ISSN 0742-0463, Journal of Volcanology and Seismology, 2019, Vol. 13, No. 5, pp. 292–304. © Pleiades Publishing, Ltd., 2019.
Russian Text © The Author(s), 2019, published in Vulkanologiya i Seismologiya, 2019, No. 5, pp. 22–35.

Fault Tectonics and Deep Structure of Seismic Zones in the Eastern Priamurye Region

T. V. Merkulova*
Kosygin Institute of Tectonics and Geophysics, Far East Branch, Russian Academy of Sciences,
ul. Kim Yu Chena, 65, Khabarovsk, 680000 Russia
**e-mail: merculova@itig.as.khb.ru*

Received June 21, 2018; revised September 15, 2018; accepted May 16, 2019

Abstract—This paper is concerned with spatial relationships between seismic zones in the eastern Priamurye region ($M \geq 5$) on the one hand and, on the other, regional faults and zones of hidden faults as indicated by axes of gravity and magnetic anomalies. The seismoactive zones where $M \geq 5$ earthquakes occurred are mostly confined to regional faults, while there are two cases where no such relationship has been detected. Seismic zones are observed both at intersections of regional faults and at intersections of regional faults with hidden faults of different rank. The seismic zones comprise inclined and subvertical deep-seated faults as identified by deep seismic sounding (DSS), the earthquake converted wave method (ECWM), and magnetotelluric sounding (MTS) surveys. The seismoactive zones were studied by geophysical techniques to identify indication of fluid saturation, as follows: the seismoactive faults frequently control low velocity and low resistivity inhomogeneities in the Earth's crust and upper mantle; some seismoactive faults have displaced the Moho interface; there are dome-shaped flexures of crustal interfaces and of the Moho interface; and the crust is found to contain numerous conversion interfaces. The deep occurrence of seismoactive faults and the indications of fluid saturation suggest that the seismoactive faults in the eastern Priamurye region provide supply of fluids from the mantle to the crust.

Keywords: seismoactive zones, fault tectonics, deep structure, Amur region

DOI: 10.1134/S074204631905004X

INTRODUCTION

The controlling role of faults as weakened zones where accumulated energy is released has been pointed out by many researchers (Zobak and Zobak, 1984; Ulomov, 1993; Bulin, 2004; Sherman, 2009). All models of the earthquake focus treat a seismic event as resulting from a displacement on an active fault (Sherman, 2009). A fault is a three-dimensional body defined by its length, width, and depth, i.e., one that has a zone of dynamic influence (Sherman et al., 1983; Kocharyan et al., 2011). However, the relationship of earthquakes to faults as mapped by geological data is not invariably observed. Earthquake hypocenters are occasionally found to occur along fault zones that have no surface expression at all or which exhibit several indirect indications of so-called hidden faults (Makarov and Shchukin, 1979). The confineness of earthquakes to hidden faults that can be identified from combined geological and geophysical evidence has been found to be the case for many seismic regions all over Russia (Stognii and Stognii, 2005; Vashchilov and Kalinina, 2008; Trofimenko, 2010; Spichak, 2016). Young faults that are formed in zones of present-day destruction can also be hidden, in addition to older faults that have poor surface expression (Sherman, 2009). Earthquakes propagate nonuniformly over the fault plane, occurring in those zones only where there are intersections of differently directed faults or fault bending (Ulomov, 1993; Blinova, 2003). The seismo-generating movements in the foci zones of large earthquakes frequently involve parts of the planes of differently directed faults near their intersections (Rogozhin, 2000).

Some researchers noted in their studies of seismicity in intraplate areas that faults with different angles showed different levels of seismic activity. In some regions it is only nearly vertical faults or faults that show activity (Zobak and Zobak, 1984; Bulin, 2004). In seismic areas of the former Russian Central Asia, it is weakened inclined zones that are the most important (Lukk and Yunga, 1988).

Many publications emphasize the role of fluids in the seismic process, hence in stimulating movements on active faults (Kissin, 2001; Gufeld et al., 2011; Belyavsky and Rakitov, 2012). F.A. Letnikov acknowledged the presence of intense fluid flows rising from the asthenosphere via fault zones and giving rise to strain-stress systems that can function a long period of time (Letnikov, 2013). Geophysical studies show that the presence of fluids is indicated by regions of low

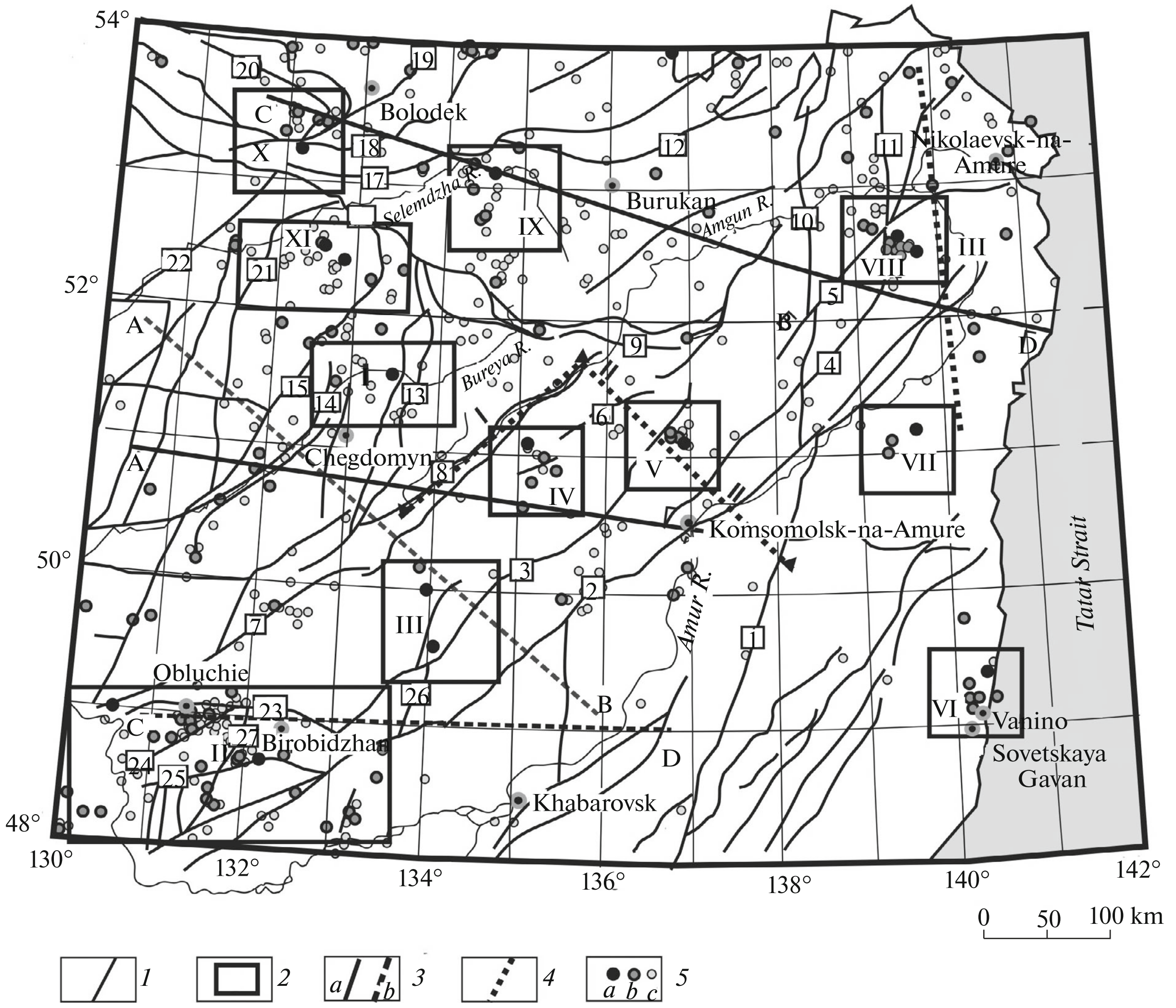

Fig. 1. The fault tectonics and seismic zones ($M \geq 5$) in the eastern Amur region. (*1*) regional faults after Zabrodin et al. (2015); (*2*) preliminary boundaries of seismic zones and their identification numbers; (*3*) lines of deep seismic surveying (*a* DSS, *b* ECWM); (*4*) MTS lines; (*5*) earthquakes (*a* $M \geq 5$, *b* $5 < M \geq 4$, *c* $4 < M \geq 3$). Numerals in squares denote faults: (1) Central Sikhote-Alin, (2) Itun–Ilan (Kharpi), (3) Kur, (4) Boktor, (5) Bichi–Amur, (6) Duki, (7) Amgun, (8) Hinggan, (9) Paukan, (10) Limurchan, (11) Vyun, (12) Assynisky, (13) Tastakh, (14) Bureya, (15) Melgin, (16) South Tukuringra, (17) Tugur, (18) Tyl, (19) Uligdan, (20) Lansky, (21) Verkhnimelginsky, (22) Selemdzha, (23) Bira, (24) Chanchung, (25) Pompei, (26) Ulikan, (27) Ditur.

velocity and higher conductivity, as well as by other features (Pavlenkova, 1996; Karakin et al., 2003; Rybin, 2011; Kushnir and Burakhovich, 2012; Moroz et al., 2015).

