INSTITUTE OF MARINE GEOLOGY AND GEOPHYSICS FEB RAS

CURRENT STATUS OF LOCAL SEISMOLOGY RESEARCH OF THE FAR EAST REGION

IMGG contribution to FP-7 Project

Search for Electro - Magnetic Earthquake Precursors (SEMEP), 2011-2012

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1 INTRODUCTION

Purpose

This document provides an overview of the results of seismological investigation for the territory of Far East region (North-West part of the Pacific). The records and analysis of the seismicity forms a component of ground-based observations aimed at the prediction of strong earthquakes. The seismological analysis was made by IMGG Team in the frame of the SEMEP Project, 2011-2012; Prof. B.W. Levin was being the Team leader.

Context

This report discusses the results of three recent studies of the analysis of regional seismicity of the territory of Sakhalin and the Kurile Islands. These studies cover the following topics.

- The monitoring of seismicity in Sakhalin and Kurile Islands regions (mean activity, zoning, etc.) as initial information to apply ground and satellite VLF method.

- Examples of successful intermediate–term earthquake prognosis in the Far East region from seismological data. These results (examples) are of high importance for the project as they provide the first possible indications of an increase in seismic activity. These results should provide the forerunner to short-term predictions including that on the base satellite observation. If not, one can expect a number of false alarm episodes.

- The development of a statistical model for seismicity and its potential for probabilistic forecasting of strong earthquake.

2. RESULTS

2.1 General aspect

The region of Sakhalin and Kurile Islands is located within the Pacific seismic belt. Therefore, this region is considered as one of the most seismically hazardous regions of the Russian Federation. The high level of seismicity in the Far East territory is illustrated by Fig. 1.

The highest level of seismicity occurs around the Kuril Islands. On average an earthquake with the magnitude equal to 5 occurs here almost every month in this area, and a disastrous earthquake with the magnitude equal to 8 occurs typically every 10 years. The majority of the earthquake sources are concentrated within the area of an inclined seismofocal zone. This zone represents a layer, running under the mainland up to a depth of about 650 km. The earthquake sources around Sakhalin are concentrated in the Earth's crust. In comparison with the Kuril Islands, the seismicity of Sakhalin is characterized by a moderate level. On average an earthquake with the magnitude equal to 5 occurs here every 2 years, and the earthquake with the magnitude equal to 7 occurs once per decade. Moderate earthquakes with a magnitude equal to or greater than 5 belong, as a rule, to three main active fault systems, namely Central Sakhalin, Western-Sakhalin and Eastern-Sakhalin as shown in Fig. 2.

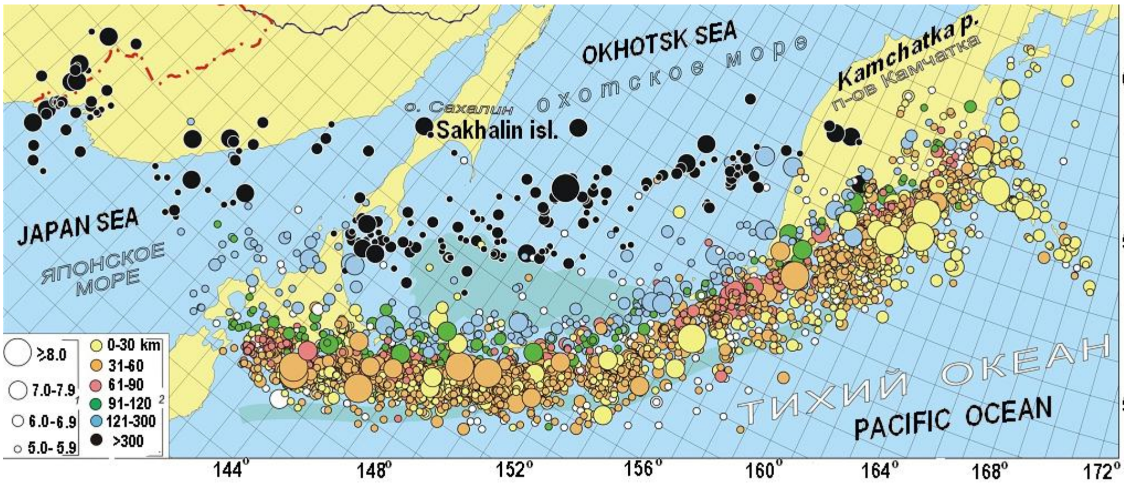


Fig. 1. Spatial distribution of the epicenters of the M ≥ 5 earthquakes at the territory of Far East Region, 1737-2005.

