DOI: 10.7343/as-2018-317

Groundwater outflows and fault density spatial relation in the Baikal rift system (Russia)

Relazioni tra sorgenti e densità di faglie nel sistema del Rift Baikal (Russia)

E.A. Kuz'mina, A.V. Novopashina

Riassunto: Nell'ambito del territorio del sistema del Rift Baikal (BRS) (Federazione russa) e il bacino di Barguzin-Baunt, la densità delle faglie attive viene confrontata con la quantità e la temperatura delle sorgenti termali e fredde per identificarne la relazione statistica geospaziale al fine di quantificare i principali fattori che governano lo sviluppo di nuove sorgenti termali. I calcoli statistici mostrano che il numero di sorgenti calde e fredde per unità di superficie aumenta proporzionalmente con il numero di faglie attive. Si è verificato come un'area con densità di faglie attive superiore a quella media sia caratterizzata dal numero massimo di sorgenti termali. Le analisi di correlazione hanno mostrato come il numero di sorgenti di acqua minerale per unità di superficie e la loro temperatura dipendano dal grado di frammentazione della crosta terrestre: le zone a densità di frammentazione ridotta sono caratterizzate da sorgenti termali meno diffuse ma più calde, mentre le zone a maggiore densità di frammentazione sono caratterizzate da sorgenti più diffuse e più fredde, che probabilmente, in un ambiente geologico più discontinuo, derivano dalla diluizione dell'acqua con acque sotterranee superficiali più fredde.

Keywords: *correlation, mineral springs, thermal springs, active faults density, the Baikal rift system.*

Parole chiave: correlazione, sorgenti minerali, sorgenti termali, densità di faglie attive, sistema del Rift Baikal.

Anna Vladimirovna NOVOPASHINA 🖃
Institute of the Earth's Crust, Siberian Branch of RAS
664033, Irkutsk, Lermontov street, 128, Russia
avn_crust@mail.ru

Elena Alexandrovna KUZ'MINA
Institute of the Earth's Crust, Siberian Branch of RAS
664033, Irkutsk, Lermontov street, 128, Russia
selenginsk2007@mail.ru

Ricevuto/*Received*: 18 February 2018-Accettato/*Accepted*: 26 March 2018
Pubblicato online /*Published online*: 30 March 2018

Abstract: *For the Baikal rift system (BRS) territory (Russian Federation) and the Barguzin-Baunt depression branch zone, active faults density is compared with the thermal and cold spring's quantity and temperature to identify the geospatial statistical relationship of those parameters with a view to quantify the main factors connected with base principles study of modern hydrothermal formation. Statistical calculations show that the hot and cold spring's number per unit area increases within the active faults number. It is established that an area with active faults density higher, than the mean value, is characterized by the maximum number of thermal springs. Correlation analysis showed that the number of modern mineral water springs per unit area and their temperature depend on the earth's crust fragmentation degree: zones of reduced density are characterized by rare but hotter thermal springs, and zones of increased density are characterized by numerous and colder thermal vents, which probably connects with water dilution by underground cold waters in a more fractured geological environment.*

Introduction

The Earth's crust in the Baikal hydrogeological region (Russian Federation) has undergone stretching processes resulting in the faults being well permeable to water.

Tectonic fractures such as strikes and strike-slips prevailing in the Baikal rift system and the Barguzin-Baunt depression branch zone are good natural drains that collect water from aquifers (Didenkov 2006, Plyusnin 2008).

Fault zones are considered to be the preferred way of migration of hot liquid (Volpi et al. 2017, Qi et al. 2017) and permeability is proportional to the density of interconnected fractures (Pola et al. 2015).

Both large regional tectonic structures and multiple local young faults (up to 10–15 km long), associated with large tectonic dislocations, play an important role in the groundwater allocation, the transit of groundwater and the process of hydraulic communication between individual aquifers.

The characteristics of crack-vein waters for watered faults zones are fixed by cold and thermal springs with an output of up to 15–20 l/s (near the rivers and foot of terraces), a temperature of 2 to 81°C and mineralization of 0.22–0.3 g/dm^3. (Plyusnin AM 2008).

The high permeability of the geological environment ensures better circulation of thermal waters, and heat flow increases the water's velocity (Plyusnin et al. 2013); therefore, the earth's crust fragmentation degree is one of the main factors of the groundwater's composition formation (Ingebritsen and Gleeson 2017).

DOI: 10.7343/as-2018-317

The earth's crust disturbance can be estimated by a quantitative parameter – the density of active faults (n). Previously, the relationship between fault tectonics and thermal springs, as well as between groundwater outlets localization and the fault structures intersections, for the BRS was noted by Pinneker et al. (1968), Kustov and Lysak. (2000), Shabynin et al. (2002), Plyusnin et al. (2006, 2013), but this interrelationship was not quantified.

In this paper, we try to identify the statistical relationship between the active faults density (n) and natural thermal (temperature is more than 20°C) and cold water spring's parameters: temperature and quantity. The active faults density and spring's parameters are obtained for different geographic scales that make it possible to establish the presence of a connection between tectonic disturbances and hydrothermal manifestations at different levels of detail. The statistical dependences of the active faults density parameter with the number of contemporary fluids and cold springs are calculated. An attempt was also made to identify the connection between the density of the fault network and the temperature of the thermal springs.

Data and Methods

The density of active faults is the number of faults per unit area. In order to avoid fractional values, the number of faults in the pallet cell per unit area has not been divided on cell area.

For the BRS territory, parameter n was calculated on the basis of an active faults digital map (Lunina 2016) (Fig. 1, a) in a 1° x 1° cell with a 0.5° overlap providing a reliable full covering of the main number of faults with lengths not exceeding 100 km and obtaining a sufficient number of faults for statistic calculations. Longer faults fall into several cells, but using a cells bigger than 1° x 1° is undesirable because the number of points for correct interpolation is insufficient.

In the Baikal rift central part, in the water area of Lake Baikal, thermal and cold water outlets are not established, therefore; the comparison of the active faults density parameter with the mineral water outlets is more reliable for the north-western part of the Baikal rift, especially for the Barguzin-Baunt depression branch, where the springs are prevalent (Fig. 1, b).

In order to enlarge the scale for the Barguzin-Baunt area, the parameter n was also obtained in 0.37° x 0.37° cells based on the earth's crust mean thickness in this zone, which corresponds to the active faults propagation depth scale (according to (Matz et al. 2001) the crust thickness in this zone is 41 km or about 0.37°).

