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FOCAL MECHANISMS OF EARTHQUAKES AND STRESS FIELD OF THE CRUST IN MONGOLIA AND ITS SURROUNDINGS

N. A. Radziminovich[1], G. Bayar[2], A. I. Miroshnichenko[1], S. Demberel[2], M. Ulziibat[2], D. Ganzorig[2], A. V. Lukhnev[1]

[1] *Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia*
[2] *Research Center of Astronomy and Geophysics of MAS, Ulaanbaatar, Mongolia*

Abstract: We have compiled and analyzed earthquake focal solutions for the territory of Mongolia and its surroundings in order to reveal a spatial variability of stress orientation and stress regimes of the crust. According to the stress inversion results, the SHmax is turning from W-E in the eastern Mongolia to SW-NE in the Gobi Altay and the central Mongolia, and then to S-N in the western part of the region. Comparison with data derived from GPS measurements shows that directions of the strain axes revealed by the geodetic and seismological observations are generally consistent. A contradiction is found for the Bolnai zone where results of GPS estimation indicate the predominance of extension (in the SE-NW direction), whereas earthquake data for the longer period of seismic observations reveal compression. Compression in this zone is mainly due to the Tsetserleg-Bolnai earthquakes contribution; however, a part of the recent data on focal mechanisms fits an extensional stress field with the NNW orientated extension axis. These data are in accordance with some published works which suggest a transtensive field from some structural geology studies in the eastern part of the Bolnai zone.

The paper is supplemented with a list of M≥4.5 earthquake fault plane solutions and unpublished focal mechanisms for some M≤4.5 earthquakes of the northern Mongolia and the southern Baikal region.

Key words: Mongolia; earthquake; fault plane solution; tectonic stress field; GPS measurements

Recommended by V.A. San'kov

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МЕХАНИЗМЫ ОЧАГОВ ЗЕМЛЕТРЯСЕНИЙ И ПОЛЕ НАПРЯЖЕНИЙ МОНГОЛИИ И ПРИЛЕГАЮЩИХ ТЕРРИТОРИЙ

Н. А. Радзиминович[1], Г. Баяр[2], А. И. Мирошниченко[1], С. Дэмбэрэл[2], М. Ульзибат[2], Д. Ганзориг[2], А. В. Лухнев[1]

[1] *Институт земной коры СО РАН, Иркутск, Россия*
[2] *Исследовательский центр астрономии и геофизики МАН, Улан-Батор, Монголия*

Аннотация: Введение. Механизмы очагов землетрясений наряду с геодезическими и другими данными служат источником информации о напряженно-деформированном состоянии земной коры. Задачи оценки тектонического режима и скорости деформирования особенно актуальны для внутриплитных областей, характеризующихся высоким уровнем сейсмичности. Одной из таких областей является Монголия, на территории которой известны землетрясения с M=8.0 (рис. 1). В представляемой работе собраны и проанализированы механизмы очагов землетрясений с M≥4.5 с целью проследить пространственную изменчивость поля напряжений земной коры.

Данные. Опубликованные данные о фокальных решениях можно разделить на две группы в зависимости от применяемых для их определения методов. К первой группе относятся механизмы, полученные моделированием волновых форм на удаленных и региональных станциях. Вторая группа решений получена при использовании метода полярности первых вступлений волн. Данный метод широко применялся для умеренной силы землетрясений северной части Монголии и Южной Сибири, что обусловлено более плотным покрытием этого региона сейсмостанциями. Используемые для анализа в данной работе решения представлены в таблице (в разделе «Дополнительные материалы») и на карте (рис. 2).

Методы. Для инверсии поля напряжений использовались два подхода. Для землетрясений основных сейсмических зон (Болнай, Гобийский Алтай, Могод и т.д.) применялась программа Win-Tensor [*Delvaux, Sperner, 2003*], в которой реализован метод right dihedra [*Angelier, 1984*]. Для получения более сглаженной по всей территории картины ориентации осей напряжений использовалась программа SATSI [*Hardebeck, Michael, 2006*], минимизирующая разницу между соседними «индивидуальными» стресс-тензорами для сейсмоактивных областей. Для более корректного сравнения сейсмологических данных с результатами GPS-измерений и визуализации сейсмотектонических деформаций представлены стереограммы средних фокальных механизмов [*Nikitin*, *Yunga*, *1977*; *Yunga*, *1990*].

Результаты. Полученные результаты показывают, что фокальные решения землетрясений южной, западной и восточной части Монголии однородны и представлены главным образом сдвиговыми и взбросовыми подвижками в очагах. Большим разнообразием кинематических типов разрывов характеризуется территория к северу от Болнайского разлома. Для непосредственно Болнайской зоны не удалось получить единого стресс-тензора. Выборка разделилась на главные толчки (Болнайское и Цэцэрлэгское землетрясения 1905 г.), состоящие из субисточников, и события, зарегистрированные в период инструментальных наблюдений. Последние показывают наличие в выборке решений, удовлетворяющих режиму растяжения. В целом, наблюдается изменение ориентации оси SHmax от направления Ю-С в западной части Монголии до ЮЗ-СВ в Гобийском Алтае и в центральной части страны и до широтного направления в Восточной Монголии.

Обсуждение результатов. Очевидно, что основные характеристики поля напряжений на представленной территории уже выявлены и описаны в предшествующих работах [*Zhalkovskii et al., 1995; Petit et al., 1996; Delvaux et al., 1998; Melnikova et al., 2004; Melnikova, Radziminovich, 2005; San'kov et al., 2005; Gol'din, Kuchai, 2007; Radziminovich et al., 2007; Parfeevets, San'kov, 2010; San'kov et al., 2011; Parfeevets, San'kov, 2012; Rebetsky et al., 2013; Tataurova et al., 2014; Kuchai, Kozina, 2015; Karagianni et al., 2015; и др.*]. Все увеличивающийся объем новых данных, с одной стороны, подтверждает сделанные ранее выводы, а с другой – позволяет выявить некоторые детали.

Результаты, полученные по сейсмологическим данным, согласуются с данными, полученными в ходе геолого-структурных работ [P*arfeevets, Sankov, 2012*] и GPS-измерений [*Calais et al., 2003; Loukhnev et al., 2010*]. Выделяется Болнайская зона, которая по геодезическим расчетам характеризуется деформацией удлинения земной коры или растяжением. Выше отмечалось, что часть фокальных механизмов соответствует такому полю напряжений. Более того, замеры трещиноватости также приводят авторов [*Parfeevets, Sankov, 2012*] к выводу о режиме транстенсии в восточной части Болнайской зоны, связанном, вероятно, с дивергенцией Евразийской и Амурской плит [*Petit, Fournier, 2005*]. Характер изменений сейсмотектонических деформаций в этом районе позволил авторам работы [*Kuchai, Kozina, 2015*] выделить, хоть и в широких пределах, границу Амурской плиты.

По данным о землетрясениях с M≥7.0 была рассчитана скорость деформации по формуле Кострова (табл. 2). Для временного интервала в 100 лет она составила 1.12×10^{20} N m yr^{-1}, что является высоким значением для внутриконтинентальных областей по сравнению с модельными значениями [*Holt et al., 1995, 2000*]. Очевидно, это связано с сильнейшими землетрясениями региона, произошедшими на протяжении небольшого интервала времени.

Заключение. Карта фокальных механизмов и результаты инверсии поля тектонических напряжений могут быть полезны при сейсмотектоническом и геодинамическом анализе Центральной Азии. В разделе «Дополнительные материалы» приведена компиляционная таблица механизмов очагов землетрясений с M≥4.5 и ранее неопубликованные механизмы очагов землетрясений Северной Монголии и Южного Прибайкалья с M≤4.5.

