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THE OCTOBER 13, 2018 DEEP EARTHQUAKE WITH M_W 6.7 IN THE KAMCHATKA SUBDUCTION ZONE WITH THE EPICENTER IN THE SEA OF OKHOTSK

The strong M_W 6.7 earthquake occurred on October 13, 2018 at 11:10 UTC (23:10 local time) in the Sea of Okhotsk at a depth of ~500 km. According to the Kamchatka Branch of Geophysical Survey of the Russian Academy of Sciences (KB GS RAS), the epicenter of the earthquake was located ≈320 km to west of Petropavlovsk-Kamchatsky and ≈160 km from the nearest Octyabrsky settlement.

Strong deep quakes are a rather rare phenomenon. They arouse high interest among researchers, as the physics of such events is not clear.

The October 13, 2018 earthquake occurred in the southern part of the focus area of the May 24, 2013 strongest (M_W 8.3) deep earthquake recorded in the Sea of Okhotsk (Fig. 1). Probably the October 13, 2018 earthquake is a part of active process in this zone, which began with the strong (M_W 7.7) July 5, 2008 event. So, the 2008 deep earthquakes occurred in the Sea of Okhotsk focus area can be considered as remote foreshocks of this event, and the October 13, 2008 earthquake as a remote aftershock. It is still unknown whether the processes in the source of the 2013 Sea of Okhotsk earthquake finished.

The data on complex earthquake processing obtained by KB GS RAS are presented in this paper.

Seismological observations in KB GS RAS are carried out using records of seismic stations in the Far East, including stations of the global network GSN (Global Seismographic Network, IRIS) located in Russia, Japan, the United States and South Korea. All seismic stations used in KB GS RAS are equipped with real-time data transmission channels. The data on these stations, including the configuration, geographic location, and the recording channels characteristics, is given in (Chebrov et al., 2013).

According to the regulations of the Tsunami Warning Service and the Urgent Reporting Service the personnel on duty in KB GS RAS should process earthquakes in real time (Chebrov et al., 2009), so they started to process the event after the alarm when seismic signal at the Khodutka station (KDT) exceeds a threshold. The results were sent to the Tsunami Centers of the Russian meteorological service Roshydromet and the Ministry of Emergencies. Strong earthquakes with the magnitude of $M \geqslant 5$, recorded at a distance of less than 1000 km from the Petropavlovsk-Kamchatsky should be processed no later than 10 minutes after the event. The signal «A strong earthquake is being recorded!» was sent to the Kamchatka Tsunami Center of Roshydromet within 1 min. The earthquake's coordinates and magnitude preliminary estimations were obtained 4 min 6 sec after the event, the final estimations (latitude 52.29° N, longitude 154.26° E, depth 526 km, M_S(PET) = 6.0, taking into account the station corrections) were obtained 6 min 6 sec after the event. A near-real-time preliminary estimation of instrumental seismic intensity according to the data of strong movement stations was carried out by special automated service (Droznin et al., 2017). A tsunami alarm was not issued, since the depth of the event significantly exceeded the established threshold (120 km), and the magnitude was significantly lower than the tsunamigenic threshold.

The final earthquake processing was carried out during the day using the data on 78 stations located in the Russian Far East. 67 phases of P waves and 36 phases of S waves were used for defining the parameters. The hypocenter is localized at coordinates φ = 52.53° N, λ = 153.87° E, depth h = 499 km. The earthquake location accuracy was 27 km in plan and 16 km in depth. Three earthquake energy parameters are determined:

- local magnitude M_L = 7.0 (obtained by the formula $M_L = 0.5K_S - 0.75$ (Chubarova et al., 2010) by recalculation from the S-wave energy class K_S = 15.4, determined by the nomogram of Fedotov (Fedotov, 1972)) ;
- magnitude by code-waves Mc = 6.3 (estimated using the data on 17 stations according to the method described in (Gordeev et al., 1999));
- moment magnitude M_W = 6.7 (obtained as the result of calculating the seismic moment tensor according to the methodology (Pavlov, Abubakirov, 2012)).