THE DATA SET AND THE METHODS OF STUDY

The data to infer the spatial distribution of moderately large earthquakes ($M \geq 5$) were taken from the catalog compiled at the Institute of Tectonics and Geophysics (ITG), FEB RAS. The catalog contains information on historical and instrumentally recorded earthquakes from the *Earthquakes in Russia* and *Earthquakes in North Eurasia* catalogs. The zones of near $M \geq 5$ earthquakes or the seismic zones where at least one $M \geq 5$ earthquake has occurred along with relatively small events have been preliminarily divided into eleven zones (Fig. 1).

Within these zones we studied relationships between earthquakes and the regional faults identified by geological surveys (Zabrodin et al., 2015). Some information on a possible participation of hidden faults in fault tectonics can be derived from axes of gravity and magnetic anomalies. The analysis used regional components of the gravity and magnetic fields and the local first-order component of the gravity field; these provide evidence of fracturing of the deeper lithosphere. Some experience has been accu-

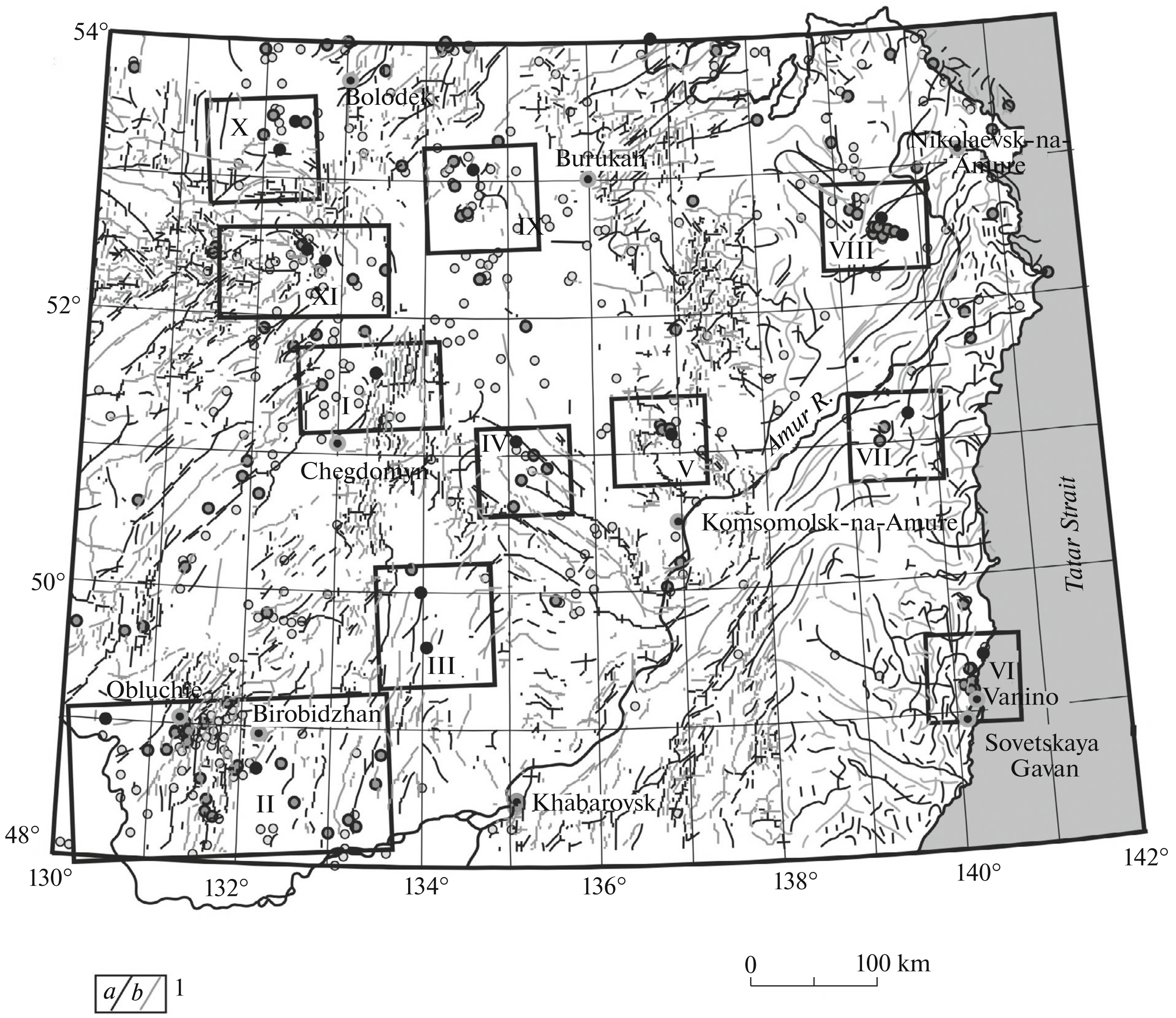

Fig. 2. The axes of regional magnetic anomalies. (1) axes of regional magnetic anomalies (*a* positive, *b* negative). For other explanations see Fig. 1.

mulated in the identification of hidden faults from geophysical data. One of the features from which to recognize the existence of a fault consists in persistent axial lines of magnetic and gravity anomalies. Linear gravity and magnetic anomalies can be due to linear geological features in faults consisting in the occurrence of magmatic rocks of basic and ultrabasic compositions (massifs and dikes). Some faults are characterized by active manifestations of granitization and metasomatism, making linear zones saturated with granite, pegmatite, and metasomatites. Local negative gravity anomalies can be a signature of structures filled with unconsolidated sedimentary deposits (basins and grabens) formed due to fault activation. Linear magnetic anomalies can also record mylonitization zones and patches of secondary alteration (Trofimenko, 2010). Linear regional gravity anomalies reflect large lithosphere blocks controlled by deep-seated faults (Tyapkin and Kivelyuk, 1982). It is known that a major fault consists of a large main rupture accompanied by minor ruptures (Seminsky, 2003), so that the distribution of anomaly axes as indicators of ruptures of different ranks is frequently complicated (Tyapkin and Kivelyuk, 1982; Trofimenko, 2010).