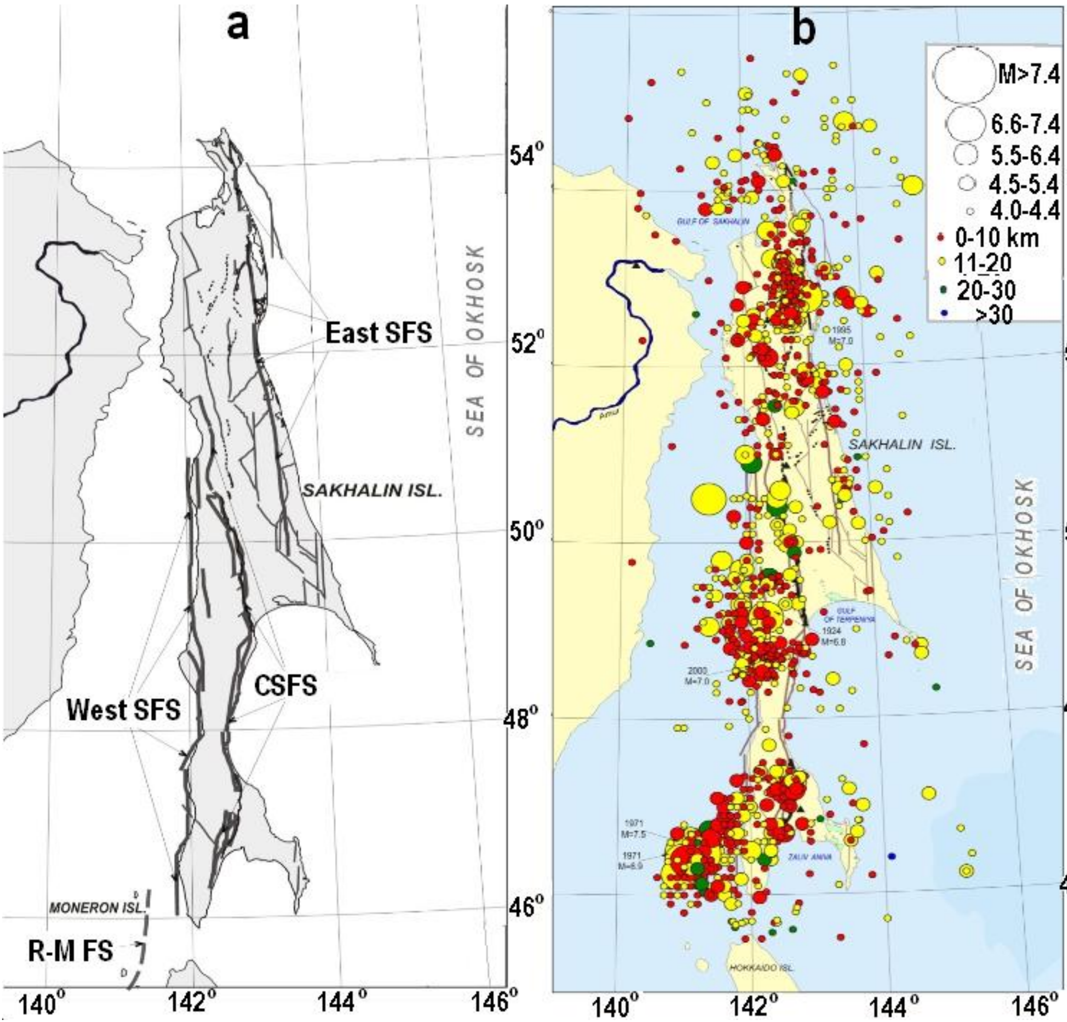


Fig. 2. Map of the active faults (a), and the distribution of epicenters of shallow earthquakes, $M \geq 3.5$, 1906-2010, (b) on the territory of the Sakhalin Isl. Abbreviations: East SFS – Eastern Sakhalin Fault System, West SFS- Western one, CSFS – Central one, R-M FS- Rebun- Moneron Fault System.

2.2 New approach to the seismic hazard evaluation at the Sakhalin - Kurile region

The maps of the general seismic zoning identification will assess the level of initial seismic hazard on the territory of Sakhalin and the Kuril Islands. The data from which such maps are made are analysed using a complicated methodology of a probabilistic seismic hazard analysis, a description of which is beyond the scope of this report.

In 2012 the researchers from IMGG FEB RAS together with scientific groups from other Russian Institutes completed the process of designing a set of the General Seismic Zoning Maps (GSZ-2012). The set of 30 maps have been created for different recurrences of seismic influences, both, as intensities of the MSK-64 scale and peak ground accelerations. The map is presented in Fig. 3, panel (a). The intensity assessments are in the accordance with the MSK-64 scale. It is oriented for the civil engineering. The map shows the areas where seismic events with intensity between 8 and 9 can occur; the calculated probability of such an event in the next 50 years exceeds the 10% level. The seismic intensity for the Kuril Islands is equal to 9.5. Fig. 3 also demonstrates the probability map, which exceeding 1% level of the calculated intensity in any point of the zone during 50 years (the average waiting period of earthquake recurrence is T = 5000 years). It is oriented on building of critical facilities. Actually the GSZ-2012 maps are a model of the long term seismic prognosis (of probabilistic kind) for Sakhalin and Kurile Islands region. These maps may be used for prognosis approach to intermediate – erm predictions, as a background to arising geophysical anomalies.

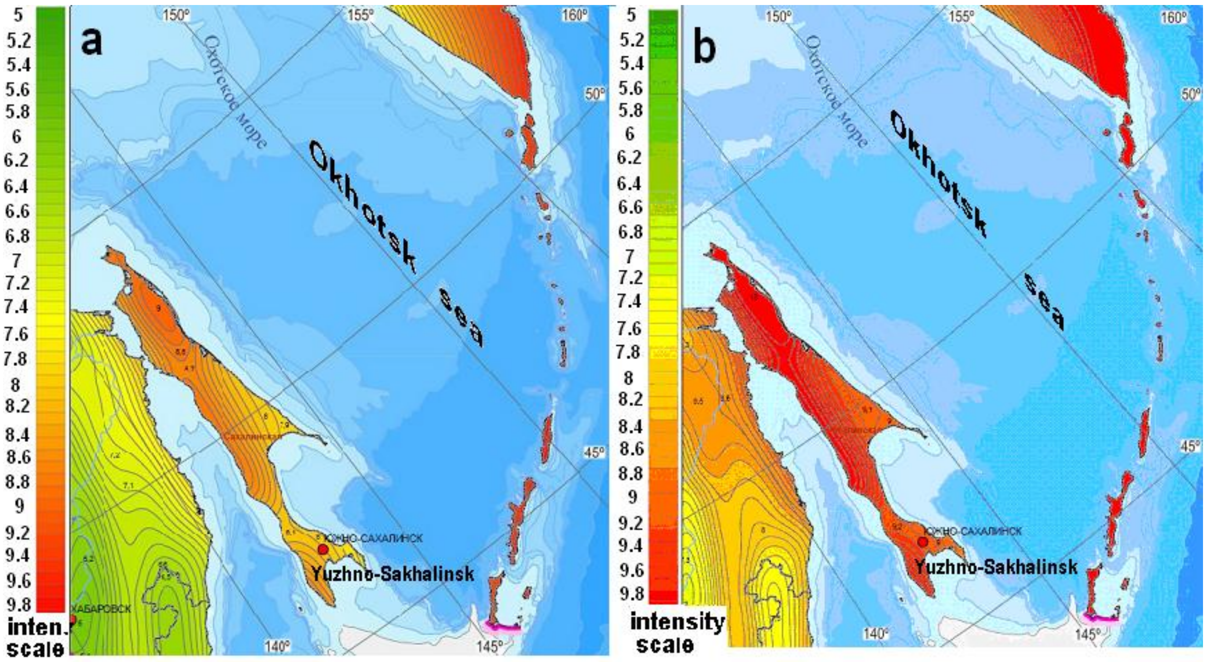


Fig. 3. Maps of the General Seismic Zoning (GSZ-2012). The left frame (a) gives the areas with 10% probability of exceeding of chosen level in 50 years, and the right frame (b) gives the same but with 1% probability of exceeding of chosen level.