Ключевые слова: Монголия; землетрясение; механизм очага; поле тектонических напряжений; GPS-измерения

On-line supplementary materials: *Focal mechanisms solutions* / Focal_solutions.xls
Supplementary materials explanations / Explanations.pdf

1. INTRODUCTION

Data on stress regimes and strain rates for intracontinental domains are of particular interest for understanding intraplate seismicity. In this respect, Mongolia is an appropriate region for research because of its location far from the plate boundaries, active tectonics, high level of seismic activity, and geodynamic position in Central Asia. It has been accepted that active deformation of the western part of Mongolia is related to the India-Eurasia collision [*Tapponnier, Molnar, 1979; Zonenshain, Savostin, 1981; and others*], although the stress transfer mechanism is under debate [*Avouac, Tapponnier, 1993; Peltzer, Saucier, 1996; England, Molnar, 1997; and others*]. The eastern part of Mongolia, which is characterized by the moderate level of seismic activity and diffusive seismicity type, might be influenced by the Pacific subduction process [*Barth, Wenzel, 2010; and others*]. This part is also assumed to belong to the Amurian block or plate, although the existence of this plate is doubted by some researchers [*De Mets et al., 1990; Calais et al., 2003; and others*]. At the same time, local mantle anomalies, such as one under the Khangay dome, whose uplift is thought to be resulting from hot mantle upwelling [*Windley, Allen, 1993; Priestley et al., 2006; and others*] should not be excluded from consideration.

Earthquake focal mechanisms along with geodetic and other data are important information to solve the problems concerning the mechanism and mode of the lithosphere deformation. However, much attention has been traditionally given to large earthquakes. Indeed, based on the data on largest earthquakes of Mongolia (M>7 and even M≥8), the principal types of movements on the main fault zones were revealed, but these data cannot provide insight into the spatial stress variability and/or heterogeneity. These issues are essential for Mongolia since the question about the balance between local mantle dynamics and far-field forces in this region is still open.

At present, there are a lot of current stress studies based on earthquake focal mechanisms for the Central Asia, including Mongolia. Different approaches have been used to constrain the present-day stress and strain state of the crust, among which are widely used stress inversion procedures [*Petit et al., 1996; Delvaux et al., 1998; Déverchère et al., 2000; San'kov, Parfeevets, 2005; Parfeevets, San'kov, 2010, 2012; Karagianni et al., 2015; and others*], the method of seismotectonic deformation estimation [*Zhalkovskii et al., 1995; Melnikova et al., 2004; Melnikova, Radziminovich, 2005; San'kov et al., 2005; Gol'din, Kuchai, 2007; Radziminovich et al., 2007, 2008; San'kov et al., 2011; Tataurova et al., 2014; Kuchai, Kozina, 2015; and others*], and the method of cataclastic analysis [*Rebetsky et al., 2013; Leskova, Emanov, 2014; and others*].

In this study, we have compiled and analyzed fault-plane solutions for M≥4.5 earthquakes available for the region study since 1900 (until 1960 it concerns only large earthquakes with M≥8). Furthermore, unpublished focal mechanisms for some M≤4.5 earthquakes of the northern Mongolia and the southern Siberia are given in the Supplementary Materials. These solutions were not involved in the analysis due to the lower magnitude and possible hierarchical mode of the crust stress state. The main aim was to trace a spatial variability of stress orientation and stress regimes throughout the territory of Mongolia and its surroundings. For that, a stress inversion was applied to the data as well as seismotectonic deformation estimation. Then, the obtained results were compared with the geodetic measurement data for this region.

2. DATA

The published data on focal mechanisms of the Mongolian earthquakes can be categorized into two groups according to an approach to their determination, namely waveform modelling and first motion polarity methods. Different techniques of surface and body waves modelling using teleseismic records were applied to study both large and moderate earthquakes. Moreover, fault plane solutions for some large earthquakes (Fig. 1), such as the 1905 Tsetserleg-Bolnai earthquakes, the 1931 Fu Yun earthquake, the 1950 Mondy earthquake, the 1957 Gobi-Altai earthquake, the 1967 Mogod event, and the 2003 Chuya event were confirmed by the surface ruptures reports [*Vosnesensky, 1962; Florensov, Solonenko, 1963; Okal, 1976, 1977; Khilko et al., 1985; Huang, Chen, 1986; Baljinnyam et al., 1993; Kurushin et al., 1997; Bayasgalan, Jackson, 1999; Bayasgalan et al., 2005; Schlupp, Cisternas, 2007; Ulziibat, 2006; Emanov, Leskova, 2005*]. A significant part of the solutions comes from the Global Centroid-Moment-Tensor Project (former Harvard CMT Project) [http://www.globalcmt.org]. The first motion approach has been widely used for the northern part of Mongolia and the neighbouring regions of Russia due to denser seismic stations covering these regions. The main contribution to the first motion solutions of the earthquakes was made by A.V. Solonenko and co-authors [*1993*] who re-estimated the solutions from their earlier reports and presented the revised focal solutions in the international format (in terms of parameters of nodal planes and axes rather than cosine or sinus to the poles of the planes). Now, a regular source of information on focal solutions is the annual catalogue "Earthquakes of the Northern Eurasia" (former "Earthquakes in the USSR") published by the Russian Geophysical Survey. For the territory of China, only focal mechanisms from the world seismic agencies are taken

