Origins and Methodology of the Russian Energy K-Class System and Its Relationship to Magnitude Scales

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INTRODUCTION

The size of local and regional earthquakes in the former Soviet Union (USSR) has been given by the energy class (*K*-class) system since the late 1950s. *K*-class was originally developed as a rapid and simple means of estimating the radiated energy (E) from an earthquake and was defined as

$K = \log_{10} E$ (in joules).

The nature, origin, and methodology of this system are poorly known to Western seismologists studying Soviet and Russian seismological data, and yet are of great interest and importance to those conducting detailed research on the seismicity of the former USSR. Since its inception, *K*-class has been the primary means of quantifying the size of small events in the former USSR and continues to be used for that purpose today. In most of this region, scientists employed the method of Rautian (1960), using the maximum horizontal (for the S wave) and vertical (for the P wave) amplitudes, which became the standard for local and regional networks in the early 1960s. In this paper, we describe the origins and basic principles of the energy class system, as well as the methodology generally used today by the regional networks (figure 1) of the states of the former USSR.

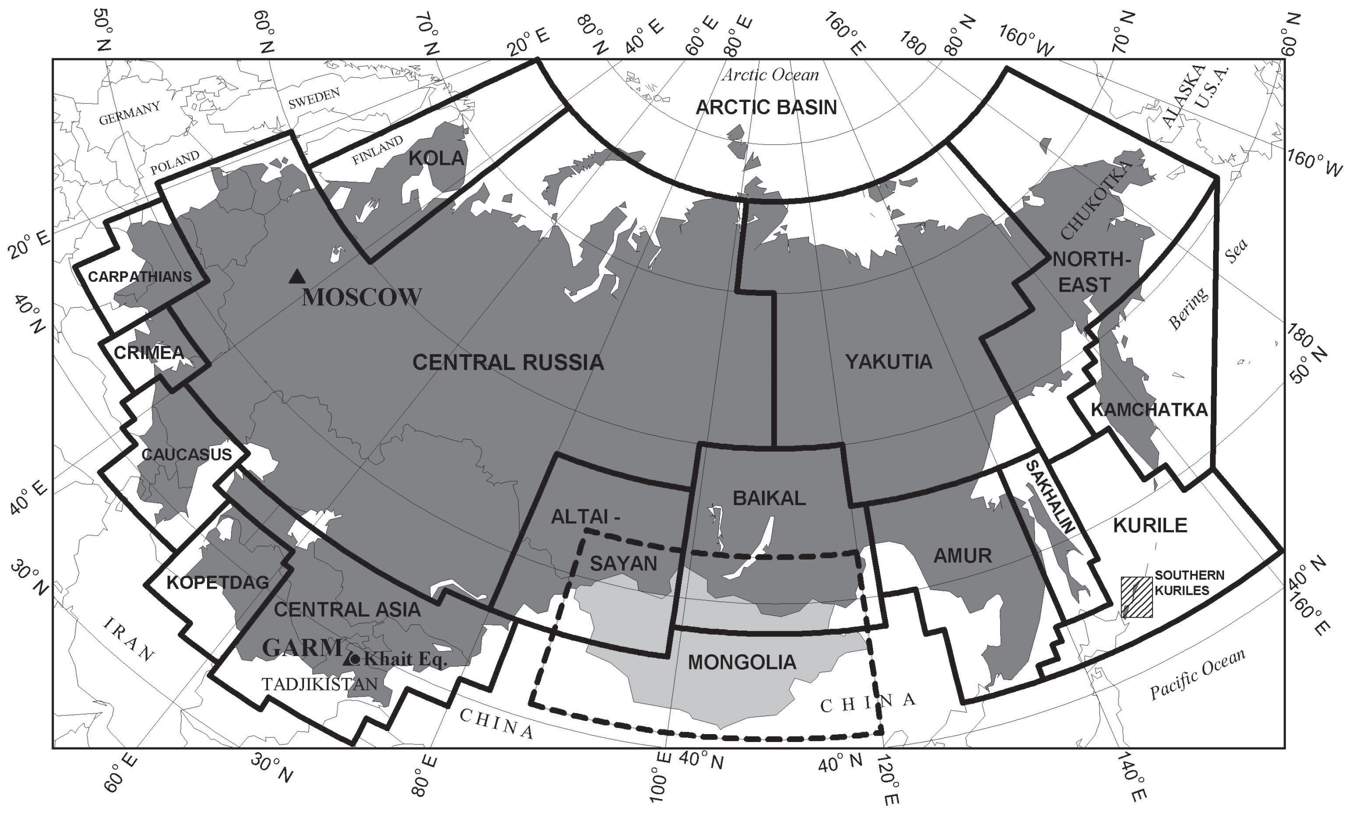
HISTORICAL BACKGROUND

Shortly after World War II, between 1946 and 1949, three large earthquakes occurred in Soviet Central Asia and triggered an intense study of seismicity. After the magnitude 7.4 Khait earthquake of 10 July 1949, the Geophysical Institute (now the Institute of Physics of the Earth) of the USSR dispatched an expedition to Garm, Tajikistan (figure 1), to deploy a temporary network around the epicentral region. This Complex Seismological Expedition (CSE), which included the senior authors of this paper (Khalturin and Rautian) at its inception, became permanent in 1954.

The study of regional seismicity was not well-developed at that time, so there were no specifications for seismic stations and proper instrumentation had not yet been developed. Even the goals of the study of local seismicity were still being discussed. Procedures for measurements, data processing standards, and documentation did not exist in any formal manner. At the beginning, the members of the expedition considered themselves pioneers as they tried to understand what earthquakes were, how to describe them, and how to determine the regional seismicity. At that time, Western scientific publications were seldom available in the USSR, even at the Geophysical Institute in Moscow. This did not worry the members of the expedition; they had a good education in physics and fresh views. They did not become followers, but proposed their own ideas and fields of study and developed new methods based on the data they obtained.

Seismic activity in the Garm region remained high, even several years after the Khait earthquake. During 1955, 5,000 earthquakes were recorded by seismic stations in an area of 1 × 1.5 degrees. The members of the expedition had to process all of these earthquakes by hand; thus relatively simple, usually graphical, methods were required. The first goal was to find an accurate, but simple, way to determine the hypocenters and origin times at a time when the computer era had not yet begun. Because of the strong lateral velocity heterogeneities, methods like that of Wadati (*e.g.,* Wadati 1927, 1933) were unsatisfactory. Thus Riznichenko (1958) proposed a graphical method valid for a constant velocity or horizontally layered medium. Rautian further developed this method, which calculated graphical templates based on given velocities and station locations, for the case of any 3-D velocity variations (Nersesov and Rautian 1960). This was applied to a simple, but realistic, velocity model of the Garm region resulting in graphics that did not require any separate calculations. As a result, four technicians could process 3,000–5,000 earthquake hypocenters per year with an error of no more than 2–3 km.

The next step was to quantify earthquake size. At the time, most members of the expedition did not know about the



▲ **Figure 1.** Index map showing names of and boundaries between regional networks in the former Soviet Union. Other locations mentioned in the text are also labeled.

