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The Moment Tensors, Focal Mechanisms, and Stresses on Sakhalin Island

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Abstract—We report determinations of the focal mechanisms for Sakhalin earthquakes during 2006 through 2015 by two different methods: the polarity of first motions using the FOCMEC program and the inversion of waveforms using the ISOLA program. We show that the resulting moment tensor solutions fairly well fit the tectonic crustal stresses for Sakhalin as determined by previous workers. We have examined the component of the moment tensor that involves a linear dipole. This is at its maximum in areas of active mud volcanism and industrial activities in oil-and-gas fields.

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INTRODUCTION

The study of seismotectonic regime in Sakhalin is of great interest for researchers. This is largely due to hydrocarbon extraction in this seismic region and to the associated ecological and economic risks. The first case that comes to mind is the 1995 Neftegorsk earthquake, the largest catastrophic earthquake in contemporary Russia, which killed over 2000 residents and caused large-scale damage. Geotectonic research is based on geological, geodetic, and seismological data, with the latter kind of data including information on moment tensors and focal mechanisms.

The determination of focal mechanisms for Sakhalin earthquakes has been handled for several decades by a team at the Institute of Marine Geology and Geophysics (IMG&G) of the Far East Branch of the Russian Academy of Sciences (FEB RAS) along with colleagues at the Sakhalin Branch of the Geophysical Service (SB GS) RAS under the general leadership of L.N. Poplavskaya. Data on the mechanisms of individual earthquakes were published in papers devoted to the events, with much of this material being found as catalogs in the seismological annual publications entitled *Earthquakes in the USSR* and *Earthquakes in North Eurasia*. In 2014 all data so far obtained on focal mechanisms for the 1962–2011 earthquakes in the Sakhalin region were rearranged to form a catalog and were used for the monograph (Konovalov et al., 2014). The data on these earthquakes for a 50-year period were interpreted as leading to the conclusion that the crust on Sakhalin Island is under horizontal compression whose axis is either east–west or east–northeast to west–southwest. The average axis of tensile stresses in all areas (except for that around the Deryugin deep-sea basin) is closer to the vertical direction. This is consistent with the fact that the mechanisms so far determined are dominated by reverse-oblique movement.

However, this period of 50 years is merely a short episode in the seismotectonic history of the island. Geological research showed (Kozhurin, 2013) Sakhalin to have been dominated by right lateral slip movements over longer time spans. The best known of all Sakhalin earthquakes, the 1995 Neftegorsk event, is also classified as a right lateral slip combined with a smaller reverse movement.

It is clear that the catalogs should be updated with earthquake information and, since it is difficult to expand the catalogs with large past earthquakes, because no records of regional seismic stations are available for the pre-1950 period, it would be reasonable to try to furnish more of the smaller earthquakes to the catalogs, since focal mechanisms for these can easily be determined due to the development of digital seismograph networks and the use of advanced methods for determining the seismic moment tensors of earthquakes. The present paper has for its goal a gradual transition from the earlier method of first motions to the modern method of waveform inversion.

At the same time, the use of seismic moment tensor determinations in the practice of seismological observations revealed that the earthquake mechanisms in areas that show volcanic or geothermal activity involve a component that characterizes changes in the volume of explosive or implosive types (Vavryčuk, 2002). Such mechanisms can result from both strike-slip movements and opening fissures due to tension in the rupture zone. Such fissures can be caused by excessive pore pressure and by the presence of hot fluids. The presence of body forces causes a non-zero trace to appear in the seismic moment tensor. However, the determination of the isotropic component in the moment tensor is difficult when the relevant data are scarce, hence we assume that the trace is zero. Nevertheless, the so-called linear vector dipole, which too is not a component of a dipole, and which describes sums of strike-slip movements on nonparallel areas, was also estimated here. Non-strike-slip components also occur in anisotropic media.

For this reason special practical interest occurs for the acquisition of raw data and the study of the relative content of a linear vector dipole in the moment tensor, and this is also true in areas of oil and gas fields that are developed on Sakhalin Island, since the content could have been caused by manmade impacts on a rock mass.

We present data on computed mechanisms and seismic moment tensors for the crustal earthquakes that have occurred within the Sakhalin region during the last decade. We are especially interested in comparatively small events for the 2010—2015 period; as well, we list the mechanisms of the larger post-2006 events that we have revised following the same method.

A catalog of resulting mechanism solutions is presented in the table. Figures 1 and 2 show the epicenters of the earthquakes we used, as well as a comparison of stereograms for focal mechanisms and moment tensors in the double couple approximation, with the northern half of the island shown in Fig. 1 and the southern half in Fig. 2.

THE METHOD

The mechanisms were determined by independent application of two different techniques.

In the first place, the focal solutions were obtained from *P* first motions following the procedure described by Konovalov et al. (2014), with the FOCMEC program (Snoke et al., 1984) being used as the basic algorithm for the computations. As well, more correct solutions were obtained by supplementing the data with *SV* and *SH* first motions (Konovalov et al., 2014). This approach has been used at the IMG&G FEB RAS during recent decades and showed good performance. However, it is rather time consuming and does not invariably yield a stable solution when the data are not numerous.

Secondly, the seismic moment tensor was determined using the ISOLA software package developed by Dr. E. Sokos, University of Patras, Greece and Prof. J. Zahradnik, Charles University, Prague (Sokos and Zahradnik, 2008, 2013). The method was described in sufficient detail in (Křížová et al., 2013); since we are new to this method, the leading elements of it will be discussed below.

