Volcanism and expanding seismicity in the Baikal Rift System: assessment of its current state from hydrogeochemical monitoring data

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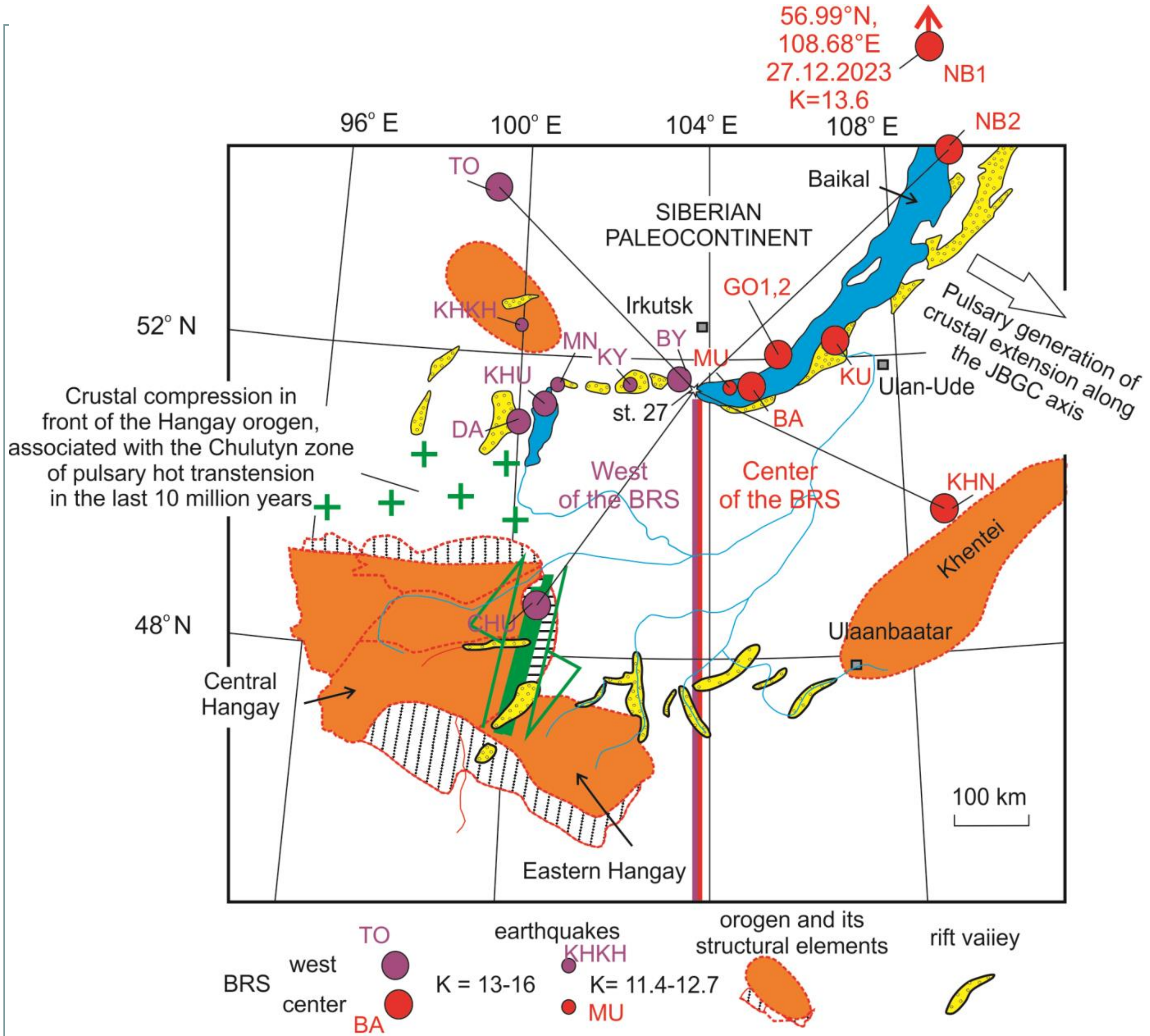
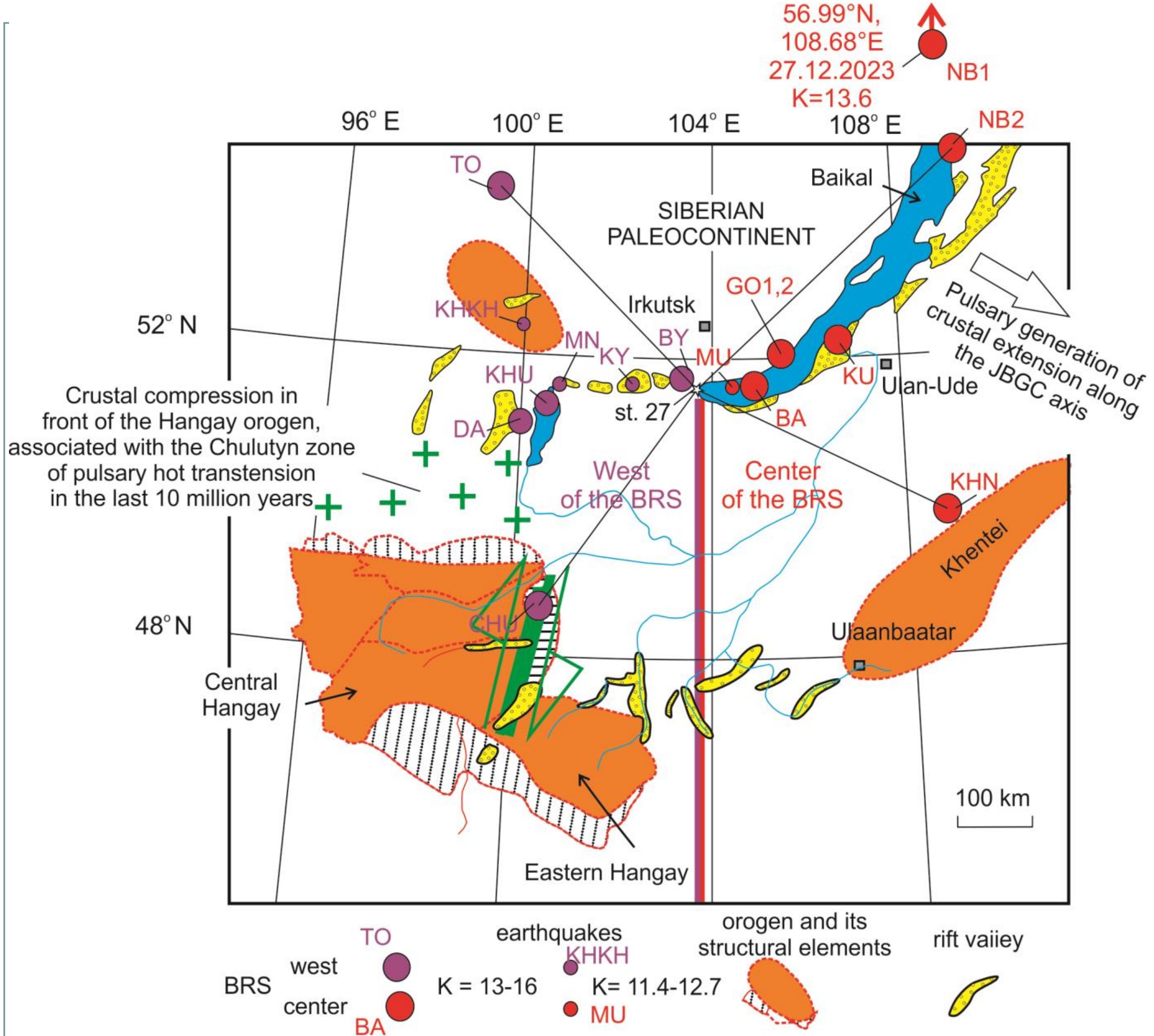
Earthquakes



On June 13, 2020, the Kyren earthquake of moderate strength (K=11.7) occurs in the central Tunka Valley. On July 6, the Murino earthquake with elevated earthquake energy (K=12.3) follows in a water area of Lake Baikal. Finally, on September 21, the first large (K=14.6) Bystroe earthquake of the Baikal-Khubsugul seismic reactivation occurs

Scheme of distribution of large earthquakes in the center and west of the BRS in 2020–2025. Data from Irkutsk: Baikal Branch of the Federal Research Center Unified Geophysical Service of the Russian Academy of Sciences, 2025. http://www.seis-bykl.ru

Analysis of nearby and distant strong earthquakes from station 27 in the western and central parts of the BRS, as well as late earthquakes, allowed us to draw a general conclusion: large seismic events of its central part are followed with large seismic events of the western part



Scheme of distribution of large earthquakes in the center and west of the BRS in 2020–2025. Data from Irkutsk: Baikal Branch of the Federal Research Center Unified Geophysical Service of the Russian Academy of Sciences, 2025. http://www.seis-bykl.ru

In the figure shows the spatial-temporal distribution of earthquakes in the western BRS, which is affected by additional compression, and in its central part, which experiences extension. In 2020–2023, four time intervals of different durations are distinguished: 1) 01.01.2020 – 01.08.2021; 2) 01.11.2021 – 05.07.2021; 3) 06.18.2021 – 04.30.2022, and 4) 05.02.2022 – 12.25.2023.