Gutenberg and Richter (1942) concept of magnitude. Initially, V. I. Bune, who was then director of the Tajik Seismological Institute, developed a scale in which energy was estimated by noting the maximum distance to which earthquakes were recorded and the displacements and phases observed at regional and teleseismic distances (Bune 1955, 1957; Solov'ev 1961). This method was time-consuming and required information from outside the expedition. At the same time he also proposed his version of calculating energy from surface waves (Bune 1956) in instrumental records following the method of Golitsyn (1919). This method missed the main part of energy in short-period arrivals, which underestimated the energy, and the assumption of spherical spreading in the calibration overestimated the energy. These two factors tended to cancel each other out yielding results that were reasonable. Bune (1956) also erroneously assumed that attenuation close to the source (< 100 km) was the same as at greater distances (100–400 km). Because of this assumption, the results at close distances tended to underestimate the energy by 1–2 orders of magnitude (Katok 1964). So, these early proposals had problems.

In 1955, the new leader of the expedition, Igor Nersesov, told Rautian, "Tatyana, do something to measure the size of earthquakes." Although Nersesov was undoubtedly aware of magnitude by this time (see below), he sought an independent method that would be better or easier. Rautian decided to use energy, which is a quantity with a physical reality, as the primary measurement. She excluded Golitsyn's (1919) erroneous assumptions and focused on a procedure that was simple and clearly defined, with little freedom given to operators.

THEORETICAL BACKGROUND FOR THE *K*-CLASS

The detailed theoretical background for the determination of the *K*-class is presented in Rautian (1958, 1960) and is only summarized briefly below for the non-Russian reader.

Ideally, if energy spreads out uniformly in all directions, $E = 4\pi r^2 k\varepsilon$; where ε is the total energy density that crosses normal to a unit area on a surface of radius r following an earthquake and k is a coefficient that accounts for the effects of the Earth's surface, the incidence angle, the relationship between measured maximum amplitude on a single component and total vector, etc.

This condition is valid only near the hypocenter, at distances of no more than 10–20 km. At these distances, the source signal has not yet been modified by scattering processes and can be assumed to be a short pulse moving away from the source and perpendicular to the wave front. Anelasticity does not strongly affect the amplitudes of the direct wave at these small distances; thus it was assumed that it could be neglected. Since the earthquake source process is short, later arrivals are scattered waves with random directions that do not come from the origin and, in a strict calculation of energy flux, the vector sum should be zero and can be ignored. Thus 10 km was chosen as the reference distance to which the energy density was normalized. At greater distances, the waveform becomes more complex due to scattering and multiple phases.

The 100-km distance used by Richter (1935) for the definition of the M_L scale is not proper because the waveform at that distance is complex and strongly dependent on the local structure of the Earth's crust and its thickness. The direct wave is superimposed by scattered phases and cannot be distinguished from them. In addition, waves from the Moho arrive at distances depending on the crustal thickness; at about 80 km in the Caucasus and 150 km near Garm.

The instrumentation at Garm recorded displacement; thus to get energy density both amplitude and frequency needed to be measured. After looking at thousands and thousands of seismograms, Rautian visualized the wave as the superposition of two or more pulses of different frequencies and realized that seismic energy came in a wide frequency band. The first version of what became the energy class tried to separate different frequencies visually and measure each of them separately to calculate total energy. However, visual "spectral analysis" of a seismogram by different members of the expedition showed that measuring frequency content by eye was too complicated; each person calculated different frequencies and the results were very scattered.

AMPLITUDE-ONLY APPROACH AND CALIBRATION

As a result of this variability, it was necessary to go back and develop a simpler method. The energy density at short distances is dependent on the amplitude, frequency, and duration of the signal. Observations showed that the duration of the signal at distances more than 20 km was controlled primarily by the distance and that the frequency was dependent on the energy of the earthquake and the hypocentral distance (Rautian 1960). Therefore, measuring amplitude alone was sufficient to obtain an estimate of energy to within 0.3–0.5 orders of magnitude; although energy was retained as the basic unit, the estimate was based solely on amplitude because it was easy to measure. The amplitudes used were A_P, the maximum P wave on the vertical component, and A_S, the maximum S wave on the one of horizontal components (east-west or north-south, whichever was greater). Since the S wave was stronger than the P wave (and often the principal wave recorded) and the S/P ratio varied among different stations because of the radiation pattern, Rautian proposed using the sum of these two waves, $A_P + A_S$, to crudely reduce the scatter and smooth the effects of the radiation pattern. This solution was not ideal, but it was practical. At regional distances up to 800 km, the maximum amplitude arrivals of P and S could be Pg and Lg.

To calibrate the amplitude-only estimate to energy, Rautian personally measured the energy of a large number of earthquakes by using visually estimated spectra. Because of the technology of the time, she made many simplifying assumptions. The details are presented in Rautian (1960), but in brief, to calculate E, the pulse duration (τ), amplitude (A), and frequency (f) of the arrivals were measured. The energy density, ε, was then determined by $\varepsilon = (Af)^2 \tau$; a series of corrections (k) for magnification, total vector, surface effects, units, etc., were then applied. The dependence of $k\varepsilon$ on distance, r, was determined by examining the variation at stations at different distances for a given earthquake. The resultant curve was used to normalize ε to a distance of 10 km. Then, $\log E$ (normalized to 10 km) = $\log 4\pi k\varepsilon$.

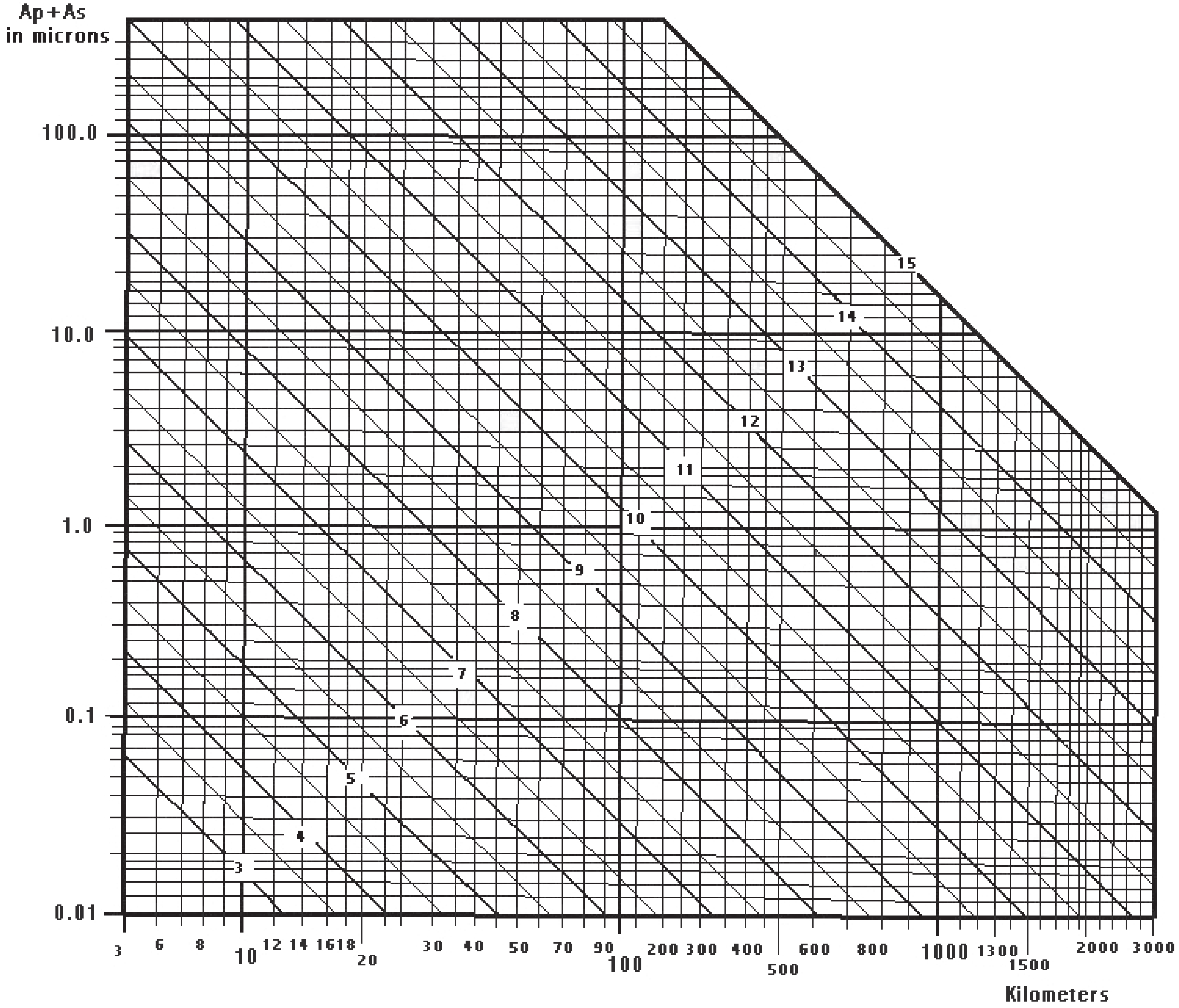
The amplitude measurements, $[A_P(r) + A_S(r)]$, were also normalized to $r = 10$ km using the amplitude-distance relationship (see below). The resulting relationship was $\log E$ (at 10 km in joules) = $1.8 \log [A_P(10 \text{ km}) + A_S(10 \text{ km})] + 6.4$. Thus, it turned out that an amplitude of 100 microns at a distance of 10 km corresponded to $\log E$ of 10. The correlation was done with events over a wide range of $\log E$ values, from 5 to 13.

