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Hydro-isotopic ($^{234}U/^{238}U$) zoning of groundwaters in the seismically active southern margin of the Siberian craton, Russia

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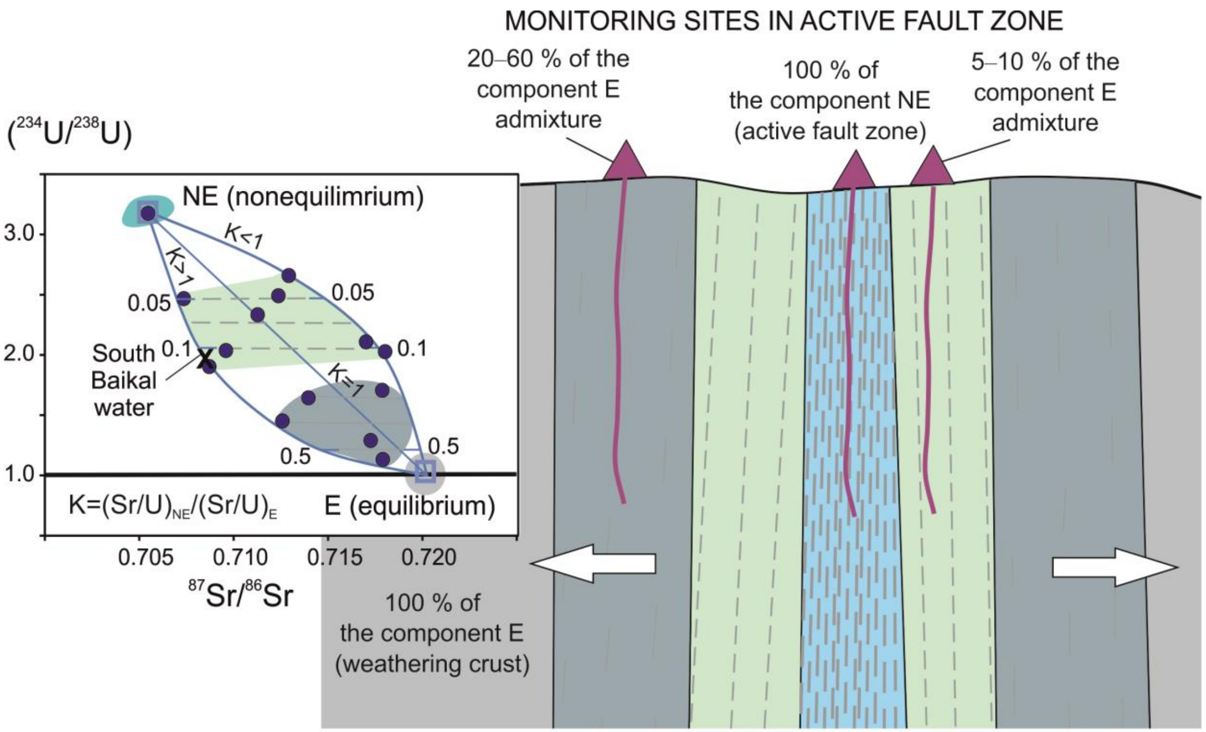
An analysis of earthquake epicenters of the South Baikal basin reveals a quasi-periodic character of seismic reactivation.

Since middle 2012, the $^{234}U/^{238}U$ activity ratio (AR) has been monitored in groundwater of the Kultuk area. Recorded AR temporal variations demonstrates crack open/closing responses to seismogenic state in active faults of the South Baikal basin.



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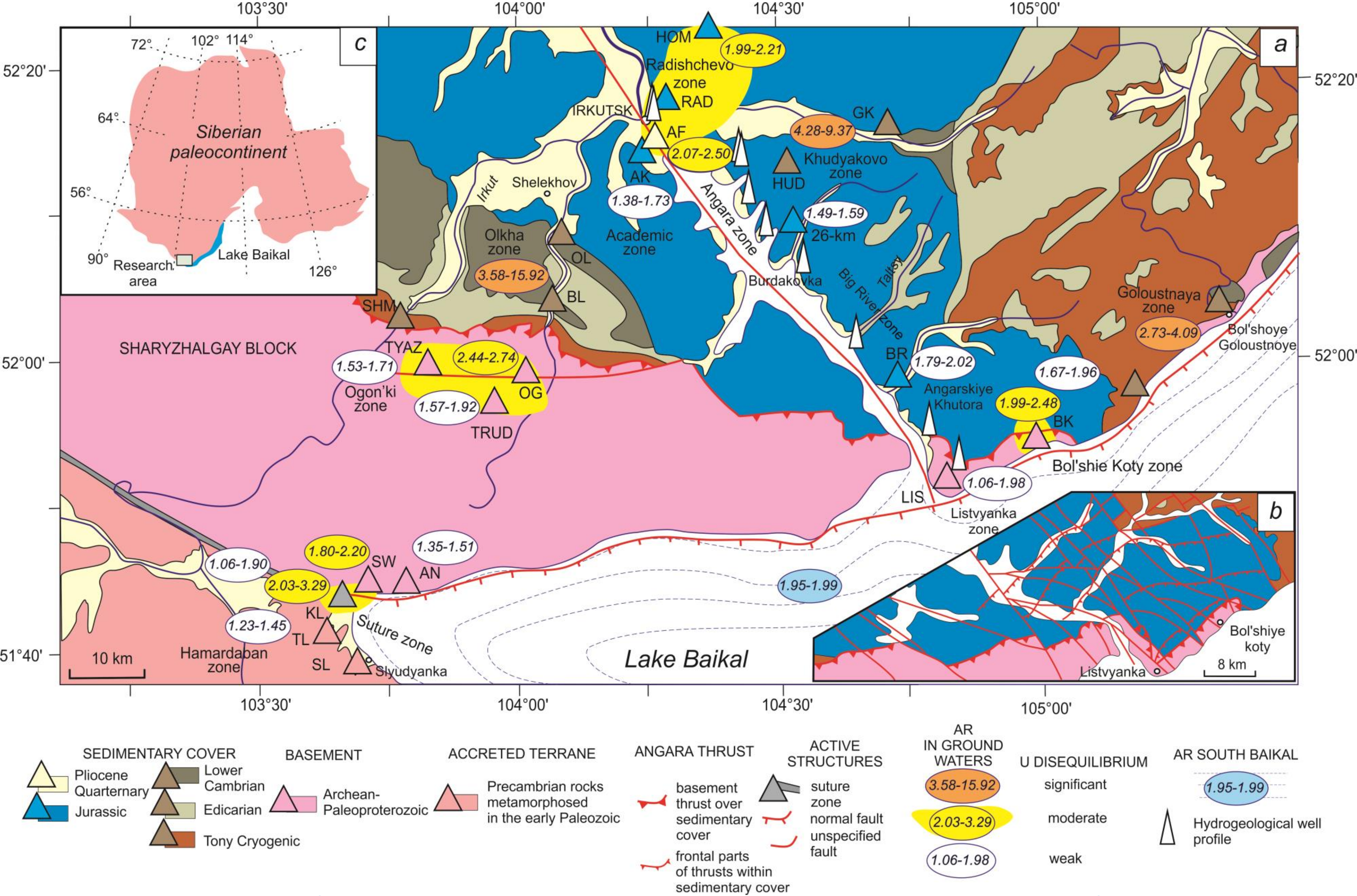

Fig. Zoning scheme of *AR* in groundwater in Irkutsk Prebaikalia. Inset *b* shows faults in the area of Listvyanka village [*Zamaraev et al., 1983*] and inset *c* indicates the location of the work area in the south of the Siberian paleocontinent.