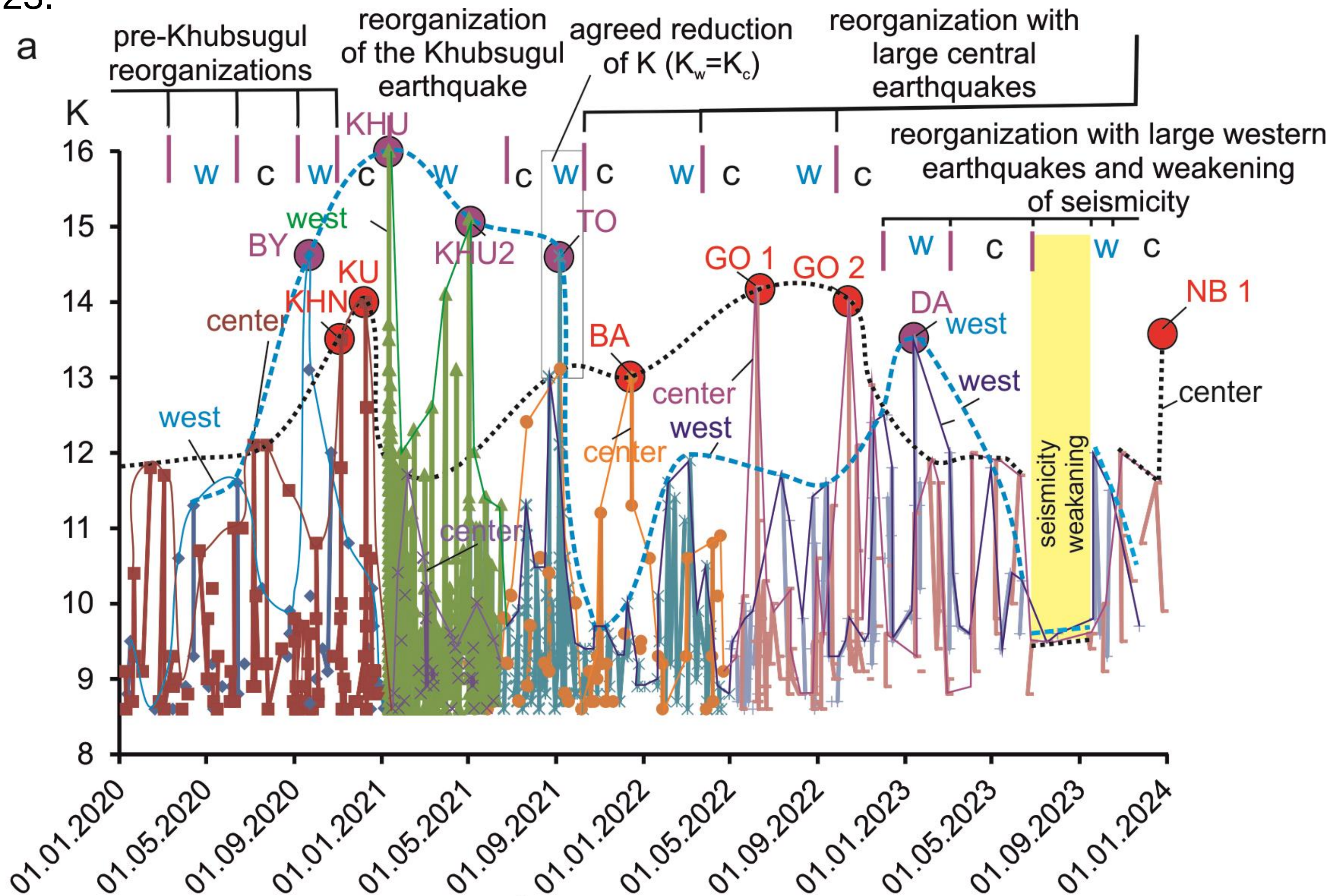
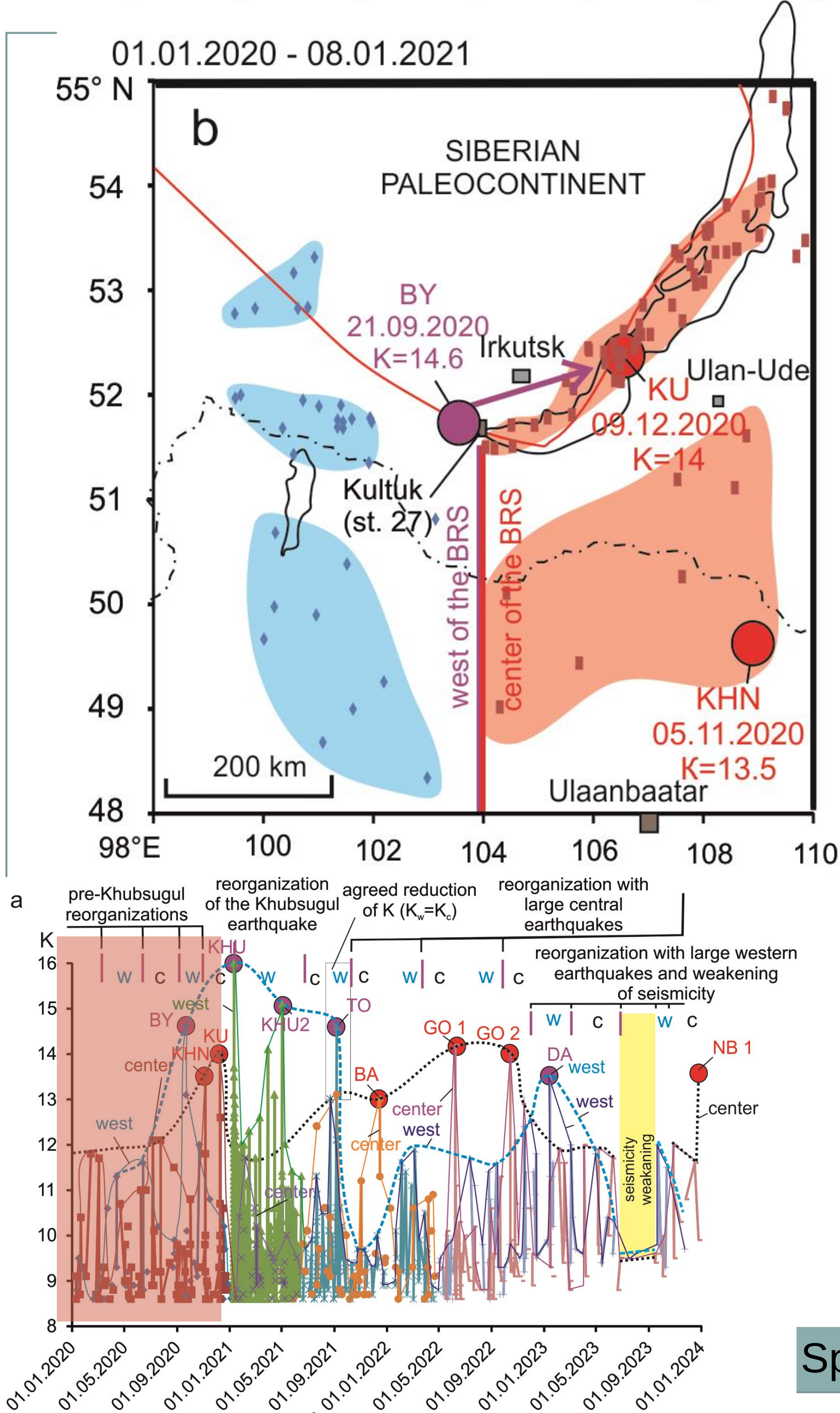
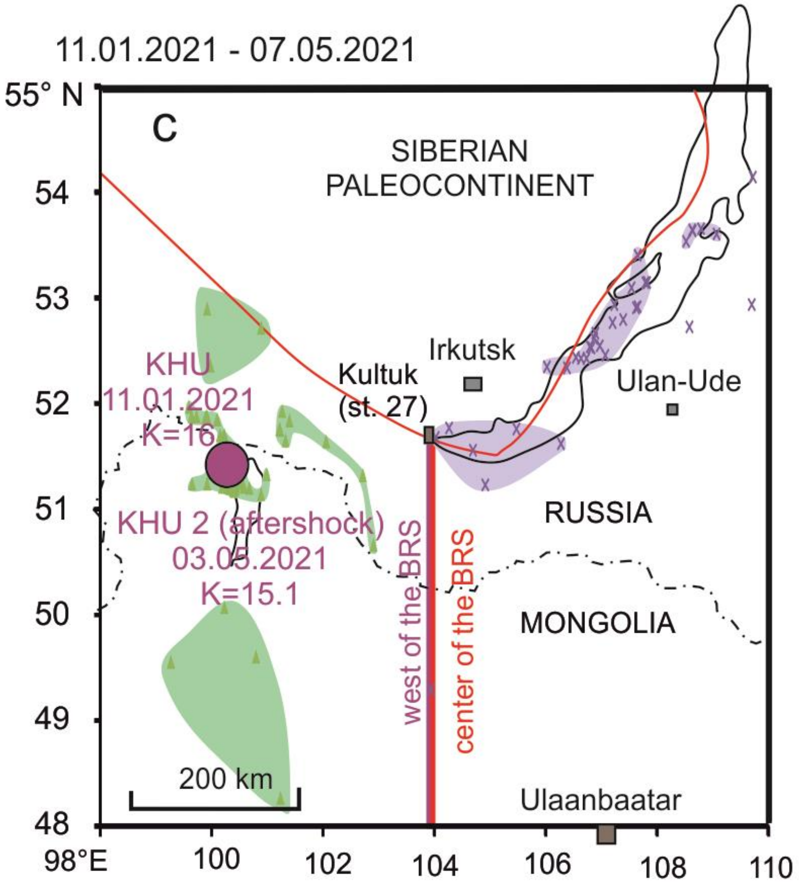


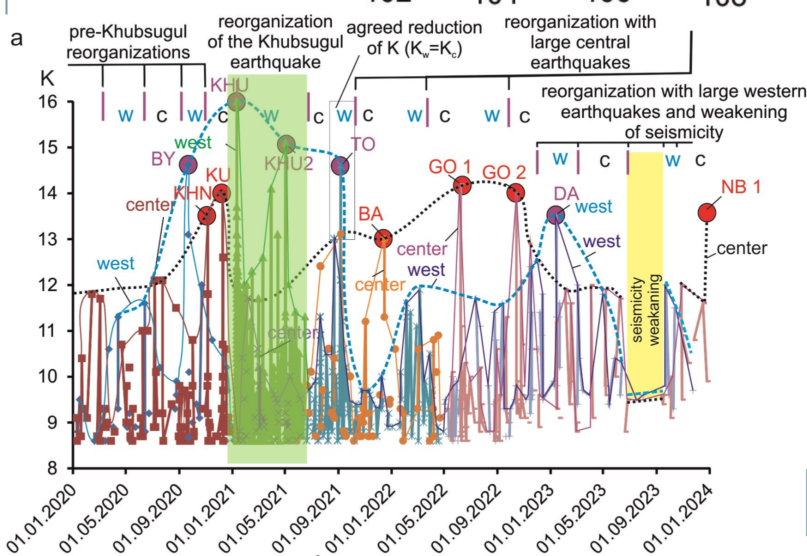
Diagram of energy-class temporal variations of earthquakes of the Baikal-Khubsugul reactivation in 2020–2023 in the central and western BRS



The first interval last about 1 year. The epicenters of small earthquakes in the central BRS are concentrated in a water area of Southern and Middle Baikal. Although the epicenter of the large Bystroe earthquake characterizes the compression environment in the west of the BRS is located near the southwestern end of the zone of small earthquakes of Southern and Middle Baikal. The epicenters are dispersed across the Transbaikalia and adjacent Mongolia. To the northeast of Ulaanbaatar, between the Bystroe earthquake of 21.09.2020 and the Kudara earthquake of 09.12.2020, there was a large seismic shock (K=13.5) on 05.11.2020. Three large earthquakes of 2020 (including Bystroe one) are spatially associated with the central BRS

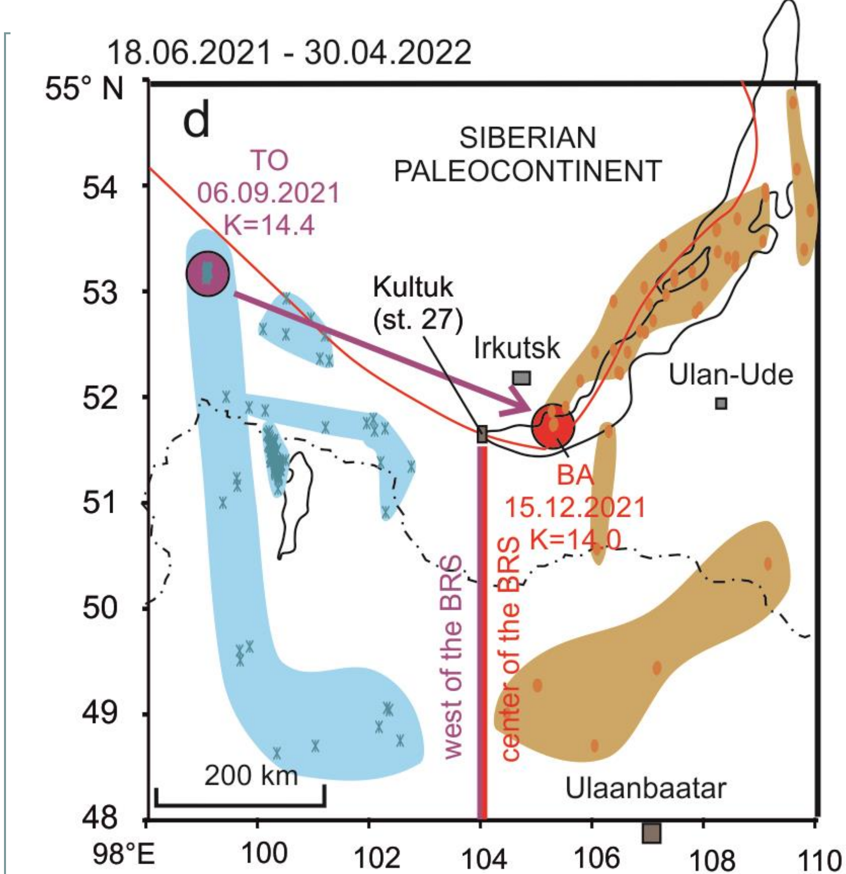
Spatial-temporal distribution of earthquake epicenters

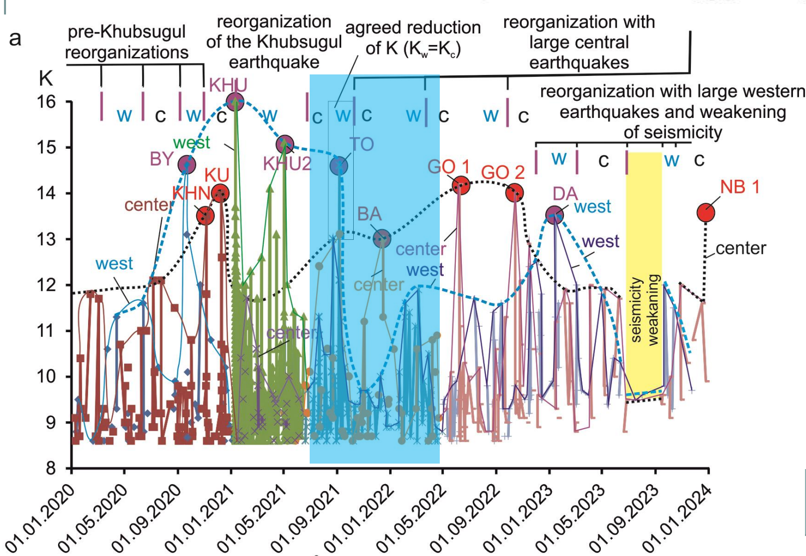




The large Khubsugul earthquake of January 11, 2021 marks a redistribution of seismic activity of the BRS from the center to the west. A pronounced cluster of Khubsugul aftershocks persists not only in 2021, but also throughout the subsequent time, up to 2025. In the time interval from January 11, 2021 to May 7, 2021, small earthquakes continue to form isolated epicentral fields, forming an extended north-south strip in the western BRS. There are no earthquakes in the Ulaanbaatar region. In the Baikal water area, separate clusters of epicenters of Southern and Middle Baikal are reactivated