The seismic moment tensor M_{pq} is related to the displacement field as follows (Aki and Richards, 1983):

$$u_n = M_{pq} * G_{np,q}, \tag{1}$$

where u_n (n = 1, 2, 3) is the displacement component; $G_{np,q}$ is the derivative of Green's function that gives the pth displacement component due to the action of unit force in the qth direction; and * denotes convolution. The seismic moment tensor is symmetrical and has six independent components that characterize the strain at the source. It can be represented by a linear combination of six elementary M^i tensors:

$$M_{pq} = \sum_{i=1}^{6} a^i M^i_{pq}, \tag{2}$$

where the a^i are scalar coefficients. Each tensor is a model source for a set of synthetic seismograms u_n whose combination with weight constants a^i allows determination of the desired moment tensor:

$$M = \begin{pmatrix} -a_4 + a_6 & a_1 & a_2 \\ a_1 & -a_5 + a_6 & -a_3 \\ a_2 & -a_3 & a_4 + a_5 + a_6 \end{pmatrix}. \tag{3}$$

The scalar seismic moment

$$M_0 = \sqrt{\frac{\sum_{p=1}^{3}\sum_{q=1}^{3}(M_{pq})^2}{2}}, \tag{4}$$

allows determination of the moment magnitude (Kanamori, 1977):

$$M_w = \frac{2}{3}(\log M_0[Hm] - 9.1) \tag{5}$$

The contribution of the bulk (non-shear) part of the moment tensor is estimated as (Vavryčuk, 2002)

$$ISO = \frac{1}{3}\frac{Tr(M)}{|M_{|\max|}|} \times 100\%, \tag{6}$$

where $M_{\max}$ is the maximum (in absolute value) eigenvalue of the tensor M, with Tr(M) being the trace of the tensor.

The contribution of the linear vector dipole (CLVD) is estimated as

$$CLVD = -2\frac{M'_{|\min|}}{|M'_{|\max|}|}(100\% - |ISO|), \tag{7}$$

where $M'_{|\min|}$ is the minimum (in absolute value) eigenvalue of the deviatoric part of the moment tensor, and $M'_{|\max|}$ is the maximum (in absolute value) eigenvalue of the deviatoric part of the moment tensor.

Earthquake parameters of Sakhalin region, their source mechanisms and seismic moment tensors obtained using ISOLA (a) and FOCMEC (b)

