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System for geophysical observation on the drifted ice floes for investigation of the lithosphere structure in the Arctic (Project)

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Abstract. The Project aims at developing a geophysical observation system on drifting ice floes with the purpose of studying the lithosphere structure in the Arctic Regions. Exploration of the Arctic region is actual task that affects political and economic interests of several country. The knowledge of the lithosphere deep structure beneath the Arctic Ocean is necessary to reconstruct the stages of the regional geological evolution, which, in turn, provides important information for exploration of new mineral deposits and to understand their origin. Although the Arctic attracts much attention, the scientific investigations there advance quite slowly. The harsh climatic conditions and large expenses slow down realization of the fieldwork in high latitude areas. Therefore, scientists from over the world looks for new technologies, which could optimize and reduce the costs of the fieldworks that aimed at investigation of the geological structure beneath the Arctic Ocean. The main task of the Project is to develop the methodology of long-term multidisciplinary geophysical observations that are meant to study structure of the crust and offshore seismicity in the Polar Regions. To this proposes, the observation systems have to be adopted to the conditions of the deep sea covered by paleocrystic floes and should take into account drift of the ice floes. In the framework of the Project, the prototypes of such observation systems will be developed and tested in the natural conditions on ice of the Arctic Ocean and in other water reservoirs. Here, instead of standard methods, we propose performing complicated, but more efficient experiments with deployment of various geophysical equipment of the ice floes. The drift of the ice floes will provide the movement of the instruments above study area and thus will improve data coverage. The observation systems of the passive seismological and magnetotelluric sounding methods supplemented by the electromagnetic sounding method with innovative controlled source will be designed for installation on top of the drifted ice floes. The practical implementation of this set of the methods will be significantly less expensive than currently used technologies of active seismic survey, for example.

1. Introduction

The Project aims at developing a geophysical observation system on drifting ice floes with the purpose of studying the lithosphere structure in the Arctic Regions. Exploration of the Arctic region is actual task that affects political and economic interests of several country. The knowledge of the lithosphere deep structure beneath the Arctic Ocean is necessary to reconstruct the stages of the region geological



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evolution, which, in turn, provides important information for exploration of new mineral deposits and their origin. Although the Arctic attracts much attention, the scientific investigations there advance quite slowly. The harsh climatic conditions and large expenses slow down realization of the fieldwork in high latitude areas. Therefore, scientists from over the world looks for new technologies, which could optimize and reduce the costs of the fieldworks that aimed at investigation of the geological structure beneath the Arctic Ocean. The main task of the Project is to develop the methodology of long-term multidisciplinary geophysical observations that are meant to study structure of the crust and offshore seismicity in the Polar Regions. To this proposes the observation systems has to be adopted to the conditions of the deep sea covered by paleocrystic floes and should take into account drift of the ice floes. In the framework of the Project, the prototypes of such observation systems will be developed and tested in the natural conditions on ice of the Arctic Ocean and other water reservoirs.

Recent state of knowledge about structure of the Arctic Region is based on works of Russian (Soviet) and international polar scientists. Initially, the drifted research stations “North Pole” and hydrogeographic survey, which were supported by the military, have played an important role. The seismic methods and aeromagnetic measurements have been used at that time. However, the goal of that research was investigation of the ocean bathymetry. The geophysical investigation of the Arctic Region with the geological proposes gets real only during the last decades. Note that most of geophysical studies in the shelf zone are based on standard methods of marine geophysics in areas with lite ice conditions. Big progress was achieved within the “Marine Arctic Geological Expedition” (JSC MAGE) conducted in collaboration with several institutions in the framework of the project “Arctic-2014” (Kazanin et al., 2015). Unique results were obtained with the use of reflection and refraction seismic methods based on under ice observations. This very complicated and expensive field campaign involved special ships and atomic icebreaker making possible conducting observations in areas with thick ice reaching up to 240 centimetres thickness. These and other offshore campaigns requested enormous funds for performing standard marine geophysical methods, which in the polar conditions are very expensive. A cheaper alternative of polar studies is based on large and global scale investigations with the use of seismology, tectonic reconstructions, paleomagnetic analysis, magnetotelluric data, which provide indirect and generalized information about geological structure of the region.

