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Original article

The 2021 M_w 6.7 Khankh earthquake in the Khuvsgul rift, Mongolia

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ABSTRACT

A M_w 6.7 occurred at Lake Khuvsgul in northwestern Mongolia at 05:32:56 AM Ulaanbaatar time on the 12th of January 2021. The epicenter of the event was offshore south of the Doloon Uul peninsula around 30 km SSW of Khankh village. Shaking was felt within most of central and western Mongolia, including the capital city Ulaanbaatar ~600 km from the epicenter. The earthquake appears to have ruptured the Khuvsgul fault along the western coast of Lake Khuvsgul. The earthquake is the largest in Mongolia since the M_w 6.3 Busiin Gol earthquake in 1991. Our research team from the Institute of Astronomy and Geophysics, Mongolian Academy of Sciences visited the epicenter area for 5 days soon after the earthquake and installed four broad-band seismic stations and searched the area for geological evidence of the earthquake. The location, azimuth, dip and depth of this earthquake defined by moment tensor solutions calculated by the international seismological centers and analysis of InSAR interferograms and field observations. The projected intersections of the east-dipping nodal planes with the surface for solutions of the international seismological centers and researchers correlate relatively well with the mapped strike and location of the old tectonic scarp of the Khuvsgul fault although we have not discovered any primary co-seismic surface rupture. The InSAR interferogram demonstrates the sharp discontinuity and fringes in the area between the Western Range and Doloon Uul peninsula which implies surface deformation. Aftershocks that have continued during the three months subsequent to the earthquake define overall strike of the mainshock rupture.

Keywords: Basin, co-seismic, epicenter, fault and solutions

INTRODUCTION

In this paper, we present the fault plane solutions of the Khankh earthquake M_w 6.7 and discuss its relations with the underlying Khuvsgul fault, through analysis of satellite images, InSAR data and co-seismic surface rupture features revealed by the field visit.

The Khuvsgul (it is written as Hövsgöl according to Baljinnyam et al., 1993), Darkhad and Busiin Gol basins are considered to be the south-west termination of the Baikal rift system. The Baikal rift is defined by an alignment of north-east-trending elongated basins stretching from Mongolia to Russia for roughly 1700-1800 km. The rift zone consists of numerous basins including Busiin Gol, Darkhad, Khuvsgul, Tunka, Baikal, Angara, Muya and Khara from the south-westernmost continuation in Mongolia to the north-easternmost tip in Russia.

The scientific study of Lake Baikal began from the 18th century geographic expeditions of the Russian Geographical Society. The first scientific realization of the Baikal basin in the frame of tectonic context was reported by Obruchev in 1938. In the literature, Lake Baikal is expected to fill out a graben formed by expansion of tectonic blocks. Pavlovsky (1948) revealed the similarity to the east African rift.

Several hypotheses and models on the origin and evolution of the rifting have been proposed (such as Florensov, 1969; Molnar and Tapponnier, 1975; Zonenshain and Savostin, 1981; Logatchev et al., 1993; Ivanov, 2004; Petit and Deverchere, 2006). Molnar and Tapponnier (1975) interpreted that the Baikal rift zone is a manifestation of the India-Eurasia collision. Logatchev (1993) and Logatchev et al. (1983) argued that the initiation and development of the rift is an independent structure associated with the local thermal processes in the mantle without any direct relation to the collision of India-Eurasian plates. Recent studies by Petit and Deverchere have been able to confirm earlier findings by Tapponnier and Molnar.

