The relations between seismically active and electrically conductive zones

Isnau G. Kissin and Aleksander I. Ruzajkin
Joint Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

Abstract
The higher electrical conductivity of rocks in the middle and lower parts of the Earth's crust is generally related to the presence of fluids in rocks. The metamorphic processes of dehydration contribute to release of fluids, above all, water; these processes are also responsible for an increase in rock porosity and fracturing. These processes influence the stressed-strained state of the medium under specific conditions. A probable mechanism of earthquake source formation on the contact of blocks with different rates of dehydration and, consequently, different electrical conductivity is discussed. The spatial positions of electrically conductive and seismically active zones are correlated and definite relations between them are found with special reference to the vast area of the Northern Tien Shan within Kirgizstan and some other regions. The greatest concentration of earthquake sources is observed mainly near the contacts between blocks with contrastingly different electrical conductivity values and on sites with a sharp drop in conductive-layer depths.

Key words *earthquake – electrical conductivity – metamorphic process – fluid – dehydration*

1. Introduction

Elucidating the relation between the seismicity and electrical conductivity of different structures in the Earth's crust is of interest for seismic zoning and prediction. If such a relation is found, this will make it possible to determine, to a high degree of accuracy, the places of probable earthquakes and to predict their time, using characteristic variations in apparent resistivity values. Above all, the extent of water saturation of the Earth's crust must be the link between seismicity and electrical conductivity. This index has a major effect on the resistance of rocks and their strength characteristics. The information about depth fluids may be obtained in combined interpretation of geophysical data, above all, electrical, velocity, and reflectivity characteristics (Hyndman *et al.*, 1993). Petrological data, related to studying metamorphic processes, which proceed with fluid participation, should also be used for this purpose (Fyfe *et al.*, 1978).

The trigger effect of water on the development of natural and induced earthquake sources has been discussed by many scientists. We made an attempt to determine the influence of metamorphic processes, resulting in water release, on the stressed-strained state of the medium during the preparation of earthquakes and to elucidate, allowing for this influence, the relations between seismically active and electrically conductive zones.

2. The effect of fluids on the electrical conductivity of the Earth's crust

According to magnetotelluric measurement data, the typical electrical conductivity of the lower continental crust is 100-1000 times

Mailing address: Dr. Isnau G. Kissin, Joint Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia; e-mail: Strakhov@dir.iephys.msk.su

larger than that of dry rocks determined in the laboratory and is 10-100 times as high as the electrical conductivity of the upper crust (Hyndman *et al.*, 1993). There are two viewpoints concerning the nature of the electrical conductivity of the Earth's crust: it is connected with fluids (mainly water) or it is connected with rocks containing graphite and sulfide minerals. The presence of mineralized water in rock pores and fractures, as well as in intergranular space makes it possible to explain, in many cases, the distribution of electrically conductive zones of structures of different age in the crust and a good correlation between rock resistivity velocities and absorption of seismic waves (Hyndman *et al.*, 1993). In regions where this correlation does not exist, particularly at very low apparent resistivities of conductive layers, these layers are associated with rocks containing graphite or sulfides.

Large variations in the apparent resistivity of electrically conductive zones under the action of stress before and after earthquakes may be the confirmation of the fluid nature of these zones. The effect of stress results in a change in systems of interconnected water-bearing fractures, but influences little the electrical conductivity of solid inclusions. Such resistivity variations were observed, for example, on the Bishkek Experimental Site in Kirgizstan (Velikhov and Zeigarnik, 1993). Resistivity changes at frequencies of less than 0.25 Hz reflect the development of deformation processes in an electrically conductive horizon, which occurs at a depth of more than 10 km (fig. 1).

Metamorphic dehydration of rocks is the main factor which ensures water release and an increase in the porosity and fracturing of the rocks in the middle and lower parts of the crust. In rocks having a complex chemical composition, dehydration may proceed for a long time (Fyfe *et al.*, 1978). The released water cannot move away rapidly due to the presence of a low-permeable screen between the middle and upper crust. This screen is observed in many regions where it has high apparent resistivity values and seismic velocities. Thus, the water-saturated rocks in the electrically conductive zones of the middle and lower

