GEOFIZIKA VOL. 15 1998

Original scientific paper
UDC 550.341

Spectral characteristics of earthquakes along plate boundaries

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Received 9 July 1998, in final form 21 December 1998

Earthquakes are investigated with epicenters located along divergent and along convergent plate boundaries.

Two criteria are applied in order to distinguish between earthquakes featuring anomalous »long-periodic« and »short-periodic« radiation of body-waves: 1) deviation of the corner period T_c of the P-waves from the regression between T_c and the moment magnitude M_w; and 2) the values of stress drop $\Delta\sigma$.

It is found that earthquakes along divergent boundaries radiate the seismic energy mainly at longer periods, and, vice versa, that such along convergent boundaries radiate energy mainly at shorter periods. The average stress drop for the former earthquakes is estimated thereby to be 33 bars and for latter – 89 bars.

In a regional scale, for earthquakes in the Japan-Kuril area it is found that the corner periods for strike-slip events are larger than those for thrust events.

The results confirm the findings of investigations based on the creepex distribution along divergent and convergent boundaries, as well as the findings related to the dependence of creepex on the source mechanism.

Keywords: seismic moment, corner period, principle of self-similartity, stress drop, focal mechanism.

1. Introduction

The displacement spectrum of body waves corrected for geometrical spreading and anelastic attenuation (referred below to as the *source spectrum*) provides information on source parameters, such as the scalar seismic moment and the dimension of the fault area. At low frequencies the peak-amplitude source spectrum has an asimptote equal to the scalar seismic moment M_0, and at high frequencies it behaves as $M_0(\omega^2/\omega_c^2)^{-1}$, where ω_c is the corner frequency corresponding to the intersection of the low and high-frequency spectral asymptotes. The corner frequency is equal to $2(\tau_r \tau_c)^{-1/2}$, where the parameters τ_r (rise time), and τ_c (rupture time) are related to the fault dimension (Lay and Wallace, 1995). Though the rupture time depends on the direction of radiation in the source, the averaged value may be assumed as L/V_r (L is the fault length, V_r is the rupture velocity), and the rise time is usually accepted as $W/2V_r$, where W is the fault width (Aki and Richards, 1980). Thus, the corner period $T_c = 2\pi/\omega_c$ allows to estimate the fault area $S = LW$:

$$T_c = \frac{\pi\sqrt{S}}{V_r\sqrt{2}} \tag{1}$$

The source spectrum provides, among others, information about the state of stress in the seismic zone. According to the principle of self-similarity, the corner period, at which the maximum energy is radiated during the event, is proportional to $\sqrt[3]{M_0}$. The coefficient in this relationship depends on the geometry of the source model (shape of the fault, direction of fracturing), and on the stress drop. These factors may vary for earthquakes in different tectonic settings. Thus, in practice the self-similarity is satisfied only approximately, and the proportionality between the corner period and the seismic moment is justified only in a statistical sense. As a result, the spectral parameters for individual earthquakes may noticeably and significantly deviate from the mean values. The analysis of significant deviations should allow to discriminate between earthquakes which occured under different failure conditions (strength, density of cracks, rheological characteristics of the fault material, etc.).

To discriminate between earthquakes radiating the energy primarily either in the long- or in the short-period ranges, Prozorov and Hudson (1974) proposed to use the parameter called *creepex* as a measure for the deviation of the actually measured surface wave magnitude M_S from the mean relationship $M_S(m_b)$. The relationship was determined as the linear orthogonal regression between M_S and m_b. The analysis in different tectonic zones has shown that creepex is mainly positive for earthquakes with epicenters along divergent boundaries, and negative for earthquakes with epicenters along convergent boundaries. This means that earthquakes along divergent boundaries radiate the energy primarily in the long-period, and earthquakes along convergent boundaries – in the short-period range (Kaverina et al, 1996). Such approach is based on the values of M_S and m_b, systematically published by the responsible agencies. The magnitude values – as it is well known – have uncertainties, so that conclusions based on them will be justified only on the basis of a sufficiently large body of data.

