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Cold Seeps and Heat Flow: Gas Hydrate Provinces Offshore Sakhalin Island

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Abstract: Gas hydrates were found in bottom sediments on the western slope of the Kuril Basin from the side of the Terpeniya Gulf (Okhotsk Sea) at 1020 m depths during expeditions in 2012 and 2013. However, on the eastern slope of the Tatar Strait, gas hydrates were sampled at an unusually shallow 322 m depth. During our research, we identified gas hydrate provinces based on both bottom water and sediment temperature measurement data and heat flow, earthquake, cold seep and sea current data analyses. These provinces have similar hydrological regimes, providing suitable temperature conditions for the existence of gas hydrates, to those at a 322 m depth in the Tatar Strait (Japan Sea) and at 725 and 1020 m depths on the slope of the Kuril Basin (Okhotsk Sea).

Keywords: methane; gas hydrate; provinces; heat flow; cold seep; currents; helium; hydrogen; Sakhalin Island; gas geochemical fields; earthquakes; thermal spring; mud volcano; hydrocarbon

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1. Introduction

The issue of gas hydrate accumulation in the global ocean has long-term relevance. Climate change is a common challenge for all mankind, and greenhouse gas emissions are the most important cause of climate warming. As one of the largest organic carbon pools on Earth, natural gas hydrate releases huge amounts of methane from its decomposition, which may have an important impact on the global marine environment and climate [1].

To date, all areas with gas are closed to continental and island slopes and foots, as well as deep-water areas of the marginal seas, where they are often associated with underwater mud volcanoes or clay diapirs [2,3]. Numerous seismic studies have revealed all horizons of gas hydrate formations on the continental slopes and foots or slopes of accumulative hills such as the Outer Ridge of the Blake Plateau [4,5]. These horizons are the basement of gas hydrate deposits, indicated by bottom-stimulating reflectors (BSRs), with a capacity of 200 to 400 m and stretching parallel to the bottom. The main reasons for the association between gas hydrates and continental slopes and foots are the most favorable combinations of thermobaric conditions, increased organic matter content and its deep biochemical processing, and the flow of thermogenic and deep hydrocarbon gases and fluids through fault zones. It is also necessary to note the filtration and diffusion processes and the wide scale of oil and gas formation in perioceanic deflections.

Marginal seas are specific morphostructures of the Pacific mobile belt, well developed only in its western part. The Okhotsk and Japan Seas are essential parts of the western Pacific trench, arc and basin system and are sensitive to global changes. Studying gas hydrate provinces on Sakhalin Island's shelf and slope is urgent in light of the current global changes.

Gas hydrate occurrence is one of the most important issues related to assessing climate and hydrate interactions. About 99% of gas hydrates form in marine sediments [6] on continental slopes at water depths of greater than ~500 m in temperate latitudes and ~300 m at high latitudes, where bottom waters are colder. These depths indicate the lowest P–T (pressure–temperature) limit for the gas hydrate stability zone (GHSZ) on continental slopes, where the stability zone disappears. In the sea, such conditions can be created due to the transit of cold water. At the same time, temperature measurements should be carried out not only in precipitation, but also in the water column, considering it is an integral part of the system, including hydrate-containing precipitation [7]. As pressure increases downslope, so does the GHSZ thickness in the sedimentary section, and this may eventually cover the highest few hundred meters of sediments with a bottom depth of over 1000 m [8]. Gas hydrates found at a 320 m depth in the Tatar Strait are a unique case for the 48° N latitude zone. The key point here is that cold subarctic waters come here from the Okhotsk Sea and form a proper temperature regime. Gas hydrates need to overcome several issues to form and exist, such as having a stable intensive gas income, proper temperature and pressure. The western Sakhalin shelf meets all of these points.

The temperature regime in the subsurface sediment layer (where gas hydrates are accumulated) depends both on the bottom water and on the heat flow affecting the sediments from above and below. This paper presents the results of the interplay investigation between two fundamental factors—heat flux and the distribution of sea currents and the associated water temperatures—to clarify the complex role of a temperature regime in the formation of gas hydrates.

The use of information on heat flows for zoning gas hydrates, mapping anomalies, identifying links with tectonic structures, etc., gives a positive result when constructing a scheme of endogenous regimes, identifying fault–magmatic activation zones, constructing tectonic maps, etc. [7]. In addition, the regional seismic situation is an important factor affecting the mode of gas release from the lithosphere. Our article presents the zoning of gas hydrate provinces based on the geological, geophysical, seismic and oceanographic characteristics of the shelf and slope of Sakhalin Island.

1.1. Background and Overview

Gas hydrates were sampled in the bottom sediments at a 1020 m depth on the western slope of Terpeniya Bay of the Kuril Basin (Okhotsk Sea) within the framework of the international project, The Sakhalin Slope Gas Hydrate Project II (SSGH Project II), 2012–2017. This is the first discovery of gas hydrates in the South Okhotsk Sea. Gas hydrates were retrieved at a 322 m depth on the eastern slope of the Tatar Strait, the northernmost part of the Japan Sea. A total of 43 gas flares were also detected for the first time in the Tatar Strait [9].

Two gas hydrate areas were newly found during cruise 62 of the RV "Akademik M.A. Lavrentiev". One was found to the north of the Kuril Basin's western slope, and the second one is on Sakhalin's western slope (south of the 2012 gas hydrate sampling point) [10]. Two gas hydrate-bearing areas were discovered in the Tatar Strait during cruise 70 by RV "Akademik M.A. Lavrentiev" [11,12].

The depth of the gas hydrate presence in the Okhotsk Sea significantly exceeds the depth in the Japan Sea. However, the conditions required for the formation and existence of gas hydrates have been created in both seas. The Tatar Strait gas hydrates are distinctive because they occur at such a low depth (Table 1).

Table 1. Gas hydrates discovered during the cruises RV "Akademik M.A. Lavrentiev" 62 (LV62) in June 2013 and 70 (LV70) in June 2015.

Depth, m	Station	Area
322	LV70-09HC	Japan Sea (Tatar Strait)
750	LV70-13HC	Japan Sea (Tatar Strait)
330	LV70-21HC	Japan Sea (Tatar Strait)
725	LV62-07HC	Okhotsk Sea (Western Kuril Basin slope)
1050	LV62-08HC	Okhotsk Sea (Western Kuril Basin slope)
323	LV62-17HC	Japan Sea (Tatar Strait)
322	LV62-26HC	Japan Sea (Tatar Strait)

Active geological processes (volcanism, seismicity, faulting, sedimentation, contact and thermal metamorphism, etc.) along the boundaries of lithospheric plates in the western Pacific Ocean results in gas hydrate formation. Most of the gas hydrate accumulations were found in sediments of Quaternary age. The multi-tiered occurrence of gas hydrates has also been established in the Atlantic Ocean [13].

Via hydroacoustic surveying (the presence of gas flares), high-resolution seismic profiling (the presence of a reflective horizon BSR) and geological research (lithological features of the sediment), the search for interconnections with sources of hydrocarbon gases (isotopic and gas-geochemical composition of gases) are the main factors for gas hydrate description and zoning. Local variations in the heat flow are likely to reflect focused fluid flow along faults or other structurally controlled pathways [14,15], which play an important role in determining the spatial and temporal distributions of deformation at continental margins and, as a result, in the formation and decomposition of gas hydrates.