#	Date	Time	Φ	λ	H_C/H	M_w/M_L	*T*		*P*		NP1			NP2			*k*	*DC*	*Vr*	Tensor components						exp
	day.month.year	h:min:sec	°	°	км		pl	az	pl	Az	stk	dip	rake	stk	dip	rake	°	%		Mrr	Mtt	Mpp	Mrt	Mrp	Mtp	
1b	June 6, 2005	4:17:10.1	52.8	144.07	15	5.7	64	350	14	111	175	36	52	39	62	114										
2a	Aug. 17, 2006	15:20:34.1	46.51	141.92	10	5.6	77	144	5	255	176	51	106	332	42	71	16	79	0.67	2.65	–0.34	–2.31	–0.51	–0.60	0.64	17
2b					15	5.9	69	144	3	241	170	51	117	310	46	60										
3a	Nov. 10, 2006	8:53:47.7	52.63	142.54	9	–	40	135	4	229	175	66	146	280	59	28	14	88	0.43	1.89	–0.60	–1.29	–1.15	–1.60	3.51	14
3b					20	4.7	40	150	4	240	190	64	148	290	60	29										
4a	Aug. 2, 2007	2:37:39.5	46.81	141.81	2	6.1	68	38	16	263	161	62	74	13	32	118	33	77	0.82	1.56	–0.06	–1.50	0.64	0.86	0.02	18
4b					11	6.3	79	188	1	93	194	45	105	353	47	75										
5a	Aug. 2, 2007	5:02:16.0	46.72	141.71	4	5.7	71	148	12	278	200	59	107	350	35	65	28	82	0.71	3.05	0.53	–3.58	–0.97	–1.43	0.40	17
5b					14	6.0	67	216	14	90	203	35	123	344	62	69										
6b	Aug. 22, 2009	10:26:41.0	52.63	144	12	5.0	47	262	20	149	282	41	156	31	74	52										
7a	Mar. 16, 2010	09:44:13.5	52.08	142.17	8	5.7	67	187	4	87	200	45	123	337	54	61	59	77	0.55	3.62	1.10	–4.72	–1.36	0.58	0.24	17
7b					5	5.7	54	350	4	86	144	52	42	25	59	134										
8a	July 9, 2010	15:17:44.9	52.11	142.25	18	5.1	64	140	16	265	329	34	53	192	63	112	38	88	0.42	4.50	0.33	–4.83	–1.82	–3.02	1.01	16
8b					4	5.1	68	34	12	271	23	36	121	167	59	69										
9a	Sept. 2, 2010	7:08:00.6	52.03	142.32	15	4.3	57	102	31	256	176	77	102	314	18	49	51	89	0.39	1.97	–0.34	–1.63	–0.03	–3.67	0.92	15
9b					19	4.6	72	284	17	88	171	28	80	2	62	95										
10a	Mar. 6, 2011	15:48:53.2	52.1	142.2	6	–	85	350	0	83	169	45	84	358	45	96	27	60	0.47	8.85	–1.79	–7.06	0.826	0.17	0.61	16
10b					9	4.6	64	351	6	249	4	45	127	137	56	59										
11a	Dec. 12, 2011	9:28:40.1	50.64	143	5	5.4	68	315	9	68	355	57	114	136	40	58	28	93	0.41	1.29	–0.06	–1.23	0.27	0.59	0.66	17
11b					5	4.9	53	2	16	249	17	41	145	134	68	55										
12a	Oct. 21, 2012	11:57:26.4	53.41	142.55	5	4.8	57	171	13	60	183	41	138	307	64	57	55	59	0.46	1.38	0.22	–1.60	–0.96	0.44	1.27	16
12b					11	4.8	70	343	1	75	4	49	117	146	48	62										
13a	Jan. 24, 2013	14:15:48.6	53.39	142.66	4	4.5	77	0	6	242	142	52	76	344	40	108	53	98	0.20	6.96	–1.23	–5.73	1.99	–0.73	3.12	15
13b					1	4.3	60	324	24	104	28	71	108	163	26	48										
14a	Feb. 28, 2013	20:37:00.7	52.01	142.25	8	3.8	52	185	5	88	211	52	140	329	60	46		58	0.37	4.03	3.02	–7.05	–2.03	0.90	0.13	14
15a	May 25, 2013	6:19:20.7	46.96	142.54	4	3.7	53	16	15	127	180	41	35	62	68	126	33	48	0.53	1.00	0.00	–1.00	0.86	0.40	–1.27	14
15b					8	3.7	38	30	10	292	167	71	36	63	56	157										
16a	July 4, 2013	11:08:28.0	46.76	141.73	9	4.9	73	122	15	274	191	60	99	354	31	75	67	81	0.53	2.59	–0.22	–2.37	0.54	–1.40	–0.05	16
16b					10	4.9	16	63	50	312	360	70	–52	114	42	–149										
17a	Oct. 14, 2013	8:36:25.6	51.44	143.4	4	4.2	67	28	5	287	177	53	62	39	45	123	26	64	0.54	2.27	–0.26	–2.01	1.00	–0.68	–0.69	15
17b					10	4.1	66	4	4	259	150	52	60	6	44	120										
18a	Nov. 24, 2013	10:20:28.2	52.05	142.28	7	4.9	80	2	3	251	152	49	78	351	42	104	39	97	0.75	2.85	–0.26	–2.59	0.56	–0.18	0.88	16
18b					12	5.0	67	317	21	116	32	67	98	193	25	72										
19a	Nov. 25, 2013	3:23:53.7	45.88	141.88	13	5.1	66	35	17	263	159	64	71	17	32	123	10	83	0.67	5.14	0.16	–5.30	2.45	–3.16	0.04	16
19b					13	5.0	62	24	14	267	158	63	63	26	38	132										
20a	Feb. 19, 2014	12:49:06.7	52.15	143.27	13	4.7	55	111	13	220	155	65	125	276	42	39	52	67	0.63	1.03	–0.85	–0.18	–0.15	–1.05	0.77	16
20b					9	5.0	71	262	15	54	331	62	100	131	29	72										
21a	May 23, 2014	23:42:41.8	49.32	142.88	10	4.1	9	349	5	79	34	87	170	124	80	3		94	0.50	0.08	1.55	–1.63	0.22	0.21	0.64	15
22a	June 30, 2014	20:58:12.5	51.57	143.09	7	4.4	69	158	1	251	180	50	118	321	47	61	37	90	0.83	3.95	0.16	–4.11	–1.27	–0.64	1.72	15
22b					20	4.5	69	237	16	101	212	32	118	360	62	74										