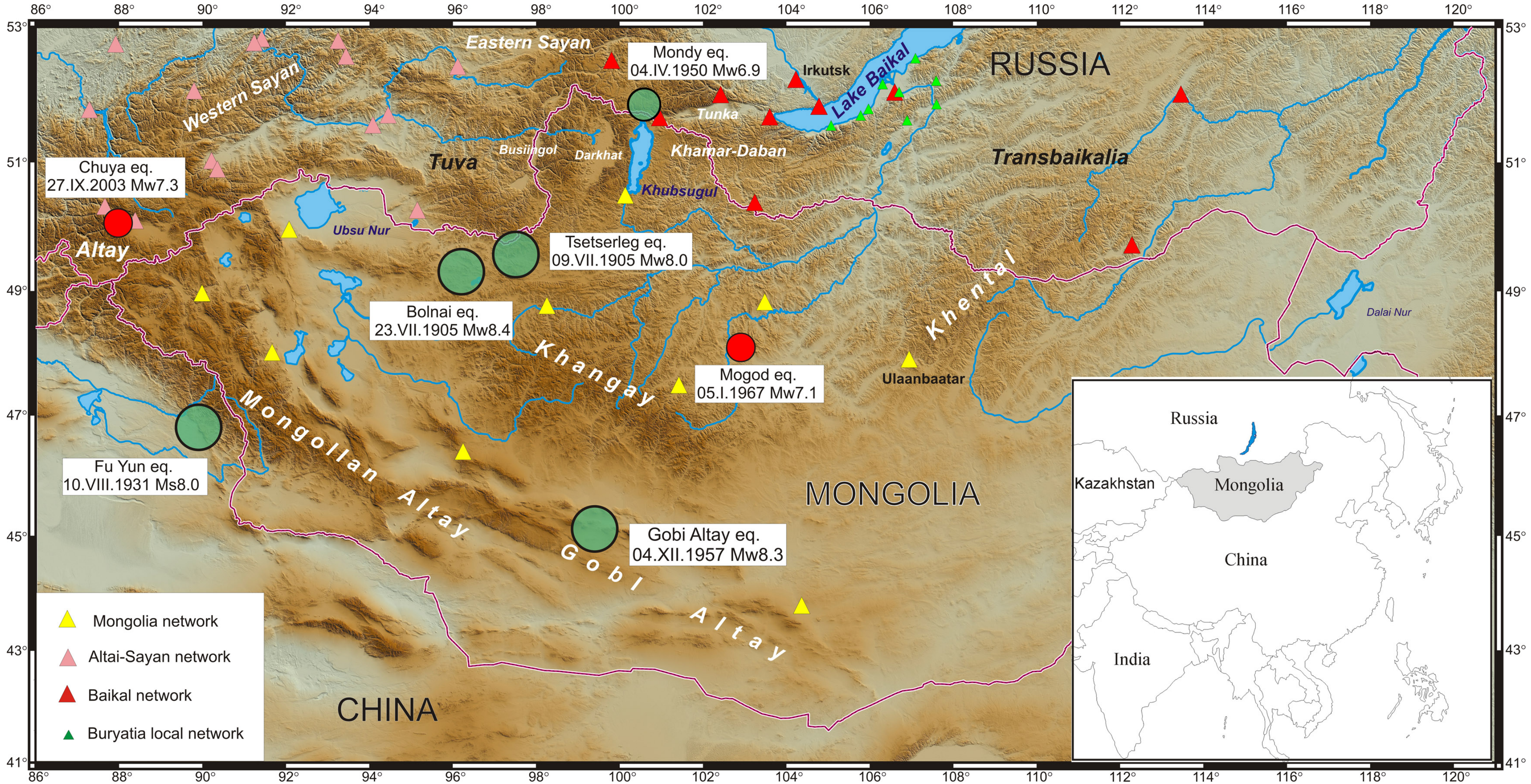

Fig. 1. The map of topography, seismic networks and the largest earthquakes of the study region. Events in the pre-instrumental period of observations are shown by green transparent circles; earthquakes recorded by the regional networks are shown by red circles.

Рис. 1. Карта рельефа, сейсмических сетей и крупнейших землетрясений исследуемого региона. Зеленые прозрачные кружки – события в период доинструментальных наблюдений; красные кружки – землетрясения, зарегистрированные региональными сетями.

because the regional sources of data are not readily available.

For earthquakes that occurred from 1996 to 2008, we examined both the analogous and digital seismograms of the Baikal, Mongolian and Altay-Sayan regional networks to constrain the focal mechanisms using polarity of Pn and Pg arrivals. A part of the solutions was published in annual issues of “Earthquakes of the Northern Eurasia”; here a list of solutions for weak earthquakes is presented. A compilation of earthquake fault plane solutions is given in Supplementary Materials.

Most of M≥4.5 earthquake mechanisms were shown in the map issued in 2011 [*Map of focal mechanisms…, 2011; Radziminovich et al., 2011; Sodnomsambuu et al., 2011*]. This map with additions is given in Fig. 2. In the event that both first motion and CMT solutions are available, the former is preferably shown. Although the geometry and kinematic types of fault planes determined by different authors are similar in most cases, mechanisms for some earthquakes differ (Fig. 3). The most important variation case for understanding of regional seismotectonics is the 1950 Mw 6.9 Mondy earthquake. Its final solution is given in [*Delouis et al., 2002*]. Figure 3 also shows a rare case of focal solutions determined for an earthquake of the Transbaikalia region. This is the 2006 Mw 4.5 Balei earthquake for which the published mechanisms also vary. The fault plane solution obtained from the first motion polarities [*Melnikova et al., 2011*] is of reverse-fault type, whereas the seismic moment tensor inverted from the phase and amplitude spectra of body and surface waves shows a pure strike-slip motion [*Barth, Wenzel, 2010*]. The third available solution, which we accept as the most reliable one, was derived in [*Radziminovich et al., 2012*] by using the surface wave amplitude spectra along with the first motion polarities at the local stations. This focal mechanism suggests a reverse slip with a strike-slip component on NW and N-S planes that is consistent with the structural position of the source.

3. METHODS

In our study, two approaches were used to inverse the regional stress field. The first was to divide the region into the subareas corresponding to the major structural units as well as the main zones of seismicity, and to invert the focal mechanisms of the earthquakes of each subarea for stress. For inversion a program Win-Tensor [*Delvaux, Sperner, 2003*] was used that implements the right dihedra method [*Angelier, 1984*] and a dynamic rotational optimisation procedure. In this software package, the graphical right dihedra method was developed for estimating stress ratio $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$.

The second way was to obtain the stress field over the whole region provided by the data, since the subarea data sampling may be incorrect and, moreover, it does not allow tracing the spatial stress variations. To meet this objective, we applied SATSI software, which is a damped inversion devised by [*Hardebeck, Michael, 2006*]. This method is based on the linear inversion technique [*Michael, 1984*] and minimizes the difference in stress between adjacent subareas where a single stress tensor was obtained. As noted by the authors of this method, damped inversion removes stress variation artifacts and resolves stress rotations more appropriate in comparison with a simple smoothed model or a moving-window inversion. For damped inversion, a scalar damping parameter that controls the relative weighting of the data misfit and the model length in the minimization should be set. To choose the damping parameter, we examined the trade-off curve between misfit and model length for a range of damping values and selected value e=0.6 (Fig. 4) that was near the corner of the trade-off curve, i.e. where both the model length and data variance were relatively small.

Probably, it is more reasonable to compare GPS strain patterns not with stress inversion results but with seismotectonic strain. For this, we visualized the averaged focal mechanism for each subarea applying the method of seismoteconic deformation described in [*Nikitin, Yunga, 1977; Yunga, 1990*]. Unlike the stress inversion, this approach takes into account the magnitude of earthquakes in samples; thus, a contribution of each event to the strain is determined by its magnitude. Strain patterns from GPS measurements were derived using horizontal GPS velocities within the Baikal-Mongolian network [*Lukhnev et al., 2010*]. Strain parameters were calculated according to the formulae taken from [*Turcotte, Shubert, 1985*]. Correctness of computation results was tested on the data from Tables 1 and 2, and Fig. 2 from the above mentioned paper [*Lukhnev et al., 2010*].

4. RESULTS

The first conclusion evidently inferred from the map is that the focal solutions of earthquakes in the southern Mongolia are rather homogeneous, whereas in the northern part they are widely variable (see Fig. 2). Indeed, the earthquakes in the major part of the Mongolian territory and the neighbouring regions of China are characterized by strike-slip and reverse movements. The strike-slip compressive stress regime (following the classification by [*Delvaux et al., 1997*]) with SHmax azimuth 220° was deduced for the Gobi Altai area (Table 1). The same regime was found for the Mongolian Altai, but the orientation of the SHmax here was determined as 195°. The pure strike-slip regime was