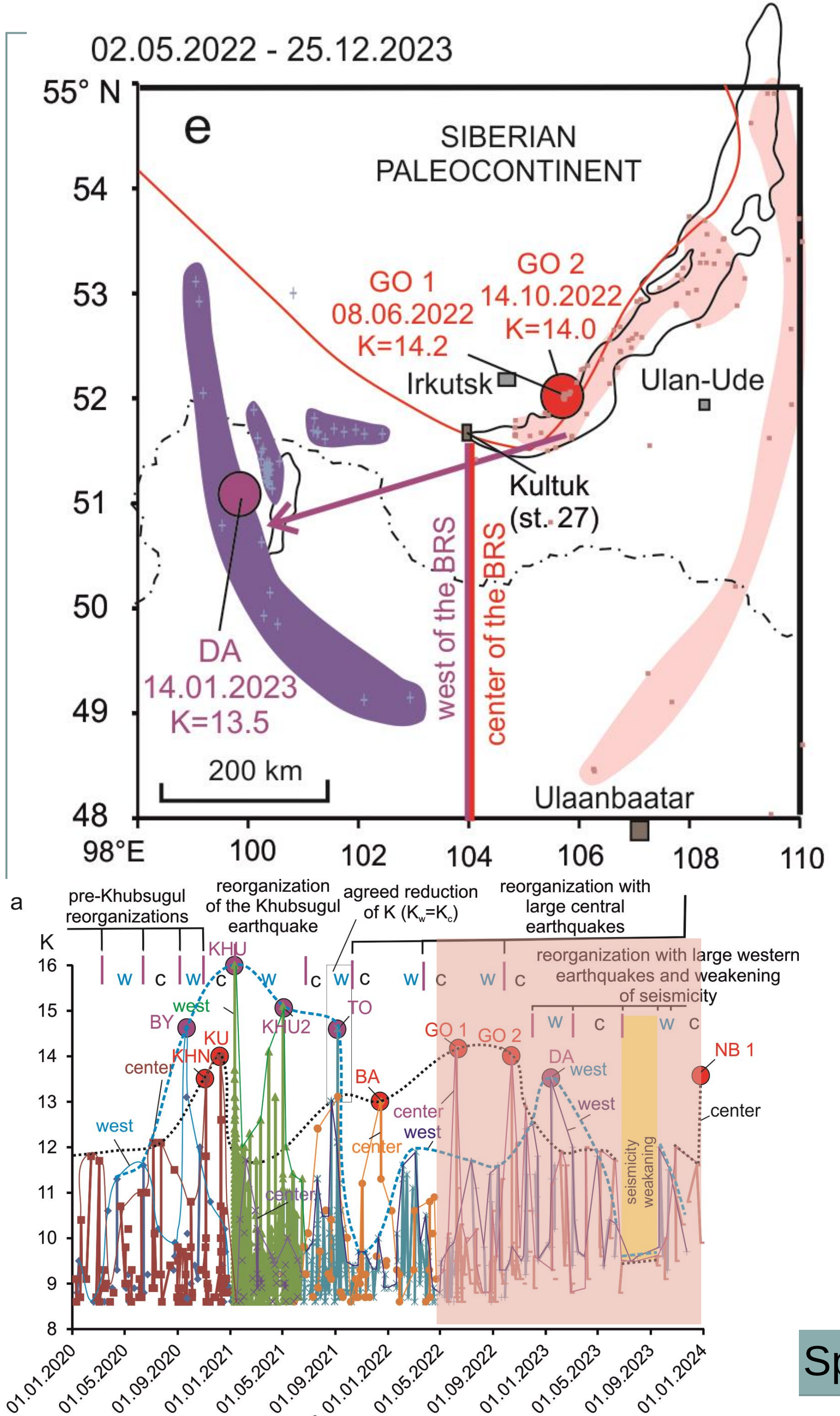
Spatial-temporal distribution of earthquake epicenters





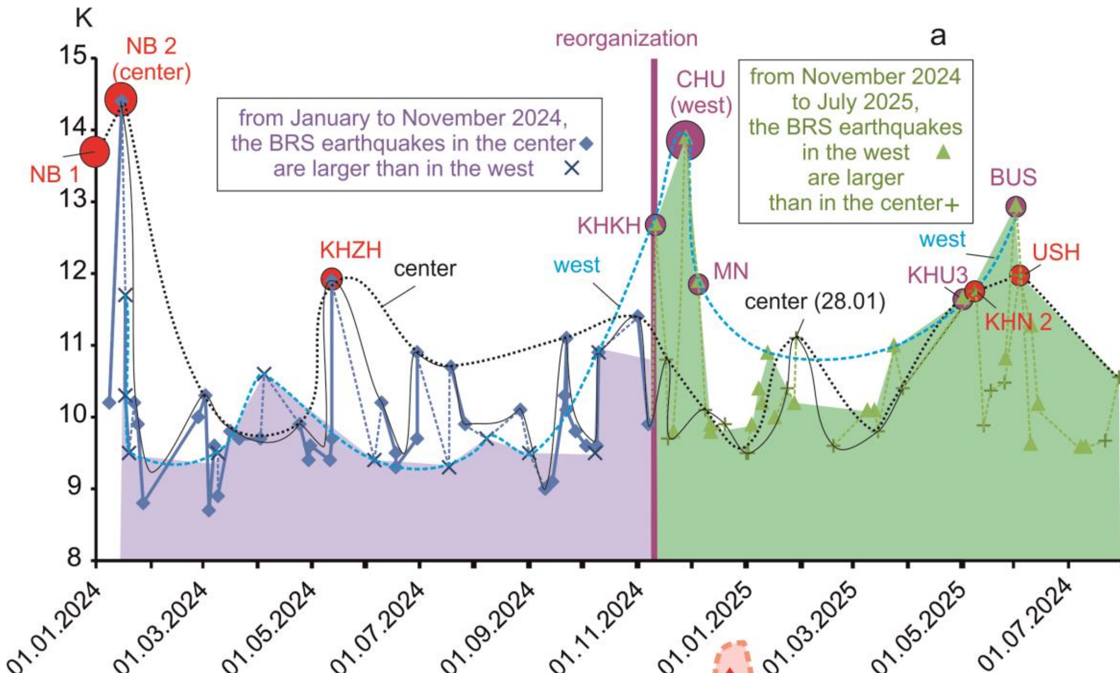
In the time interval from June 18, 2021 to April 30, 2022, the large Tofalar earthquake of September 06, 2021 characterizes the shift of seismic activity to the northern end of the north-south strip, which is limited by the Main Sayan Fault (MSF) – the suture zone of the Siberian paleocontinent. A small epicentral cluster shifts along the MSF, from the epicenter of the Tofalar earthquake towards Lake Baikal. On December 15, 2021, the large Babushkin earthquake occurs in Southern Baikal. In this time interval, large seismic activity moves from the western BRS to its central part along the suture zone of the Siberian paleocontinent. At a distance from it to the south (in Mongolia), epicentral fields of small earthquakes are formed again, forming an angular combination of north-south and west-east bands

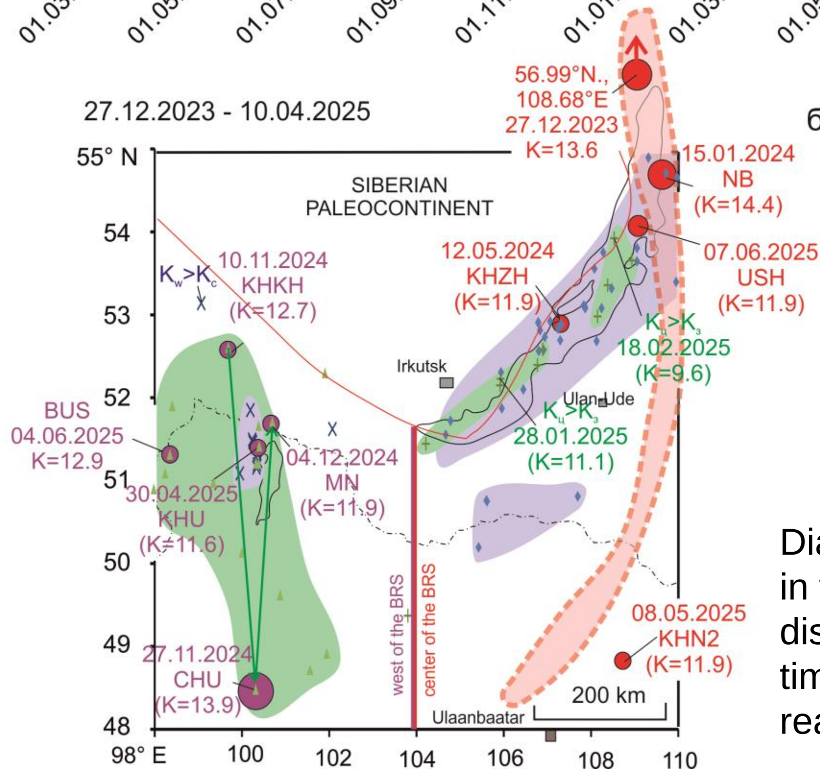
Spatial-temporal distribution of earthquake epicenters



In the time interval from May 2, 2022 to December 25, 2023, two large earthquakes in the center of the BRS (Goloustnoe 1 and Goloustnoe 2) are followed by the large Darkhat earthquake in the west of this structure. The Goloustnoe earthquakes are located in the water area of Southern and Middle Baikal. The Darkhat earthquake shifts west of Khubsugul and enters an extended epicentral arc, the northern segment of which is directed north-south, and the southern one turns to the east. A similar (even longer) seismic arc is designated in the eastern part of the territory. Its northern segment is directed north-south, the southern one turns to the west with an exit almost to Ulaanbaatar. Unlike the western arc with the large Darkhat seismic event, there are no large earthquakes in the eastern arc of North Baikal – Ulaanbaatar

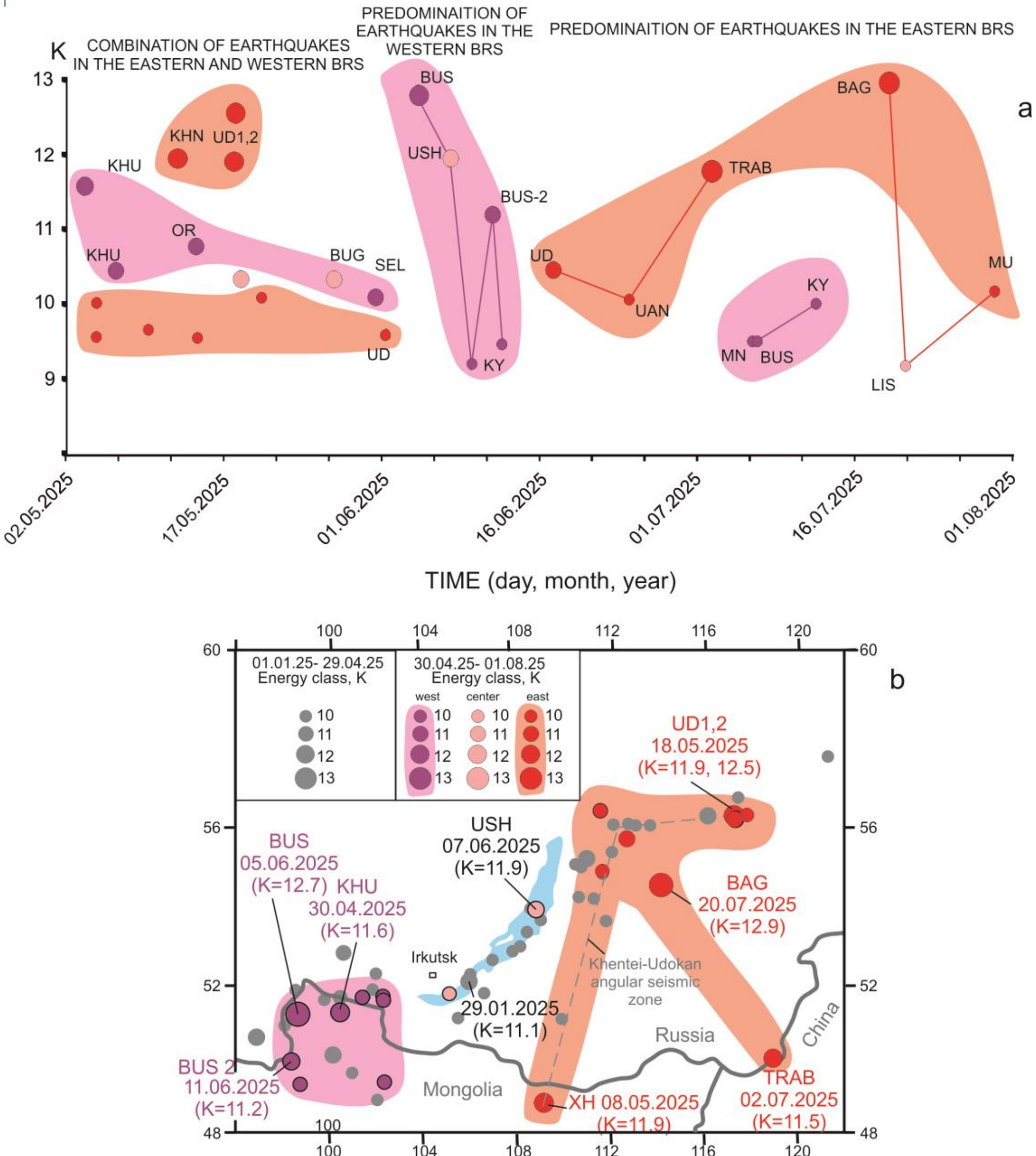
Spatial-temporal distribution of earthquake epicenters





The large North Baikal earthquake is followed by the large Chulutyn earthquake. The North Baikal earthquake inherits the North Baikal – Ulaanbaatar seismic arc of 2022–2023. The Khuzhir earthquake of moderate strength occurs in Middle Baikal, in the central part of the seismic zone of South and Middle Baikal. From January to November 2024, the seismic activity of the center-northeast of the BRS predominates. During this time interval, in the west, earthquakes occur in the aftershock cluster of the main Khubsugul event.