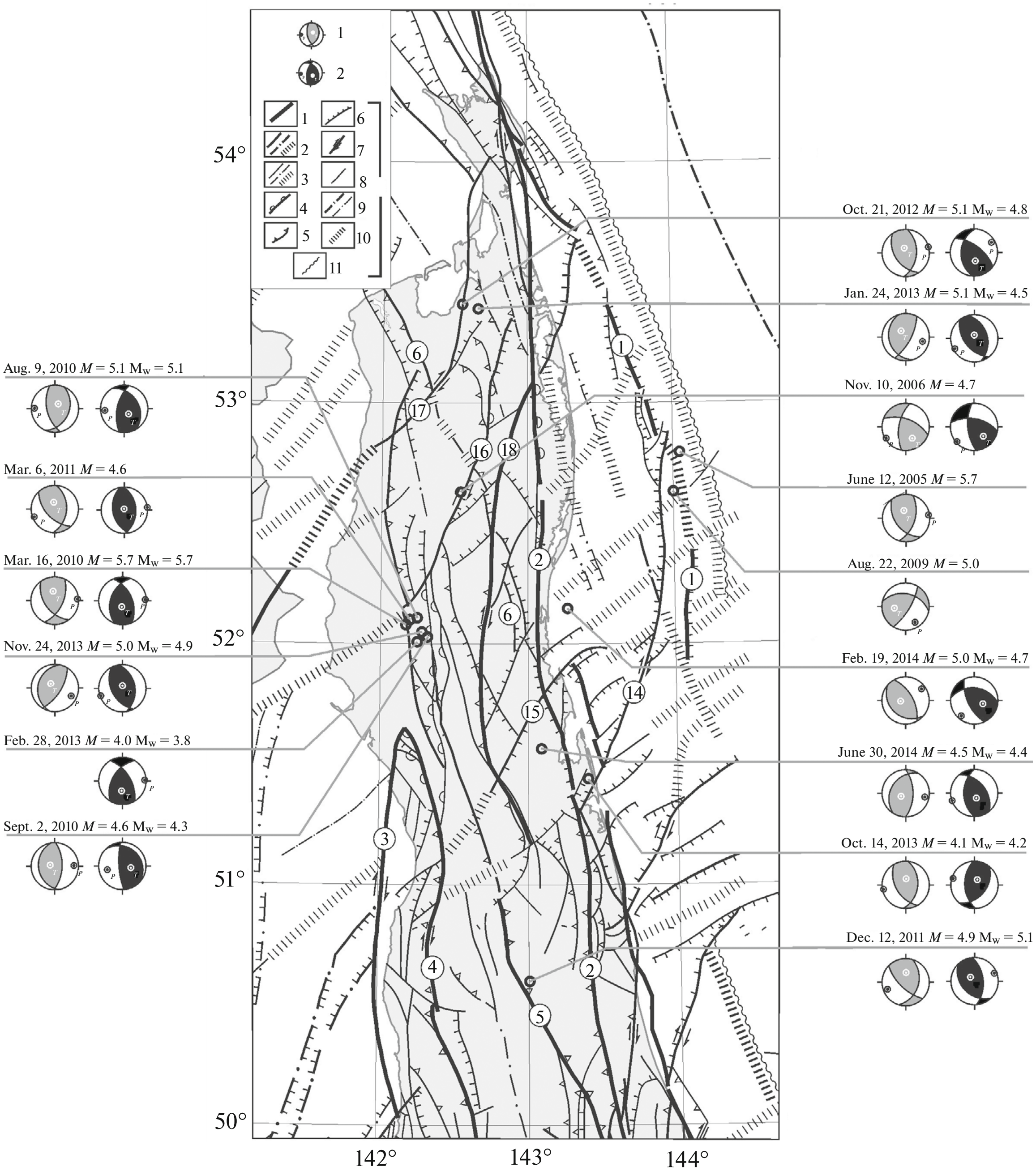

Fig. 1. The epicenters of earthquakes used in this study and a map of faults on Sakhalin Island after (Kharakhinov, 2010), northern part. (1) a stereogram of earthquake mechanisms obtained by FOCMEC; (2) a stereogram of moment tensors in the double-couple approximation; the solution was obtained using ISOLA; (3) fault ranks (1 deep faults, 2 regional faults, 3 zonal faults); (4–7) fault kinematics (4 thrusts, 5 reverse, 6 normal, 7 strike-slip); (8–10) range of fault action (8 crust, 9 lower sediments and consolidated crust, 10 consolidated crust); (11) zone of high crustal cracking.

Faults: 1 Eastern Sakhalin, 2 Hokkaido–Sakhalin, 3 Western Sakhalin, 4 Central Sakhalin, 5 Pervomaiskoe, 6 Western Baikalian, 15 Tym', 16 Gyrgylan, 17 Eastern Baikalian, 18 Upper Pil'tun, 20 Western Odoptu.

The contribution of the double couple (DC) is estimated as

$$DC = 100\% - |ISO| - |CLVD|. \quad (8)$$

The ISOLA makes it possible to find the full seismic moment tensor or else to restrict oneself to finding the deviatoric part only ($DC + |CLVD| = 100\%$, $ISO = 0$), as being the more stable procedure; this has been done in the present study.

The method for determining the moment tensor is based on the search for an optimal coincidence between the synthetic waveforms as calculated using