A number of studies are devoted to the zoning of gas hydrate accumulations of the western Pacific segment (Pacific gas hydrate ring). The Bering, Okhotsk, Japan, East China, South China, SuluSulavesi, Phillipine Seas, as well as the waters of Australia and New Zealand [16–18], have gas hydrate provinces. The most representative deposits of gas hydrates (numerous samples of massive aggregates) were found in the Okhotsk, Japan and East China Seas and the northern part of the South China Sea. The gas hydrate content of the eastern segment of the Pacific gas hydrate belt is considered in detail and described in [19–21]. Numerical modeling and experimental measurements deal with gas hydrate dissociation and formation and related physical parameters [22,23]. Paper [24] presents the research of multiphase flow and heat transfer in porous matters as well as calculation of the effect on the relative permeability of hydrate-containing deposits.

Much research [25–31] deals with the geochemical, geological and thermobaric conditions of gas hydrate formation in detail based on direct research methods. Numerous cases of discovered gas hydrate locations need specification and zoning and, as before, the role of the temperature regime and the factors influencing its change are one of the most controversial problems in the formation and dissociation of underwater gas hydrates.

1.2. Hydrological Framework

The hydrological regime of the bottom water provides proper temperature and salinity conditions for gas hydrate formation [32].

Consistent currents play a key role in the general circulation of the Japan Sea. The cold Liman current is observed in the northwestern part of the sea off the coast of Primorye. The Tatar Strait is known for its complex system of currents. The hydrological regime here is formed by the combined influence of the Tsushima current and the West Sakhalin and Liman currents. An important contribution is also made by the migration of the cold waters of the Amur Estuary brought into the strait from the north. Based on the analysis of data on wind and Amur flow over a 10-year period (2002–2011) in works [33,34], it was shown that the combination of climatic fluctuations in Amur flow and wind conditions in the Amur Estuary and adjacent waters during the open-water period contribute to the frequent formation of the intensive removal of desalinated cold waters of the Amur plume into the Tatar Strait [35].

Water column temperature increases linearly from the sea bottom to the surface according to CTD measurements conducted in the southern part of the Tatar Strait, characterized by relatively large depths. However, small-depth (about 320 m) gas hydrate areas have temperatures that remain relatively constant from the bottom to the seasonal pycnocline layer (50 m depth).

The gas hydrates found in the Tatar Strait are located near the West Sakhalin current, which brings the cold waters of the Primorsky current that in turn carries the subarctic waters of the Okhotsk Sea through the Nevelsky Strait (Figure 1).

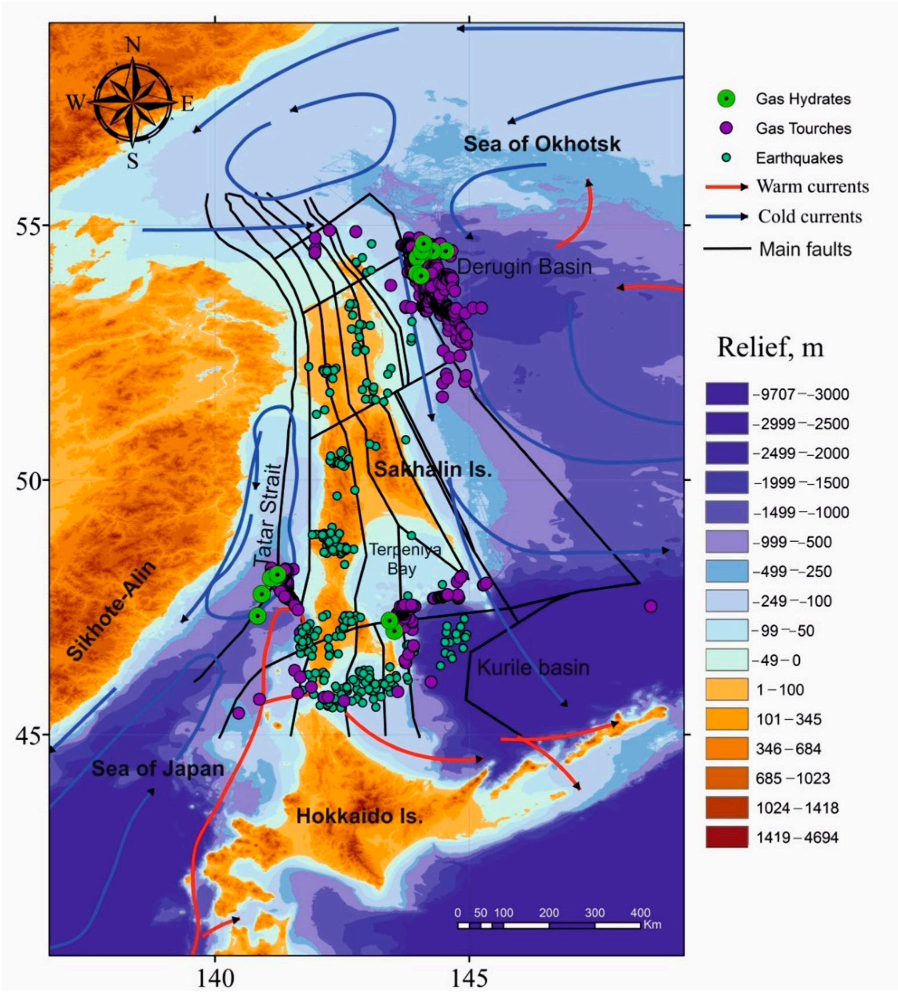

Figure 1. A schematic map of discovered gas hydrates on the shelf and slope of Sakhalin Island and the general circulation of the waters of the Okhotsk Sea (according to [36]) and the Japan Sea (according to [37,38]).

Gas hydrates on the north eastern Sakhalin slope are under the influence of the East Sakhalin Cold current, which passes along the eastern shores of the northern extremity to the Terpeniya peninsula. The current carries cold waters from the northern isolated part of the Okhotsk Sea, where slowly melting floating ice stagnates for a long time in spring.

1.3. Geological Setting and Prospects of Gas Emission in the Research Area

The modern continental margin of the northwestern part of the Pacific Ocean includes pre-Cenozoic and Cenozoic structural elements of the northern part of the Japan Sea (Tatar Strait), the bottom of the Okhotsk Sea, Hokkaido Island, Sakhalin Island, the Koryak Highlands, Kamchatka Peninsula and the Kuril Islands. Due to the convergence, transform and collision interaction of lithospheric plates during the Late Mesozoic and Cenozoic times, the geological structure of the region was created. One of the crucial characteristics of oil and gas-bearing areas is gas emissions from the lithosphere, which is clearly present in the Okhotsk Sea region. [39].

Sakhalin is characterized by a wide spread of thick marine Paleogene and Neogene deposits, large concentrations of fossil and brown coals associated with continental strata, and widely manifested signs of oil and gas potential, as well as oil and gas deposits. However, Sakhalin has very few manifestations of intrusive magmatic formations and volcanogenic subaerial strata, which are so typical for the adjacent continent.