The density value refers to the cell center. For establishing the nature of the probability distribution of the fracture density value, the number of cells of each density is calculated and the modal, median and mean values of n (histogram in Fig. 4, a) are determined.

For every density range, the number of springs is obtained, both cold (according to (Pinneker et al. 1968)) and hot (according to (Tkachuk 1957) (histogram in Fig. 4, b).

In both scales (0.37° x 0.37° and 1° x 1°), the number of thermal springs per unit area was counted as an index of subsurface activity. To obtain an indicator of the general watering of tectonic structures, the cold groundwater exits per unit area were also calculated.

For the Barguzin-Baunt depression branch, the values of the maximum and mean hydrothermal water temperature were obtained in the 0.37° x 0.37° cells to avoid excessive temperature values averaging in the 1° x 1° cells.

The advantage of the 1° x 1° pallet cells is the possibility to obtain a sufficient number of springs for the correlation dependencies construction, but the disadvantage is the excessive averaging of the active faults density parameter n.

To establish the connection between the faults density and the number of springs in the pallet cell, correlation dependences were constructed.

The significance of the correlation was determined by using the test statistics of the correlation coefficient significance (t), calculated by the formula:

$$t = \left(0.5 \bullet \ln\left(\frac{1+r}{1-r} - \frac{|r|}{2(n-1)} \right) \sqrt{n-3} \right)$$

where n is the number of points in the sample, and r is the Pearson correlation coefficient. The calculated test statistic ε was compared with the tabulated value of the Student's coefficient in the probability confidence interval 0.95 <p< 0.999. If the estimated value of ε exceeds the table value, a decision of correlation coefficient significance is made.

Results

The active faults density maxima are characteristic for the Tunka and Baikal depressions, the northern part of the Baikal depression, for the jumper between the Verkhneangarsk and Muyakansk depressions, the Muya and Chara depressions, and for the depressions of the Barguzin-Baunt depression branch: Barguzin, Amut and Baunt (see Fig. 1, b). The highest values of density are observed in the Middle Baikal region, Barguzin depression, as well as the jumper between Barguzin and Amut.

The depressions are framed by zones of large active faults, fractured in a high degree by local faults and filled by coarse deposits (depth more then 8000 m in the Baikal depression and from 1000 to 1500 m in other depressions), that creates favorable conditions for filling the earth's crust by underground (Yasko 1982) and atmospheric waters penetrating to the depths, and mixing with those fluids coming from the lower layers to form hot springs (Plyusnin 2008) (Fig. 2, Fig. 3).

Different fracturing and the presence of permafrost characterize hydrogeological massifs as hydrogeological structures with sharp differences in in the rock watercut degree.

The water content of rocks increases from diorites to granites. Proterozoic formations are more waterlogged due to the numerous phases of tectogenesis. Increased watering of