In the present study we use another approach for the analysis of the spectral content of the earthquakes in different tectonic zones. Concerning the method, the authors have proposed earlier to estimate the source spectra from teleseismic broadband records using so-called spectral calibrating functions. The latter were calculated for adequate models of velocity and anelasticity in the Earth's mantle (Duda and Yanovskaya, 1994; Yanovskaya et al., 1996, Lyskova et al., 1998). Accordingly, the spectra of P-wave energy radiated from the source are parametrized by the so-called spectral magnitudes, which are related to the radiated energy in the respective frequency intervals; the intervals are taken arbitrarily as one octave wide. The plots of spectral magnitudes as function of period allow to estimate the corner period T_c (with an accuracy of ±0.5 octave), the corner period corresponding to the maximum value of the spectral magnitudes.

The average relationship between the corner period and the seismic moment, or the moment magnitude ($M_w = 0.64 \log M_0 - 10.73$ according to Kanamori (1978)) follows from the proportionality between the moment and T_c^3. As mentioned above the coefficient in this relationship is related to the stress drop. Of course, the parameters of individual earthquakes may deviate significantly from this relationship, due to differences in the values of the stress drop for individual earthquakes, as well as to other factors. Consequently earthquakes, whose spectra are characterized by a corner period larger than that corresponding to the average relationship $T_c(M_0)$ are recognized as earthquakes radiating energy at periods longer than 'normal' earthquakes with the given seismic moment M_0, and vice versa. Besides, the »long-periodic« earthquakes are characterized by lower values of the stress drop, if compared with »short-periodic« earthquakes.

For the purpose of identifying »long-periodic« and »short-periodic« earthquakes we use in the present study the following two criteria:

– deviation of the corner period T_c from the regression $T_c(M_w)$, and

– the values of stress drop, $\Delta\sigma$.

Using these criteria makes it possible to recognize the prevailing type of focal mechanism for »long-periodic« and »short-periodic« events.

2. Data analysis

The broadband records of IRIS stations were utilized to estimate source spectra, spectral magnitudes and corner periods for earthquakes with epicenters along divergent and along convergent plate boundaries. Only events recorded by 5 or more stations were used. The epicentral distances varied in the range 20–90 deg. The epicenters of the events analysed are shown in Fig. 1.

The source spectra of a given earthquake were calculated for each station, and then the spectra and the spectral magnitudes of the earthquake were averaged. The corner period was estimted as that corresponding to the maximum value of the average spectral magnitudes (Fig. 2). The seismic moment M_0 was determined from the displacement spectrum of the source as that corresponding to the level of its low-frequency asymptote. The values of

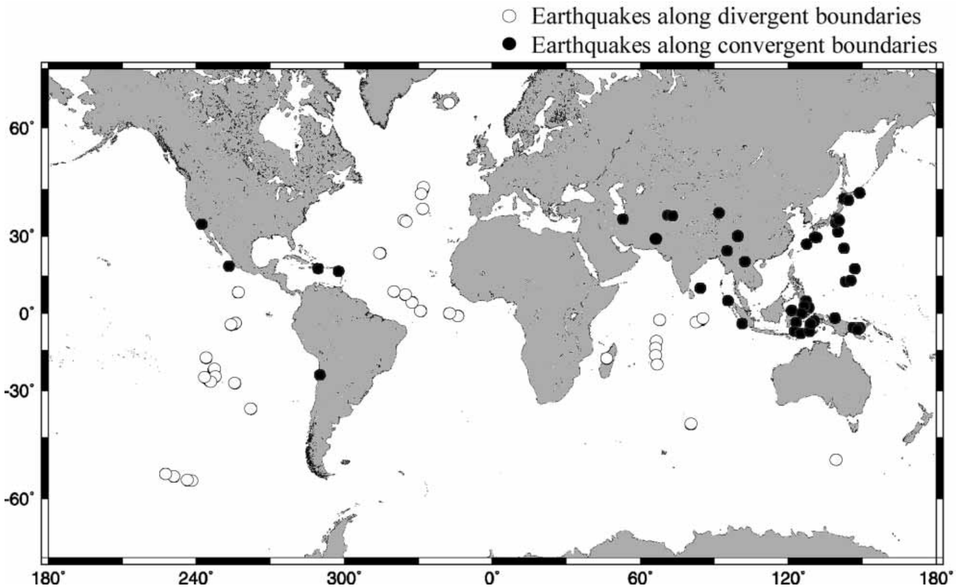


Fig. 1. Distribution of earthquakes analysed. The epicenters of the events along divergent and convergent boundaries are indicated by solid and empty dots respectively.