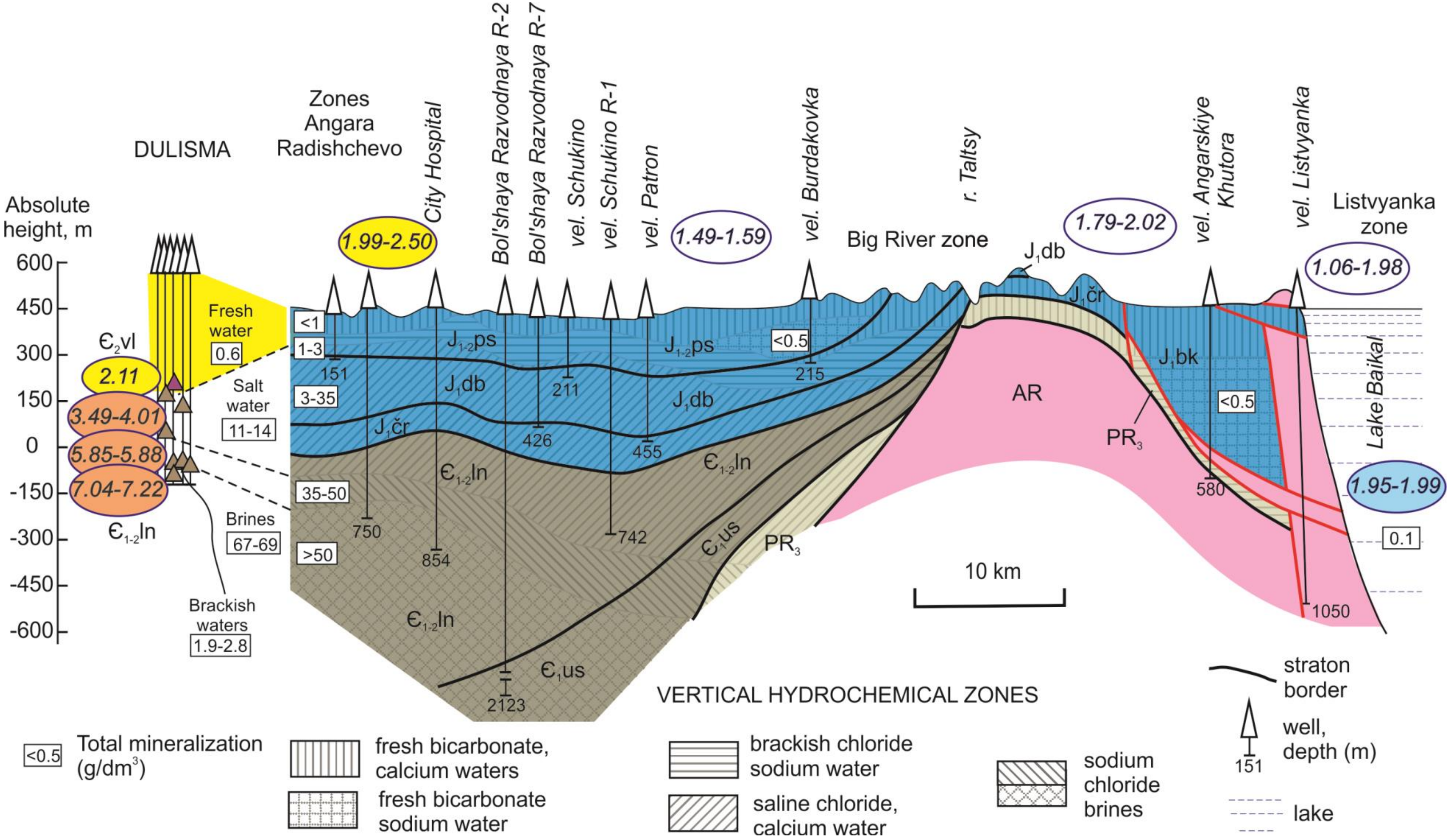

Fig. Correlation scheme of the hydrochemical sections Irkutsk–Listvyanka of the Irkutsk Depression (southern edge of the Siberian paleocontinent) and the Dulisma oil and gas condensate field (inner part of the paleocontinent). Stratigraphic units are shown. Vertical hydrochemical zones are identified. AR values are obtained in the Dulis’ma section. The Irkutsk–Listvyanka profile is modified after [*Pinneker et al., 1968*].

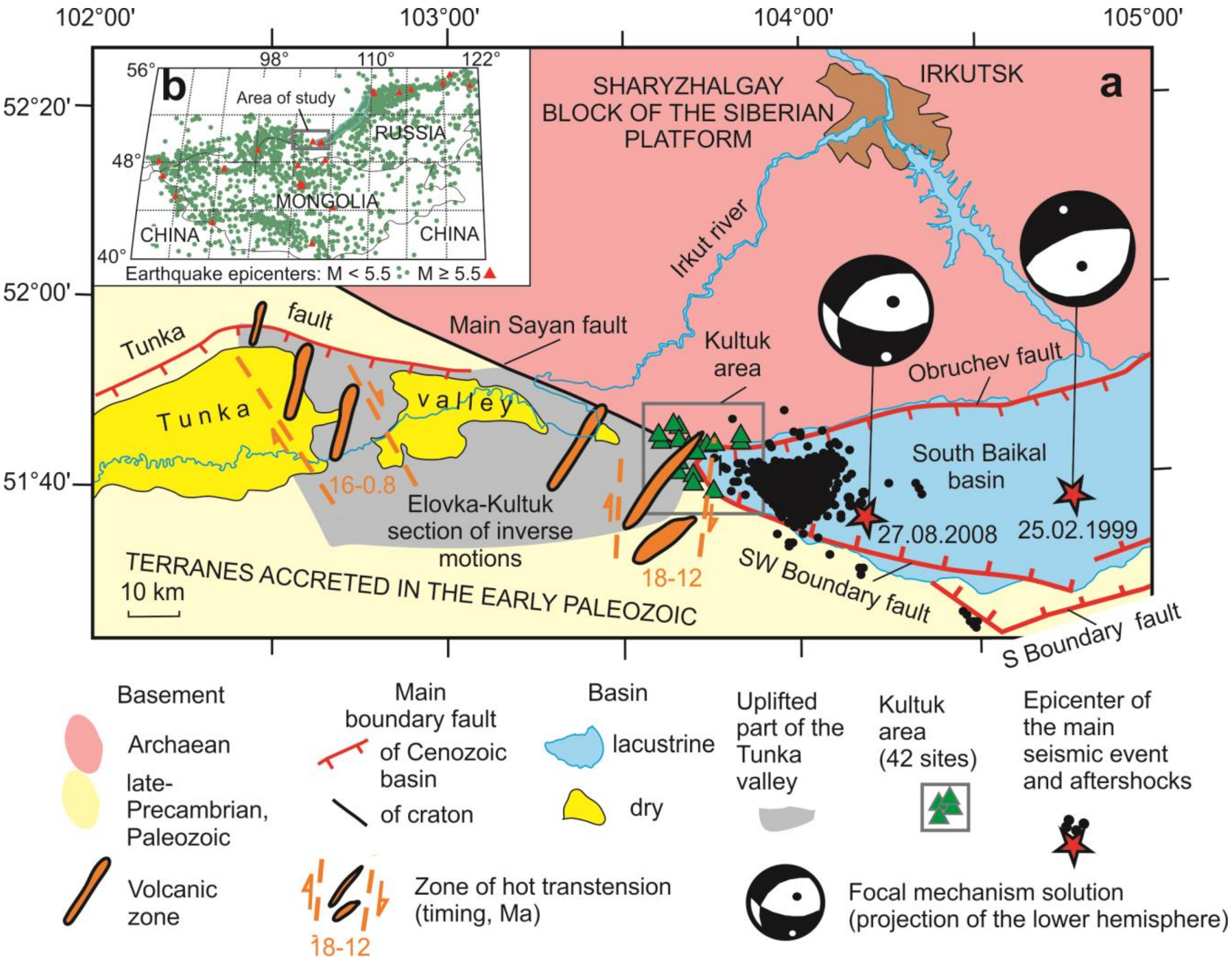

Fig. Spatial position of the Kultuk area for earthquake prediction between the extended South Baikal basin and compressed inverted part of the Tunka valley. On panel *a*: master faults of the South Baikal basin are adopted from Florensov (1968), epicenter and mechanism of the main seismic shock and aftershocks of the 2008 Kultuk earthquake are shown after Melnikova et al. (2012), epicenter of the 1999 South Baikal earthquake after Radziminovich et al. (2006), zones of hot transtension after Rasskazov et al. (2013). On panel *b*: earthquake distribution in the Baikal-Mongolian region in 1960–2003 is plotted after Sherman (2014).

The Kultuk area is defined as the area between the lacustrine South Baikal basin and the Tunka valley.
The epicenter of the Kultuk earthquake was 40 km east-southeast of the Kultuk village. From a spatial shift of aftershocks, seismogenic rupture was inferred to be directed from the main epicenter to the Kultuk area, therefore it was designated as a potential location of a future large earthquake presumably accommodated in the Main Sayan fault zone. Both $^{234}U/^{238}U$ activity ratio (AR) and an uranium concetration [U] were monitored in groundwater samples from the Kultuk area for earthquake prediction.