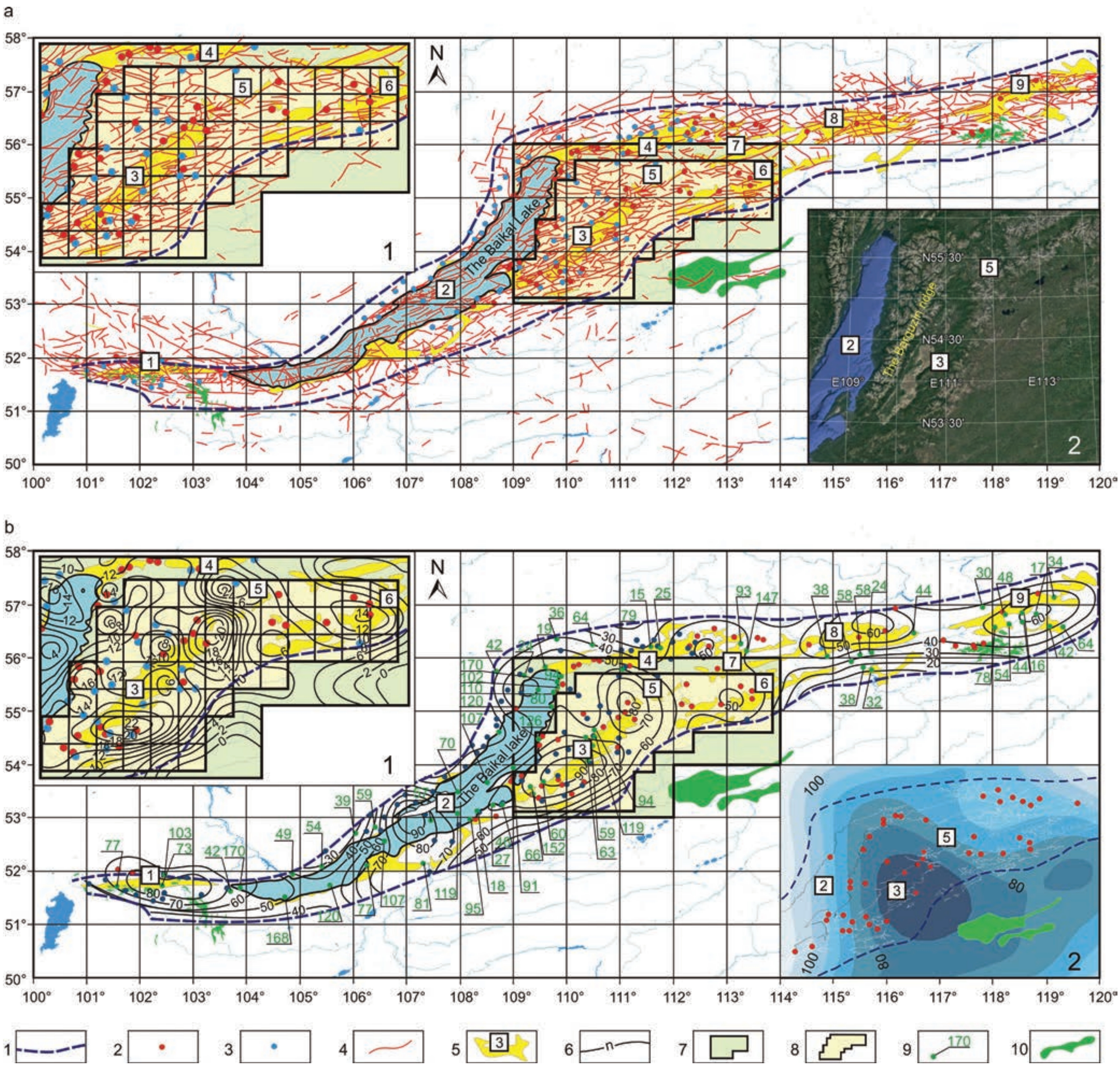

Fig. 1 - The Baikal rift system (Russia) map: a – the map of active faults (according to (Lunina 2016) and springs (points) of the BRS area (cold (up to latitude 114°) according to (Pinneker et al. 1968) and hot according to (Tkachuk 1957)). b – the BRS active fault density map (isolines) for the 1° x 1° cell size and the springs (points). 1 – contour of the BRS. 2 – thermal springs, 3 – cold springs, 4 – active faults, 5 – depressions with their numbers (in squares: 1 – Tunka, 2 – Baikal, 3 – Barguzin, 4 – Verkhneangarsk, 5 – Amut, 6 – Baunt, 7 – Muyakansk, 8 – Muya, 9 – Chara), 6 – isoclines Contour lines of active fault density (n), 7 – The Barguzin-Baunt depression branch polygon contour for 1° x 1° cell size, 8 – The Barguzin-Baunt depression branch polygon contour for 0.37° x 0.37° cell size. 9 – points of heat flux measurements with the marks of values (mW/m^2) by (Golubev 2007, Lysak 2002). 10 – basalt fields. The sidebar 1 of Fig. 1a shows the 0.37° x 0.37° cells at the Barguzin-Baunt depression branch area. The sidebar 2 of Fig. 1a shows the relief of the Barguzin-Baunt depression branch area. The sidebar 1 of Fig 1b shows fault density isolines (n), calculated in 0.37° x 0.37° cells. The sidebar 2 of Fig 1b shows the boundary of the lithosphere-asthenosphere (km) under the Barguzin-Baunt branch (Petit and De´verche`re 2006).

Fig. 1 - Mappa del Sistema del Rift Baikal BRS (Russia): a - Mappa delle faglie attive (da Lunina 2016) e delle sorgenti (punti) dell'area BRS fredde (fino a latitudine 114°), secondo Pinneker et al. (1968), e calde, secondo Tachuk (1957). b - Densità di faglie attive (isolinee) e sorgenti (punti) per celle 1°x1°. 1 – Isolinee del BRS, 2 – Sorgenti termali, 3 – Sorgenti fredde, 4 – Faglie attive, 5 – Bacini e loro numero (nei riquadri: 1 – Tunka, 2 – Baikal, 3 – Barguzin, 4 – Verkhneangarsk, 5 – Amut, 6 – Baunt, 7 – Muyakansk, 8 – Muya, 9 – Chara), 6 – Isolinee della densità di faglie attive (n), 7 – Isolinee del bacino tettonico Barguzin-Baunt per celle 1°x1°, 8 – Isolinee del bacino tettonico Barguzin-Baunt per celle 0.37° x 0.37°, 9 – Punti di misura del flusso di calore con valori (mW/m^2) (Golubev 2007, Lysak 2002), 10 – Campi di lava basaltica.

Il riquadro 1 di Fig.1a mostra le celle 0.37° x 0.37° del bacino tettonico Barguzin-Baunt. Il riquadro 2 di Fig.1a mostra il rilievo bacino Barguzin-Baunt. Il riquadro 1 di Fig.1b mostra le isolinee di densità delle faglie. Il riquadro 2 di Fig.1b mostra il limite litosfera-astenosfera (km) sotto bacino Barguzin-Baunt (Petit et al. 2006).

DOI: 10.7343/as-2018-317

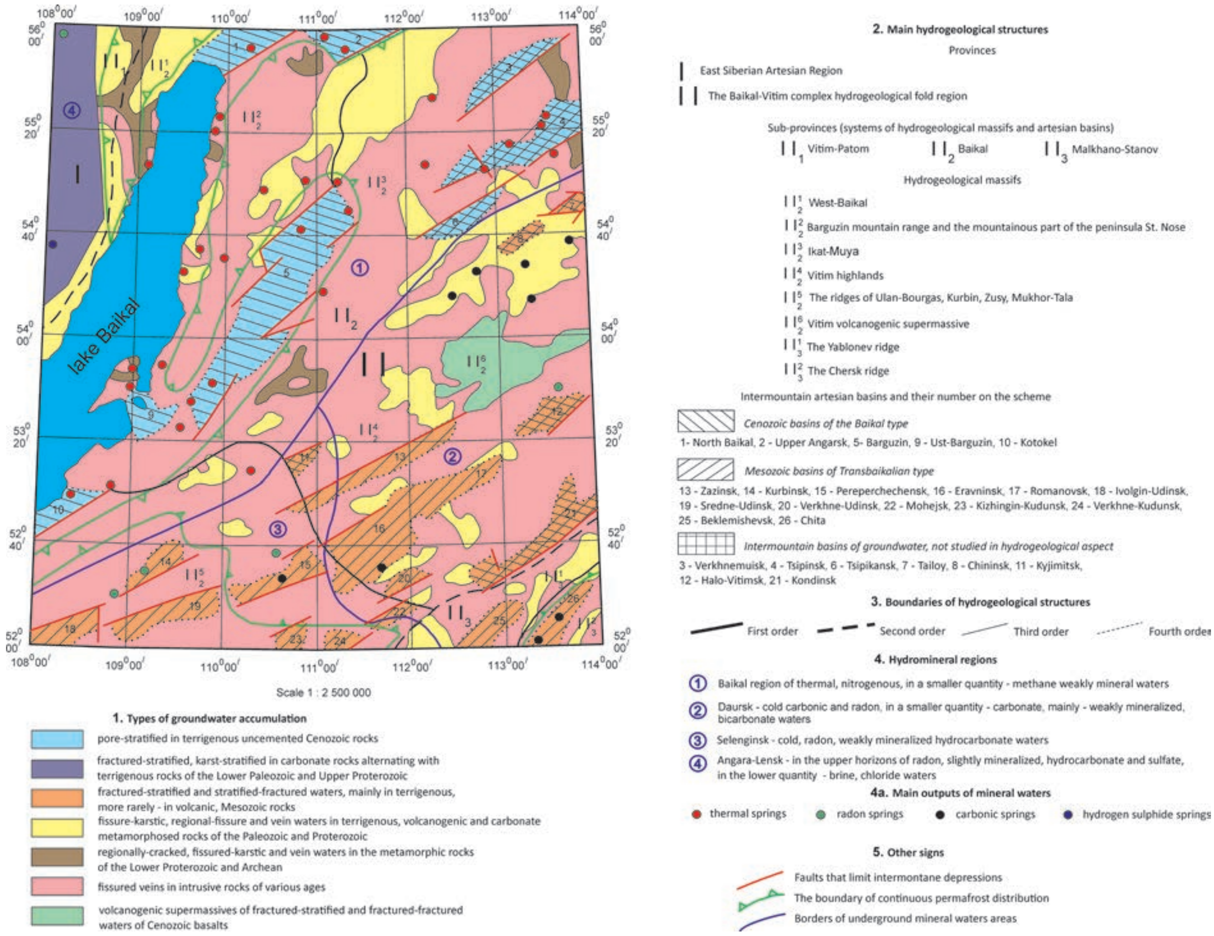

Fig. 2 - The hydrogeological sketch of the Barguzin-Baunt depression branch.