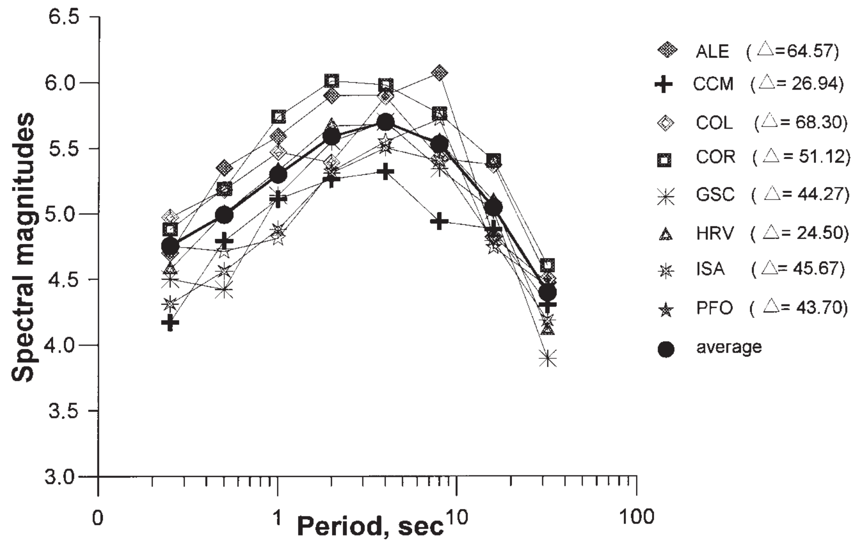


Fig. 2. Example of individual measurements and average spectral magnitudes of the earthquake in the Dominican Republic region (January 15, 1992). The corner period is estimated as 4 s.

M_0 estimated in such manner differ slightly (rms deviation 0.24) from those reported by CMT, probably due to the fact that the former are based on P-wave spectra only. However, to ensure uniformity of the data, the determinations of seismic moments as obtained in the present investigation were utilized.

The moment tensors as reported by the Harvard Centroid Moment Tensor Catalog (*http://www.seismology.harvard.edu/projects/CMT*) were used for the analysis of the source radiation of earthquakes within a given region, the Japan-Kuril region, and in order to classify these earthquakes according to their focal mechanisms.

3. Correlation between corner period and M_w

The corner periods versus the moment magnitudes M_w for the earthquakes in Fig. 1 are plotted in Fig. 3. In spite of the scattering it is fairly clear that on the average the corner periods for the sources along divergent boundaries are larger than the ones along convergent boundaries. This confirms the conclusion drawn by Kaverina et al. (1996) that earthquakes along divergent boundaries radiate seismic energy mainly at longer periods, whereas along convergent boundaries the energy is radiated primarily at shorter periods. The orthogonal regression line connecting log T_c and M_w as calculated on the basis of all data is also shown in Fig. 3.

To calculate the orthogonal regression line we assumed the standard error of log T_c to be the same for all data, and twice as large as the standard error for M_w. As mentioned above, the corner period is estimated with a precision of one octave (the error of log T_c is thereby 0.3), and for the error of log M_0 we assumed the *rms* deviation of our estimates from the CMT reported values, i.e. 0.24, so that the error of M_w could be taken as $0.24 \times 0.64 = 0.15$.

