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Review

The Main Geohazards in the Russian Sector of the Arctic Ocean

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Abstract: The Arctic region, including vast shelf zones, has enormous resource and transport potential and is currently key to Russia's strategic development. This region is promising and attractive for the intensification of global economic activity. When developing this region, it is very important to avoid emergency situations that could result in numerous negative environmental and socio-economic consequences. Therefore, when designing and constructing critical infrastructure facilities in the Arctic, it is necessary to conduct high-quality studies of potential geohazards. This paper reviews and summarizes the scattered information on the main geohazards in the Russian sector of the Arctic Ocean, such as earthquakes, underwater landslides, tsunamis, and focused fluid discharges (gas seeps), and discusses patterns of their spatial distribution and possible relationships with the geodynamic setting of the Arctic region. The study revealed that the main patterns of the mutual distribution of the main geohazards of the Russian sector of the Arctic seas are determined by both the modern geodynamic situation in the region and the history of the geodynamic evolution of the Arctic, namely the formation of the spreading axis and deep-sea basins of the Arctic Ocean. The high probability of the influence of seismotectonic activity on the state of subsea permafrost and massive methane release is emphasized. This review contributes toward better understanding and progress in the zoning of seismic and other geological hazards in the vast Arctic seas of Russia.

Keywords: Arctic region; geohazards; earthquakes; underwater landslides; tsunamis; gas seeps

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1. Introduction

Currently, there is an intensification of the development of the Russian sector of the Arctic: oil and gas terminals are being built, offshore platforms are being operated, and the role of the Northern Sea Route in cargo transportation is increasing. As the climate warms, which is most pronounced in the Arctic region, and sea ice cover decreases, this economic activity will increase. In order to prevent possible man-made disasters associated with the operation of the emerging infrastructure and with designing its facilities, it is necessary to carefully assess seismic hazards and other potential geological hazards (geohazards). Geohazards are geological objects, phenomena, and processes that can adversely affect the ecosystem or lead to its complete destruction [1]. At the same time, potential geohazards associated with deep lithospheric processes include, first of all, manifestations of seismicity and related phenomena. Motions in active fault zones under water areas and accompanying earthquakes can be associated with such dangerous natural phenomena as underwater landslides, the liquefaction of marine soils, tsunamis, underwater volcanism, hydrothermal activity, and focused gas discharge (gas seeps) on the seabed.

Earthquakes are extremely dangerous, sudden, difficult-to-predict phenomena that result in numerous human losses and large-scale destruction. The regulatory maps of general seismic zoning of the Russian Federation (OSR-2016) [2], necessary for assessing the seismic hazard of construction sites, currently lack zoning of macroseismic intensity for the vast shelf zones of Russia, especially their Arctic parts. This is explained by the inaccessibility of the Arctic seas for large-scale seismotectonic studies, as well as the fact that, until recently, only a few objects were built on the shelf, for which individual engineering work was carried out to clarify the seismic characteristics in the construction area. Regulatory zoning maps of the above-mentioned secondary, seismicity-related, marine-hazardous phenomena are also currently lacking.

Despite the large gaps in the study of the Russian Arctic, the available data are sufficient to conclude that a number of Arctic areas are of great interest for studying geohazards. A striking example is the Laptev Sea region, the most seismically active in the Russian sector of the Arctic Ocean, which is determined by its location at the junction of the continental shelf structures with the mid-ocean Gakkel Ridge.

The purpose of this study is to generalize and analyze the scattered available information on the main geohazards in the Russian sector of the Arctic Ocean, as well as to discuss the probable patterns of their spatial distribution and the possible relationship of this distribution with the geodynamic situation of the Arctic region. For this purpose, an extensive dataset was prepared, with information on seismic exploration and seismological observations in the region, on the location, activity and characteristics of active faults, on the magnitudes of seismic events and locations of earthquake epicenters, areas of possible tsunami and underwater landslide generation, and manifestations of gas seeps. In this case, our own seismological data, obtained during observations in the Arctic seas using ocean bottom seismographs (OBSs), were also used.