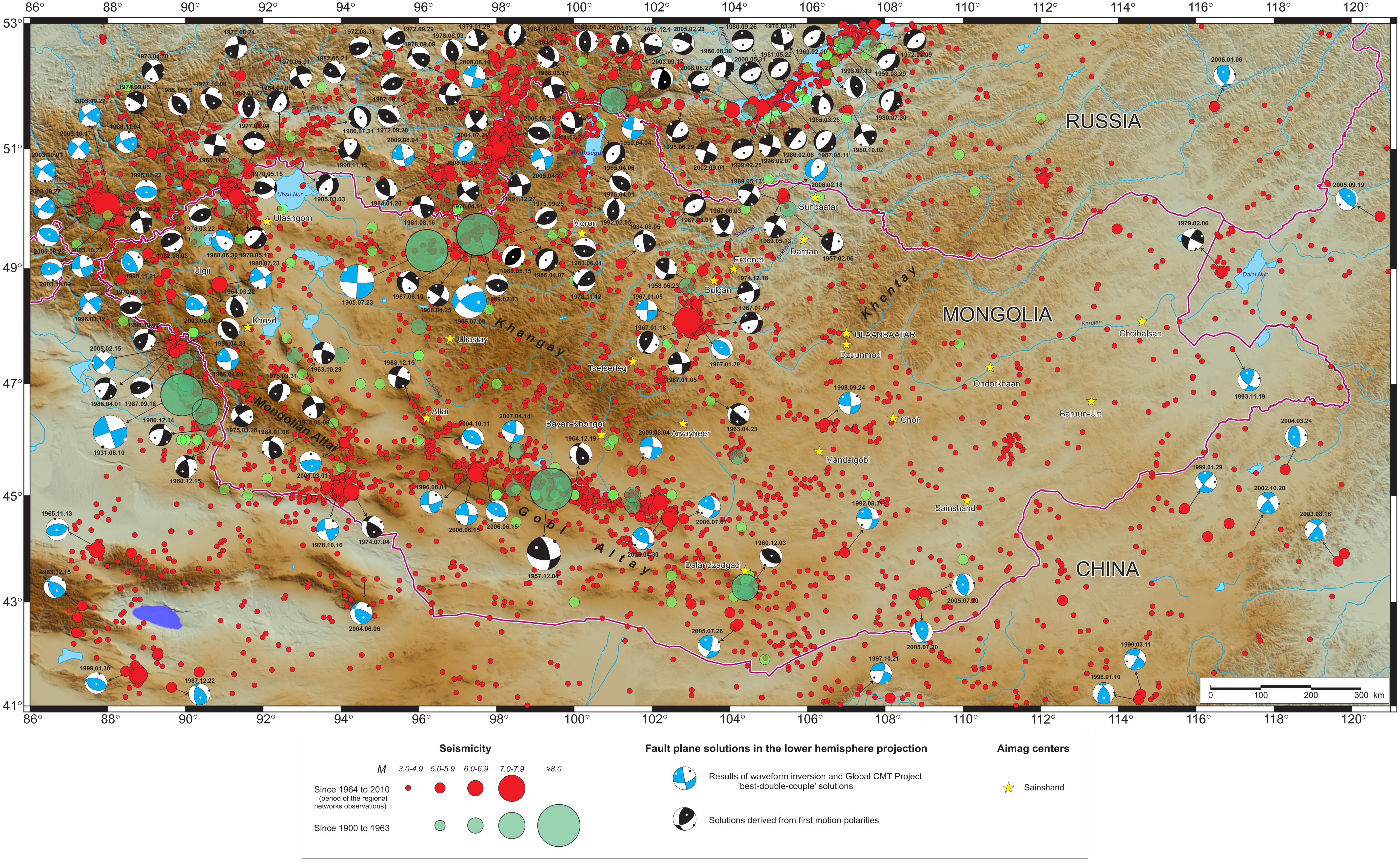

Fig. 2. The map of focal mechanisms of earthquakes in Mongolia and its surroundings [*Map of focal mechanisms…, 2011*, with additions].

SRTM files [*Jarvis et al., 2008*] were used to make topography in Mercator projection, WGS 84. Seismicity data (from 1964 to 2010) were taken from the regional catalogs issued by the Baikal Division of the Siberian Branch of the Russian Geophysical Survey, the Altay-Sayan Division of the Siberian Branch of the Russian Geophysical Survey, and the Mongolian national network.

Рис. 2. Карта механизмов очагов землетрясений Монголии и сопредельных территорий [*Map of focal mechanisms…, 2011*, с дополнениями].

Использованы файлы SRTM [*Jarvis et al., 2008*] для изображения рельефа в проекции Меркатора, WGS84. Эпицентры землетрясений (1964–2010 гг.) взяты из региональных каталогов Байкальского филиала Сибирского отделения Российской геофизической службы, Алтае-Саянского филиала Сибирского отделения Российской геофизической службы и Монгольской национальной сети.

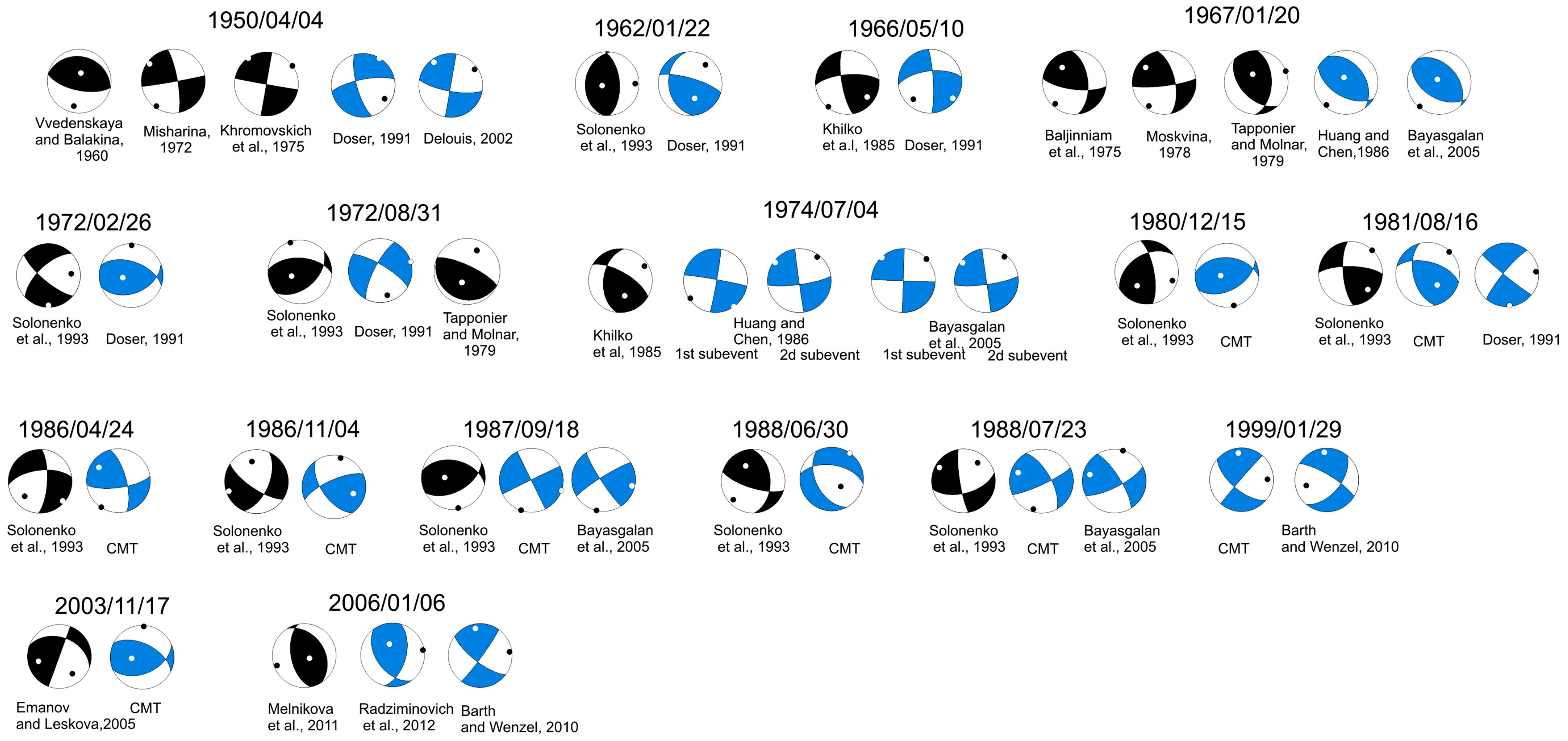

Fig. 3. Focal mechanisms of the earthquakes with some variations in the solutions determined by different authors and with different approaches.

Рис. 3. Механизмы очагов землетрясений, для которых имеется несколько решений, полученных разными авторами, а также с использованием различных подходов.

