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Change of seismic hazard levels in complete 12-year seismogeodynamic cycle of the South Baikal Basin: results of hydroisotopic ($^{234}U/^{238}U$) monitoring

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Abstract. In the western part of the South Baikal Basin, spatial-temporal distribution of earthquake epicenters is characterized by quasi-periodic seismic reactivations. The strongest earthquakes occurred in 1999 (South Baikal, Mw = 6.0), 2008 (Kultuk, Mw = 6.3) and 2020 (Kudara, Mw = 5.4). Since 2013, we have been monitoring the $^{234}U/^{238}U$ activity ratio (*AR4/8*) in groundwater as an indicator of crack open/closing that promotes/prevents water circulation in active faults of the basin. From monitoring results, we define the concept of a complete seismogeodynamic cycle as a change from crustal compression to extension occurred during 12 years with a successive increase in seismic hazard levels.

Key words: *$^{234}U/^{238}U$, groundwater, earthquake, active fault, Baikal.*

Смена уровней сейсмической опасности в полном 12-летнем сейсмогеодинамическом цикле Южно-Байкальской впадины: результаты гидроизотопного ($^{234}U/^{238}U$) мониторинга

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Аннотация. В западной части Южно-Байкальской впадины пространственно-временное распределение эпицентров землетрясений характеризуется квазипериодическими сейсмическими активизациями. Наиболее сильные землетрясения произошли в 1999 г. (Южно-Байкальское, Mw = 6.0), 2008 г. (Култукское, Mw = 6.3) и 2020 г. (Кударинское, Mw = 5.4). С 2013 г. нами проводился мониторинг отношения активностей $^{234}U/^{238}U$ (*ОА4/8*) в подземных водах как показателя раскрытия/закрытия трещин, способствующего/препятствующего циркуляции воды в активных разломах впадины. По результатам мониторинга мы определили понятие полного сейсмогеодинамического цикла как смены сжатия растяжением коры, происходившего в течение 12 лет с последовательным возрастанием уровней сейсмической опасности.

Ключевые слова: *$^{234}U/^{238}U$, подземные воды, землетрясение, активный разлом, Байкал.*

Introduction

Time and place prediction of strong earthquakes remains an unsolved problem. The only way to solve this problem is to monitor phenomena that accompanied the development of seismogenic deformations. More than 600 precursors, which preceded and accompanied large earthquakes, have been recognized. Among these, hydrogeological and hydrogeochemical effects play an important role (Johnson et al., 1974; Chia et al., 2008; King et al., 1995; Tsunogai, Wakita, 1995; Claesson et al., 2004; Sukhija et al., 2010; Reddy et al., 2011; Shi et al., 2015; Boldina, Kopylova, 2017).

An active state of a fault might be defined through measurements of a $^{234}U/^{238}U$ alpha activity ratio (AR4/8) in groundwater. Variations of this parameter are explained by excess recoil of ^{234}U into water that is circulated through rocks and minerals impacted by deformation (Cherdyntsev, 1969; Chalov, 1975). In this method, chemically separated alpha-emission rates of U isotopes are measured and deviations from equilibrium between ^{234}U and ^{238}U ($^{234}U/^{238}U$ alpha activity ratio = 1, corresponding to an atomic ratio of 5.47×10^{-5}) are used to infer excess recoil (Fig.1).

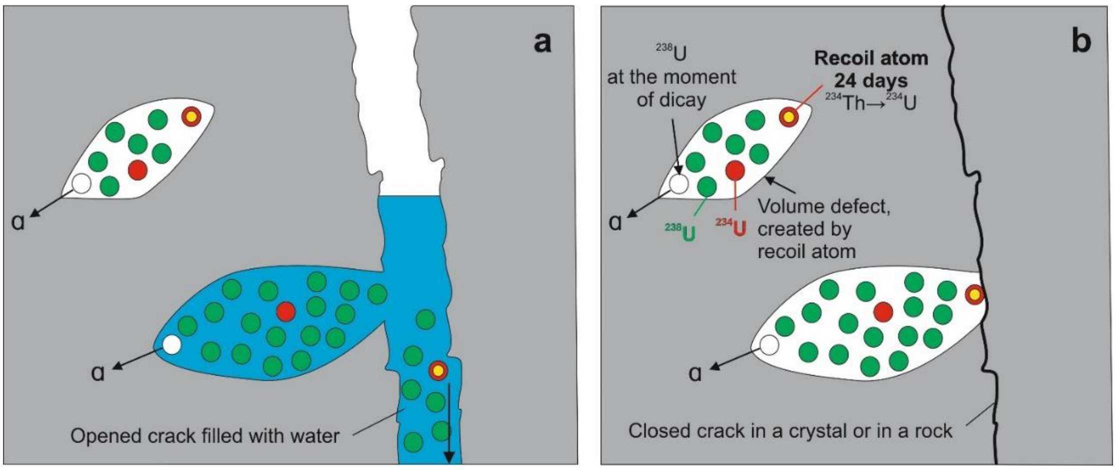

Fig. 1. Explanation of the Cherdyntsev-Chalov effect by micro-crack open/closing. a – recoil atom ^{234}U enrichment of groundwater circulated through open micro-cracks; b – no enrichment due to the micro-crack closing that limits the groundwater circulation.

Рис. 1. Объяснение эффекта Чердынцева-Чалова открытием/закрытием микротрещин. a – обогащение атомом отдачи ^{234}U подземных вод, циркулирующих в открытых микротрещинах; b – обогащение атомом отдачи предотвращается закрытием микротрещин, ограничивающим циркуляцию подземных вод.

In the Baikal Rift System, large earthquakes occurred in the historical past and might happen in the future (Solonenko, 1974; Sherman, 2014). Experience has been already accumulated in terms of probabilistic theoretical analysis of earthquakes for a medium-term forecast (Ruzhich, 1997; Sherman, 2009, 2013; Timofeev et al., 2013). For earthquake prediction, however, early detection of a large earthquake is required for detecting its preparation through monitoring of known precursors as well as clarifying the character of the evolution and physical nature of seismic process that precede earthquakes.

In the South Baikal area, earthquakes of M_W from 5.8 to 7.5 occurred in 1769, 1771, 1779, 1839, 1862, 1866, 1885, 1902, and 1959. During the last two decades there were two more large seismic events: the 1999 South Baikal earthquake (M_W = 6.0) and the 2008 Kultuk earthquake (M_W = 6.3) (Radziminovich et al., 2006; Melnikova et al., 2012). The epicenter of the Kultuk earthquake was 40 km east-southeast of the Kultuk village. Both $^{234}U/^{238}U$ activity ratio and a [U] were monitored in groundwater samples from the Kultuk area (Fig. 2).