2. A Review of Seismic Exploration and Seismological Observations in the Russian Sector of the Arctic Ocean

2.1. Seismic Exploration

One of the main methods for studying the geological structure of sedimentary basins in the Arctic waters is seismic profiling (mainly using the CDP method). A systematic study of the region using geophysical methods has been actively carried out since the 1970s [3,4]. However, until the 2000s, the main regional studies were concentrated in the Barents and Kara Seas, while the shelves east of Taimyr and the oceanic part remained poorly studied [4–6] (Figure 1a).

Since the 2000s, as a result of a series of state projects on mapping the Arctic seas and the Arctic Ocean, areal seismic works of various scales have been carried out in the waters of the northern part of the Barents and Kara Seas, the Laptev Sea, and the East Siberian and Chukchi Seas [5,6] (Figure 1b). The main performers of geophysical studies at this stage were Sevmorgeologiya, the Marine Arctic Geological Exploration Expedition (MAGE), Yuzhmorgeologiya, and Dalmorneftegeofizika (DMNG).

A significant part of the geological and geophysical data was obtained as a result of field work carried out with the aim of substantiating the legal shelf of the Russian Federation in the Arctic Ocean. These works began in the late 1980s–early 1990s [7]. The first Submission of the Russian Federation regarding the extended continental shelf to the UN Commission on the Limits of the Continental Shelf was sent in 2001. Then, from 2005 to 2014, a long series of comprehensive expeditions were carried out in the Arctic Basin, designed to substantiate the revised submission [8–11]. Active geological and geophysical work in the Russian sector of the Arctic Ocean in general, and in the Eurasian Basin in particular, continues to this day [12].

The generalization of accumulated geophysical data made it possible to form ideas about the geological and tectonic structure of the region [4–6,14–19]. In 1995, the regime of the latest movements of the West Arctic continental margin of Eurasia was characterized [20]. In 2004, the Geological Institute of the Russian Academy of Sciences prepared the atlas, *Geology and mineral resources of the shelves of Russia* [21], containing a map of the latest faults in the Arctic seas. By 2008, several versions of tectonic maps and diagrams had been compiled [5,6,22–27].