Fig. 2 - Schema idrogeologico del bacino tettonico Barguzin-Baunt.

tectonic zones is noted in carbonate rocks, which is explained by intensive karst processes that create large cavities containing a considerable amount of groundwater.

The main source of groundwater recharge is the infiltration of surface runoff around the perimeter of the depression coming from the surrounding ridges (Fig. 1, a, side bar 2; Fig. 2). There is a thermal spring's formation conceptual model in the Fig. 3. Artesian basins of the Baikal type (Fig. 2) reach a depth of not less than 2000 m (Molotov 1999) to 5000 m (the Baikal depression) and located in (and under) the Cenozoic intermontane depressions (Lomonosov 1974).

The active faults of the Baikal rift system are characterized by elevated values of the heat flux (reaching values of 170 mW/m^2) (Fig. 1, b) and geothermal gradient (Lysak 2002).

Intensive deep heat removal is also observed on mountain jumpers between depressions, which are penetrated by local faults with thermal conductive zones. The ridge slopes are also thermally active.

Geothermal anomalies can be associated with the rise of asthenospheric domes and the presence of magmatic chambers under the rift depressions, which are the source of deep heat entering the Earth's surface with underground fluids along deep faults.

Some researchers (Matz et al. 2001) suggest the existence of the most elevated sections of the anomalous mantle along the maximum relief values contour.

The boundary of the upper mantle and the crust is between 35 and 40 km. The main seismically active layer of the BRS is within 15–25 km, but some earthquakes occur in the lower crust at a depth of 30–35 km. Seismicity has a significant effect on the environment permeability (Kuang and Jiao 2014) and earthquakes at the boundary between the lower crust and the upper mantle can cause an increase in the pore pressure of fluids in the lower layers (Parotidis et al. 2003). The lower plastic layers of the lithosphere are thickened under the Barguzn-Amut area (Devershere et al. 1991). The results of the lithosphere-asthenosphere boundary modeling using the gravimetric method show that the minimum depths (70 km) are obtained for the areas near Khamar-Daban and Vitim ((Petit and De´verche`re 2006, Dobrynina et al. 2016) (Fig. 1, b).

Here we attempted to relate our data of thermal water exits to the result obtained by determining the area of the anomalous mantle range and depth for Barguzn-Amut depression area. The scheme shows (Fig. 1, b, side bar 2) that a large part of the hot springs is related to the minimum depth

DOI: 10.7343/as-2018-317

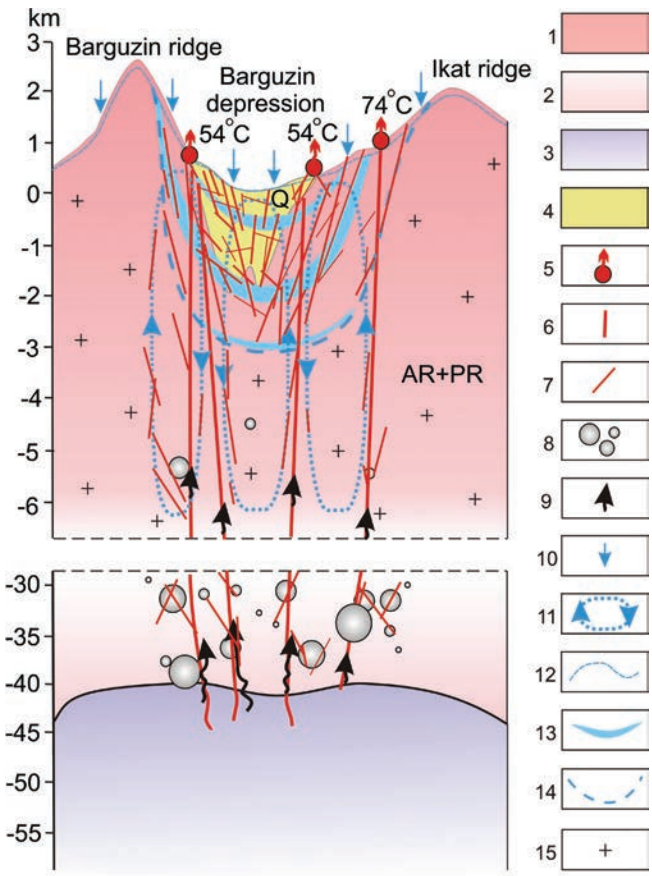

Fig. 3 - Thermal spring's formation conceptual model of the Barguzin depression area (using (Lomonosov 1974)). 1 – upper crust (granite rocks), 2 – lower crust, 3 – upper mantle (according to Devershere et al. 1991), 4 – depression, 5 – thermal springs, 6 – deep faults, 7 – local faults, 8 – hypocenters of earthquakes, 9 – fluids, 10 – meteoric water, 11 – convective cells, 12 – groundwater level, 13 – impermeable rocks, 14 – boundary of artesian basin, 15 – foundation of an artesian basin.

Fig. 3 - Modello concettuale di formazione delle sorgenti termali nel bacino Barguzin (Lomonosov 1974). 1 – Crosta superiore (rocce granitiche), 2 – Crosta inferiore, 3 – Mantello superiore secondo Devershere et al. (1991), 4 – Bacino tettonico, 5 – Sorgenti termali, 6 – Faglie profonde, 7 – Faglie locali, 8 – Ipocentri dei terremoti, 9 – Fluidi, 10 – Acque meteoriche, 11 – Celle convettive, 12 – Livello di falda, 13 – Bacini artesiani, 14 – Limite del bacino artesiano, 15 – Rocce impermeabili

of the anomalous mantle inhomogeneity under the lower boundary of the earth's crust. There are multiple basaltic fields of different ages on the surface not far of these zones (Fig.1).