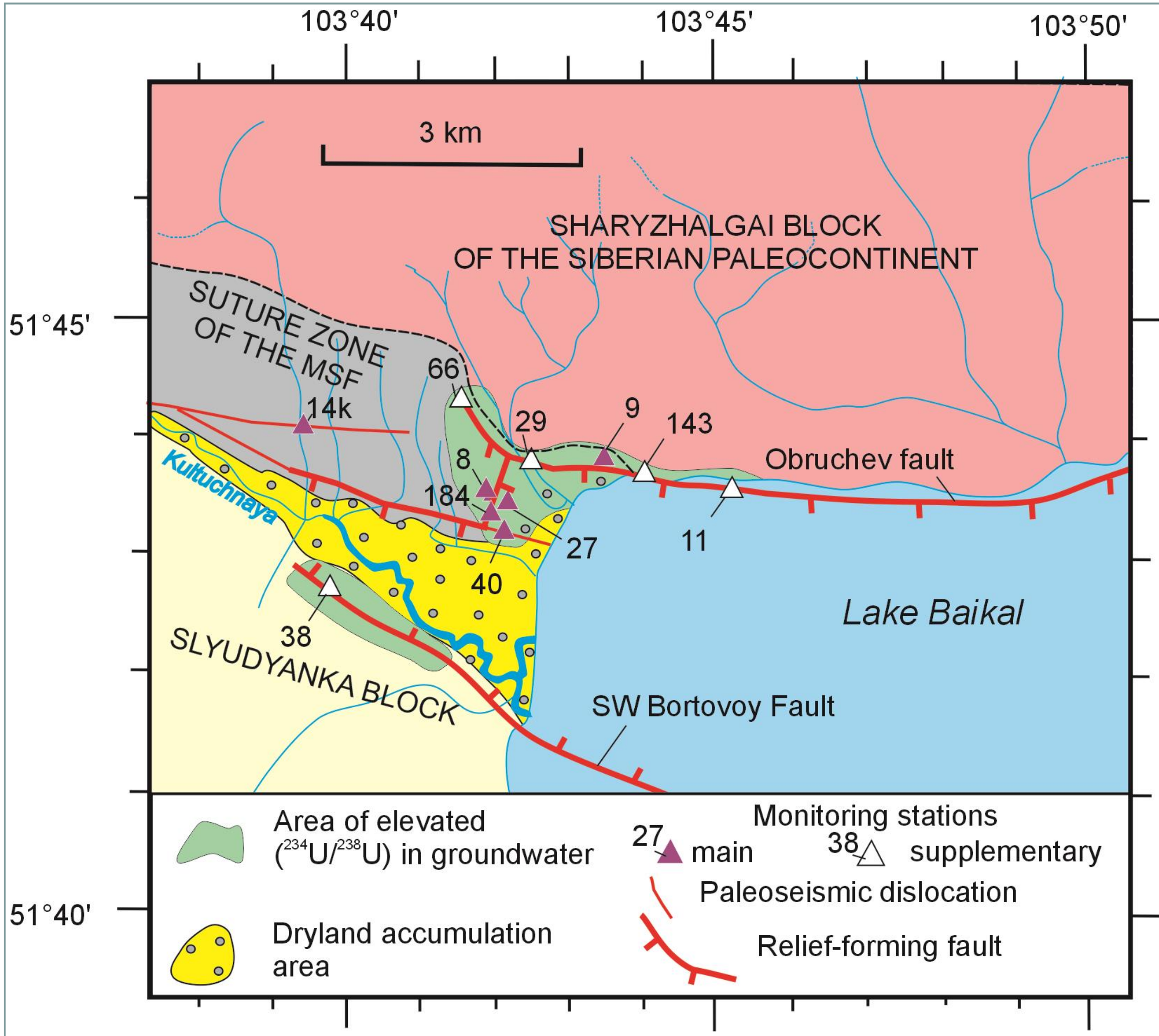
Diagram of energy-class temporal variations of earthquakes in the central and western BRS (*a*) and spatial-temporal distribution of earthquake epicenters (*b*) in 2024–2025. This time interval refers to the North Baikal-Hangay seismic reactivation.



In the time interval from January to April 29, 2025, seismic zones are clearly defined: in the northeast of the BRS – Khentei-Udokan, angular, in the center – Middle-Baikal, linear, and in the west – Sayan, areal. This time interval is predominated by small earthquakes with an energy class not exceeding 11.1.

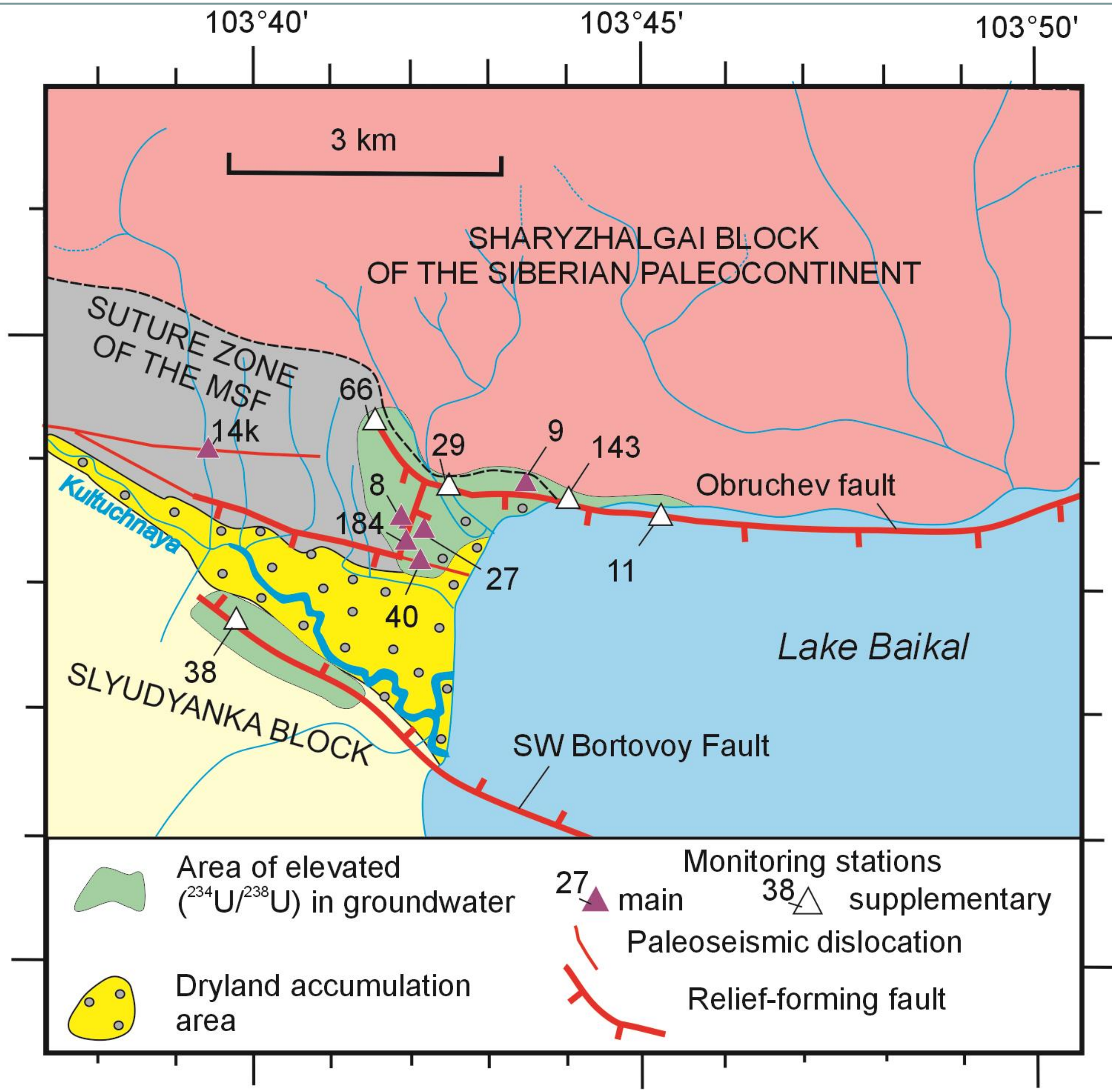
Diagram of energy-class temporal variations of earthquakes in the western, central, and eastern BRS in April 30–July 31, 2025 (*a*) and spatial-temporal distribution of earthquake epicenters (*b*).

Hydrogeochemical monitoring



Location of station 27 and other main and supplementary stations for hydrogeochemical monitoring of active faults on the western coast of Lake Baikal (Kultuk area). Paleoseismic dislocations in the suture zone of the Main Sayan Fault (MSF) are shown after (Chipizubov, Smekalin, 1999).

Permanent monitoring of groundwater in the axial part of the BRS has been performed at the Kultuk area with a sampling frequency of once every 2 weeks on average since 2012 at six main stations. The main monitoring stations have different settings in active faults of the structural junction between the South Baikal Depression and the Tunka Valley and differ significantly in hydrogeochemical parameters of groundwater. The wells have a depth of 60 to 120 m.

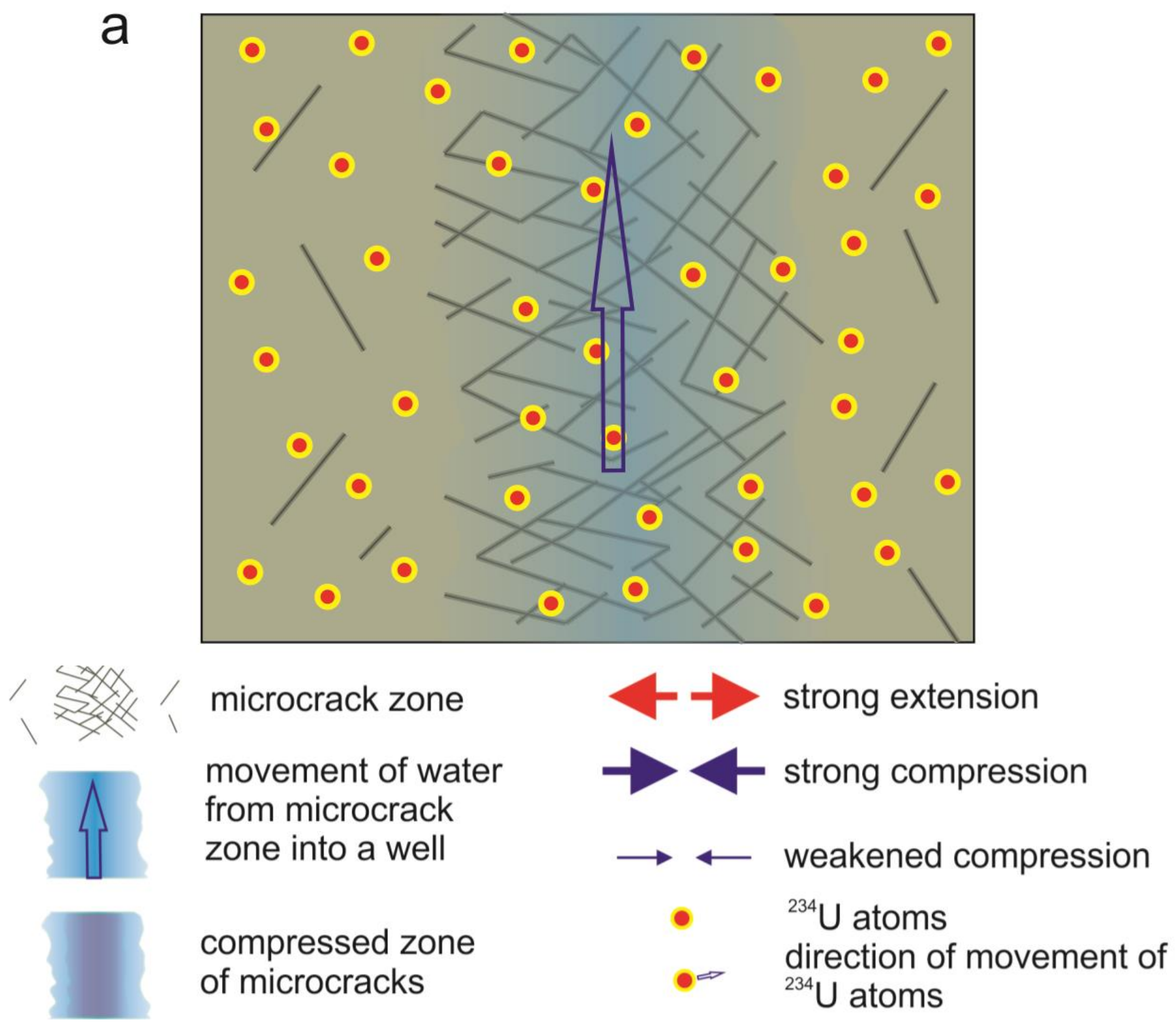


For this study, a monitoring series of groundwater from station 27 is selected, which has the composition of the final component of the Kultuk reservoir in the suture zone of the Main Sayan Fault (MSF) with the most nonequilibrium U and the least radiogenic Sr (Rasskazov et al., 2015, 2020).