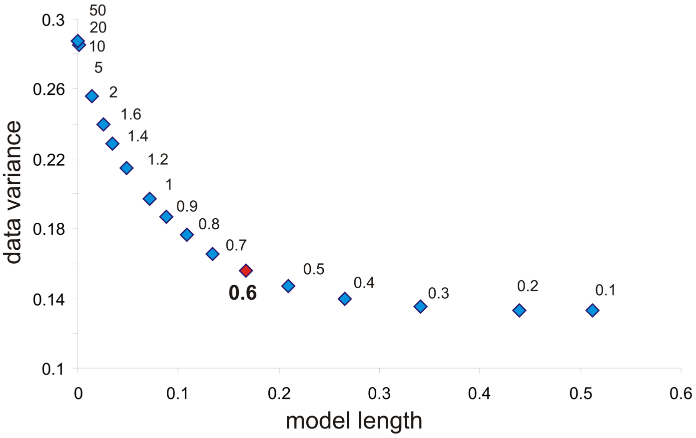

Fig. 4. The trade-off curve between model length and data variance for the full range of possible values of damping parameter *e*. Numbers indicate values of *e*.

Рис. 4. График для выбора оптимального значения параметра сглаживания *e*. Кривая показывает соотношение между длиной модели и дисперсией данных. Числа указывают значение *e*.

revealed for the Mogod seismic area, named so after the 1967 Mw 7.1 earthquake. The eastern part of the studied region is poorly provided by focal mechanisms, although it is still seismically active. The available solutions, which are mainly GCMT ones and the data from [*Barth, Wenzel, 2010*], show the compressive strike-slip regime with 262° of the SHmax orientation (Fig. 5).

The more complex pattern is observed in the area to the north of the Bolnai zone where the stress regime is converted from compression resulted from the India-Eurasian collision to local extension of the Baikal rift. The central part of the Baikal basin is characterized by a pure extension in the NW-SE direction, whereas earthquakes located at its southern termination have a significant strike-slip component along with normal faulting, and this gave grounds to conclude that this area is subject to transtension [*Radziminovich et al., 2006*]. Compression becomes stronger westward so that the Sayan Mountains are under the strike-slip field and Tuva region is under the compressive strike-slip regime.

The Bolnai area encompasses the rupture zones of the Tsetserleg-Bolnai M 8.0 earthquakes. While making inversion, we revealed that the sample contained too diverse solutions to yield a satisfactory result, so it was divided into several subsets. The 1905 mainshock subset consisting of several subevents [*Schlupp, Cisternas, 2007*] clearly shows the strike-slip compressional regime with SHmax azimuth 22°. As to the earthquakes recorded by the regional networks for the last 50 years, their focal mechanisms are very heterogeneous, and the low quality of the stress solution for the whole subset resulted in separating it into two opposed stress tensors fitted the data, namely compressional and extensional ones (Table 1).

Table 1. **Stress inversion results for different areas using the method and stress regime classification by D. Delvaux**

Таблица 1. **Результаты инверсии тектонических напряжений для разных районов, полученные по методу Д. Дельво**

Area	N	σ_1	σ_2	σ_3	R	R`	F1	Q	Regime
Baikal	24	76/140	01/234	14/324	0.56	0.56	16.5	B	pure extensive
Bolnai 1	8	01/022	03/293	87/131	0.02	2.02	9.8	A	strike-slip compressional
Bolnai 2	11	07/296	08/205	79/069	0.71	2.71	19.0	B	pure compressional
Bolnai 3	8	78/216	08/085	09/354	0.36	0.36	25.6	C	pure extensional
Eastern Mongolia	12	07/262	79/033	07/171	0.27	1.73	25.7	C	compressive strike-slip
Goby Altai	13	00/220	12/130	78/310	0.05	2.05	15.0	B	compressive strike-slip
Mongolian Altai	35	00/015	19/285	71/105	0.19	2.19	43.3	C	pure compressive
Mogod	15	03/059	63/155	27/327	0.62	1.38	23.1	C	pure strike-slip
Sayan	8	16/077	72/229	08/345	0.42	1.58	39.6	C	pure strike-slip
Tuva	18	07/031	62/286	27/125	0.12	1.88	54.2	C	compressive strike-slip
Ubsu Nur	20	07/203	46/106	43/299	0.29	2.29	75.4	C	pure compressive

Note. N – number of focal solutions in a sample; σ_1, σ_2, σ_3 – orientation (inclination/azimuth) of the principal stress axes (maximum, intermediate, and minimum compression, correspondingly); Q – tensor quality rank (from A (best) to E (worst)); R – stress ratio (ranges from 0 to 1); R` – stress regime index; F1 – slip-shear misfit angle; Regime – stress regime. Bolnai 1 is the 1905 mainshock subset, Bolnai 2 and Bolnai 3 are the subsets representing the recent earthquakes.

Примечание. N – количество решений механизмов очагов землетрясений для данной выборки; σ_1, σ_2, σ_3 – ориентация (угол наклона / азимут) главных осей напряжений (максимальное, среднее и минимальное сжатие, соответственно); Q – качество решения (от A (лучшее) до E (худшее)); R – коэффициент, показывающий соотношение осей напряжений (в диапазоне от 0 до 1); R`– показатель режима напряжений; F1 – угол между вектором скольжения и теоретическим направлением скалывания. Болнай 1 – данные по главному сейсмическому событию 1905 г.; Болнай 2 и 3 – данные по землетрясениям инструментального периода наблюдений.

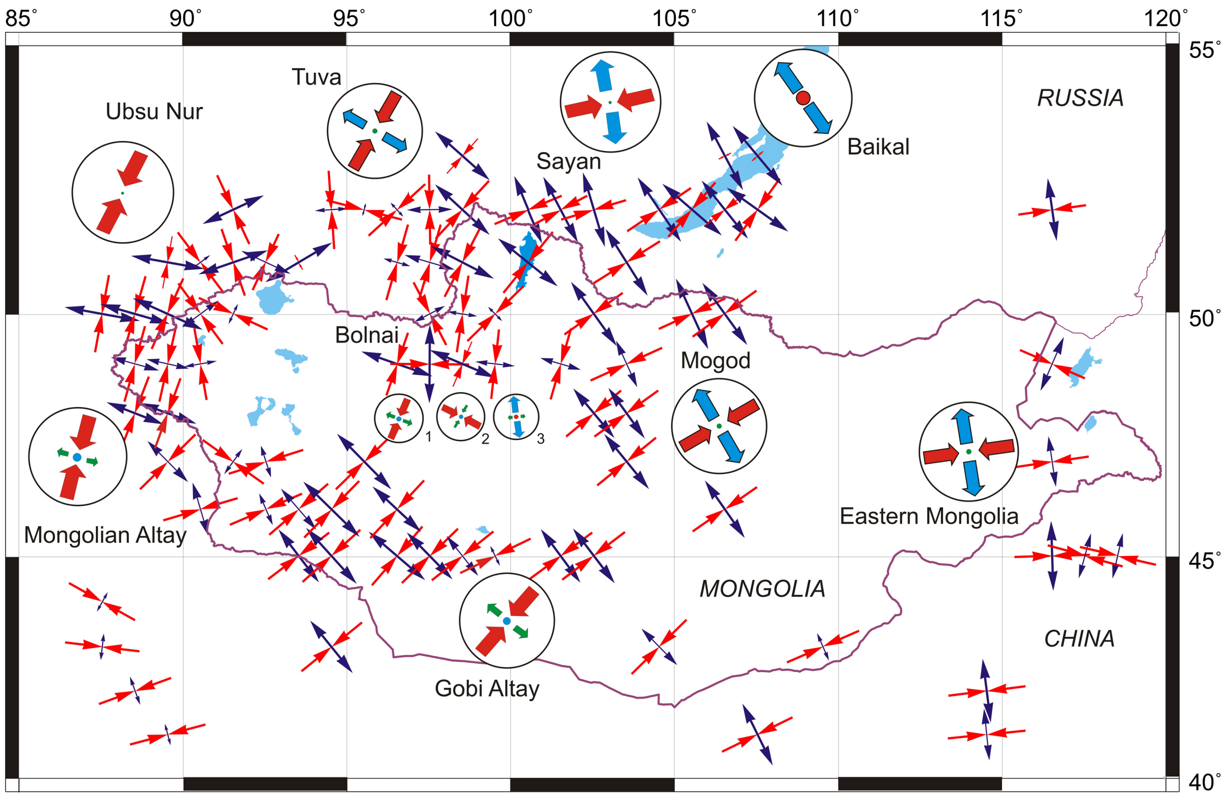

Fig. 5. Stress inversion results for the main active domains (in circles) and after the damped stress inversion for 1°-spaced grid.