On the basis of the regression line the average relationship between log T_c and log M_0 is:

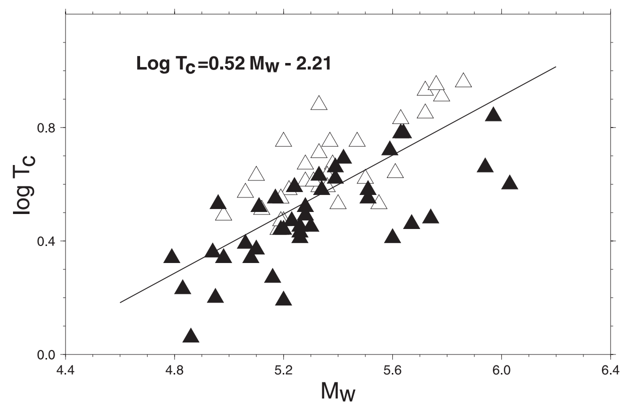


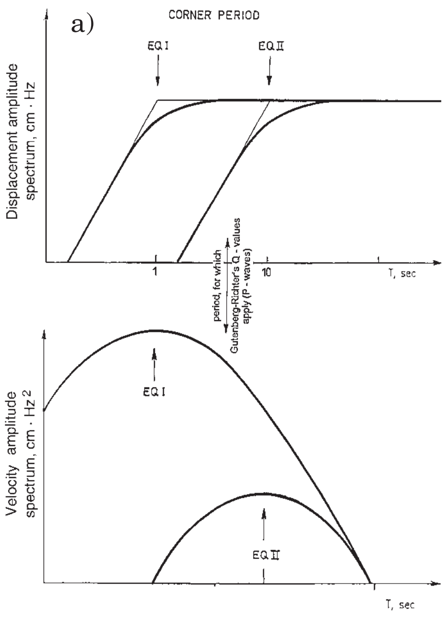
Fig. 3. Dependence of the corner period T_c on the moment magnitude M_w. The straight line corresponds to the linear orthogonal regression between T_c and M_w for all earthquakes. It is evident that the earthquakes with epicenters along divergent boundaries (empty triangles) radiate at larger periods than the earthquakes along convergent boundaries (solid triangles).

$$\log T_c = 0.33 \log M_0 - 7.78 \qquad (2)$$

This confirms well the assumption of self-similarity of earthquakes, according to which $T_c \propto \sqrt[3]{M_0}$.

4. Relation between energy magnitude and moment magnitude

From the source spectrum we may calculate the P-wave energy by intergrating the energy density over the entire range of measurable frequencies. The authors (Yanovskaya et al., 1996) introduced the 'energy magnitude' M_e related to the total P-wave energy radiated during the earthquake. The energy magnitude is controlled mainly by the P-wave energy radiated at periods near the corner period, whereas the moment magnitude M_w is based on the seismic moment and characterizes the radiation at very long periods. Therefore, it seems that if the radiation spectra are described by the ω^2-model, we may expect that for one and the same seismic moment, and consequently for one and the same M_w, the sources with a longer corner period will have a smaller energy magnitude M_e and vice versa. From Fig. 4a it is seen that two different earthquakes can have one and the same seismic mo-



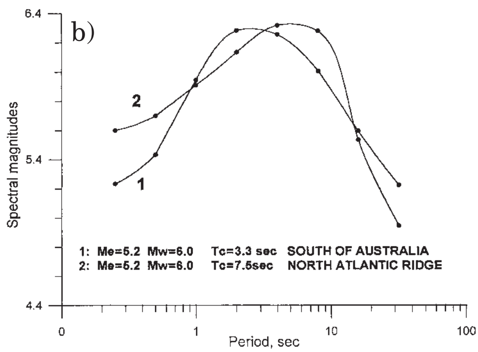


Fig. 4. Illustration of no general validity of the ω^2-model for individual earthquakes. a) – envelopes of theoretical displacement and velocity spectra for two earthquakes with one and the same seismic moment but shorter corner periods. It is evident that in case of a shorter corner period the radiated energy should be larger, and vice versa. b) – spectral magnitudes for two real earthquakes with one and the same seismic moment and different corner periods. In both cases the radiated energy (and the seismic moment) is the same within error limits. Note a difference with the theoretical curves in Fig. 4a.

ment M_0, but different corner periods, and different body wave magnitudes m_b, and thus different energy magnitudes M_e: energies released during these earthquakes are proportional to the areas under the velocity amplitude spectra. It is evident that in case of a shorter corner period the radiated energy should be larger and vice versa.