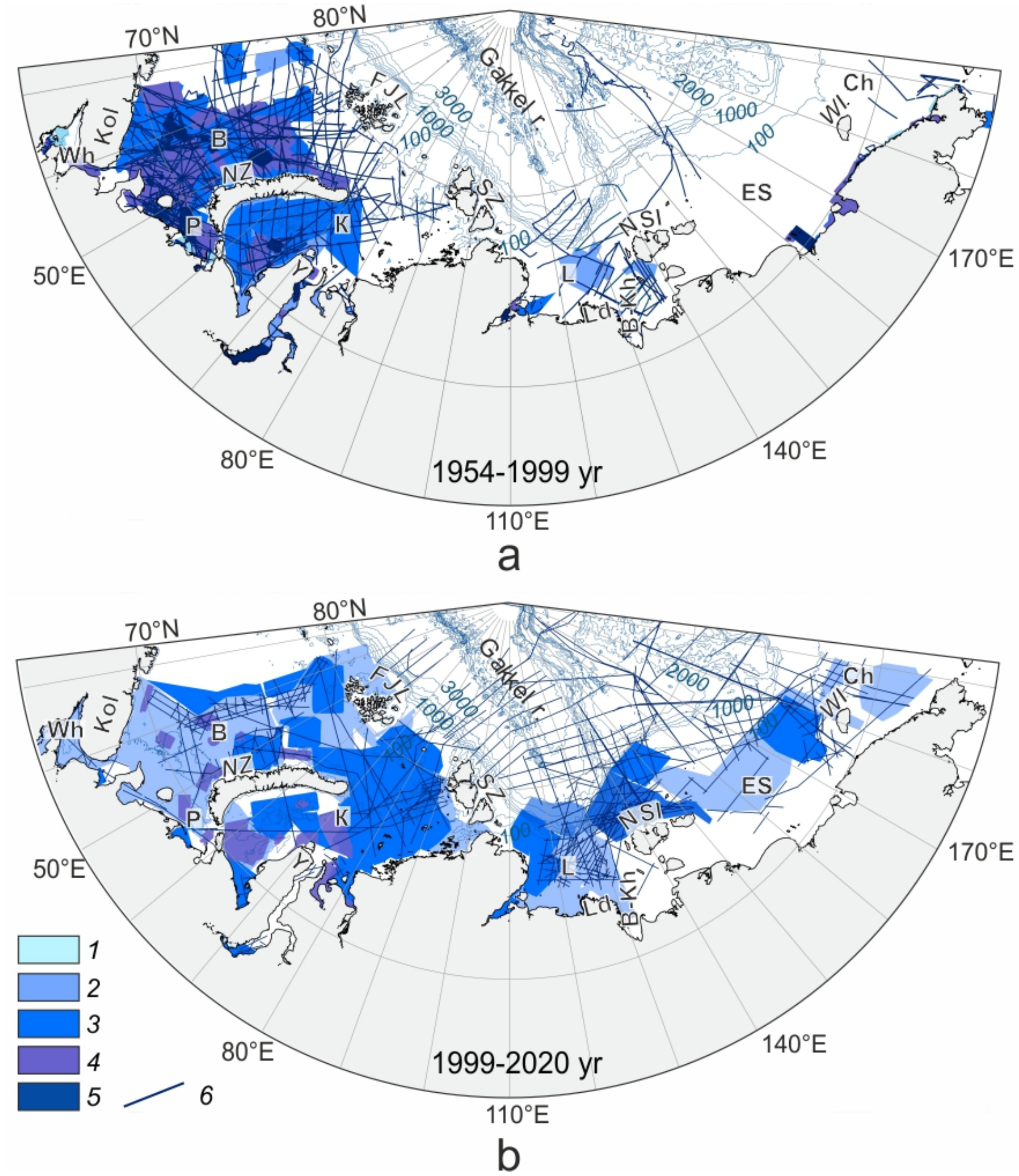

Figure 1. Maps of geophysical exploration of Arctic seas of Russia, prepared according to [13]: seismic works carried out from 1954 to 1999 (**a**) and from 2000 to 2020 (**b**). Areal seismic works were carried out to develop geological maps of the following scale: 1—1:2,500,000; 2—1:1,000,000; 3—1:500,000; 4—1:200,000; 5—1:100,000; 6—individual seismic profiles. Seas: B—Barents; Wh—White; P—Pechora; K—Kara; L—Laptev; ES—East Siberian; Ch—Chukchi. Archipelagoes: FJL—Franz Josef Land; NZ—Novaya Zemlya; SZ—Severnaya Zemlya; NSI—New Siberian Islands; WI—Wrangel Island.

The mapping of the main active faults was also continued by the Geological Institute of the Russian Academy of Sciences [21]. Since 2015, the interactive database of the active faults of Eurasia has been constantly updated [28].

The currently relevant geological information is summarized in a compilation of sheets from the third generation of the State Geological Map (SGM) at a scale of 1:1,000,000. Most of the maps from the SGM third generation set have been published for a significant part of the Russian sector of the Arctic. The exceptions are areas such as the north of the Laptev Sea and the East Siberian Sea [29].

2.2. Seismological Observations

2.2.1. On-Land and Marine Seismological Observations

Despite the interest in the complex geodynamics of the Arctic region, information on its seismicity is based mainly on data from a few land-based seismic stations, which allow us to have a very rough idea of the distribution of epicenters. Currently, there is a fairly sparse network of seismic stations from the Geophysical Service of the Russian Academy of Sciences (GS RAS) [30] and several other organizations (Figure 2). Most of them are concentrated in the Western Arctic sector, within the Kola Peninsula, and the western part of the Kara Sea coast, on the Yamal Peninsula in particular. This is explained, firstly, by the better accessibility of these regions and the dynamic development of their infrastructure compared to the Eastern Arctic sector, and secondly, by the need to monitor oil and gas provinces where hydrocarbon production is actively taking place. It is noteworthy that several seismic stations have recently been deployed by the Federal Research Center for Integrated Arctic Research of the Ural Branch of the Russian Academy of Sciences on the Franz Josef Land and Severnaya Zemlya archipelagos [31,32].