Our analysis of gravity and magnetic fields, the decomposition into a regional and a local components, and the identification of anomaly axes were carried out using the COSCAD 3D program developed by A.V. Petrov (Petrov et al., 2010). The multifunctional COSCAD 3D program is a tool for a full statistical, spectral-correlation, and gradient analyses of gravity and magnetic fields. The program uses linear optimizing filters that decompose a field into components, eliminate trends, enable a correct estimation of anomaly shape, and estimate the depths of anomaly-producing bodies. The detection algorithms can detect

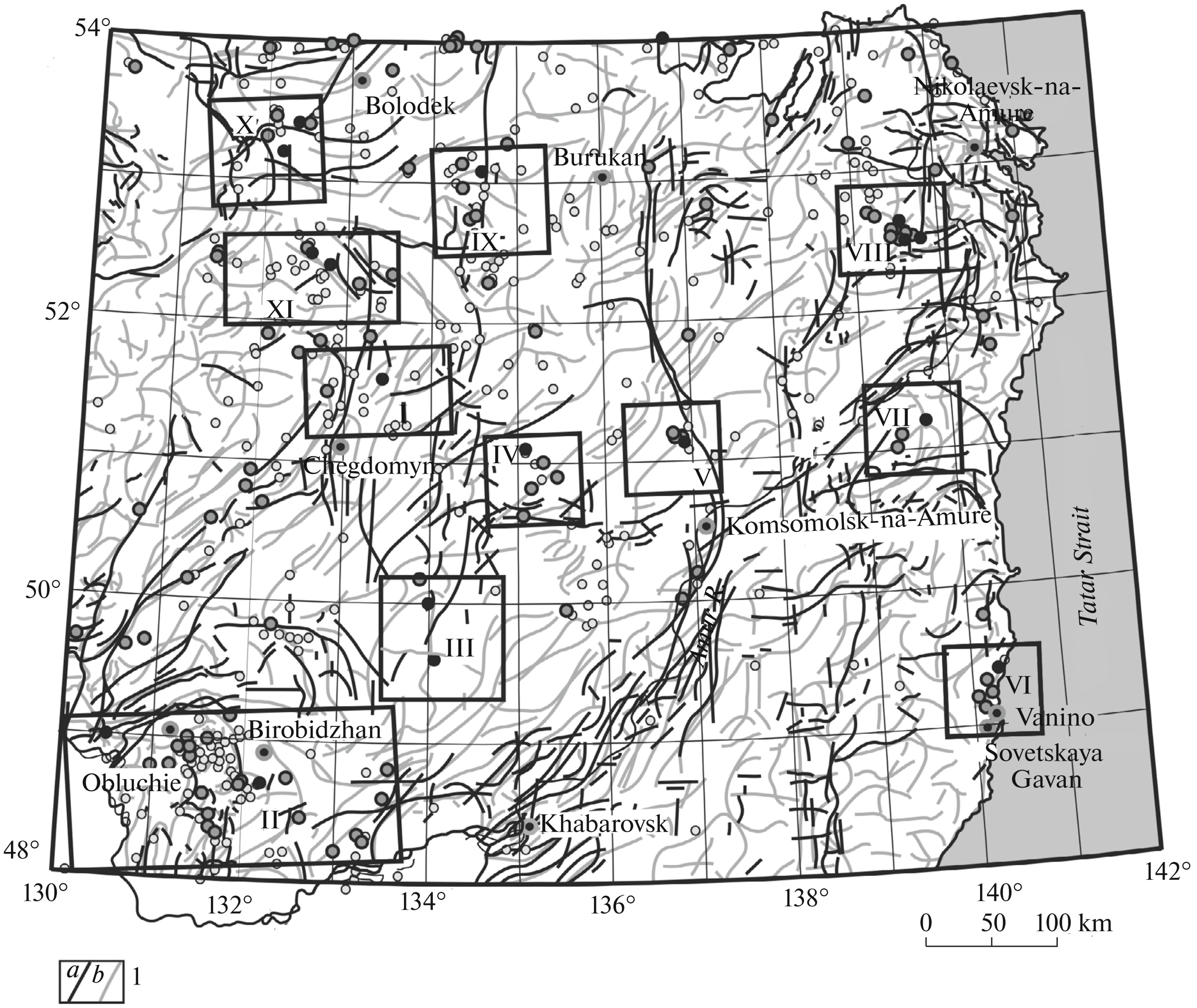

Fig. 3. The axes of gravity anomalies. (1) Axes of gravity anomalies (*a* regional anomalies, *b* local anomalies of the first order). For other explanations see Fig. 1.

linear anomalies, which is important for the study of tectonic faults.

The features of the structure of seismoactive zones was studied based on data derived from deep seismic prospecting using deep seismic sounding, converted earthquake waves, and magnetotelluric sounding methods (Kaplun, 2004; Kaplun and Malyshev, 2010; Bormotov and Merkulova, 2012). Our profiles of deep surveying had earthquake data collected from 100-km bands on both sides of a profile.

AN ANALYSIS OF FAULT TECTONICS AND DEEP STRUCTURE OF SEISMOACTIVE ZONES IN THE PRIAMURYE REGION

Zone I. The $M \geq 5$ earthquakes occurred in the zone of dynamic influence due to the Tastakh fault striking nearly north–south (see Fig. 1). Apart from nearly north–south strikes, the axes of the gravity and magnetic anomalies also strike nearly east–west and northeast (Figs. 2, 3). The $M \geq 5$ earthquakes occurred in a fault zone traceable down to a depth of 30 km as shown by deep seismic sounding data; that zone bounds a low velocity inhomogeneity in the middle crust in the depth range 17–22 km (Fig. 4).

Zone II. This seismic zone is controlled by major regional faults striking northeast, the Ushu–Kharpi and the Amgun, with a network of considerably shorter faults striking in different directions between these two major faults (see Fig. 1). One of the $M \geq 5$ earthquakes occurred near the Amgun fault. Another large earthquake was confined to the Pompei (Bidzhan) fault striking nearly east–west. The smaller $M < 5$ earthquakes concentrated along the nearly east–west Pompei fault and the northeast *Chángchūn* and Ditur faults.

The data obtained from converted earthquake waves show that this extensive seismoactive area was formed where a deep-seated steeply-dipping zone

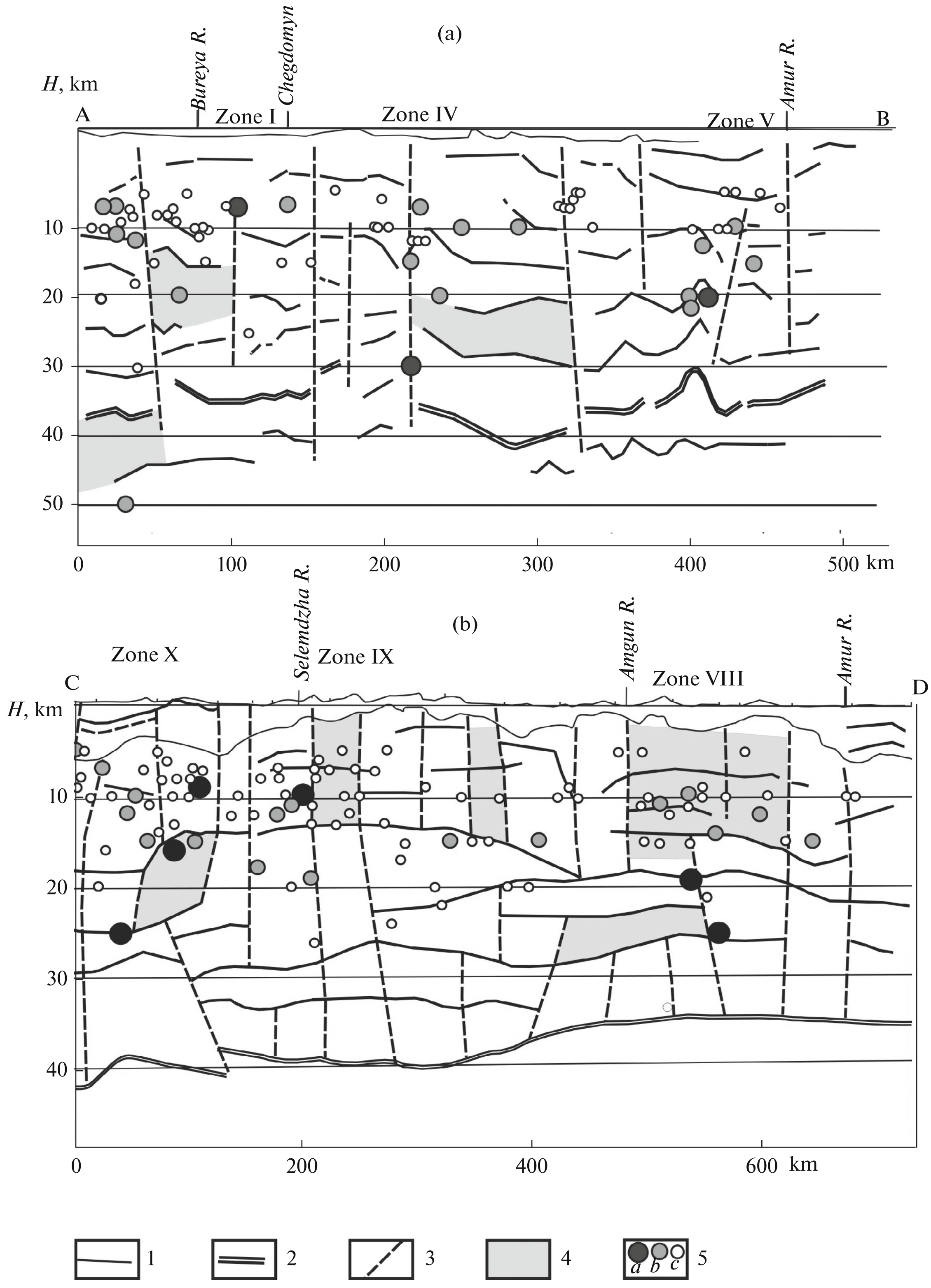

Fig. 4. The results of deep seismic prospecting using the deep seismic sounding method. (a) AB profile, (b) CD profile. (1) seismic interfaces; (2) Moho; (3) faults identified from seismic data; (4) low velocity regions after (Bryansky, 1992); (5) earthquakes (*a* $M \geq 5$, *b* $5 < M \geq 4$, *c* $4 < M \geq 3$).