However, real earthquakes display more complex patterns of spectra. In Fig. 4b spectral magnitudes for two earthquakes with epicenters in the regions south of Australia and on the North Atlantic ridge are demonstrated. Spectral magnitudes as function of the period reflect the velocity spectrum at the focus (Duda and Yanovskaya, 1994). It is obvious from the figure that these events can not be separated on the '$M_w - M_e$' diagram, as $M_w(1) = M_w(2)$ and $M_e(1) = M_e(2)$.

A distinction between the two earthquakes can be made only on the basis of the corner period T_c. From this we conclude that the corner period T_c is an independent additional parameter characterising the »size« of an earthquake, and that it is mandatory to publish it together with the magnitude M_w or M_e.

For many earthquakes it is found that the velocity spectra in the source differ from those predicted by the model: they behave as shown in Fig. 4b, and the energy magnitudes do not always differ for different corner periods even if the seismic moments are identical. Consequently, the spectral magnitudes, as also the moment magnitudes and the energy magnitudes are complementary quantities reflecting the strength of the earthquake. The quantities need to be determined independently of each other, and any regression relation between the quantities reflects some average condition, from which in general significant deviations are observed for individual earthquakes, as well as for earthquake populations.

The data for M_w versus M_e are drawn in Fig. 5. The regressions based on the data for divergent and convergent boundaries practically coincide. Thus,

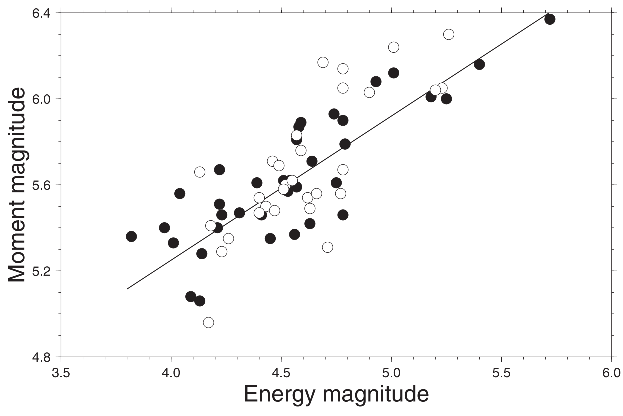


Fig. 5. The moment magnitude M_w versus the 'energy' magnitude M_e for the events shown in Fig. 1. The energy magnitude is defined according to Gutenberg-Richter's relation: $\log E = 1.56\, M_e$, where the energy E is calculated by integrating the source spectrum $S(\omega)$:

$$E = \frac{1}{8\pi^2 \rho_0 a_0^5} \int_0^\infty \omega^2 S^2(\omega) \mathrm{d}\omega.$$

the energy magnitude is a characteristic of the earthquake size supplementary to the moment magnitude. Both magnitudes correlate only within liberal limits. The energy magnitude may be used preferably in the cases when the spectral density is not available at large periods.

5. Stress drop

The data on seismic moments and corner periods are used to estimate the fault area S (formula (1)) and the stress drop $\Delta\sigma$ according to the relationship

$$\Delta\sigma \approx C \frac{M_0}{S^{3/2}} \quad (3)$$

where the constant C depends on the geometry of the fault and on the source mechanism. In (1) we assumed the rupture velocity as 0.9β, where β is the shear wave velocity (assumed to be equal to 3.2 km/s). The constant C in (3) was taken the same as in (Kanamori and Anderson, 1975), i.e. $\log C = -20.6$, if M_0 is measured in dyne-cm, and S in km^2.

Although the mechanisms of earthquakes in different tectonic zones are likely to be different, we assume one and the same source model for all earthquakes. Therefore, the values obtained on this assumption should be regarded not as estimates of real S and $\Delta\sigma$, but rather as quantities permitting to relate statistically the earthquakes in different tectonic zones to each other. The values of S versus M_0 in a logarithmic scale are shown in Fig. 6.

