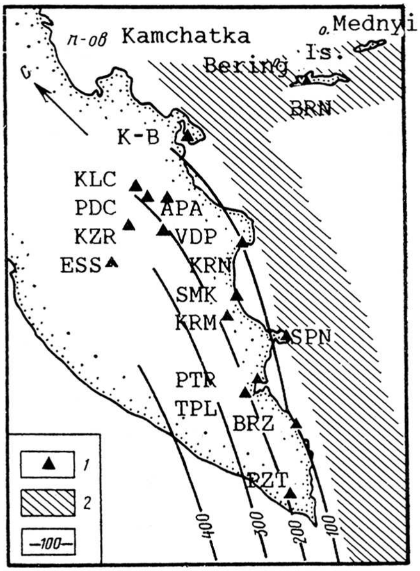


Fig.1. Regional seismograph network in Kamchatka. 1 - stations; 2 - area of maximum shallow seismicity; 3 - lines of equal depth for the Wadati-Zavaritskii-Benioff zone (inferred). Code: BRN - Bering Is., K-B - Krutoberegovo, KLC - Klyuchi, PDK - Podkova, APA - Apakhonchich, KZR - Kozyrevsk, VDP - Vodopadnyi, KRN - Kronotskii, ESS - Esso, SMK - Semyachik, KRM - Karymskii, SPN - Shipunskii, PTR - Petropavlovsk-Kamchatskii, TPL - Topolovo, BRZ - Berezovaya, PZT - Pauzhetka.

The $K^{F68}_{S1,2}$ scale which is used to interpret the Kamchatka network records relies on the energy of "direct" S waves in the frequency range 1 to 4 Hz. The S energy outside of this range is discharged, as is the energy of scarce P waves. This does not usually involve large errors /10/. The range of visible coda frequencies is $0.7 \le f \le 2$ Hz /3/. The coda of near earthquakes at 1 Hz and higher frequencies is mainly due to scattered shear waves /13/, so in our case the amplitudes of "direct" S and the coda are due to waves of the same type. The spectral ranges of these waves overlap. The contribution of surface waves, if any, must be manifest in both cases. The above considerations suggest a fairly close relationship between the $K^{F68}_{S1,2}$ values and the energy estimates based on the coda.

The current notion on how the coda forms states that it is due to scattering of "direct" waves at numerous heterogeneities in the earth. Their amplitudes thus effectively average the source radiation pattern and the diversity of seismic ray paths in a real laterally heterogeneous medium. It is universally recognized that these factors cause a large scatter of estimates in the energy and magnitude classification of earthquakes based on "direct" seismic waves. The use of the coda reduces the scatter appreciably. Moreover, it makes an accurate identification of S superfluous. This simplifies the measurement procedure and eliminates the main source of gross errors (wrong S-P) when the energy class is determined in the express mode from a small number of stations.

Earlier, two methods have been proposed for using coda-waves as a basis of earthquakes classification: one using the coda amplitude and the other the visible record length. The second method is faster and eliminates the need for some of the site corrections /14/. In Kamchatka, however, this method is unreliable, because during cyclones and storms in the Pacific the microseism level increases by several times and may give rise to large errors. The measurement procedure for the coda amplitude can be more easily formalized and the results are less amenable to distortion by microseism variations, the extra labour input being insignificant.

We measured coda amplitudes by the technique we used earlier to study time variations of the coda envelope /2/. The coda amplitude is here defined as the sum of the largest swings on both sides of the baseline ("double amplitude") over a time interval of 10 s. Each time interval was measured from the earthquake origin time. In this research we used the amplitudes measured earlier /2/ and some new measurements.

We plotted mean coda envelopes using two techniques: the alignment method and the "gradient" method which was used by Fedotov /10/. The first procedure requires that the coda envelopes of individual earthquakes plotted on a log scale be aligned at the point t=105 s by translation along the amplitude axis. Some envelopes did not contain the point t=105 s (they ended earlier or began later than that). These were moved along the amplitude axis to fit the previously obtained curves. The first step in the "gradient" procedure was to find a difference between the adjacent values for each envelope. It was done using the formula

$$\delta_i \log (2A) = \log (2A(t_i)) - \log (2A(t_{i+1}))$$

The results were then averaged for several envelopes and stacked ("integrated"). The step I procedures were made on a computer. Since the curves obtained by the two techniques were practically identical, we concluded that no serious experimental mistakes were involved (Fig.2,a). Next we had to find out whether the behaviour of the coda envelope shape was the same in all three channels. We found that the coda envelopes based on the same group of earthquakes did not show any significant differences between the two horizontal and the vertical component (see Fig.2,b,c,d). The same result was obtained for three-component stations operating in Soviet Central Asia /9/. Thus, the energy classification of Kamchatka earthquakes based on the coda amplitude can rely on horizontal or vertical records using a single standard coda envelope.