The only one aftershock with M_L = 4.2 (K_S = 9.9) was recorded on October 14, 2018 at 01:28 UTC.

Focal mechanism of the earthquake (Fig. 1) and the scalar seismic moment M_0 were calculated from the waveforms of body and surface waves at 18 broadband seismic stations in Kamchatka, Sakhalin, and the Kuril Islands. We used the nonlinear algorithm for calculating the seismic moment tensor for a double-couple source model (Pavlov, Abubakirov,

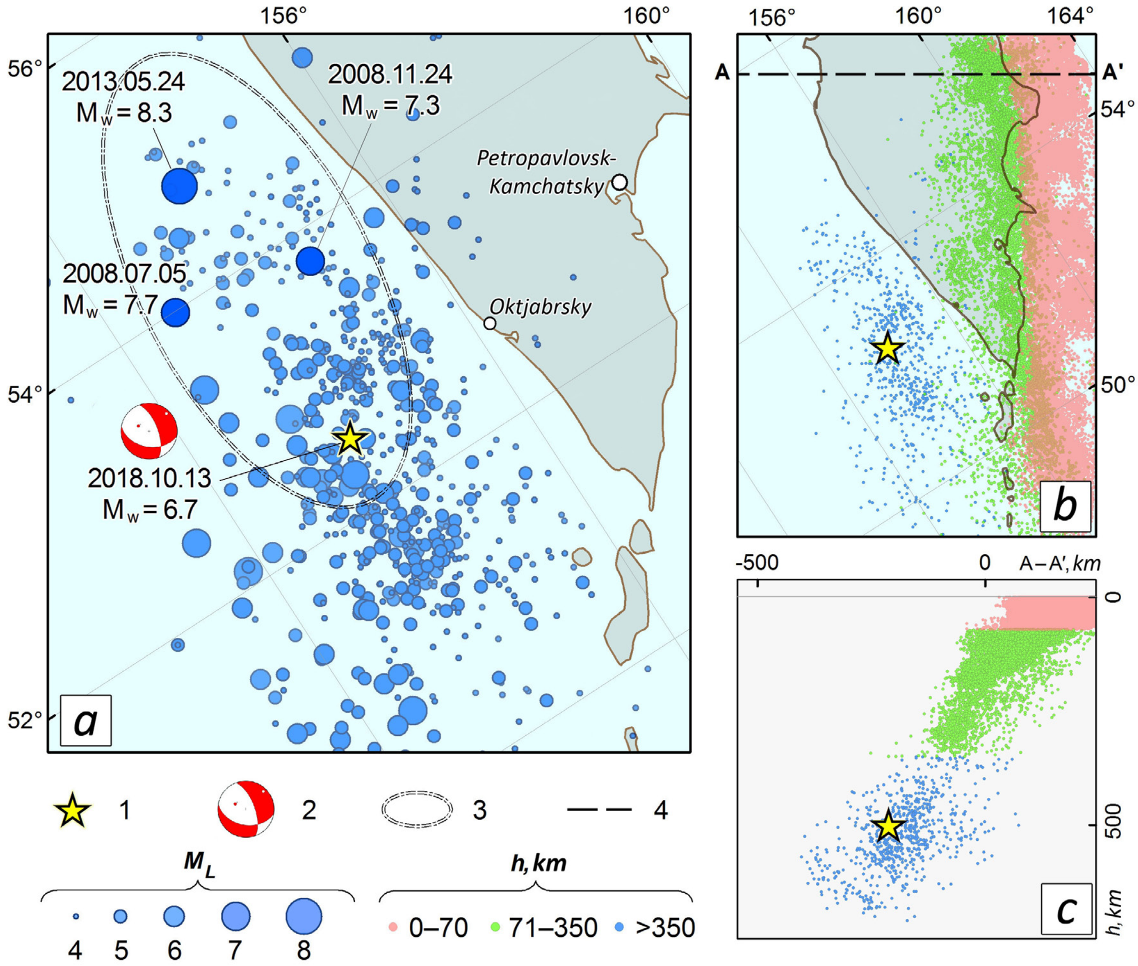

Fig. 1. Earthquake on 13, October 2018, M_W = 6.7 location map relative to the deep earthquakes epicenters (h ⩾ 350 km) of the Kamchatka subduction zone (*a*); earthquake epicenters of the Kamchatka subduction zone (*b*) and earthquake hypocenters of the Kamchatka subduction zone projected on axis A–A'(*c*) with M_L ⩾ 3.5: 1 — earthquake epicenter on 13, October 2018; 2 — focal mechanism stereogram of the earthquake on 13, October 2018; 3 — approximation ellipse of aftershocks zone after the strongest deep earthquake on 24, May 2013, constructed according to the data of the first month after the main shock and containing 90% of aftershocks; 4 — vertical section line (A–A') across the focal zone. M_L — the local magnitude of an earthquake, the circle size corresponds to the magnitude value; h — the earthquake depth, different colors correspond to the specified ranges of the hypocenter depths. Earthquakes 05, June 2008, M_W = 7.7 and 24, November 2008, M_W = 7.3 are described in (Chebrova et al., 2014); 24, May 2013, M_W = 8.3 — in (Strong ..., 2014, Chebrova et al., 2015).

2012, 2017). The tension axis of the mechanism is oriented horizontally (angle of incidence 12°) in the north-east — south-west direction (azimuth 44°). The compression axis has an azimuth of 296° and a dip angle of 55°. One of the nodal planes — P1 has a submeridional (azimuth φ = 340°) strike, the second P2 — sub-latitudinal (φ = 100°) one. The plane P2 (angle of incidence δ = 43°) lies more hollow