The formation and accumulation of hydrocarbons mainly occurs in sedimentary basins, which are areas of prolonged immersion in the Earth's crust. At the same time, the sedimentary layer is heated by ascending heat flows that activate gas generation. Areas with natural gas emissions are found within powerful (over 2 km) sedimentary strata containing various accumulations of hydrocarbons as oil and gas deposits, gas hydrates and methane-saturated sediments. A necessary condition for the hydrocarbon degassing of such sites is, as a rule, the presence of disjunctive breaks [40]; additional ones are folded dislocations, as well as increased seismicity.

The geological and geophysical data show that currently, favorable conditions have developed in the considered areas for methane emission [41]. The most favorable areas for the occurrence of underwater methane discharge in the Okhotsk Sea are the eastern shelf and slope of Sakhalin Island and the western part of the Deryugin Depression, while in the Japan Sea, this area is the southwestern shelf and slope of Sakhalin Island.

The study areas of the 62 and 70 cruises of the RV "Akademik M.A. Lavrentiev" cover the northeastern Tatar Strait and the western Kuril Basin slope (Figure 2A). The study areas of the Sakhalin Slope Gas Hydrate Project cruises (2007–2012) onboard RV "Akademik M.A. Lavrentiev" cover the northern Sakhalin slope [42,43] (Figure 2).

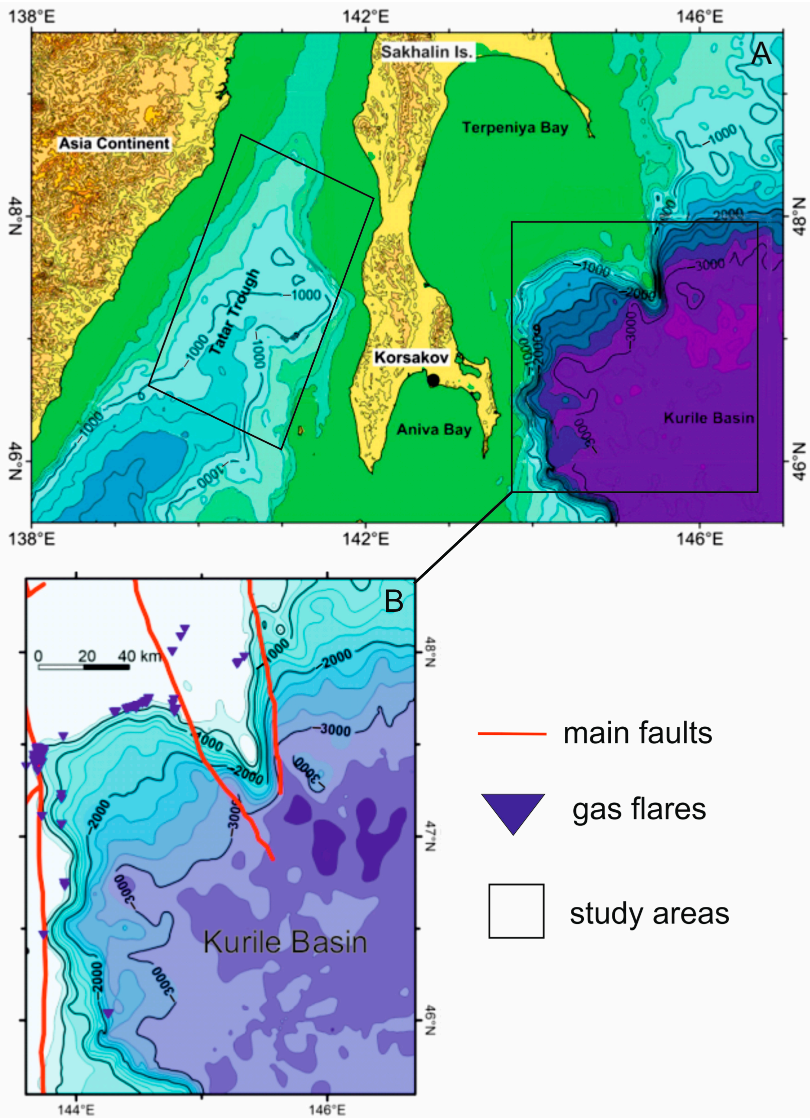

Figure 2. (**A**) Location of study areas of 62 and 70 cruises of RV "Akademik M.A. Lavrentiev". (**B**) Fault systems of the western Kuril Basin slope marked by thick red lines [44].

1.3.1. Tatar Strait

Tatar Trough was formed due to a rifting process that started in the Middle-Late Oligocene and continued to the end of the Miocene [44]. The Tatar Strait is a large trough (rift) 1200 km in length and 60–300 km wide. Sikhote-Alin mountain structures and the Western Sakhalin Mountains frame the strait from the west and east, respectively. The trough is filled with the Mesozoic-Cenozoic sedimentary and volcanogenic sedimentary rocks.

Cenozoic sediments of the Western Sakhalin Mountains are steeply inclined to the west and largely disturbed by discharge and upsurge dislocations. Movements along the faults range from tens and hundreds of meters to several kilometers. Volcanoes active 5–10 million years ago are associated with the fault zone.

The Tatar Trough has an asymmetric structure with its greatest depth (8–10 km) on the Sakhalin part. Deep faults dissecting the Earth's crust are clearly marked. High heat flow, magmatic activity and seismic activity point to modern tectonic activity. The rift of the Tatar Strait is the northern extension of the spreading center that is located in the deep-sea basin of the Japan Sea. The Tatar Strait includes three sedimentary basins made up of the Cenozoic terrigenous, to a much lesser extent, volcanogenic formations with a capacity of up to 8000 m. These are the North Tatar, South Tatar and Isikari-West Sakhalin basins, separated by uplifts, within which the Cenozoic capacities usually do not exceed the first hundred meters.

The North Tatar Basin occupies the northern part of the strait from 52° N to the cape of Lamanon. The Basin is a sharply asymmetrical graben-shaped structure stretching from north to south for 350 km and expanding in the same direction from 50 to 150 km. The thickness of the Oligocene-Quaternary sedimentary deposits in these bends is 7–8 km. The South Tatar sedimentary basin occupies the southern part of the strait, excluding the shelf of southwestern Sakhalin, which belongs to the Isikari-West Sakhalin Basin. The basin structure is formed by the Primorsky monocline and two deep-sea bends: Terneysky and Olga. The Ishikari—Western Sakhalin Basin stretches for almost 800 km from the southern part of central Hokkaido to the Western Sakhalin Mountains with a width of 20–25 km to 50–60 km. In the south of the Tatar Strait, the contours of the basin are confined to its shelf part with extensions on the island land. The Moneron, Kholmsky and Yasnomorsky bends, separated by anticline uplifts, are the main structural elements of the Tatar Strait. The Cenozoic formations reach 7 km thickness in the depots of these deflections.