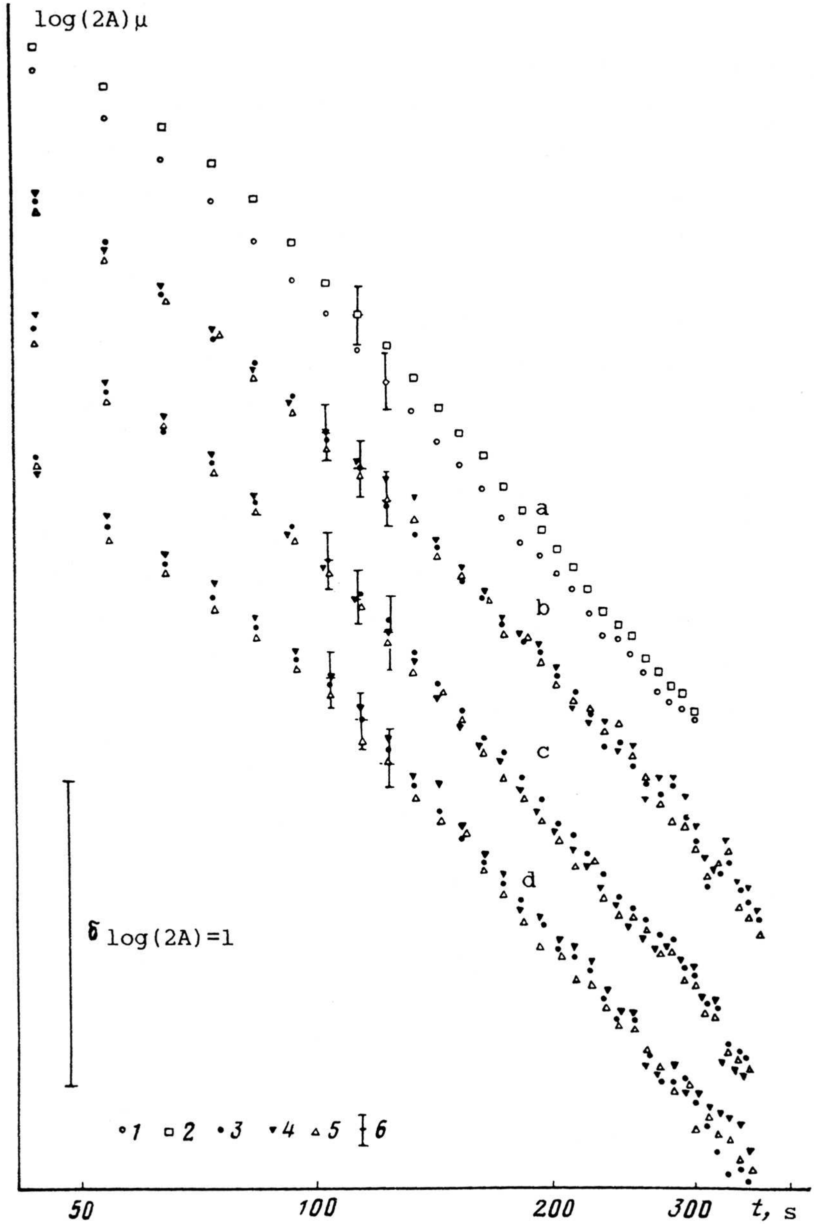


Fig.2. Mean coda envelopes based on data from different components using different techniques. (a) regional means obtained by two techniques; (b) curves based on SPN data; (c) same, KLC; (d) same, KRN. 1 - mean envelopes obtained by the alignment technique; 2 - same, gradient technique; 3 - same, for Z component; 4 - same, for NS component; 5 - same, for EW component; 6 - standard deviation.

## RELATION BETWEEN THE CODA AMPLITUDE LEVEL AND THE $K_{S1,2}^{F68}$ ENERGY CLASS

Our choice of the parameter determining the coda amplitude level was the quantity $\log(2A_{100})$ where $2A_{100}$ is the peak-to-peak envelope amplitude for a fixed delay t=100 s as measured from the origin time. The first step to compute $2A_{100}$ was to measure the coda trace amplitudes for a range of delays. The 2A(t) results were converted to ground motion amplitudes using the rated seismograph magnification (disregarding the visible period). Then a specific amplitude 2A(t) at a specific delay t was used to compute $\log(2A_{100})$ by

$$\log(2A_{100})=\log(2A(t))+\log(a(100)/a(t)),$$

where a(t) is the overall mean code envelope for the region which has the mapping of a calibration function and a(100) is the value of that envelope at t=100 s. Fig.3 presents experimental relationships $2A_{100}(N_{S1,2}^{F68})$ based on vertical recordings at four seismic stations. The straight lines are given by

$$K_{S1,}^{F68}2=1.60\ \log(2A_{100})+11.0+C,$$

where C has the meaning of a site correction. We used $C\equiv 0$ for the vertical component at PTR station. The slope 1.60 has been found acceptable for all stations. For this reason has new parameter "coda-based energy class", $K_c$, was defined by

$$K_c=1.60x(\log(2A(t))+\log(a(100))-\log(a(t)))+11.0+C.$$

The function log a(t) for the Kamchatka instrumentation and other conditions is given in Table 1. Note that $\log a(100)\equiv 0$. The above formula is represented as a nomogram in Fig.4 which gives $K_c$ (without correction) based on coda amplitude 2A at a fixed time t as measured from the earthquake origin time.