Vectors give the orientations of maximum (red) and minimum (blue) compressional horizontal stress SH and Sh. An arrow length depends on the inclination to the horizon. Inversion results obtained by Tensor program (in circles) show also intermediate axis orientations (green). Names of the main active domains and the inversion results correspond to Table 1.

Рис. 5. Результаты инверсии тектонических напряжений, полученные для основных активных областей (в кружках) и в ходе линейной инверсии со сглаживанием для сетки с шагом 1°.

Векторами показана ориентация максимальных (красные) и минимальных (синие) горизонтальных напряжений сжатия SH и Sh. Длина стрелок зависит от угла наклона к горизонту. Результаты инверсии, полученные с помощью программы Tensor (в кружках), показывают также ориентацию промежуточной оси (зеленого цвета). Названия основных активных областей и результаты инверсии соответствуют данным таблицы 1.

Another complex area is the territory to the west and north from the Ubsu Nur Lake. It is subject to the S-N compression; nevertheless, diversity of focal solution types here resulted in the largest misfit angle.

The damped inversion results are more smoothed when compared to the stress tensors for subareas. It should be noted that in the outermost SW part of the region, within the China territory, SHmax suddenly becomes oriented in the SE-NW bearings. Such orientation (more precisely, NNW) of the compression axis was in one fault plane solution among others mechanisms; furthermore, the available focal solutions in this area are solitary while the method requires adjacent data. Thus, this is an artefact due to the limited data set for this area. As a whole, the results show that SHmax is turning from the W-E direction in the eastern Mongolia to NE-SW in the Gobi Altay and the central Mongolia, and then to S-N in the western part of the region (Fig. 5).

5. Discussion

The regularities revealed on the recent seismological data are generally consistent with the Late Cenozoic tectonic stress features inferred from a structural analysis of the active fault zones [*Parfeevets, Sankov, 2010, 2012*], as well as with the recent geodetic data. The GPS velocity field shows two main trends (Fig. 6): the NE trend within Jungaria, the Mongolian Altay, and the Great Lakes Valley, and the SE trend for the central and eastern Mongolia [*Calais et al., 2003; Lukhnev et al., 2010*]. The change between these trends spatially coincides with the Khangay dome and the Bolnai zone, being the northern boundary of the dome.

Figure 7 shows the strain patterns within the Baikal-Mongolia GPS network and the stereograms of average mechanisms that actually represents seismotectonic strain. The stereograms were obtained for the

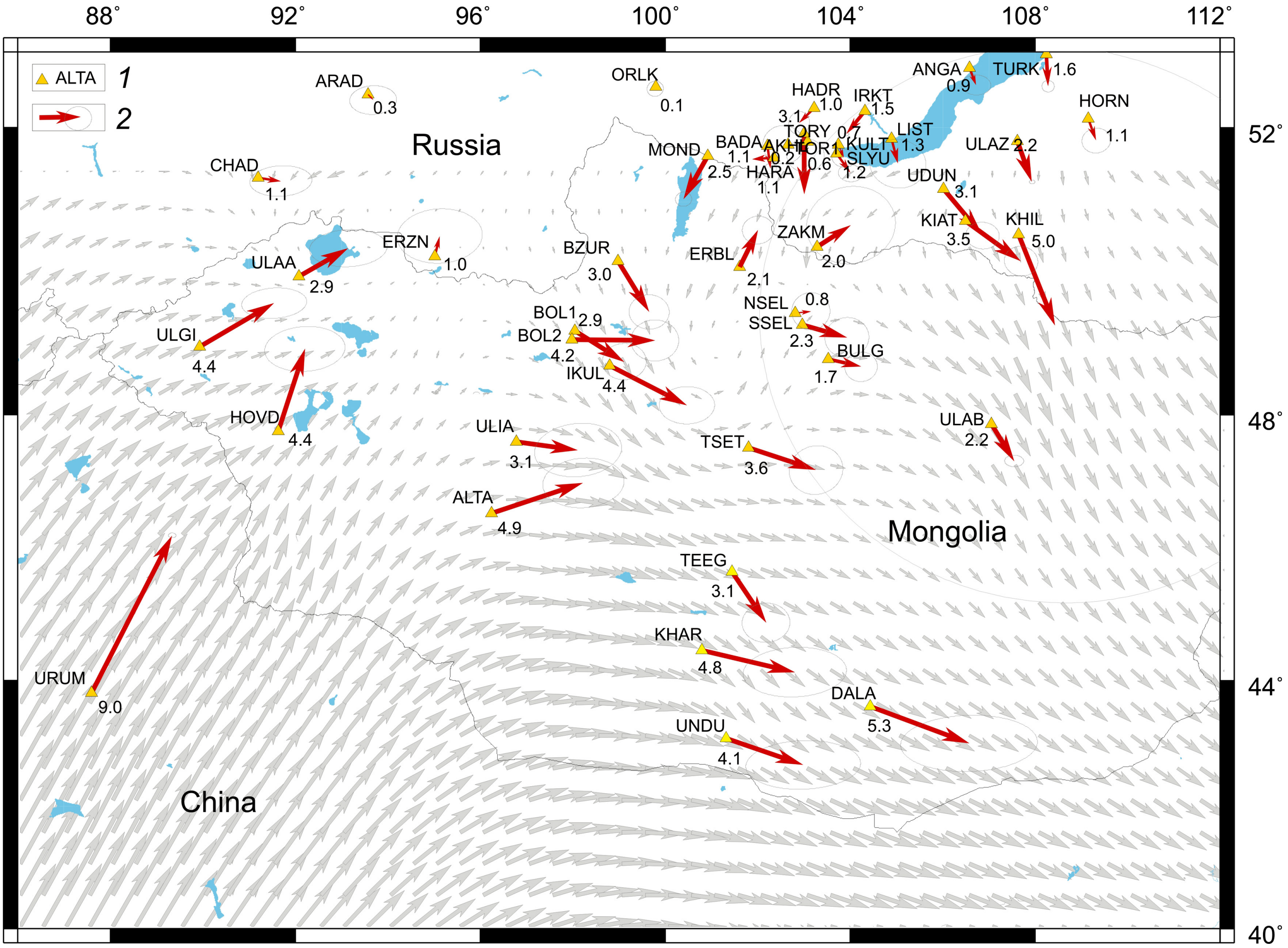

Fig. 6. The field of GPS horizontal velocities with respect to Eurasia for 1994–2007.