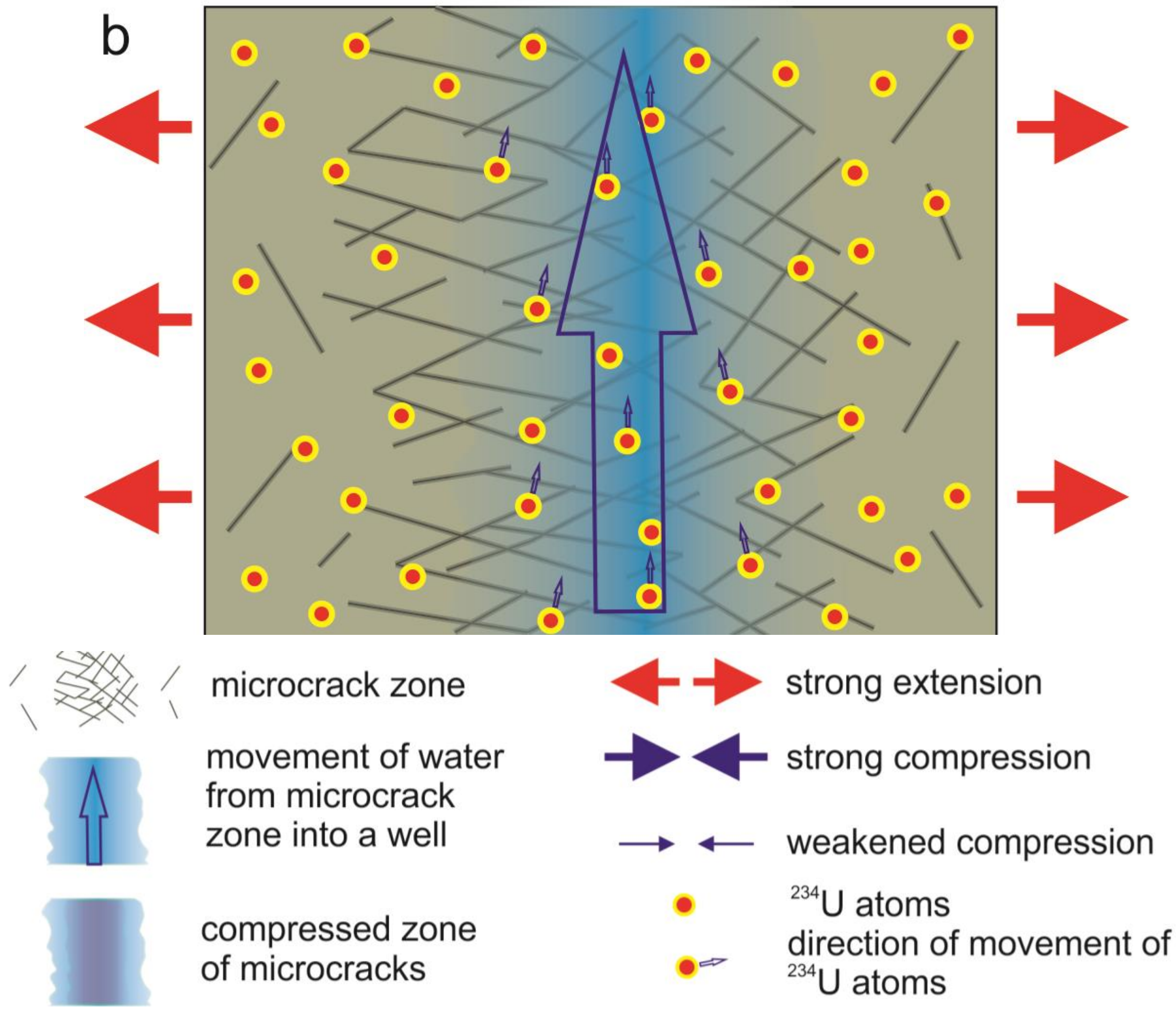
Location of station 27 and other main and supplementary stations for hydrogeochemical monitoring of active faults on the western coast of Lake Baikal (Kultuk area). Paleoseismic dislocations in the suture zone of the Main Sayan Fault (MSF) are shown after (Chipizubov, Smekalin, 1999).

Initial neutral regime.

^{234}U ($A4_{background}$)=~0.83 (A.U.)

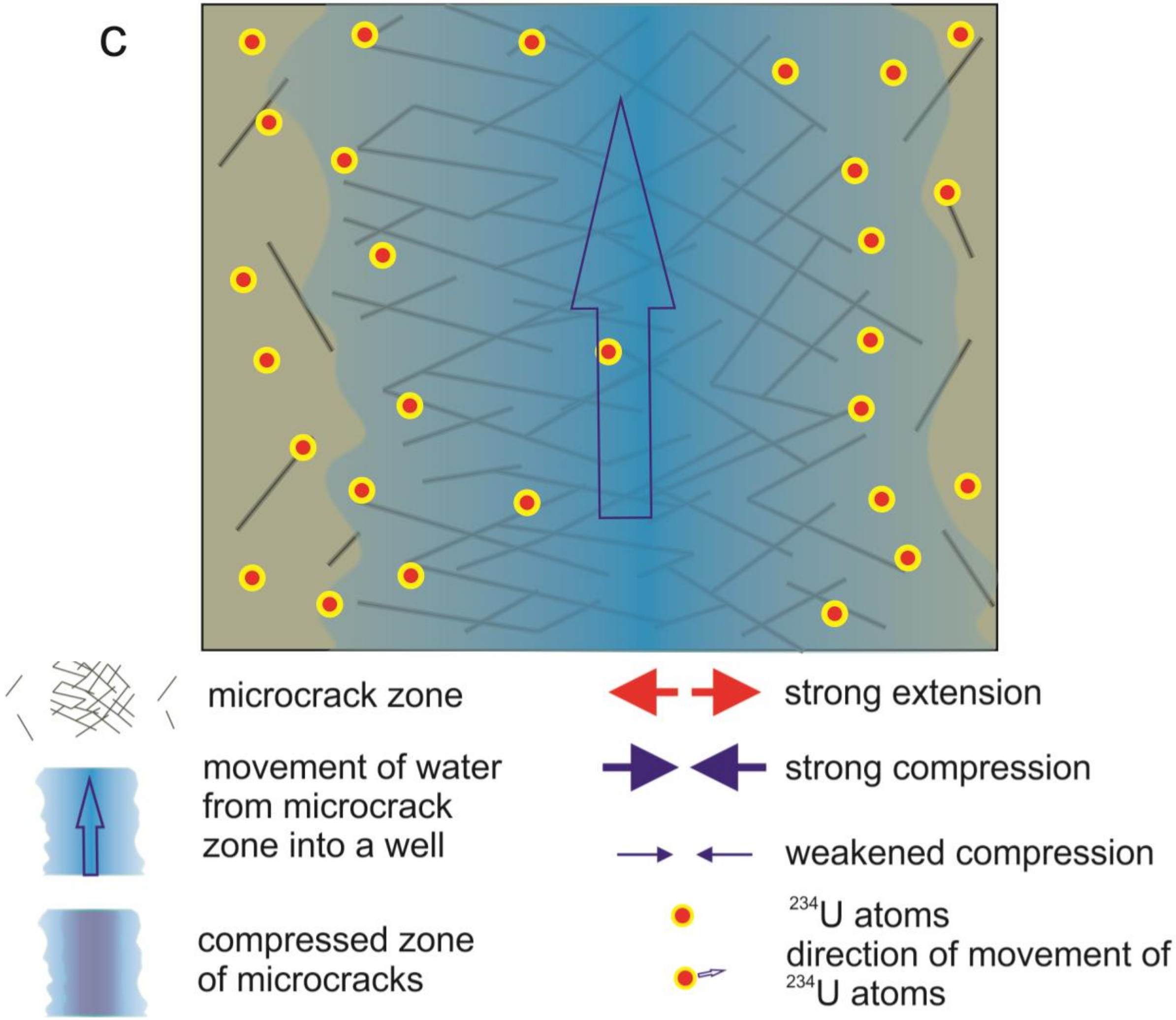


Microcrack opening.
^{234}U atoms are washed out by water from active fault zone

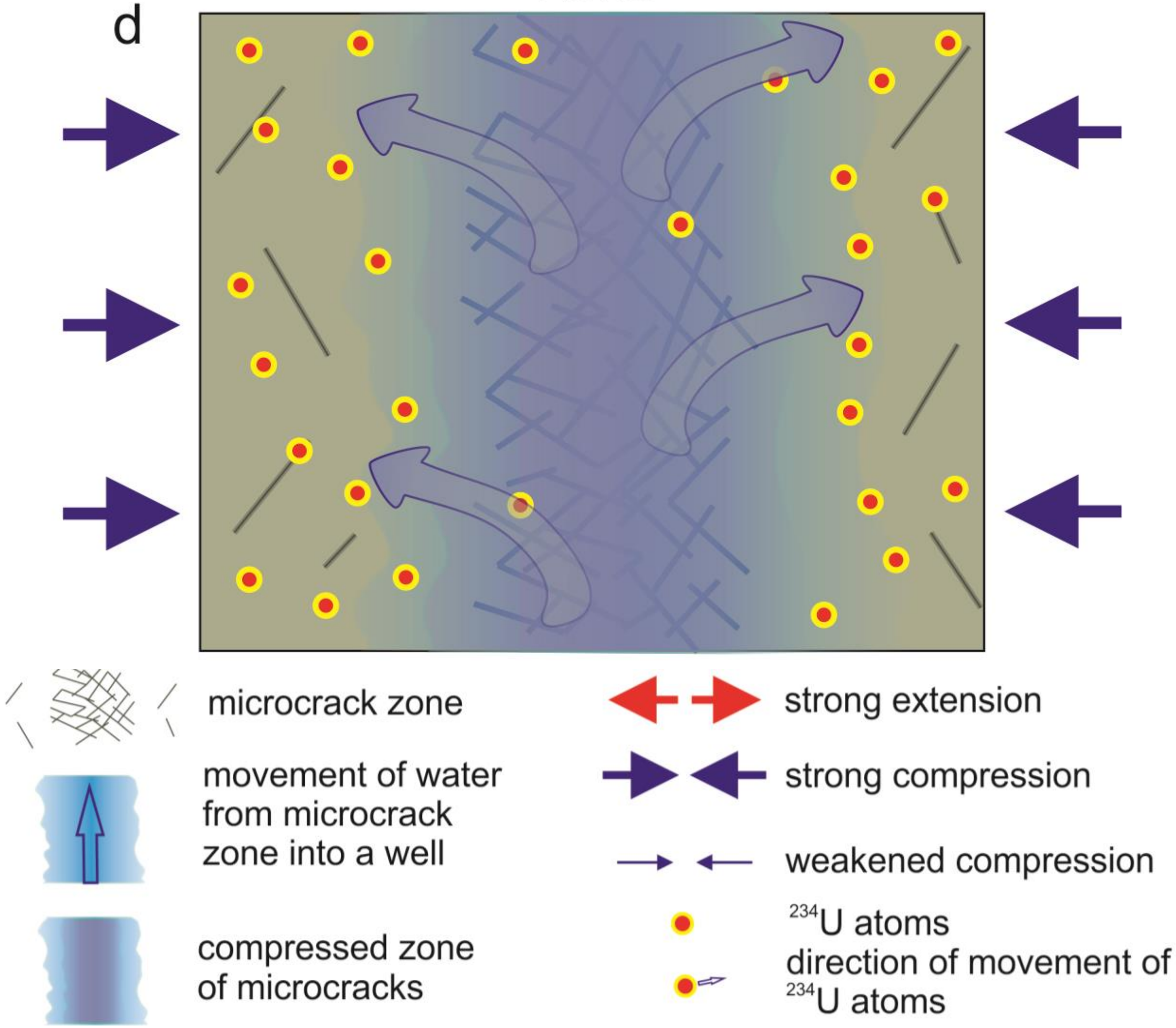


Washing results in depletion of active fracture zone by ^{234}U atoms (A4 < <0.83 (A.U.))