Why the coefficient 1.8? If the spectral content did not change with energy, it should have a value of 2.0. If the corner frequency, f_0, separating the spectrum into its flat part ($f < f_0$) and its steep, high-frequency part ($f > f_0$), changes as $(\log f_0 / \log E) = -1/3$ (see Kanamori and Anderson 1975), the coefficient should be 1.5. In 1956, however, the expedition chose to believe the empirical data and not to follow a simple assumed model with, at the time, unknown validity. Zapol'skii and Khalturin (1960) found that the dominant frequency of small earthquakes decreased much more slowly with magnitude; this was later confirmed with more data (Rautian *et al.* 1978)

Many years later, while studying the source spectra of earthquakes, Rautian and Khalturin realized the reason. Almost all earthquakes have a broad velocity spectrum with two corner frequencies, f_1 and f_2. The velocity spectra are, on average, flat between f_1 and f_2, and the ratio f_2 / f_1 is on average about 10. Thus the spectral content does not change as fast as a spectrum with a single corner frequency implies. The coefficient of 1.8 reflects such kinds of spectra and events and is thus intermediate between 2.0 and 1.5.

Rautian wanted to call this new scale "energy." However, Nersesov said, "No, do not be so hasty, let us call it simply energy class." Since the Russian spelling of class is класс, the scale was defined as $K = \log E$, in joules. The first outline of the energy class scale was presented in Rautian (1958) and then combined with the expedition's 1957 report on procedures for analyzing earthquakes and published as *Methods for the Detailed Study of Seismicity* (Riznichenko 1960). It was not perfect, but it was useful and appeared at the right time. The use of K-class to represent $\log E$ was widespread in the former USSR by 1961.

The shape of the calibration curve with distance is, in general, similar to that of Richter's (1935) for M_L and is approximately r^{-2} up to 60–100 km, where waves coming from the Moho create a "hump." Beyond 100–200 km, the shape of the amplitude-distance curve is not simple because of the changing spectral content of the waves with distance, due both to attenuation and the appearance of larger, lower frequency waves at the larger distances. For simplicity in use in calculating the K-class, the log-distance scale was adjusted to make the amplitude-distance curve a straight line (figure 2). Thus while the distance axis appears to be logarithmic, examination of it in detail will show that the horizontal scale was altered to incorporate the "hump" (compare with figure 6).



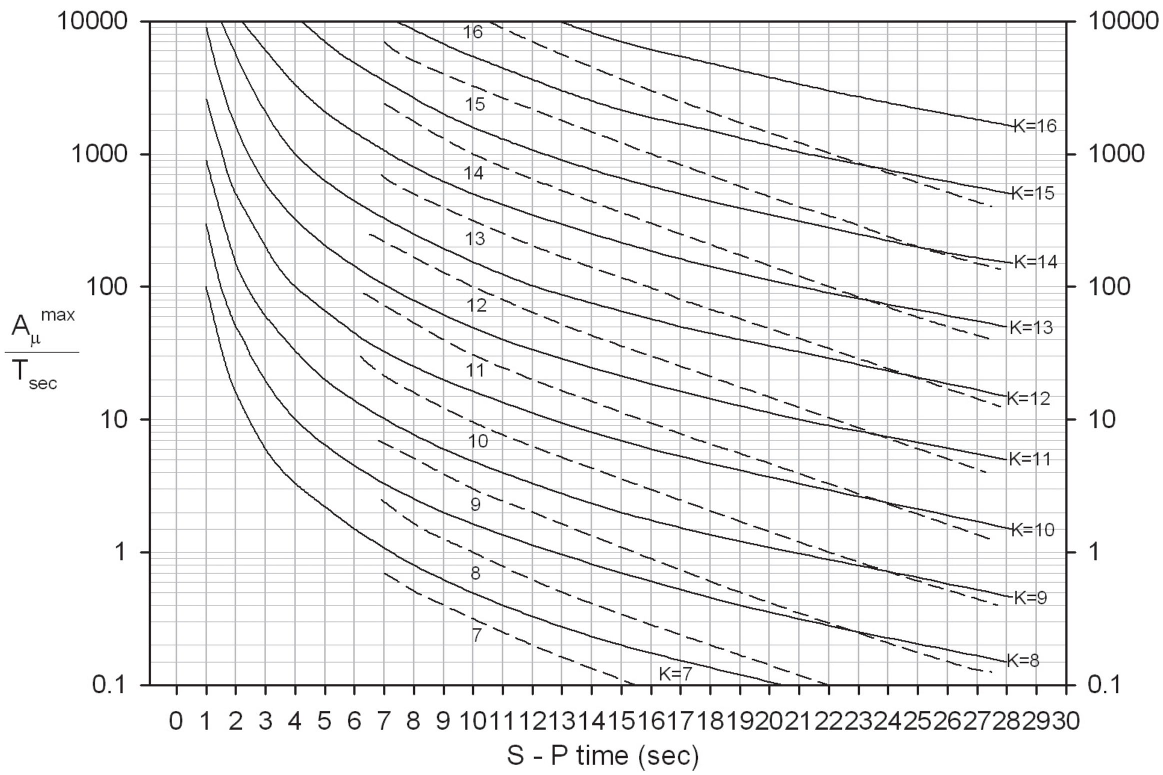
▲ **Figure 2.** The Rautian (1960) K-class nomogram calibrated for SKM seismometers. Note that the horizontal (distance) scale is not truly logarithmic; see text for explanation. Vertical (sum of amplitudes) axis in microns.