There are carbon dioxide, nitrogen and methane waters of a mixed gas composition, predominantly nitrogen in the Baikal rift zone. The hydrothermal water temperature varies between 20–81°C, with a predominance of hot (above 40 degrees). Nitrogenous terms, associated with young active faults, are also prevalent in the zone of the Barguzin-Baunt depression branch (Fig. 2).

The number of pallet cells (0.37° x 0.37°) distributed by density is shown in Fig. 4, a. There is a diagram of the BRS thermal springs (Fig. 4, b) and cold (Fig. 4, c) distributed by the value of the faults density n (Fig. 4, b). For a given size of the pallets, the modal value of the faults density is 6–7, the median value is 9, and the mean value is 9.8. The diagram in Fig. 2, b shows that a greater number of springs, both cold and hot, corresponds to the increased density (above then mean value): 90% of thermal and 70% of cold springs, and 94% – thermal and 88% – cold springs correspond to the density values higher than the modal (above 7 at a given size of the cells). These results are shown in the Tab. 1.

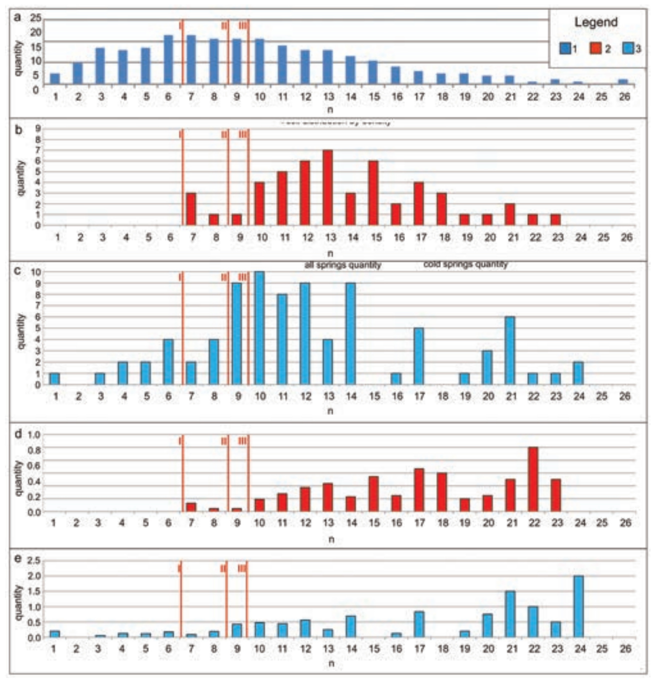

Fig. 4 - Distribution histograms: a – distribution of the cells number (0.37° x 0.37° cell size) by parameter n, b – distribution of the thermal springs number by n, c – distribution of the cold springs number by n, d – distribution of the mean thermal springs number per unit area by parameter n, e – distribution of the mean cold springs number per unit area by parameter n. 1 – cells quantity, 2 – quantity of thermal springs, 3 – quantity of cold springs. I – modal value of active faults density, II – median value of active faults density, III – mean value of active faults density.

Fig. 4 - Istogrammi di distribuzione rispetto alla densità di faglie (n): a – Distribuzione del numero di celle (dimensione 0.37° x 0.37°), b – Distribuzione delle sorgenti termali, c – Distribuzione delle sorgenti fredde, d – Distribuzione del numero medio di sorgenti termali per unità di area, e – Distribuzione del numero medio di sorgenti fredde per unità di area.1 – quantità di celle, 2 – quantità di sorgenti termali, 3 – quantità di sorgenti fredde. I – moda della densità di faglie attive, II – mediana della densità di faglie attive, III – media della densità di faglie attive.

The maximum quantity of the thermal spring's number is observed at a density of 13, and cold at a density 10.

The thermal springs are concentrated in the range of n 10–13, which is characterized by a maximum number of earthquake swarms and strong earthquakes (magnitude M > 5). This means there is a connection of thermal springs to the seismic-active fault zones. The joint phenomenon of seismic and hydrothermal activity is observed at an increased density (above the mean value), but not the maximum, which indicates the confinement of hydrothermal to the zones of deep faults of the generating earthquakes.

The maximum density of faults is not characterized by the peak of seismic activity, and is associated with a network of multiple and shallow cracks, connected mainly with earthquakes of low magnitudes. These zones of the Baikal

Tab. 1 - Statistical distributions of hot and cold sources of BRS by n.

Tab. 1 - Distribuzione statistica di sorgenti calde e fredde nel BRS.

fault density n	1	2	3	4	5	6	7	8	9	10	11	12	13
number of cells	5	10	17	16	17	23	23	21	21	21	18	16	16
number of thermal springs	0	0	0	0	0	0	3	1	1	4	5	6	7
number of cold springs	1	0	1	2	2	4	2	4	9	10	8	9	4
mean thermal springs number per unit area	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.05	0.05	0.19	0.28	0.38	0.44
mean cold springs number per unit area	0.2	0.00	0.06	0.13	0.12	0.17	0.09	0.19	0.43	0.48	0.44	0.56	0.25

continues

fault density n	14	15	16	17	18	19	20	21	22	23	24	25	26
number of cells	13	11	8	6	5	5	4	4	1	2	1	0	2
number of thermal springs	3	6	2	4	3	1	1	2	1	1	0	0	0
number of cold springs	9	0	1	5	0	1	3	6	1	1	2	0	0
mean thermal springs number per unit area	0.23	0.55	0.25	0.67	0.60	0.20	0.25	0.50	1.00	0.50	0.00	0.00	0.00
mean cold springs number per unit area	0.69	0.00	0.13	0.83	0.00	0.20	0.75	0.15	1.00	1.00	2.00	0.00	0.00

rift system are characterized by a slow migration of seismic activity, possibly accompanied by a change in the pore pressure of the fluids and migration of fluids from the lower crust and upper mantle in the creep part of the fault, as the more weakened zone (Novopashina and Sankov 2018).

The mean number of springs per unit area (Fig. 4, d, e) is calculated by dividing the total quantity of thermal and cold springs corresponding to each density range. The diagram shows that with an increasing density, there is a tendency of the mean number of cold and hot springs per unit area to rise.

There is a low correlation of the active faults number with the thermal springs number (n_{therm}) for the whole territory of the BRS is obtained (Fig. 5). The correlation coefficient r = 0.44 (ε = 4.3 with tabular ε = 3.7, sample n_{therm} = 91 values and p = 0.999).