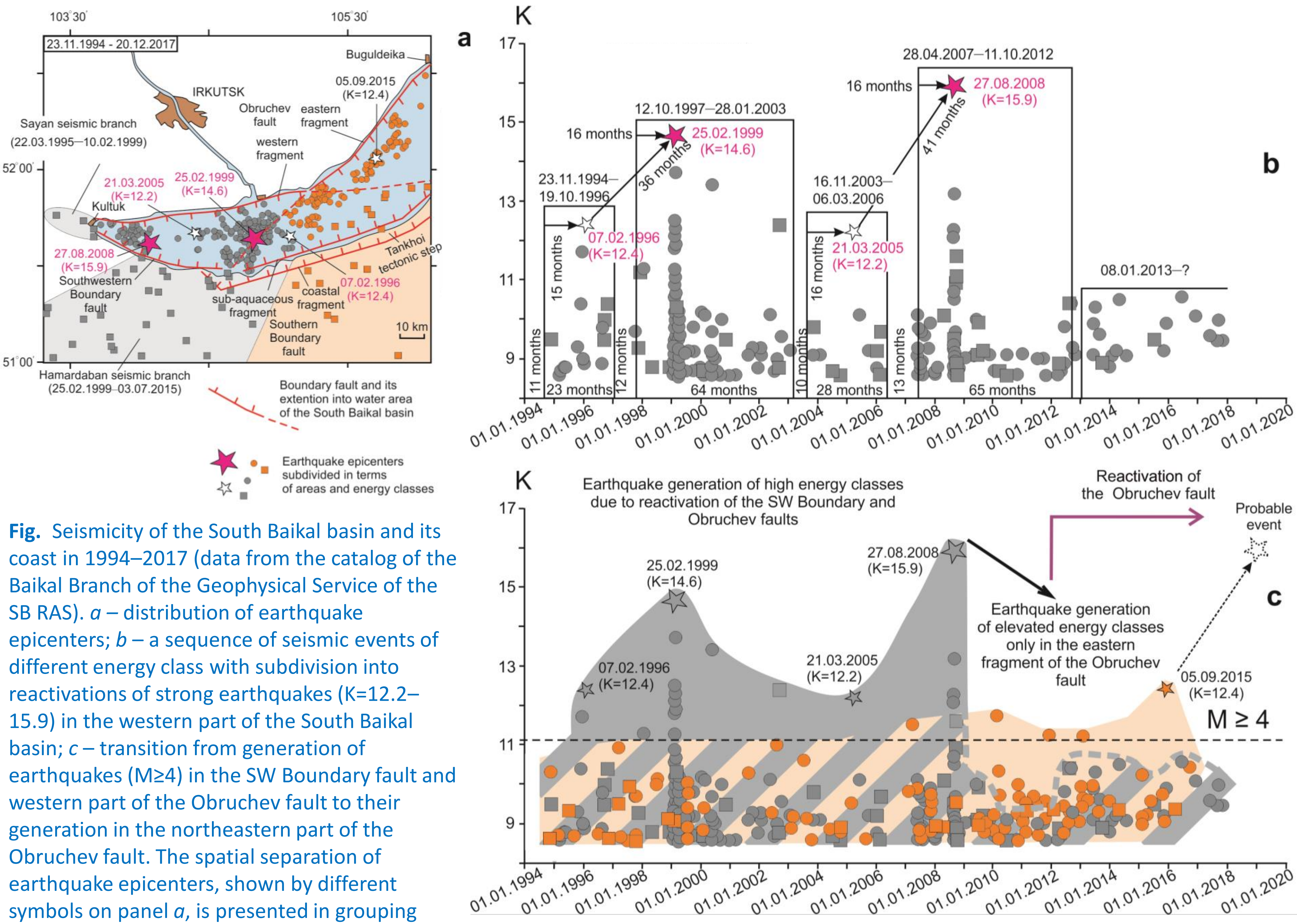

Fig. Seismicity of the South Baikal basin and its coast in 1994–2017 (data from the catalog of the Baikal Branch of the Geophysical Service of the SB RAS). *a* – distribution of earthquake epicenters; *b* – a sequence of seismic events of different energy class with subdivision into reactivations of strong earthquakes (K=12.2–15.9) in the western part of the South Baikal basin; *c* – transition from generation of earthquakes (M≥4) in the SW Boundary fault and western part of the Obruchev fault to their generation in the northeastern part of the Obruchev fault. The spatial separation of earthquake epicenters, shown by different symbols on panel *a*, is presented in grouping earthquakes with different energy class on panels *b* and *c*.

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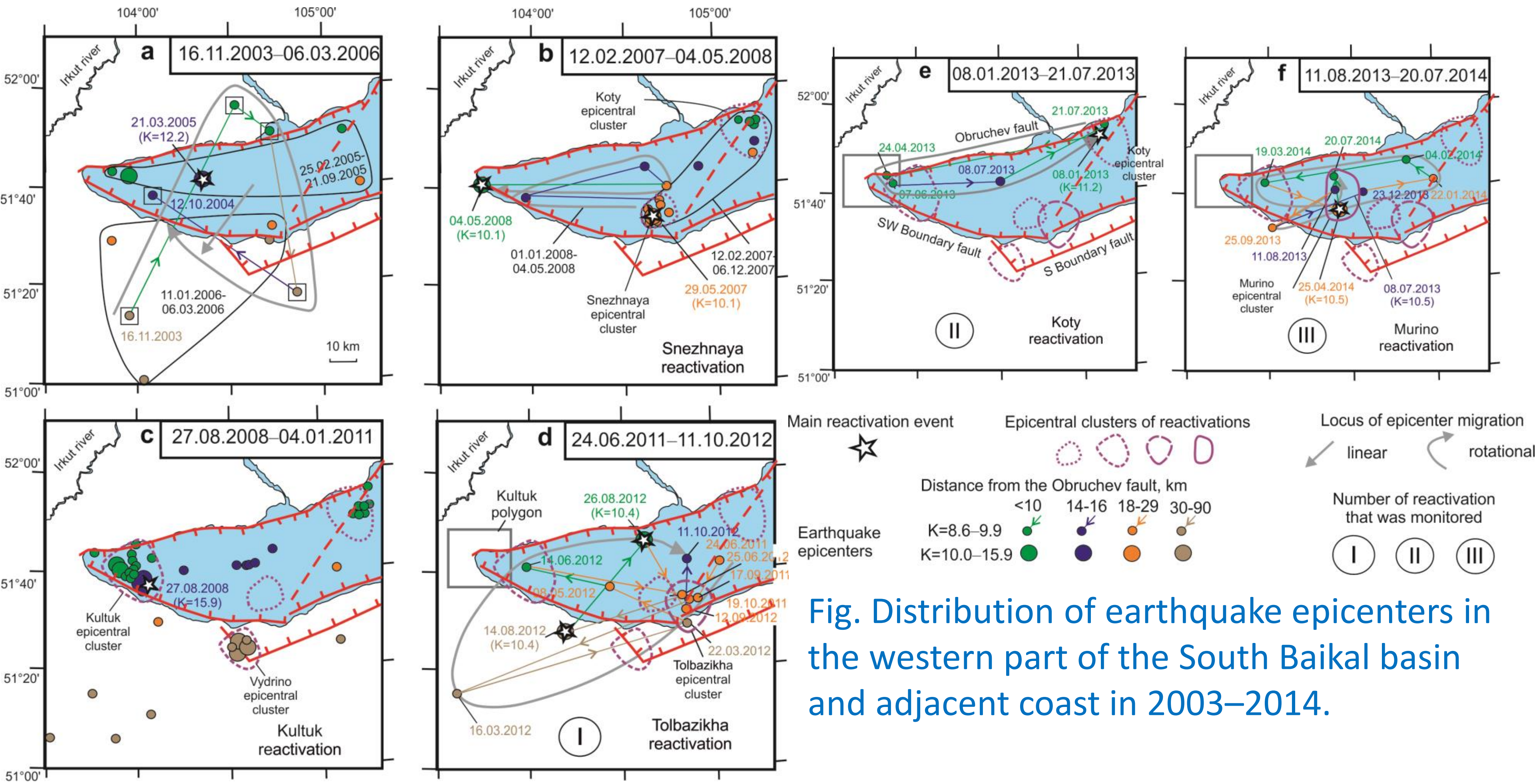


Fig. Distribution of earthquake epicenters in the western part of the South Baikal basin and adjacent coast in 2003–2014.

In 2003–2004, earthquakes were sparse and dispersed in lake areas along its southern and northern coasts. In 2005–2006, the major earthquake of 21.03.2005 (K = 12.2) was marked by an epicenter in the central part of the lake area. Over time, the major Kultuk event of 2008 (M=6.3) took place. We identify a sequence of seismic reactivations, during three of which (I – Tolbazikha, II – Koty, and III – Murino) we monitor 234U/238U activity ratio (AR) and an uranium concentration [U]. We started the monitoring in 2012.