C

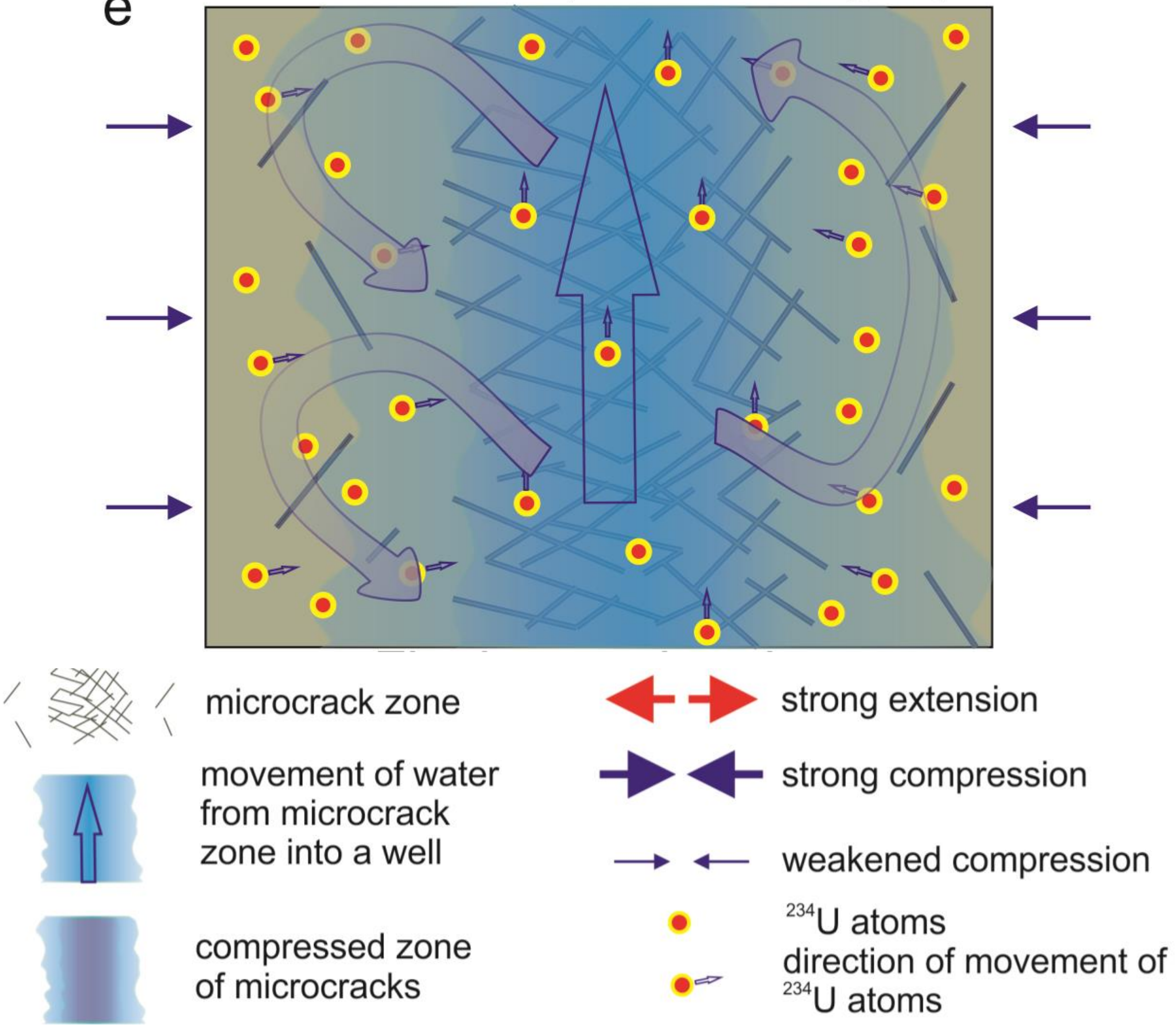


Compression after extension. Water with a deficit of ^{234}U atoms (A4 < <0.83 (A.U.) is squeezed out compressed zone



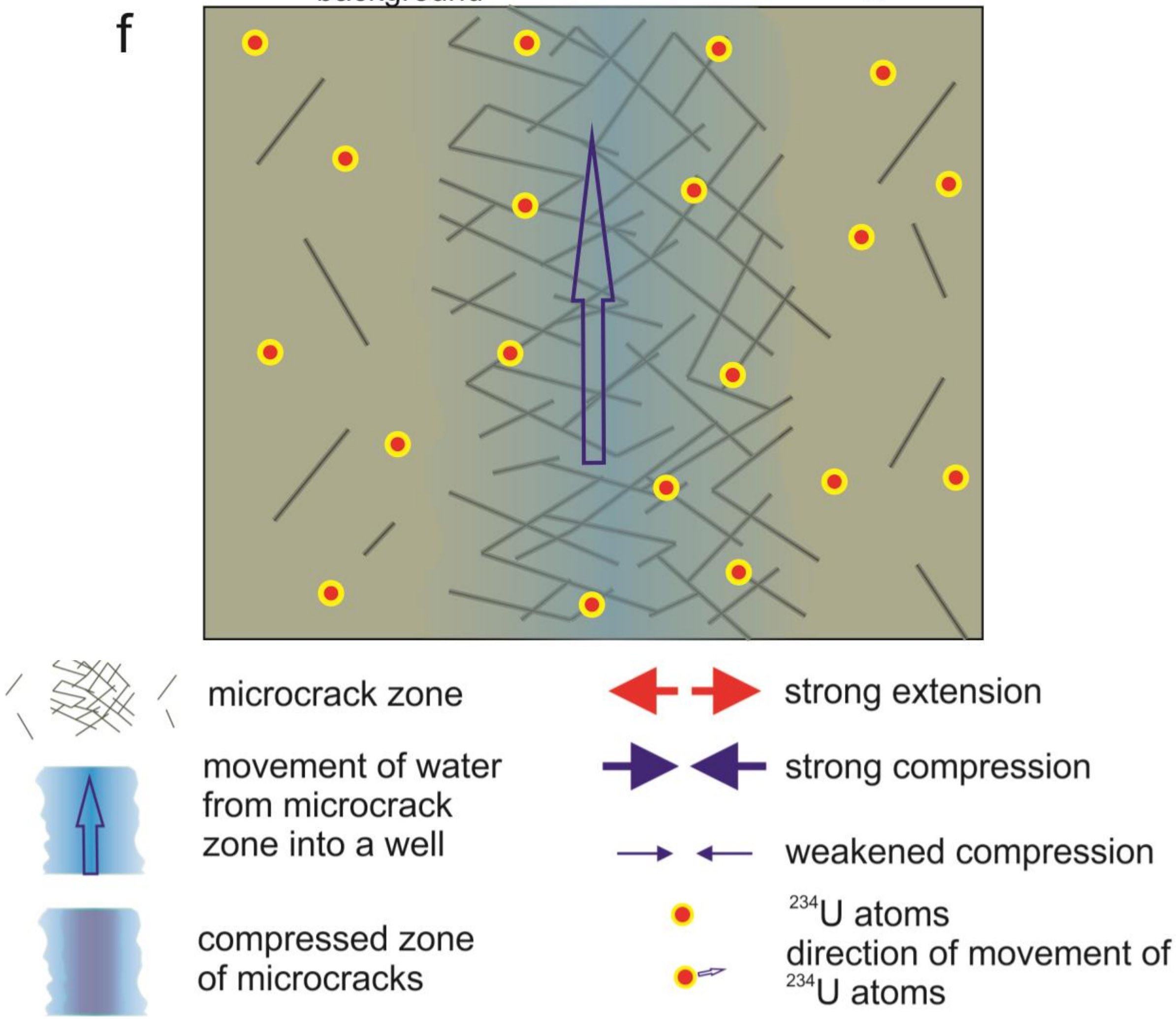
Weakening of the compression zone. ^{234}U atoms are transported by water from periphery to axis of active fault (A4 is averaged).