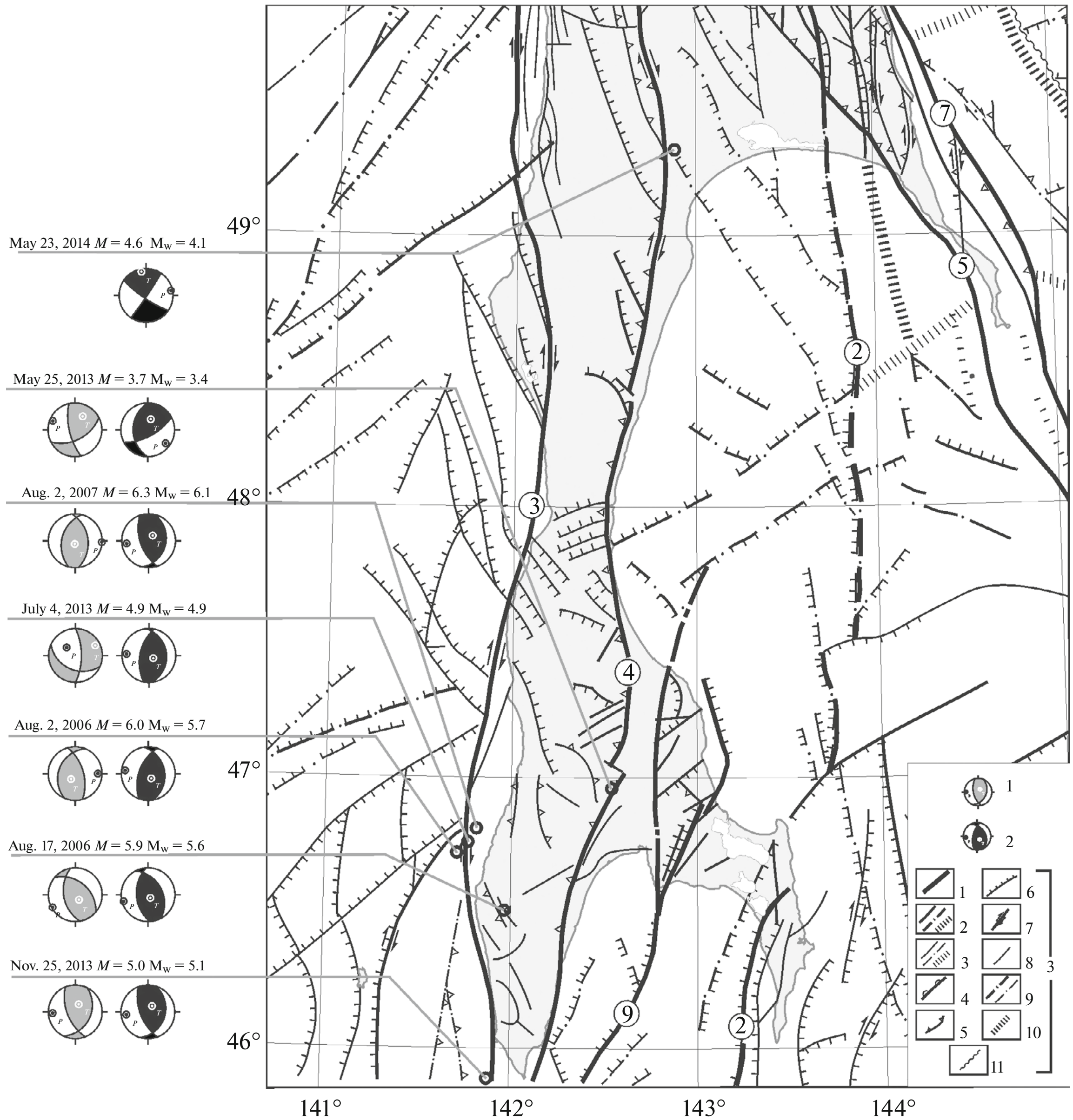

Fig. 2. The epicenters of earthquakes used in this study and a map of faults on Sakhalin Island after (Kharakhinov, 2010), southern part.

(1) a stereogram of earthquake source mechanisms obtained by FOCMEC; (2) a stereogram of moment tensors in the double-couple approximation; the solution was obtained using ISOLA; (3) fault ranks (1 deep faults, 2 regional, 3 zonal); (4–7) fault kinematics (4 thrusts, 5 reverse, 6 normal, 7 strike-slip); (8–10) range of fault action (8 crust, 9 lower sediments and consolidated crust, 10 consolidated crust); (11) zones of high crustal cracking.

Faults: 2 Hokkaido–Sakhalin, 3 Western Sakhalin, 4 Central Sakhalin, 5 Pervomaiskoe, 7 Pogranichnyi (Bogatinskii), 9 Susunai.

Green's functions and actually recorded seismograms filtered in the low frequency range. The method of iterative deconvolution is described in (Kikuchi and Kanamori, 1991), although ISOLA has some differences concerning the set of basic sources. The centroid center and the time t_0 are also unknown parameters to be refined during the determination of the optimal tensor by searching on a grid and maximizing the correlation between the raw data d and synthetic data s. The resulting parameter Vr is a basic one (but not the only one) for estimating the quality of the final solution:

$$Vr = 1 - |d{-}s|^2/|d|^2. \tag{9}$$

The ISOLA uses the source time function in the form of a delta function or a triangle of a specified duration; as well, one can find a composite source consisting of several consecutive sources. We used the simplest option of a single source in the form of a delta function.

THE DATA SET

For the first method: the basic epicenter coordinates were taken to be those in the earthquake catalogs compiled by the SB GS RAS for the southern part of the island and data from a catalog based on records of the local network due to the IMG&G FEB RAS for the northern part (Stepnov et al., 2013), with the epicenter coordinates and depth being held fixed. To read the signs we used records of seismic stations operated by the SB GS RAS, IMG&G FEB RAS, FEB RAS, the NIED agency (Japan), and teleseismic stations of the global seismographic network (GSN).

The input data for the second method to be used in inversion were records of near broadband stations operated by the SB GS RAS (Okha, Tymovsk, Yuzhno-Sakhalinsk); seismic stations of the FEB RAS broadband network (Khanchuk et al., 2011) (Chegdomyn, Vanino, Nikolaevsk-na-Amure); records of the local network of stations in northern Sakhalin (Stepnov et al., 2013) and of the F-Net operated by the NIED agency, Japan (Kubo et al., 2002) installed on Hokkaido. Since we were mostly concerned with records of comparatively small earthquakes (M ~ 4.0–5.0) we made sure our decisions were sound by supporting them with the signs of the first motions as read from seismograms of the same stations.

Our basic model of crustal and upper mantle structure was that used at present by the NIED agency (Kubo et al., 2002) for similar purposes in Japan. However, we tried a composite velocity model for northern Sakhalin, the lower part being as in the NIED model mentioned above, while the upper, crustal part was developed specifically for northern Sakhalin, and is at present used for hypocenter location based on data of a local network (Stepnov et al., 2013).

The raw velocigrams were converted to true ground displacements using the sensor transfer functions. Real and synthetic seismograms were filtered in the range 0.03–0.3 Hz, the range being chosen individually to fit an earthquake taking account of the recording instruments. The epicenter coordinates were held fixed and depth was the parameter to be determined (*Hc* in table).

RESULTS AND ANALYSIS

A total of 22 seismic events were used, with the solutions being occasionally arrived at by a single technique only of out those mentioned above. For convenience in comparison between variants we calculated the Kagan angle (Kagan, 1991), the so-called *k-angle*, which is the minimum angle through which the double couple mechanism is to be rotated for perfect coincidence with the other. To do this we used the korr_kag algorithm from the ISOLA program package (Sokos and Zahradník, 2013) (*k* in table).