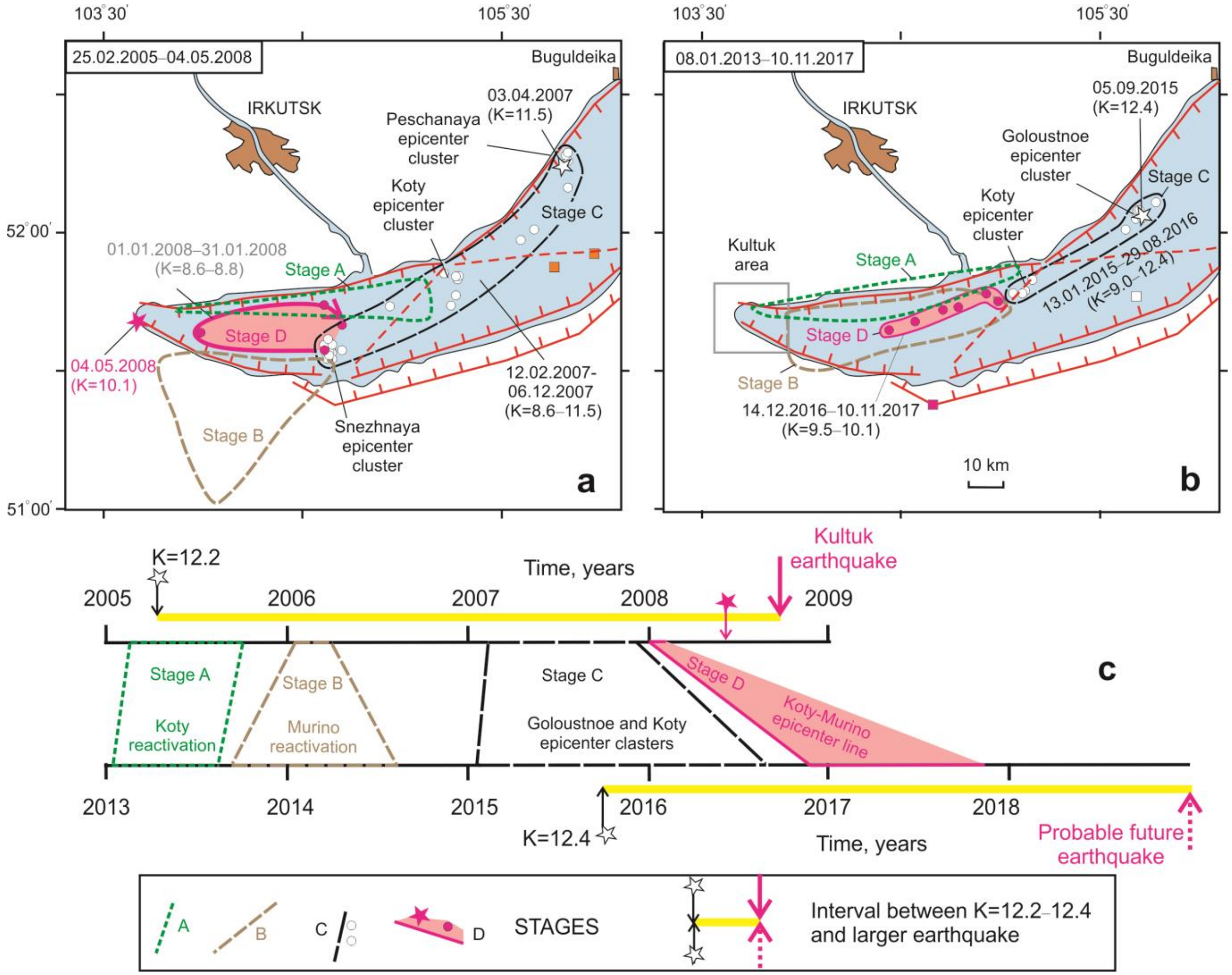
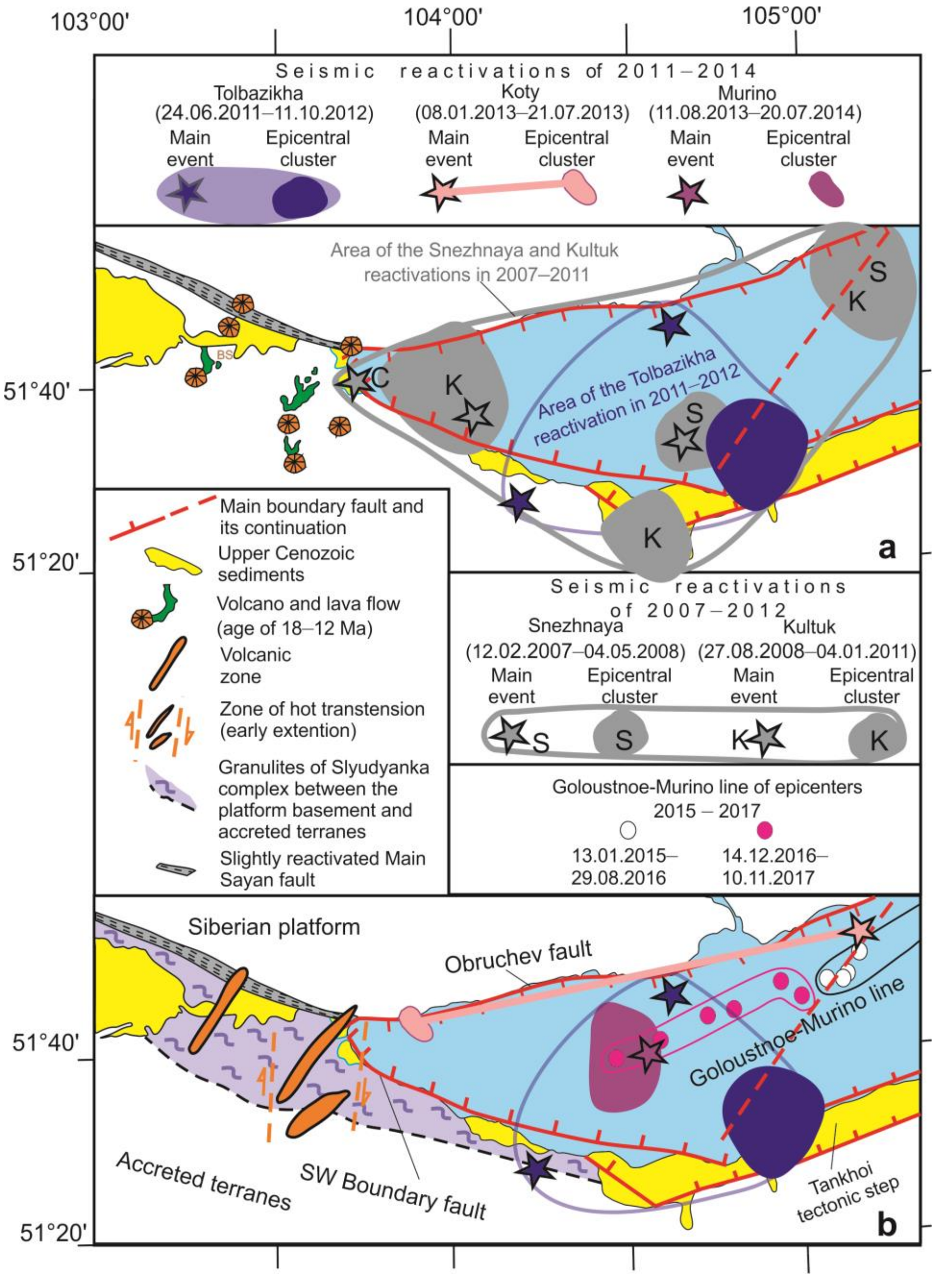


Fig. Comparisons of spatial-temporal patters of earthquake epicenters related to build-up of the Kultuk and probable future earthquakes.
a – stages A–D; *b* – similar stages of a probable future large earthquake; *c* – correlation of the stages on time scales.

From the first earthquake of the Koty reactivation on 08.01.2013 until the next large earthquake, seismicity developed over 5 years, similar to the stages A, B, C, and D of the Kultuk earthquake, which lasted 3 years and 2 months. In both cases, stages A and B occurred during the initial 1.5 years, and the stage C began approximately 2 years after onset of the stage A (respectively, in early 2007 and 2015). Subsequently, stage C of large earthquake build-up lasted 1.5 years longer than the respective stage C of the Kultuk earthquake build-up. The new stage D may be also longer than the respective stage D of the previous Kultuk earthquake build-up.



Highlighting the role of major event epicenters and epicenter clusters in every seismic reactivation, one can see their distribution in the Snezhnaya, Kultuk, and Tolbazikha reactivations of 2007–2012 along the northern and southern boundary faults of the South Baikal basin. In the Snezhnaya and Kultuk reactivations, the area of the major seismic events was the largest. In the Tolbazikha reactivation, it was reduced with the subsequent transition to the narrow linear epicenter zone of the Koty reactivation in front of the western fragment of the Obruchev fault and to the Goloustnoe-Murino locus in front of both the western and northeastern fragments of the fault.

Sampling of groundwater was initiated in the Kultuk area 2 weeks after the 14.06.2012 earthquake of the Tolbazikha reactivation.

Fig. Synthesis of data on spatial-temporal evolution of seismicity in the western part of the South Baikal basin before and after the Tolbazikha reactivation that finalized the 2003–2012 seismic interval.

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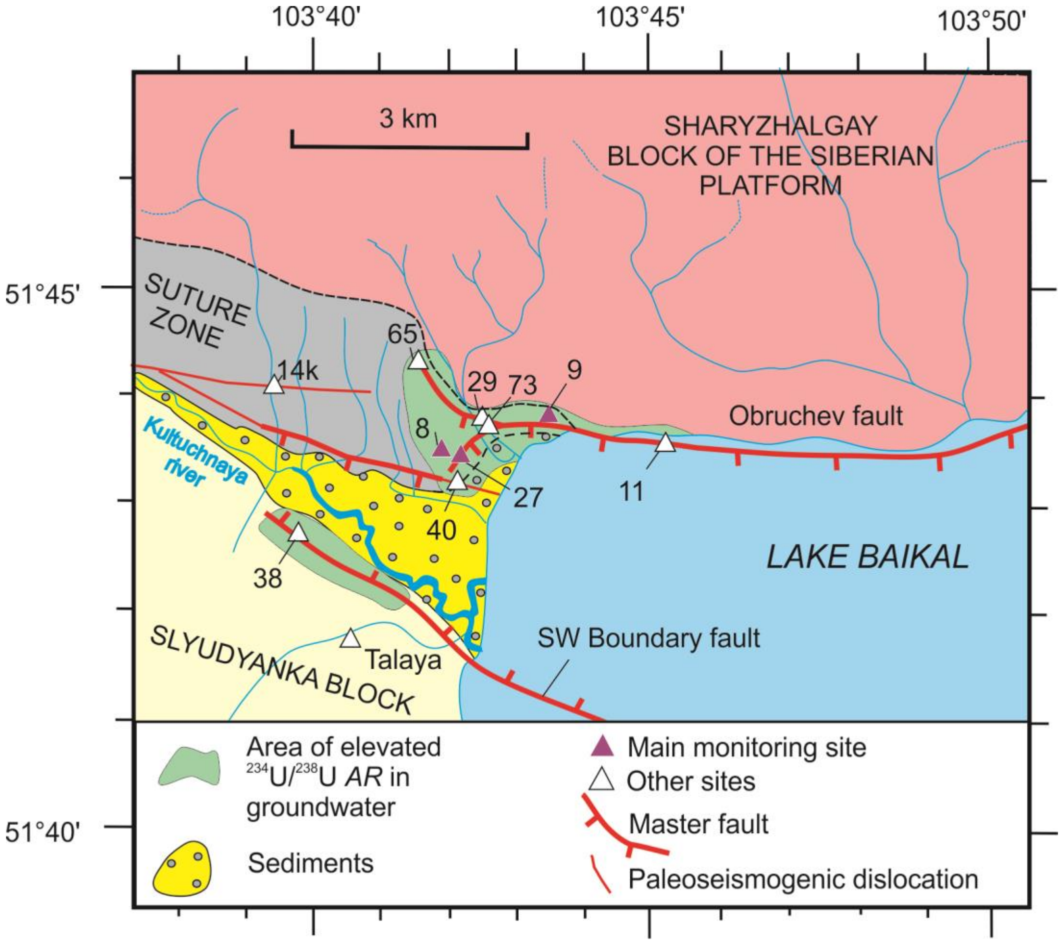


Fig. The Kultuk area for earthquake prediction. Areas of elevated *AR* values in groundwater are highlighted after Rasskazov et al. (2015). Paleoseismogenic dislocations in the Main Sayan fault zone are shown after Chipizubov and Smekalin (1999).