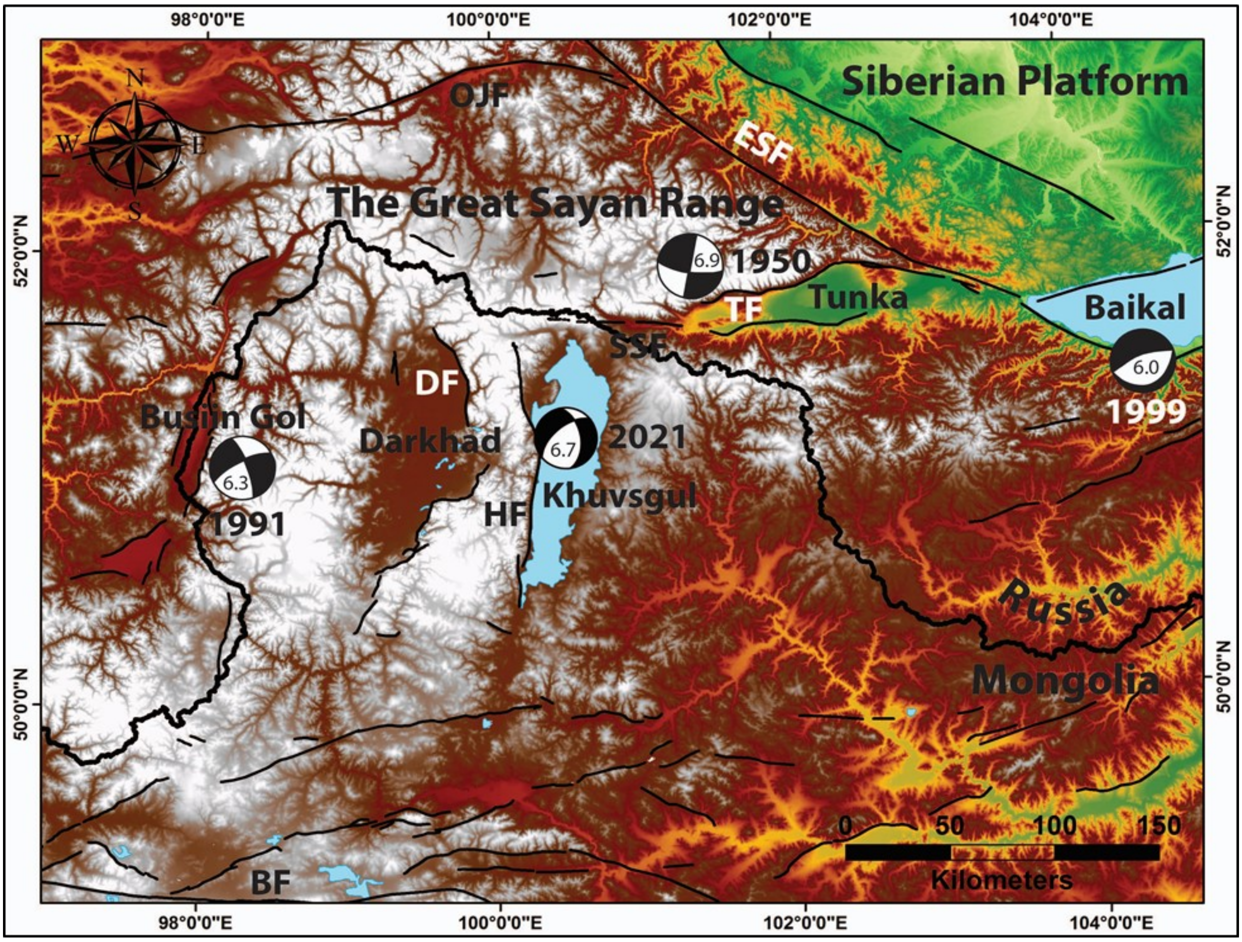


Fig. 1. General map of the Busiin Gol, Darkhad, Khuvsgul, Tunka at south-western edge of the Baikal rift system. Focal mechanisms of earthquakes ($M_w \geq 6.0$) and active faults are plotted on Shuttle Radar Topography Mission (SRTM). Elevations are from ~500 (light-green) to ~3500 m (white). The thick curved black line is the border between Mongolia and Russia. The focal mechanism solutions for $M_w \geq 6.0$ events are from Bayasgalan et al. (2005) and Ritz et al. (2018). Black lines represent the active faults, including Khuvsgul fault (HF), South Sayan fault (SSF), Darkhad fault (DF), Busiin Gol fault, Oka-Jombolok fault (OJF), Eastern Sayan fault (ESF) and Bulnai fault.

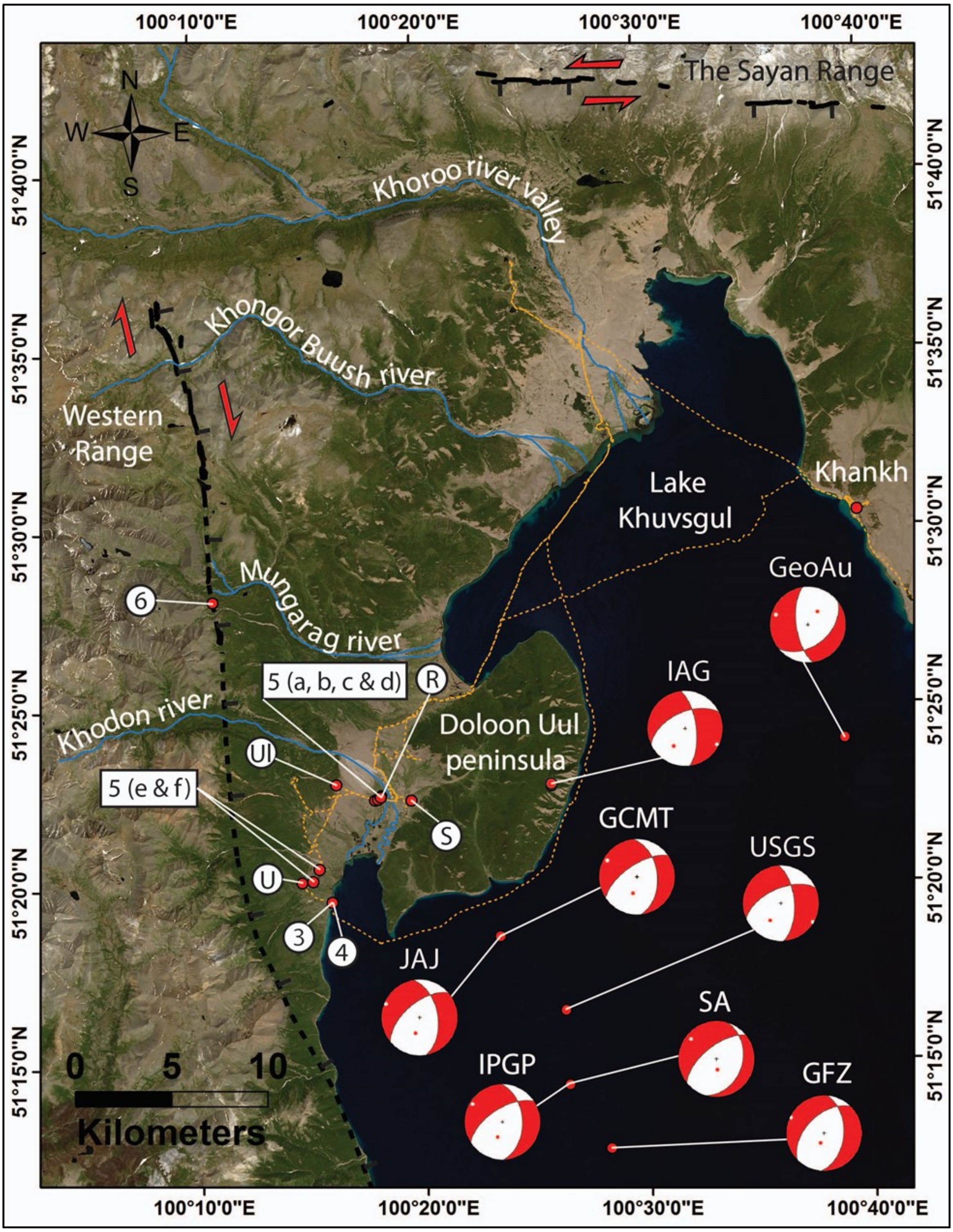


Fig. 2. The epicenter area of the Doloon Uul peninsula. The Base Map is based on the Landsat 8 image. Tectonic scarps of Khuvsgul and Sayan faults are marked by the thick black lines. The dashed black line is the inferred Khuvsgul fault. Golden dashed lines are our tracks during the field research work. Capital letters (U, Ul, R and S) represent the locations of the herder families who are Ukhnaa, Ulziibat, Rinchen and Sodkhuu where we collected the macro-data. Numbers of 3, 4, 5 and 6 express the locations of the field photographs for Figs. 3, 4, 5 and 6 respectively. Fault plane solutions are modified from the official websites and personal communications. See the Table 1 for the detailed information.

Several investigations (Calais et al., 2003; San'kov et al., 2000; Ritz et al., 2018) have been conducted to estimate the rates and amounts of opening of the Baikal rift from GPS measurements and slip-rates along the basin bounding faults from geological observations. GPS measurements suggests a crustal extension of ~4 mm/year across the main portion of the Baikal rift (Calais et al., 2003). The central Baikal basin is bounded by the Siberian platform to the west. Zonenshain and Savostin (1981) and more recently Barth and Wenzel (2010) showed that the Baikal rift system is a boundary of the Amurian plate. Khuvsgul, Darkhad and Busiin Gol basins in the Mongolian territory which define the southwestern limit of the rift sytem have N-S trending azimuths, whereas the Central Baikal and other basins in the Russian territory has dominantly SW-NE oriented strikes (Fig. 1).

GEOLOGY

The basement geology of the Busiin Gol, Darkhad and Khuvsgul rifts regions are accreted Neoproterozoic and Paleozoic accretionary wedge and island arc terranes (Badarch et al., 2002). It is composed of Neoproterozoic metamorphic, volcanic rocks and ophiolite. Some part of the basement rocks are covered by Neoproterozoic-Lower Cambrian shelf carbonate rocks of the Khuvsgul basin and intruded by post-collisional Ordovician, Devonian and Permian granites. The central section of the Baikal rifting initiated in Oligocene and other neighboring basins were developed during Miocene (Florensov, 1969; Logatchev, 1993). The rifting of Lake Khuvsgul began in the Late-Miocene and the Darkhad and Busiin Gol depressions initiated later in the Middle-Pliocene (Logatchev, 1993).