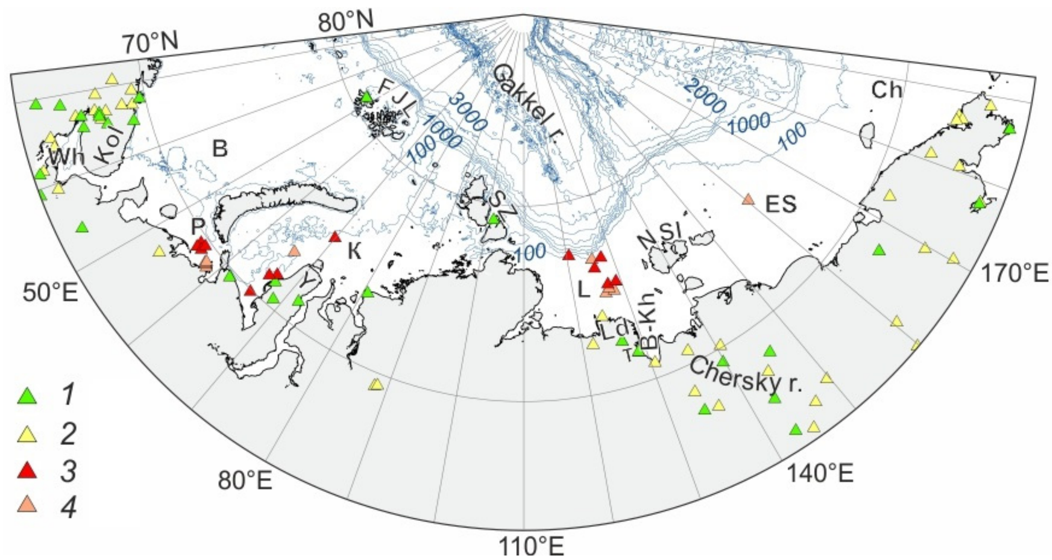

Figure 2. Permanent and temporary seismic stations in the Arctic part of Russia. 1—currently operating on-land stations; 2—currently inactive on-land stations of the GS RAS and other organizations [30]; 3—OBSs of the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) with a recording period of 3–7 months; 4—OBSs of the IO RAS with a recording period from 1 h to 15 days [37]. FJL—Franz Josef Land; NZ—Novaya Zemlya; SZ—Severnaya Zemlya; NSI—New Siberian Islands; WI—Wrangel Island; B-Kh—Buor-Khaya Bay; T—Tiksi; Peninsulas: Y—Yamal; Kol—Kola. Seas: B—Barents; Wh—White; P—Pechora; K—Kara; L—Laptev; ES—East Siberian; Ch—Chukchi.

The most seismically active area among the Arctic seas is the shelf and continental slope of the Laptev Sea, determined by their location at the junction of the Gakkel Ridge, the northernmost segment of the global system of mid-ocean ridges. In addition to the work of several stationary seismic stations of the Yakut branch of the GS RAS in the area of the village of Tiksi since the mid-1980s, several local instrumental seismological studies have been conducted in the Laptev Sea region: the expeditions of the Sevmorgeologiya in 1972–1976 (the area of the New Siberian Islands) [33] and 1985–1988 (the Lena delta and the coast of the Buor-Khaya Bay) [34]. This made it possible to register a significant number of weaker events with a magnitude of less than 4 in the Laptev Sea region and to compile a seismological data bank for the Arctic region [35].

Until recently, the understanding of the seismic and geodynamic characteristics of the Arctic region was based primarily on records from remote land-based seismographs. Since about the mid-2000s, the recording capabilities of the GS RAS seismic network have increased significantly, and the corresponding database [36] has begun to include characteristics of weak earthquakes with a magnitude of less than 3. However, the number of seismic stations is still insufficient for a detailed study of such a vast region. In particular, most of the seismic stations of the Yakutsk branch of the GS RAS in the Arctic are located to the southeast of the Laptev Sea region, along the seismically active Chersky Ridge. To the east, along the coast of the East Siberian and Chukchi Seas, there are only a few seismic stations.