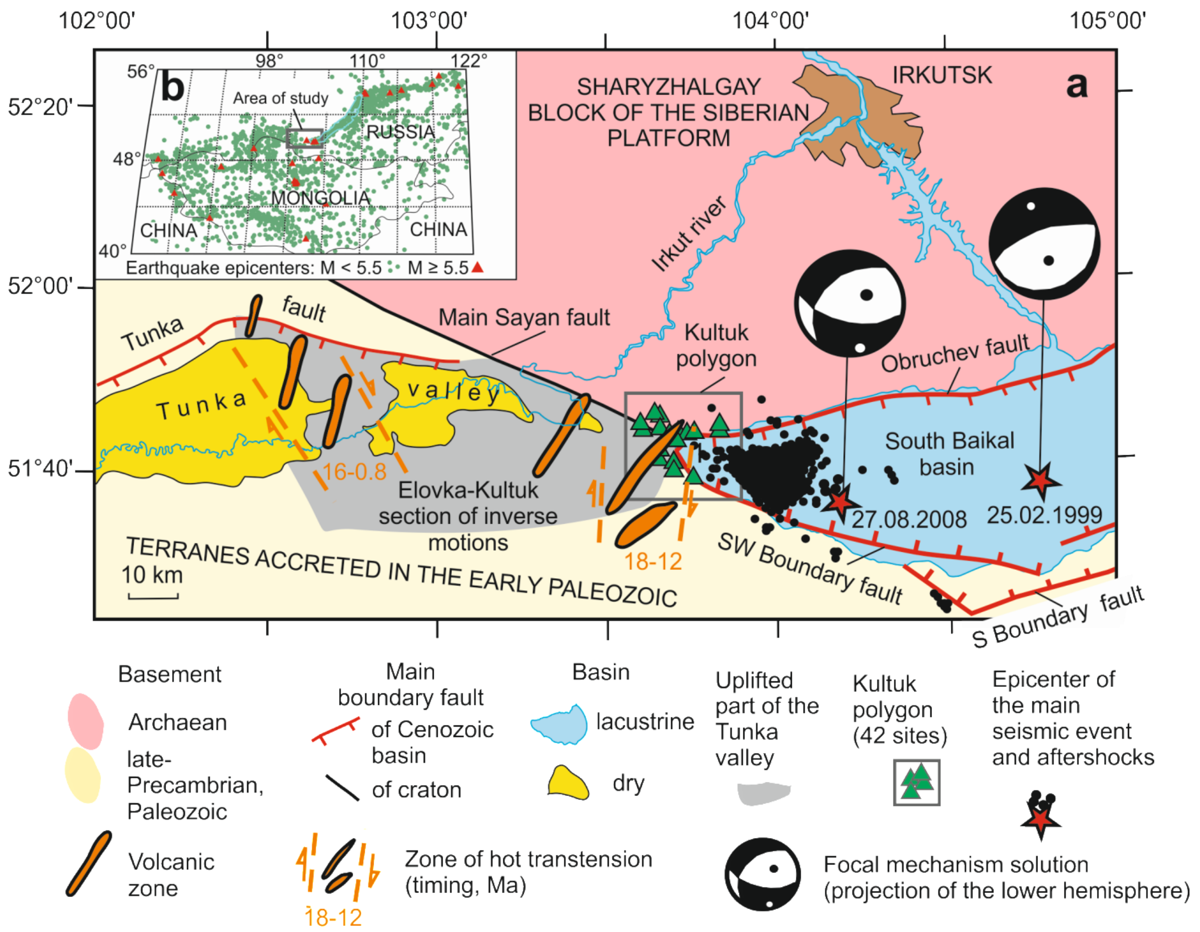

Fig. 2. Spatial position of the Kultuk area for earthquake prediction between the extended South Baikal Basin and compressed inverted eastern part of the Tunka Valley. On panel a: master faults of the South Baikal Basin are adopted from Florensov (1968), epicenter and mechanism of the main seismic shock 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).

Рис. 2. Пространственное положение Култукского сейсмопрогностического полигона между растягивающейся Южно-Байкальской впадиной и сжимающейся инвертированной восточной частью Тункинской долины. На панели а: рельефообразующие разломы Южно-Байкальской впадины показаны по работе Н.А. Флоренсова (1968), эпицентр и механизм главного сейсмического толчка и афтершоков Култукского землетрясения 2008 года – по работе В.И. Мельниковой и др. (2012), эпицентр Южно-Байкальского землетрясения 1999 г. – по работе Н. Радзиминович и др. (2006), зоны горячей транстенсии – по работе С.В. Рассказова и др. (2013). На панели б: распределение землетрясений в Байкало-Монгольском регионе в 1960–2003 гг. по работе С.И. Шермана (2014).

Monitoring site and analytical techniques

The Kultuk sites for earthquake prediction were chosen for hydrogeochemical monitoring in an area of a sharp transition from the East Tunka (Elovka-Kultuk) compressional block to the South Baikal extensional one. The sites are located within the hydrogeochemical zone of mylonites designated the Main Sayan fault in its junction with the Obruchev and South-Western boundary faults, which limit the western part of the South Baikal Basin, respectively, from the north and south. We focus on results obtained for station 21 (School N 7).

Samples were taken mostly in 1–3 weeks. In 2014 and in 2020–2022, intervals between samples were reduced to 4 days. For analysis, a volume of 0.5 liter of water was collected into a bottle of polyethylene terephthalate (PET). A factory-sealed bottle of deep Baikal water with dissolved solid concentration as low as 100 mg/L was opened just before sampling, emptied and thoroughly rinsed with sampled water. If short-term storage (up to 3 months) was required, selected samples were passed through membrane filters (0.45 μm) and acidified with nitric acid that was distilled twice using the Savillex DST-1000 sub-buffering system. Samples were stored in a refrigerator.

To determine the isotope composition of U in natural water, U was separated using ion exchange resin TRU Resin-B (50-100μm, Triskem Int., France) using polypropylene columns containing 0.5 ml of TRU resin. Uranium was eluted with 1.5 ml of 0.1 M ammonium oxalate $(NH_4)C_2O_4$. The elutants were diluted 2-fold with 3 % HNO_3 and analyzed according to methods developed earlier (Chebykin et al., 2007). Analytical studies were performed using the ICP-MS method on an Agilent 7500 ce quadrupole mass spectrometer in the collective use center "Ultramicroanalysis" (Limnological institute of the Siberian Branch of the Russian Academy of Sciences, Irkutsk). To control the quality of measurements, a standard sample of the isotope composition of natural U GSO 7521-99 (Urals Electrochemical Plant, Novouralsk) was used. A typical error in the determination of isotope ratios (1σ) was about 1% relative to a measured value.