A significant influence on the correlation might be those cells of the pallet that cover the Baikal lake territory where there is no data of springs. As a result the correlation coefficient may be underestimated. The correlation mean level of the faults network density with the hydrothermal spring number can also be explained by the fact that water does not rise over all active faults due to the hydrodynamic conditions variety caused by unevenness in the tectonic stress field structure.

The correlation of the springs number from n for the Barguzin-Baunt depression branch zone is more indicative. Here, there is a closer correlation between the number of thermal water sources and n (r = 0.67, ε = 4.4 for tabulated 3.4 $<p<$ 3.5 and p = 0.999) (Fig. 6).

Also, the correlation dependence between the maximum and mean thermal springs temperature with the parameter n is calculated for this territory (Fig. 7).

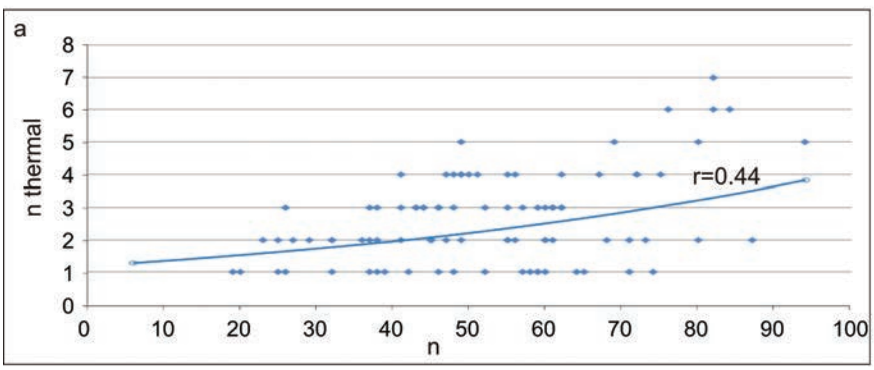

Fig. 5 - Correlation dependence between the thermal spring's quantity (n thermal) and the parameter n for a 1 ° x 1 ° cell size with 50% overlap for the Baikal rift system area.

Fig. 5 - Correlazione tra in numero di sorgenti termali (n thermal) e la densità di faglie (n) per celle 1° x 1° con 50% di sovrapposizione per il BRS.

The mean thermal spring temperature value in this zone has a significant high reverse correlation with n (r = -0.69, ε = 2.1 at tabular ε = 2.09 and p = 0.95) (Fig.5, a). There is a significant high statistical inverse relationship between the maximum temperature of the thermal springs and the density of faults n (see Fig. 5, b) (r = -0.75, ε = 2.6 and ε = 2.1 at tabular ε = 2.52).

Discussion

The statistics of the cold and hot spring number distribution by active faults density parameter calculated with different scales shows the spatial relationship of these parameters. The statistical calculations carried out for the territory of the entire BRS and the Barguzin-Baunt depression branch allowed us to identify the tendency of an increase in the springs number per unit area (both cold and thermal) with an increase of the active faults density n.

Both in the entire Baikal rift system and in the Barguzin-Baunt depression branch, the faults density is above the specified mean value, where a combination of the maximum number of hot and cold springs is observed.

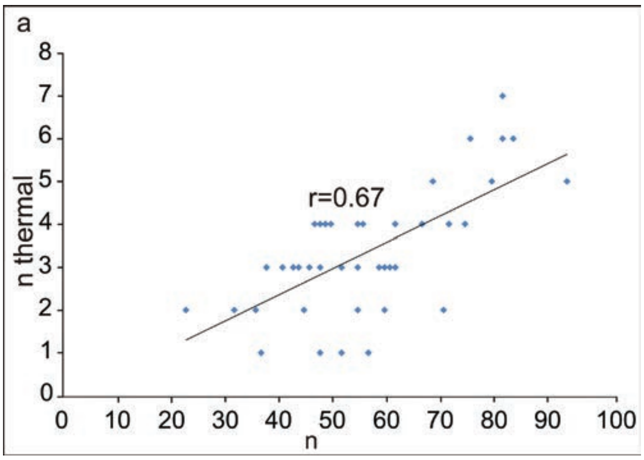

Fig. 6 -Correlation dependence between the thermal spring's quantity and the parameter n for the Barguzin-Baunt depression branch for a 1° x 1° cell size with 50% overlap.

Fig. 6 - Correlazione tra in numero di sorgenti termali (n thermal) e la densità di faglie (n) per celle 1° x 1° con 50% di sovrapposizione per il bacino tettonico Barguzin-Baunt.

Such a distribution can be explained by the fact that the number of springs per unit area rises with the increase in the density of faults (see Fig. 4, b, c), but the number of cells of increased density is much less than the number of cells with a density slightly above the mean value (see Fig. 4, a); as a result, the total number of springs is higher.

In general, there is a clear tendency of a rise in the average number of springs per unit area with an increasing active faults density (see Fig. 4, d, e). The density of 13 at a palette cell size of 0.37° x 0.37°, where the majority of thermal springs are concentrated, is characterized by high seismic activity: most of the strongest earthquakes and earthquake swarms are confined to the zones with this density.

Thus, the region with increased values of faults density is distinguished, characterized by a high subsoil activity (tectonic, seismic activity and elevated mantle) manifesting itself in a combination of hydrothermal and seismic activity.

Exits of high-temperature waters indicate the deep heat sources present in the depths of the earth's crust, appearing on the earth's surface from underground with fluids along deep faults (Kustov and Lysak 2000). Ground and artesian waters mix with fluids coming from lower layers and form hot terms (Plyusnin 2008).

The initial depth at which fluids migration originates is determined by their genesis, that may be due to intense dehydration in the lower crust above the high-temperature sections of the upper mantle, where partial melting occurs (Kissin 2009). In the hydrothermal water, prevalent in the study area, some chemical elements of probably endogenous origin are observed: S, F, Cl. The results of physico-chemical modeling shows that the concentration of S (Kuz'mina et al. 2015) and Cl is not provided only by the country rocks, and most likely has a fluid component.