2.3. Pilot predictions of strong earthquake by seismological data

The seismologists from IMGG have had definite success in the field of pilot forecasts/predictions of strong earthquakes. The term "earthquake prediction" may be interpreted in many different ways. For the sake of precision we imply only the definition given by the group of scientists from the US National Academy of Sciences [Allen et al. 1976]. It reads as follows: "*An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction".*

If the noted conditions have been fulfilled partially we prefer to use a term of the "earthquake forecasting" for such a prognosis.

A system of well known and original methods has been used for identifying the final stage of strong earthquake preparation. These methods are based upon the following properties of seismic regime: intensity of earthquake flow, the nonlinearity of seismic process, seismic gaps, quiescences and pauses, anomalies in b-value, latent periodicities, etc. The following seven recognized analysis methods for earthquake prediction appear to work for the Far East region:

- The intermediate-term earthquake prediction method of the large, magnitude 8.0 or more, earthquakes (the algorithm M8, [Keilis-Borok, Kossobokov , 1990]).
- The methods and algorithm of intermediate-term prognosis of the time of occurrence of strong earthquakes (Q1-technique, [Tikhonov, 2006]).
- The method of prognosis of the time of occurrence of strong earthquakes on the base of forerunner of "seismic pause" type [Tikhonov, 2012].
- The method of evaluation of the probability of occurrence of not large earthquake on the base of the recurrence of the time intervals between sequential seismic events [Tikhonov, 2002].
- The method of revealing of latent periodicities, synchronized the occurrence of strong earthquakes, and prognosis of seismically dangerous intervals of time in separated areas [Tikhonov, 2004, 2010].
- Mapping of locations of the positions of prognostic earthquakes with the help of modifying ZMAP method [Tikhonov, 2005].
- The method of self-developing processes [Malyshev, 1991; Tikhonov, Kim, 2010].

This methodology has been used for the expert evaluation of the seismic situation in the Sakhalin and Kurile regions. Let's consider some examples of successful intermediate-term predictions of destructive earthquakes, which were prepared by Dr. Tikhonov, IMGG. The alarm period of these forecasts (predictions) is, as a rule, made for a period of around 3-5 years in the future. Due to the intermediate term nature (several years) of these forecasts short term VLF variations (about a week ahead) can not be taken into consideration, although they were available from the PTK receiver, Petropavlovsk-Kamchatsky.

The first example is a result of retrospective analysis of the strong earthquake that occurred in Neftegorsk in 1995. The consequences of this event were catastrophic: Neftegorsk town was razed to the ground, 1841 persons were killed. In 1989 Dr. Kim (IMGG) had identified a large area of seismic quiescence in the North-Eastern part of Sakhalin Island. In fact, there were no registered earthquakes with a magnitude equal to or more than 3 in this area since 1984 (Fig. 4). We have been studying the intermediate precursors of the Neftegorsk earthquake by means of the M8 algorithm. An adjustment of the algorithm has been applied based on the data of the regional catalogue since 1964. Identification of the "alarm periods" has been searched over the period from 1979 to 1993. Over this period of 14 years there was only one "alarm period" that was detected since 1991. One can see in the right hand panel of Figure 4 the implementation of the earthquake prediction as a result of the Neftegorsk earthquake on the 27th of May, 1995.