A complex seismic source cannot be described by a couple of forces only in the form of a double couple. The moment tensor for such an earthquake will involve, apart from a couple of forces, also a linear vector dipole and an isotropic component. The latter has not been estimated in the present study, as mentioned above. We determined and analyzed the components of the non-double-couple moment tensor in the form of a linear vector dipole only.

The work carried out here presents a comparison of two different techniques as applied to the source mechanism of a moderate earthquake. It can be gathered by comparing their stereograms (see Figs. 1 and 2) that the emerging solutions are not identical. Although the type of slip is generally the same, the azimuths and dip angles of the nodal planes differ considerably (by up to 40° for azimuth and by 60° for the Kagan angle). The azimuth of the axis of intermediate stresses (the intersection of nodal planes) may occasionally be opposite; still, the axis attitude is only slightly variable, remaining nearly horizontal. The greatest difference was found for the earthquake of July 4, 2013, where the Kagan angle between the solutions was $k = 67°$, the type of slip changed from a normal oblique as obtained by the first technique to reverse. Although the solution obtained by the first technique is sufficiently reliable (24 self-consistent signs of first motions in P and 12 signs in *SV* and *SH*, the scatter of solution variants does not exceed 15 degrees), the variant obtained by the second technique is more to be expected, since a series of well-known Nevel'sk earthquakes occurred at the same source in 2007 (Konovalov et al., 2015b; *Nevel'skoe zemletryasenie ...,* 2009) (the events of August 2, 2007, see Fig. 2) and had reverse-slip movements.

This difference between determinations can be explained by the difference between the methodologies: the polarity of the first motions estimates the orientation of the fault plane at the initial moment, while the waveform inversion is based on a centroid model that is an average for the fault plane as a whole. The initial direction of slip may change afterwards and this will rotate the solution. Another explanation appeals to the limited accuracy of the resulting solutions. The calculations are based on an approximate model of crustal structure that is unable to incorporate all local and regional inhomogeneities. The closer the stations (and this is to be the case for comparatively small earthquakes), the greater effects local inhomogeneities have on the solutions. One way to improve the accuracy and stability of the results both when using first motions and for waveform inversion is to make the network of broadband stations denser and to improve the quality of their records (signal/noise ratio), as well as to refine velocity structures; the ideal procedure would be to use 3D models.

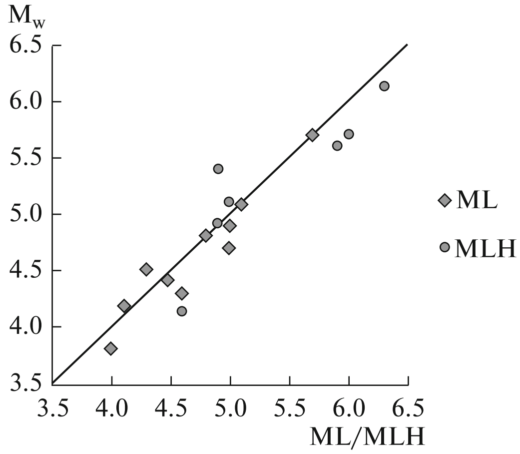

Fig. 3. The agreement between magnitude estimates ML and MLH in regional catalogs due to IMG&G FEB RAS and SB GS RAS and M_w as obtained using ISOLA for the earthquakes in the table.

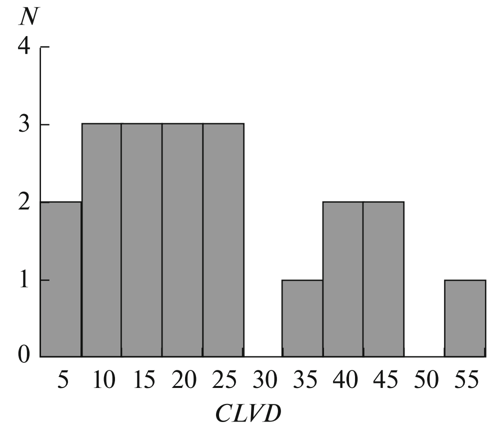

Fig. 4. The distribution of the numbers of earthquakes used in intervals of the percentage for the *CLVD* moment tensor component.

The average depth of the model centroid is one of the parameters that are determined when calculating the seismic moment tensor using the ISOLA program package. The table lists calculated depth values for the moment tensors and data from the SB GS RAS catalog for the northern part of the island and the IMG&G FEB RAS catalog for the southern part. It can be seen at a glance that these estimates are very consistent among themselves, which probably stems from the factors discussed above.

Special mention should be made of the depth parameters for the two largest events during the last decade: the Nevel'sk earthquakes of August 2, 2007 (see table, nos. 4 and 5); their source mechanisms were determined anew using ISOLA, and the results were found to be in overall agreement with those derived previously (Konovalov et al., 2015b). The centroid depth was $H = 2$ km for the first earthquake and $H = 4$ km for the second; these values are much smaller than the respective hypocenter depths ($H = 11$ km and $H = 14$ km). The catalog depth value based on data from the local network is not in doubt, but the shallower centroid depth may also be an objective feature of the rupture reaching the ground surface, as shown by irreversible seafloor uplifts off the Nevel'sk shore (*Nevel'skoe zemletryasenie ...,* 2009).