The first version of the *K*-class scale was calibrated for the VEGIK short-period seismometer ($T_0 = 0.1–0.8$ sec), which was in common use in the 1950s. Later these were replaced at many stations by the SKM seismometer ($T_0 = 0.2–1.5$ sec) and more recently by SM3 seismometers. The amplitude-distance calibration curves differ on these two instruments. Some early calibration curves also delineated a band within which an integer *K*-class value was assigned. Later, the lines were drawn to represent a specific *K*-class value. Figure 2 shows the nomogram for SKM instrumentation.

ACCURACY OF THE *K*-CLASS DETERMINATION

Based on extensive study, the error in calculating the *K*-class was determined to be about 0.35 Log units between stations. As with magnitude, this is due to site effects as well as the source radiation pattern, heterogeneities in the crust, the variation of the ratio between the maximum amplitude on one component to the total vector, etc. A site effect can be corrected for, but other sources of scatter still exist in the data and accuracy does not change significantly even after a site effect correction; thus no such correction was used at Garm. However, such corrections were used subsequently in other networks.

Second, a systematic error exists because the method ignores the spectral content. The effects of this differ randomly among earthquakes within the same area and systematically between events in different tectonic settings. As a result, *K*, as estimated from displacement, differs from the energy, as calculated from spectrum. This difference is a function of the earthquake source “rigidity.” For individual events, this source component of the



▲ **Figure 3.** First South Kurile *K*-class nomogram variant calibrated for VEGIK seismometers. Dashed lines represent classification for intermediate focus earthquakes. Vertical axis amplitude in microns (μ), period in seconds.

deviation of *K* is the same among all the seismic stations. For example, in the Garm region, the source deviation is about zero for earthquakes in the northern part of the region (Paleozoic granites and thrusting) but is 0.2–0.4 in the southern part of the region (Meso-Cenozoic rocks with some normal faults). The largest difference between *K* and log *E*, as calculated from event spectra, was found in the Kopetdag area, where most earthquakes occur in soft and strongly fractured rock and where strike-slip faulting predominates. In this region, the earthquakes typically have low-frequency source spectra and the *K* values are overestimated by 0.7–1.0 compared to energy calculated from their spectra.

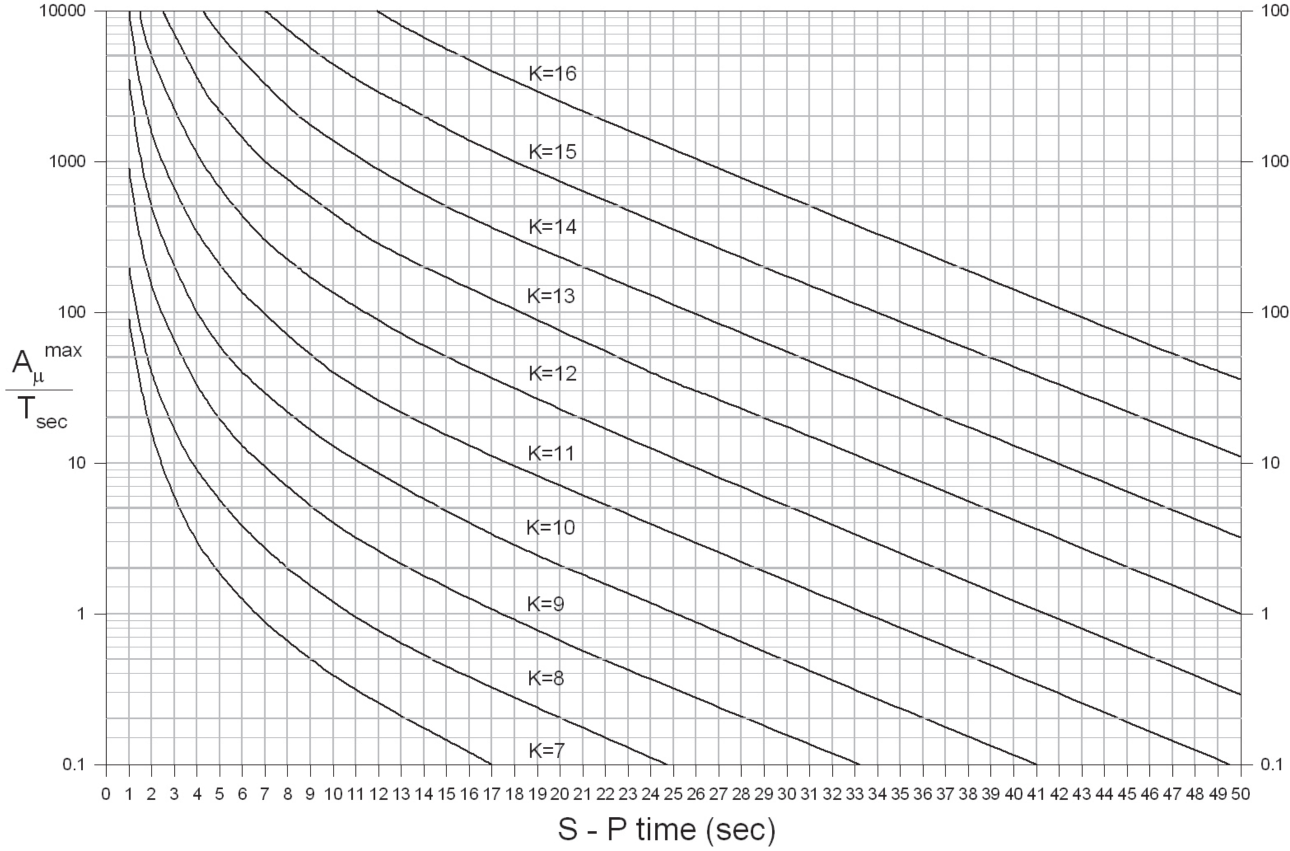
However, in most regions there was a reasonable correspondence between *K* and energy, and the correspondence was the best in crystalline rocks and regions of thrust tectonics.

NATIONAL APPLICATION OF THE *K*-CLASS

Because the CSE developed into a strong regional network, young scientists from many parts of the former Soviet Union came to Garm to learn the expedition's methods and standards of data documentation. In other republics of the USSR, the regional networks developed a few years after the Garm network began; most of them accepted the Garm method as it was already finished (Riznichenko 1960), and therefore it became the national standard. When compilation of the annual *Zemletrayseniya v SSSR* (*Earthquakes in the USSR*) began in 1962, almost all of the regional networks estimated *K* for their part of the catalog using the Rautian (1960) nomogram; today, energy class is calculated for almost all the regional earthquakes in the former Soviet Union.

The Kamchatka and Sakhalin regional networks did not follow the Garm method. They created their own *K*-scales, which were different from the national ("continental") standard, because they presumed that the differences in tectonic setting (subduction zone), velocity structure, and attenuation would be important.