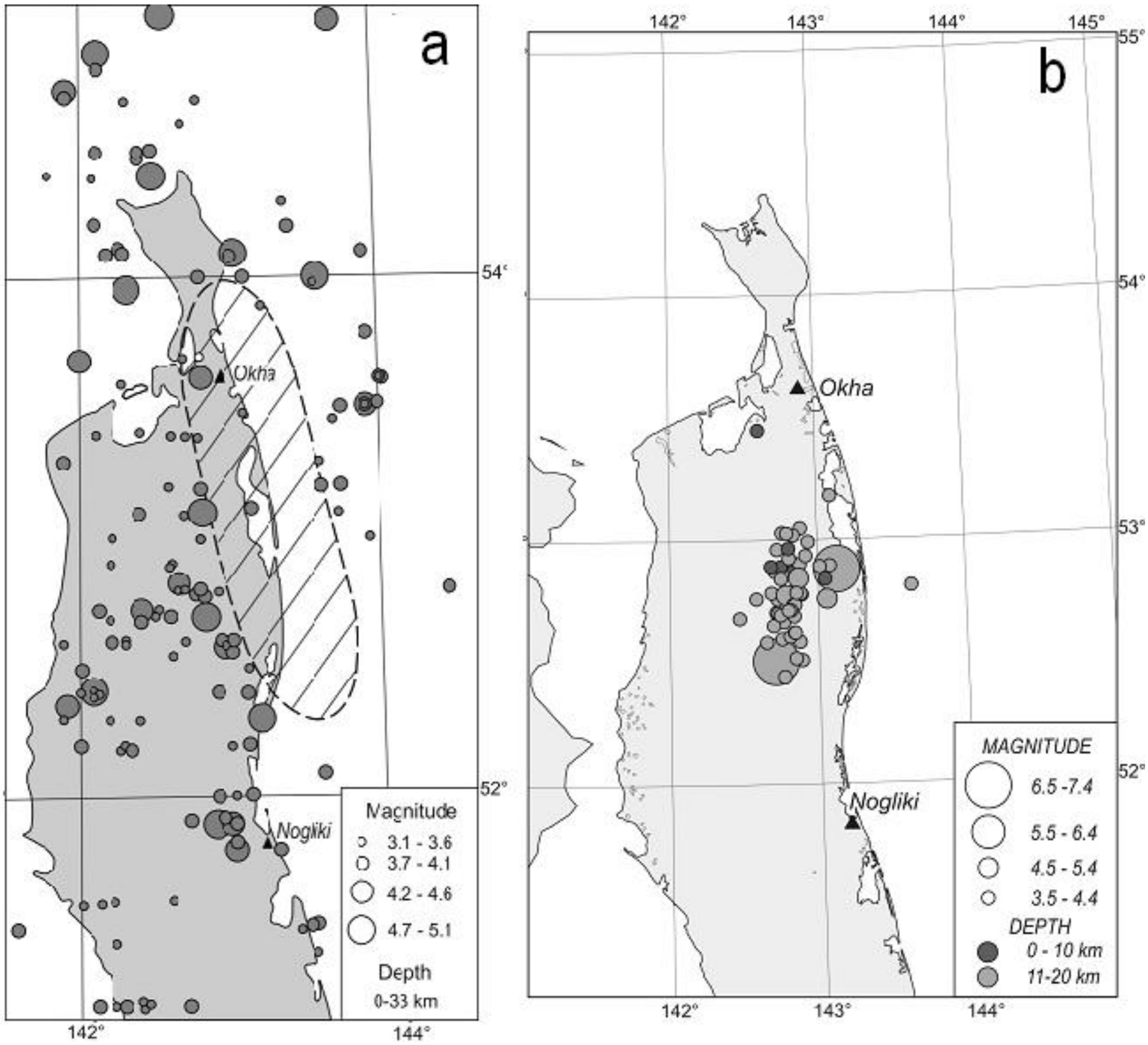
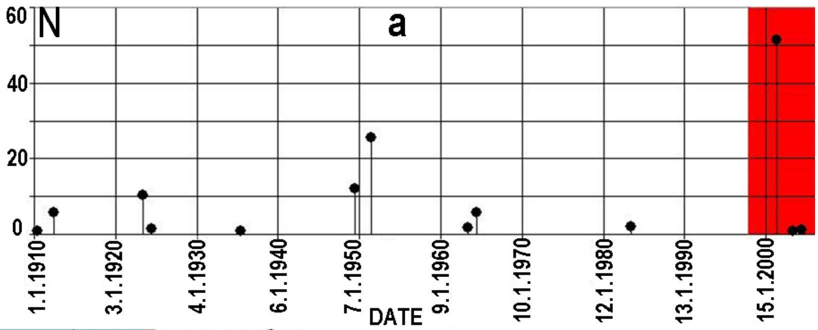


Fig. 4. Retrospective forecasting earthquake of the May 27, 1995 (Mw=7.1), Neftegorsk, North-Eastern part of Sakhalin Isl. a - seismic quiescence zone (hatched area) since July 1984 for M≥3.0; b- the realization of forecasting in the May, 1995. Circles mark epicenters of main shock and first-day aftershocks with M≥3.5.

The second example demonstrates the intermediate-term prognosis of the Takoe earthquake swarm in 2001. The prediction is based on the quasi-cyclic recurrence of shocks with magnitude equal to or more than 4 that have been identified within the southern segment of the Central Sakhalin fault system (Fig. 5 a, according to [Tikhonov, 1997]). This event preparation has been discovered in 1997. The “alarm period” is highlighted in red. Later there was an intense series of earthquakes in the Dolinsk district that occurred within the same time interval (Fig. 5 b).

The next example is the successful real-time prediction of the destructive Nevelsk earthquake of 2.08.2007, Mw=6.2 [Tikhonov, Kim, 2010]. Nevelsk town was very heavily damaged as a result of the earthquake. There were two precursors that played the main role in identification of a strong earthquake preparation on the South-Western shelf of Sakhalin. They have been named “seismic gaps of the first and second kind”. The second precursor is often called seismic quiescence. Fig. 6 shows the mentioned forerunning factors as a shaded square and as the area outlined by dotted lines. The characteristics of the Nevelsk earthquake were in such as that of predicted intervals.



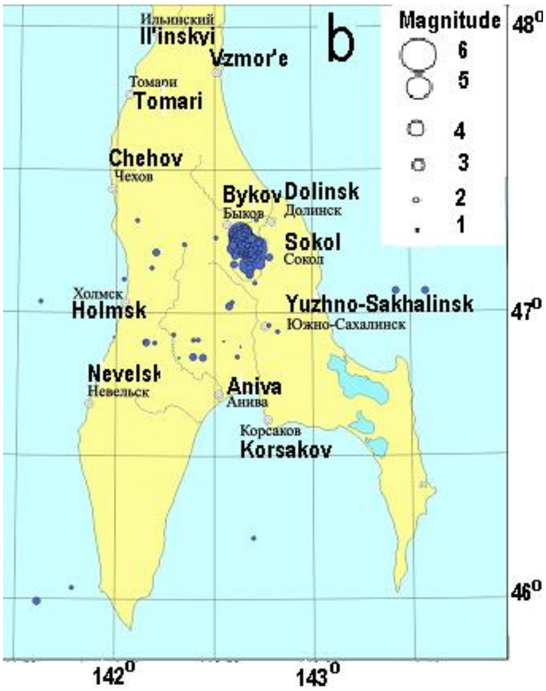


Fig. 5 Intermediate-term prognosis of Takoe earthquake swarm. The frame (a) shows a quasi-cyclic recurrence of the events (M≥4) for period 1910-2005, the recurrence time is about T=13.7 ± 3.0 years. N denotes the number of conventional events. Red stripe – prognosis of seismo-active period The frame (b) represents a realization of intermediate-term prognosis of the 2001 Takoe earthquake swarm (Mmax = 5.6). The map of the epicenters is given, according to Sakhalin Branch of GS RAS.

On the basis of these and some other precursors seismologists form IMGG developed intermediate-term prediction for a strong earthquake. The authors of the prediction made in December 2005 are Ivan Tikhonov, Kim Chun Oun, Alexey Ivaschenko and Lidiya Poplavskaya. The prediction data has received support from the Russian Expert Council for Earthquake Prediction, Seismic Hazard and Risk Assessment. The experience of this prediction has been accepted by the seismological society as a classic one. The Nevelsk earthquake and its intermediate prediction have been described in two monographs and a number of articles [Levin, Tikhonov, 2009; Tikhonov, Kim, 2010; Tikhnov, Rodkin, 2011].