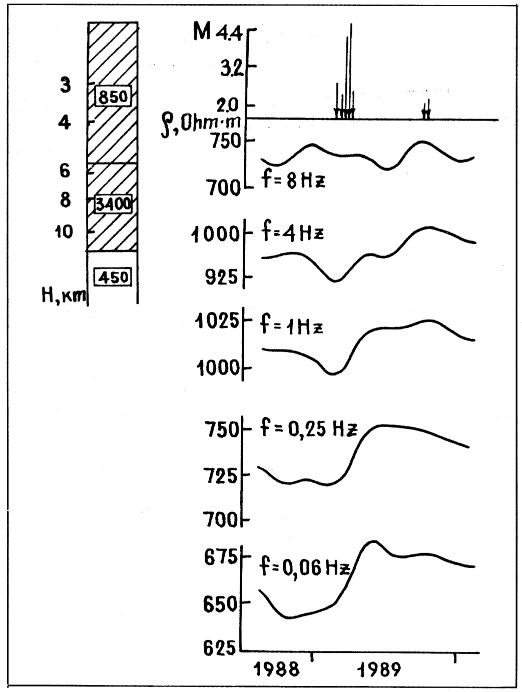

Fig. 1. Geoelectrical profile: zones with various apparent resistivity values ($\Omega \cdot m$) and plots of changes in resistivities after smoothing with a low-frequency filter (from data of repeated frequency sounding in point 35 of the Bishkek Experimental Site). Arrows show earthquakes with different magnitudes (Velikhov and Zeigarnik, 1993).

parts of the crust, being of a fluid nature, are preserved with compensation for migratory losses of water by its supply as a result of metamorphic dehydration.

3. The influence of metamorphic dehydration of rocks on seismic activity

It is known that reactions of metamorphic dehydration of rocks are accompanied by formation of porosity corresponding to the quantity of released water and proceed largely with heat absorption (Fyfe *et al.*, 1978). In the majority of these reactions, the total volume of formed solid and fluid products is larger than the volume of initial minerals, and the solid skeleton volume decreases as a result of reactions. For example, the volume of solid minerals per gram-molecule decreases by 20 cm^3 in the reaction between analcime and quartz with formation of albite and water, characteristic of the zeolite facies of metamorphism (Fyfe *et al.*, 1978). A similar result is also produced by metamorphic reactions of carbonate decomposition to release carbon dioxide.

The volume of pores and fractures decrease on fluid evacuation from them under the action of lithostatic pressure, and rocks are compacted. At various stages of dehydration the total volume of reaction products may be larger or smaller than the initial volume depending on reaction velocities and water evacuation. In this case, the sign of the volumetric strain changes but the rock compacts with time. The largest strain is experienced by rocks with high water saturation and large rates of its variation. Not only lithostatic pressure but also horizontal stress, existing in the Earth's crust, influences the direction of deformation.

If conditions of rock dehydration and, consequently, rock deformation are different in adjacent blocks of the Earth's crust, differential stresses, which may result in formation of faults and development of seismic sources, must appear at the contact of the blocks and in the cover strata (fig. 2). In the course of dehydration, water is released under great pressure and, because of the low permeability of cover rocks, hydraulic rupture generates fractures along which water may move to the area of the source of an earthquake, which is about to occur. The trigger action of these injections contributes to stress release. Most favorable condi-