In fact, the attenuation in these Pacific regions was found to be stronger than on the continent. The first local *K*-class scale developed in the Russian Far East was based on the southern Kurile network deployed on Iturup, Kunashir, and Shikotan islands in 1957. Energies were calibrated using a similar approach to Rautian (1960) incorporating amplitude, frequency, and duration (Fedotov *et al.* 1961; Fedotov 1963). Two variant nomograms were produced, one that separated intermediate from normal focus earthquakes (figure 3), and a second that was an average for all events down to a depth of 160 km (figure 4). For simplicity of calculation, only the maximum amplitude of the *S* wave in microns was used; however, unlike the Rautian (1958, 1960) system, it was normalized by period, *T*, and the curves were in terms of the *S* – *P* time. The distance calibrations in terms of both amplitude and energy were performed using events of energy class 11 at different focal depths; because of the similarity of the curves for depths greater than 50 km, they were averaged in the first variant as an intermediate depth nomogram. The authors noted that in using the second



▲ **Figure 4.** The second Southern Kurile variant nomogram as extended for Kamchatka. Vertical axis amplitude in microns (μ), period in seconds.

nomogram, variations of greater than 0.5 K units could occur at $S - P$ distances greater than 20 sec because of the uncertainty in depth. These nomograms were used in Sakhalin and the Kuriles from 1961 to 1965.

This curve and methodology was also applied to the Kamchatka area when regional stations were deployed in 1961 (Fedotov *et al.* 1964). The only initial change was to extend the distance range to $S - P$ times of 50 sec (figure 4).

Subsequently, the southern Kurile nomogram was revised by Solov'ev and Solov'eva (1967), primarily because of differences in attenuation observed as the network was enlarged and additional data were acquired; the methodology of using $A_{S_{\max}} / T$ remained the same (figure 5). This nomogram was used in both the Kuriles and Sakhalin Island starting in 1965 (Kondorskaya and Shebalin 1977). The current Kamchatka nomogram is shown in figure 6.

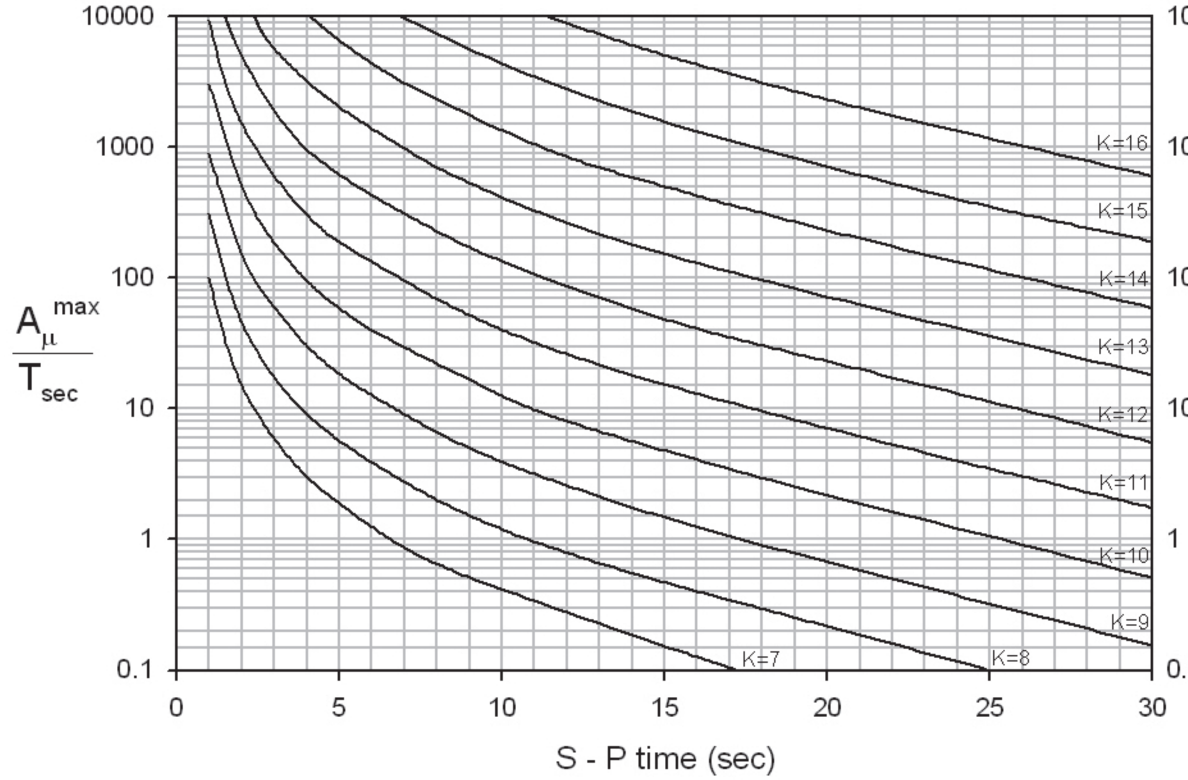
There is a significant difference between the "continental" (Rautian 1958, 1960) and Far Eastern relationships (figure 7). The energy class calculated using the first Kurile and Kamchatka nomogram is lower than the Rautian (1960) value by ~0.5–0.7 log units and by ~1.5–1.7 log units using the Sakhalin nomogram of Solov'ev and Solov'eva (1967). In the compilation by Kondorskaya and Shebalin (1977), the Fedotov (K_F) and Solov'ev (K_S) determinations were reduced to the Rautian standard by: $K = K_F + 0.6$ and $K = K_S + 1.7$.

The difference in shape can be ascribed to variations in attenuation and propagation of *Lg* phases between the continent and subduction zones (Rautian *et al.* 1981). However, the difference in intercept, which is controlled by energy at short distances, is more difficult to explain. Rautian (1960) uses units of amplitude, A, on the vertical axis of the nomogram, while the Far Eastern nomograms use A / T. Since for $K = 10$, the general frequency of earthquakes in central Asia is about 3 Hz, an amplitude of 100 microns at 10 km for a $K = 10$ event corresponds to $A / T = 300$ micron/sec. On the Far Eastern variants, the corresponding value ($S - P \sim 1.2$ sec) is about 2,000. Thus, the discrepancy is likely a result of an error in the method of calculating energy and/or calculation of the coefficient.