The target geological structures in the Arctic are overlain by the deep ocean water layer and partly by the ice floes. This is the main problem, which has to be solved at a stage of the project development. This situation strongly limits the list of the technologies that could be applied. In particular, a number of ground-based technologies, methods of remote sensing with use of air and spacecraft, and even some approaches of marine geophysics could not be applied in areas covered by ice floes. What do we have? Standard methods of active seismic in the polar conditions are very expensive and logistically difficult. Satellite gravimetric and magnetometric investigations provide important information about regional structures, however, its resolution not enough to reveal local features that are the most important from the practical point of view. Electromagnetic methods with the use of natural fields could provide important information, but they also do not provide sufficient resolution. Thus, the technologies with active sources have to be used. Still, traditional methods of electromagnetic sounding with artificial sources aimed at providing the distribution of resistivity in geological media become inefficient in regions covered by thick high-conductivity sea water layer. On the other hand, the ice floes prevent the use of some marine technologies (for example CSEM), which are effective on the clear water. Instead of standard methods, we propose here another setup of the observation systems presuming deployment of measuring instruments on the ice floes. The drift of the ice floes will provide the movement of the instruments above study area and good data coverage. In the following, we propose several geophysical methods specially adapted for the condition of the deep water covered by ice floes.

The proposed set of the passive seismological and magnetotelluric sounding methods supplemented by the method of the electromagnetic sounding with innovative controlled source will be designed for installation on top of the drifted ice floes. The practical implementation of this set of the methods will

be significantly less expensive than currently used technologies of active seismic, for example. The list is open and could be extended with other geophysical methods which are suitable for the polar condition. We propose a new approach that could be used for investigation of the geological structure of the ocean bottom in the areas covered by ice floes and does not required big expenses. At the same time, these investigations could provide detailed information about different structural features and discontinuities and point on potential mineral deposit sites.

Geophysical investigations with system installed on drifted ice floes is a novel direction and many aspects require consideration that is more detailed. The theory and field practice of marine MTS postulate that optimal results could be obtained if electro-magnetic measurements conducted close to the see bottom. In our case, measurements have to be conducted on a top of ice floes. We do not find any practical works of such kind. Theoretical studies based on mathematical modelling show that if measurements performed on the top of the ice floes then effectivity became lower but still sufficient [1]. We propose to use powerful controlled electro-magnetic source on the drifted ice floes in the Arctic, which is a novel task. Now scientists including the Project participant test this technology [2], [3].

2. Seismological monitoring

For the first time the idea to use the drifting ice floes for installation of the seismic network have been proposed several years ago. Since 2007 such kind of the experiments carried out by the Alfred Wegener Institute in Bremerhaven (AWI Bremerhaven) and directed by Vera Schlindwein [4]. The migration trajectories of stations from one of these networks have shown in the figure 1. This network were installed on the drifted ice floes in the Gakkel ridge region. During operation period a lot local earthquakes that occur in the spreading zone and several regional and teleseismic events were recorded. The examples of records of these events [5] are presented in figure 2. One can see that beside clear P-wave, the converted SgP-phase could be reliably detected. The SgP-phase could be easily converted to the S-wave.