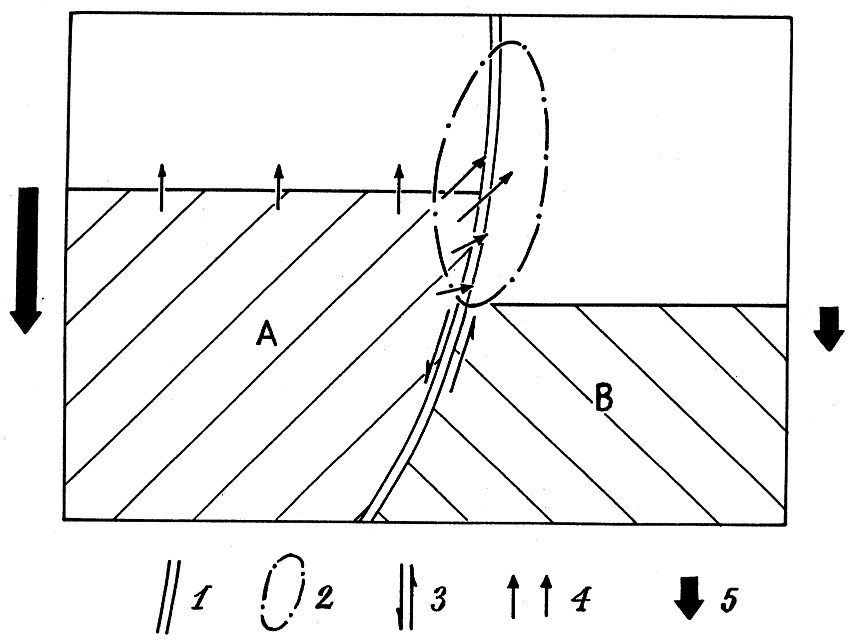

Fig. 2. A scheme of localization of earthquake sources on the contact of blocks of the Earth's crust with different conditions of rock dehydration. Block A is with a high degree of water saturation; Block B is with a low degree of water saturation. 1 = the zone of contact between blocks (a fault); 2 = the contour of the area of source localization; 3 = directions of reciprocal displacements of blocks; 4 = paths of hydraulic rupture and fluid injection; 5 = relative deformations of blocks for equal interval of time.

tions for development of fractures formed by hydraulic rupture and for a short-term increase in seepage from water-saturated sites to potential earthquake sources are in deep-fault zones near which these sources are commonly localized. This pattern shows that there exists a duplex mechanism of the influence of the metamorphic dehydration of rocks on the seismic process: formation of differential stresses and a decrease in rock strength in the earthquake source zone when water moves to it under high pressure.

The discussed mechanism of the influence of metamorphic dehydration of the Earth's crust on earthquake generation is in compliance with the existing data for some regions on the relations between seismically active and fluid-saturated horizons of the Earth's crust. Electrical conductivity, seismic velocity, and wave absorption values may indicate the degree of the water (fluid) saturation of the crust in different structures. The seismicity-generating and water-saturated stages of the consolidated continental crust are separated. The first stage mainly occurs in the upper crust (down depths of 15-20 km) and the second stage occurs in the middle and lower parts of the crust.

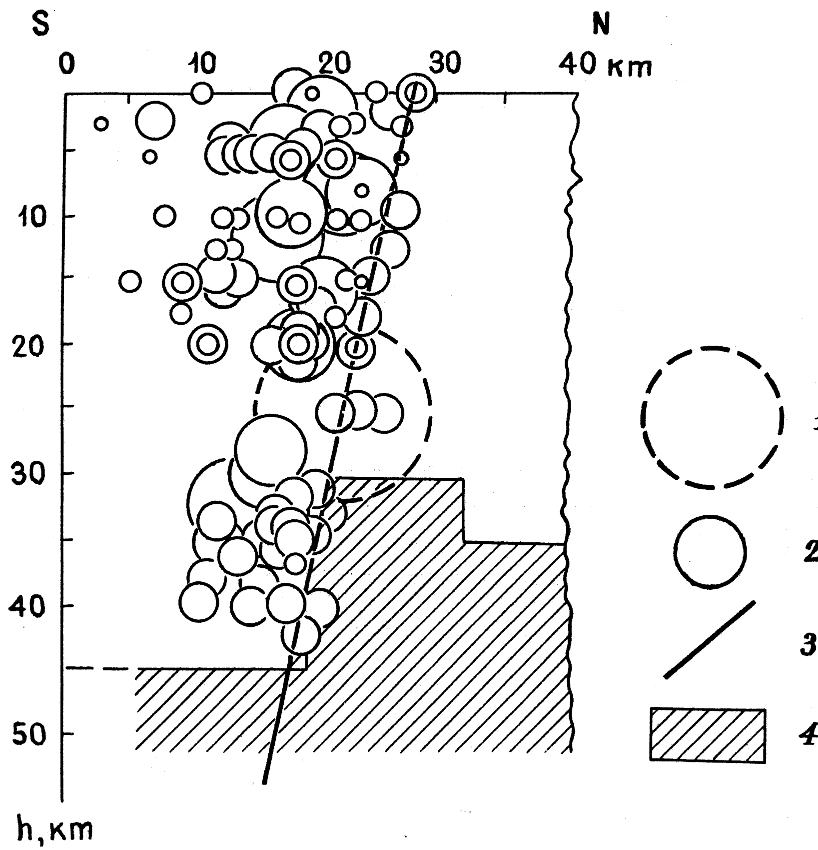

Fig. 3. Submeridional section of a cloud of aftershocks of the Zhalanash-Tyupskoe earthquake (Kvetinskiy *et al.*, 1993). 1 = the hypocenter of the main shock; 2 = hypocenters of aftershocks of different magnitudes; 3 = the position of the nodal plane; 4 = a high-absorption zone ($Q_s < 60$).