The list of successful prognosis includes the case of the catastrophic Shikotan earthquake, 1994 in the Kurile Islands region. The preliminary adjustment of the M8 algorithm was performed using the seismic catalogue for the period from 1962 to 1978. The evolution of the seismicity has been studied within the circular areas with the radius of 427 km. Then the data from 1979 has been used to forecast an earthquake with the magnitude equal to or more than 7.5. The hazardous situation has been identified since July 1992 in the circular area located in the Southern Kuril Islands. The period of seismic quiescence indicated the possibility of an expected extensive earthquake. This area has had no events with magnitude equal to or more than 6 since 1987. Based on these factors an intermediate-term prediction was developed that an extensive earthquake would take place within the 5 year period 1993-1998. The prediction has been registered in July 1992 in the Russian Academy of Sciences. Our prediction has been fully proven out on October 4th 1994 when a destructive earthquake on Shikotan Island took place.

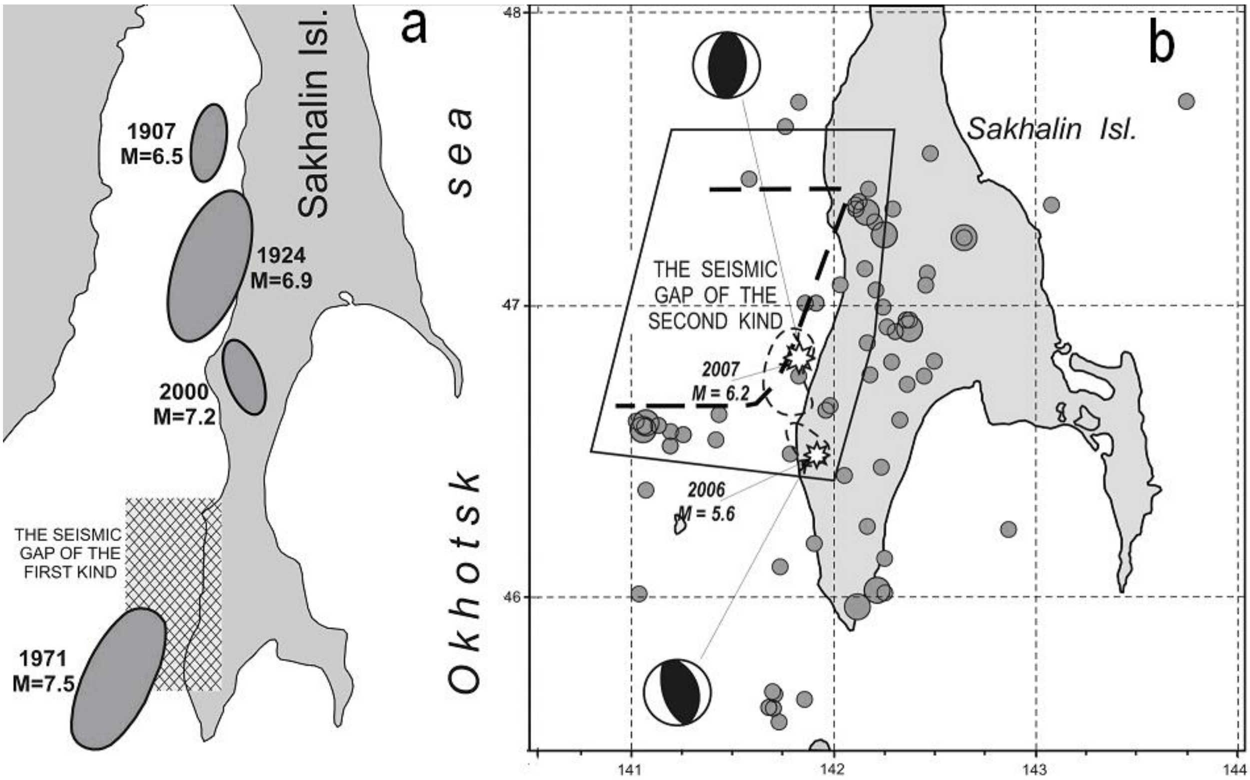


Fig. 6. Precursory features which allowed a successful prediction of the Nevelsk earthquake, 2.08.2008, Southern Sakhalin [Tikhonov, Kim, 2010]: a - seismic gap of the first kind; b- seismic gap of the second kind

Seismologists from IMGG also analyzed the case of catastrophic Simushir earthquakes of 16.11.2006, Mw=7.9 and 13.01.2007, Mw=8.2. These events occurred outside the zone controlled by South Sakhalin and South Kuriles seismic networks. Retrospective prognosis for Simushir earthquakes was prepared on the basis of data from remote seismic stations [Tikhonov et al, 2008]. The method of modelling of self-developing processes [Malyshev, 1991] were applied for the prognosis justification. The results of Tikhonov et al. (2008) argue that the ability to successfully forecast the Simushir earthquakes in real time (in a similar manner to the case of Nevelsk) would have been possible provided that a sufficient volume of real time data were available.

The only case for an unsuccessful intermediate–term prognosis is that for the sub-region shown in Fig. 7. An intermediate-term forecast was made for an event to occur to the south east of Urup and Simushir Island. The data used for the forecasting were taken from the NEIC/USGS catalogues which contained events occurring in the period from December 1995 until December 2007. Only events with M ≥ 4 were taken into account without missing events. The algorithm Q1 aimed at the detection of the joint occurrence of a seismic gap and change in *b*-value was used [Tikhonov, 1999; 2000]. This algorithm was used to identify the time period for the increased probability for a large (M ≥ 7.5) earthquake in the Southern Kuril Islands since the last large earthquake occurring here in December 03, 1995. The algorithm was examined the time period from 1962 until 1995. Thereafter this algorithm was started in the real time regime. The anomalies in four predictive functions of the Q1 algorithm were revealed on December 2007. The zone of seismic quiescence statistically proved by the use of the Q1 algorithm is shown in Fig. 7.