Among 42 drill holes and springs, seven were selected for permanent hydroisotopic monitoring. Five monitoring sites (8, 9, 27, 40, and 38) were wells in the Kultuk village as deep as 120 m, one (14k) was a spring, another (11) – a water intake from Lake Baikal. Sites 9, 8, and 27 are along the Obruchev fault, site 38 at the SW Boundary fault, sites 40 and 14k at local paleoseismogenic dislocations of the Main Sayan fault. The water intake site (11) mainly reflects the composition in the littoral zone of Lake Baikal with an admixture of a component entering from the Obruchev fault. We present results of hydroisotopic monitoring in sites 8, 9, and 27, located in the Obruchev fault. For comparisons, we integrate results of hydroisotopic monitoring of site 14k and data of deformational and temperature monitoring of rocks in the Talaya adit .

While analyzing *AR* variations in groundwater during 2012–2014, 4 phases are distinguished on diagrams of sites during every seismic reactivation:

(1) an initial phase *a* with earthquake epicenters remote from the Kultuk area,
(2) an intermediate phase *b* with earthquake epicenters in the Kultuk area or near it,
(3) a final phase *c* with new remote earthquake epicenters, and
(4) an aseismic phase *d*.

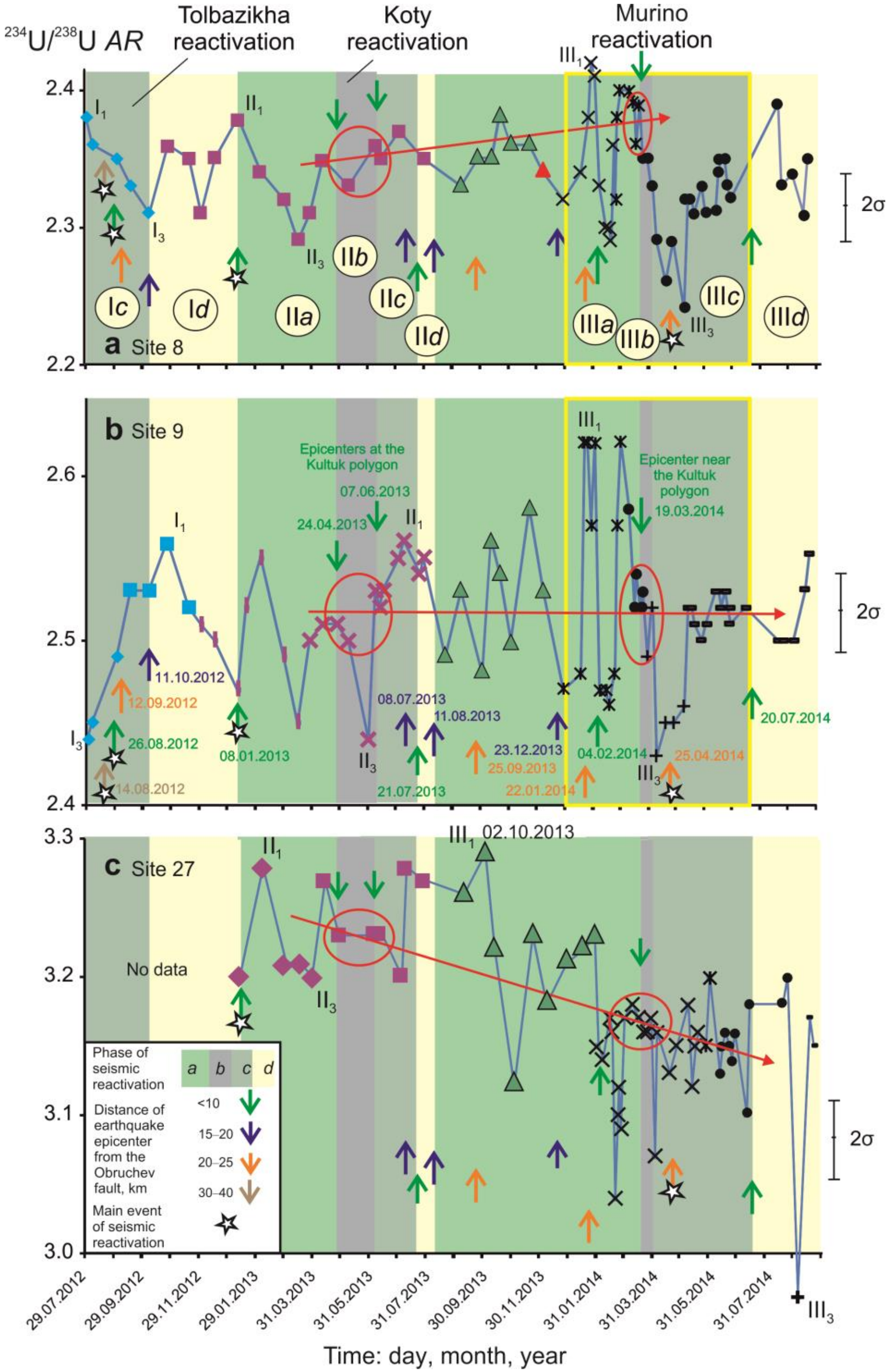
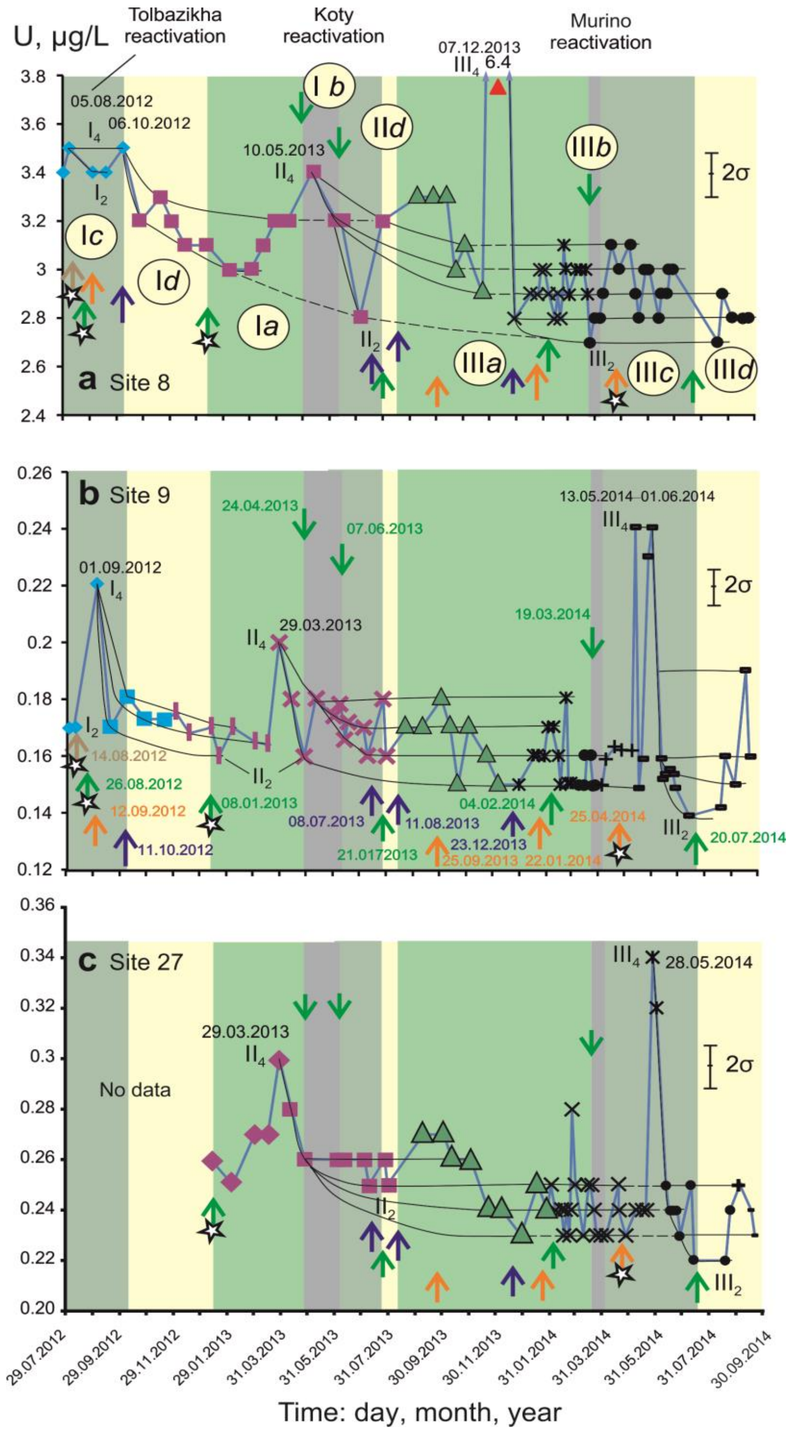


Fig. Temporal *AR* variations in groundwater from sites 9 (*a*), 8 (*b*), and 27 (*c*) in the context of seismic reactivations in the western part of the South Baikal basin. The extreme components of seismic reactivations are indicated for each site. Red ellipses mark data points that correspond to the phases II*b* and III*b*, when seismic events occurred in the Kultuk area or its vicinity. Red arrows indicate trends of isotope ratios fixed at the phases II*b* and III*b*. The yellow rectangles on panels *a* and *b* indicate the interval (first half of 2014), in which *AR* oscillations in sites 9 and 8 were mutually consistent. One bar on the abscissa axis corresponds to one month.