Analysis of seismicity

A series of seismic shocks that occurred in the South Baikal Basin in connection with the preparation and implementation of the Kudara earthquake on December 10, 2020 were similar to the one of seismic shocks associated with the Kultuk earthquake on August 27, 2008. From spatial-temporal distribution of the earthquake epicenters of these reactivations, stages of their preparation: A, B, C, D and E that served as the basis for interpreting results of hydrogeochemical monitoring at the Kultuk area with a forecast of a strong event that took place at the end of 2020 (Rasskazov et al., 2020) (Fig. 3)). Before the Kultuk event, at stage A, epicenters were distributed along the Obruchev fault, at stage B they shifted to the south, at stage C, to the northeast, and at stage D, to the west. At this stage, in early 2008, the epicenters migrated from the Snezhnaya epicentral cluster to Kultuk and back. Then on May 4, an earthquake occurred in the Kultuk region and 3.5 months later, there was a strong Kultuk seismic shock. After extensive aftershock activity (stage E), earthquake epicenters showed similar migration stages ABC and D in 2013–2017 with transition after October 10, 2017 to aseismic state.

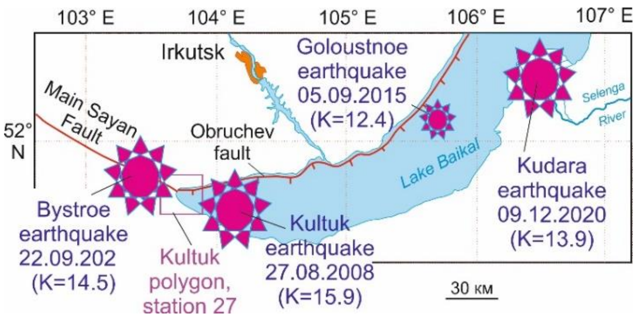

Fig. 3. Epicenters of medium and strong earthquakes in 2015–2020.

Рис. 3. Эпицентры землетрясений средней силы и сильных землетрясений 2015–2020 гг.

The recognized stages of migratory seismicity were compared with results of hydrogeochemical monitoring obtained in 2013–2020 at the Kultuk area. In May 2020, when the aseismic state had already lasted more than 2.5 years, a paper predicted seismic activity with a strong earthquake in South Baikal in 2020–2021 was published (Rasskazov et al., 2020). By analogy with the seismic scenario of 2008, the strong earthquake should have been implemented after the one in the Kultuk area. Seismicity indeed resumed in the second half of 2020 in accordance with the suggested scenario (Fig. 4).

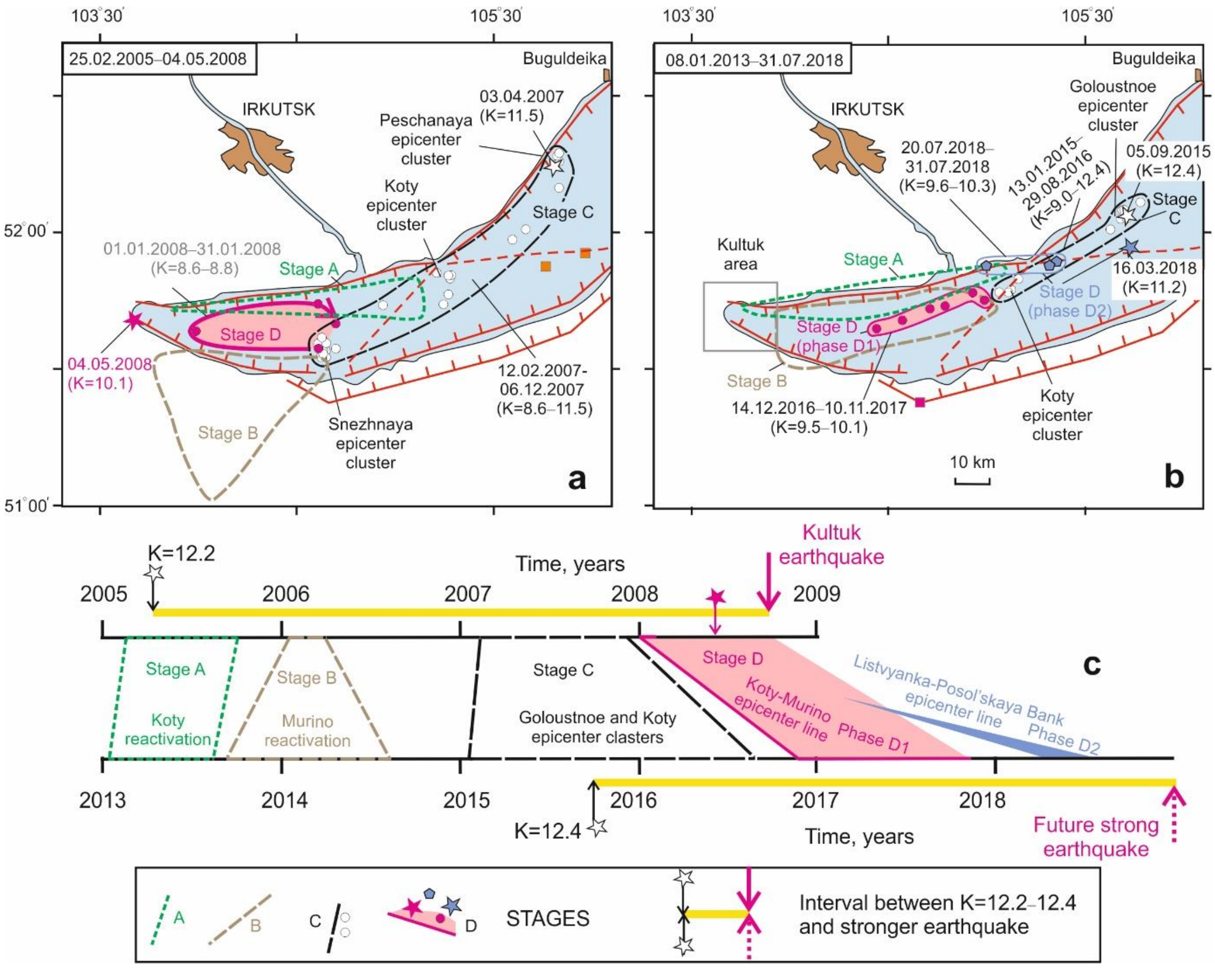

Fig. 4. Stages of spatial-temporal distribution of earthquake epicenters in 2005–2008 after the K=12.2 event before the 2008 Kultuk strong earthquake (a), the same stages of a longer interval of 2013–2020 before the 2020 Kudara strong earthquake (b), and comparison of the stages on a time scale (c). The scheme [Rasskazov et al., 2020] is supplemented with events of the second half of 2020. Data of the Baikal branch of the Federal Research Center "Unified Geophysical Service of the Russian Academy of Sciences" is used.