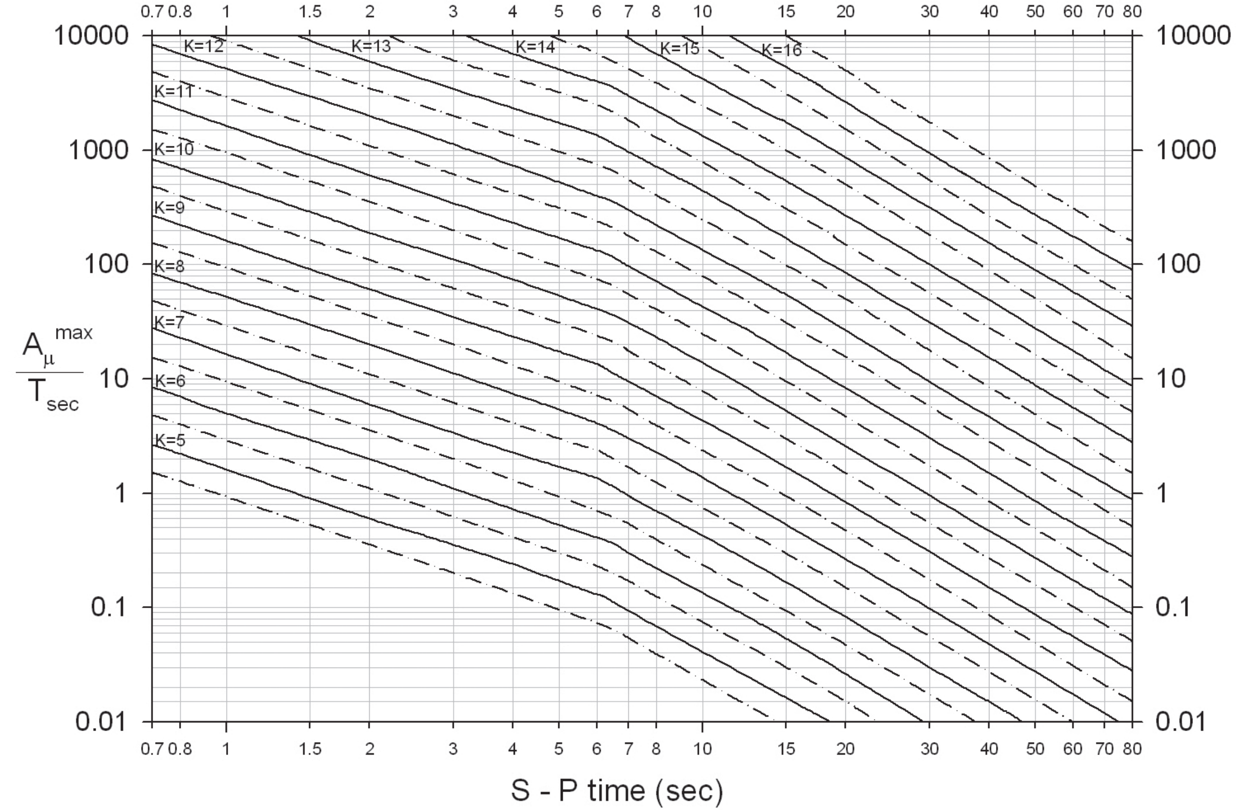
Outside the USSR, Mongolia was the only country to use the K-class extensively; this resulted from the fact that the initial Mongolian seismic network was deployed by the USSR and many of its seismologists were trained there.

REGRESSIONS BETWEEN MAGNITUDE AND *K*-CLASS

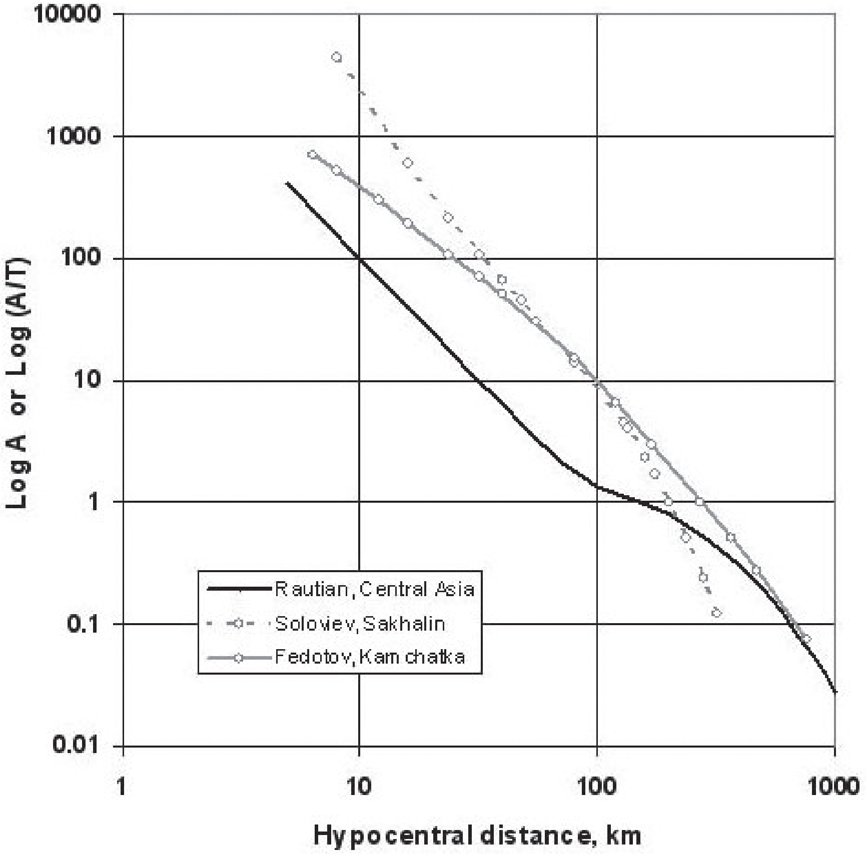
A magnitude scale first was used in the USSR at about the same time that the Garm expedition was deployed, in 1953 (Solov'ev 1961). Magnitude was used for larger earthquakes in compiling the national bulletin starting in 1955 (Solov'ev and Shebalin 1957), and was the primary measure of earthquake size used in



▲ **Figure 5.** The 1967 Kurile nomogram calibrated for SK seismometers. Vertical axis amplitude in microns (μ), period in seconds.



▲ **Figure 6.** The current Kamchatka nomogram for SKM seismometers. Dashed lines represent limits of integer determinations. Vertical axis amplitude in microns (μ), period in seconds.



▲ **Figure 7.** Comparison of the nomograms for K=10 between Rautian (1960), Solov'ev and Solov'eva (1967), and Fedotov *et al.* (1964).

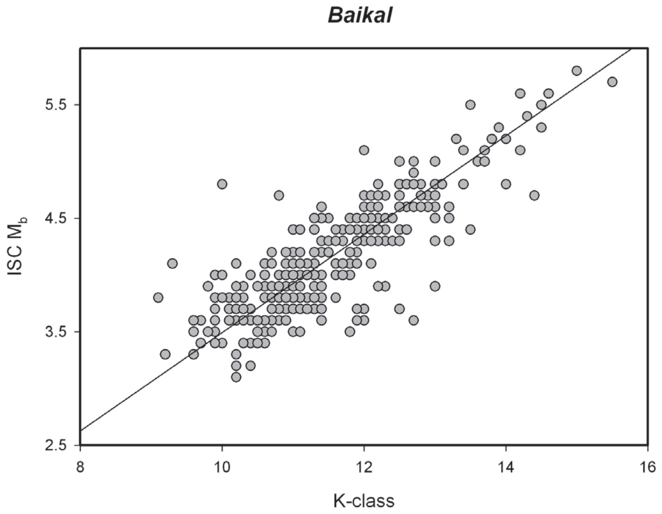
the *Atlas of Earthquakes* of the USSR (Savarensky *et al.* 1962). The so-called "Prague magnitude" (Vanek *et al.* 1962) became the accepted standard in the annual *Earthquakes in the USSR (Zemletryaseniya v SSSR)* starting with the 1962 compilation. These magnitudes were computed using A / T of Love waves recorded on *SK* instruments. Because of this definition, the use of magnitude was not practical for small events recorded by the local and regional networks, which primarily used short-period instruments. Thus in general practice in the USSR, *K*-class was calculated for smaller events and magnitude for larger events, with some overlap between magnitudes 4–5.5 (*K*-class 11–14). In addition, at the regional level magnitude was viewed more as a proxy for intensity, because they both applied to ground motion.

The primary difference between *K*-class and magnitude, M, is that the *K*-class is calibrated to a physical parameter, energy. In addition, by using both the P and S waves, the Rautian (1960) method yielded a better estimate of the ground motion that was more independent of scattering and focal mechanism effects. The Kamchatka and Sakhalin methods, however, are essentially the same as calculating M_L, although supposedly calibrated to energy.