relative to the plane P1 (δ = 65°). Displacement along both planes — fault-shear: left-side along P1 (slip λ = -54°), and right-side along P2 (λ = -141 °). The values of M_0 and M_W obtained by the formula $M_W = (2/3) \cdot (\log M_0 [N \cdot m] - 9.1)$ (Kanamori, 1977) were $1.21 \cdot 10^{19}$ N·m and 6.7, respectively. The above estimates of the focal mechanism, M_0, and M_W are in good agreement with the data from the GCMT catalog and with the USGS NEIC estimations presented in (Table 1).

The October 13, 2018 earthquake was felt on the Kamchatka Peninsula, the Komandorski and Kuril Islands with the intensity from 2 up to 4 on the MSK-64 scale (Medvedev et al., 1967) (Table 2). In Petropavlovsk-Kamchatsky, the shake intensity did not exceed 2–3. The strongest shakes were felt by inhabitants at points, located not close to the epicenter but on the eastern coast of Kamchatka of the peninsula (Fig. 2). Strong deep Kamchatka earthquakes in subduction zone under the Sea of Okhotsk are characterized by similar anomalies of macroseismic effects: increased shakes on the east coast and a wide area of felt. Similar patterns of the macroseismic field are shown in (Chebrova et al., 2014, 2015) for strong deep Sea of Okhotsk earthquakes of July 5, 2008 with M_W 7.7, November 24, 2008 with M_W 7.3, and May 24, 2013 with M_W 8.3.

Table 1. Source parameters of the deep earthquake on October 13, 2018, M_W = 6.7 according to various seismological agencies data.

Agency	Time, h:min:sec	φ°, N	λ°, E	*h*, *km*	$M_0 \times 10^{19}$, *N*m*	*Mw*	Fault planes (stk,dip,slip)	Beach ball
KB GS RAS	11:10:20	52.53	153.87	490	1.21	6.7	(340,65,-54) (100,43,-141)	
USGS NEIC[1]	11:10:22	52.86	153.24	481	1.3	6.7	(351,73,-50) (100,43,-155)	
GCMT[2]	11:10:27	52.70	153.41	477	1.38	6.7	(99,43,-157) (352,74,-49)	

Note. 1 — The National Earthquake Information Center, U.S. Geological Survey https://earthquake.usgs.gov/, 2 — Global Centroid Moment Tensor https://www.globalcmt.org.