Late-Pleistocene moraines and post-glacial sediment deposits are widespread along the river valleys around the lake (Wegmann et al., 2011; Orkhonselenge et al., 2014).

The brief characteristics of the Khuvsgul basin

The Khuvsgul basin is bounded by the Khoridol Saridag (3093 m) and Ulaan Taiga Range (3193 m) to the west and the Sayan Range (Munkh Saridag 3491 m) to the north. The eastern mountains (the highest point is the Tsagaan Uul 2367 m) are relatively low and dome shaped comparing to the western and northern ranges. Lake Khuvsgul is 136 km long and 36.5 km wide at its widest section (Fig. 1). Its depth reaches 267 m and areal expanse is 2620 km^2, with a total water volume of 381 km^3. The surface elevation of the lake is ~1645 m above sea level (Sodnom et al., 1990). A large number of permanent rivers flow into Lake Khuvsgul and the Khoroo river from the north-west is the largest among them. Only the Eg river flows out from the lake to join the Selenge river which flows into the world largest fresh water Lake Baikal.

Active faults in the Khuvsgul rift

The western side of Lake Khuvsgul is controlled by an active fault forming a half-graben structure. The half-graben is identified as the western block which features a linear and rugged topography as well as thickness of sediment deposits to the western coast by a seismic profile across the lake (Fedotov, 2007; Prokeponko and Kendall, 2008).

Active faults in the vicinity of the Khuvsgul rift have been mapped roughly by Molnar and Tapponnier (1975), relatively in detail by Zonenshain and Savostin (1981) and Khilko et al. (1985), in somewhat greater detail by Sankov et al. (2003); Arjannikova et al. (2004), Byamba (2009) and Ritz et al. (2018).

From its northern end near Khongor Buush river, the Khuvsgul fault strikes southward into Lake Khuvsgul. The NNW-trending northern segment in the surface is mapped tentatively as discontinuous and interrupted scarps from the lake margin around 51˚08′35″ N, 100˚19′15″ E the south of the Doloon Uul peninsula and northward to around 51˚36′39″ N, 100˚08′17″ E the south of the Khoroo river valley (Fig. 2). Several river valleys and risers are displaced right-laterally along the fault to the north based on satellite images.

The Sayan active fault is located along the front of the Sayan Mountain Range at the north of Lake Khuvsgul. The rivers from the range are displaced left-laterally in tens of meters by the fault. Considering the triangular facets of the

Sayan Mountain Range, it could be a normal fault with left-lateral strike-slip component. Ritz et al. (2018) estimated that the left-lateral slip rate along the Eastern Sayan fault is 1.3-3.9 mm/year.

There is no research work investigating the geological slip rate along the Khuvsgul fault.

Fault plane solutions of the Khankh earthquake

We compare different fault plane solutions by different seismological centers and researchers around the world in Fig. 2. The location, depth, strike, dip and rake of the event are summarized in Table 1. The locations of each are consistent with the event occurring on the down-dip projection of the east-dipping Khuvsgul normal fault (Fig. 2). The east-dipping nodal planes of each mechanisms are similarly consistent with normal displacement along the northerly striking Khuvsgul fault. The alignment of the estimated epicenters along a northwest trending line most likely is not tectonically significant but rather an artifact of different locations procedures and data used by the respective agencies.

The moment tensor and epicenter labeled IAG in Fig. 2 are determined via local seismic network stations which belong to MNDC, IAG (Mongolian National Data Center, Institute of Astronomy and Geophysics). We define the earthquake moment tensor inversions as the estimation of the source depth (Z), the moment magnitude (M_w), and strike, dip and rake angles for the shear dislocation source (Herrmann et al., 2011; Herrmann, 2013). The moment tensor solutions in Fig. 2 are determined with the broadband channels of the regional seismic networks for a rapid estimation of the source parameters with body waves except for Geoscience Australia (GeoAu) and Seismic Analysis (SA) which used W-phase and body wave source inversion data and methods.

We show in Fig. 7 the location of surface rupture that can be expected by propagating up dip along the fault plane and epicenter determined by each agency. The projected intersections of the nodal planes with the surface for GCMT, JAJ and IPGP solutions correlate relatively well with the mapped strike and location of the Khuvsgul fault. The projected locations of IAG, USGS and GeoAu are a few kilometers away to the east from the fault although their strikes are well directed. IPGP is focused on the right location of the big crack (Fig. 3 and 4). JAJ is perfectly fixed along the Khuvsgul fault. The waveforms of JAJ are presented in Appendix (Fig. A1).

The focal mechanism solutions are modified and plotted by Generic Mapping Tools (Wessel et

Table 1. Moment tensor solutions for the Khankh earthquake

Date	Lat (°N)	Lon (°E)	Depth (km)	M_w	Strike	Dip	Rake	Source
2021.01.11	51.380°	100.430°	12.0	6.65	353°	66°	-141°	IAG
21:32:59 (UTC)	51.281°	100.438°	8.0	6.65	356°	61°	-143°	USGS
	51.21°	100.47°	18	6.7	4°	47°	-121°	GFZ
2021.01.12 05:32:56 (UB time)	51.40°	100.65°	18	6.7	172°	65°	-126°	GeoAu
	51.31°	100.39°	14.3	6.8	354°	45°	-143°	GCMT
	51.24°	100.44°	13	6.8	358°	46°	-139°	IPGP
	51.24°	100.44°	10	6.69	16°	32°	-121°	SA
	51.31°	100.39°	15	6.63	350°	50°	-138°	JAJ

Note: Date, latitude, longitude, depth, magnitude, strike, dip of the fault plane, rake of the slip vector and abbreviations of the international seismological centers and researchers. IAG – The Institute of Astronomy and Geophysics of Mongolian Academy of Sciences; USGS – The United States Geological Survey; GFZ – German Research Centre for Geosciences; GeoAu – Geoscience Australia; GCMT – The Global Centroid Moment Tensor; IPGP – Institut de Physique du Globe de Paris; SA – Seismic Analysis, Mohammad Raeesi; JAJ – Professor James Jackson, University of Cambridge, personal communications.