Since energy is proportional to amplitude squared, in an ideal situation the relationship should be of the form magnitude = $c + 0.5K$, where c is some constant (Richter 1958). Early empirical studies using independent data suggested that the relationship between magnitude and *K*-class was $M = (K - 4)/1.8$ (Rautian 1960) for the range $4 \le K \le 13$. Similarly, Solov'ev and Solov'eva (1967) empirically obtained the relationship $M = (K_S - 2)/1.8$ for Sakhalin.

Theoretically, both m_b and M_S are tied to specific frequencies, while K is (ideally) obtained from a wide range of frequencies. In practice K is linked to the period of short-period sensors, which varies over an interval from 0.1–0.2 to 1.5–2 sec. In addition, there will be regional variations in attenuation, $Q(\omega)$, resulting from tectonic variations; in some cases these may affect very small areas. Although the major differences should be due to variations in source depth and the tectonic setting, local variations in Q and the variability of tectonic regimes in some areas result in the scattering of *K*-class values even within a specific seismic region.

These difficulties notwithstanding, the relationship between *K*-class and magnitude has been of great interest to seismologists working with data from the former USSR. In order to examine the empirical relationship between magnitude and *K*-class, we tabulated magnitude and *K*-class values reported for each of the seismic regions used in *Earthquakes in the USSR* and its successor publication, *Earthquakes of Northern Eurasia* (*Zemletryaseniya Severnoi Evrazii*), for 1970–1997. Because *K*-class and magnitude are both independent variables with their own uncertainties, one can not simply calculate a regression holding one as the dependent variable. We thus calculated an orthogonal regres-



▲ **Figure 8.** Sample orthogonal regression between *K*-class and ISC magnitude (m_b) for the Baikal region.

TABLE 1
Regressions between *K*-class and ISC Magnitude

Region	m_b	M_S
Carpathians	5.54 + 0.397 (K-14)	5.92 + 0.661 (*K*-14)
Crimea	6.20 + 0.699 (*K*-14)	Insufficient Data
Caucasus	5.60 + 0.391 (*K*-14)	6.02 + 0.782 (*K*-14)
Kopetdag	5.53 + 0.467 (*K*-14)	5.71 + 0.781 (*K*-14)
Central Asia	5.53 + 0.449 (*K*-14)	5.36 + 0.594 (*K*-14)
Altai-Sayan	5.47 + 0.482 (*K*-14)	5.37 + 0.633 (*K*-14)
Baikal	5.23 + 0.434 (*K*-14)	5.54 + 0.828 (*K*-14)
Yakutia	5.49 + 0.427 (*K*-14)	5.55 + 0.539 (*K*-14)
Northeast	5.33 + 0.445 (*K*-14)	Insufficient Data
Amur	5.01 + 0.394 (*K*-14)	5.10 + 0.755 (*K*-14)
Sakhalin	7.25 + 0.669 (K_S-14)	7.57 + 0.773 (K_S-14)
Kurile*	6.30 + 0.460 (K_S-14)	6.56 + 0.642 (K_S-14)
Kamchatka	6.11 + 0.552 (K_F-14)	6.47 + 0.838 (K_F-14)

* see text for calculation methodology

sion (see figure 8 for an example) that minimizes the sum of the squares of the distance to the regression line. It should be noted that *K*-class is calculated, and calibrated, for events generally smaller than $K = 10–11$, while teleseismic magnitudes are calculated for larger events. For smaller events of m_b (or M_S) around 4, magnitude is often calculated with very few stations or using stations with potentially weak arrivals, thus increasing the uncertainty and scatter. The Kurile *K*-class data were only available as integers, hence, each integer bin was averaged and the regression calculated based on the bin averages; *K*-class 14 bin was omitted for both M_b and M_S as they were defined by only a few points and $K = 9$ (for both M_b and M_S) and $K = 9.5$ (for M_S) were omitted because small-magnitude events were not reported.

All regressions were standardized to the form

$$\text{Magnitude} = c + s\,(K - 14).$$

This formulation eliminates having sign variations on *c* and makes comparisons clearer in the range for which *K*-class and magnitude are both calculated ($9 \leq K \leq 14$).

The m_b regressions (table 1) are generally similar, close to $5.41 + 0.43\,(K - 14)$, in the *K*-class range of interest ($9 \leq K \leq 14$) except for Crimea, Sakhalin, Kurile, and Kamchatka (figure 9A). Crimea, Sakhalin, and Kamchatka have higher *c* and *s* values than the other regions, while Kurile has a similar slope, but higher *c*. As noted above, the three Far Eastern regions use a different formulation for *K* and are therefore expected to be different from the rest of the former USSR; the difference for the Crimea may reflect a small number of data points. It is interesting that the Kurile regression differs from both Sakhalin (which administers the Kurile network) and Kamchatka (which is tectonically similar).

The intercepts, *c*, for the Sakhalin m_b relationship and Central Asia regressions are close to those calculated by Solov'ev and Solov'eva (1967; $6.59 + 0.55\,(K_S - 14)$), and Rautian (1960; $5.48 + 0.55\,(K - 14)$), respectively noted above; however, the slopes differ by more than 0.1 in both cases.