Рис. 4. Стадии пространственно-временного распределения эпицентров землетрясений 2005–2008 гг. после события К=12.2 перед Култукским землетрясением 2008 г. (a), таких же стадий более продолжительного интервала 2013–2020 гг. перед Кударинским землетрясением 2020 г. (b) и сопоставление стадий на шкале времени (c). Схема сопоставлений [Rasskazov et al., 2020] дополнена событиями второй половины 2020 г. Использованы данные Байкальского филиала ФИЦ "Единая геофизическая служба РАН".

Results of monitoring in 2013–2021

Within the Kultuk area, the deformational effect is most pronounced by high *AR4/8*values in groundwater from the well of the station 27 (School No. 7). During the observation period from January 10 to October 12, 2013, OA4/8 values fluctuated with a high frequency in the range of 3.20–3.29. Increasing seismic instability was reflected in pulses of decreasing *AR4/8* to values below 3.0 with a transition after the maximum on March 4, 2015 to low-amplitude variations, during which the main Goloustnoe seismic event of the Obruchev Fault occurred on September 5, 2015 (K = 12.4). Subsequently, there were no earthquakes with smooth variations of OA4/8 value. Frequent fluctuations of *AR4/8* that began on 08/03/2018 informed about weak hidden deformational instability of the area. After a long seismic lull in South Baikal, a noticeable seismic shock occurred in the water area of Lake Baikal on July 6, 2020 at the western end of the Goloustnoe-Murino epicentral line, and then, on the night of September 21–22, 2020, in the Bystroe village area (Main Sayan Fault), a stronger earthquake occurred that triggered seismic instability in the entire South Baikal Basin and responded with new strong Kudara earthquakes on December 9 and 10, 2020. 10 hours after the Bystraya earthquake, the value of *AR4/8* was at the lower limit since August 2018. This hydroisotopic response to preparation of the 2020 Bystraya event clearly differed from the one of the 2015 Goloustnoe event. In the next day after the Kudara earthquake (in December 10, 2021), in four days (in December 13, 2021) as well as in subsequent days, *AR4/8* values (respectively, 3.08, 3.10 and similar) did not differ from those occurred before the Kudara earthquake.

Monitoring of the station 27 demonstrated, along with *AR4/8* variations, those in concentration of the uranium-234 isotope (denoted as [^{234}U]) that gradually decreased during the preparation of the Goloustnoe event (stage C) and sequentially increased during the preparation of the Kudara one (stage D) (Fig. 5). In diagram *AR4/8* – *A4* (Fig. 6), trends responded to preparation of the Goloustnoe and Kudara earthquakes are defiantly distinguished.

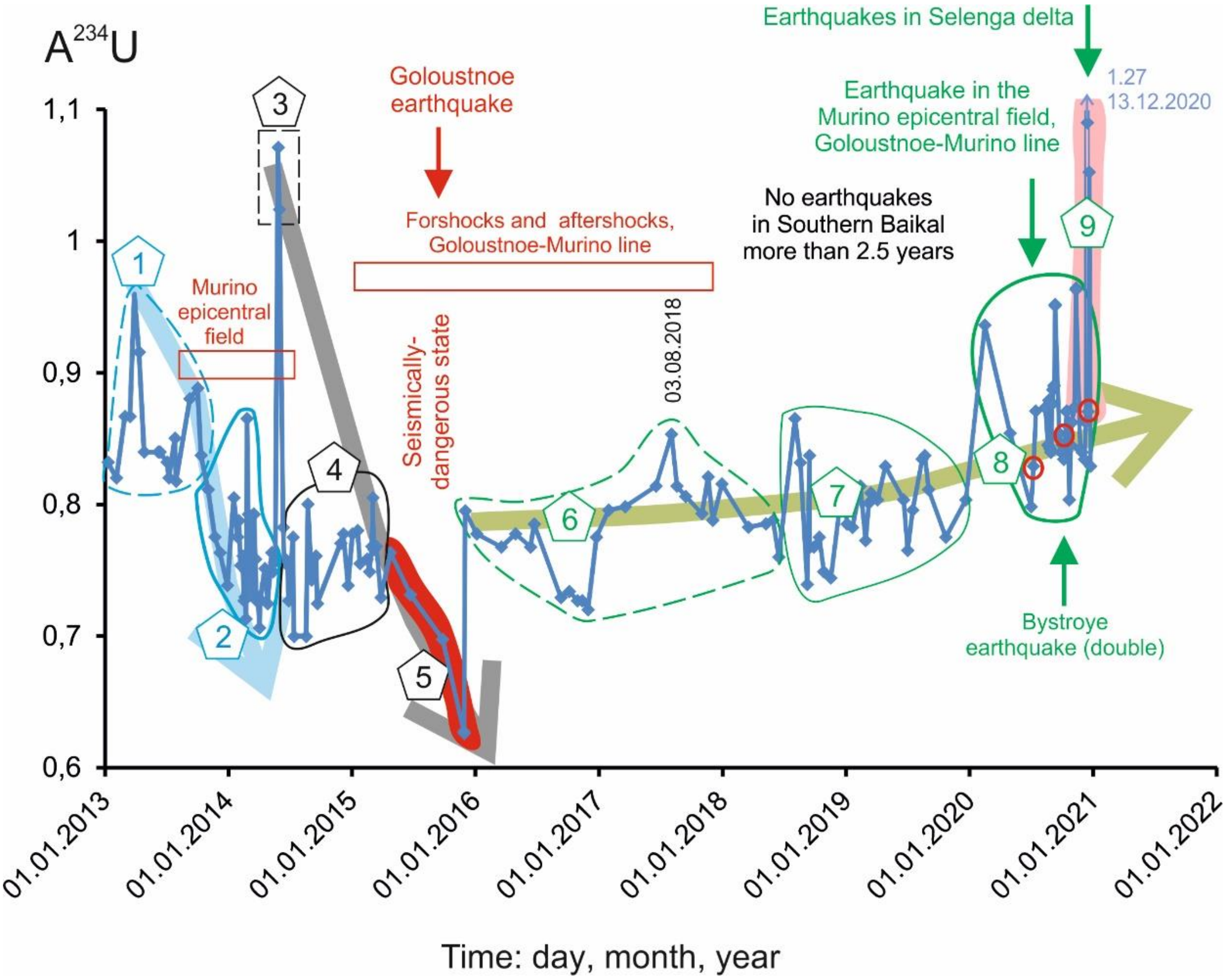

Fig. 5. A4 observation series at the station 27 responded to deformational preparation of the Goloustnoe and Kudara earthquakes.

Рис. 5. Ряд наблюдений А4 откликов подземных вод станции 27 на деформационную подготовку Голоустного и Кударинского землетрясений.