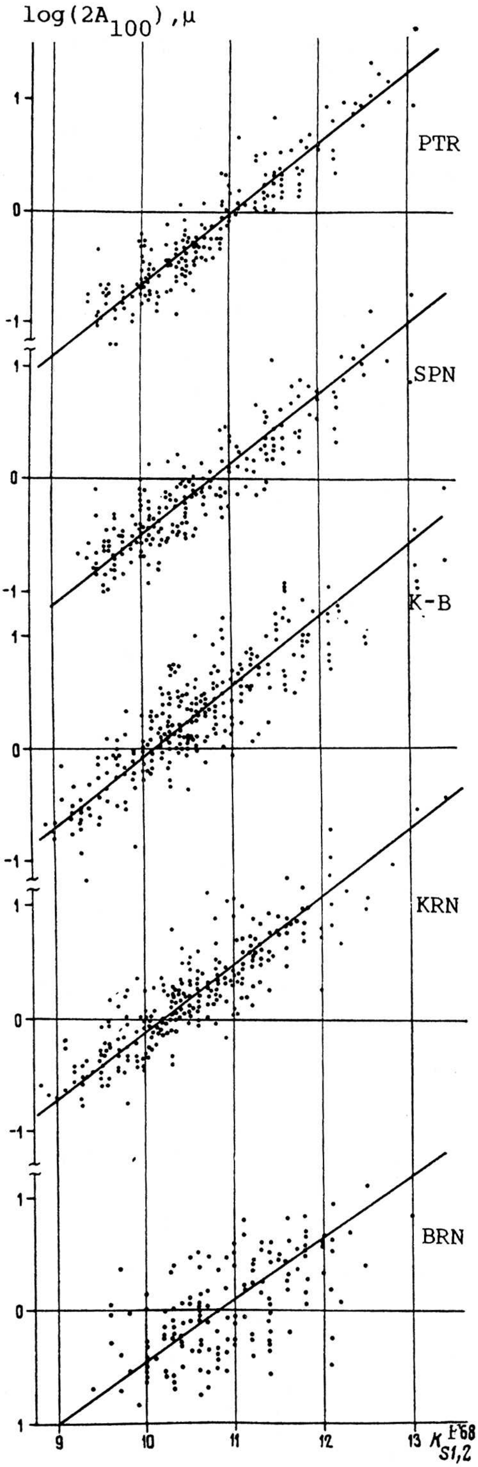


Fig.3. Correlation between coda envelope level at t=100 s and energy class $K_{S1,2}^{F68}$