The structure of the fault density network reflects the lithosphere heterogeneity of the Baikal rift system. The reduced fault density is associated with consolidated blocks of the earth's crust, and positive anomalies of n are related

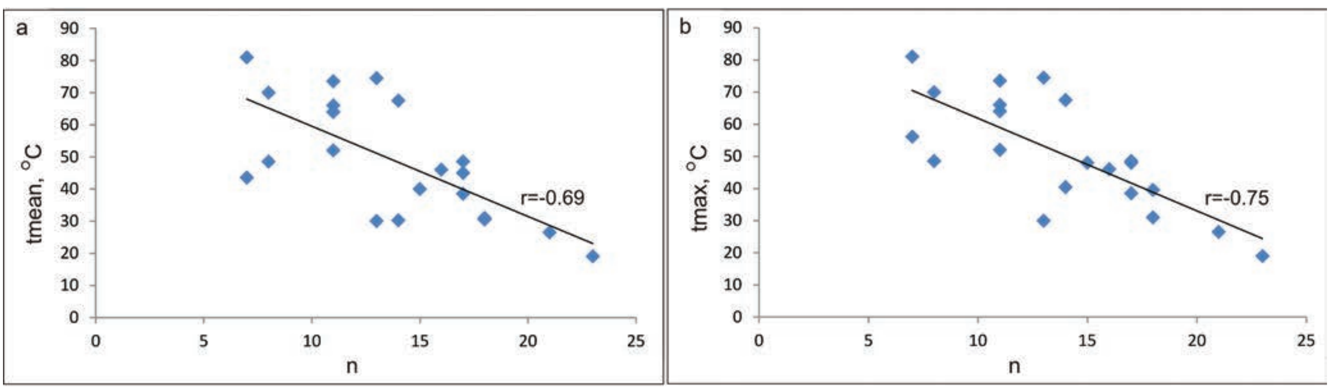

Fig. 7 - Correlation dependences between the mean (tmean) and maximum (tmax) temperature and n for the Barguzin-Bounta branch area for the 0.37° x 0.37° cell size: a – the dependence of the thermal springs mean temperature (tmean) on n. b – the dependence of the thermal springs maximum (tmax) temperature on n.

Fig. 7 - Correlazione tra la temperatura media (tmean) e massima (tmax) e la densità di faglie (n) nel bacino tettonico Barguzin-Baunt per celle 0.37° x 0.37°: a – correlazione tra temperature medie (tmean) delle sorgenti termali e densità di faglie (n), b - correlazione tra temperature massime (tmax) delle sorgenti termali e densità di faglie (n).

with interblock space. This should have a significant effect on the groundwater distribution, because fragmentation degree controls the overall transmissivity and storage capacity of the fractured aquifers (Pedretti et al. 2016). The more faulted earth's crust, having a greater water capacity, is able to contain more groundwater.

The inhomogeneity of the earth's crust in the Baikal rift system lithosphere is also manifested in seismicity. Interblock space is characterized by the migration of weak seismic activity, and the boundaries between solid blocks and fractured interblock space are marked by earthquakes of high and medium strength (Novopashina and Sankov 2018). Earthquakes of high magnitudes can cause the migration of fluids to the weakened part of the earth's crust (Becken et al. 2011), contributing to the hydration of these areas. Earthquake-induced fluid redistribution can lead to temporary changes in composition and temperature of the thermal water (Cox et al. 2015).

Also, in a number of works devoted to the dynamics of hydrothermal systems, it is noted that thermal regime depends on relief, and in particular on the topographic gradient (Volpi et al. 2017, Pola et al. 2015, Tobin et al. 2017). For example, for the model of the hydrothermal system Bormio (Italy) it is established that the heat flux can be greatly reduced by cold underground waters in the deepened relief areas with effective rechardge (Volpi et al. 2017). In the Baikal rift system, it is also observed that hotter springs are on the slopes of ridges, and colder springs are in lower relief forms – depressions (see Fig. 3).

Thereby, a high level of crustal friability and an overall increase in water mass discharge are conditions for the process of mixing and dilution.

This explains that although thermal water springs of high temperature are usually associated with tectonic fractures and intersections, the correlation dependences show that the maximum and mean temperature of springs per unit area decreases with increasing n. Such statistical dependence can be the evidence of an intensive dilution of thermal water by groundwater in a more fractured environment.

Investigation of other thermal systems, for example, the Euganean Geothermal System (Italy), shows that aquifers at different depths are hydraulically connected by faults (Pola et al. 2015). Probably, in BRS, mixing also involves the lowest water horizons by a large faults, delineating the depression (see Fig. 3). The presence of chemical elements Cl and S in the water of the nitrogen thermal springs of the Barguzin-Baunt depression branch also shows the probable hydraulic interaction of the upper and lower lithosphere layers.

The level of watercut in such areas increases in the case of stretching tectonic stresses typical for the fault structures of the Barguzin-Baunt depression branch. In less disturbed areas, due to a less intensive water circulation, the conservation of subsoil heat is better, which is reflected in the maximum temperature of thermal springs on the surface.

The revealed regularities make it possible to improve the approach, especially regarding the search for thermal water deposits and a more efficient use of recreational resources for the whole rift system.

Conclusions

The construction of correlation dependences between the number of thermal springs and the faults density n has shown the average statistical relationship for the territory of the entire Baikal rift system, that is conditioned by the influence of the limited data of the Lake Baikal area on the calculation results. For the Barguzin-Baunt depression branch territory a closer correlation of these parameters is observed.

Thus, it can be concluded that there is a tendency of an augmentation of the number of cold and thermal springs per unit area with an increasing faults density. In general, the maximum total number of springs is characteristic of a faults density above the mean value, and the maximum total of the thermal spring number value is confined to a certain narrow range of n (above mean value, but not maximum), characterized by neotectonic activity accompanied by seismicity. The density above the mean value conforms to 90% of the thermal springs.

A denser network of faults provides better water permeability, and in such conditions, high temperature water dissipates heat more intensively, mixing with artesian and groundwater. Therefore, a greater number of thermal water outcrops of lower temperature are observed on the surface in more fractured areas. The hottest thermal springs prevail in the zones of lower faults density, because the dilution and dispersion processes are less intense, and consequently, heat preservation is better.

Acknowledgment: The authors are grateful to the editors and reviewers, who contributed with their important remarks and advices to the improvement of the paper. The authors are also thankful to Robert and Sheryl Wechsler Hanshaw, K. Udo Weyer and Christoph David Hohl for proofreading of English.