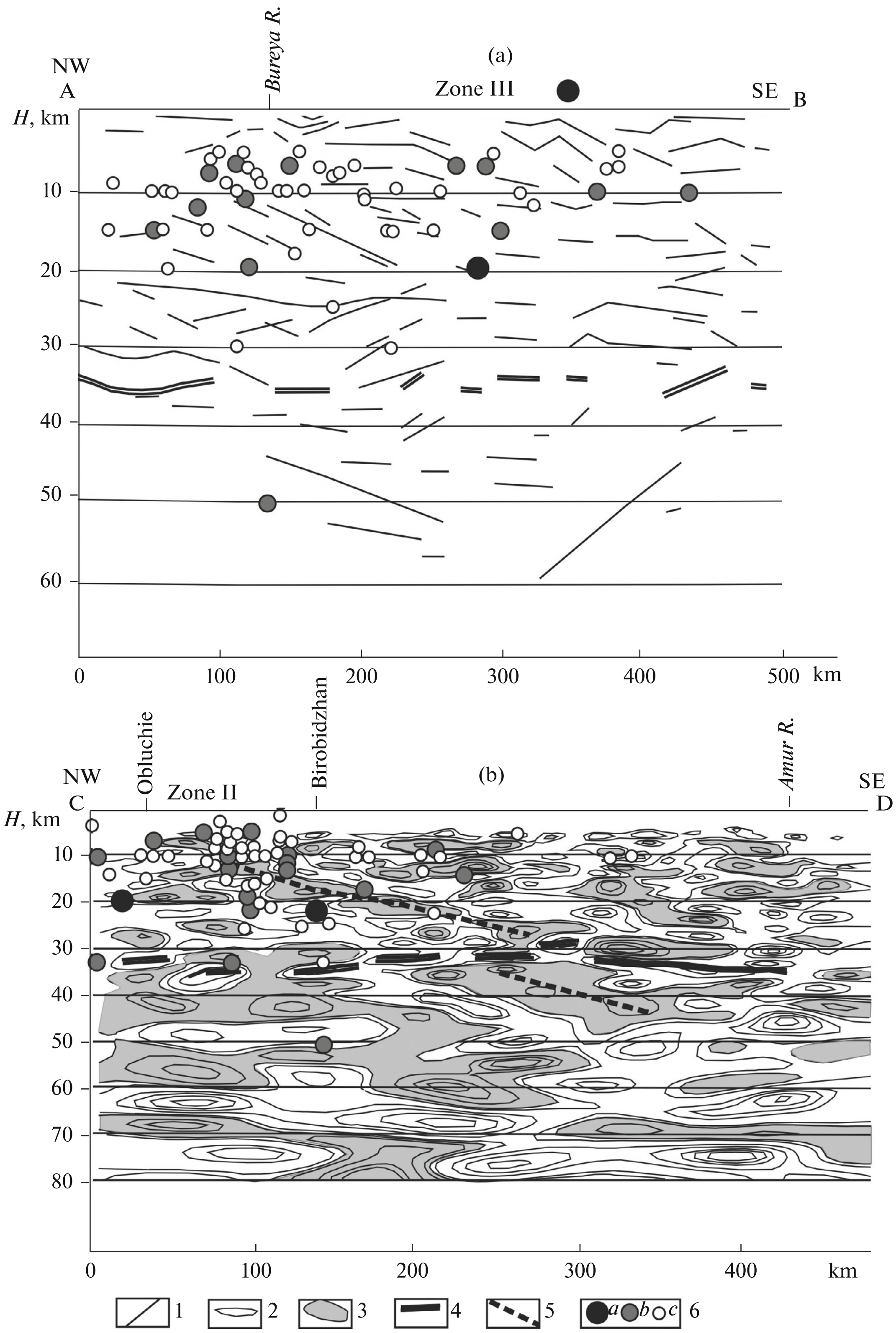

Fig. 5. The results of deep seismic prospecting using the method ECWM. (a) AB profile; (b) CD profile (Bormotov and Merkulova, 2012). (1) conversion interfaces; (2) isolines of the cumulative density distribution of conversion and reflection points; (3) low velocity regions; (4) Moho; (5) dipping detachment surface; (6) earthquakes (*a* $M \geq 5$, *b* $5 < M \geq 4$, *c* $4 < M \geq 3$). One earthquake is shown above the line of measurement, since its depth of focus has not been determined.

exposed at the surface as traceable by low velocity anomalies (Fig. 5).

Zone III. The epicenters of two $M \geq 5$ earthquakes lie in the zone of dynamic influence due to the Ulikan fault. An analysis of the axes of gravity and magnetic anomalies showed that the $M \geq 5$ earthquakes were confined to an intersection of nearly north–south, nearly east–west, and northeast striking faults.

According to the data obtained from conversions of earthquake waves, both of these earthquakes occurred in a juncture area of seismic interfaces dipping at different angles in the mantle (see Fig. 5a). Further east, smaller $M < 5$ earthquakes were confined to seismic interfaces in the upper crust, with the dip of these interfaces consistent with that of the upper mantle interface (see Fig. 5).

Zone IV. The earthquakes are confined to the termination of the northeast striking Duki fault whose direction is consistent with the local gravity anomalies. Axes of the magnetic anomalies strike northwest at the location. One notes a clearly displayed confineness of small $5 > M \geq 4$ earthquakes to the northwest striking axes of magnetic anomalies. According to deep seismic sounding data, the seismoactive zone includes a nearly vertical fault that extends throughout the crustal thickness and penetrates into the upper mantle. This fault controls a low velocity inhomogeneity at depths of 20–25 km (see Fig. 4a). According to magnetotelluric sounding data, the earthquake occurred above a nearly vertical low resistivity inhomogeneity in the upper mantle (line I in Fig. 6).

Zone V. The $M \geq 5$ earthquakes occurred in the zone of the Kur northeast striking fault, consistent with the axes of most local gravity anomalies. The magnetic anomaly axes in the area of earthquake clustering strike both nearly east–west and nearly north–south. Further southeast, the axes of small magnetic anomalies extend northwest.

The deep seismic sounding results obtained for the AB profile provide evidence of an inclined fault whose zone of dynamic influence forms a seismoactive zone (see Fig. 4a). According to magnetotelluric sounding data, the $M \geq 5$ earthquake was controlled by a low resistivity inhomogeneity that extends 110 km depth (line II in Fig. 6).

Zone VI. The zone of earthquake clustering is situated on the Tatar Strait where no regional faults have yet been identified. In addition to nearly north–south striking anomalies, there is a magnetic anomaly that strikes nearly east–west and gravity anomalies striking northeast.

Zone VII. There are no faults near the seismic zone. An $M \geq 5$ earthquake is confined to an intersection of nearly north–south and northeast striking gravity anomalies. The magnetic field has nearly east–west and northeast striking anomalies, in addition to those described above. According to magnetotelluric sounding data, the seismoactive zone is located in close proximity to deep inclined interfaces exposed at the surface. One of these interfaces flattens out at a depth of 160 km, while two other anomalies control a shallow-dipping inclined zone of lower resistivity extending from depths of 65–70 km to 25 km (Fig. 7).