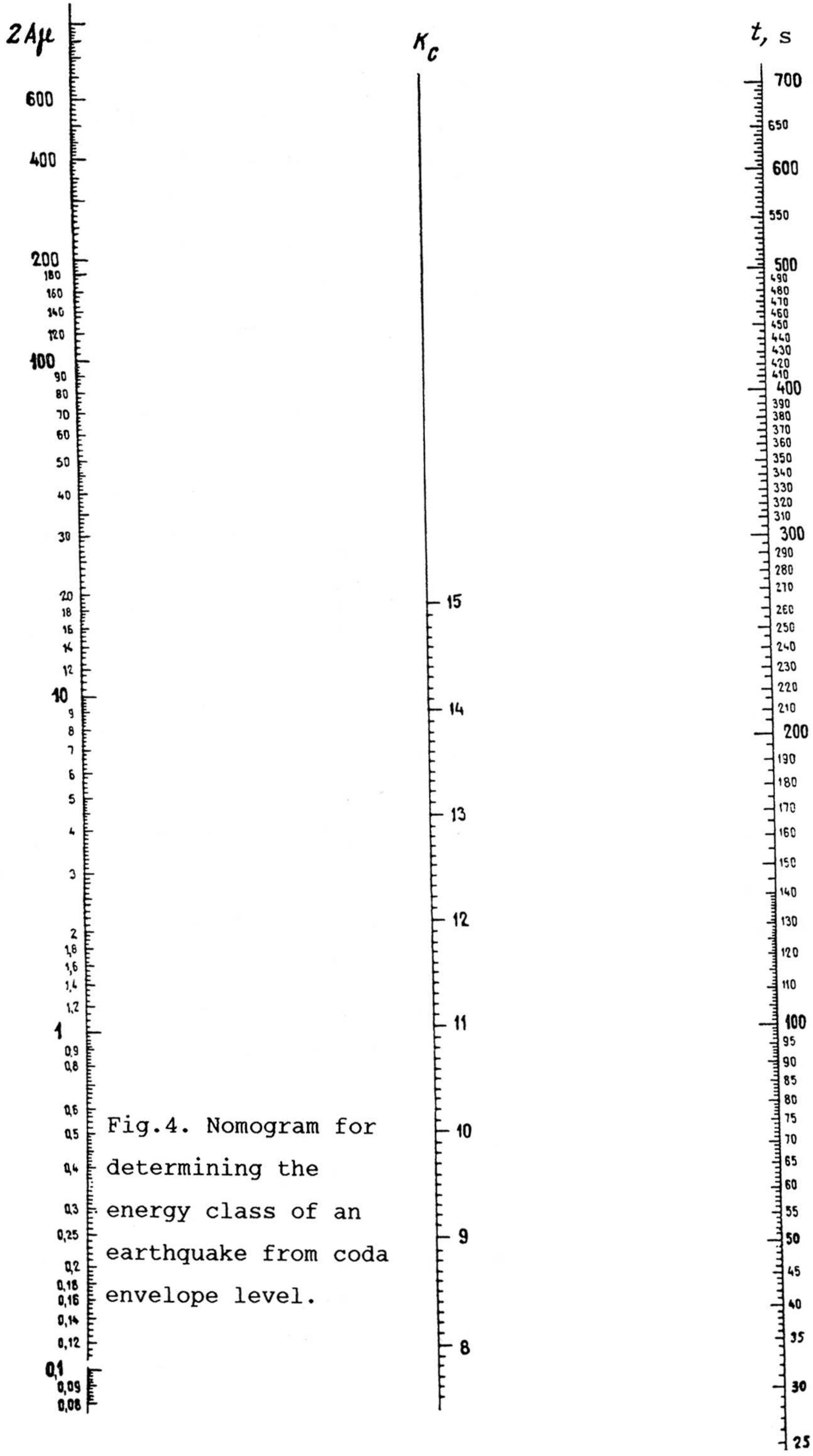


Fig.4. Nomogram for determining the energy class of an earthquake from coda envelope level.

## THE EFFECT OF POSSIBLE CHANGES IN THE CODA ENVELOPE SHAPE ON THE ACCURACY OF ENERGY CLASS DETERMINATION

The energy classification of earthquakes can be based on the coda level, because the coda envelope shape is stable. It does not vary much, in a fixed frequency range, with the geographical location of the epicentre, epicentral distance, energy, focal depth and other earthquake parameters. Moreover, after the application of corrections the coda envelope for a given earthquake has the same level at different stations irrespective of the distance /9/. The stability of the coda envelope shape has been confirmed by the results of many studies /4, 5, 7, 8, 14, 16/. An experimental study by Rautian et al /9/ contains, in particular, coda envelopes for local Kamchatka earthquakes recorded with a SKM-3 instrument at station PTR (see Fig.1). The response curves for SKM-3 and VEGIK seismometers are similar. The general conclusion in this monograph applies to Kamchatka data as well: "... the coda envelope shape does not depend on the magnitude, focal depth and epicentral distance, nor on the location of the source and station".

We compared a great number of individual coda envelopes recorded in Kamchatka and found them to be stable in that region, too. For a better substantiation of our technique we made a special investigation of a possible instability of the coda envelope shape, attempted to estimate it quantitatively, and examined its possible effect on the accuracy of the energy class determination based on the coda level. Earlier /3, 9/, some relation has been suggested between the coda envelope shape and the depth of focus, station location, and calender time. In this research we carried out a special investigation of this point.

As regards relative envelope level shifts, they can be easily identified and corrected. More hazardous are abnormally steep or abnormally flat envelopes which can in principle appreciably affect the coda-based energy estimates. We investigated this possibility using the technique we developed and described earlier /2/. We estimated the anomalous envelope slope as

$$\alpha = d/dt\,(\log A(t) - \log a(t)),$$

where a(t) is the reference and A(t) an individual envelope. The reference or basic envelope was the mean regional coda envelope estimated earlier /2/.

In this work we used records made at 12 regional stations in 1968-1984. The earthquakes were grouped by focal depths as in /10/: 0-60, 60-120, 120-200 and 200-600 km. For the first two depths ranges, the 1968-1973 (period I) and 1978-1984 (period II) data were handled separately. This choice of time periods was governed by the desire to compare the results obtained before and after the routine calibration of the seismometers made in 1973 /11/. The resulting deviations $\delta = \log A(t) - \log a(t)$ for the mean coda envelopes of some Kamchatka stations are presented in Fig.5. The difference curves are seen to be stable except for some slight individual features. The exception is the K-B station where a notable difference is seen between the relevant envelope and the reference for the focal depths H>200 km. There is not much difference in the envelope shape between periods I and II.

The data samples for the 0-60 and 60-120 km depth ranges contained a few tens of earthquakes. As to the 120-200 and 200-600 km ranges, we failed to sample more than 5-10 records for each of the 12 stations, because we needed long enough codas to estimate $\alpha$

The resulting mean $\alpha$ values were within $\pm 0.6 \times 10^{-3}$ $s^{-1}$ for almost all stations and depth ranges with the standard deviation of $(0.5\text{-}1.1) \times 10^{-3}$ $s^{-1}$. The values are presented for PTR and KRN in Table 2 as an example.