REFERENCES

Becken M, Ritter O, Bedrosian PA, Weckmann U (2011) Correlation between deep fluids, tremor and creep along the central San Andreas fault. Nature 480(7375):87–90. https://doi.org/10.1038/nature10609

Cox SC, Menzies CD, Sutherland R, Denys PH, Chamberlain C, Teagle DAH (2015) Changes in hot spring temperature and hydrogeology of the Alpine Fault hanging wall, New Zealand, induced by distal South Island earthquakes. Geofluids 15:216-239. doi: 10.1111/gfl.12093

Devershere J, Houdry F, Diament M, Solonenko N, Solonenko A (1991) Evidence for a seismogenic upper mantle and lower crust in the Baikal rift. Geophys. Res. Lett. 18(6):1099–1102.

Didenkov YuN Bychinsky VA, Lomonosov, IS (2006) The possible existence of an endogenous source of fresh water in rift settings. Russian Geology and Geophysics 10:1114–1118

Dobrynina AA, Sankov VA, Chechelnitsky VV (2016) New data on seismic wave attenuation in the lithosphere and upper mantle of the northeastern flank of the Baikal rift system Doklady Earth Sciences. 468(1):485–489. doi: 10.7868/S0869565216130168

Golubev VA (2007) Conductive and convective heat output in the Baikal rift zone. Novosibirsk. Russia

Ingebritsen S, Gleeson T (2017) Crustal permeability. Hydrogeology Journal. doi.org/10.1007/s10040-017-1663-4

Lomonosov IS (1974) Geochemistry and modern hydroform formation of the Baikal rift zone. Novosibirsk, Russia

Lunina OV (2016) The digital map of the Pliocene-quaternary crustal faults in the southern east siberia and the adjacent northern Mongolia. Geodynamics & Tectonophysics. doi.org/10.5800/GT-2016-7-3-0215

Lysak SV (2002) Heat flow in the zones of active faults in the south of Eastern Siberia. Russian Geology and Geophysics 8:791–803

Kuang X, Jiao JJ (2014) An integrated permeability depth model for Earth's crust. Geophysical Research Letters. https://doi.org/10.1002/2014GL061999

Kissin IG (2009) Fluids in the earth's crust, GeoNauka, Moscow

Kustov Yu I, Lysak SV (2000) Thermal waters of the Eastern Siberia south. Russian Geology and geophysics 6:880–895

Kuz'mina EA, Veshcheva SV, Zarubina OV, Brianskii NV (2015) Un modello fisico-chimico come strumento per spiegare la composizione delle acque termali nelle regioni tettonicamente attive *"Physico-chemical model as a tool to explain the composition of thermal waters in tectonically active regions"*. Acque Sotterranee – Italian Journal of Groundwater 13061:007–017. doi:org/10.7343/as-109-15-0136

Matz VD, Ufimtsev GF, Mandelbaym ML, Alakshin AM, Pospeev AV, Shimarev ML, Khalilov OM (2001) Cenozoic of the Baikal rift depression: structure and geological history, Geo, Novosibirsk, Russia.

Molotov VS (1999) Water resources and water management / In: Molotov VS, Shagzhiev KSh (ed.) State management of natural resources of the Baikal region, Moscow, Russia.

Novopashina AV, Sankov VA (2018) Migrations of released seismic energy in various geodynamic conditions. Geodynamics & Tectonophysics. 9(1):139-163. doi:10.5800/GT–2018-9-1-0342

Parotidis M, Rothert E, Shapiro SA (2003) Pore-pressure diffusion: A possible triggering mechanism for the earthquake swarms 2000 in Vogtland/NW-Bohemia, central Europe. Geophys. Res. Lett. 30(20):20-75. doi:10.1029/2003GL018110

Pedretti D, Russian A, Sanchez-Vila X, Dentz M (2016) Scale dependence of the hydraulic properties of a fractured aquifer estimated using transfer functions. Water Resources Research. doi.org/10.1002/2016WR018660

Petit C, De´verche`re J (2006) Structure and evolution of the Baikal rift: a synthesis. Geochemistry Geosystems. 7(11):1–26 doi:10.1029/2006GC001265

Pinneker EV, Pisarsky BI, Lomonosov IS (1968) Hydrogeology of the Baikal region, In: Pinniker EV, Shabynin LL, Yasko VG (1984) Geology and seismicity of the BAM zone (from Lake Baikal to Tynda). Hydrogeology, Moscow State University, Novosibirsk, Russia

Plyusnin AM (2008) The groundwater. In: Tulohonov AK (ed) The Baikal Lake: nature and people: encyclopedic reference book, Ulan-Ude, Russia

Plyusnin AM, Zamana LV, Shvartsev SL, Tokarenko OG, Chernyavskii MK (2013) Hydrogeochemical peculiarities of the nitric thermal water composition in the Baikal Rift Zone. Russian Geology and Geophysics 5:495–508. doi:org/10.1016/j.rgg.2013.04.002

Pola M, Fabbri P, Piccinini L, Zampieri D (2015), Conceptual and numerical models of a tectonically-controlled geothermal system: a case study of the Euganean Geothermal System, Northern Italy, Central European Geology 58(1–2):129–151. doi: 10.1556/24.58.2015.1-2.9

Psakhier SG, Ruzhich VV, Shilko EV, Astafurov SV, Smekalin OP (2004) A study of the water saturation and vibrations effect on the displacement regime in fault zones. Physical mesomechanics 1:23–30

Qi J, Xua M, An Ch, Wua M, Zhang Y, Li X, Zhang Q, Lu G (2017) Characterizations of geothermal springs along the Moxi deep fault in the western Sichuan plateau, China, Physics of the Earth and Planetary Interiors 263:12–22. doi: 10.1016/j.pepi.2017.01.001

Shabynin LL, Pisarsky BI, Sizykh Yu I, Orgilyanov AI (2002) Genesis and uniqueness of the Algin lakes (Transbaikal). Geography and natural resources. 1:116 -121.

Tkachuk VG, Yasnitskaya NV, Ankudinova GA (1957) Mineral waters of the Buryat-Mongolian ASSR. Irkutsk, Russia

Tobin BW, Springer AE, Kreamer DK, Schenk E (2017) Review: The distribution, flow, and quality of Grand Canyon Springs, Arizona (USA), Hydrogeology Journal. doi.org/10.1007/s10040-017-1688-8

Volpi G, Magri F, Frattini P, Crosta G, Riva F (2017) Groundwater-driven temperature changes at thermal springs in response to recent glaciation: Bormio hydrothermal system, Central Italian Alps. Hydrogeology Journal. doi: 10.1007/s10040-017-1600-6

Yasko VG (1982) Underground waters of intermontane depressions of Transbaikalia, Nauka, Novosibirsk, Russia