Let us discuss some examples. In the seismically active region of Northern China, strong-earthquake sources are frequently localized within the layer with high resistivity occurring between two electrically conductive layers at depths down to 10 km and more than 30 km. Repeated magnetotelluric measurements in the area of Nanping showed after the earthquake of 1976 a 70-percent decrease in apparent resistivity at the depth of the earthquake-source zone, which is indicative of an increase in water saturation. Dehydration of muscovite-quartz strata is a possible water source (Lin Changyou, 1984). Earthquake sources in many continental rift regions are located directly over waveguides, which in these structures occur at depths of about 12-15 km (Grachev, 1994). In rift regions, the depth position of waveguides and electrically conductive layers coincide, and they originate from dehydration processes (Derlyatko *et al.*, 1988). Sites with contrastingly different wave-absorption values have been delineated in the source zones of the Chilikskoe earthquake of 1889 with $M = 8.3$ and the Keminskoe earthquake of 1911 with $M = 8.2$ as well as other strong earthquakes, which occurred in the highly seismic region of the Northern Tien Shan, located north-east of Lake Issyk-Kul (Kvetinskiy *et al.*, 1993). The sources of the Zhalanash-Tyupskoe earthquake of 1978 with $M = 6.8$ and the Baisorunskoe earthquake of 1990 with $M = 6.3$ are confined to the regions with a sharp drop in the depths of the top of the layer with strong absorption of transversal waves (fig. 3). The strong absorption in this layer is explained by its higher fluid saturation (Kvetinskiy *et al.*, 1993).

All the facts given, despite different treatment of the influence of the degree of fluid saturation of the crust on seismicity do not contradict the suggested pattern of formation of earthquake sources under the effect of metamorphic dehydration. Of course, strains, which accompany such rock dehydration, are not the only cause of crustal seismicity, which is also influenced by processes occurring in the mantle. The relative contribution of these deformations to seismicity generation in different structures may be different. The significance of this contribution is supported by an increase in the electrical conductivity of the continental crust in the range from ancient stable structures to young tectonically active structures (Derlyatko *et al.*, 1988; Hyndman *et al.*, 1993), which may be explained by the higher water saturation of rocks and by the higher intensity of recent metamorphic processes in this range.

4. The relation between seismically active and electrically conductive zones in the Northern Tien Shan

The relations between seismically active and conductive zones in the Earth's crust of the Northern Tien Shan have been investigated along two profiles of magnetotelluric sounding. The measurements were carried out under the guidance of Yu.A. Trapeznikov and the records were interpreted by M.N. Berdichevskiy. The investigated region, bounded by coordinates 40.5-43.0°N and 73.0-77.0°E, is noted for high seismic activity. Block structure is a characteristic feature of its tectonics (Gubin, 1986). The boundary between blocks goes along deep faults. The schematic map (fig. 4), compiled using data from collections of papers «Earthquakes in the USSR» published in 1982-1991 by Nauka (Moscow) and «Earthquakes in the USSR Central Asia and Kazakhstan» published in 1979-1986 and 1988-1991 by Donish (Dushanbe), shows the distribution of earthquake epicenters and the depth position of earthquake sources for the 1979-1986 and 1988-1991 periods. The selection includes earthquakes with $M \geq 1.3$ from the catalog «Earthquakes in the USSR» and earthquakes with $M \geq 2.6$ from catalog «Earthquakes of the USSR Central Asia and Kazakhstan». The data from the second catalog wave taken in order to supplement data on the seismicity of the southern part of the investigated region, which are absent in the first catalog. Six earthquakes with $M \geq 4.5$ occurred in this region for the period under consideration, and the devastating Susamyrskoe earthquake with $M = 7.5$ occurred on August 19, 1992 (the epicenter of this earthquake is also shown in fig. 4). Aftershocks of strong earthquakes are not shown on