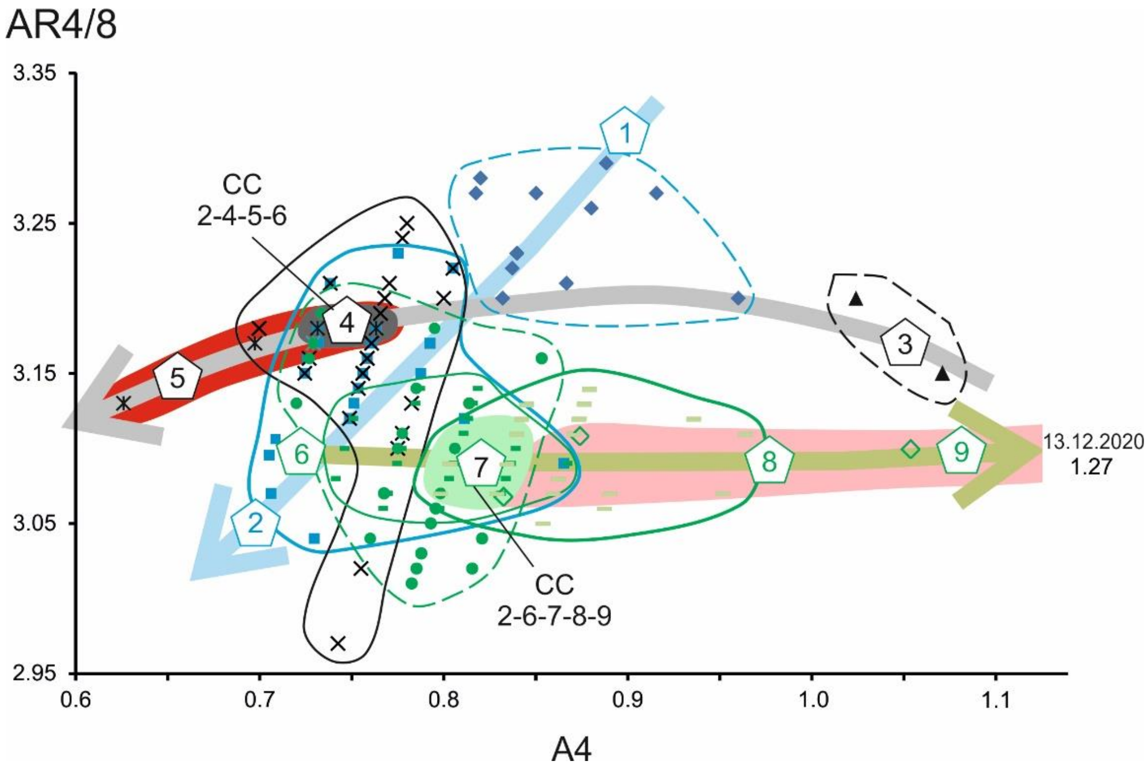

Fig. 6. Groundwater response trends on the deformational preparation of the Goloustnoe and Kudara earthquakes on the AR4/8 versus A4 diagram. Data fields 1–2 (January 1, 2013–May 20, 2014) indicate a hydroisotopic response to initial deformations. Data fields 3–4–5 (May 28, 2014–November 29, 2015) show a distinct trend of decreasing A4 during the preparation of the Goloustnoe earthquake. Data fields 6–7–8–9 (December 2, 2015 – late 2020) show the opposite trend of A4 increasing during the preparation of the Kudara earthquake. A4 = [^{234}U] = ^{234}U/(5.47×10^{-5}) μg/dm^3. CC2-4-5-6 and CC2-6-7-8-9 are common components, indicated by combinations of data fields with the corresponding numbers. Data fields 1 and 2 correspond to stages A and B of earthquake migration, the trend of data fields 3–5 corresponds to the stage C, and the one of data fields 6–9 to stages D and E.

Рис. 6. Тренды откликов подземных вод ст. 27 на деформационную подготовку Голоустного и Кударинского землетрясений на диаграмме ОА4/8 – [^{234}U]. Фигуративные поля 1–2 (1 января 2013 г. – 20 мая 2014 г.) обозначают гидроизотопный отклик на начальные деформации, а фигуративные поля 3–4–5 (28 мая 2014 г. – 29 ноября 2015 г.) дают отчетливо выраженный тренд снижения [^{234}U] при подготовке Голоустного землетрясения. Фигуративные поля 6–7–8–9 (2 декабря 2015 г. – конец 2020 г.) показывают противоположный тренд возрастания [^{234}U] при подготовке Кударинского землетрясения. [^{234}U] = ^{234}U/(5.47×10^{-5}) мкг/дм^3. ОК2-4-5-6 и ОК2-6-7-8-9 – общие компоненты, обозначенные по совмещению фигуративных полей с соответствующими номерами. Фигуративные 1 и 2 соответствуют стадиям A и B миграции землетрясений, тренд фигуративных полей 3–5 – стадии C и тренд фигуративных полей 6–9 – стадиям D и E.

The results of hydroisotopic monitoring are consistent with stages ABCD and E of earthquake migration in the South Baikal Basin. These indicate that the Goloustnoe earthquake of 2015 (K=12.4) was being prepared for 1.5 years with the response of increasing compression under the monitoring station. The mechanism of seismogenic deformations in an active fault differed from the main deformational mechanism of the structural development of the South Baikal Basin that was reflected in the stronger double Kudara earthquake in the extensional Barguzin-Selenga region, provoked by the equally strong Bystraya event in the compressional East Tunka one. The obtained hydroisotopic response of the main deformational process in the South Baikal Basin indicates a consistent increase in extension under the monitoring station in a 5-year interval, half of which turned out to be aseismic before strong seismogenic deformations occurred in the second half of 2020. In 2021-2022, the South Baikal Basin is affected by aftershock activity provided by leveling of tension-compressional tectonic stresses (stage E).

Discussion

Source and spatial transfer of neotectonic deformations in the South Baikal Basin and Tunka Valley

The South Baikal Basin exhibits a historical core of the Baikal Rift System (Logatchev, 2003). Taking into account the model of shallow seismic S-wave tomography (Mordvinva et al., 2019), crustal deformations under the basin are considered as a process of layer-by-layer thinning of the crust due to the extension of its Selenga-Barguzin part in the axis of the divergent Japan-Baikal geodynamic corridor simultaneously with the thickening of the crust of the East Tunka block during its compression due to the Indo-Asian convergent interaction.

From volcanic activity of the axial Vitim field of the Japan-Baikal geodynamic corridor, it was inferred that the Barguzin–Selenga crust was most strongly stretched about 16–15 Ma ago and was subsequently subjected to repeated stretching impulses with a quasi-periodicity of 2.5 Ma. Three quasi-periods in the interval of 18.1–11.7 Ma covered the Kamar-Stanovoi zone of hot transtension in the eastern part of the Tunka Valley. The volcanism cessation marked the change from transtension to transpression, accompanied by inversion of tectonic motions with uplift of the area (Chuvashova et al., 2017; Rasskazov and Chuvashova, 2018).