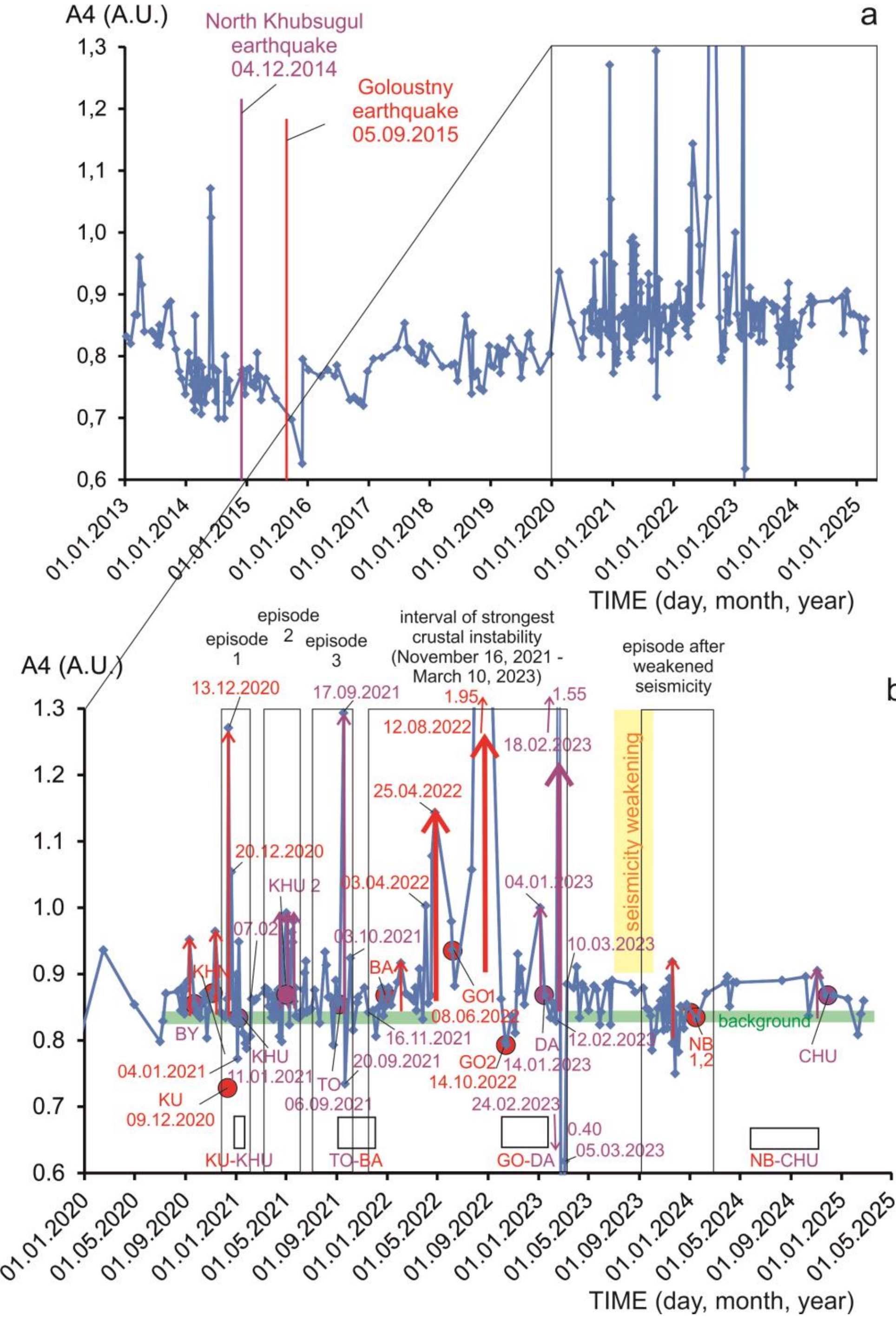
e



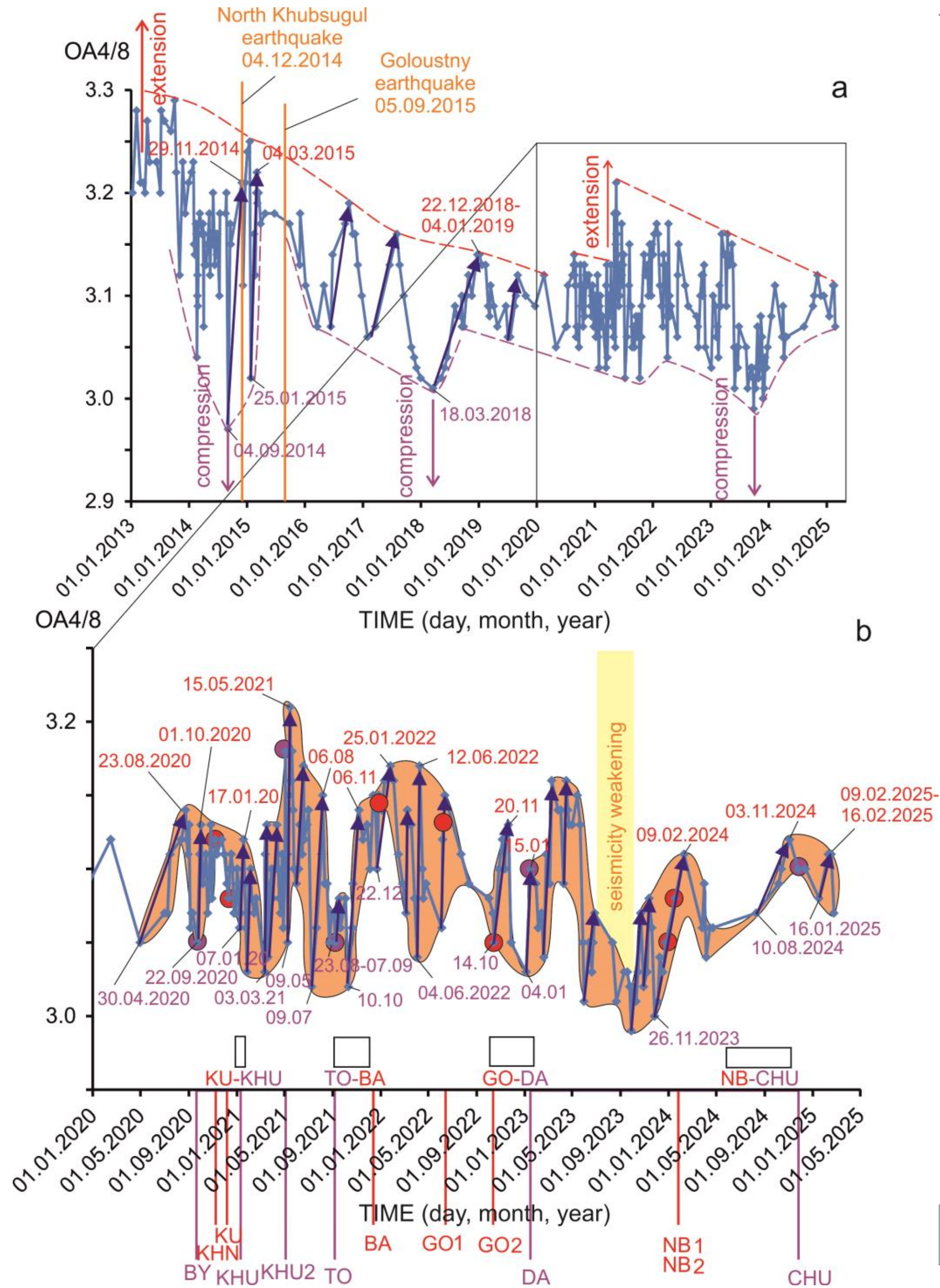
Final neutral regime. Background activities ^{234}U lower than $A4_{background}$ initial neutral regime

f



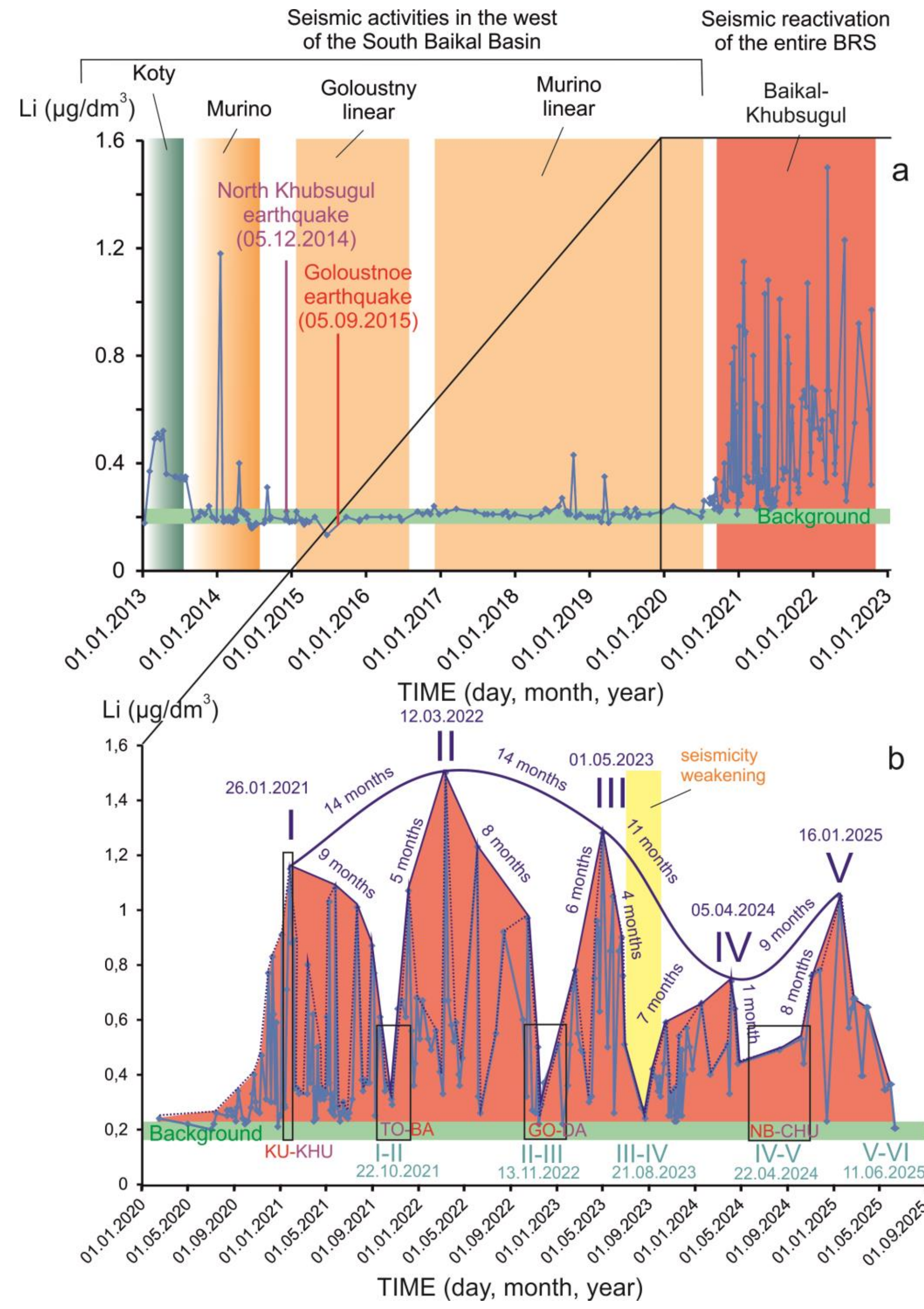


Opening and closing of microcracks in the earth's crust is reflected in more contrast temporal variations in concentration of the ^{234}U isotope in groundwater. Due to the compression of the earth's crust, microcracks close, making it difficult for groundwater to circulate. During the preparation of the Goloustnoe earthquake 1 (GO1), there is a trend of a sharp drop in A4. Afterwards, in the time interval of 2020–2025, the prevailing A4 values of groundwater at station 27 rises to the level of 2013. Over the course of five years, four short episodes and one long interval of significant A4 variations are observed.



In the diagram of OA4/8 temporal variations in 2013–2025, the lower envelope line, indicating the compression level, rises in the second half of 2018 and gradually decreases until the second half of 2021. Then the lower envelope line continues to decline with a slight rise until the second half of 2024 and rises by the end of the observation series (by now). The upper envelope line, indicating the extension level, falls by the beginning of 2020, passes the 2020–2021 step with an exit to the maximum on May 20, 2021, and generally decreases by the end of the observation series.

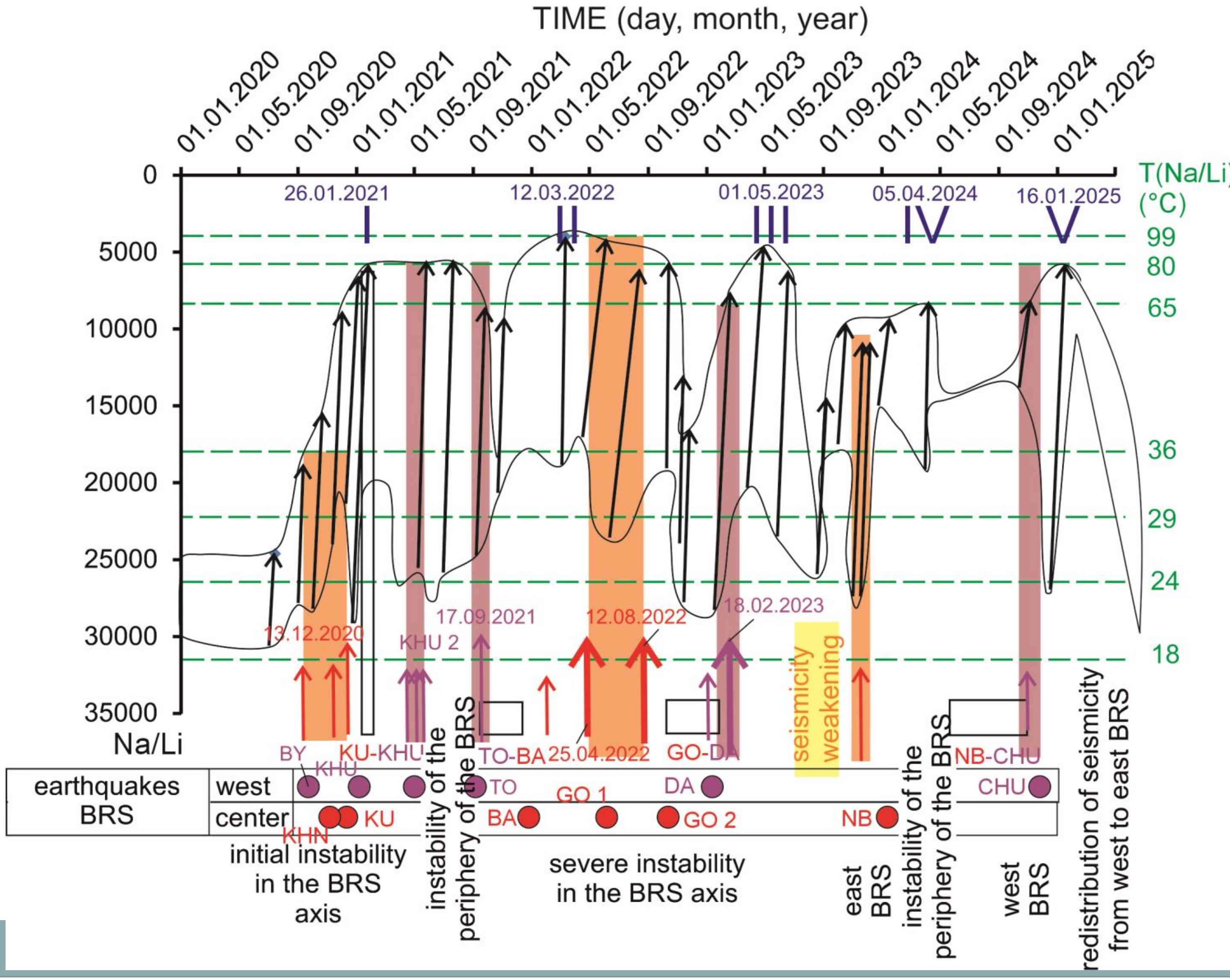
OA4/8 variations are perceived as an indicator of alternation of acting forces and turning points are perceived as moments of reorganization of this alternation.