It was of interest to compare the starting values of earthquake magnitudes and the calculated ones. The starting magnitude was MLH for events in the south of the island and ML in the north. A previous comparison showed that the magnitudes based on these scales are similar (Konovalov and Sychev, 2014), so that the calculated M_w magnitude could be compared with the two magnitudes simultaneously. The agreement between these values as shown in Fig. 3 is rather good, $r = 0.95$, with the greatest difference reaching 0.5 and no obvious trend being observable as for biased estimates, although it is difficult to judge correctly from such a small sample.

Although these determinations of seismic moment tensors for the Sakhalin region are not numerous, we attempted an analysis of the tensor components, in particular, the non-double-couple component, which is generally related either to a complex source geometry, as happens to be the case for major seismic events or to earth anisotropy. Figure 4 shows the percentage of the CLVD component in the moment tensor. Overall, the results show the prevalence of strike-slip double-couple components (over 75% of the total moment) and this is consistent with the tectonic nature of these earthquakes whose slip was in the double couple form (see table). However, it is to be noted that there are earthquakes with the CLVD component amounting to over 35% of the total moment ($DC + |CLVD| = 100\%$). One such earthquake occurred on May 25, 2013 (see table, no. 15, Fig. 2, $DC = 48\%$) in the area of the Sakhalin mud volcano. This area shows high fluid concentrations, geothermal activity at depth, and probably high pore pressure. As to seismicity, the area generates earthquake swarms. Patterns like this one concerning low DC components of the moment tensor occur in seismic regions that are mostly characterized by swarm activity (Vavryčuk, 2002).

Another example of an abnormally high non-strike-slip component was observed for an earthquake in northeastern Sakhalin (October 14, 2013, see table, no. 17, Fig. 1, $DC = 64\%$). The epicenter of this earthquake was situated near the Lunskoe oil–gas–condensate field and a few kilometers from a wastewater utilization site within the united coastal technological complex. A study of known cases of technologically induced seismicity (Adushkin and Turuntaev, 2015) showed that a liquid that is injected at high pressure into a fault may lead to loss of stability, so that the fault sides would start relative movement resulting in an earthquake (when the injection is stopped, the associated seismicity stops occurring as well after the lapse of a certain time interval). In fact, if the pressure of a liquid or gas being injected exceeds the rock strength, this results in a fracture that generates more cracks (the induced mechanism). The CLVD component in the moment tensor may indicate the presence of body forces that can lead to fracturing.

More earthquakes with high percentages of the non-double-couple also occurred in the north of the island around the town of Okha (north of the hard-hit Neftegorsk) where high activity in the extraction of oil and gas is also in progress. However, we do not possess data on the relevant areas of the field and on the technological parameters in the extraction of hydrocarbon and in liquid injection.

It should be noted that the catastrophic Neftegorsk earthquake of 1995, which might have been provoked by oil and gas extraction, in the opinion of some seismologists (Adushkin and Turuntaev, 2015), also contains an CLVD component ($DC = 60\%$) of the moment tensor. A geological survey of the surface rupture revealed that the source was a complex one, with rupturing occurring on several nonparallel fault planes.

In all probability, this mechanism can explain the high incidence of the non-double-couple component for Sakhalin earthquakes. The high CLVD component referred to above may have been due to a scatter of determination errors and this circumstance calls for a more detailed and comprehensive analysis.

A TECTONIC INTERPRETATION OF THE RESULTS

All earthquakes we have considered here occurred in a compressive setting, with the pressure axis (P-pl) being horizontal and its direction (P-az) varying between nearly east–west and southwest–northeast, except for the earthquake of August 22, 2009 (see table, no. 4) whose compression axis points southeast. This earthquake occurred in the area of a large event, the Pil'tun earthquake of June 12, 2005 (Konovalov et al., 2015a), which is a "classical" event for Sakhalin: reverse slip combined with strike-slip movement under the conditions of an east–west compression. The epicenters of these earthquakes are situated in the area of the East Sakhalin Fracture, but neither of the planes for the later event coincided with the strike of the fracture. The movement may have occurred on the secondary oblique fault as marked in the map (see Fig. 1).

Another earthquake whose compression axis does not fit the above pattern occurred in the southern part of the island on May 25, 2013 (see table, no. 15) in the Central Sakhalin Fracture zone. This event can be classified as a lateral reverse-oblique rupture under the conditions of northwest–southeast compression. As well, this event is the smallest of those with $M_w = 3.4$. The northward extension of the Central Sakhalin Fracture contains the epicenter of another strike-slip earthquake occurring on May 23, 2014 (see table, no. 21, Fig. 2).

The strike-slip component also dominates the November 10, 2006 earthquake mechanism (see table, no. 3, Fig. 1). The epicenter of that event falls in the Gyrgylan right lateral reverse-oblique fault zone (which is contained in the influence zone of the 1995 Neftegorsk earthquake). One of the 2006 nodal planes, namely, the right lateral slip component, may be compared with the fault strike. The other earthquakes are dominated by reverse movements.

The largest event in the northern half of the island is the M 5.7 Uanga earthquake of 2010 (see table, no. 7). It was studied previously (Konovalov et al., 2012). Five more earthquakes that we have used are its aftershocks, with their mechanisms being similar to the reverse-oblique mechanism of the main event to within some variation in the directions and dips of the nodal planes. Their hypocenters are situated along the dip of the Western Engizpal thrust fault.