Peaks of [U] occurred during different phases of seismic reactivations. In site 9, a maximum [U] (0.22 µg/L) occurred in the phase I*c*. It was displayed after the second major earthquake of this reactivation, the epicenter of which was near the Obruchev fault, before a small event of 12.09.2012 at the Tolbazikha epicenter cluster. In site 8, elevated [U] (3.4–3.5 µg/L) was measured in the final stage of the Tolbazikha reactivation in response to its major events on 14.08.2012 and 26.08.2012. In the aseismic interval (phase I*d*), [U] decreased to 3.0–3.3 µg/L.

Fig. Temporal variations of [U] in groundwater from sites 9 (*a*), 8 (*b*), and 27 (*c*) in the context of seismic reactivation in the western part of the South Baikal basin. Symbols of data groups as in Figs 8 and 9. In panel (*a*), the phases of small seismic reactivations from I*c* to III*d* that occurred after strong reactivation of 2007–2010, are marked in circles. Green arrows pointing down show dates of earthquakes occurred in the Kultuk area, arrows of four different colors directing up indicate dates of earthquakes that occurred outside the area at different distances from the Obruchev fault. Maximum [U] is followed with the fan of branches with the lower [U]. One bar on the abscissa axis corresponds to one month.

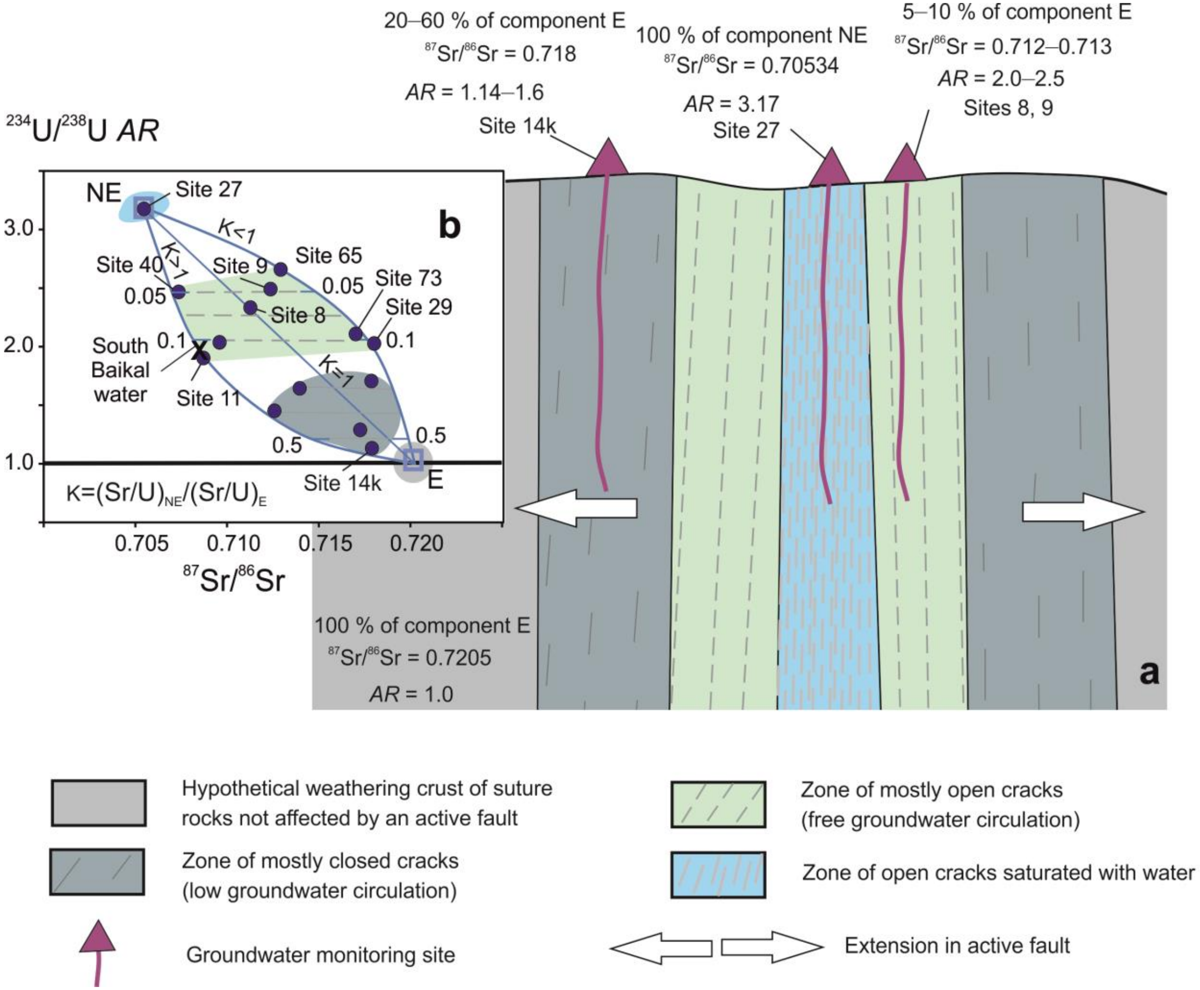


Fig. U–Sr isotope systematics of groundwater from suture rocks in the Kultuk area. *a* – model for end-member mixing on the diagram $^{234}U/^{238}U$ *AR* vs. $^{87}Sr/^{86}Sr$; *b* – subdivision of monitoring sites in terms of water circulation control by opened and closed cracks in an active fault. The end members: E – with equilibrium U, NE – with nonequilibrium U.

In the diagram of $^{234}U/^{238}U$ *AR* vs. $^{87}Sr/^{86}Sr$, a data field of groundwater from the Kultuk area is bounded by curves that converge at points corresponding to the end-members E (equilibrium U) and NE (nonequilibrium U). In the former, U is in cyclic equilibrium with an elevated Sr isotope ratio (*AR* = 1.0, $^{87}Sr/^{86}Sr = 0.7205$), in the latter, U shows a nonequilibrium signature with a lower Sr isotope ratio (*AR* = 3.3, $^{87}Sr/^{86}Sr = 0.70534$). Data points distributed between the curves are characteristic of groundwater from mylonites of the suture zone that separates the Achaean basement of the Siberian platform from the younger accreted terranes.

Those of groundwater from the Achaean block and younger Slyudyanka metamorphic subterrane are shifted to the right and to the left, respectively.

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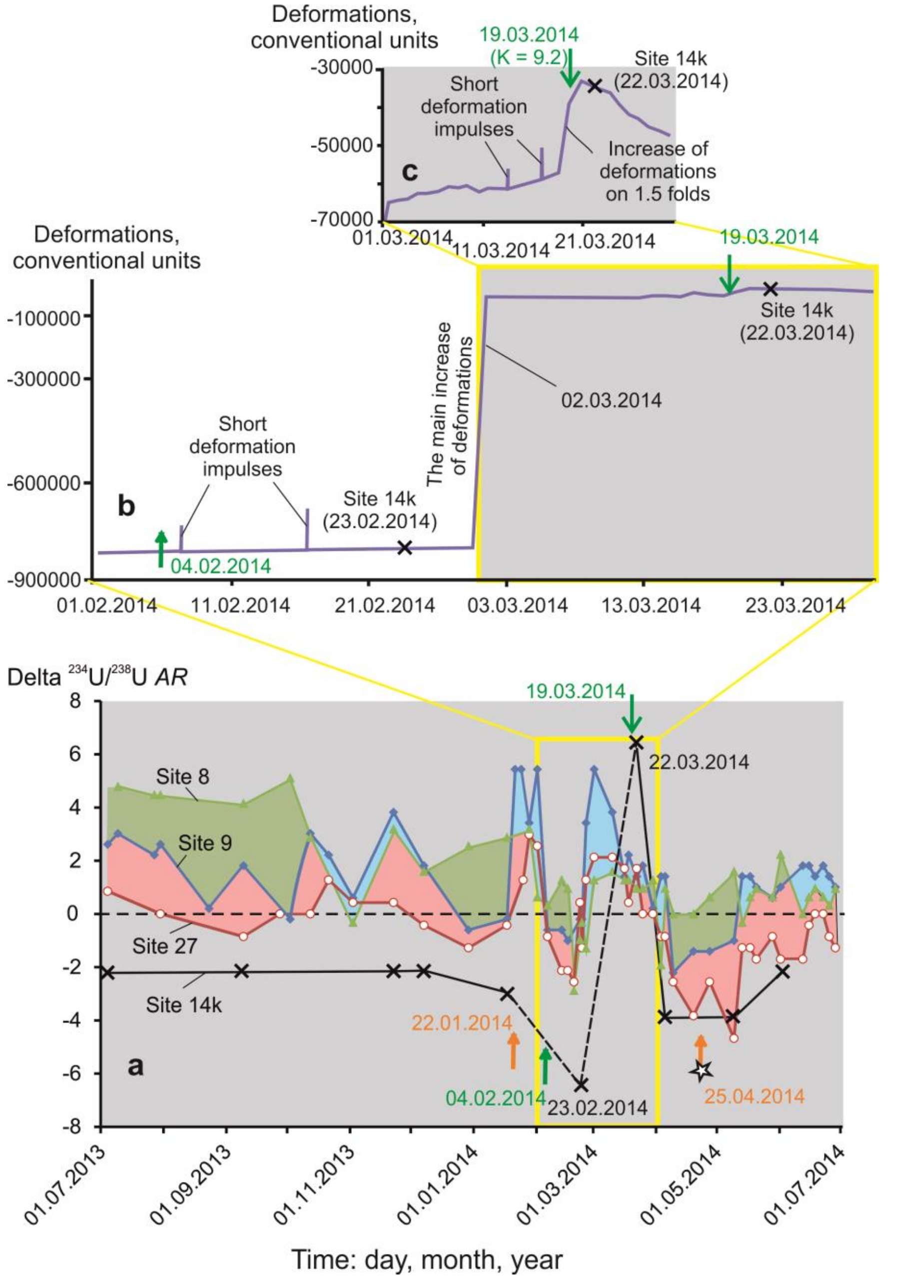


Fig. Temporal variations of a Delta *AR* in groundwater from sites 9, 8, 27, and 14k (*a*) in comparison to temporal variations of rock deformation recorded in the Talaya adit.