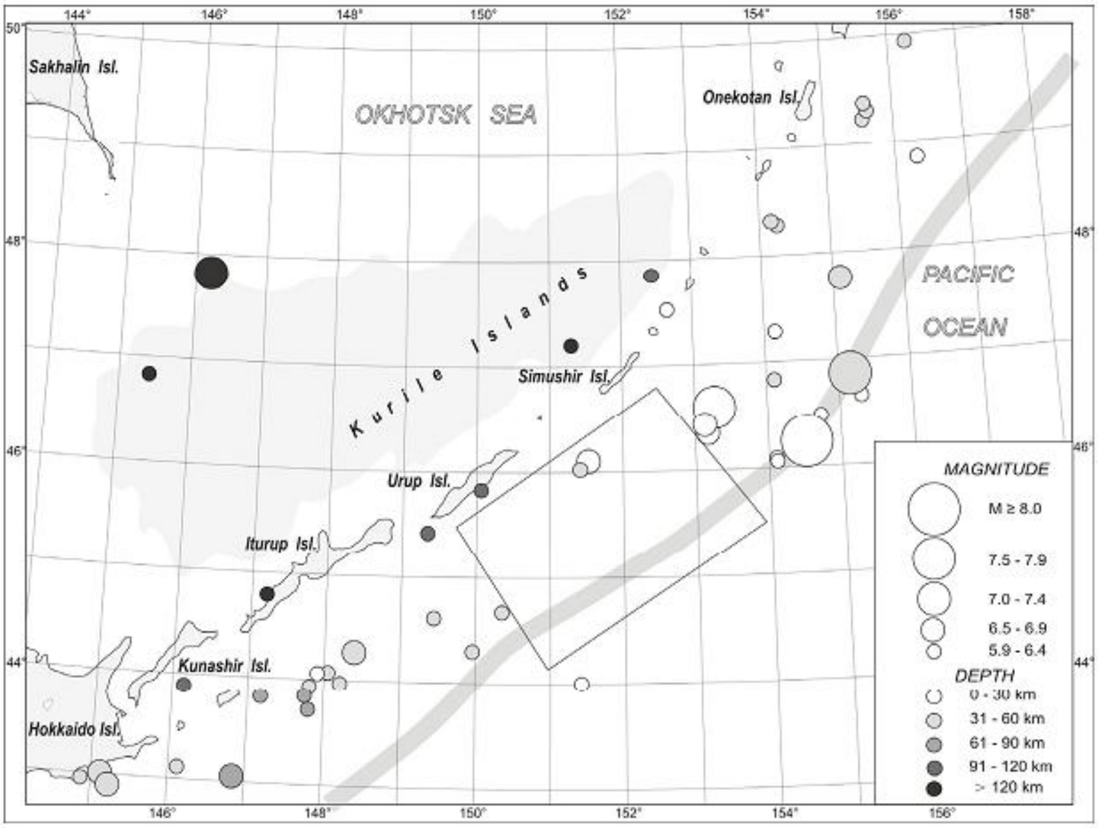


Fig. 7. Map of earthquake M ≥ 5.9 epicenters near Kuril Islands, May 1999 – January 2010. The area limited by the polygon is the area of the seismic gap of the second kind.

A potentially hazardous period for an earthquake M ≥ 7.4 was declared for the next two years (2008-2009). Note that the use of the M8 algorithm (http://mitp.ru/predictions/html) had resulted in the similar space-time period of alarm. However, the alarm has proved to be false. Until now there is no strong earthquake in the identified region of the Southern Kuril Islands.

To evaluate success rate of our approach to seismic prognosis we highlight as follows.

A total of 6 intermediate-term forecasts of potentially large earthquakes occurring is a specific region in past 20 years made. Of these 6, only one has proved unsuccessful. For the 5 successful forecasts, two were carried out retrospectively and the remaining three in real time. Thus, the real time operation of these algorithms has led to a minimum success rate of 50%.

2.4. Comparison with the case of mega-earthquake Tohoku, March 11, 2011

On the 11th of March last year there was the mega-earthquake Tokhoku. Although this earthquake occurred in the Northern part of Japan, outside the territory controlled by our seismic networks, it attracted special attention. The reason was the huge magnitude (Mw = 9.0), one of the strongest earthquakes of recent times, and its hard unprecedented influence on geoenvironments (manmade disaster on the Fukushima-1 atomic power station). The signatures of this mega-earthquake preparation and/or foreshock process in the parameters of VLF signals propagation are considered as a Deliverable of the SEMEP project. The coordinates of the hypocenter of Tokhoku mega-earthquake are: latitude 38.32° N, longitude – 142.35° E, depth 25-30 km (Fig. 8). The earthquake resulted from the crust shifts in the contact zone of the Pacific tectonic plate and Southern edge of Okhotsk sub-plate (Fig. 8 inset a, according to [Tikhonov, Lomtev, 2011]).

Fig. 8 also shows the location of epicenters of the aftershocks over the first 32 days. In the right panel of this figure one can see the example of retrospective prediction of this mega-event location in accordance with the earthquakes catalogue of the Japanese Meteorological Agency. The aftershock epicenters covered a large area 650 km in length and about 350 km in width from the Honshu coast to the deep trench and even behind it.