As for relatively recent local observations, in 2016–2020, employees of the Alfred Wegener Institute for Polar and Marine Research (Germany), the University of Potsdam (Germany), the Yakutsk branch of the GS RAS, and the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) carried out a series of field work to deploy temporary local networks of seismic stations in the vicinity of Tiksi and in the Lena Delta. In 2016–2022, in a series of marine expeditions, employees of the IO RAS carried out observations using autonomous OBSs in the Laptev Sea, as well as in the Barents, Kara, and East Siberian Seas. Registration of seismic noise and signals from local and remote earthquakes was conducted for time periods of 1 h to 7 months [37] (Figure 2).

2.2.2. Contribution of Marine Seismological Observations and Potential Cost of Geohazards

Marine seismological observations in seepage areas significantly contribute to a better understanding of the correlation between seismotectonic processes [38], locations of methane release, and the state of subsea permafrost [39,40], which plays a key role in the scales of methane release [41,42]. In particular, a good example of the described relationship can be found in the results of a geophysical work in the northern part of the Laptev Sea: The significant areas with an absence of subsea permafrost and gas hydrates in the intensive gas seepage zone were determined. The connection between gas seeps and deep-seated faults identified in seismic sections was substantiated [43,44].

The first methane release, subsea and limnic permafrost studies in the East Siberian Arctic Shelf (ESAS), the broadest and shallowest shelf of the World Ocean, and its nearshore zone, were launched by the Laboratory of Arctic Studies of the Pacific Oceanological Institute FEBRAS in the late 1990s [45]. Then the studies were extended in the frame of the International Siberian Shelf Studies (ISSS) and SWERUS [46] using triple-isotope techniques [47], electromagnetic profiling, and mathematical modeling, with validation against scientific drilling data in Buor-Khaya Bay in 2011–2015, as well as against historical drilling data obtained in the Dmitry Laptev Strait [48,49].

Massive methane release in the ESAS can be considered among the favorite climate-related geophysical and biogeochemical research topics, because potential methane release from the ESAS could be accelerated by progressive seismotectonic activity [50]. The extreme scenario of methane release from thawing permafrost beneath the ESAS [51], off northern Russia, alone comes with an average global price tag of USD60 trillion in the absence of mitigating action [52]—a figure comparable to the size of the world economy in 2012 (about USD70 trillion). The total cost of Arctic change will be much higher because related geohazards can impact the world economy in different ways.

3. Review of Geohazards in the Russian Sector of the Arctic Ocean

3.1. Major Tectonic Structures and Active Fault Zones of the Arctic Part of Russia

The Russian part of the Arctic region is conventionally divided into the West and East Arctic sectors [20], which have a number of different features of modern geodynamics. This division formally reflects the division of Northern Eurasia into the Pacific and Atlantic segments, with a boundary along the Gakkel Ridge and its continental continuation onto the shelf of the Laptev Sea and further into the Momsky Rift [53]. The location of the main tectonic structures and large active fault zones in the Russian sector of the Arctic seas is shown in generalized form in Figure 3.