The Tatar Strait is well investigated in terms of oil and gas geology [44]. Numerous structures formed by gas penetration into the sedimentary cover were revealed by seismic investigations here. However, gas seeps and gas hydrates in the Tatar Trough were found for the first time in the 59th cruise of the RV "Akademik M.A. Lavrentiev" (2012) performed in within the international project Sakhalin Slope Gas Hydrates (SSGH). Gas flares were only observed on the north-eastern slope of the Tatar Trough, according to the data collected within the study area. They show up in the area that extends across the shelf break and upper slope at a distance of around 80 km. The maximum depth of the gas flares is 340 m and their height is limited to 300 m.

1.3.2. Western Kuril Basin Slope

The eastern Sakhalin slope has its southern end facing the Kuril Basin. The Kuril Basin of the Okhotsk Sea belongs to the young back-arc depressions. The thickness of the crust here is about 8–10 km, of which 4 km is a sedimentary cover. It is divided into two complexes according to seismic data. The deposits of the Upper Pliocene-Quaternary complex with a thickness of up to 800–1000 m are composed of overlapping turbidites and volcanogenic rocks. The lower complex with a capacity of over 3000 m is represented by the Oligocene-Miocene, mainly clay rocks with rare layers of volcanogenic material. The sedimentary stratum lies on a foundation consisting of basalts and their tuffs, alternating with volcanogenic sedimentary and siliceous formations.

Faults divide the depression into separate grabens. The remains of an ancient subducted plate of the Okhotsk Sea have been found in its western part. The oceanic crust of the Kuril Basin moved under the continental crust of Sakhalin about 100 million years ago. The presence of ophiolite complexes here confirms this. A rift structure is fixed in the central part of the Kuril Basin. The depression is characterized by a high heat flow. The temperature reaches 1200 °C at a depth of 25 km [45].

Back-arc spreading is thought to be responsible for the formation of the Kuril Basin, which is underlaid by an oceanic crust with a thick sedimentary cover. The basement can be found at a depth of up to 8 km below sea level and is connected to the seismic layer with a velocity of between 4.8 and 5.2 km/s. At 11–13 km below sea level, the Moho discontinuity occurs [46].

The slope of the Kuril basin is the transition zone between the continental crust of the Sakhalin shelf and the oceanic crust of the Kuril Basin. The thickness of sediments strongly varies here and the acoustic basement outcrop on the steep parts of the slope. The mudstones in the lower part of the sedimentary section of the western Kuril Basin slope are made up of complexes of the Paleocene-Eocene and the Early Oligocene radiolarians as exhibited by drainage data [47–49]. The strata of the Late Oligocene-Early Miocene age and the Early Miocene-Middle Miocene age form the layer above the tuff-diatomite layer. In the basement, Cenozoic sediments overlap with unconformity volcanic-clastic and volcanic-sedimentary rocks.

The slope of the Kuril Basin shows three deep-seated faults (see Figure 2B). These faults are part of the East Sakhalin fault, which is composed of dextral strike-slip conjugated thrusts that strike from north to south, reverse faults that strike from the northwest and normal faults that strike from north to east [50,51]. The eastern side of the Kuril Basin is encircled by one fault in the central Terpeniya Bay, while two faults limit the Terpeniya Ridge. The distribution of shallow earthquakes indicates that the recent activity of these faults has decreased from east to west.

Gas flares within the western Kuril Basin slope were registered at depths from 2200 to 240 m. Their maximum concentration was observed in the north-western side of the investigated area at a depth interval 500–2000 m. Gas flares here were located near shelf break and on the northern edge of the NW-striking canyon. One gas flare was found near the southern frame of the study area at a depth of 2200 m. It is located on the top of a rise and is traced practically up to the sea surface; thus, its height is about 2200 m. It is the highest flare among all known gas flares on the eastern Sakhalin slope [52].

1.3.3. Northeastern Sakhalin Slope

The Okhotsk Sea is located on the Okhotsk plate, squeezed between four major plates: North American, Eurasian, Pacific and Amur. The western boundary of the Okhotsk Plate follows the Hokkaido-Sakhalin dextral shear zone. The Okhotsk and Amur plates are separated by a transform fault that can be traced over a distance of 2000 km from the northern tip of Sakhalin Island. This boundary on Sakhalin corresponds to a system of the NS dextral strike–slip faults. The eastern slope of Sakhalin has a sedimentary nature and its sedimentary cover reaches 10–12 km here [44]. The north-eastern Sakhalin slope belongs to the East Sakhalin subsidence area stretching in the NS direction along the Sakhalin cost [53]. It includes three troughs and the largest among them is the Deryugin Trough that corresponds to the Deryugin Basin and adjacent shelf and slope in the bottom relief.

A major structural suture separating Sakhalin Island from the Derugin Basin is supposed to be located under its eastern slope [54]. The basement of the Deryugin Trough subsides from east to west up to a depth of more than 8–9 km under the Sakhalin shelf.

Several canyons with north-eastern direction and fault nature are in this area. The largest fault is Lavrentiev Fault [55], which separates the northern segment from the southern one. A number of faults were also mapped to the north and south from this fault [56,57].

2. Materials and Methods

In this study, we used data from gas-geochemical studies and CTD measurements performed during marine expeditions by the RV "Akademik M.A. Lavrentiev", cruise 62 (LV62) in June 2013 and cruise 70 (LV70) in June 2015. The bottom sediment temperature in the Tatar Strait was determined during the marine expedition on the RV "Akademik Oparin", cruise 61 in November–December 2020. The temperature was measured via the TESTO 735-2 ("Testo AG", Testo Instruments Co., Ltd., Titisee-Neustadt, Germany) with a measurement error of 0.002 °C.

Also, we involved the Sakhalin data of project SSGH 2007–2012, an international collaboration effort between scientists from Japan, Russia and Germany to investigate natural gas hydrate accumulations on the northeast continental shelf and slope of Sakhalin Island [42,43], to compare them with the considered areas.

A few methane flares were found on the northeastern Sakhalin shelf and slope in the Okhotsk Sea in 1988 [58]. Since then, gas-hydrate-bearing sediments have been confirmed to be widely distributed in the area [19]. In the period from 1998 to 2006, methane fluxes and gas hydrate in the area were studied in the frame of the Russian–German project "Kuril-Okhotsk Sea Marine eXperiment" (KOMEX) (1998–2004) and the Russian–Japanese–Korean project "Hydro-Carbon Hydrate Accumulations in the Okhotsk Sea" (CHAOS) (2003, 2005, 2006). In these international projects, interdisciplinary investigations in geology, geophysics, gas geochemistry, morphology, biology and oceanography were carried out to examine gas-hydrate-related phenomena in the area. As a results of these efforts, more than 200 new gas flares and ten new areas with gas hydrate were discovered, and methane distributions in the water and sediment columns were measured in detail [59–65].

Various sea layers were sampled using NISKIN bathometers that were shut down during the 12-position rosette upcast on cruises 62 and 70 of the RV "Akademik Oparin". CTD measurements were used to select horizons from the sub-sea layer to the bottom. (Table 2). All observations were carried out to the bottom. The bottom water in areas with high methane content was studied with special attention. The temperature, salinity, dissolved oxygen, turbidity, and fluorescence profiles of seawater were obtained.