By now, the established mechanism of neotectonic deformations in the crust along the axis of the Japan–Baikal geodynamic corridor resulted in the contrast development of the crust in the South Baikal Basin and Tunka Valley (Rasskazov et al., 2021). Seismogenic deformations are leveled in the 38–39 km layer with thinner crust (up to 35 km) in the Barguzin-Selenga area of extension and its greater thickness in the East Tunka area of compression (up to 49 km) (Krylov et al., 1980, Mordvinova et al., 2019). An even greater increase in the thickness of the crust in the West Tunka block of the Tunka Valley (up to 54 km) (Mats et al., 2001) is provided by the long-range transfer of deformations through the leveling layer (Fig. 7).

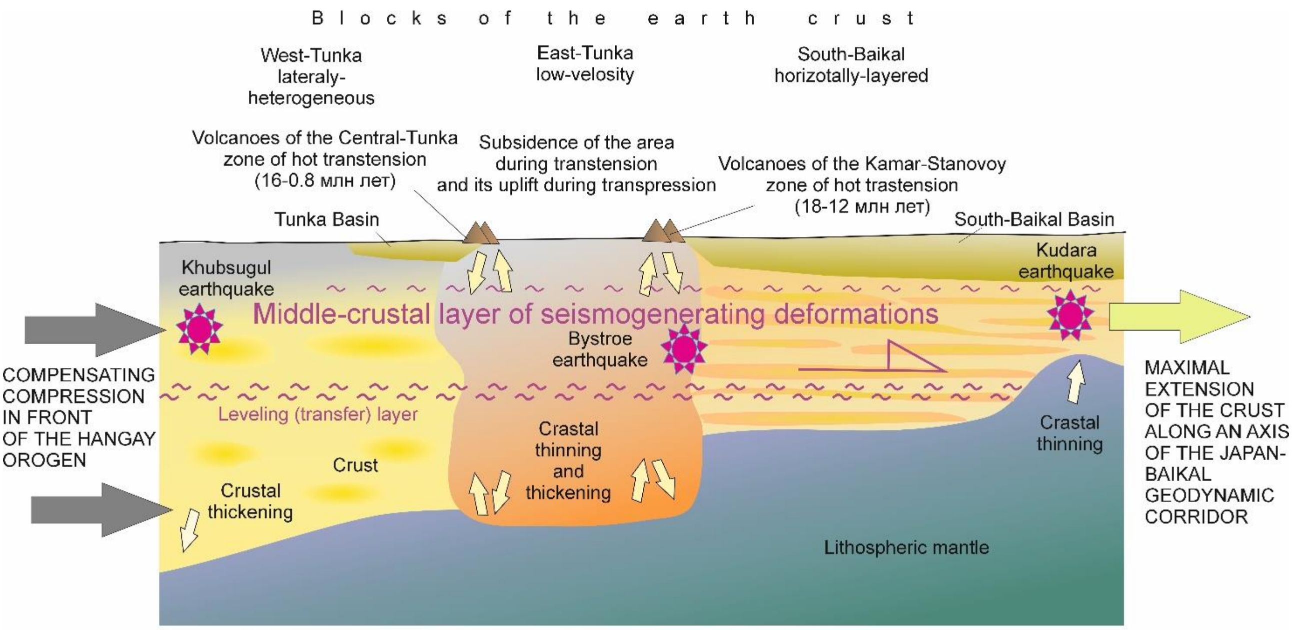

Fig. 7. Scheme of seismogenic deformations that developed in the crust of the South Baikal Basin and Tunka Valley at the end of a seismogeodynamic cycle. The leading seismogeodynamic factor is the generation of crustal extension in the axis of the Japan-Baikal geodynamic corridor with the manifestation of the Kudara earthquake; the provoked one is compression in front of the Hangay orogen, which compensates this extension with manifestations first the Bystroe and then the Khubsugul earthquakes.

Рис. 7. Схема сейсмогенных деформаций, получивших развитие в коре Южно-Байкальской впадины и Тункинской долины при завершении сейсмогеодинамического цикла. Ведущий сейсмогеодинамический фактор – генерация растяжения коры в оси Японско-Байкальского геодинамического коридора с проявлением Кударинского землетрясения, провоцируемый фактор – сжатие во фронте Хангайского орогена, компенсирующее это растяжение с проявлением сначала Быстринского, а затем – Хубсугульского землетрясений.

The spatial-temporal distribution of medium and strong earthquakes in the South Baikal Basin during the development of a complete seismogeodynamic cycle is not irregular, but initiating effect of crustal extension in the South Baikal Basin and compensating one of crustal compression at structural ends of the Tunka Valley. An epicenter of the 2008 Kultuk earthquake was located near the Kultuk structural junction; therefore, the leveling deformation transfer in the crust could have propagated no further than the East Tunka block. An epicenter of the 2020 Kudara earthquake was much further from the Kultuk structural junction, in the Selenga delta. This event provoked a compensatory compression of the crust with leveling movements from Khubsugul to Middle Baikal. The triggering of the strong Khubsugul earthquake and aftershock activity showed the full amplitude of the compensating movements in the leveling layer.

The development of a complete seismogeodynamic cycle in hydroisotopic responses with change of seismic hazard levels

Under gravitational forces, the upper part of the crust is affected b all-round compression, against which stretching impulses appear. Since the *A4* and *AR4/8* groundwater maxima and minima indicate the conditions for closing and opening of micro-fractures, in analysis of time series, these parameters are presented in terms of temporally-varying crustal compression and extension in the South Baikal Basin.

Stages of earthquake preparation in the South Baikal Basin, recognized from the spatial-temporal distribution of their epicenters (Fig. 8), are supplemented by sharp changes in the *RA4/8* and *A4* observation series at the station 27 (Fig. 9). Accordingly, seismic hazard levels in the South Baikal Basin are indicated within the framework of a complete seismogeodynamic cycle (Fig. 10).