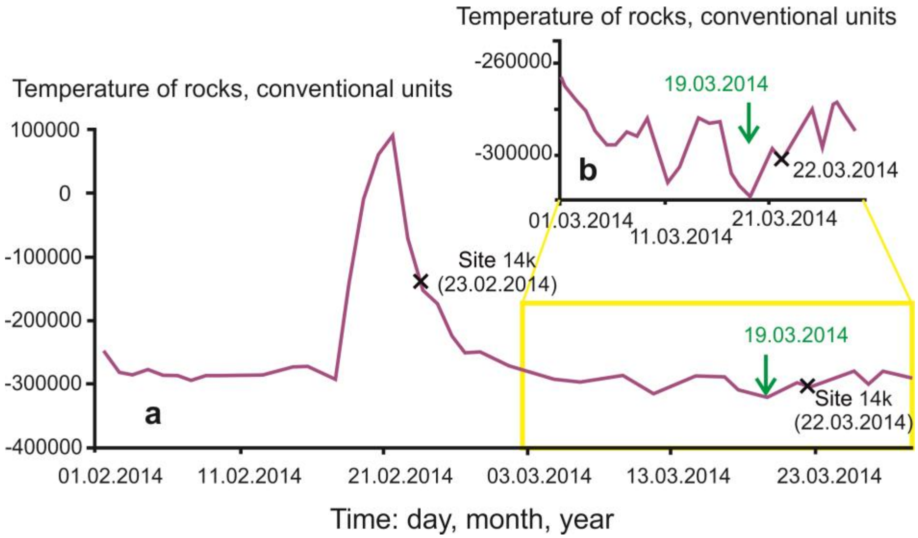
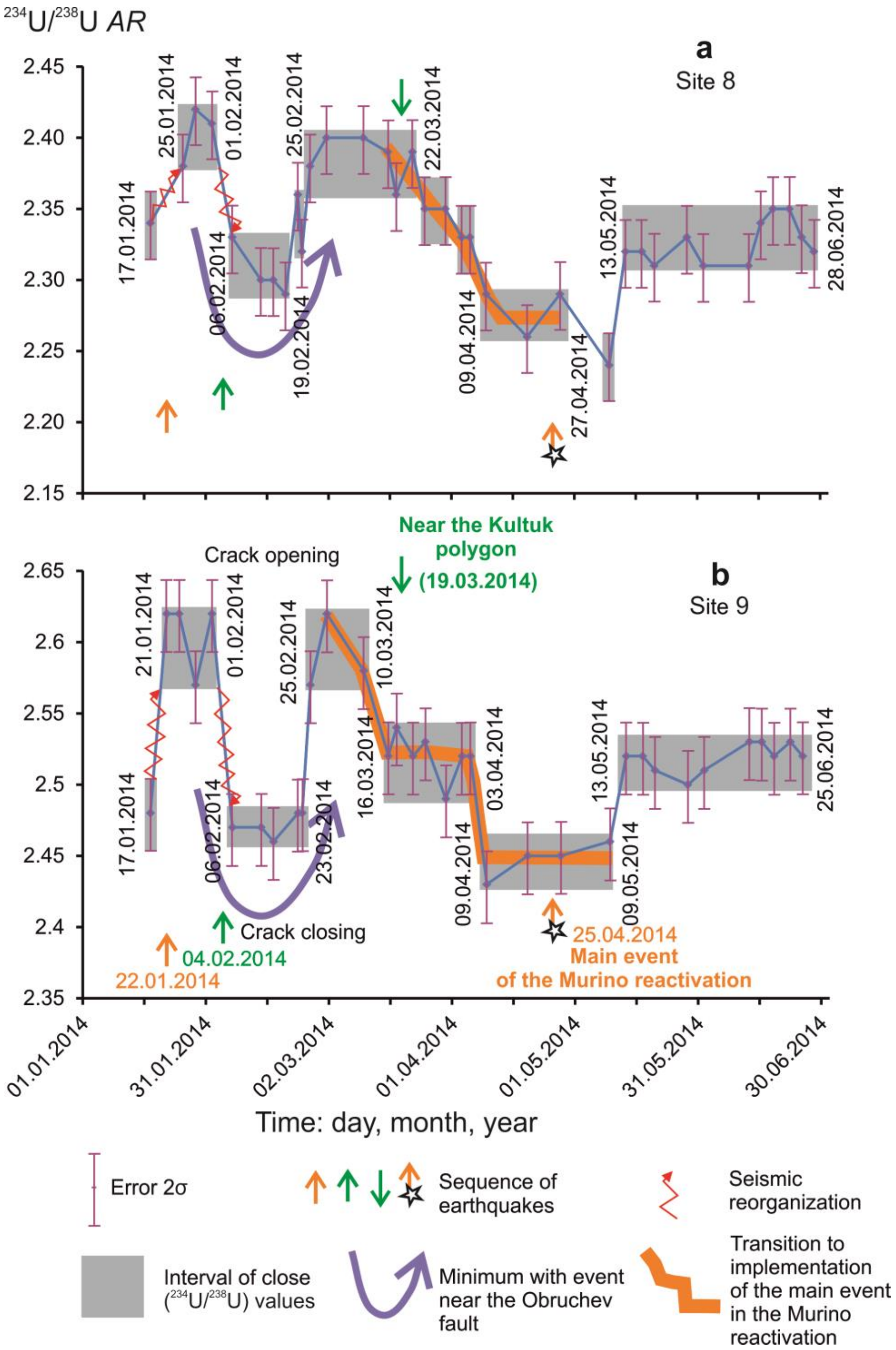


Fig. Variations of temperature in rocks of the Talaya adit recorded in a first approximation (*a*) and with a high resolution (*b*) as compared to timing of an earthquake of 19.03.2014 and sampling of site 14k on 23.02.2014 and 22.03.2014.

Deformation monitoring in the Talaya adit (location in Fig. 7) revealed signs of instability (short multi-amplitude deformation impulses) after an earthquake of 04.02.2014 that occurred near the Obruchev fault. A water sample, taken in site 14k in 23.02.2014, showed a Delta *AR* minimum value. Conversely, the deepest temperature minimum of 19.03.2014 corresponded to a pronounced Delta *AR* maximum and accompanied by an earthquake



When evaluating *AR* data of site 9 for the Murino reactivation (Fig. a), temporal steps of close values within error are separated by rapid transitions. On 01.01.2014–30.06.2014, the step intervals increased from 10 to 43 days. A small earthquake of 19.03.2014 occurred at the beginning of the intermediate step with an *AR* value of ~2.52. The major event of the Murino reactivation of 25.04.2014 was in the middle of the lowest step with an *AR* value of ~2.44. Similar alternating *AR* maxima and minima of site 8 (Fig. b) showed additional intermediate data points between the temporal steps.

Fig. Relationship between *AR* steps in sites 9 (*a*) and 8 (*b*) during the Murino reactivation (at the first half of 2014). One step designates a time interval in which *AR* values are comparable to each other within error.