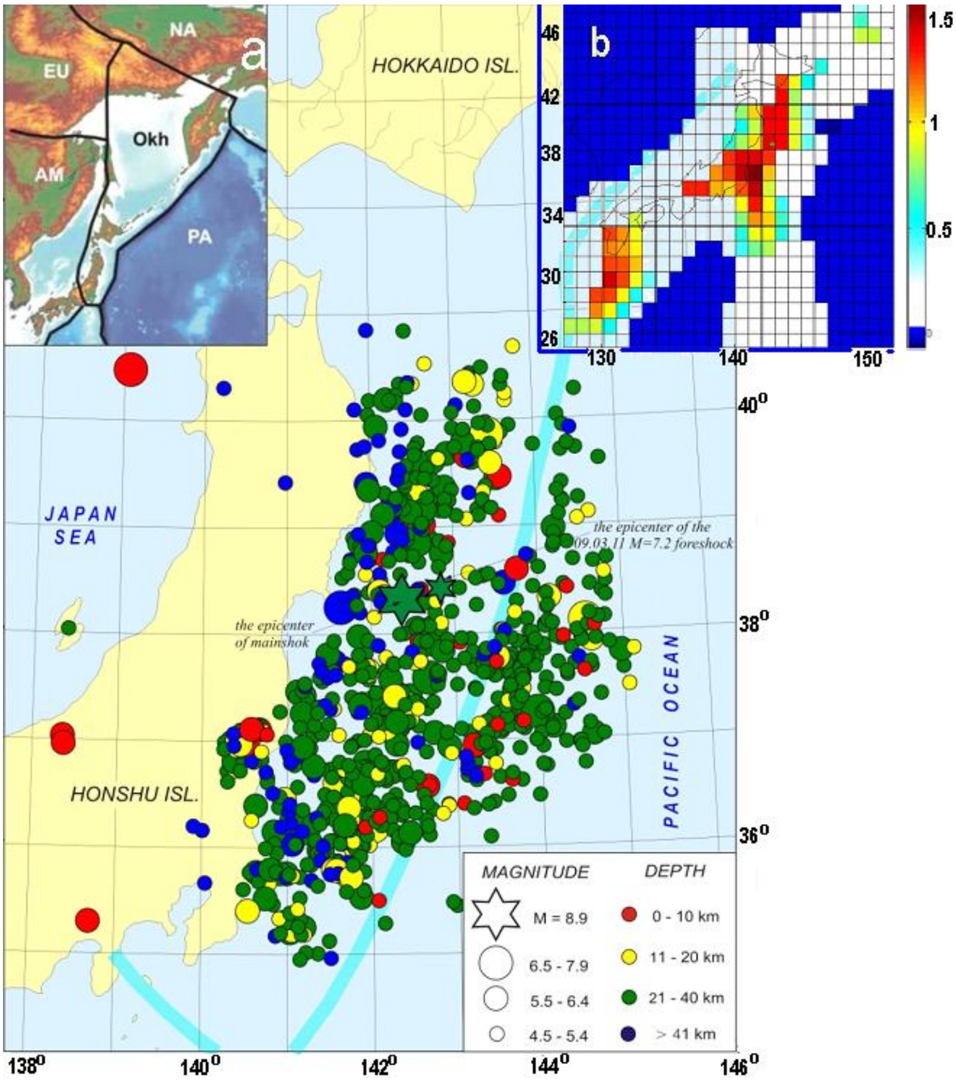


Fig. 8. Map of epicenters of the Tohoku earthquake, its foreshock and aftershocks, registered during 32 days according to the NEIC/USGS operative catalogue's data [Tikhonov, Lomtev, 2011]. Inset (a) gives schematically the interaction of tectonic plates: Pacific Plate (PA), Amur Plate (AM), North American one (NA), Okhotsk sub-plate (Okh), and Eurasian Plate (EU). Inset (b) shows the decrease in the b-value parameter in the area of the Tohoku earthquake (2011, M=9, Japan) in comparison of time interval 2006-2010 with the previous time interval 1996-2005 [Rodkin, Tikhonov, 2013].

2.5. Partial prognosis for prolongation of ground VLF monitoring at Sakhalin

The last aspect relevant to further ground VLF signal observations is where on Sakhalin can we predict the most likely place for another powerful, similar to the Nevelsk event? Can we pinpoint the place of the next strong earthquake? In our opinion (based on the above results), the main threat for the next few years lies in the seismic zone situated to the South of the Poyasok Isthmus (in the vicinity of latitude 48° N). Fig. 9 demonstrates that this is a distinct region of seismic quiescence (seismic gap of the second kind). Aimed with this intermediate-term prognosis we will continue to monitor VLF radio signals using ground based observations at Sakhalin in order to provide a shot-term prognosis for the occurrence of a major earthquake.

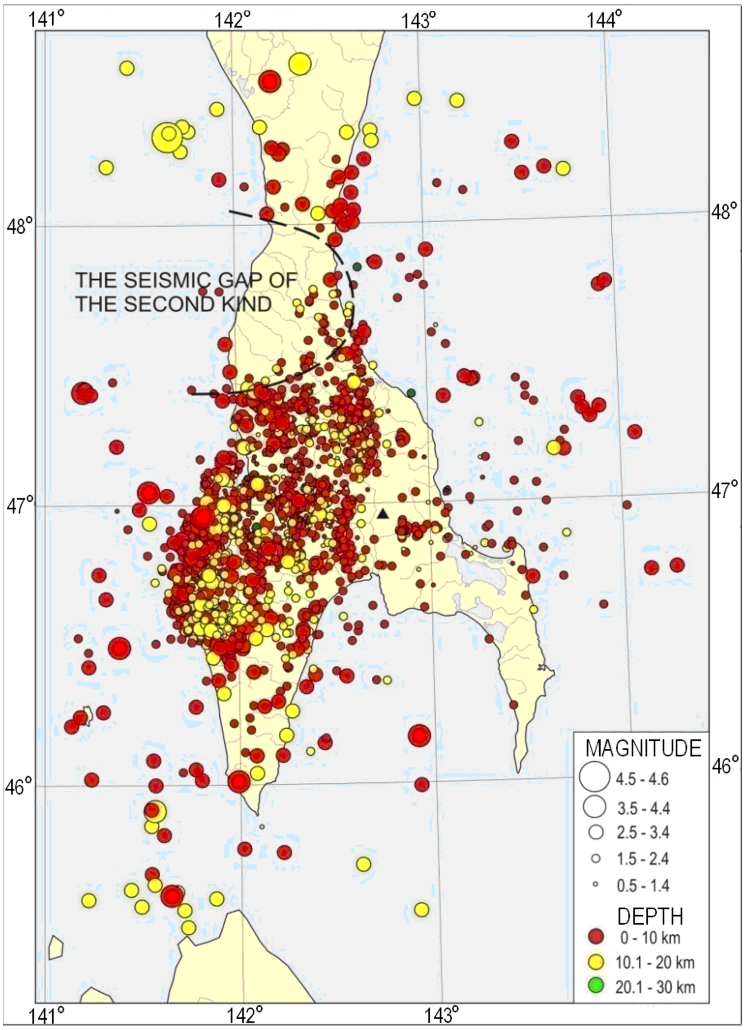


Fig. 9. Map of earthquake epicenters of the Southern Sakhalin for period 2009-2011. The seismic gap of the second kind (the precursor) is outlined with the dash line.