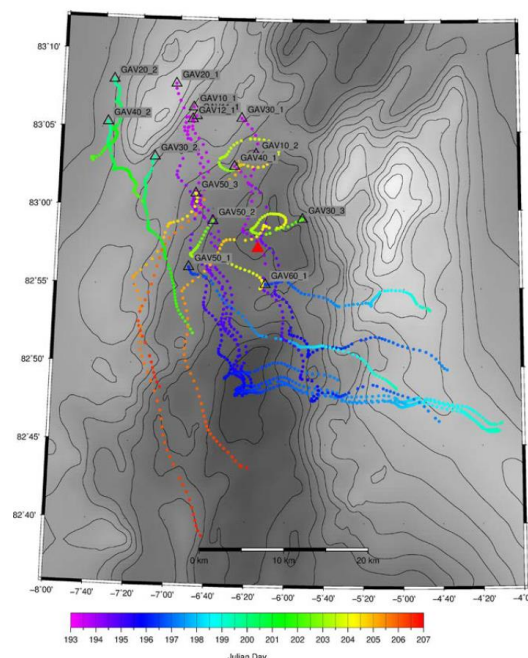


Figure 1. Trajectories of migration of seismic stations installed on drifting ice. The initial position of the stations is shown by triangles; the time of their functioning is marked by color. This network was installed on the drifted ice floes in the Gakkel ridge region.

This experiment has shown that seismic networks, installed on the ice floes provide valuable records of the P- and S-waves that could be used for the seismic tomography and other proposes. In spite of promising results obtained by the specialists from the AWI, we do not know any similar works performed by other institutions. Apparently, this approach should be developed and applied in Russian part of the Arctic. The aim of the Project is to develop technologies that will help to realize this proposal

In the framework of the Project, we propose to develop the method of seismological observation that used networks installed on the drifted ice floes. We will further develop and improve this technology on a base of theoretical modeling and field experiments. The main idea is to install a network of portable broadband seismometers on the ice floes. These seismometers will autonomously record the seismicity and GPS position during certain time period (for example one month). Analysis of the recorded data will include identification of local earthquakes and picking of the arrival times of different phases. Previous works show that such type of the observation system allows robust registration of the converted S-P phase. The 3D distribution of the P- and S- wave velocities beneath the sea bottom and location of the local earthquakes will be obtained after the iterative tomographic inversion of the arrival times. This inversion can be based on the existing tomography codes, such as LOTOS code [6]. However, the existing algorithms cannot be directly applied to the floating network data and will require some modifications. The updated version of the algorithm should take into the account the following points: (1) starting reference velocity model should include information about the water layer according to the available bathymetry; (2) the converted PS waves recorded at the drifting ice should be reduced to the S-rays ended at the sea bottom; (3) the structure of the input data has to be changed because of the constantly changed station positions due to the ice drift.

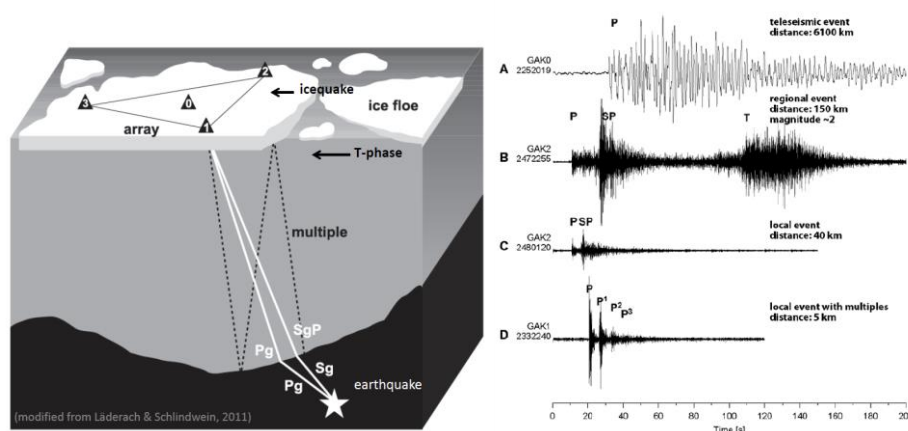


Figure 2. Scheme of arrival of seismic rays at the station, installed on ice. Right: examples of seismograms recorded by the station on a drifting ice floe, from teleseismic, regional and local events. Multiple waves reflected from the bottom and ice are also shown.