Table 2. Materials researched.

Cruise	Study Area	Water Samples, pcs	Analyst	CTD Stations, pcs
LV62	Tatar Strait, Japan Sea 19 June–5 July 2013	79	O. Vereshchagina	15
LV70	Tatar Strait, Japan Sea 14 June–30 June 2015	192	O. Vereshchagina, N. Sokolova	17

3. Results and Discussion

In situ measurements in the Tatar Strait of the Japan Sea (Figure 3) and in the Terpeniya Gulf of the Okhotsk Sea (Figure 3) show almost the same temperature for both areas at 400 m depth. Deeper, the temperature remains stable and positive for both areas as well; it is even higher for the Tatar Strait.

Figure 3a shows two groups of temperature profiles in the Tatar Strait, which could be associated with the depth of the water: in shallower stations at the horizon of 50–70 m, the temperature drops sharply to 0 °C and then almost does not change with depth; at deeper stations at horizons from 50 to 300 m, there is a gradual decrease in the temperature.

The research area experiences intensive influence of cold currents providing water inflow in horizontal directions at various depths, as well as vertical water migration [37]. This factor contributes to water mixing, and cold currents allow for the maintenance of a relatively stable water temperature.

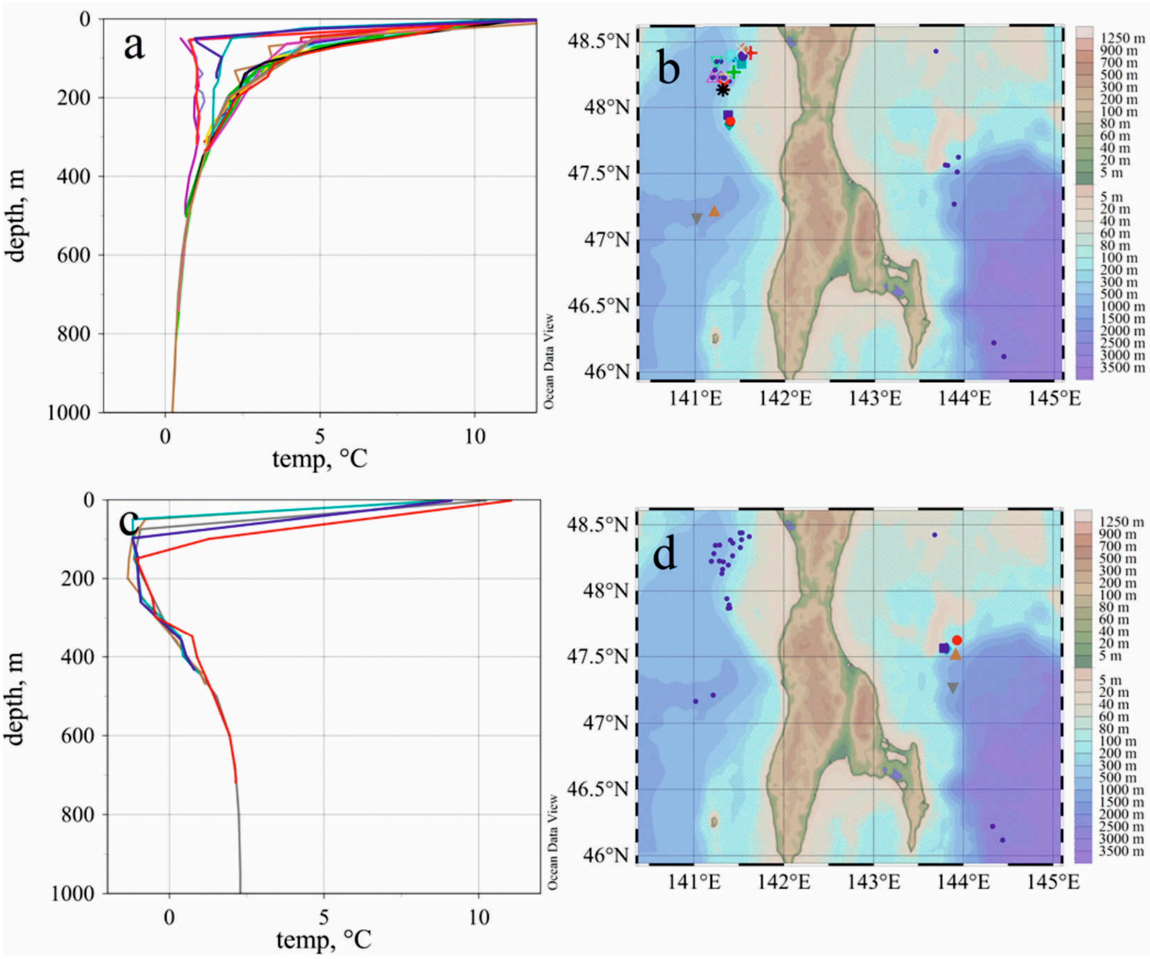

Figure 3. Temperature (**a**,**c**) in water column within the gas hydrate area in the Tatar Strait (West Sakhalin) (**b**) and in the Okhotsk Sea (East Sakhalin) (**d**) via data obtained in cruise 62 and 70 of the RV "Akademik Oparin". The color of the line (**a**,**c**) corresponds to the color of the symbol (**b**,**d**).

We used a gravimetric sampler to obtain bottom sediment core and measured its temperature at various layers (Figure 4) on cruise 61 onboard RV "Akademik Oparin".

We identified some temperature patterns depending on the seabed depth:

1. The sediment temperature equals that of water and ranges from 2 to 3 °C for up to 300 m of bottom depth.

2. The sediment temperature (1.6–2.5 °C) exceeds (0.5–1.5 °C) for bottom depths ranging from 300 to 550 m. Lower sediment layers face temperature increase.

3. The sediment temperature (0.8–1.7 °C) exceeds bottom water temperature (0.2–0.4 °C) within bottom depths ranging from 750 m to 1000 m. Lower sediment layers also face temperature increase.

The average sediment temperature and the bottom water temperature are influenced by depth, leading to a general trend where the bottom water is colder than the sediment by 1 °C. The bottom water temperature tends to decrease uniformly with depth. This decrease becomes smoother lower than 500 m. The sediment temperature change can be divided into two patterns: a gradual decrease to 500 m, then an abrupt decrease by 0.5 °C and a further gradual decrease to 1000 m of bottom depth.

Figure 4 shows that the bottom water temperature at the depth of 280 m is slightly lower (1.5–2.5 °C) than the sediment temperature (2.5–3 °C). Moreover, the temperature of the sediment changes slightly at various horizons and decreases smoothly with bottom depth decrease (3.5–2 °C at 160–280 m bottom depth, respectively).