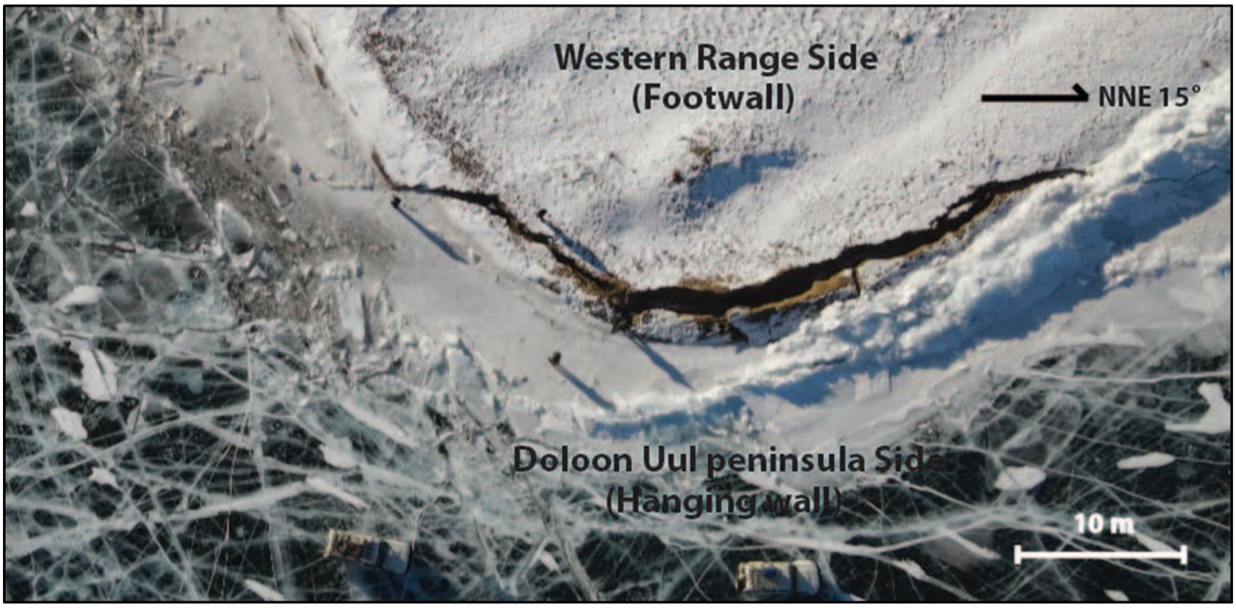


Fig. 3. A drone image for the big crack. It is only site with considerable surface offset that is most likely associated with the earthquake during our field route. The western side (Footwall) moves upward relative to the eastern side (Hangingwall). The people and cars provide for scale. Image by Bayaraa.

Fig. 4. A photograph for the big crack. The width of the surface rupture is ~1.3 m. Photo by Bayasgalan

al., 2013) and demonstrated in Appendix Fig. A2.

Thousands of aftershocks have been recorded after the mainshock of the 2021 M_w 6.7 Khankh earthquake. According to IAG news as of March 10, 2021, there have been ~40,000 aftershocks

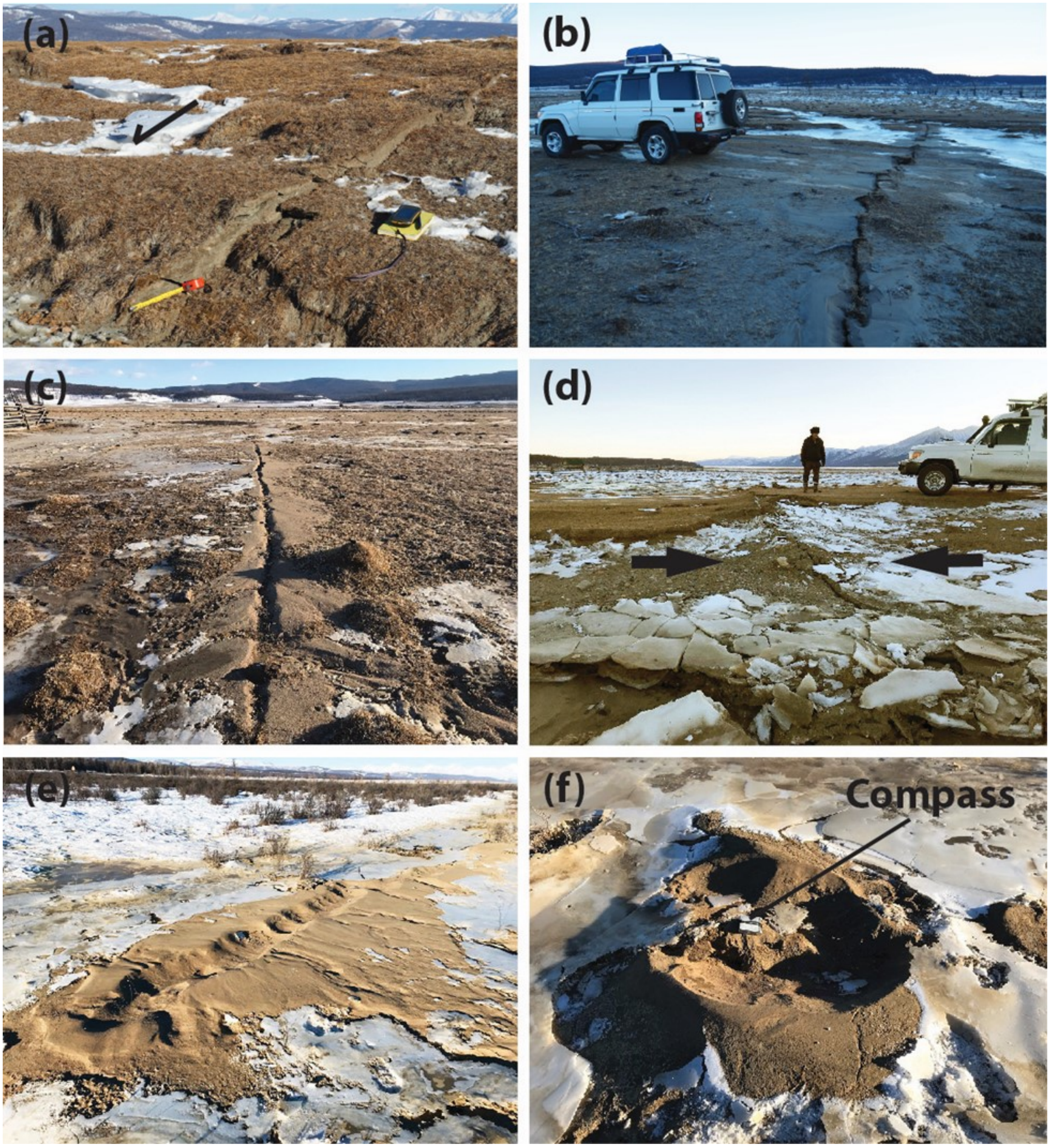


Fig. 5. Micro-features related with the earthquake in the low area between the Doloon Uul peninsula and the Western Range. (a) photo shows a normal fault of ~10 cm with left-lateral strike-slip component of ~5 cm. The western side is up. (b) photograph expresses a right-stepping micro-tension-cracks that implies the left-lateral strike-slip fault. There are the linear cracks with sand liquefaction and sand volcanoes on (c, e, f) photos. Photo (d) shows the small-thrust fault due to local micro-compression. Photos by Battogtokh and Bayasgalan.

recorded by the seismic network, among which ~180 are magnitude 3.5 and above.