The theoretical modelling will include creation of a realistic synthetic model and its reconstruction with use of available methods. Parameters of the ice drift and distribution of seismicity obtained from previous field experiments [5] will be used for the creation of the synthetic model. We will create synthetic velocity model (with realistic shapes of anomalies or “Checkerboard” type of model). The created synthetic model and real distribution of the events will be used for the calculation of the travel times. In the next step, we will “forget” the model structure and events parameters and will reconstruct the model using absolutely the same steps of algorithm performance as in the case of the real data inversion. Thanks to the personal communications of the project participants with the German

scientists, we have an access to the data obtained during several experiments conducted by the AWI Bremenhaven. This give us possibility to test developed technologies with the real data sets and to obtain tomographic models of real geological structures in the Gakkel region in the Arctic. The experimental part of the project will include installation of seismic stations on the ice in different water basins. In the end of the first year, to investigate various technological aspects the seismic stations will be installed on the ice of the Arctic Ocean at the vicinity of Tiksi. Except for the drift of the ice floes, this experiment will appropriately simulate the conditions of drifting ice in the Arctic. The registration period from December 2018 to April 2019 will be enough to register sufficient number of seismic events occurred at different distances. After analysis of the record of these events, we will be able to make a conclusion about effectivity of the proposed observation system. Beside body wave, we will try to extract the record of the Rayleigh waves. In addition, we will investigate if it is possible to make seismic noise correlation analysis and extract information about surface waves. According to our knowledge, there is not studies that used such analysis performed for the stations installed on the ice on water basins.

3. Electrical prospecting with controlled sources

We offer a unique electromagnetic sounding technique, based on the excitation of a certain (TM) polarization of electromagnetic field that technically is provided by using a specific field source (circular electric dipole - CED). This technique (Vertical Electric Currents Soundings – VECS, [7]) allows recording subtle anomalies in a response due to deep compensation caused by physical processes common background of the conductive geoelectric section, including a layer of sea water. The technique has already been widely tested at various sites onshore primarily with hydrocarbon deposits, and proved highly effective. Both theoretical aspects of the novel method and results of practical applications have already been extensively published. The VECS method is characterized by the use of specific source of field, which may seem very complicated from the traditional point of view. This is a fair price that we pay for high performance and which usually is indicated as a disadvantage, given the need to move the source. However, the issue is resolved in the most satisfactory way under this project - we employ the ice-drift to make it move. Within the project we propose a rationale for the following method of electromagnetic sounding in the geological environment of the ocean floor to a depth of several kilometers in order to determine resistivity distribution pattern, as well as other geoelectric parameters that reveal various regional and local geological objects by moving the entire experimental setup over the Arctic basin.

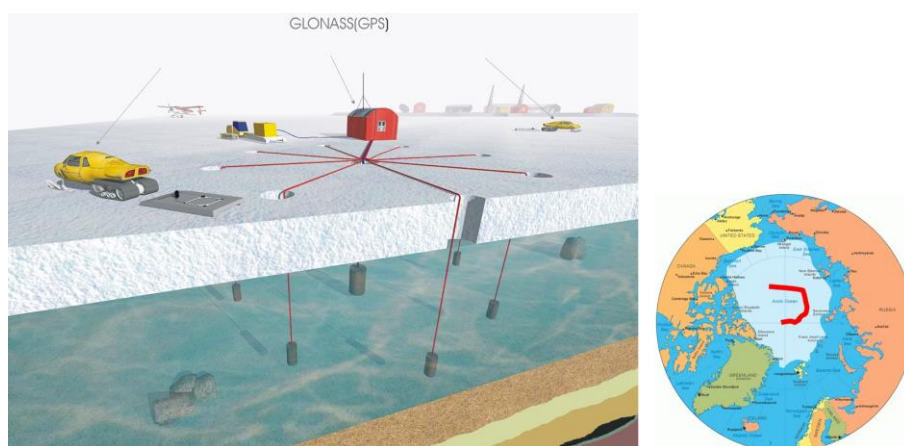


Figure 3. General view of the feed array on the Arctic ice and possible research area.