3. SUMMARY

The character of the spatial distribution of the seismicity in Sakhalin - Kurile has been studied in detail. New General Seismic Zoning (GSZ-2012) maps have been developed this year by researchers from IMGG FEB RAS together with scientific groups from other Russian Institutes. The maps give the more precise assessment of seismic hazard for Sakhalin and Kurile Islands territory in terms of MSK-64 scale intensities and peak ground acceleration A number of well-known and original methods have been used for expert evaluation of the seismic situation in the Sakhalin - Kurile region, including the recognition of the final stage of strong earthquake preparation. The methods of earthquake prediction/forecasting are based on the following properties of seismic regime: intensity of earthquake flow, the nonlinearity of seismic process, seismic gaps, quiescence and pauses, anomalies of b-value, latent periodicities, end others. In spite of that the temporal regime of the seismicity remains vague, several intermediate - term predictions of the destructive earthquakes in the Far East territory (by IMGG seismologists) were successful.

The modified map of General Seismic Zoning (actually, long-term prognosis map) and the approach to intermediate-term earthquake predictions in Sakhalin - Kurile region provide a necessary background for analysis of VLF anomalies in relevance to strong earthquake (electromagnetic precursors). Refinement of the seismological methods for the intermediate-term prognosis of strong earthquake activity is the main result of the seismological analysis which has been conducted in the frame of the SEMEP project. The prospect of integrating both seismological and VLF radio-signals methodologies and the subsequent creation a forecasting system looks realistically. The concept of such a system would rely on the intermediate prognosis generated by the seismological analysis to define the area/region that should be closely monitored by methods used for a short term prognosis such as those based on VLF data. However, the implementation of such a system is beyond the scope of SEMEP, since both seismological and VLF analysis methods used complicated algorithms (M8 algorithm, Q1 technique for seismic catalogs, neural network for VLF signals variations).

References

Allen, C.R., W. Edwards, W.J. Hall, L. Knopoff, C.B. Raleigh, C.H. Savit, M.N. Toksoz, and R.H. Turner, 1976. Predicting earthquakes: A scientific and technical evaluation – with implications for society. *Panel on Earthquake Prediction of the Committee on Seismology, Assembly of Mathematical and Physical Sciences, National Research Council, U.S. National Academy of Sciences, Washington, D.C.*

Keilis-Borok V.I., Kossobokov V.G. Premonitory activation of earthquake flow: algorithm M8, Physics of the Earth and Planetary Interiors. 1990. V.61. No. 1-2. P. 73-83.

Levin B.W., Tikhonov I.N. (editors). The 2 August, 2007 Nevelsk earthquake and tsunami, Sakhalin Island. Moscow: Yanus-K, 2009. 204 p. (In Russian).

Malyshev A.I. Dynamics of self developing processes, Volcanology and Seismology. 1991. No. 4. P. 61-72. (In Russian).

Rodkin M.V., Tikhonov I.N. On the Seismic Regime of the Japan Region before the Tohoku Mega-Eathquake (Mw=9), Journal of Volcanology and Seismology. 2013. V. 7. No. 4. P. 243-252.

Tikhonov I.N. Quiescence Period prior to Strong Earthquakes in the Kuril – Kamchatka Zone, Russian Journal of Pacific Geology. 2012. V. 6. No. 1. P. 78-85.

Tikhonov I.N. and Rodkin M.V. The current state of art in earthquake prediction, the typical precursors, and the experience in the earthquake forecasting at the Sakhalin Island and the surrounding areas // Earthquake Research and Analysis / Book 5. Ed. Prof. Sebastiano D'Amico. ISBN 979-953-307-681-1. 2011

Tikhonov I.N., Lomtev V.L. Tectonic and seismological aspects of the Great Japan earthquake of March 11, 2011, Geodynamics & Tectonophysics. 2011. V. 2. No 2. P. 145–160. (In Russian).

Tikhonov I.N., Kim Ch. U. Confirmed prediction of the 2 August 2007 M_W 6.2 Nevelsk earthquake (Sakhalin Island, Russia), Tectonophysics. 2010. V. 485. No 1-4. P. 85-93.

Tikhonov I.N., Vasilenko N.F., Zolotukhin D.E., Ivel'skaya T.N. et al. Simushir Earthquakes and Tsunamis of November 15, 2006, and January 13, 2007, Russian Journal of Pacific Geology. 2008. V. 2. No. 1. P. 1-14.

Tikhonov I.N. Methods of earthquake catalog analysis for purposes of intermediate- and short-term prediction of large seismic events. Institute of Marine Geology and Geophysics Far Eastern Branch RAS, Vladivostok, Yuzhno-Sakhalinsk, 2006. 213 p. (In Russian).

Tikhonov I.N. Detection and Mapping of Seismicity Guiescences Prior to Large Japanese Earthquakes, Volcanology and Seismology. 2005. No. 5. P.1-17. (In Russian).

Tikhonov I.N. A technique of large earthquakes periodicities revealing and of prediction of time intervals with higher probability of their occurrence. Preprint. Yuzhno-Sakhalinsk, Institute of Marine Geology & Geophysics FEB RAS. 2004. 33 p. (In Russian).

Tikhonov I.N. The law of periodicity of temporal intervals between consecutive earthquakes, Reports of Earth Sciences (Doklady AN). 2002. V.387. No. 2. P. 250-252. (In Russian).

Tikhonov I.N. Some patterns in seismic dynamics of the Southern Sakhalin region, Bulletin Seismological Association of the Far East. 1997. V.3. No. 3. P. 192-211.

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