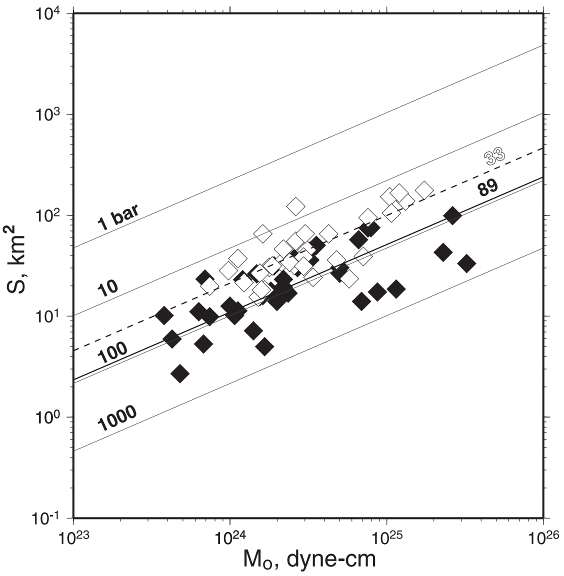


Fig. 6. The fault area S versus the seismic moment M_0. The straight lines correspond to constant stress drops. The average stress drop for earthquakes with epicenters along divergent boundaries (empty diamonds) is found to be 33 bars, and along convergent boundaries (solid diamonds) – 89 bars.

The straight lines correspond to constant stress drops with values as indicated (Kanamori and Anderson, 1975). The broken line and the thick solid line correspond to the average relationships for earthquakes along divergent and convergent boundaries, respectively. On this background the average stress drop for earthquakes along divergent boundaries is estimated to be 33 bars, and for earthquakes along convergent boundaries it is is found to amount to 89 bars, the ratio between the two stress drop values being qualitatively in agreement with the expectation based on the present understanding of tectonic movements.

6. Analysis of source parameters for earthquakes in the Japan-Kuril zone

Within one and the same tectonic zone the spectral characteristics depend in general on the source mechanism, the location and the depth. We selected 104 earthquakes in the Japan-Kuril subduction zone with different mechanisms falling into three groups: thrust faulting, normal faulting, and strike-slip. The epicenters and mechanisms are shown in Fig. 7.

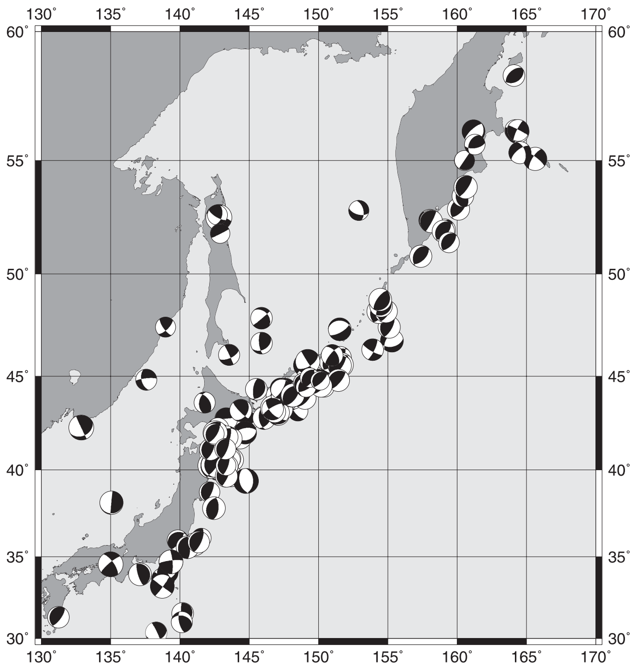


Fig. 7. Locations and mechanisms of earthquakes in the Japan-Kuril subduction zone. The data on CMT moment tensors were used to discover differences in source radiation for different source mechanisms.

To separate the earthquakes with different focal mechanisms we applied the method originally proposed by Frohlich and Apperson (1992). All our events are plotted on the triangle diagram (Fig. 8), where the vertices of the triangle stand for normal, strike-slip and thrust focal mechanisms, respectively. Dip angles (for the mutually perpendicular T, B, P axes relative to horizontal) for normal, strike-slip and thrust events are equal to $\delta_T = 0°$, $\delta_B = 0°$, $\delta_P = 90°$; $\delta_T = 0°$, $\delta_B = 90°$, $\delta_P = 0°$ and $\delta_T = 90°$, $\delta_B = 0°$, $\delta_P = 0°$, respectively. On the triangle diagram the position of the earthquake with a given focal mechanism depends only on δ_T, δ_B, δ_P.