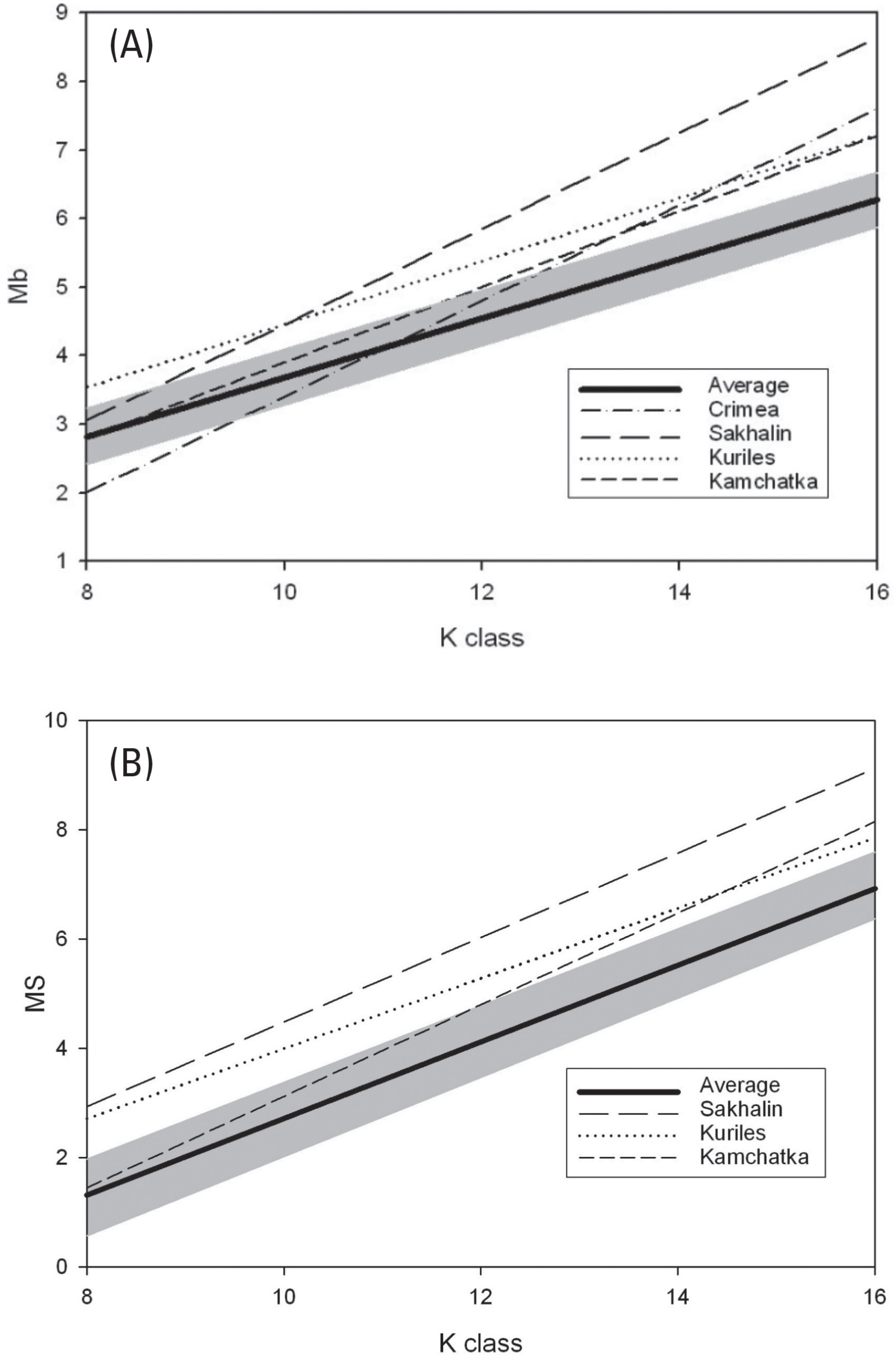
The M_S regressions are more variable (table 1 and figure 9B), reflecting the fact that the methodology and frequencies for calculating m_b and *K* are much closer than those for determining M_S. Slopes for the M_S values vary from 0.5 to 0.8, and the mean regression is $5.52 + 0.702\,(K - 14)$, excluding the Carpathians, which are based on very limited data, and the Russian Far East, which have *c* values > 6.4. In general, however, most of the curves are fairly close to each other in the $10 \leq K \leq 14$ range (figure 9B). Again, the Far Eastern regions are expected to be somewhat different because of the different methodologies used for *K*.

We note, however, that both *c* and *s* can vary considerably (0.5 in *c* and 0.1 in *s*) depending on the regression methodology and algorithm, data set used, cut-off magnitudes and *K*-classes, and to what degree the data are cleaned.

DISCUSSION

K-class is calculated from, and calibrated to, short-period instruments. Therefore like m_b, *K*-class saturates; because of the similarity in the frequency response of former USSR and Western short-period seismometers, saturation probably occurs at about the same level $K \approx 16–17$.

Because of the standard of using magnitude in the West, many regional events in the former Soviet Union reported in Western catalogs list magnitudes calculated from *K*-class using a locally derived regression. Examples (table 2) include the data for the Crimea and Chukotka (although the Chukotka relationship is particularly abnormal) in the *New Catalog of Strong Earthquakes in the USSR* (Kondorskaya and Shebalin 1977), the digital SSR catalog distributed by the U.S. National Geophysical Data Center, and the Kamchatka data in the International Seismological Centre (ISC) catalog. However, this is not always



▲ **Figure 9.** Comparisons of orthogonal regressions between *K*-class and (A) m_b and (B) M_S for various regions of the former USSR. Most regressions fall within the shaded region; the mean of those regressions is shown as a black line. Outlier regressions are shown and labeled.

TABLE 2
***K*-class Conversions to Magnitude**

Source	Region	Relationship
Rautian (1960) empirical		$M = 5.56 + 0.556\ (K\text{-}14)$
Solov'ev and Solov'eva (1967) empirical	Sakhalin	$M = 6.67 + 0.556\ (K\text{-}14)$
Kondorskaya and Shebalin (1977)	Crimea	$M = 6.00 + 0.571\ (K\text{-}14)$
Kondorskaya and Shebalin (1977)	Chukotka	$M = 5.00 + 0.667\ (K\text{-}14)$
ISC (September, 1995–June, 1999*)	Kamchatka	$m_b = 6.00 + 0.503\ (K_F\text{-}14)$
ISC (September, 1995–November, 1996*; January, 1999–present)	Kamchatka	$M_L = 6.40 + 0.503\ (K_F\text{-}14)$
* see text		

explicitly stated, causing confusion as to what the primary determination was and how it was derived.

In addition, there may be procedural changes that affect the magnitudes reported when calculated from *K*-class. For example, in Kamchatka, the equation used by the ISC for the m_b calculation is 6.0 + 0.5 (K – 14). Over the years, however, there have been significant changes in what has been reported in the ISC catalog. The m_b and M_L values, as calculated from *K*-class, were reported to the nearest tenth of magnitude to the ISC starting in September 1995. In all cases M_L was 0.3 greater than m_b. In January and February of 1996, the same regressions were used, but m_b and M_L were reversed, *i.e.*, m_b was reported 0.3 magnitude units greater than M_L. In March 1996, it reverts to the original equation, and beginning in November 1996, M_L was no longer reported. In January and February 1999, M_L is again reported, with M_L 0.3 magnitude units greater than m_b. From March–June 1999, M_L and m_b are reported only to the nearest integer *after* calculating the regression; hence M_L and m_b are either equal or M_L is one magnitude unit greater. Starting in July 1999, m_b is no longer reported, and M_L is reported as an integer. Starting in May 2001, M_L is again reported as a decimal. Thus care needs to be taken when doing long-term statistical analysis of magnitude information from the regional networks.

CONCLUSIONS

K-class was developed as an easy and rapid way to quantify local and regional earthquakes based on a physical quantity. Since the late 1950s, *K*-class has become the standard for quantifying smaller earthquakes in the former USSR and continues to be used today, often at the expense of reporting magnitude, except for larger events. Essentially 100% of the events in the former Soviet Union have been quantified by *K*-class, while only 1–2% have calculated magnitudes.

Although digital methods have been developed to calculate energy from teleseismic data (*e.g.*, Choy and Boatwright 1995; Newman and Okal 1998) and regional data (*e.g.*, Boatwright *et al.* 2002), they still require an understanding of, or correction for, the focal mechanism, site amplification, scattering, and/or other regional geologic factors that preclude their use on a massive scale. Especially in the former USSR, where some networks still operate with analog systems and depend on technicians to read arrivals, the *K*-class method remains a useful and (relatively) standardized tool that can be rapidly applied. The methodology for the *K*-class was appropriate for the time, although the calculation by hand using only amplitude was tedious and not entirely accurate for estimating the true energy because frequency is not used; low-frequency earthquakes have overestimated values of *K*, with errors reaching 0.5–1.0 units.

The senior authors hope that with digital recording and advances in processing capability, the calculation of the energy class can return to its original intent, calculated directly and routinely from the energy density. They believe that using the later part of the coda for source spectra estimation (Rautian and Khalturin 1978) is the most appropriate way to get seismic energy along with seismic moment, apparent stress, etc. This method was developed for analog records with band-pass filters and can be easily adapted for digital instrumentation use. The size of earthquakes for which the method can be applied depends on the density of the seismic network. For small events, energy class could still be used.

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