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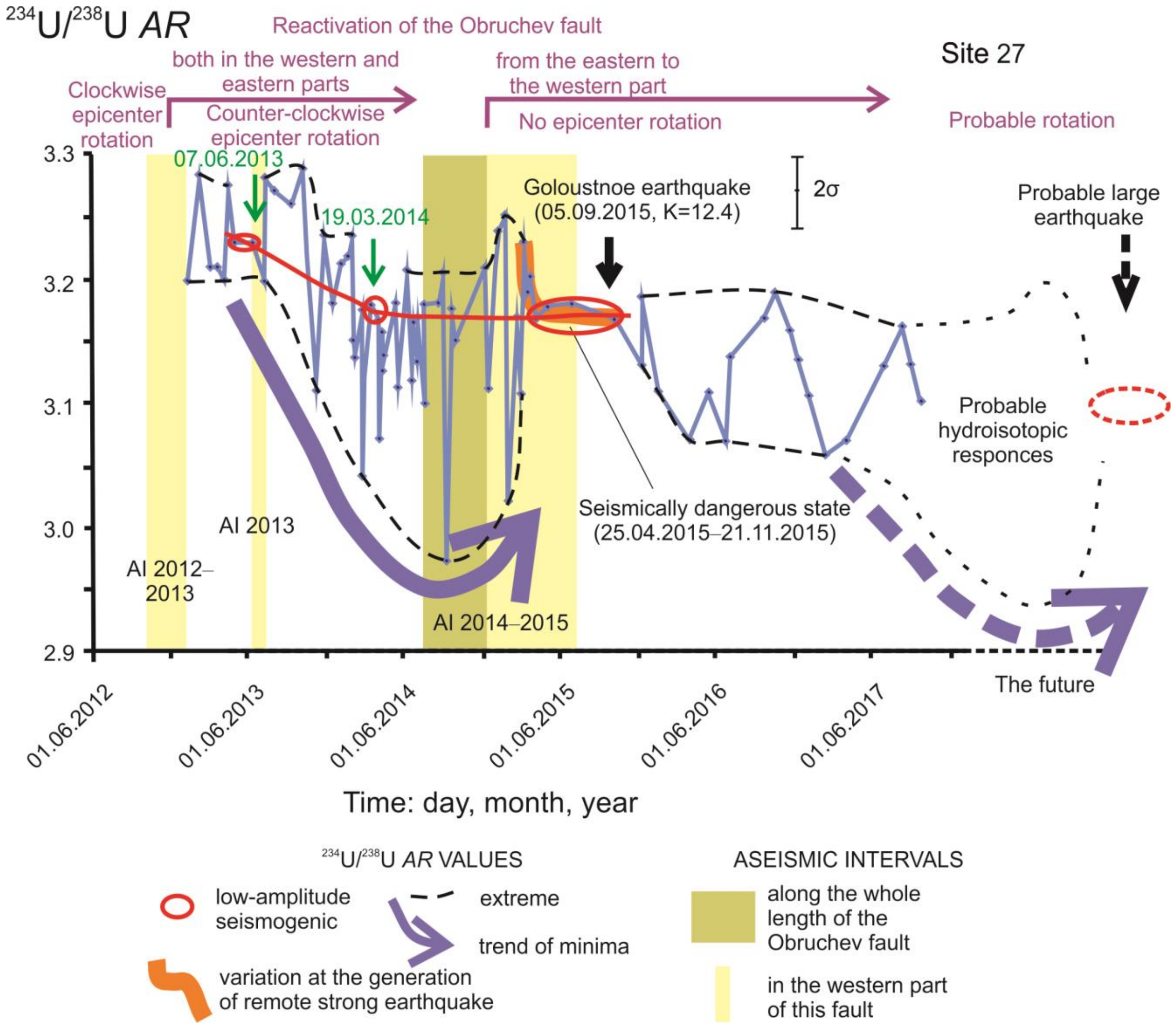

Fig. Temporal variations of an *AR* in groundwater of site 27 from 2013 to 2017 and proposed future hydroisotopic responses to build-up and occurrence of a probable large earthquake.

As compared to small seismic shocks in the Kultuk area, the larger remote earthquake of 05.09.2015 (K = 12.4), called the Goloustnoe earthquake, was reflected in a longer interval of *AR* responses. The graphs, compressed along the time axis , demonstrate changes of extreme isotope ratios as indicators of crack open/closing state in the Obruchev fault preceded this earthquake since 2013.

The uniform small amplitudes suggest a seismically dangerous state of the Obruchev fault. An *AR* level of 3.18, measured in site 27 at this time, corresponded to the one of the preceded local earthquake in the Kultuk area on 19.03.2014

AR responses to the Goloustnoe earthquake build-up in sites 8 and 9 differed from the response of site 27. The minimum of site 8 was reached before the aseismic interval of the entire Obruchev fault, the minimum of site 9 was reached after this interval. The subsequent transition of the Obruchev fault to a seismic state was accompanied by asynchronous *AR* variations at these sites, while synchronization occurred at the end of the seismic state. In contrast to site 27, low-amplitude intervals of sites 8 and 9 were followed by an increasing *AR*.

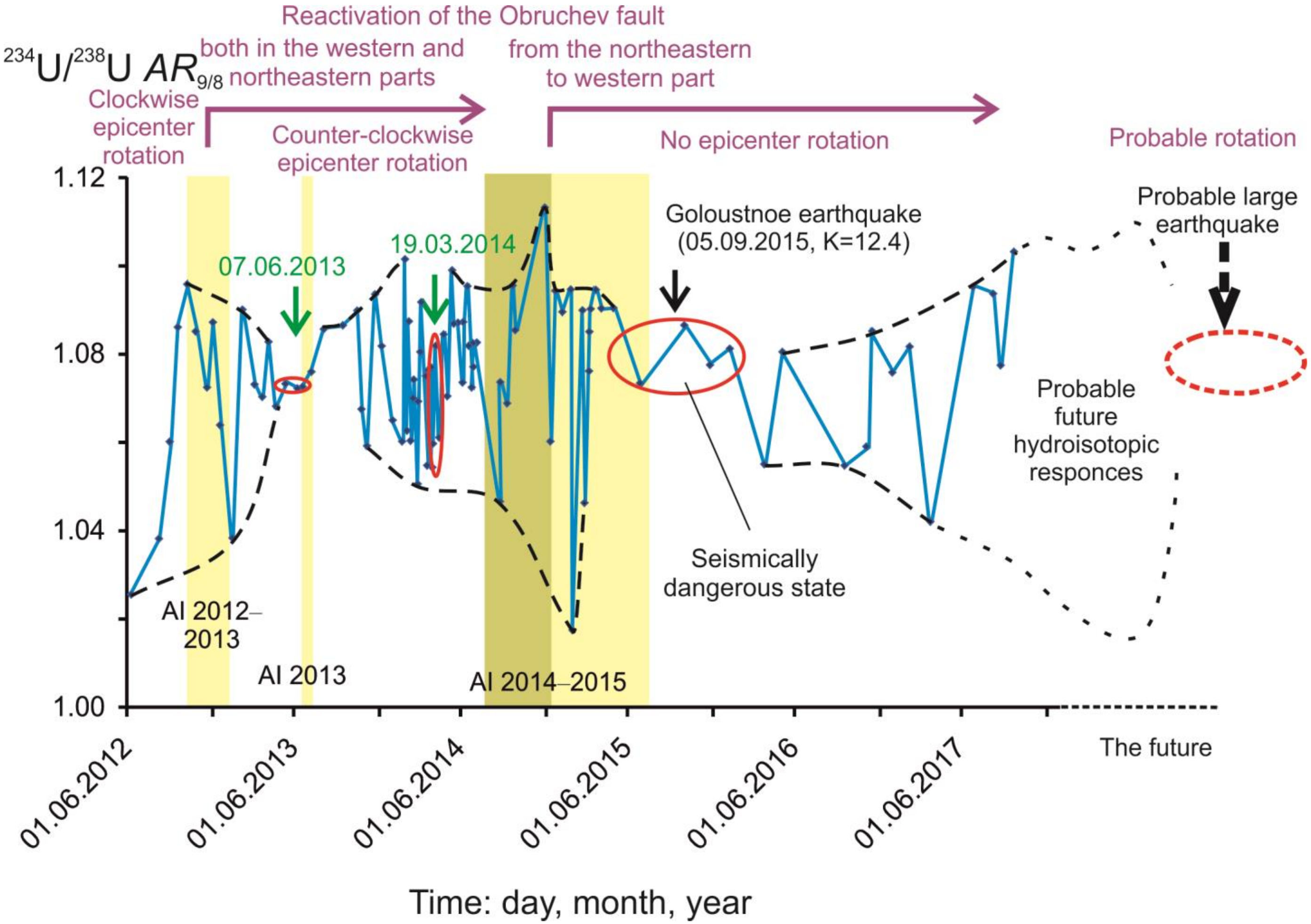

Fig. Temporal variations of an *AR* in groundwater of sites 8 (*a*) and 9 (*b*) from 2012 to 2017.

Transitions from high- to low-amplitude *AR* fluctuations, accompanied by small seismic events in the Kultuk area and by the remote large earthquake, are also clearly revealed in the combined $AR_{9/8}$.

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CONCLUSION

The largest 1999 South Baikal (MW = 6.0; К = 14.6) and 2008 Kultuk (MW = 6.3, K = 15.9) earthquakes corresponded to seismic intervals of 1994–2003 and 2003–2012. Seismic reactivation of the latter was exhibited by concentration of seismicity along the Obruchev and SW Boundary faults of the basin. During this reactivation, epicenters rotated clockwise. In 2013–2014, epicenters localized along the Obruchev fault and rotated counter-clockwise with subsequent concentration along the Goloustnoe-Murino line without any rotation.

Since middle 2012, the 234U/238U activity ratio (AR) has been monitored in groundwater of the Kultuk area. Recorded AR temporal variations demonstrated crack open/closing responces to seismogenic state in active faults of the South Baikal basin.

The hydroisotopic responses to seismic events and recorded data on deformation and temperature variations in rocks are informative for a comprehensive assessment of seismogenic potential of active faults in the South Baikal basin. The patterns of AR variations in groundwater from sites of the Kultuk area can serve as the basis for prediction of a large seismic event in the South Baikal basin.

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More details about the topic under discussion are presented in the paper:

Sergei Rasskazov, Aigul Ilyasova, Sergei Bornyakov, Irina Chuvashova, Eugene Chebykin. Responses of a 234U/238U activity ratio in groundwater to earthquakes of the South Baikal basin, Siberia // Frontiers of Earth Science. 2020. doi:FESCI-2019-0149.R1