Zone VIII. A zone of earthquake clustering is noted at the intersection of the Vyun nearly north–south fault and the Bichi–Amur northeast striking fault. According to deep seismic sounding data, the $M \geq 5$ earthquakes are clustered on a gently-dipping fault identified from deep seismic sounding surveys at depths of 15 to 35 km that controls a low velocity inhomogeneity at depths of 23–26 km in the middle crust (see Fig. 4b). In the upper crust, the seismoactive zone comprises nearly vertical faults bordering a low velocity area. According to magnetotelluric sounding data, the zone of higher seismicity was formed in a low resistivity (200–500 Ohm) area in the upper crust (MTS 82), while the resistivity in neighboring segments exceeds 1000 Ohms (MTS 103, 111). The resistivity decreases to 20–50 Ohms at depths of 25–40 km (see Fig. 7).

Zone IX. The earthquake clusters are observed between major nearly east–west regional faults, that is, the Tugur and the Paukan faults. The earthquakes in the zone align in a nearly north–south direction, in agreement with the nearly north–south direction of the regional gravity anomaly. The $M \geq 5$ earthquake is confined to an intersection of the axes of smaller local magnetic and gravity anomalies striking in different directions, nearly north–south, northeast, and nearly east–west. According to deep seismic sounding surveys, the $M \geq 5$ earthquake occurred on the nearly vertical fault that controls the low velocity inhomogeneity in the upper crust down to a depth of 15 km (see Fig. 4b).

Zone X. The zone includes earthquakes occurred at the intersection between the Tuksi nearly east–west regional fault and northeast striking faults (the Selemdzha and the Uligdan). This direction of the regional fault is consistent with that of the axes of magnetic anomalies. The axes of regional gravity anomalies in that zone also have nearly northsouth and northwest strikes, in addition to the two directions described above. According to deep seismic sounding data, the seismoactive zone includes a deep-seated fault that is nearly vertical in the upper crust and dips in the lower crust; the fault controls a low velocity inhomogeneity in the middle crust (see Fig. 4b).

Zone XI. Two collocated $M \geq 5$ earthquakes form, along with smaller earthquakes, a northwest striking zone, parallel to the South Tukuringra (Paukan) regional fault, which probably lies in the zone of dynamic influence of the fault. The northwest orientation of the zone of earthquake clustering coincides with that of most magnetic and gravity anomalies. An analysis of the gravity field shows that the zone was formed in an area where the northwest and northeast striking axes intersect.

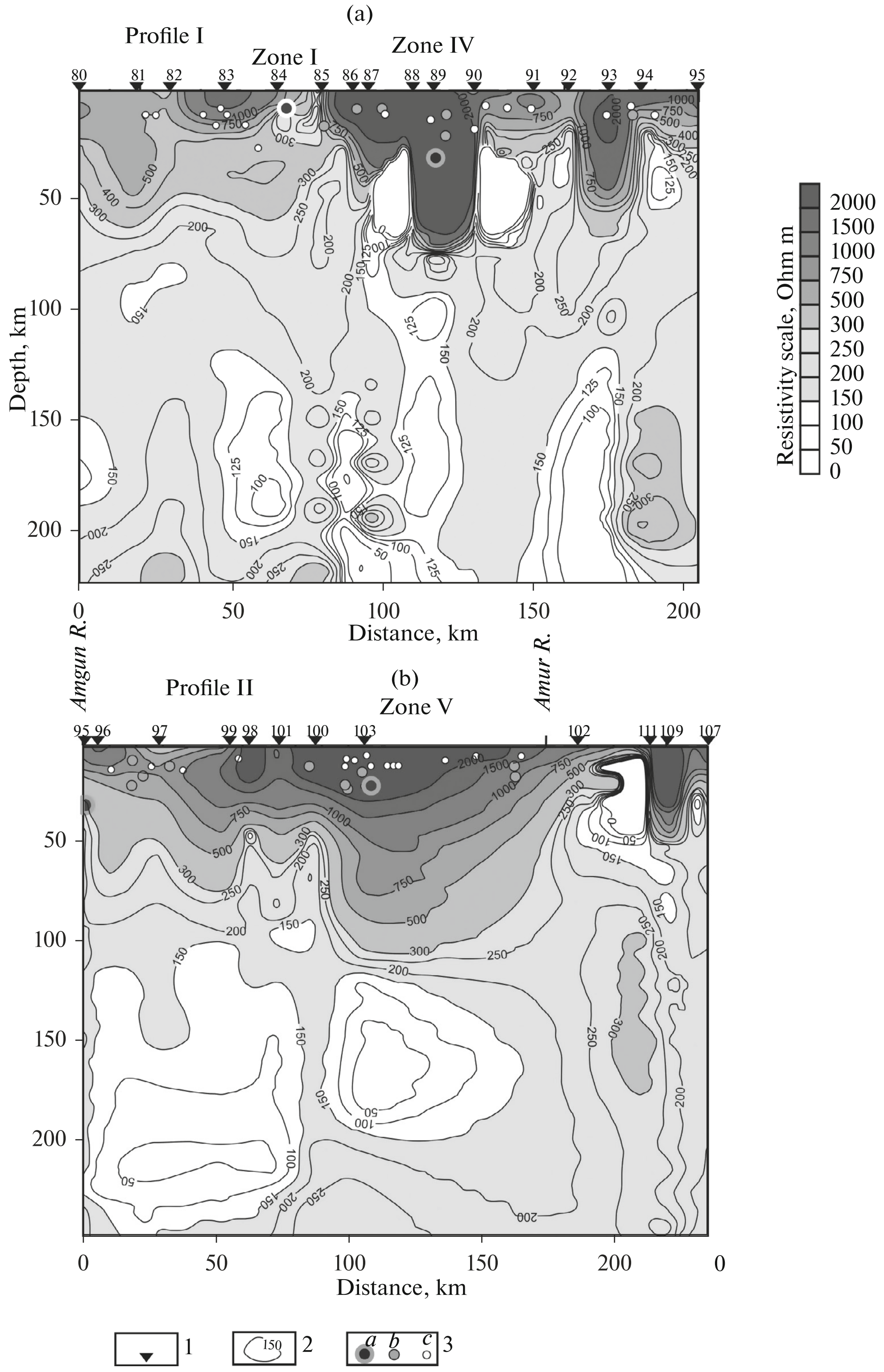

Fig. 6. The results of deep surveying using the MTS method (Kaplun, 2004). (1) MTS stations; (2) resistivity isolines, Ohm; (3) earthquakes (*a* $M \geq 5$, *b* $5 < M \geq 4$, *c* $4 < M \geq 3$).

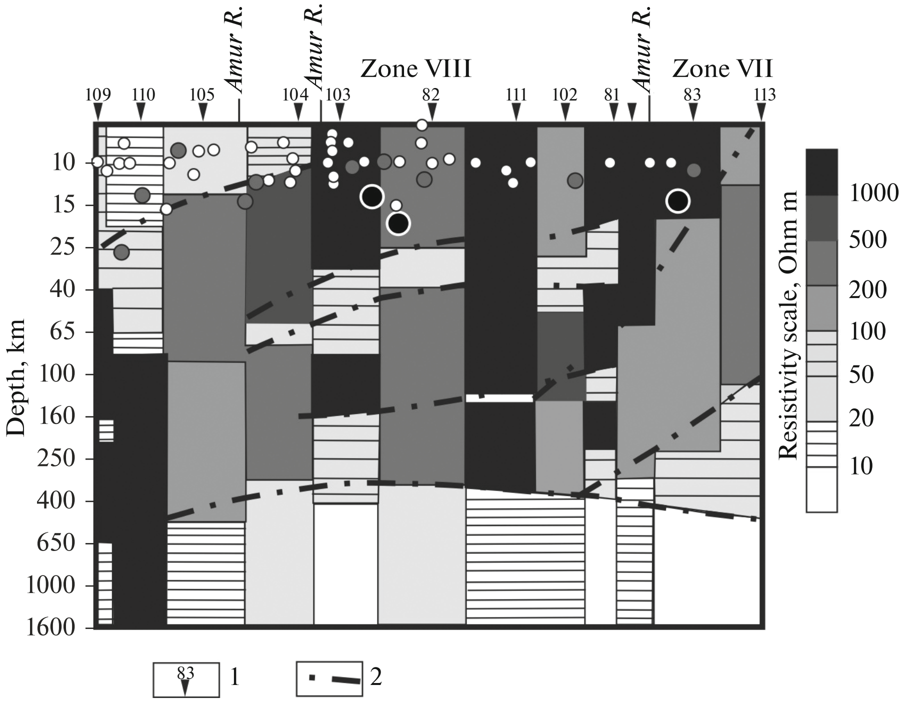

Fig. 7. The results of deep surveying using the MTS method on profile III (Kaplun et al., 2010). (1) MTS stations; (2) boundaries of geoelectric layers. For other explanations see Fig. 6.