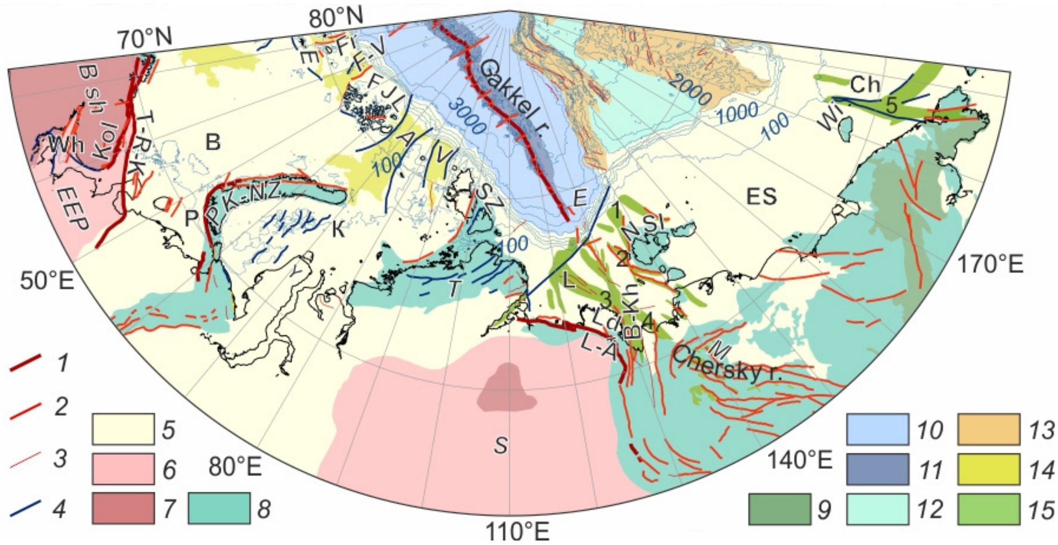

Figure 3. A scheme of the major tectonic structures and active fault zones in the Russian sector of the Arctic, compiled on the basis of published materials. Active fault zones: 1—main, deep, and long-lived faults (T–R–K—Trollfjord–Rybachy–Kildin lineament; Gakkel r.—rift zone of the Gakkel spreading ridge; L–A—Lena–Anabar fault); 2—regional; 3—small faults outcropping on the surface; 4—inferred active faults. Main structural elements: 5—sedimentary basins on land and areas of Cenozoic subsidence of the Arctic continental margin of Eurasia; 6—platforms (EEP—East European; S—Siberian); 7—crystalline shields (Bsh—Baltic Shield); 8—folded regions (PK–NZ—Pai-Khoi–Novaya Zemlya; T—Taimyr); 9—volcano–plutonic belts; 10—ocean basins (E—Eurasian); 11—Gakkel mid-ocean ridge; 12—basins with transitional crust; 13—continental blocks of the Central Arctic uplifts; 14—troughs (E—Erik–Eriksen; O—Orly; F–V—Franz–Victoria; A—St. Anna; V—Voronin); 15—rifts: M—Momsky; 1—Anzhu; 2—Belkovsko–Svyatonossky; 3—Ust–Lensky; 4—Ust–Yansky; 5—Chukotka and Alaska. Seas: B—Barents; Wh—White; P—Pechora; K—Kara; L—Laptev; ES—East Siberian; Ch—Chukchi. Archipelagoes: FJL—Franz Josef Land; NZ—Novaya Zemlya; SZ—Severnaya Zemlya; NSI—New Siberian Islands; WI—Wrangel Island. Ld—Lena Delta.

The West Arctic sector includes the Barents, Kara, Pechora, and White Seas and their continental framework. The tectonic structure of this region was considered in the works [8,17,54] and many others.

The region is a passive continental margin consisting of sedimentary basins of shelf seas surrounded by a chain of orogens (Scandinavia, Novaya Zemlya, and Taimyr), a protrusion of the Baltic Shield, and marginal shelf rises (Spitsbergen, Franz Josef Land, and Severnaya Zemlya). The current stage of tectonic development of the region is limited by the Upper Oligocene–Lower Miocene and is characterized by active, contrasting, high-amplitude, and differentiated movements of large blocks of the Earth's crust, expressed in the subsidence of basins of shelf seas and the uplift of orogens and marginal shelf rises [20]. In parallel with this, there was a gradual development of superimposed troughs in the northern and western parts of the Barents Sea [55]. A number of studies confirm the tectonic nature of the troughs on the outer boundary of the shelf of the Barents and Kara Seas [55–57]. Systems of modern normal faults are formed along the sides of the Orly Trough in the northwestern part of the Barents Sea [58] and the Voronin Trough in the northern part of the Kara Sea [59]. Faults along the sides of the remaining troughs have been identified less reliably.

As a result of neotectonic movements, weakened zones with young, activated, or rejuvenated faults are concentrated along the boundaries of large blocks of the Earth's crust: the East European Platform, the orogens of the Pai-Khoi-Novaya Zemlya folded system, and the marginal uplifts of the Barents Sea. Displacements along active fault zones are expressed in the modern relief, accompanied by seismicity and degassing processes with the formation of pockmarks and gas craters [57,60,61].