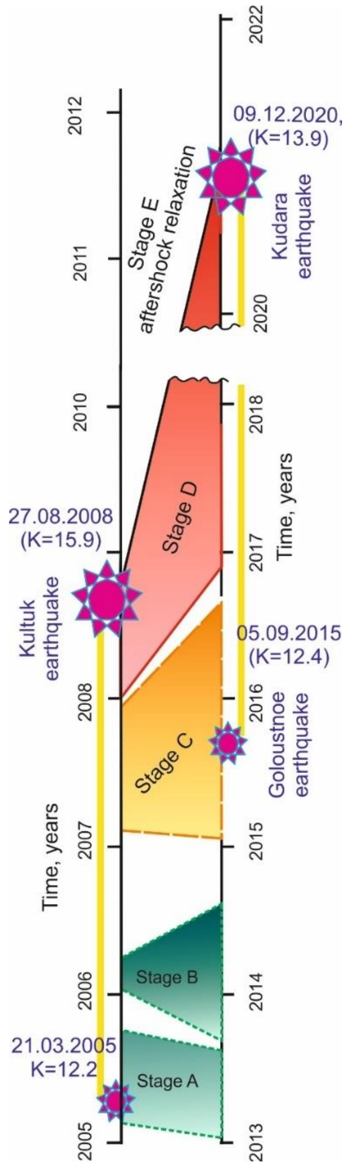

Fig. 8. Stages of earthquake preparation. Green level – no danger, yellow-orange level – elevated danger, red level – maximal hazard.

Рис. 8. Смена уровней сейсмической опасности на стадиях подготовки землетрясений во временных интервалах 2005–2012 и 2013–2022 гг. с цветовыми уровнями сейсмической опасности. Зеленый уровень не опасен, желтый-оранжевый уровень – возросшая опасность, красный уровень – максимальная опасность.

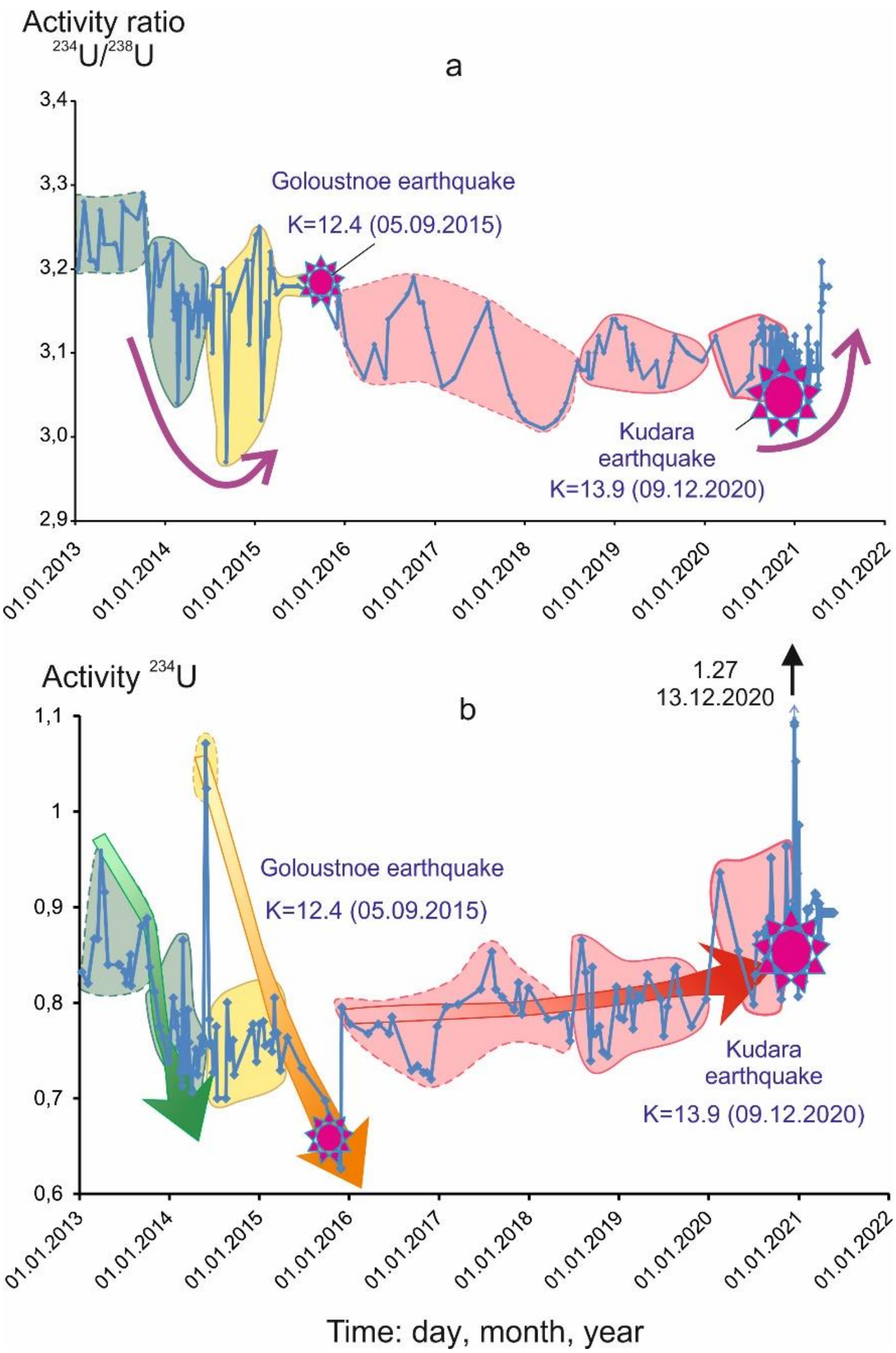

Fig. 9. Change of seismic hazard levels in the South Baikal Basin in AR4/8 (a) and A4 (b) observation series at the station 27. The levels are shown by color.

Рис. 9. Смена уровней сейсмической опасности в рядах наблюдений OA4/8 (a) и A4 (б) на станции 27. Уровни показаны цветом.