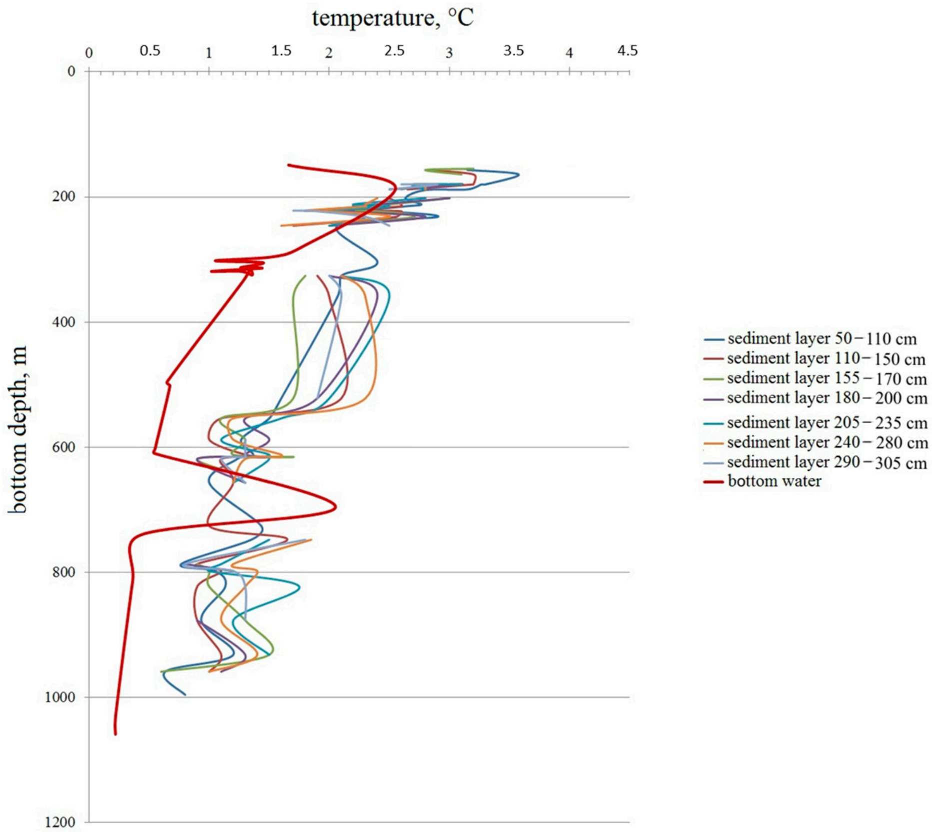

Figure 4. Bottom seawater temperature (thick red line) and bottom sediment temperature (thin colored lines) at various core layers were measured in the Tatar Strait (Sea of Japan). The vertical scale shows bottom depth, horizontal one is temperature.

The bottom water temperature decreases gradually (from 1.5° to 0.5 °C) while bottom depth changes (from 300 to 500 m). However, sediment temperature is relatively constant and ranges from 1.5 °C to 2.5 °C.

The bottom water temperature also decreases gradually from 0.5 °C to 0.2 °C at 500–1000 m bottom depth. The sediment temperature drops sharply by 0.5 °C and maintains relative stability in the range of 1.2–1.7 °C at 500 m bottom depth and lower. It is noteworthy that the sediment temperature is relatively similar for various horizons of sediment at a 500–750 m sea depth. However, at 800–1000 m sea depth, the sediment temperature goes higher for the lower core horizons.

Such temperature differences between bottom water and sediment in this area can be influenced by high values of heat flow (Figure 5).

The temperature of the bottom water in the area of gas hydrates in the Tatar Strait (Japan Sea) is slightly lower than the bottom water temperature in the Okhotsk Sea. However, the values of the heat flow in the Tatar Strait, on the contrary, are higher. These factors contribute to the necessary conditions for gas hydrates formation at a low sea floor depth (320 m).

The gas hydrate stability profile for the Okhotsk Sea correlates with that for Tatar Strait (Figure 6), which confirms similar conditions for the existence, formation and destruction of gas hydrates.

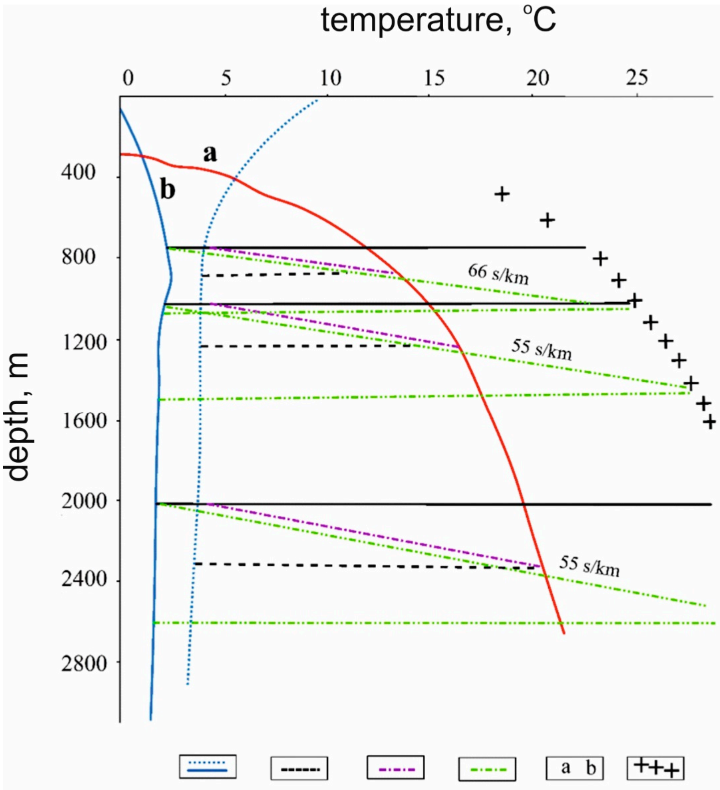

Figure 5. Gas hydrate thickness zone dependence graph on the bottom water temperature, sea depth and temperature gradient in sediment (according to [7], with amendments and additions, redo). 1—sea bottom; 2—the theoretically determined bottom of the methane gas hydrate layer in typically oceanic conditions [66]; 3—the bottom of the gas hydrate layer in the sediments of the Okhotsk Sea; 4—geotemperature gradient; 5—temperature profile: a—oceanic [66], b—Okhotsk Sea; 6—profile of the gas hydrate stability zone in the Okhotsk Sea [7].

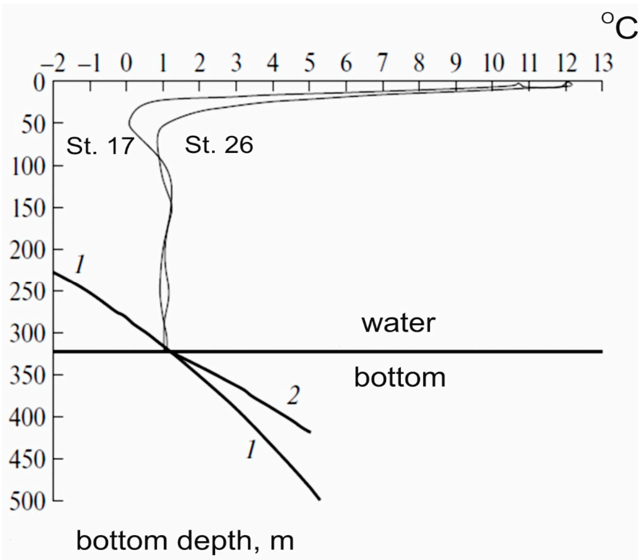

Figure 6. Stability diagram of methane hydrates (100% CH_4) found in the Tatar Strait in the water layer (1) and bottom sediments (2—terrigenous pelite with a density of 1733 kg/m^3) to 322 m depth. St.17 and St.26—temperature profiles in water at stations 17 and 26 [67].