A single moderate-magnitude earthquake (Mw = 5.4) with reverse-oblique sense of displacement occurred in the middle of the island on December 12, 2011 (see table, no. 11, Fig. 1) in the Pervomaiskoe fault zone. A series of earthquakes of which we have used two events (October 21, 2012 and January 24, 2013) occurred in the northernmost tip of the island on the extension of the East Baikal Fracture. Their slip type was reverse, although the solutions obtained by the two techniques are considerably different. We obtained mechanism solutions for three comparatively small earthquakes that occurred on the northwestern coast of the island. Even though the respective estimates differ, they can still be classified as having the reverse type of movement (see Fig. 1).

The largest events in the southern part of the island during the last decade were the Nevel'sk earthquakes of August 2, 2007 (see table, nos. 4 and 5) in the southern flank of the Western Sakhalin Fracture. They are undoubtedly thrust events, similarly to the Gornozavodsk earthquake of August 17, 2006 (see table, no. 1, Fig. 2). Calculation of the moment tensor confirmed the deviations of its nodal planes from the north–south direction as obtained previously from first motion polarities (Konovalov et al., 2015b), but which have not been reported by other agencies. The earthquake of July 4, 2013 mentioned above occurred in the source zone of the Nevel'sk earthquakes, and its thrust type of faulting derived by ISOLA is close to those of the main Nevel'sk events.

The earthquake of November 25, 2013 was a thrust event that involved a small strike-slip component. It occurred off Cape Kril'on, also in the Western Sakhalin reverse-overthrust fault zone.

INFORMATION–TECHNOLOGICAL SOFTWARE SUPPORT

The main goal for this publication of moment tensor determinations and fault-plane solutions for Sakhalin earthquakes was to provide analytical materials for independent researchers who are interested in comprehensive studies of strain and stress in the Earth. In addition, public access to such results on a web page allows rapid comparison of the solutions with other seismological agencies with a view to rapid assessment of the seismic process in the source zone of an earthquake.

It was decided for the publication of our results to use the existing SRSS information resource (http://imgg.ru/ru/srss). The SRSS is the web interface of an automated seismicity monitoring system that is operated on Sakhalin. The present information resource was developed by researchers at the IMG&G FEB RAS; it has the necessary base for storing and visualizing the results of determinations considered in the present paper. The SRSS makes an earthquake catalog for the Sakhalin region for the last 6 months available, with tools for selecting the stored seismic events by date, time, magnitude, latitude, longitude, and other earthquake parameters. Each earthquake the SRSS contains reflects grouped information, e.g., location parameters, calculated intensity, and other data.

In the present work we have updated the SRSS in order to store and visualize seismic moment tensor data and fault-plane solutions for the Sakhalin region. Toward that goal, we have modified the SRSS database structure and developed an additional tab of the web interface. In this way, when a moment tensor or a fault-plane solution becomes available for a specific earthquake, the operator in his/her capacity as the administrator uses a web blank form to enter the calculated results, which are stored in the SRSS data base and remain associated with a particular seismic event. Earthquakes that have moment tensor results and fault-plane solutions added to the database are shown by the SRSS with the additional information tab that contains data from a table. For a single earthquake one can add several solutions of the moment tensor (fault plane) with indication of the most likely solution. In addition, stereograms can be constructed automatically for various variants of solutions based on the parameters of fixed nodal planes (NP1 and NP2). The solutions can be visualized using the OBSPY software framework (Beyreuther et al., 2010).

These results furnish a base for developing software and technical designs in the determination of seismic moment tensors (source mechanisms) and moment magnitudes for the Sakhalin region, also for an area where oil–gas fields are being exploited on an industrial basis.

CONCLUSIONS

To sum up, the above results from the determination of source mechanisms for moderate earthquakes on Sakhalin Island in 2006–2015 using two different techniques are in overall agreement with the results published in (Konovalov et al., 2014), in spite of some discrepancies between the respective solutions. The earthquakes reflect the ongoing compression of the island land, with the compression axis being nearly horizontal and striking either nearly east–west or from east-northeast to west-southwest.

Our solutions are dominated either by reverse or thrust faulting that is generally combined with some strike-slip component. The strike-slip movement prevailed in the rupture zones of three earthquakes.

The ISOLA software package has proved to be effective for determining the source mechanisms of Sakhalin earthquakes. Among these results we obtained solutions for two earthquakes that did not provide enough *P* onsets to be processed using the alternative technique. There are noticeable discrepancies between the solutions obtained with the two techniques, with a considerable difference being observable for one earthquake, including the type of slip, while the types of slip in all the other cases were identical.

We have analyzed the moment tensor component that contains the linear vector dipole and that takes the maximum values in areas of active mud volcanism (in the south of the island) and in areas of industrial activity in oil–gas fields (in the north). These areas typically show a swarm type of seismicity. This feature calls for a more careful study in order to be able to explain its physical origin. The method should be tested on explosions for future use to determine the isotropic moment tensor components.

We integrated the software technical solutions for determining the moment tensor along with a web application to publish routine determinations. These results provide a basis for the development of software technical solutions with a view to automatic seismic moment tensor determinations (source mechanisms) and moment magnitudes for Sakhalin earthquakes, including an area of industrial exploitation of oil–gas fields.

Further improvements on the quality and numbers of solutions require development of broadband seismographic stations on Sakhalin Island and in adjoining areas, enhancement of observation quality, especially at low frequencies, refinement of crustal and upper mantle velocity structure, and the passage to 3D models in the future.

The sum of these results provides satisfactory experimental material for studies on the state of stress in the earth.

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