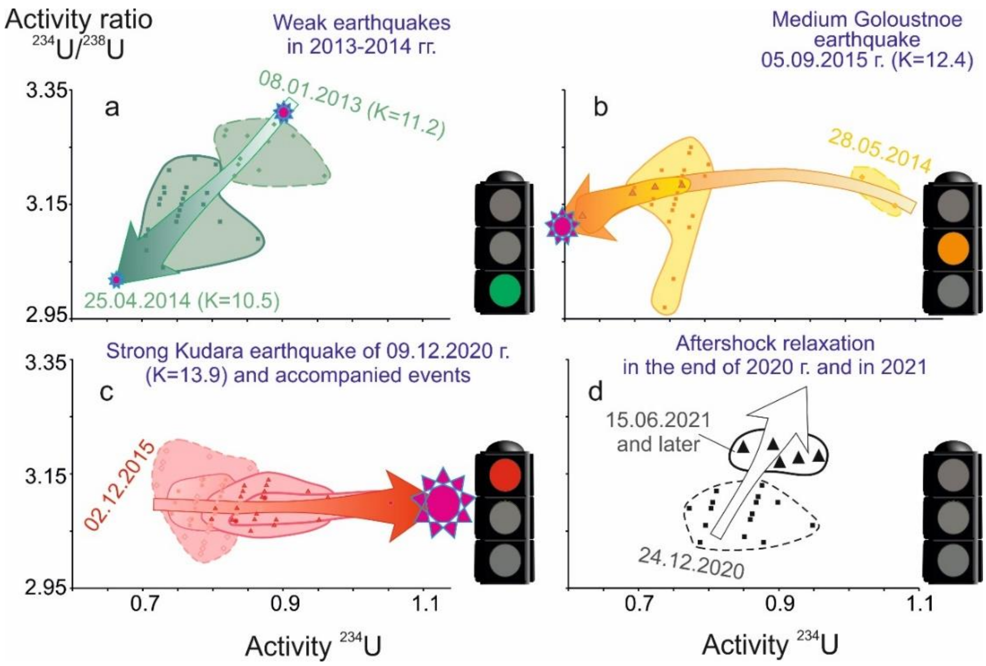

Fig. 10. Change of seismic hazard levels in the South Baikal Basin during the complete (2008–2020) seismogeodynamic cycle from a green level (a) through yellow-orange (b) to a red one (c) with transition to the new seismogeodynamic cycle. The levels are shown by color.

Рис. 10. Смена уровней сейсмической опасности в Южно-Байкальской впадине в течение полного (2008–2020 гг.) сейсмогеодинамического цикла от зеленого уровня (a) через желто-оранжевый (b) к красному уровню (c) с переходом к новому сейсмогеодинамическому циклу (d). Уровни сейсмической опасности показаны цветом.

In 2013–2014 weak earthquakes of the green level of seismic hazard occurred. The decrease in *RA4/8* and *A4* in groundwater indicated a relative decrease in the role of crustal extension and increase in compression. A sharp increase in *A4* on May 28, 2014 turned into a trend of a gradual decrease in this parameter, at the minimum of which on September 5, 2015, the Goloustnoe earthquake of medium strength occurred. Just like in 2013-2014, seismogenic tensile stress of the crust decreased, but in the implementation of the Goloustnoe earthquake during the seismic geodynamic cycle, the minimum crustal extension was achieved. The increase in seismic hazard to yellow and orange levels essentially did not change the nature of seismogenic deformations in the initial stages of the seismogeodynamic cycle development.

Subsequently, the character of earthquake preparation changed. On December 2, 2015, the *RA4/8* and *A4* values of groundwater were still at a minimum. But over the next 5 years after the Goloustnoe earthquake, both parameters consistently increased. The trend corresponded to the red level of seismic hazard. On December 9, 2020, the strong Kudara earthquake occurred in the Selenga delta, which was preceded (as a trigger) by the Bystraya earthquake on September 22, 2020, and followed by the strong Khubsugul earthquake on January 12, 2021.

The Kudara earthquake of December 9, 2020 completed the seismogeodynamic cycle started from implementation of the Kultuk earthquake of August 27, 2008. High *RA4/8* and *A4* values measured in groundwater indicate that tensile forces in the crust have reached the maximum in the axial part of the Japan-Baikal geodynamic corridor. The subsequent (provoked) Khubsugul seismic events marked involvement of the compressive compensation mechanism for the Kudara crustal extension. By December 24, 2020, both the *RA4/8* and *A4* values in groundwater decreased to average levels. Since June 15, 2021, both parameters showed an upward trend, which indicated an increase in the crustal extension. At that time, aftershock activity continued in the Khubsugul region, and the compensation mechanism for the leveling layer of the crust must have been operating. Just as before the Kudara event, the seismogenic tensile stress of the crust increased, but along the trend of a significant shift in *A4* values. Crustal extension increased, but it was not similar to the extreme Kudarya phase. Direction to the beginning of the green trend of 2013–2014 can be interpreted as evidence of a transition to the development of a new seismogeodynamic cycle.

Conclusion

From observation of 2013–2021, a complete seismogeodynamic cycle (i.e. a cycle of compression and extension of the crust) is recognized in the South Baikal Basin, which gives an idea of the pulsating development of seismogenic deformations in the Baikal seismic zone as a time-ordered process. The distinguished stages of strong earthquake preparation (A, B, C, D) and implementation (E) are consistent with the deformational stages indicated by hydrogeochemical monitoring. The seismic stages correspond to the trends of successive change in the RA4/8 and A4 in groundwater with access to extreme values corresponding to seismic events (Fig. 11). The values of one and/or the other parameter consistently increase due to the opening of micro-cracks (stretching of the crust), which enhances the effect of the transition of ^{234}U recoil atoms into circulating groundwater, and decrease due to the closing of micro-cracks (compression of the crust), which prevents this effect.

The evidence obtained on the complete seismogeodynamic cycle yields an idea about seismicity in the central part of the Baikal Rift System as an ordered process that can be studied and predicted.

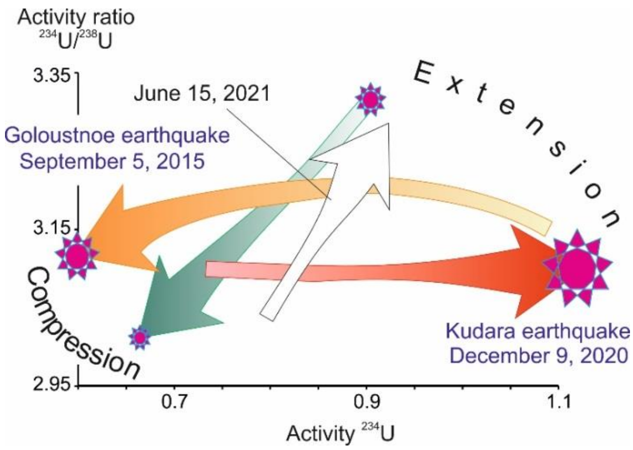

Fig. 11. Reconstruction of the complete seismogeodynamic cycle in the crust from monitoring results in the station 27. Seismic stages correspond to trends in successive change in AR4/8 and A4 in groundwater that reach extreme values corresponding to strong seismic events. Weak non-hazardous earthquakes in 2013–2014 (green level) were followed by an increase of danger in 2015 in a yellow-orange level and by the further development of hazardous state in late 2020 – early 2021 in a red level with subsequent exit to the new seismogeodynamic cycle (to the state of 2013).

Рис. 11. Реконструкция полного сейсмогеодинамического цикла по результатам мониторинга подземных вод ст. 27. Сейсмическим стадиям соответствуют тренды последовательного изменения ОА4/8 и А4 в подземных водах с выходом на экстремальные значения, соответствующие сильным сейсмическим событиям. Слабые неопасные землетрясения 2013–2014 гг. (зеленый уровень) сменялись нарастанием опасности желто-оранжевого уровня в 2015 г. и красным уровнем сейсмической опасности в конце 2020 г. с последующим выходом в новый сейсмогеодинамический цикл (к состоянию 2013 г.).

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