RESULTS AND DISCUSSION

An analysis of regional faults and the locations of $M \geq 5$ earthquakes showed that most seismoactive zones are confined to regional faults; however, there are two cases where no such relationship has been identified (zones VI and VII). There is no doubt that intersections of faults are important factors in earthquake localization, but the fact that the seismic zones are confined to intersections of regional faults identified from geological evidence is uncertain, being well-defined in only two cases (zones X and VIII). The earthquake clustering zones are mostly localized at intersections of regional faults with the magnetic and gravity anomaly axes that indicate the participation of faults of different orientations in these intersections (zones V, IV, II, and III). As an example, apart from nearly east–west anomalies consistent with the direction of the Ulikan fault, zone III also includes nearly east–west gravity anomalies. In zone IV, the magnetic field shows northwest striking anomalies, in addition to the northeast gravity anomalies that coincide with the Duki fault orientation. In two cases the seismoactive zones are not found to be confined to regional faults and do not take an active part in the intersections, thereby indicating the presence of hidden faults and ruptures of different ranks in the lithosphere of the region, which can be identified from axes of gravity and magnetic anomalies.

The formation of zones of more intense fracturing is due both to ancient faults and ruptures striking nearly north–south and nearly east–west and to northwest striking anomalies that are indicators of younger faults. It can therefore be asserted that the formation of seismoactive zones is affected by deep fragmentation and fracturing of the crust due to faults of different ranks.

However, it should be noted that there are intersections, both of anomaly axes and regional faults, where no earthquakes occur at the present time. The lack of seismicity at the intersections of faults and ruptures can be explained by healing, i.e., strength rehabilitation of the rock underwent destruction processes. In addition to field surveys, experimental studies have been carried out to consider various aspects of this phenomenon; as well instrumental evidence has been obtained corroborating the strengthening of a fault after an earthquake (Ruzhich et al., 1990; Medvedev et al., 2014; Kocharyan, 2014). Mechanisms have been proposed to explain strength rehabilitation and healing of microcracks due to earthquakes of different intensity (Kocharyan, 2014). It is that, apart from healing, the lack of seismicity at intersections of faults and hidden ruptures can be explained by other factors that affect seismicity.

According to deep seismic sounding and conversions of earthquake waves, $M \geq 5$ earthquakes in the eastern Priamurye region have been recorded both in inclined fault zones (zones II and V) and along subvertical faults (zones I, IV, and IX), as well as faults that are subvertical at the top and inclined in the lower part (zones VIII and X). The inclination of a fault probably slightly affects its seismic activity in the Priamurye region.

Deep geophysical studies showed that the present-day seismicity in the Priamurye region is affected by deep faults that generally extend throughout the crustal thickness and penetrate into the mantle. The influence of mantle processes on seismicity in the study area is demonstrated by results from magnetotelluric sounding and the method of converted waves from earthquakes. The MTS profile I runs along collocated faults (the Hinggan and the Amgun) striking northeast (see Fig. 6). It can be seen on the geoelectric section that the structure of different segments of the collocated faults is different, both in the crust and the upper mantle. The $M \geq 5$ earthquakes (zones I and IV) occurred above subvertical low-resistivity inhomogeneities in the upper mantle that extend from 120 km depth in the former case and from 100 km in the latter. A single earthquake of magnitude below 5 has occurred above the third inhomogeneity. The other MTS profile (profile II) crosses the northeast striking Kur fault. Seismoactive zone V is confined to a low-resistivity inhomogeneity at a depth of 110 km in the upper mantle. The participation of mantle processes in the formation of seismoactive crustal structures is corroborated by studies in other intraplate seismic regions: deformation processes involve the entire lithosphere rather than the crust only (Ulomov, 1993; Petrishchevsky, 2007; Dolginov et al., 2011; Moroz et al., 2015).

Crustal seismic interfaces around faults in a seismoactive zone can be dipping and can experience ruptures and displacement. The Moho interface can also be disturbed by ruptures and displacements (see Fig. 4, zones IV and X). The behavior of seismic interfaces near seismoactive faults occasionally involves sharp dome-shaped flexures that complicate the behavior of seismic interfaces within the crust and disturb the behavior of the Moho (see Fig. 4, zone V). Breaks in the Moho and its dome-shaped flexures are treated by researchers as indication of mantle fluid intrusion into the crust and its degassing (Belyavsky and Rakitov, 2012; Rudnitskaya et al., 2013). Similar features have been found in the focal zones of large earthquakes. The geological–geophysical model for the focal zone of the Altai earthquake (2003, $M = 7.3$) involves a subsidence of the Moho from a depth of 45 km to 55 km and an increase in resistivity by two orders of magnitude in a zone adjacent to the focal area (Kadurin et al., 2013).

According to the ECWM, the crust around seismoactive zone III is saturated with conversion interfaces whose dips are consistent with the dip of the seismic interface in the upper mantle in the depth range 40–50 km (see Fig. 5c). The $5 < M \geq 4$ and $4 < M \geq 3$ earthquakes are confined to dipping seismic interfaces or form dipping linear zones that seem to be continuation of crustal dipping interfaces. The $M \geq 5$ earthquakes occur above the junction of two dipping interfaces in the mantle. Dipping seismic interfaces in the mantle are thought to be related to mantle zones that flatten out toward low velocity areas (Pavlenkova, 1996, 2011). A similar situation is typical in areas of large earthquakes in the Caucasus and in the Koryak region (Kadurin et al., 2013). The crust in the focal zones of these seismoactive regions is saturated with seismic conversion interfaces that are characterized by breaks and dips, thus creating the impression that the medium has undergone faulting there. In these regions researchers have established a close relationship between the earthquake focal zones and deep inclined faults whose roots are in the mantle; these are also considered to serve as supply canals for fluids to penetrate from the mantle into the crust (universal fluid conductors) (Kadurin et al., 2013). According to the existing concepts, the lower boundary of penetration of faults into the mantle is suggested to be the top of the asthenospheric layer, because deep faults can exist in solid rocks only (Bondur et al., 2016). In the case of major mantle gently dipping fault zones, the seismoactive zones are formed in Piamurye as close to their exposure at the surface (see zone II in Fig. 5 and zone VII in Fig. 7) so above mantle inhomogeneities toward which they flatten out (see zone III in Fig. 5 and zone VIII in Fig. 7).

The great depths of seismoactive faults in the eastern Priamurye region and their features such as displacements of the Moho interface, the presence of dome-shaped and dipping seismic interfaces, suggest that they are faults which conduct fluids from the mantle into the crust. The fluid saturation is also confirmed by the fact that seismoactive faults frequently bound low velocity inhomogeneities in the crust detected from deep seismic sounding, or that seismoactive zones lie above low resistivity areas inferred from magnetotelluric sounding in the upper mantle. Lower resistivity and low velocity zones provide evidence of a fluid in these (Kissin, 2001, 2015). Geochemical evidence has been acquired that shows the presence of mantle-derived fluids in the focal zones of large earthquakes in seismoactive regions (Kopnichev and Sokolova, 2005).

Indirect evidence for fluid saturation in seismoactive zones of the Priamurye region is provided by a high correlation between earthquakes and the axes of regional magnetic anomalies. As an example, zone IV shows a clearly displayed correspondence between the $M \geq 4$ earthquakes and the northwest orientation of magnetic anomalies. The magnetic anomalies indicate the locations of numerous dikes of various composition and age, vein and fissure zones that are saturated with hydrothermal fluids, which reflect the movement of fluids during different time intervals. The authors suggest that maps of the magnetic field can illustrate the interaction between the crust and the deep mantle, as well as other aspects of Earth dynamics; they can also provide some information which allows for determining the locations of future large earthquakes (Soloviev et al., 2016).