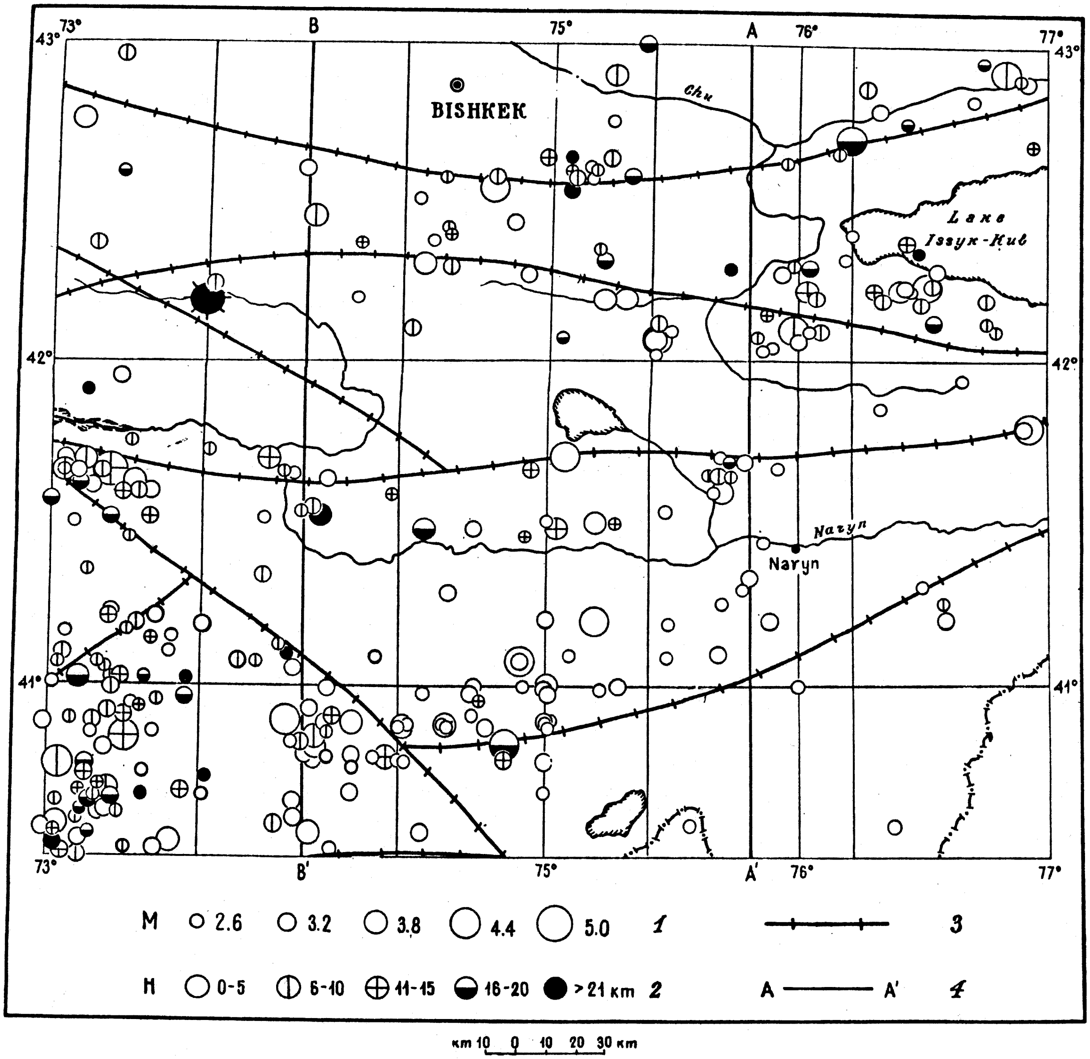

Fig. 4. A schematic map of the distribution of the epicenters of earthquakes with $M \geq 2.6$ in the investigated region of Central Kirgizstan for the 1979-1986 and 1988-1991 periods. 1 = earthquake magnitudes; 2 = earthquake source depths; 3 = deep-fault zones; 4 = section lines.

maps and sections (figs. 5 and 6). Earthquake epicenters are grouped in the form of area and strips, which often are located near deep-fault zones.