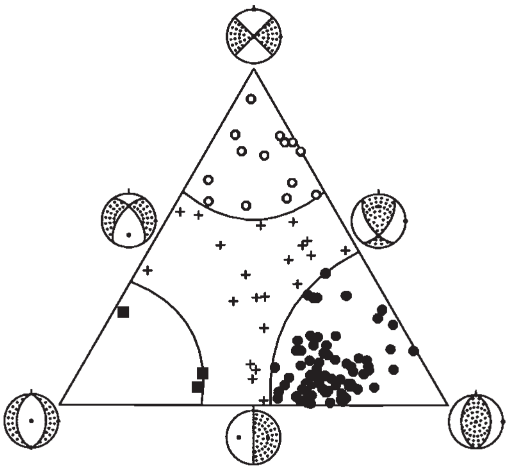


Fig. 8. Triangle diagram separating earthquakes with different focal mechanisms. The three vertices correspond to pure normal (left), pure strike-slip (top), and pure thrust (right) fault mechanisms. The focal mechanism position on the diagram depends only on δ_T, δ_B, δ_P – the dip angles of T, B and P axes. The curved lines correspond to $\delta_T = 50°$, $\delta_B = 60°$, $\delta_P = 60°$. Strike-slip events are denoted by empty circles, thrust events – by solid ones.

According to Frohlich and Apperson (1992) we considered an event as normal, if δ_P exceeded 60°, as strike-slip, if δ_B exceeded 60° and as thrust with δ_T greater than 50°.

By using the criteria introduced earlier, we make a comparison of strike-slip and thrust events as extremes, to determine the peculiarities of their spectral content. (Normal fault events are excluded from the consideration, because of their scarcity in this tectonic enviroment, see Fig. 8). If the spectral characteristics depend on the mechanism, we should expect the difference in the relationship between log T_c and M_w, to be analogous to that for divergent and convergent boundaries (Fig. 3). Fig. 9 shows the ortogonal regressions between log T_c and the moment magnitude M_w for the earthquakes with strike-slip (empty triangles) and thrust (solid triangles) focal mechanisms.

Despite of the scattering and despite of the relatively small number of strike-slip events (Fig. 8), we can conclude from Fig. 9, that strike-slip earth-

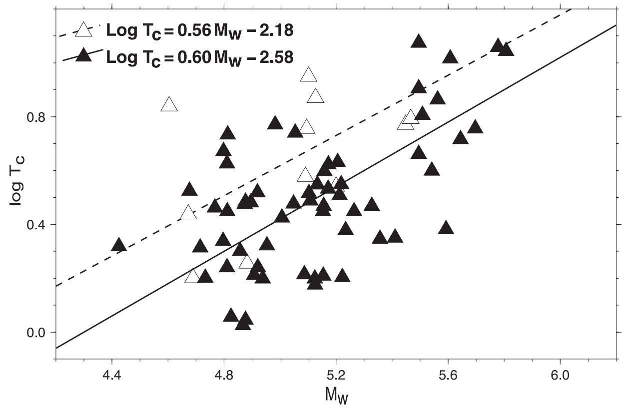


Fig. 9. log T_c versus the moment magnitude M_w for strike-slip (empty triangles) and thrust (solid triaangles) events.

quakes radiate energy at longer periods, than earthquakes with a thrust mechanism. This result agrees again with the inference made by Kaverina et al. (1996), who investigated the dependence of creepex on the source mechanism. According to the authors strike-slip faults have positive values of creepex (anomalously large values of M_S, as measure of longperiodic radiation), while thrust faults have negative ones (anomalously large values of m_b, as measure of shortperiodic radiation).

Fig. 10 finaly demonstrates the values of the fault area versus seismic moment. The figure may be compared with Fig. 6, which applies worldwide.