The field work report following the Khankh earthquake

The research team from the Institute of the Astronomy and Geophysics in Ulaanbaatar city set off after 3 days after the earthquake and arrived in the Khankh village at the northern coast of Lake Khuvsgul on 17th January. We worked for two days in the epicentral area in the vicinity of the Doloon Uul peninsula.

With the help of local herders, we located numerous cracks. The cracks with 1-5 cm of

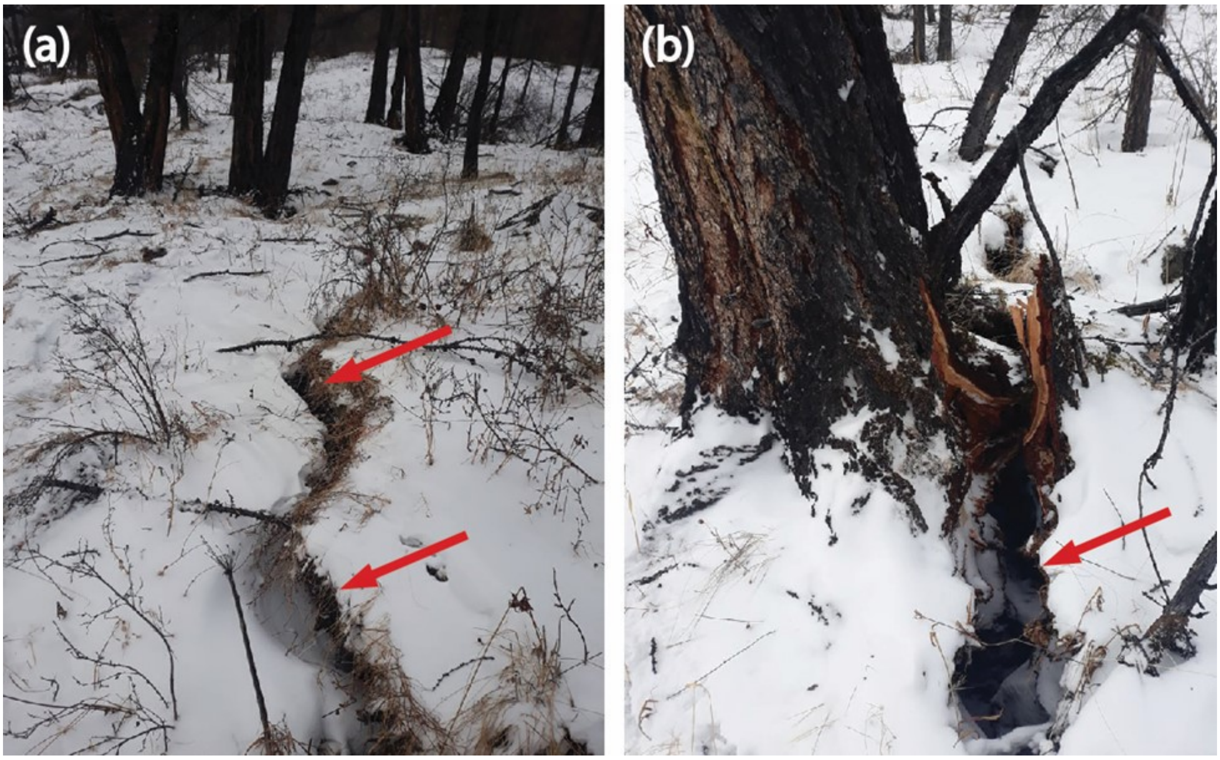


Fig. 6. Cracks in the Western Range. (a) an elongated crack with width of ~10 cm is marked by the red arrows. (b) a big tree is broken by the co-seismic event. The local name of the location is the Artsatiin Khash. Photos by Batdelger

widths were seen in many places in the low area of the Mungarag and Khodon between the Doloon Uul peninsula and the Western Range (Fig. 5). The length of the cracks are several hundreds of meters and even might reach up to several kilometers. The strikes of the cracks are chaotic. Some cracks are NW trending and some of them are NE oriented. Moreover there are cracks with azimuth along latitude. At 51˚20′12″ N, 100˚15′03″ E, we observed a linear structure with many sand volcanoes and linear liquefaction cracks (Fig. 5-e-f). This structure extended continuously for approximately 700 m (the dashed track on Fig. 2).

One possible mechanism of such phenomena is that during the earthquake soil particles are rearranged and compacted, forcing out water onto the surface, to create sand volcanoes, sand boils and surface cracking. Such kind of phenomena happened during the 2010 Canterbury Earthquakes in New Zealand (Royal.., 2010).

The central part of the low area was the most affected place where a herder's (Fig. 2) food storage log cabin was nearly collapsed and the herdsman had to move to his summer house in a couple of kilometers to the south. This place was next to the river which has a permanent water flow due to many springs. At this site we found many cracks with a wide spread of orientation and all the offsets in this area were on the order of few centimeters (Fig. 5-a, b, c and d). Some of the opening cracks produced a T-shaped structure. We also discovered a site with small amount (5-10 cm) of left-lateral offset at 51˚22′34.9″N, 100˚18′11.1″E (Fig. 5-a). NNW 335˚ trending right-stepping cracks are documented at 51˚22′29.1″ N, 100˚18′2.0″ E (Fig. 5-b). We interpret these surface cracks to also be secondary fissures related with local uplift of watery horizon.

We could see only site with a considerable surface rupture is likely to be related with the earthquake that moved during the latest event (Fig. 3 and 4). This ~45 m rupture was found near the shore of the lake and had a strike of NNE 15˚, which was characterized by a ~1.3 m opening fissure with about 20-30 cm of vertical offset, with the east side being down.

DISCUSSION

The strong earthquake struck after the surface of Lake Khuvsgul was completely frozen. Every year the lake is ice covered from middle of December to middle of June for ~6 months. The average thickness of ice is 40-70 cm. The magnitude 6.7 earthquake neither caused a major surface rupture, nor a break in the ice.