The estimates of $\alpha$ for the groups K-B (200-600), KRN (200-600), and APA (120-200) were outside the above interval. The largest deviation was observed for the group K-B (200-600) (see Fig.5):

$\alpha=-1.5\times10^{-3}\pm1.0\times10^{-3}$ $s^{-1}$ and the anomaly was not recognized to be significant. To sum up, nearly all variations of the log envelope slope fell within the range $\pm1\times10^{-3}$ $s^{-1}$ and most of them within $\pm0.6\times10^{-3}$ $s^{-1}$.

Table 1. Overall Mean Coda Envelope Based on Data from Regional Kamchatka Stations

| $t$ | $\lg a(t)$ | $t$ | $\lg a(t)$ |
|---|---|---|---|
| 25 | (1.096) | 160 | —0.577 |
| 30 | 0.973 | 180 | —0.710 |
| 40 | 0.732 | 200 | —0.870 |
| 50 | 0.562 | 250 | —1.161 |
| 60 | 0.415 | 300 | —1.387 |
| 70 | 0.292 | 350 | —1.588 |
| 80 | 0.199 | 400 | —1.750 |
| 90 | 0.097 | 450 | —1.907 |
| 100 | 0.00 | 500 | —2.066 |
| 120 | —0.208 | 550 | —2.208 |
| 140 | —0.402 | 600 | —2.328 |

Note. Time t is measured from earthquake origin time. The real log a accuracy is restricted to two decimal places.

It should be made clear that abnormally steep or flat envelopes largely affect the conversion of coda amplitude 2A(t) into $2A_{100}$. The error involved can be considered to be $\Delta\log 2A_{100}=\alpha(t-100)$. As t usually ranges between 50 and 200 s, even a pronounced anomaly ($\alpha=$ $10^{-3}$) will produce the maximum error $\Delta\log 2A_{100}=0.1$, which gives $\Delta K_c=0.16$. As a rule, the error is much smaller and can be minimized by averaging over the stations. So, we can recognize this source of error to be unimportant.

Table 2. Values of $\alpha\times10^3$ for Stations PTR and KRN

| Depth range, km | $\alpha\cdot10^3$ (PTR) | $\alpha\cdot10^3$ (KRN) |
|---|---|---|
| 0—60 | —0.15 | +0.03 |
| 60—120 | —0.22 | —0.22 |
| 120—200 | —0.13 | +0.03 |
| 200—600 | —0.27 | —0.71 |

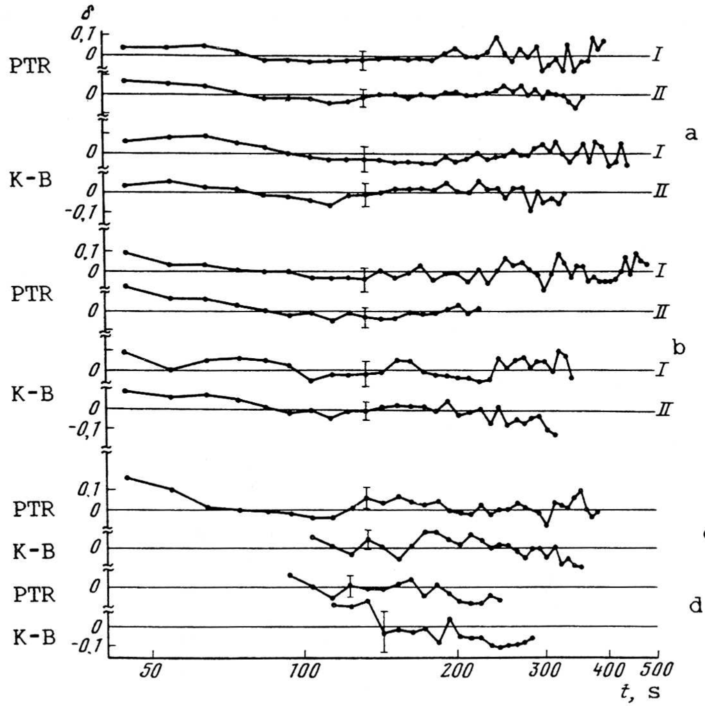


Fig.5. Difference curves for mean coda envelopes at PTR and K-B. I and II are periods of observation (see the text); (a) thru (d) samples of earthquakes grouped by depth of focus, km: (a) 0-60, (b) 60-120, (c) 120-200, (d) 200-600. The standard deviation is for the time interval 65-265 s, the data scatter being greater outside it.

The mean station envelopes for six best-studied stations and the focal depths of 0 to 100 km are presented in Fig.6. Here again, the differences from the mean regional curve are small except for station BRN where the coda was probably contaminated with the T phase as mentioned in /3/. So, the BRN data were discarded.

Earlier /2, 3/ we observed negative $\alpha$ anomalies of the order of $-2x10^{-3}$ $s^{-1}$ for periods of a year or two before and after large earthquakes (M about 8) at several stations near the epicentral areas. As attenuation changes during such anomalous periods, any stable magnitude or energy scale is prone to be affected by systematic errors and the $K_c$ error may be as great as 0.2-0.3.