The data on the seismoactive zones as canals for fluids moving from the mantle explain the fact that the locations of seismoactive zones do not invariably correlate with faults exposed at the surface. Fluids can move along fractured and disintegrated zones formed due to ancient processes and are permeable at present. In areas where permeable zones are absent, the penetration of mantle fluids into the crust results in the structural and metamorphic transformations of rocks that reduce rock strength; this can be regarded as the initial phase in the formation of a new fault (Rebetsky, 2009). Certain seismoactive zones in the Priamurye region originate due to participation of young northwest striking faults that do not form major faults at the surface. The faults of this orientation are probably at the formation stage in the Priamurye region.

In the opinion of many researchers, the seismicity in intraplate areas, and the Priamurye region is one, is due to strain waves generated by geodynamic processes at plate boundaries (Sherman et al., 2013; Rudakov, 2014; Trofimenko et al., 2015). When moving from the source of their excitement, strain waves cause unstable states in disturbed volumes of a geological medium. Zones of high deep permeability that can conduct fluids will probably act as “rheologic traps” that capture the energy of strain waves and transform it into earthquakes. The fluid saturation in the seismoactive zones of the eastern Priamurye region that act as “rheologic traps” correlates with processes at plate boundaries as sources of strain waves (Sherman, 2009). Fluids also take part in these processes. The seismicity of the Priamurye region is affected by zones of interaction between the Indian and Eurasian plates (the Pamir–Hindu-Kush area) and the subduction of the Pacific plate (*Geodinamika* ..., 2006; Stepashko, 2011; Trofimenko et al., 2015). The zones of earthquake clustering at depths of 100 and 200 km in the Hindu Kush are argued to be related to the physico-chemical processes induced by fluids (Pavlenkova, 2011). An upward migration of earthquake hypocenters has been detected in the Pacific region (the Kuril–Kamchatka and the Japanese segment of the subduction zone); the migration starts from depths of 600–700 km and is accompanied by the migration of fluids into the crust (Molchanov, 2011).

CONCLUSION

Our study has shown that hidden faults have contributed greatly to the formation of the seismoactive zones of the eastern Priamurye region, in addition to faults identified from geological data. The hidden faults combined with regional faults form intersections, which are regions of intense faulting and permeability, and which are presently active. Therefore, there is the need to further develop methods for identification of hidden faults with subsequent classification of these into main faults and faults of lower ranks based on geophysical anomalies and other evidence. The results of geophysical surveys at depth using deep seismic sounding, the method of converted waves from earthquakes, and MTS, point to the participation of mantle processes in activation of earthquake slip episodes in the eastern Priamurye region. Geophysical data are used to find indirect indications of fluid saturation in the seismoactive zones: the control of low resistivity and low velocity inhomogeneities, breaks and displacement of the Moho, dome-shaped flexures of crustal interfaces, and the numerous conversion interfaces. The role of mantle processes and the revealed indirect evidence for fluid saturation allow us to consider the seismoactive zones in the eastern Priamurye region as the canals providing supply of mantle fluids into the crust.

FUNDING

This work was performed as part of the State Assignment for the Kosygin Institute of Tectonics and Geophysics, Far Eeast Branch, Russian Academy of Sciences with partial support by the Russian Science Foundation, project no. 16-17-00015.

REFERENCES

Belyavsky, V.V. and Rakitov, V.A., Fluid saturation in the focal zones of earthquakes in the Altai–Sayan region, *Geofizika,* 2012, no. 3, pp. 40–47.

Bondur, V.G., Garagash, I.A., Gokhberg, M.B., and Rodkin, M.V., The evolution of stresses in southern California based on a geomechanical model and current seismicity, *Fizika Zemli,* 2016, no. 1, pp. 120–132.

Bormotov, V.A. and Merkulova, T.V., The Cenozoic phase in the evolution of the northern branch of the Tang-Lu–Sea–of-Okhotsk rift system: Deep structure and seismic geodynamics, *Tikhookean. Geol.,* 2012, vol. 31, no. 1, pp. 26–41.

Blinova, T.S., Disturbances in the Earth’s crust and their role for the prediction of geodynamically unstable zones in the western Urals region, *Izv. Tomsk Polytech. Univ.,* 2003, vol. 306, no. 4, pp. 44–50.

Bryansky, L.I., Density structure of the Earth’s crust and upper mantle in the Soviet part of the Asian margin: Problems and results of gravity modeling, in *Problemy tektoniki, energeticheskie i mineralnye resursy Severo-Zapadnoi Patsifiki* (Problems of Tectonics, Energy and Mineral Resources in the Northwest Pacific Region), Khabarovsk: Priamursky Filial Geograficheskogo Obshchestva DVO AN SSSR, 1992, Part 2, pp. 9–18.

Bulin, N.K., Relationships between the seismicity in the northern and central areas of the Russian Platform to seismic velocity anomalies in the lithosphere and geodynamics of adjacent regions, *Litosfera,* 2004, no. 1, pp. 21–30.

Vashchilov, Yu.Ya. and Kalinina, L.Yu., Deep-seated faults and lineaments, and the location of earthquake epicenters in the Russian Northeast on land, *J. Volcanol. Seismol.,* 2008, vol. 2, no. 3, pp. 158–169.

Geodinamika, magmatizm i metallogeniya Vostoka Rossii (The Geodynamics, Magmatism, and Metallogeny in the Russian East), Khanchuk, A.I., Ed., Vladivostok: Dalnauka, 2006, Book 1.

Gufeld, I.L., Matveeva, M.I., and Novoselov, O.N., Why can't we predict large crustal earthquakes? *Geodinamika i Tektonofizika,* 2011, vol. 2, no. 4, pp. 378–415.

Dolginov, E.A., Kao, T.D., Le, V.Z., et al., On a possible deep nature of a seismic anomaly in northwestern Vietnam and its relationship to the late Jurassic–Early Cretaceous reactivated "hot spot" system, *Izv. Vuzov. Ser. Geologiya i Razvedka,* 2011, no. 2, pp. 11–16.

Zabrodin, V.Yu., Rybas, O.V., and Gilmanova, G.Z., *Razlomnaya tektonika materikovoi chasti Dalnego Vostoka Rossii* (The Fault Tectonics of the Mainland Russian Far East), Vladivostok: Dalnauka, 2015.

Zobak, M.D. and Zobak, M.L., The stress field and intraplate earthquakes in the United States, *JRAS,* 1981, vol. 46, no. 2, pp. 157–181.

Kadurin, I.N., Konovalov, Yu.F., Maukhin, A.V., et al., Developing M.K. Polshkov's ideas on methods of exploration geophysics in application to the study of crustal structure in earthquake-prone areas of Russia, *Geofizika,* 2013, no. 6, pp. 59–64.

Kaplun, V.B., A geoelectric model for the lithosphere of the Komsomolsk and Badzhal ore areas inferred from MTS observations, *Tikhookean. Geol.,* 2004, vol. 23, no. 6, pp. 84–93.

Kaplun, V.B. and Malyshev, Yu.F., Deep structure of the Nizhneamur unique structure, in *Problemy seismichnosti i sovremennoi geodinamiki Dalnego Vostoka i Vostochnoi Sibiri* (Problems of Seismicity and Present-Day Geodynamics: The Russian Far East and Eastern Siberia, Proc. scientific symp., June 1–4, 2010, Khabarovsk: ITiG bv/ Kosygina DVO RAN, 2010, pp. 32–34.

Karakin, A.V., Kuryanov, and Pavlenkova, N.I., *Razlomy, treshchinovatye zony i volnovody v verkhnikh sloyakh zemnoi obolochki* (Faults, Cracked Zones, and Waveguides in the Upper Layers of the Terrestrial Shell), Moscow: VNIIgeosistem, 2003.

Kissin, I.G., A fluid system and geophysical inhomogeneities in the consolidated continental crust, *Vestnik OGGGGN RAN. Ser. Elektrichestvo,* 2001, vol. 17, no. 2, pp. 1–22.