Paper [67] gives the results of statistical estimates of water parameters and thermophysical calculations in the upper bottom sediments layer, obtained for the Tatar Strait region, where methane hydrates were found. The main factor influencing the state of methane hydrates in this area is a long-term trend of water temperature increasing in the Tatar Strait. The influence of variability in water salinity and sea level and seasonal variability in the temperature of the bottom water on the state of methane hydrates lying in bottom sediments is insignificant [67].

The hydrogeological situation in the bottom deep part of the sea favors the creation of a cooling zone in the near-surface part of the sedimentary cover due to very low temperatures of the bottom water layer (about 2 °C) in the Okhotsk Sea and leads to the occurrence of large capacities of the hydrate-containing strata [67]. This is also true for the Tatar Strait, which has a similar temperature regime of the bottom and above-bottom water layers.

Lots of active gas outlet areas—gas flares—were detected with acoustic methods during expeditions by POI FEB RAS [9–11,52,68]. That is, 1168 pcs are in the northeast Sakhalin Island water area, 213 pcs in the southeast (Terpeniya Gulf) and 228 pcs in the southwest (Tatar Strait). The gas flares are mostly located near fault lines (Figure 7).

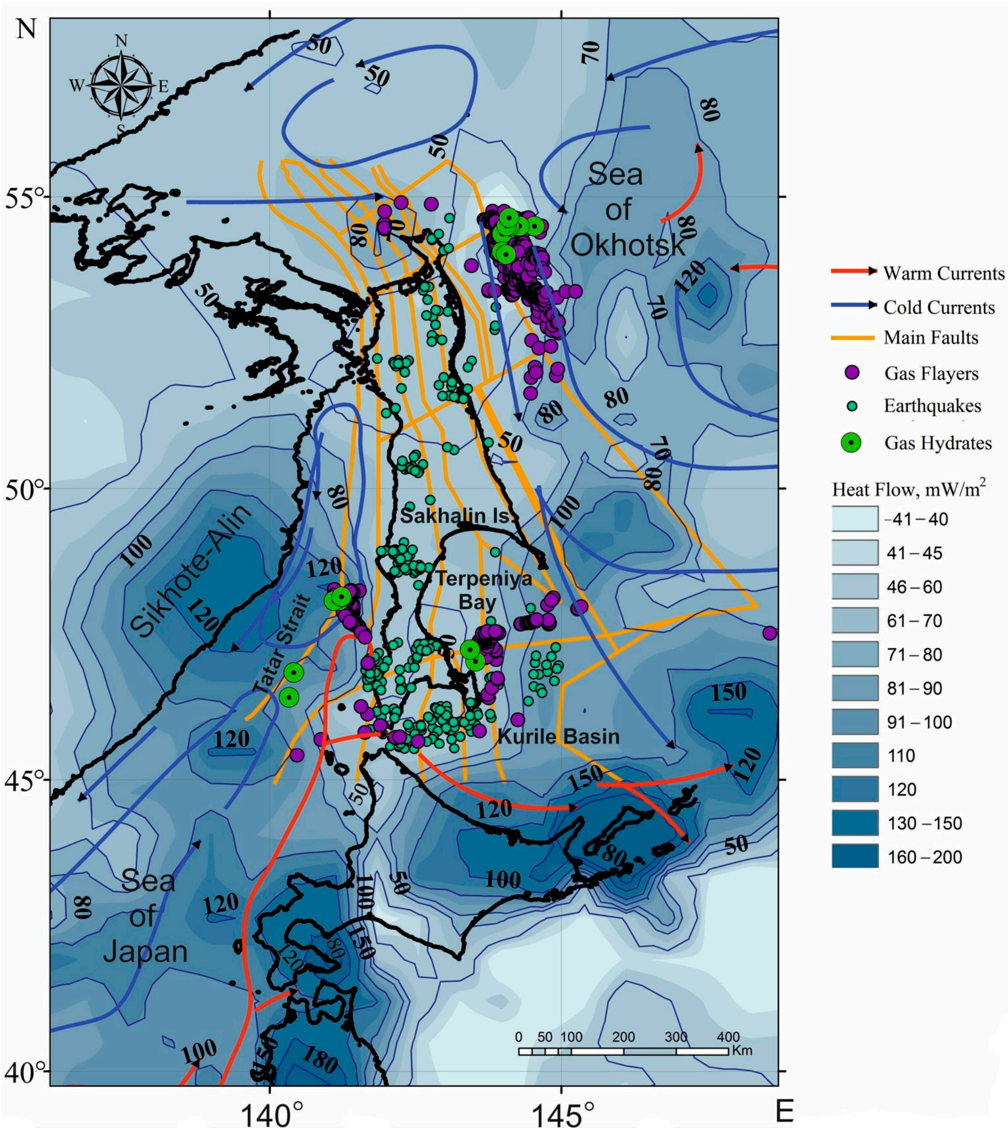

Figure 7. Heat flow distribution scheme [45], earthquakes [69], gas flares, gas hydrates and main faults [70] near Sakhalin Island. Regional faults: 1—East Sakhalin, 2—West Sakhalin, 3—Central Sakhalin, 4—Hokkaido Sakhalin, 5—North Sakhalin, 6—Tyuliney, 7—shelf margin, 8—East Sakhalin, 9—Starodubsk [70].

Gas flares were observed in the upper part of the Tatar Trough eastern slope during cruises 59 and 62 by RV "Akademic M.A. Lavrentyev" [9,52], spatially coinciding with elongated depressions. The location of the lower boundary of the gas flares field (340 m) correlates well with the observed outcropping of the gas hydrate stability zone based at 300m water depth [10]. In this connection, we may suppose that the origin of depressions is associated with hydraulic fracturing caused by gas hydrate decomposition that leads to growth in the pore pressure in the upper part of the sedimentary section. We also should not exclude the presence of deep faults along which gas migration from sediments to the surface occurs.

A huge methane bubble flow from the bottom (named F-1—"Kuril flare") whose top almost reached the sea surface was found at 2200 m water depth in the Kuril Basin. This flare of about 2000 m height is likely to be the highest one ever reported [52].

The hydrothermal areas of Japan and Okhotsk seas have some differences according to their heat flow distribution zones. The value of the heat flow in the gas flare zone ranges from 50 to 70 W/m^2 for the Okhotsk Sea and 80–120 W/m^2 for the Japan Sea. Some zonality can be distinguished when comparing fault systems and heat flow: in the northern and southern regions of Sakhalin Island, the zones of concentration and intersection of fault lines coincide with the heat flow low-value zones. The territory of the island is located in the zone of heat flow minimum values (for the region under consideration). Gas flares and hydrates were discovered in regions with higher heat flow (Figure 7). A large zone of low heat flux (50 W/m^2) lies in the northern part of Sakhalin Island. There is a fault with gas flares at the eastern edge of this zone, and we can see a similar zone on the southern part of the island that is smaller in area. Gas flares and gas hydrates lie at the boundary of 50–70 W/m^2 heat flow area for both zones. Gas flares are not only located in the zone of higher values of heat flow in the Tatar Strait, but are also located in close proximity to the fault line.