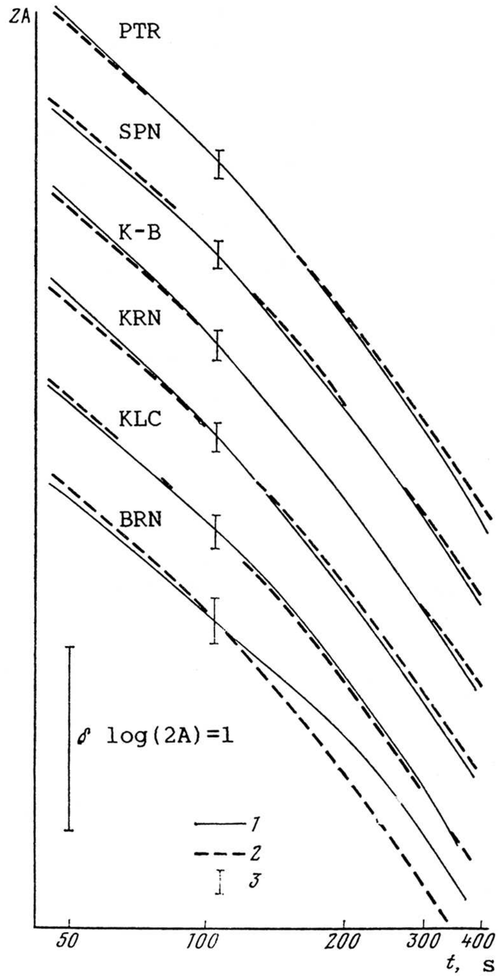


Fig.6. Mean coda envelopes for some of the Kamchatka stations and the summary envelope averaged over the stations. 1 - mean coda envelopes for individual stations; 2 - overall coda envelope for Kamchatka; 3 - standard deviation for data points of individual envelopes.

We have also investigated the effect of energy class $K_{S1,2}^{F68}$ on envelope shape, again by computing $\alpha$. We expected that as smaller shocks would be of higher frequencies, their envelopes would be steeper. The trend out to be as expected but was more pronounced in the range of K=8-10. With K=10-14 $\alpha$ was close to zero ($\pm 0.4 \times 10^{-3}$ $s^{-1}$) and decreased to $-1 \times 10^{-3}$ $s^{-1}$ for K=9. This trend continued to about $-2.5 \times 10^{-3}$ $s^{-1}$ for K=8. This fact is not very important in routine work, but acquires significance in some special cases (e.g., for a sequence of shocks near the station). In such cases corrections can be computed by the formula $\Delta \log A_{100} = \alpha(K) x (t-100)$, if necessary.

The application of the $K_c$ scale to small shocks is impeded by the fact that the coda is often drowned in the microseisms even at the station nearest to the epicentre. For the microseism level of Kamchatka, the rough limits of the hypocentral distance (r) where $K_c$ can still be found are

| K | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|
| r, km | 40 | 80 | 160 | 300 | 600 |

Considering the network density and distances to the main source zones in Kamchatka, $K_c$ cannot be determined for most of the K=8 shocks and for a large number of the K=9 events.

<u>Corrections to $K_c$ Values Determined by the Nomogram</u>

The coda envelope level can be systematically shifted by the effects of various factors (for a fixed $K_c$) relative to a chosen reference level. In our case it was the vertical component at station PTR. We discovered three sources of systematic error: seismometer component, station site, and the depth of focus. We computed corrections for all of them.

Table 3. Site Corrections $\delta_{st}$

| Station site | $\delta_{st}$ | Station site | $\delta_{st}$ |
|---|---|---|---|
| PTR | 0 | KRN | —0.8 |
| SPN | —0.2 | KLC | —0.8 |
| TPL | —0.2 | KZR | —1.0 |
| PZT | —0.3 | APA | —0.8 |
| KRM | —0.5 | VDP | —0.8 |
| ESS | 0 | PDK | —0.9 |
| SML | —1.1 | BRN | (—0.2) |
| K-B | —0.9 | | |

Table 4. Corrections for Depth of Focus $\delta_{depth}$

| Depth range, km | $\delta_{depth}$ | $\Delta K^{F68}_{S1,2}(H)$ |
|---|---|---|
| 0—60 | 0 | 0 |
| 60—120 | +0.2 | +0.2 |
| 120—200 | +0.5 | —0.2 |
| 200—600 | +0.7 | —0.6 |

Effect of seismometer component. The level of the coda envelope recorded by the horizontal component is higher than that of the veritcal component. We found this difference to be almost the same at all stations and computed the correction $\delta_{comp}$=-0.3 to be applied to the $K_c$ values based on horizontal recordings.

Site effect. We found the site effect to be rather large in Kamchatka. The site corrections $\delta_{sb}$ (relative to PTR, the base station in the national seismic network, ESSN) are listed in Table 3. Although the correction for station BRN has been formally included, the envelopes obtained at this station are anomalous and should not be used for determining $K_c$. The stations can be divided into two groups: the southern stations with $\delta_{st}$=0-0.5 and the northern ones with $\delta_{st}$=0.8-1.0. Exceptions are BRN and ESS.