The magnetotelluric sounding profiles AA′ and BB′ go along the meridians 75.82° and 74.00°E, respectively. Sections, where zones with different apparent resistivity values are delineated (figs. 5 and 6), were constructed for comparing seismic and geoelectrical data in the strip adjoining these profiles. Projections of hypocenters of earthquakes with $M \geq 1.3$, located in the strip formed by lines drawn parallels to lines AA′ and BB′ at a distance of 40 km at both sides from them, are also shown on the profiles. These hypocenters were determined from observation data in the 1988-1991 period (figs. 5 and 6). As is seen on the sections, the majority of earthquake hypocenters are located at depths of down to 10 km and only a small number of them are recorded at depths of more than 20 km.

The presence of a continuous conductive layer with apparent resistivity values ranging from 7.5 to 35 $\Omega \cdot$ m is the common geoelectrical feature of both the profiles. The top of this layer is generally at a depth of 30 km and locally at a depth of 20 km. The bottom of this layer is at depths from 45 to 50 km and from 35 to 40 km on some sites. Such a position of

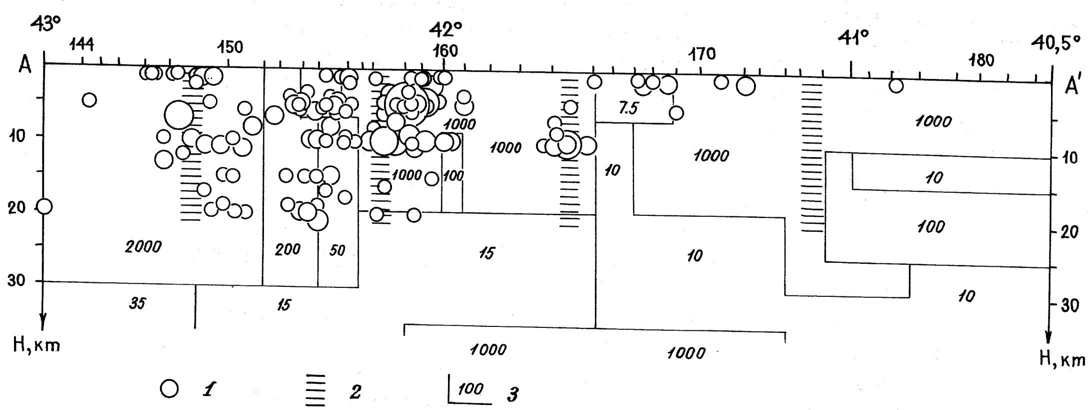

Fig. 5. Distribution of earthquake hypocenters along the section on the line AA′. The numerals along the line AA′ are the numbers of sounding points. 1 = projections, on the section plane, of the hypocenters of earthquakes with different magnitudes; 2 = deep faults; 3 = boundaries of sites with different apparent resistivity values (the numerals are resistivity values in $\Omega \cdot$ m).

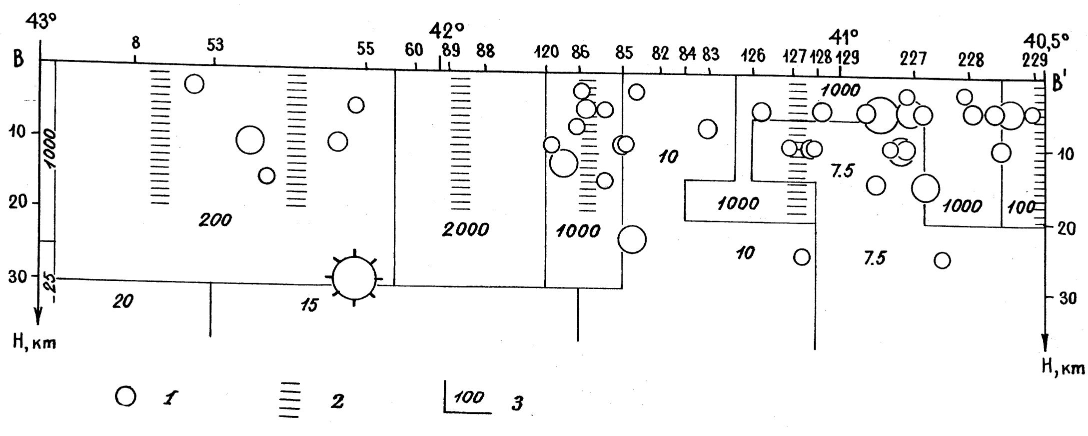

Fig. 6. Distribution of earthquake hypocenters along the section on the line BB′. The symbols are those in fig. 5.

the conductive layer corresponds to data, obtained from magnetotelluric measurements, on the higher electrical conductivity of the middle and lower parts of the continental crust in many regions of the world (Hyndman *et al.*, 1993). Subvertical branches go locally from the conductive layer and extend to the near-surface zone. On some sites, these branches are in the vicinity of large faults and probably coincide with their depth extension. A second conductive horizon is traced at a depth of 10-15 km in the southern part of the profile AA′ (fig. 5).