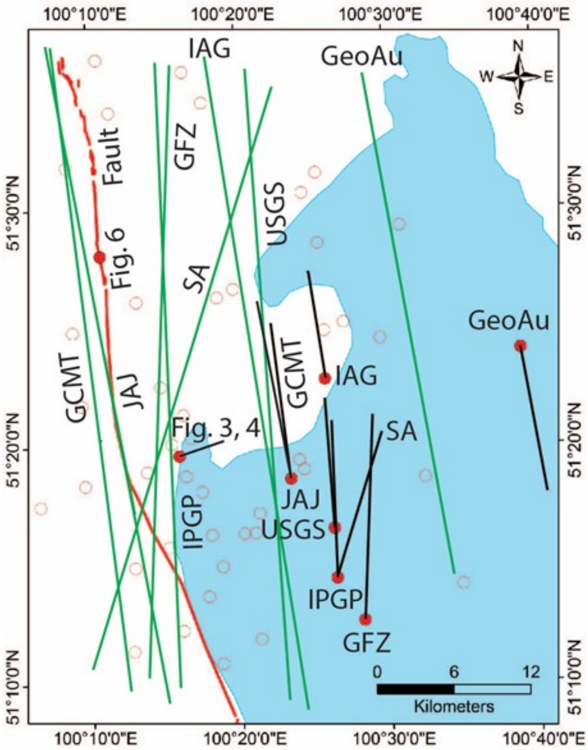
No seiche waves sufficient to break the ice in the lake water is perhaps the result of (i) high-frequency waves (longer-frequency waves traveling through the ground create seiches) were generated because the seismic epicenter was too close under the lake floor and (ii) the ice cover of the lake was able to barrier an initial oscillations to produce seisches despite the fact that ice cover is too thin compared to the lake water and in addition (iii) normal faulting of the 2021 Khankh earthquake is probably less favorable to generate tsunamis and seiches compared to thrust events (Seattle.., 2014).

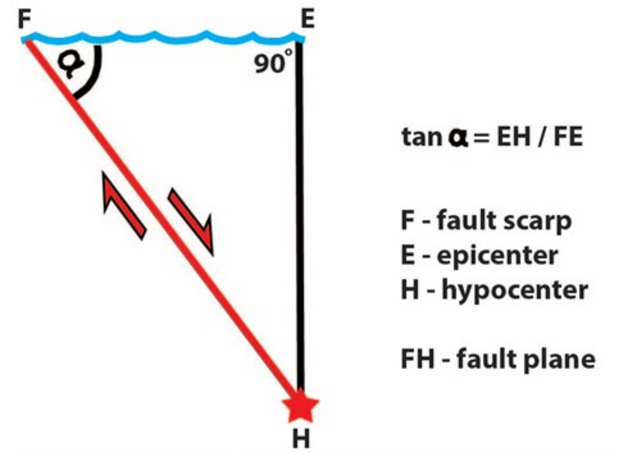
The earthquake was nonetheless strong in shaking. It was felt on the 8th floor of an apartment building of Ulaanbaatar city (Battogtokh's home address) waking up with a feeling of being pushed from below at a distance of ~600 km away. According to interview with local herders Ulziibat, Ukhnaa and Sodkhuu who live in the epicenter area of the Doloon Uul (Fig. 2), they all said that there was a monstrous noise during the earthquake and it was as if they were thrown with their houses. That said the real damage was relatively modest, perhaps because homes are generally constructed from wooden logs rather than stone or concrete. According to herder Ulziibat, the wave of the first strong earthquake seemed to be directed from south to north, and the second one seemed to be directed along the latitude. They expected like that because their houses were shaken in those directions. The location of his house is NNW-SSE oriented. Moreover, a Russian Jeep (UAZ-469) which had been parked in front of his house was thrown in ~30 cm and returned to its place. The herdsman showed us the wheels patterns on fresh snow. There was a strong tremor around a herder Rinchen's house. His livestock barn was collapsed and 1-2 logs in his log house were pulled out about ~5 cm like other herder families' houses. Near his house and barn, there were chaotic cracks with sandy water. We discovered a micro-normal fault with left-lateral strike-slip component.

We ordered a real-time KOMPSAT-3 satellite imagery with a ground-resolution of 0.7 m via the Active Tectonics Laboratory of Korea Institute of Geoscience and Mineral Resources (KIGAM) and did reconnaissance on it but we did not discover any major surface rupture that might be associated with the co-seismic event.

Sentinel-1 interferograms provided additional information to characterize the surface deformation associated this earthquake. Yet, the first post-seismic Sentinel-1 image was not available until we almost finished the field work in the epicenter area. The InSAR interferogram (Fig. 8), reveals fringes along the western side of the lake implying deformation on the surface where in Khodon and Mungarag low area between the Doloon Uul peninsula and the Western Range as well as in the Artsatiin Khash place in the Western Range. Although we already did the field routes and traverses through the high-effected area between the Doloon Uul and the Western Range based on the record of our GPS tracks (Fig. 2 and Fig. 8), there were not any primary surface ruptures except the most prominent one with a length of ~45 m and micro -cracks we mentioned above. We could not manage to visit the site where InSAR most likely indicates a primary surface rupture because of the winter weather condition. But we verified tentatively that the sharp fringes in the Western Mountains might be local effects as well. We asked a herdsman who lives in the place to check if there were any noticeable surface cracks around this area. He informed that there were an interrupted cracks with width of ~10 cm in the area called Artsatiin Khash (Fig. 2 and 6). We had better check the area and execute more geological investigations in the upcoming summer.

However, there are the sharp effects and fringes in the InSAR (Fig. 8) along the west shores of the lake. The fringes disappear as soon as it emerges the lake shore because it is connected





Abbreviated names	Depth (EH) / km	Dip angle	Distance (FE) / km
IAG	12	66°	5.3
USGS	8	61°	4.4
GFZ	18	47°	16.7
GEOAU	18	65°	8.3
GCMT	14.3	45°	14.3
IPGP	13	46°	12.5
SA	10	32°	16
JAJ	15	50°	12.5

Fig. 7. Model of the projected fault scarps. The black lines show the strikes that were calculated by the seismological centers. The green lines are the projected (visualized) fault scarps based on information of the focal mechanisms (Fig. 2 and Fig. A2). The red circles except two circles (Figs. 3, 4 and 6) are the epicenters of the focal mechanisms. Figs. 3, 4 and 6 are the considerable surface rupture (See Fig. 2) during the co-seismic process. The hollow red circles represent aftershocks between M_w 4.1 and M_w 5.4 from the open-source data of USGS. The table demonstrate the distances between the projected fault scarps and the epicenters.

to the water. The InSAR fringe pattern implies that large portion of the rupture might be underneath the lake.

Continuous preexisting tectonic scarps and right -lateral cumulative displacements are visible around the Khongor Buush river valley (around at 51°35′05″ N, 100°09′11″ E (southwest of the Emeel Mountain (Fig. 2) on Landsat 8, Google Earth and Bing Map. Any fresh surface rupture was not discovered along this segment on the real-time KOMPSAT imagery acquired after the earthquake. However, the focal mechanisms from IAG, USGS, GCMT, IPGP and JAJ are determined as the dextral strike-slip fault with normal component trending NNW that are convenient with the old dextral tectonic scarps on the satellite images. A large number of weak aftershocks have been recorded along this segment.

CONCLUSIONS

M_w 6.7 earthquake has a high-chance to produce a surface rupture with a co-seismic offset of ~0.5 m and a length of ~25 km providing that we consider the empirical relations of the magnitude by Wells and Coppersmith (1994). In contrast with it, there is a little-chance to be that much rupture on the surface according to during our field visit, local herders' traverses and even during reconnaissance on the real time KOMPSAT-3 satellite images.