Table 2. Macroseismic effect of the earthquake on October 13, 2018, M_W = 6.7.

Intensity	Observation point name (epicenter distance, km)
4	Kronoki (533)
3–4	Severo-Kurilsk (259), Uzon (462)
3	Cape Shipunskiy (418), Chazhma (597)
2–3	Pionerskiy (321), Petropavlovsk-Kamchatsky (326), Ust-Kamchatsk (696), Nikolskoe (848)
2	Semyachik (442), cape Afrika (736), Yuzhno-Kurilsk (1113), Goryachii Plyazh (1119)

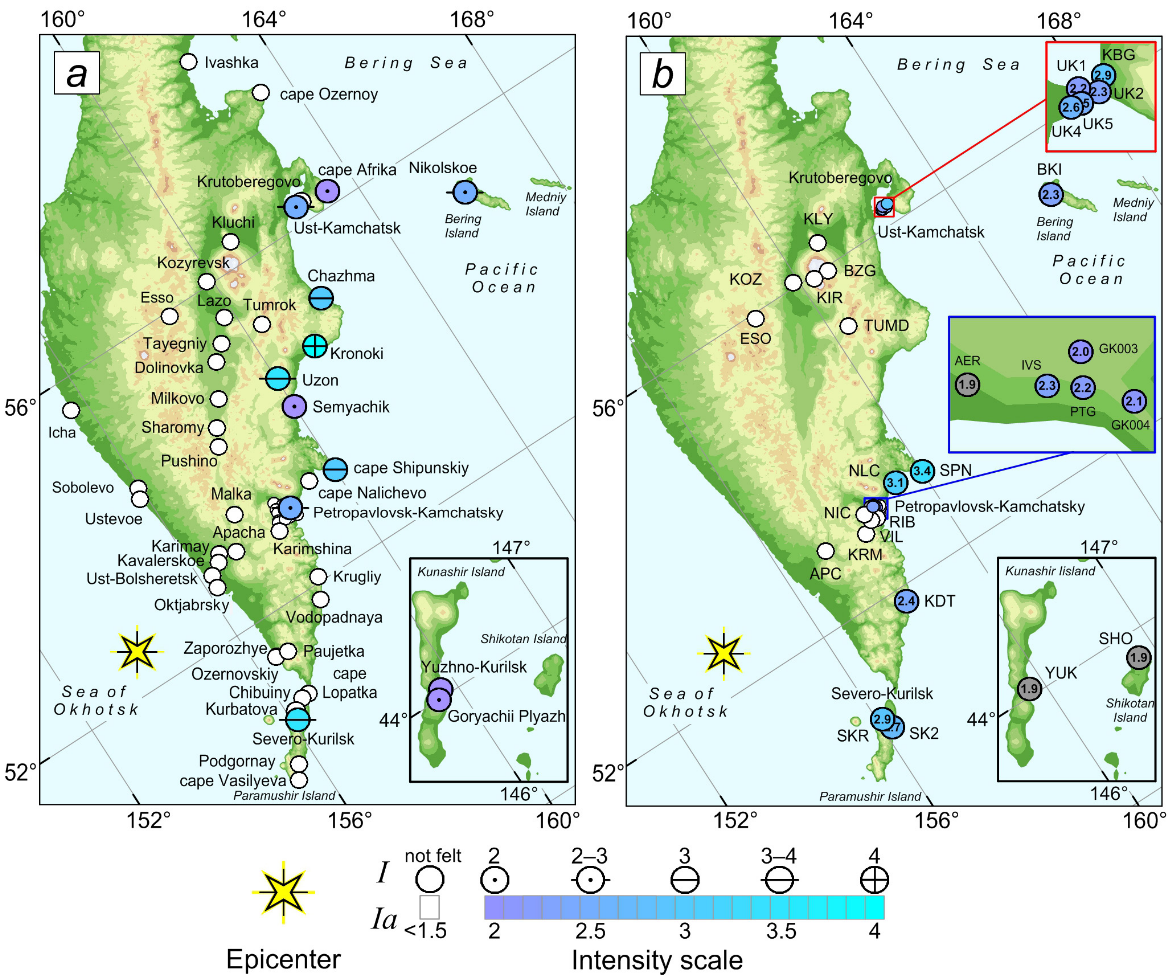

Fig. 2. Map of seismic intensity (*a*) and instrumental intensity (*b*) distribution from the earthquake on 13, October 2018 on the territory of Kamchatka, the Northern and Southern Kurile Islands: *I* — macroseismic intensity; *Ia* — intensity, calculated from the peak ground acceleration on the horizontal channels of the accelerometers.

Strong ground motion parameters estimations were made using the records of the Far Eastern digital seismic stations network (Table 3) using the software package briefly described in (Guseva et al., 1989). Ground velocities were obtained by integrating acceleration records. The instrumental intensity *Ia* was calculated by the formula $Ia = 2.5 \log (a_p) + 1.89$ (GOST R 57546–2017), where ap is the peak ground acceleration (cm/s²) on horizontal channels. The highest values of ground accelerations and the corresponding instrumental intensity Ia were observed not at the points closest to the epicenter, but on the eastern coast of Kamchatka (Fig. 1*b*). For example, at Apacha (APC, r = 547 km) and Karymshina (KRM,

Table 3. Peak ground accelerations and velocities for seismic stations that recorded the earthquake on October 13, 2018 ($M_W = 6.7$) with peak ground acceleration $a_p \geqslant 1$ cm/s².