<u>Focal depth.</u> The coda envelopes and the nomogram were first plotted for the events with focal depths H=0-60 km which constitute the bulk of the Kamchatka earthquakes. For deeper shocks the $K_c$ values found from the nomogram (Fig.4) were systematically lower than $K^{F68}_{S1,2}$. The $\delta_{depth}$ corrections computed for larger focal depths are given in Table 4. The bottom line in Table 4. quotes the corrections from /10/. The $\delta_{depth}$ corrections reduce $K_c$ values to the $K^{F68}_{S1,2}$ values of the regional catalogue and the $\Delta K^{F68}_{S1,2}$ (H) corrections are applied to the $K^{F68}_{S1,2}$ values found from the nomogram to obtain energy estimates unaffected by focal depth. The latter are not used in routine work. If necessary, the best coda-based estimate of the source energy can be obtained by using $\delta_{depth}+\Delta K^{F68}_{S1,2}$ (H).

## Reliability of $K_c$ Estimates

The $K_c$ estimate is the result of averaging the individual values obtained for different stations and components using the amplitudes measured at different times. As the systematic errors can be eliminated by the above corrections, we assume the error of a $K_c$ determination to be the sum of three independent random components $\varepsilon_{st}$, $\varepsilon_{comp}$, $\varepsilon_T$ with zero means, each being due to one of the above sources (station, component , amplitude reading). Proceeding from the assumptions that the number of amplitude readings for one component, and the numbers of components and stations are fixed, we denote them as N, M, and $N_{st}$ and define

$$\varepsilon^*_{comp} = \varepsilon_{comp} + \frac{1}{N}(\varepsilon_{T,1} + \varepsilon_{T,2} + \ldots)$$

$$\varepsilon^*_{st} = \varepsilon_{st} + \frac{1}{M}(\varepsilon^*_{comp,1} + \varepsilon^*_{comp,2} + \ldots)$$

$$\varepsilon_s = \frac{1}{N_{st}}(\varepsilon^*_{st,1} + \varepsilon^*_{st,2} + \ldots).$$

The $\varepsilon_T$ variance can be estimated as

$$\sigma^2(\varepsilon_T) = \frac{1}{N-1}\sum_{i=1}^{N}(K_i - K^{(T)})^2$$

$$K^{(T)} = \frac{1}{N}\sum_{i=1}^{N} K_i, \quad i = 1, 2, \ldots, N,$$

where $K_i$ are the estimates of $K_c$ based on particular amplitude readings. A similar estimate can be obtained from several components:

$$\sigma^2(\varepsilon^*_{comp}) = \frac{1}{M-1}\sum_{j=1}^{M}(K_j - K^{(K)})^2$$

$$K^{(K)} = \frac{1}{M}\sum_{j=1}^{M} K_j, \quad j = 1, 2, \ldots, M,$$

where $K_j$ is the $K^{(T)}$ value for the j-th component. It is easy to see that

$$\sigma^2(\varepsilon^*_{comp}) = \sigma^2(\sigma_{comp}) + \frac{1}{N}\sigma^2(\varepsilon_T).$$

This procedure can be repeated for averaging over stations and yields

$$\sigma^2(\varepsilon^*_{st}) = \sigma^2(\varepsilon_{st}) + \frac{1}{M}\sigma^2(\varepsilon^*_{comp}).$$

We estimated $\sigma^2(\varepsilon_T)$, $\sigma^2(\varepsilon^*_{comp})$, $\sigma^2(\varepsilon^*_{st})$ using the samples of about 100 events with $N_T$=3, M=3, and $N_{st}$=6-10. The resulting estimates were $\sigma(\varepsilon_T) = 0{,}20$, $\sigma(\varepsilon^*_{comp})=0.15$, $\sigma(\varepsilon^*_{st})=0.20$, whence $\sigma(\varepsilon_{comp})=0.1$ and $\sigma(\varepsilon_{st})=0.18$. Those were rough numerical results, because of a considerable scatter of different samples (different time periods, focal depths, stations, and components).

We are now able to determine the uncertainty of $K_c$, i.e., the typical difference $\varepsilon_c=K_c-K_c^{(ideal)}$ between the actual $K_c$ estimate and some ideal $K_c$ estimate based on a large number of stations, readings and events. Under our assumptions we have

$$\sigma_M^2(\varepsilon_s) = \frac{1}{N_{st}}(\sigma^2(\varepsilon_{st}) + \frac{1}{M}(\sigma^2(\varepsilon_{comp}) + \frac{1}{N}\sigma^2(\varepsilon_T))).$$

We shall get numerical estimates by using two procedures, each involving $N_{st}$ stations and one reading on each of three or on one component (M=1 or 3, N=1). With the typical value $N_{st}$=5 and the above numerical values, we get $\sigma_1 = 0{,}13$ and $\sigma_3 = 0{,}10$. The accuracy is thus close to 0.1. We emphasize that the second procedure (M=3) requires that readings on different components should be taken at different times (at least 10 s apart), otherwise the uncertainty would grow. Note that the accuracy was as good as that because we eliminated the site effect. If $K_c$ is computed without site corrections, the standard deviation of the $K_c$ value based on five stations becomes as large as 0.35.