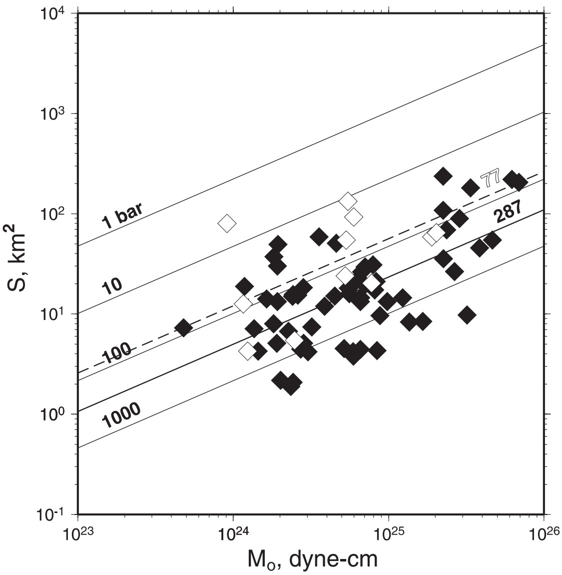


Fig. 10. The fault area S versus the seismic moment M_0 for earthquakes in the Japan-Kuril zone with strike-slip (empty diamonds) and thrust (solid diamonds) focal mechanisms. The average stress drop for strike-slip events is equal to 77 bars, and for thrust events – 287 bars. The average stress drop for this zone is estimated as 234 bars, which is larger than the average for earthquakes along convergent boundaries (89 bars).

The broken line and the solid thick line correspond to the average relationships for strike-slip and thrust earthquakes respectively. The strike-slip events are characterized by smaller values of the mean stress drop (77 bars), than thrust ones (287 bars). The mean stress drop in the Japan-Kuril zone was found to amount to 234 bars. This value is higher than that obtained for the earthquakes along convergent boundaries at large (Fig. 6), which indicates eventually that the tectonic stress in this subduction zone is generally higher than in other zones.

7. Conclusions

The deviation of the corner period from the regression line log $T_c(\mathrm{M_w})$ can be used as a criterion for discrimination between 'normal' earthquakes and earthquakes radiating energy primarily in low- and high-frequency ranges. Application of this criterion to the earthquakes with epicenters along divergent and convergent boundaries allows to conclude that on the average the events along divergent boundaries are more »long-periodic« and events along convergent boundaries – more »short-periodic«. Consequenly the former are characterized by a lower, and the latter by a higher stress drop. The mean values of stress drop amount to 33 bars for divergent boundaries and 89 bars for convergent boundaries. The stress drop in the Japan-Kuril subduction zone is found to be even higher than the average for earthquakes with epicenters along convergent boundaries at large and a measurable difference in the source radiation spectra and thus in stress drops is revealed for the earthquakes with different mechanisms in this zone.

Acknowledgments – The research was performed within the framework of the partnership program of Hamburg and St.Petersburg universities. Financial support was obtained from RFFI (grant 96-05-00003G) and DFG. One of the authors (E. L. Lyskova) was the recipient of a scholarship by Deutscher Akademischer Austauschdienst, Bonn. All support is gratefully acknowledged. The authors are grateful to an anonymous reviewer whose comments allowed us to improve the paper.

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SAŽETAK

Spektralna svojstva potresa na dodiru tektonskih ploča

E. L. Lyskova, T. B. Yanovskaya i S. J. Duda

Proučavani su potresi na konvergentnim i divergentnim mjestima dodira tektonskih ploča. Potresi karakterizirani anomalno dugoperiodičkom odnosno kratkoperiodičkom radijacijom prostornih valova razlučeni su na osnovi devijacije graničnog perioda T_c P-valova (regresijom T_c i momentne magnitude M_w), te razmatranjem iznosa pada napetosti na rasjedu, $\Delta\sigma$.

Ustanovljeno je da potresi na konvergentnim granicama zrače seizmičku energiju uglavnom na duljim periodima nego oni na divergentnim granicama. Prosječni pad napetosti za potrese duž konvergentnih granica iznosi 33 bara, a za one na divergentnim 89 bara.

Na području Japana i Kurilskih otoka »strike-slip« potresi imaju veći granični period od »dip-slip« potresa. Rezultati su u skladu s istraživanjima *creepex* razdiobe duž konvergentnih i divergentnih granica, kao i ovisnosti *creepex*-a o žarišnom mehanizmu.

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