The East Arctic sector includes the Laptev Sea, East Siberian Sea, and Chukchi Sea. It is assumed that the modern tectonic activity of the Laptev Sea is associated with the extension and formation of a series of rifts along the continental continuation of the Gakkel spreading ridge [62]. The fault network, identified mainly by potential fields, is distributed along the main grabens of this rift system [63], while signs of modern fault activity in the upper part of the sedimentary cover have not been specifically mapped and are known at isolated areas on the shelf, shelf edge, and Gakkel ridge [64]. The main sources of information on active faults on the Laptev Sea shelf are the SGM sheets 1:1,000,000 and published tectonic schemes [63].

Analysis of potential fields revealed the block structure of the basement of the East Siberian and Chukchi Seas [65], which made it possible to assume a series of intersecting active faults of strike–slip kinematics on the shelf of the East Siberian Sea [21]. A later interpretation of seismic sections showed that no faults were recorded in the Cenozoic sedimentary cover of the East Siberian Sea [66].

The active fault scheme shown in Figure 3 is based on 1:1,000,000, third-generation SGM sheets. The SGM sheets contain tectonic schemes that show faults, including those that reach the surface. Another important source of information is the maps of neotectonic structures [21]. When compiling the map from [21], faults that have been active since the Neogene were taken into account, many of which may not be active at present. Therefore, this map was used in combination with additional materials containing information on fault activity [5,6,67–76].

Faults are considered active if they have moved during the Quaternary or show signs of modern activity [77,78]. Often these signs are revealed fragmentarily, and the exact location of the active section is unknown. Since this situation is typical for the Arctic region as a whole, it makes sense to differentiate faults in the general scheme according to the degree of reliability of their activity or location. In this case, direct measurements of crustal block displacement, the severity of faults in the modern relief, faults on seismoacoustic sections, earthquake epicenters associated with faults, focused methane emissions from marine sediments, and geochemical anomalies are taken into account.

The most obvious and reliable in terms of location, structure, and activity is the position of the Gakkel spreading ridge. Less reliable and mainly based on relief are the transform faults of the Eurasian Basin.

Active faults on the shelves of the Arctic seas are distinguished with varying degrees of reliability. The most clearly manifested and reliably mapped are the rejuvenated deep faults at the boundaries of large blocks, especially in cases where they partially intersect land. Examples of such faults are the Lena–Anabar fault in the Lena delta, separating the Laptev Sea sedimentary basin and the Siberian platform, and the Trollfjord–Rybachy–Kildin ligament at the boundary of the Baltic Shield and the Barents Sea block. A rift system, including active faults, has formed on the Laptev Sea shelf [62,79–81], but there is no precise information on the position of the active faults. The largest active faults probably correspond to extension detachments [63]. The remaining active faults on the shelf are identified less reliably, but it can be assumed that they are confined to the sides of large rifts [59].

3.2. Seismicity in the Russian Sector of the Arctic Region

In the framework of this work, a joint catalog of earthquakes in the Russian sector of the Arctic was prepared, combining data from the largest electronic databases of the GS RAS [36], ISC [82], and USGS [83]. The ISC and USGS databases, in turn, combine information provided by a number of organizations and agencies. In addition, data from catalogs, prepared based on the results of processing records and obtained using autonomous OBSs of the IO RAS [38], were added to the joint catalog—it contains information on the dates and times at the source, coordinates and source depths, and magnitudes and sources of information on approximately 13,000 seismic events. The corresponding distribution of epicenters is shown in Figure 4 against the background of the active faults (see Section 3.1).