In parallel, the fault scarp associated with the earthquake might have been produced on the floor of Lake Khuvsgul along the western coast. In that case, we speculate that the northernmost tip of the rupture is the big crack at 51°19′37″ N, 100°15′55″ E where we see the most prominent normal fault scarp at the lake shore despite the fact that it terminates in a distance of only ~45 m from the shore. The western side of the fault scarp moved up for 25-30 cm compared with the eastern side. Moreover the location and kinematics of this tiny-length fracture is relatively convenient with the fault

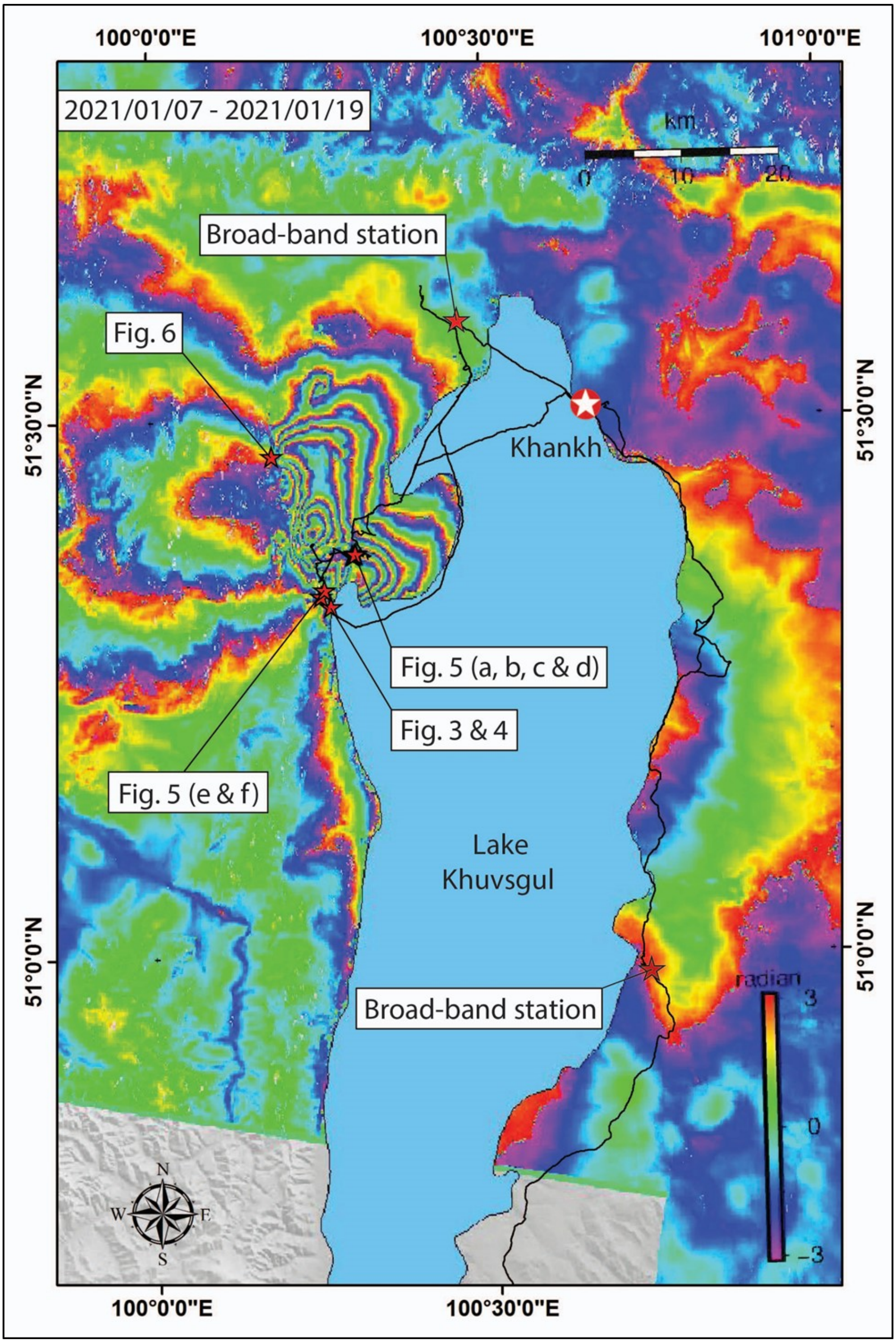


Fig. 8. A Sentinel-1 InSAR interferogram from data of a descending track covering the Khankh earthquake M_w 6.7. The red stars represent the locations of Figs. 3, 4, 5 and 6 and also show the locations of the broad-band seismic stations those were installed by us in order to record aftershocks. The black curved traverses express our track during the field work. The white star marks the Khankh village.

plane solutions which were calculated by JAJ, GFZ and IPGP.

Although there are a considerable amount of elongated small cracks with chaotic azimuths and width of 1-5 cm in the Khodon delta between the Doloon Uul peninsula and the Western Range those cracks are clearly site effects associated with the strong earthquake. Therefore all kind of features of kinematics such as micro-thrust, micro-normal faults with left-lateral component and micro-right-stepping tension-cracks to express left-lateral strike-slip faults are discovered in this area.