A pulse-feed array of circular electric dipoles is arranged on the ice (once and very carefully) (illustrated by figure 3) and is grounded at the center and at the ends of radial feeders through holes in the ice. CED radius (length of the radial line) can be up to 5-10 km (question to be studied). The observation system consists of electric receivers in the form of fixed, water-grounded, horizontal and vertical lines, as well as spatially distributed magnetic field measurement system, operated by the mobile inductive sensors. Alternatively, we have to decide whether to do continuous measurements (which is all but impossible), or to carry out measurement runs, tying it to a certain point, and repeat it over time (a day means 5-7 km of ice-drift). This issue is yet to be studied. Anyway, based on the experience of VECS application, the measurements may comprise the band along the source path with width equal to ten radii. So, given the CED radius is 10 km, we get total length of 4000 km of ice floe drift (which is consistent with the average for the Soviet NP stations), or 400 000 square kilometers of the surveyed area in the shape of, interestingly, very elongated winding corridor. The interpretation, which should include both 1D and 3D approaches, will extremely increase its confidence level due to the persistently accompanying seismic soundings, which will ultimately provide reliable a priori information on the boundaries. In the attached file, we provide a rationale for the CED- techniques applications. Moreover, CED-based techniques as applied in the project will address and other configurations of the receiver-transmitter array, which theoretically claim to be highly effective under the conditions considered.

4. Magnetotelluric investigations

In the addition to electromagnetic sounding with controlled source, we propose to use magnetotelluric (MT) sounding. The MT sounding could resolve deeper part of Earth than transient electromagnetic sounding (TEM), which provide better resolution in the upper part of the study volume. MT method uses natural fields and do not requires power sources in the addition to one used for the TEM. It is reasonably to perform geomagnetic-variation measurements in addition to the MT sounding. The theory and field practice of marine MT postulate that optimal results could be obtained if electromagnetic measurements conducted close to the sea bottom. In our case, measurements have to be conducted on a top of ice floes. Theoretical studies based on mathematical modelling show that if measurements performed on the top of the ice floes then effectivity became lower but still sufficient [1]. In the framework of the Project, we will investigate the applicability of the method in the polar conditions. Preliminary, to perform the MT sounding we propose to use the same system of electrical receivers, which have a form of vertical and horizontal lines, as one used for TEM. The CED source will be used for signal registration. That will provide possibility to register the vertical electrical component of the MT field, which is novel issue of the MT sounding. The standard method of MT sounding based on horizontally layered model, activated by the vertically incident plane wave. The influence of vertical component of the electric field is considered as neglect. On the border with weak conductive layer (atmosphere or ice), this component reduce to a zero value. However, if there are lateral inhomogeneity in the media or in the electromagnetic source field then vertical component of the electric field could become significant. Value of registered electrical component depend from length of the receiver line. Realization of the long vertical receiver line is technically difficult (even in the marine condition due to the sea undertows). The use of CED for registration of the vertical component is not applied in the actual practice. Therefore, it is of interest for scientist because it open a new possibility for interpretation of the vertical component of the electrical field. Presence of the vertical component could indicate the anisotropy of deep conductive layers. The use of CED with increased length of the radial lines will provide the ability to reveal such layers. Theoretical studies and mathematical modelling (including 3D) will be used for feasibility demonstration of each method. The field experiments in winter conditions on the ice of fresh and salty water basin are proposed. In the framework of the Project, we will study the different scientific aspects of the planned geophysical experiment in the Arctic. For example, we will calculate the necessary amount of the power sources. The planned geophysical works with fixed measurement configuration will provide high quality of the retrieved data. Thus, the necessary amount of repeated measures will significantly reduce. Another

positive factor is absence of the industrial electromagnetic noise in the Polar Regions. However, a telluric noise and noise induced by local ice movements still could play an important role. Important part of the experiment concern the retrieving the registered data, its temporal storage and near real-time transfer to the mainland. Apparently, the data processing center that work in the near real-time regime have to be organized. This center should control the retrieving data and provide capability to identify possible defects in the observation systems (it will be impossible to return and repeat the measurements). Furthermore, it could be necessary to change parameters of measure instruments (for example, current impulse time, time of the signal registration for the TEM etc.) due to the ongoing results. Taking into account necessity for 3D analysis the use of a supercomputer may be necessary.

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