	Station name	Code*	Δ, *km*	*r*, *km*	a_p, *cm/s²*			υ_p, *cm/s*			*Ia*
					E	N	Z	E	N	Z	
1	Severo-Kurilsk	SKR	258	562	2.05	-2.42	0.69	-0.117	-0.095	-0.042	2.9
2	Plato	SK2	264	564	2.12	1.82	1.09	-0.179	0.205	0.091	2.7
3	Khodutka	KDT	298	581	1.62	-1.31	-0.74	0.069	0.086	-0.038	2.4
4	Aerologicheskaya stanciya	AER	321	593	-0.82	1.01	0.50	-0.268	-0.242	0.068	1.9
5	Institute	IVS	324	595	-1.44	-0.78	-0.49	-0.246	-0.138	0.076	2.3
6	Gorkogo	PTG	325	596	-1.30	0.76	-0.40	-0.186	0.114	0.034	2.2
7	Mishennaya	MSN	326	596	5.07	-3.58	-1.28	-0.957	-0.641	0.097	3.7
8	Shkola N40	GK003	327	596	1.12	-0.97	-0.55	0.219	0.150	-0.050	2.0
9	Bolnitsa	GK004	327	597	1.24	-1.13	-0.64	0.092	-0.074	-0.034	2.1
10	Nalytchevo	NLC	375	624	-1.39	-2.92	-0.83	-0.111	0.176	-0.046	3.1
11	Shipunskiy	SPN	418	651	-3.55	-3.98	2.48	0.248	0.238	-0.119	3.4
12	Avtodor	UK4	694	855	1.67	-1.85	0.61	-0.142	-0.116	-0.062	2.6
13	Ust-Kamchatsk Delta	UK5	696	857	-1.71	1.82	-0.52	0.160	-0.139	-0.065	2.5
14	Administraciya UK	UK1	700	859	1.28	1.14	-0.53	0.195	-0.116	0.062	2.2
15	Vodozabor	UK2	701	860	-1.35	1.44	0.52	-0.095	-0.135	-0.081	2.3
16	Krutoberegovo	KBG	706	865	2.06	2.43	0.76	-0.196	-0.211	-0.077	2.9
17	Bering	BKI	846	983	1.00	1.44	0.66	0.075	0.101	-0.047	2.3
18	Shikotan	SHO	1094	1202	1.02	-0.97	-0.57	-0.058	0.061	-0.031	1.9
19	Yuzhno-Kurilsk	YUK	1114	1220	-1.05	0.94	-0.83	-0.124	0.191	0.060	1.9

Note. * — regional station code (stations location is shown in the fig. 2*b*); Δ — epicentral distance; *r* — hypocentral distance; a_p — peak ground acceleration on HN channels; υ_p — peak ground velocity on recovered records.