Kissin, I.G., *Flyuidy v zemnoi kore: geofizicheskie i tektonicheskie aspekty* (Fluids in the Earth's Crust: Geophysical and Tectonic Aspects), Moscow: Nauka, 2015.

Kopnichev, Yu.F. and Sokolova, I.N., The ascent of mantle fluids in the rupture zones of large earthquakes and in major fault zones: Geochemical evidence, *Vestnik NYaTs RK,* 2005, Issue 2, pp. 147–155.

Kocharyan, G.G., The scale effect in seismotectonics, *Geodinamika i Tektonofizika,* 2014, vol. 5, no. 3, pp. 353–385.

Kocharyan, G.G., Kishkina, S.B., and Ostapchuk, A.A., The earthquake-generating width of a fault zone, *Dokl. Akad. Nauk,* 2011, vol. 437, no. 2, pp. 254–257.

Kushnir, A.N. and Burakhovich, T.K., Anomalies of electrical conductivity and intraplate earthquakes in the western Ukrainian Shield and the Volyn–Podolsk plate, *Geofiz. Zhurn.,* 2012, vol. 34, no. 4, pp. 157–165.

Letnikov, F.A., Synenergetics of processes occurring in zones of deep faults, in *Proc. All-Russia conference devoted to the 70-year jubilee of the Chair of Dynamic Geology "Dynamic Geology in the 21st Century: Problems and Vistas",* Moscow, November 22–23, 2013, Moscow: PERO, 2013, pp. 54–56.

Lukk, A.A. and Yunga, S.L., *Geodinamika i napryazhenno-deformirovannoe sostoyanie litosfery Srednei Azii* (Geodynamics and the State of Stress and Strain in the Lithosphere of Middle Asia), Dushanbe: Donish, 1988.

Makarov, V.I. and Shchukin, Yu.K., Estimating the activity of hidden faults, *Geotektonika,* 1979, no. 1, pp. 96–109.

Medvedev, V.Ya., Ivanova, L.A., Lysov, B.A., et al., An experimental study in the decompression, permeability, and healing of silicate rocks in fault zones, *Geodinamika i Tektonofizika,* 2014, vol. 5, no. 4, pp. 905–917.

Moroz, Yu.F., Moroz, T.A., and Loginov, V.A., The deep structure of the Olyutorskii earthquake rupture zone in the Koryak Upland: Geophysical evidence, *J. Volcanol. Seismol.,* 2015, vol. 9, no. 3, pp. 197–209.

Pavlenkova, N.I., The role of fluids in generating seismic stratification in the crust, *Fizika Zemli,* 1996, no. 4, pp. 51–61.

Pavlenkova, N.I., The rheologic properties of upper mantle in North Eurasia and the nature of regional boundaries as inferred from observations of superlong lines, *Geologiya i Geofizika,* 2011, vol. 52, no. 9, pp. 1287–1301.

Petrishchevsky, A.M., The relation of seismicity to lithospheric density inhomogeneities in the Russian Far East, *J. Volcanol. Seismol.,* 2007, vol. 1, no. 6, pp. 410–420.

Petrov, A.V., Yudin, D.B., and Syueli, Kh., The processing and interpretation of geophysical data using probabilistic statistical approaches by theCOSCAD 3D computer technology, *Vestnik KRAUNTs, Nauki o Zemle,* 2010, no. 2, pp. 126–132.

Rebetsky, Yu.L., Stresses, strength, internal structure, and metamorphic transformations in the body of a fault, in *Tektonofizika i aktualmye voprosy nauk o Zemle* (Tectonophysics and Urgent Issues in Earth Sciences), Proc. All-Russia conference, Moscow: IFZ RAN, 2009, vol. 2, pp. 55–57.

Rogozhin, E.A., The tectonics of zones of large earthquakes, *Ross. Zhurn. Nauk Zemle,* 2000, vol. 2, no. 1, pp. 37–62.

Rudakov, V.P., On the role of geodeformation wave processes in the precursory processes of large earthquakes, *Geofiz. Zhurn.,* 2014, vol. 36, no. 4, pp. 85–93.

Rudnitskaya, D.I., Staroseltsev, V.S., and Salnikov, A.S., Constructing a crustal macromodel using Reapak technology along the 3-DV geotraverse, eastern Siberia, *Geofizika,* 2013, no. 1, pp. 19–26.

Ruzhich, V.V., Medvedev, V.Ya., and Ivanova, L.A., The healing of seismoactive faults and earthquake *Seismichnost Baikalskogo rifta (prognosticheskie aspekty)* recurrence, in (*The Seismicity of the Baikal Rift: Prediction Aspects*), Novosibirsk: Nauka, 1990, p. 44–50.

Rybin, A.K., *Glubinnoe stroenie i sovremennaya geodinamika Tsentralnogo Tyan-Shanya po rezultatam magnitelluricheskikh issledovanii* (Deep Structure and Present-Day Geodynamics of Central Tien Shan Based on Results of

Magnetotelluric Surveys), Moscow: Nauchyi Mir, 2011.

Soloviev, A.A., Gorshkov, A.I., and Soloviev, A.A., The application of data from lithospheric magnetic anomalies to the problem of identifying the locations of possible earthquake occurrence, *Fizika Zemli,* 2016, no. 6, pp. 21–27.

Seminsky, K.Zh., *Vnutrennyaya struktura kontinentalnykh razlomnykh zon. Tektonofizicheskii aspekt* (The Internal Structure of Continental Fault Zones: The Tectonophysical Aspect, Novosibirsk: SO RAN, Filial GEO, 2003. Spichak, V.V., The identification of potential earthquake locations from geophysical data, *Fizika Zemli,* 2016, no. 1, pp. 47–56.

Stepashko, A.A., The deep basis of seismotectonics in the Russian Far East: The Amur region and the Maritime Territory, *Tikhookean. Geol.,* 2011, vol. 30, no. 1, pp. 3–15.

Stognii, G.A. and Stognii, V.V., *Geofizicheskie polya vostochnoi chasti Severo-Aziatskogo kratona* (The Geophysical Fields in the Eastern Part of the North Asian Craton), Yakutsk: GUP NIPK Sakhapoligrafizdat, 2005.

Trofimenko, S.V., A tectonic interpretation of a statistical model for the distribution of gravity and magnetic azimuths in the Aldan Shield, *Tikhookean. Geol.,* 2010, vol. 29, no. 3, pp. 64–77.

Trofimenko, S.V., Bykov, V.G., and Merkulova, T.V., Seismicity migration in the zone of convergent interaction between the Amur plate and the Eurasian plate, *J. Volcanol. Seismol.,* 2015, vol. 9, no. 3, pp. 210–222.

Tyapkin, K.F. and Kivelyuk, T.T., *Izuchenie razlomnykh zon geologo-geofizicheskimi metodami* (The Study of Fault Zones Using Geological and Geophysical Methods), Moscow: Nedra, 1982.

Ulomov, V.I., The global orderliness of seismogeodynamic structures and some aspects of seismic zonation and long-term earthquake prediction, in *Seismichnost i seismicheskoe raionirovanie Severnoi Evrazii* (Seismicity and Seismic Zonation of North Eurasia), Moscow: OIFZ RAN, 1993, issue 1, pp. 24–44.

Sherman, S.I., A tectonophysical model of a seismic zone: The Baikal Rift system, *Fizika Zemli,* 2009, no. 1, pp. 8–21.

Sherman, S.I., Bortnyakov, S.A., and Buddo, V.Yu., *Oblasti dinamicheskogo vliyaniya razlomov* (rezultaty modelirovaniya) Areas of Dynamic Influence Due to Faults: A Modeling Study), Novosibirsk: Nauka, 1983.

Sherman, S.I., Strain waves as a triggering mechanism of seismicity in seismic zones of the continental lithosphere, *Geodinamika i Tektonofizika,* 2013, vol. 4, no. 2, pp. 83–117.

Molchanov, O.A., Underlying mechanism of precursory activity from analysis of upward earthquake migration, *Nat. Hazards Earth Syst. Sci.,* 2011, vol. 11, pp. 135–143. www. nat-hazards-earth-syst-sci.net/11/135/2011

Translated by A. Petrosyan