Earthquake sources are located, with rare exceptions, above the continuous conductive layer. The greatest concentration of earthquake sources is observed near contacts between blocks with contrastingly different resistivity values and on sites with a sharp drop in depths of the top of the conductive layer. This is well seen on the profile AA′ (fig. 5) between points 150 and 160 and between points 160 and 170, as well as on the profile BB′ between points 120 and 85, 129 and 227. The source of the Susamyrskoe earthquake of August 19, 1992 with $M = 7.5$ is located over the top of the conductive layer, near the contacts of blocks with resistivity values of 200 and 2000 $\Omega \cdot$ m (fig. 6).

The investigations, conducted in the area of the Northern Tien Shan, and individual examples from other regions are indicative of the common features of the relation between seismically active and conductive zones: these zones are confined to different stages of the Earth's crust and these is a denser concentration of earthquake sources at sites with contrastingly different electrical conductivity values.

5. Concluding remarks

Metamorphic processes, which occur in the depth zones of the continental crust with participation of fluids, are one of the factors determining the tectonic regime. These processes also influence the electrical conductivity of the crust. The presented data testify that the metamorphic dehydration of rocks may have a substantial effect on seismic activity. Thus, there is a possibility to associate the specific features of the geoelectrical profile of the crust and the distribution of earthquake sources. Some examples and our investigations support this possibility.

We may suppose that localization of earthquake sources near the contacts of blocks with contrastingly different electrical conductivity values and seismic characteristics of rocks may also be found in other regions. In this case, further investigations will specify the relations between seismically active and electrically conductive zones as applied to structures with definite seismic and geoelectrical characteristics.

Acknowledgements

The authors are grateful to Prof. M.N. Berdichevskiy of the Moscow State University who was the initiator of the investigations discussed. The work was accomplished with the support of the International Science Foundation, the Government of Russia (Grant N J 84100), and the GEON Association.

REFERENCES

DERLYATKO, E.K., G.V. KRASNOPEVTSEVA and I.A. REZANOV (1988): Correlation between waveguides and electrically conductive layers in the continental crust, *Dokl. Akad. Nauk SSSR,* **301** (5), 1083-1087 (in Russian).

FYFE, W.S., N.J. PRICE and A.B. THOMPSON (1978): *Fluids in the Earth's Crust* (Elsevier, Amsterdam), pp. 436.

GRACHEV, A.F. (1994): On the nature of the New Madrid zone of high seismic activity on the North American Platform, *Fizika Zemli*, **12**, 12-23 (in Russian).

GUBIN, I.E. (Editor) (1986): *Litosfera Tian-Shanya (The Lithosphere of the Tien Shan)*, Nauka, Moscow, pp. 157 (in Russian).

HYNDMANN, R.D., L.L. VANYAN, G. MARQUIS and L.K. LAW (1993): The origin of electrically conductive lower continental crust: saline water or grafite?, *Phys. Earth Planet. Int.*, **81**, 325-344.

KVETINSKIY, S.I., YU.F. KOPNICHEV, N.N. MIKHAILOVA, A.N. NURMAGAMBETOV and M.KH. RAKHMATULLIN (1993): Heterogeneties of the lithosphere and the asthenosphere in source zones of strong earthquakes in the Northern Tian Shan, *Dokl. Ross. Akad. Nauk*, **329** (1), 25-28 (in Russian).

LIN, CHANGYOU (1984): Phase transition dehydration: a possible way of interior source of the water in the local region, *Northwest. J. Seismol.*, **6** (1), 84-92.

VELIKHOV, E.P. and V.A. ZEIGARNIK (Editors) (1993): *Proyavleniya Geodinamicheskikh Protsessov v Geofizicheskikh Polyakh, (Reflection of Geodynamical Processes in Geophysical Fields)*, Nauka, Moscow, pp. 160 (in Russian).