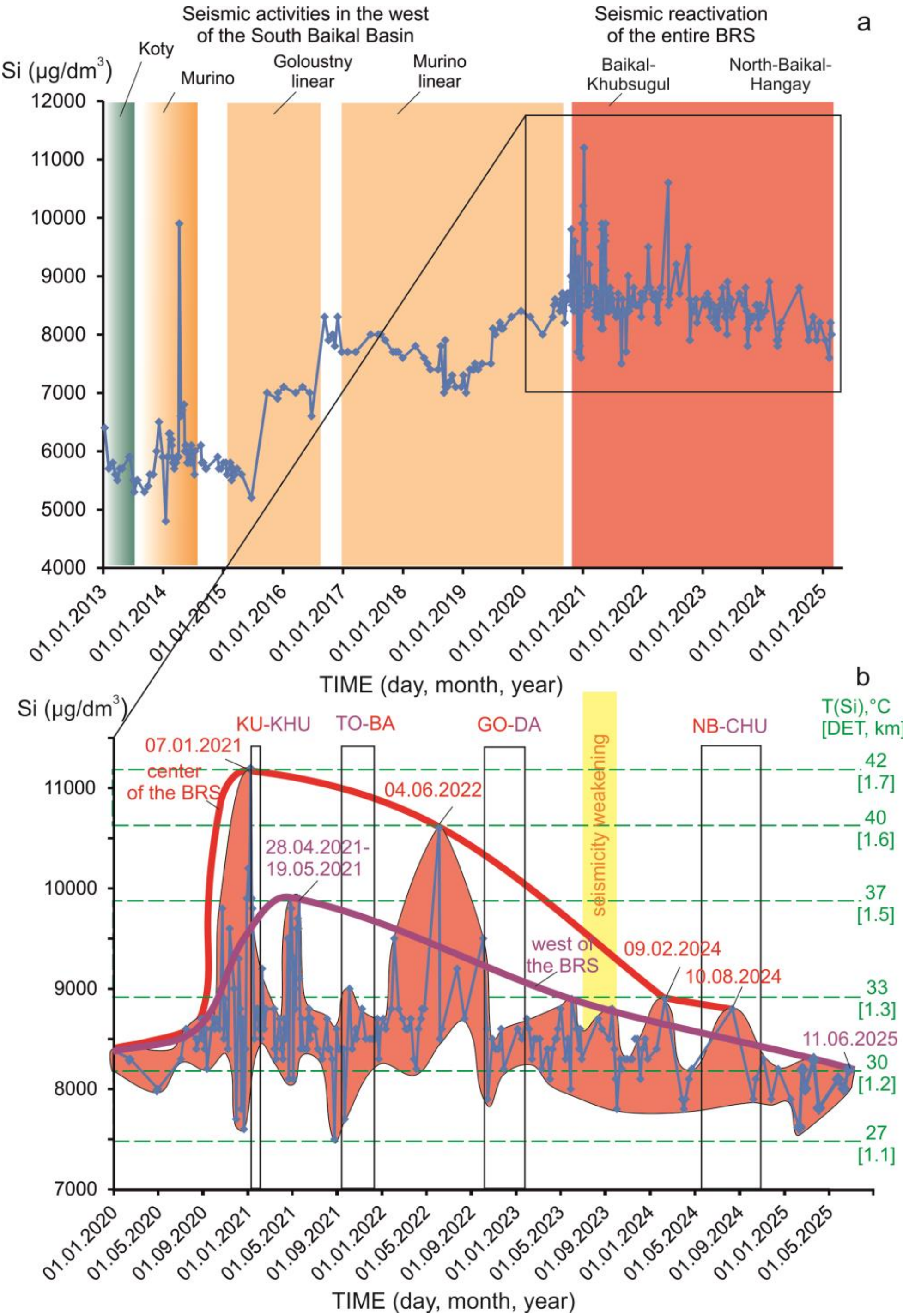


Li-deformation responses are displayed in groundwater at station 27 in 2013–2015, before the North-Khubsugul and Goloustnoe earthquakes. After these seismic events, during the Murino seismic reactivation, Goloustnoe one with a linear distribution of earthquake epicenters and the Murino with the same linear distribution of earthquakes in 2015–2020, the Li concentration is determined mainly at the background level (about 0.2 μg/dm^3). Since the beginning of the Baikal-Khubsugul reactivation in 2020, the Li concentration has been consistently increased and fluctuated with a large amplitude.

In 2021–2025, five Li maxima are designated that correspond to the first 5 months of each year (from January to May).

Temporal variations in the Na/Li ratio in groundwater at station 27 are characterized by variations similar to the temporal variations in Li concentration. Li maxima correspond to Na/Li ratio minima

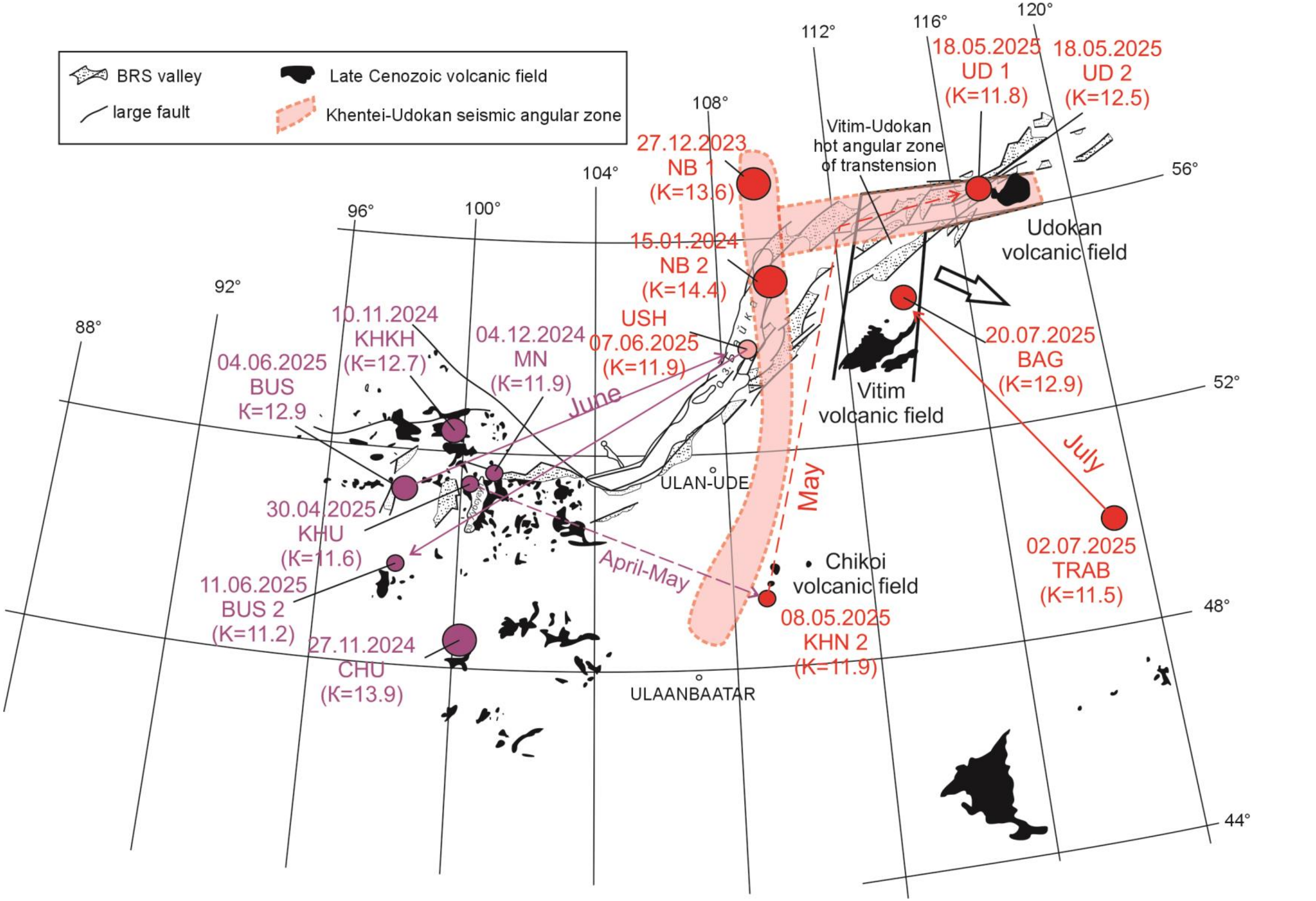




The diagram shows a stepwise increase in Si in the groundwater of station 27 with a division into early, middle and late time intervals. The low level is recorded in the early time interval (2012–2015), the high level in the late time interval (2019–2025), and the intermediate level in the middle time interval (2015–2019). The jump in Si concentration from the early to the middle interval occurs after the Goloustnoe earthquake (September 5, 2015). The late time interval corresponds to the Baikal-Khubsugul and North-Baikal-Hangay seismic reactivations. With the onset of the Baikal-Khubsugul reactivation, the Si concentration and GET increased.

If in March-June 2025 (or later) the Si concentration in groundwater at station 27 increases to the concentration value of the red envelope line, this increase will serve as a signal of the beginning of seismicity reorganization with a redistribution of activity from the west to the center of the BRS.

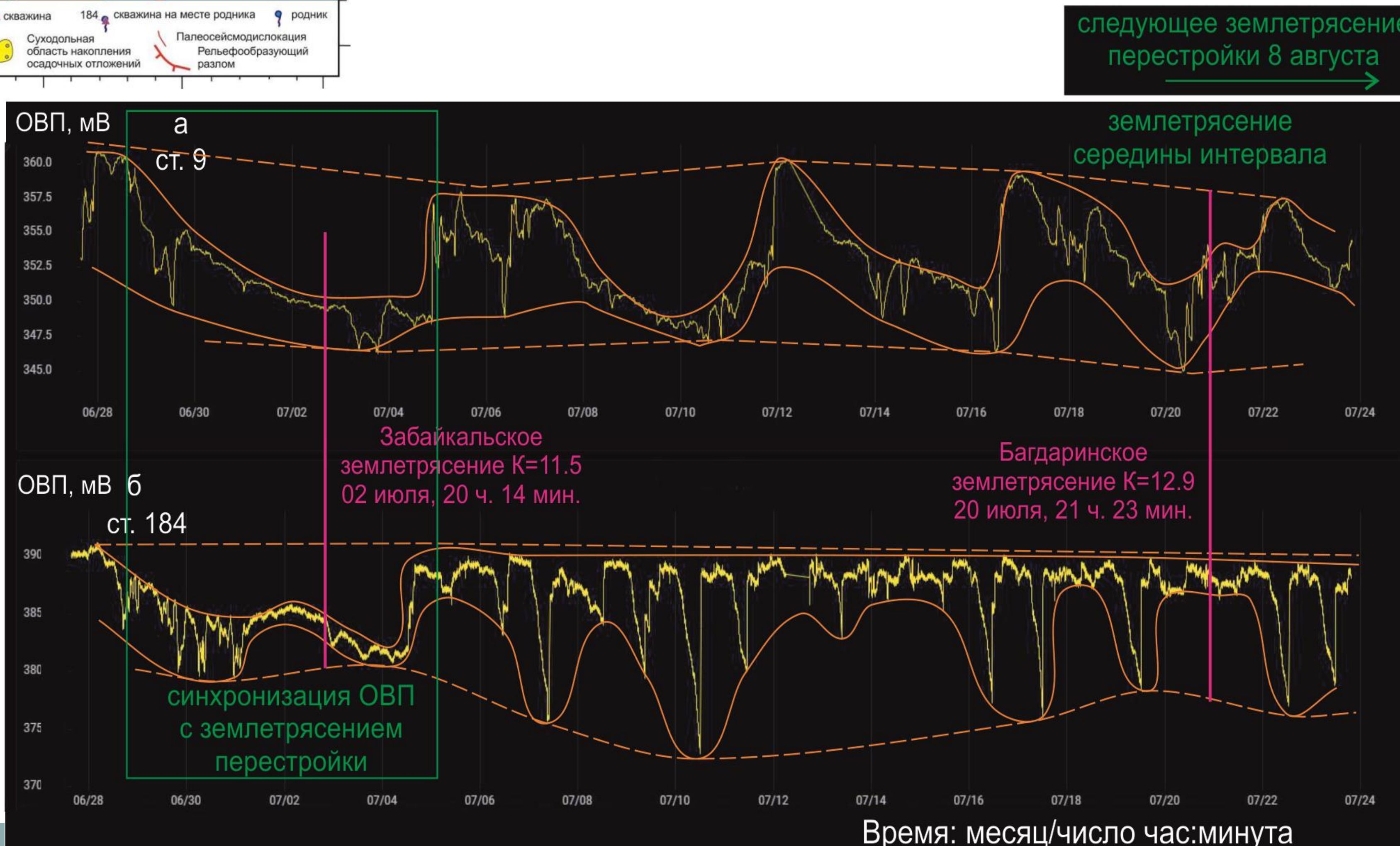
Structural control of seismicity by Cenozoic hot angular zones: present-day state of the earth's crust assessment



Spatial distribution of large and moderate earthquakes of the North Baikal-Hangay seismic reactivation relative to the Cenozoic volcanic fields of the BRS.

The scheme is provided to define a state of the earth's crust of the BRS in May-July 2025.

Hydrogeochemical monitoring has been accompanied by real-time measurements of the oxidation-reduction potential (ORP), pH, and temperature in two wells since December 2023 (Rasskazov et al., 2023).



Conclusion

- In 2020–2025 expanding seismogenic deformations in the earth's crust of the Baikal rift system are consistent with variations of Li, Na, Si, and U components in groundwaters from a sensitive point at structural junction between the South Baikal Basin and Tunka Valley
- Large earthquakes designate concentration of seismogenic deformations at the western, central or eastern Baikal Rift System
- In mid-2025 seismic activities redistribute from the western to eastern Baikal Rift System
- We identify the Khentei-Udokan angular seismic zone, that approaching Ulaanbaatar

Thank you for your attention