Red arrows show directions and velocities (mm/yr) with 95% confidence limit; light grey arrows show vectors averaged on a 30′×30′ regular grid. The map is based on the data from Table 1 in [*Lukhnev et al., 2010*]. *1* – abbreviated station name and velocity (mm/yr); *2* – direction and velocity with 95% confidence ellipse.

Рис. 6. Поле горизонтальных скоростей по данным GPS относительно Евразии с 1994 по 2007 г.

Направления и скорости (мм/год) с 95%-ным доверительным интервалом показаны красными стрелками; светло-серые стрелки показывают векторы скоростей, интерполированные по сетке 30′×30′. Карта базируется на данных из таблицы 1, опубликованной в [*Lukhnev et al., 2010*]. *1* – сокращенное название станции и скорость (мм/год); *2* – направление и скорость с 95%-ным доверительным эллипсом.

main seismic zones (like the stress inversion subareas) so that they do not coincide fully with the geodetic triangles. Nevertheless, the general features can be compared. For the southern and western areas, where strong earthquakes occurred like the 1957 M 8.3 Gobi-Altay earthquake or the 1931 M 8.0 Fu Yun earthquake in Mongolian Altay, the strain patterns obtained from GPS and seismological data are consistent, whereas the above mentioned Bolnai zone shows a contradiction. The results of GPS estimation indicate the predominance of extension (in the SE-NW direction), while compression was revealed for the longer period of seismic observations. Yet, the seismotectonic strain shows compression that was provided mainly by the Tsetserleg-Bolnai earthquakes; however, we noted above that a part of the recent data on focal mechanisms fits an extensional stress field with the NNW oriented extension axis. The diversity of the recent focal solutions might be caused by postseismic relaxation or stress perturbation after the mainshocks or it could reflect the different scale of the considered earthquake. In addition, there is an ambiguity related to comparison between GPS and seismicity data on account of different spatial and time domains to be compared, and complexity of the rupture kinematics in case of a large earthquake.

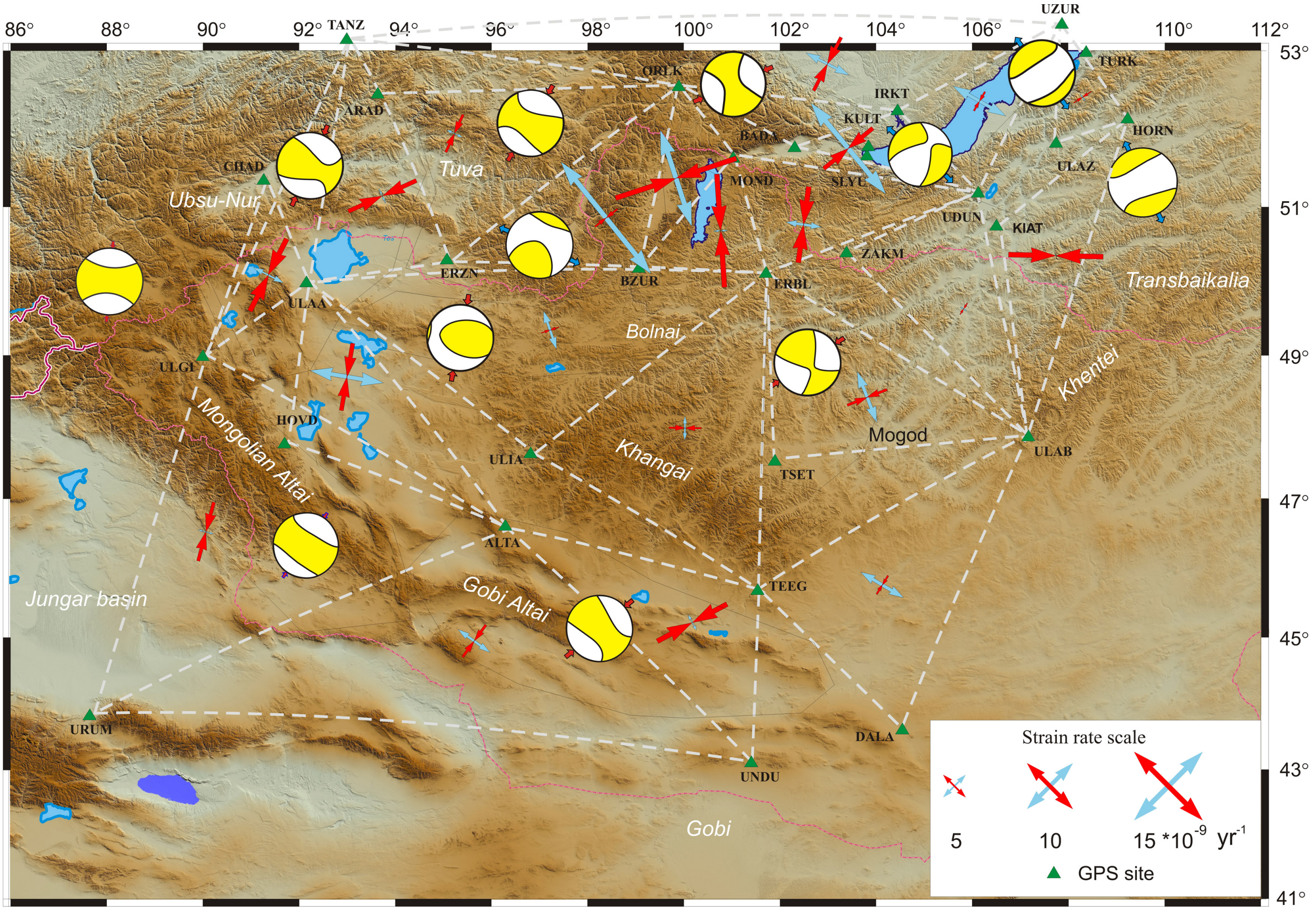

Fig. 7. Strain patterns within the Baikal–Mongolia GPS network.

Red and blue arrows show principal shortening and stretching strain axes derived from the GPS velocity data from Table 1 in [*Lukhnev et al., 2010*]. Seismotectonic strain is visualized by yellow stereograms, which are the averaged focal solutions for the main seismic zones outlined by thin black lines.

Рис. 7. Ориентация и скорость деформации земной коры в пределах Байкало-Монгольского GPS-полигона.

Оси укорочения и удлинения, установленные по данным GPS-векторов (таблица 1 [*Lukhnev et al., 2010*]), показаны красными и синими стрелками. Сейсмотектонические деформации показаны на стереограммах (желтый) как усредненные решения механизмов очагов землетрясений для основных сейсмических зон, оконтуренных тонкой черной линией.

However, another confirmation of the transtensive field existence in the eastern part of the Bolnai zone comes from Quaternary fault-slip data [*Parfeevets, Sankov, 2012*]. The extension here is supposed to be related to the divergent motions between the North Eurasia and Amurian plates [*Petit, Fournier, 2005*]. Changes in seismotectonic deformations in this area were also reported by O.A. Kuchai and M.E. Kozina [*2015*] who outlined there the boundary of the Amurian plate.

The complexity of focal solutions is also observed in the NW part of the study region. Despite this area is subjected to the S-N compression, normal fault earthquakes are rather numerous there. This area is also distinguished by the fact that seismicity is mainly confined to the ridges and uplifts rather than to basins (*e.g.*, Tuva basins, Great Lake basin, Ubsu-Nur basin). S.V. Gol`din and O.A. Kuchai [*2007*] explained these two observations by the block structure of the Altay-Sayan area, and, more precisely, by “the hierarchic systems of rigid and plastic blocks (rheological structure)”. In other words, the basins are supposed to be aseismic rigid block; as to normal slip focal solutions found here, they are thought to occur in regions of strain shadow.