We will consider the relation between $K_c$ and $K_{S1,2}^{F68}$. To find out whether $\varepsilon^*_{sc} = K_c - K_{S1,2}^{F68}$ has a zero mean we grouped our data by $K_{S1,2}^{F68}$ ranges and focal depths. All group means were close to zero. The next step was to examine the variances. The quantity $\varepsilon^*_{sc}$ is the sum of three random components: the "internal" error of the $K_{S1,2}^{F68}$ scale or $\varepsilon_s$, the "internal" error of the $K_c$ scale or $\varepsilon_c$, and the error due to the discrepancy between the two scales, $\varepsilon_{sc}$. According to /10/, $\sigma(\varepsilon_S) = 0.2$. Our estimate was $\sigma(\varepsilon_c) = 0.1$. Using experimental data was found $\sigma(\varepsilon^*_{sc}) = 0.4$. The scale discrepancy error is thus $\sigma(\varepsilon_{sc}) = 0.33$. This is greater than the "internal" error for either scale. We are now in a position to find the uncertainty of the coda-based $K_{S1,2}^{F68}$ value. The most important case of fast determination based on a single station and involving the second amplitude measurements procedure (M=3) gives $\sigma_3 = 0{,}23$; when combined with $\sigma(\varepsilon_{sc}) = 0.33$, this gives $\sigma = 0.4$ for the uncertainty.

## Procedure of $K_c$ Determination

To instruct the user, we will describe the procedure for determining $K_c$ by steps. The description concerns the second procedure (amplitudes are measured on three components at each station) with some explanations of the first procedure (one component at a station).

1. Choice of a measurement window. Add the interval $t_s-t_p$ to the S arrival, i.e., find the time $t_{C1}-t_s+(t_s-t_p)$. If the coda level at that time instant is below the peak-to-peak microseism amplitude, measurement is impossible. Otherwise, find the time instant $t_{C2}$ where the coda amplitude is about twice the microseism amplitude. The measurement window is the interval from $t_{C1}$ to $t_{C2}$.

If S arrival cannot be unidentified, find the maximum peak in the S-wave group (the earliest of the three peaks for the three components). Let the time of that maximum be $t_A$, then we set $t_{C1}=t_P+2(t_A-t_P)$. If the trace is beyond the seismogram or hazy, $t_{C1}$ is to be chosen as the time when the peak-to-peak amplitude has dropped to 5 cm. If the resulting window is larger than 150 s, it should be shortened by diminishing $t_{C2}$.

2. Choice of a peak. Break the window into three equal parts; mark the more prominent peak (locally greatest by absolute value) of the first part on the first component, that of the second part on the second component, and that of the third part on the third component. The components are numbered here in the order they follow each other on the seismogram. The operations of the first procedure are: find the most prominent peak on the EW component in the middle part of the window. In case the EW component is defective, use the NS component. If the measurement window is shorter than 15 s, choose the peaks from a window for each component without breaking it. If you doubt which peak to choose, vote for the earliest of the candidates.

3. 2A(t) computation. Measure the peak-to-peak amplitude in millimeters as usual, from a peak to the larger of the two adjacent peaks of opposite sign (in contrast to the technique used in /2/ where 2A was the amplitude range in a 10 s window).

Calculate 2A in microns using the nominal magnification of the component.

4. Time determination. Determine t for each of the measured peaks: find the time interval from the P arrival to the measured peak, $\Delta t_1$, and add $\Delta t_P$, the P travel time for a given station: $t=t_1+t_P$.

If one station is used and there is a clear-cut S arrival, calculate $\Delta t_P$

calculate $\Delta t_P = \frac{1}{\varkappa - 1}(t_S - t_P)$ where $\varkappa = V_P/V_S$. If there is no easily identifiable S, find the time to the maximum peak in the S-wave group, as in Step 1 and calculate $\Delta t_P=t_A-t_P$.

5. $K_c$ estimation from one station. Use the nomogram with t and 2A as entries, find $K_c$ for each component, add $\delta_{comp}=0.3$ if the component is EW or NS, and average the estimates over the components.

6. Final $K_c$ estimation. Execute Steps 1 to 5 for each station, add site corrections to the $K_c$ values averaged over the components, and average the results.

## Conclusion

A technique has been developed following the approach of /9/ for classifying Kamchatka earthquakes using the coda-based energy as a basis. The scientific basis and internal consistency of the technique have been investigated. Corrections have been computed to eliminate systematic errors due to the site and focal depth effects. The uncertainty of the method is estimated in relation to different sources of error. The procedure of computing earthquake energy from coda amplitudes is described in detail.

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