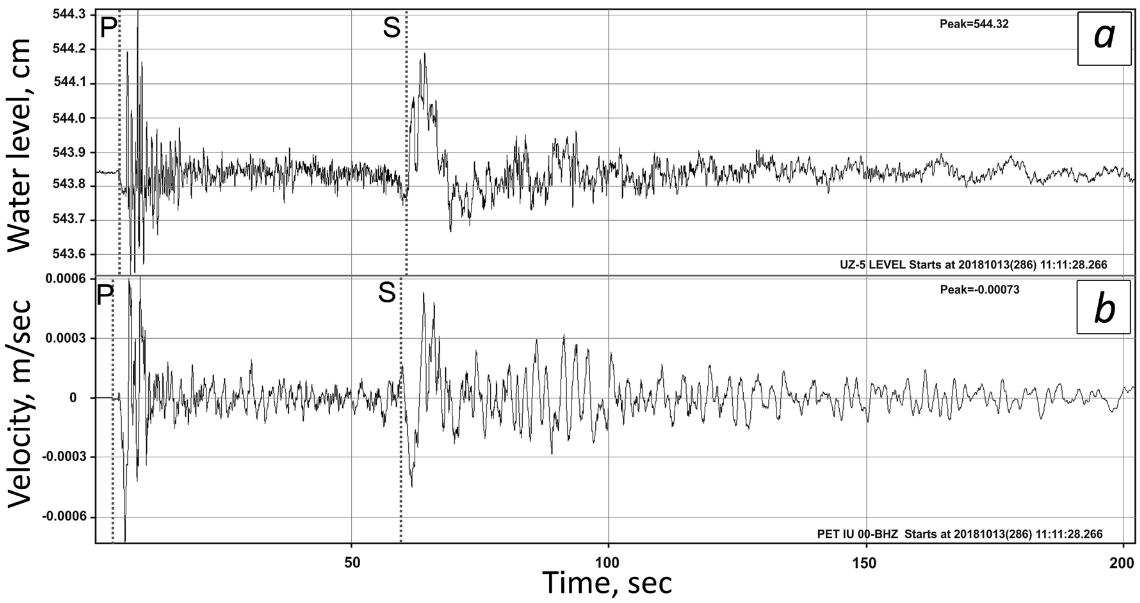

Fig. 3. High-frequency (40 Hz record) water level variations in the YuZ-5 well (*a*) in comparison with the seismic record on the BHZ channel of Petropavlovsk seismic station (PET, 53.02° N, 158.65° E, h = 100 m), located at a distance of 28 km from well (*b*).

r = 577 km) stations located at comparable distances from the epicenter (Fig. 1*b*), but inland from the eastern coast of Kamchatka, the amplitudes of ground acceleration were less than 1 cm/s^2, the instrumental intensity at these stations was *Ia*(APC) = 0.9 and *Ia* (KRM) = 1.5 respectively.

The October 13, 2018 earthquake also manifested itself by the water level variations in the YuZ-5[1] (latitude 53.17° N, longitude 158.41° E, depth 800 m, water level 1–1.5 m deep) borehole. For the first time in Kamchatka, P and S seismic waves phases, obtained according to high-frequency data with a frequency of 40 Hz, were recorded (Fig. 3). The technical equipment for pressure / water level recording in the YuZ-5 borehole was provided by the Israel Geological Survey as a part of joint experiment on high resolution measurement of the groundwater fluctuations level.

This work continues the series of KB GS RAS urgent data publications about strong ($M_w \geqslant 6.5$) Kamchatka earthquakes of recent years (Chebrov et al., 2016, 2017).

[1] Information about the network of hydrogeodynamic observation points is presented on the page http://www.emsd.ru/lgi/hydrodynamical.

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