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Appendix

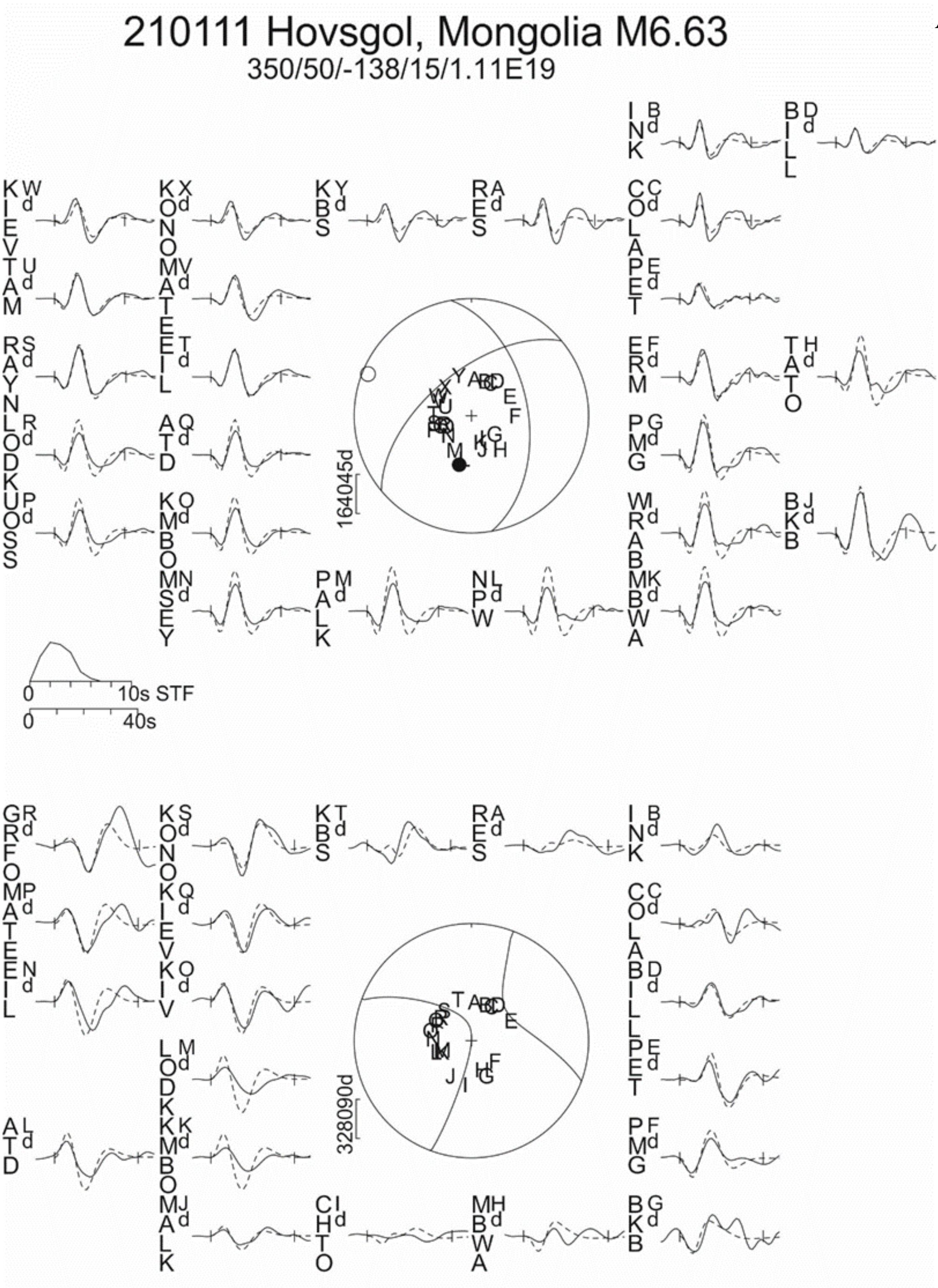

Fig. A1. P and SH waveforms for 210112 Khankh event. The event header shows the strike, dip, rake, centroid depth and scalar seismic moment of the minimum misfit solution. The upper focal sphere shows the lower hemisphere stereographic projection of the P waveform nodal planes, and the positions of the seismic stations used in the modelling routine. The lower focal sphere shows the SH nodal planes. Capital letters next to the station codes correspond to the position on the focal sphere. The solid lines are the observed waveforms, and the dashed lines are the synthetics.

Appendix

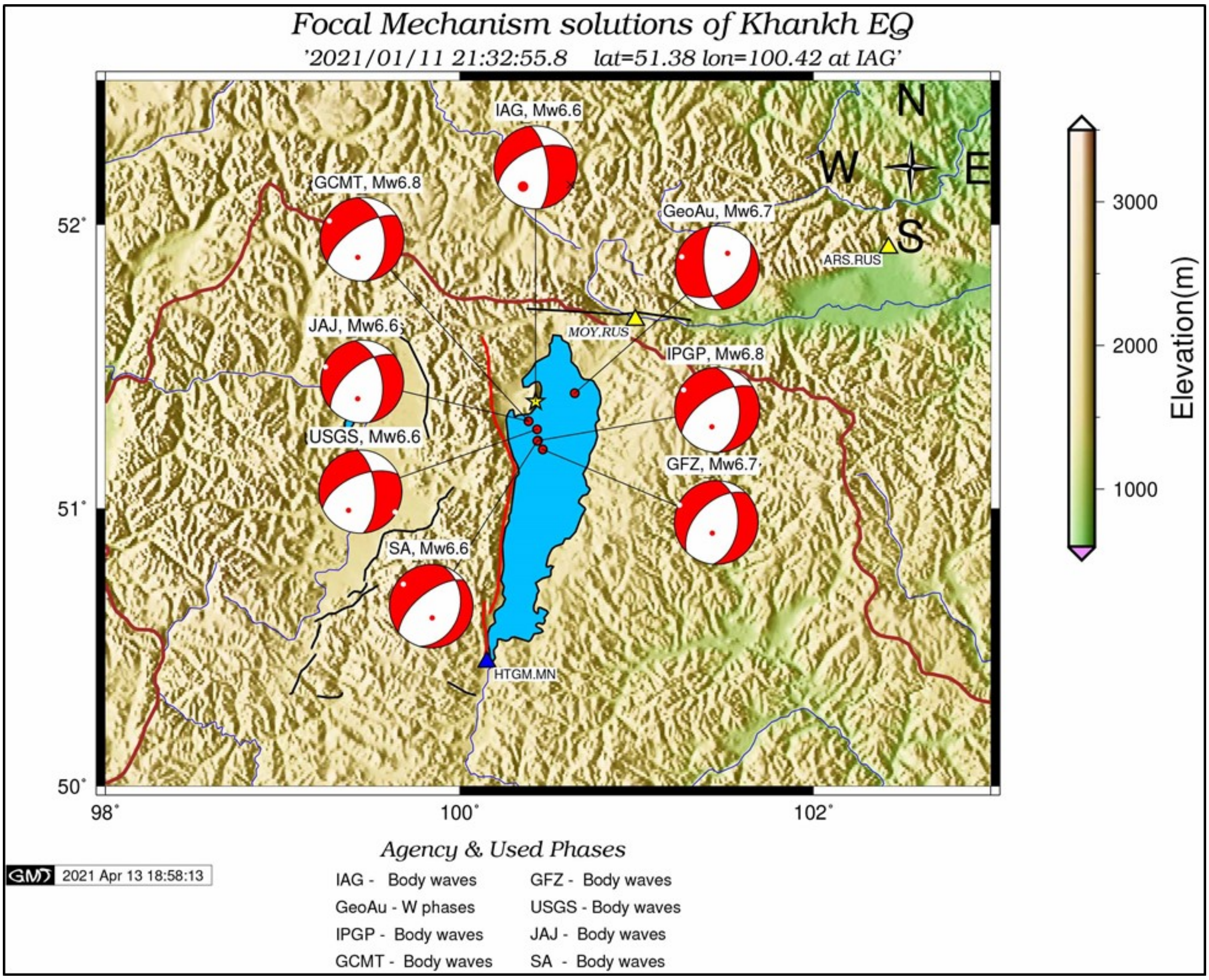

Fig. A2. The focal mechanism solutions are modified and plotted by Generic Mapping Tools (Wessel et al., 2013). The fault plane solutions of USGS, GCMT, GeoAu, IPGP and GFZ are from the web-based open-source data. JAJ and SA are from the personal communications. The fault plane solution of IAG was determined in the Mongolian National Data Center. All focal mechanisms were estimated with moment magnitude (M_w). The yellow triangles show the locations of the Russian local seismic stations. The blue triangle shows the location of the Mongolian local seismic station.