Gas-geochemical studies [71,72] revealed two first–order ecological and gas-geochemical zones on Sakhalin Island: (1) methane and (2) carbon dioxide–methane. The distribution of earthquake epicenters appears to be harmonious within this division. The validity of such a division of the island is consistent with the features of its geological structure and various gas-geochemical regimes [71,72]. According to such, the active methane manifestations are characteristic of the northern part, while the CO_2 output is minimal here and vice versa for the southern region. It is probable that the different gas-geochemical regimes of the south and north of Sakhalin Island are also associated with similar distributions of the heat flow, resulting in turn from the features of the geological structure. Moreover, it is possible to distinguish the western and eastern regions of Sakhalin Island and its offshore areas as the heat flow increases when moving from land and this growth is bigger in the Tatar Strait.

Monograph [7] summarizes, analyzes and systematizes the available geological and geophysical materials based on the results of research carried out by the Institute of Marine Geology and Geophysics (IMGG) of the Far Eastern Branch of the Russian Academy of Sciences in the Okhotsk Sea and the Tatar Strait since the 60s of the twentieth century. Paper [7] is devoted to dependence research of gas hydrate formation zones in the Okhotsk Sea and the gas hydrate stability zones.

Seismic sections revealed abnormally high-amplitude, parallel-to-the-bottom reflections (BSR) in the upper part of the sedimentary cover on the slopes of the South Okhotsk basin, the depressions of Deryugin and TINRO and in the deflections of the central part of the sea at its depths of more than 400–500 m. The authors [7] interpreted BSR anomalies as a phase boundary between hydrates and free gas with a high-speed model.

Peripheral depressions and deflections of the Okhotsk Sea have many common features such as high heat flow, reduced thickness of the crystalline basement, high amplitudes of the Neogene subsidence of the foundation roof often accompanied by uncompensated sedimentation, a decrease in the depth of the Mohorovicic surface, characteristic stretching of morphostructures, etc. This proves the thermal erosion of the lower crust, the rise of isotherms under the deflections, the processing of the granite–metamorphic layer and similar features inherent in rift structures. The upper mantle determines the main share of the heat flux recorded on the Earth's surface in the region, and its thermal activity caused thermal destruction of the Earth's crust, which was accompanied by the formation of sedimentary basins in the Cenozoic, which was especially active at the end of the Paleogene and post-Miocene time. The calculation of temperatures in the sedimentary cover of the Okhotsk Sea basins made it possible to identify deflections with the most optimal geothermal parameters for the formation and preservation of hydrocarbons (the shelves of the northeast of Sakhalin Island, the northwest of the Kamchatka Peninsula and certain zones of the northern Okhotsk Sea) according to [7]. Papers [73–76] show that the seismic regime affects the intensity of gas emission.

Figure 7 shows earthquake epicenters, which are located in the areas of the southern and northern parts of Sakhalin Island and are geographically close to the gas hydrate provinces under consideration. Papers [73–76] show that the seismic regime affects the intensity of gas discharge.

The gas hydrate areas of the Okhotsk Sea experience geological, seismic and geophysical conditions similar to the Tatar Strait and face almost the same hydro- and geophysical conditions as well.

The heat flow measured in submarine gas discharge fields in the Okhotsk Sea has a low value [77], as the decomposition heat of gas hydrates is 420–500 kJ/kg. Heat absorption during the destruction of the hydrate layer can also reduce the background heat flow by 30–60 MW/m^2 in the discharge zone over a 200–100 year period. This effect is probably occurring due to the existence of low-heat-flow areas in the zones of active gas seepage from near-surface hydrate layers against the background of a relatively increased heat flow in the Okhotsk Sea [7].

Heat flow from below and cold water masses from above result in temperature variation in the sediment along these core horizons, with higher temperatures being observed at lower sediment horizons. Gas hydrates under these conditions are in a kind of «thermal trap», which contributes, on the one hand, to their formation and, on the other hand, to their stable existence and accumulation. Gas hydrates of low depth (320 m) in the Tatar Strait were formed and continue to exist in conditions similar to the gas hydrates of the Okhotsk Sea due to the combined effects of heat flow and cold subarctic waters brought to this area from the Okhotsk Sea.

Paper [7] gives diagrams of the Mohorovicic surface depths (in km), identified isostatic gravitational anomalies and anomalous magnetic and gravitational fields of the Okhotsk Sea region and adjacent water areas. Based on this data, the authors [7] identified gas hydrate zones. These zones have common features as follows: similar values of heat flow (60–80 MW/m^2), belonging to the zone of magnetic provinces (Tatar Strait, East Sakhalin, Deryuginskaya), being in the zone of anomalous gravitational provinces (Tatarskaya, Sakhalin, Deryuginskaya), and surface depths of Mohorovicic in these areas being 27–29 km with a variation of 19–31 for the Okhotsk Sea as a whole and the Tatar Strait. In addition, a strong marker of intense gas discharge areas is gas flares, which are present in large numbers in each area of gas hydrates [73,78,79].

As part of our research, we distinguished three gas hydrate provinces of the Sakhalin Island water area: the Tatar Strait, the East Sakhalin and the Deryuginskaya. Both the geological structure features and structural element compositions of Sakhalin, Hokkaido and the adjacent sea bottom areas also justify the selection of the proposed provinces. A single Hokkaido-Sakhalin folded region [80] includes combined folded structures (the Sorachi–Iezo system is a continuation of the western Sakhalin folded system on the Hokkaido, the Kamuikotan structure is the central Sakhalin subduction structure, the Hidaka tectonic belt is the East Sakhalin folded system, the Tokoro structure is the Okhotsk subduction suture and the Idonnappu suture shear zone is the Mereya suture zone). Therefore, it seems possible to consider the proposed gas hydrate provinces as components of the Hokkaido-Sakhalin folded region.

4. Conclusions

The general geological, geophysical, hydrological and seismic features of gas hydrates areas of the Tatar Strait (Japan Sea) and east Sakhalin Island offshore (Okhotsk Sea) were considered. It was determined that low-depth (320 m) gas hydrates in the Tatar Strait experience similar geophysical, seismic and hydrological conditions as those of the Okhotsk Sea (1000 m). Three provinces located in the southwest, southeast and northeast of the Sakhalin Island were distinguished: the Tatar, East Sakhalin and Deryuginskaya, respectively. These gas hydrate provinces are characterized by the massive presence of gas flares, which are an indicator of gas emissions. A similar hydrological regime providing the necessary low temperature of the bottom water comparable to subarctic Okhotsk Sea water is the key factor in the formation and existence of the Tatar Strait gas hydrate province as an integral part of the Hokkaido-Sakhalin folded region.

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