We roughly estimated the strain rate for the territory of Mongolia using the widely known Kostrov`s formulae [*Kostrov, 1974*] as summed moment tensors of earthquakes divided by shear modulus, volume and time interval of observations. Only earthquakes with M≥7.0 (the Mw 6.9 Mondy event was also included)

Table 2. **Components of the seismotectonic strain rate tensor**

Таблица 2. **Компоненты тензора скорости сейсмотектонической деформации**

ε_{xx}	ε_{yy}	ε_{zz}	ε_{xy}	ε_{yz}	ε_{xz}	ε_{ij}, (yr^{-1})
0.89	−4.04	3.13	−42.4	2.03	−3.80	10^{-9}

Note. Elements of the symmetrical strain rate tensor obtained by summing moment tensors of earthquakes with M≥7.0 and dividing the results by the time interval (100 years) and the crust volume (1200×2900×20 km). Coordinate axes x, y and z are east, north, and up, respectively. Minus and plus indicate shortening and stretching of the crust, respectively.

Примечание. Компоненты симметричного тензора скорости деформации получены путем суммирования моментов тензоров землетрясений магнитудой M≥7.0 и деления результата на временной интервал (100 лет) и объем коры (1200×2900×20 км). Оси координат x, y и z – восток, север, вверх соответственно. Знаки – и + указывают на сокращение и растяжение земной коры, соответственно.

that constitute significant strain release were considered. Values of the average strain rate tensor components are shown in Table 2. The largest value is about 42×10^{-9} yr^{-1} for the horizontal shear component ε_{xy} that exceeds the shortening rate estimated for different parts of Mongolia from GPS measurements, which ranges approximately from 3×10^{-9} to 25×10^{-9} yr^{-1} [*Lukhnev et al., 2010*]. In case of summing only scalar seismic moments of the earthquakes, the seismic strain rate is 8.7×10^{-9} yr^{-1}. For the time interval of 100 years, the seismic moment release is approximately 1.12×10^{20} N m yr^{-1}. Even such rough estimates of the strain rate and seismic moment release are rather high for the intracontinental setting. It has been already noted by W.E. Holt and his colleagues, who reported that in the 20th century the earthquake moment release rate in Mongolia was about a factor of 4 higher than the model long-term rate [*Holt et al., 1995, 2000*]; this is obviously due to the occurrence of several great earthquakes close in time and space. Proximity of the four earthquakes with M≥8 implies a possible link between them, for example, through viscoelastic stress transfer, as was tested in [*Chery et al., 2001*].

6. CONCLUSIONS

In this report, we have gathered earthquake focal solutions for the territory of Mongolia and its surroundings in order to reveal a spatial variability of the stress orientation and stress regimes of the crust. Our results do not bring much change in the already published results for this territory [*Zhalkovskii et al., 1995; Melnikova et al., 2004; Melnikova, Radziminovich, 2005; San'kov et al., 2005, 2011; Gol'din, Kuchai, 2007; Parfeevets, San'kov, 2010; Rebetsky et al., 2013; Kuchai, Kozina, 2015; and others*] indicating that the main characteristics of the present-day regional stress field are quite steady.

The map of focal mechanisms shows that the earthquake focal solutions in the southern and western parts of Mongolia and the neighbouring regions of China and Russia are quite uniform (strike-slip and thrust movements). The more complex pattern is observed in the area to the north from the Bolnai zone where the stress regime is thought to be converted from compression due to the India-Eurasian collision to local extension due to the Baikal rifting. The complicated picture of focal mechanisms distribution in the Altay-Sayan area may be explained by the block structure of this territory.

According to the stress inversion results, the SHmax is turning from W-E in the eastern Mongolia to NE-SW in the Gobi Altay and the central Mongolia and then to S-N in the western part of the region. The regularity can be explained by the recent geodynamics of this part of Asia.

The strain axes directions revealed by the geodetic and seismological observations are generally consistent. As for the strain rate, clustering of large earthquakes in time due to mutual triggering may be an additional factor (along with the incompleteness of seismic catalogues) that complicates the comparison of geodetic and seismic strain rate.

The data compiled and visualized in this study show the spatial gaps to be covered by earthquake focal solutions. For instance, the vast areas of the eastern part of Mongolia and Transbaikalia remains insufficiently studied that should be compensated not only 'for the sake of pure scientific interest' but mainly for seismic hazard assessment of the capital of Mongolia. Ulaanbaatar, the largest city at the region with population about 1,200,000 people, has recently faced with increasing the seismic activity in its vicinity. Therefore, a proper knowledge of kinematic type of active faults under the recent stress regime is strongly needed to constrain potential earthquake scenarios.

We hope that the map and the stress inversion results can be a useful tool for geodynamic and seismotectonic analyses of this part of Asia and it will facilitate better understanding of spatial co-existence of different stress regimes.

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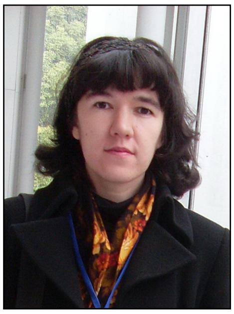

Radziminovich, Natalia A., Candidate of Geology and Mineralogy, Senior Researcher
Institute of the Earth's Crust, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
Tel.: 89642160520; ✉ e-mail: nradzim@crust.irk.ru

Радзиминович Наталья Анатольевна, канд. геол.-мин. наук, с.н.с.
Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
Тел.: 89642160520; ✉ e-mail: nradzim@crust.irk.ru

Bayar Gangaadorj, Researcher
Research Center of Astronomy and Geophysics of MAS
Ulaanbaatar 210351, Mongolia
e-mail: bayart@rcag.ac.mn

Баяр Гангаадорж, научный сотрудник
Исследовательский центр астрономии и геофизики МАН
210351, Улан-Батор, Монголия
e-mail: bayart@rcag.ac.mn

Miroshnichenko, Andrei I., Candidate of Geology and Mineralogy, Senior Researcher
Institute of the Earth's Crust, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
Tel.: +7(3952)429534; e-mail: mai@crust.irk.ru

Мирошниченко Андрей Иванович, канд. геол.-мин. наук, с.н.с.
Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
Тел.: (3952)429534; e-mail: mai@crust.irk.ru

Demberel Sodnomsambuu, Director, Professor
Research Center of Astronomy and Geophysics of MAS
Ulaanbaatar 210351, Mongolia
e-mail: demberel@rcag.url.mn

Дэмбэрэл Содномсамбуу, директор, профессор
Исследовательский центр астрономии и геофизики МАН
210351, Улан-Батор, Монголия
e-mail: demberel@rcag.url.mn

Ulziibat Monkhoo, Head of the Seismological Department of RCAG
Research Center of Astronomy and Geophysics of MAS
Ulaanbaatar 210351, Mongolia
e-mail: ulzibat@rcag.url.mn

Ульзибат Монхо, начальник отдела сейсмологии
Исследовательский центр астрономии и геофизики МАН
210351, Улан-Батор, Монголия
e-mail: ulzibat@rcag.url.mn

Ganzorig Davaasuren, Researcher
Research Center of Astronomy and Geophysics of MAS
Ulaanbaatar 210351, Mongolia
e-mail: ganzorig@rcag.url.mn

Ганзориг Даваасурен, научный сотрудник
Исследовательский центр астрономии и геофизики МАН
210351, Улан-Батор, Монголия
e-mail: ganzorig@rcag.url.mn

Lukhnev, Andrei V., Candidate of Geology and Mineralogy, Senior Researcher
Institute of the Earth's Crust, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
Tel.: +7(3952)429534; e-mail: loukhnev@crust.irk.ru

Лухнев Андрей Викторович, канд. геол.-мин. наук, с.н.с.
Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
Тел.: (3952)429534; e-mail: loukhnev@crust.irk.ru