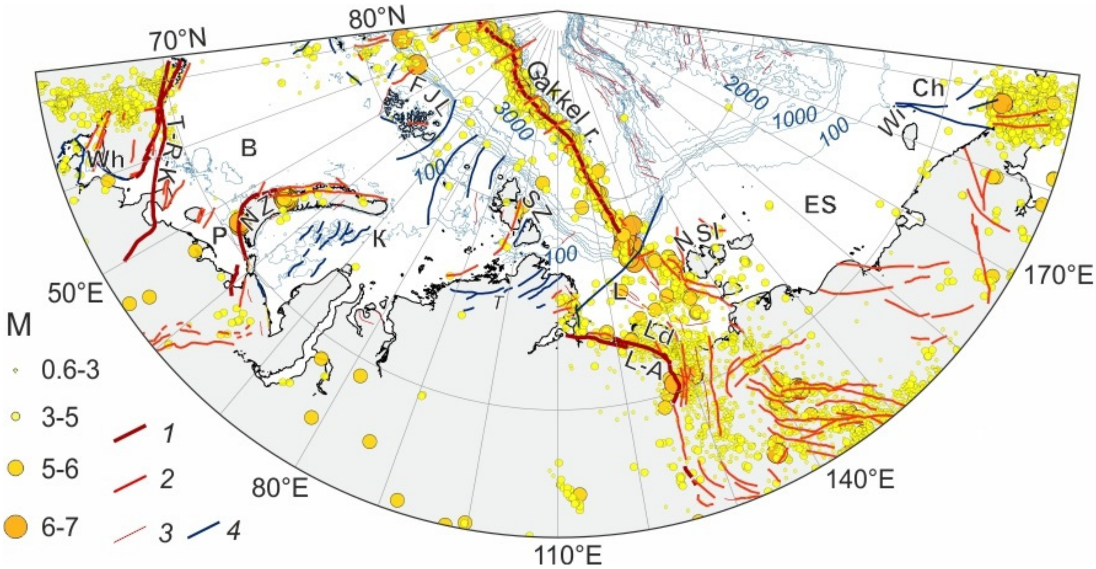

Figure 4. Th distribution of earthquake epicenters and the main active fault zones in the Russian sector of the Arctic region. M—earthquake magnitudes; active fault zones: 1—main, deep, and long-lived faults (T–R–K—Trollfjord–Rybachy–Kildin lineament; Gakkel r.—rift zone of the Gakkel spreading ridge; L–A—Lena-Anabar fault); 2—regional; 3—small faults outcropping on the surface; 4—possible active faults. Seas: B—Barents; Wh—White; P—Pechora; K—Kara; L—Laptev; ES—East Siberian; Ch—Chukchi. Archipelagoes: FJL—Franz Josef Land; NZ—Novaya Zemlya; SZ—Severnaya Zemlya; NSI—New Siberian Islands; WI—Wrangel Island. Ld—Lena Delta.

In the Arctic region, there are a number of seismically active zones of varying intensity, shape, and size, the main one of which is the so-called Mid-Arctic Belt (Gakkel Ridge) [10], confined to the divergent boundary of the Eurasian and North American lithospheric plates. The Gakkel Ridge has a complex segmented structure and a significant number of volcanic centers. The recording of low-magnitude earthquakes of the ridge at regional distances, which became possible due to the development of instrumental observations on the Arctic archipelagos of Spitsbergen, Franz Josef Land, Severnaya Zemlya, and Novaya Zemlya, allowed us to conclude that the swarm seismicity of the ultraslow-spreading Gakkel Ridge is probably caused by a combination of volcanic activation processes and seismotectonic destruction, especially pronounced in the locations of transverse faults [84–86]. Some expeditions included studies on recording local earthquakes from the ice near the Gakkel Ridge. This helped to study the features of the swarm seismicity of the Gakkel Ridge and even to construct seismotomographic models [87–93].

In addition to the obvious Mid-Arctic Belt, earthquake epicenters are also found in the areas of all the Arctic seas of the Russian sector, as can be seen from modern electronic catalogs (Figure 4). Among the shelf parts of the Russian Arctic seas, the largest number of epicenters are observed on the shelf of the Laptev Sea. The Laptev Sea is one of the few regions of the Earth where the transition from a mid-ocean spreading ridge to a continental rifting (Laptev Sea rift system) occurs [38,94–96]. The modern seismic activity of the Laptev Sea shelf is mainly concentrated within the East Laptev province of grabens and horsts and is located between two extensional detachments [38]. This is due to the fact that, at present, the continuation of the extension axis of the Gakkel Ridge on the Laptev Sea shelf is shifted eastward toward the New Siberian Islands and is located in the vicinity of a group of extensional detachments stretched along the eastern boundary of the Anisin, Zarya, and Belkovsko–Svyatonossky rift chain. The more ancient extension axis, located along a group of detachments marking the eastern boundary of the Ust–Lena and Omoloysky rift system, and continuing the axis of the Gakkel Ridge, is currently much less active [38]. In addition, intense seismicity is observed in the vicinity of the Lena–Anabar fault, which separates the Laptev Sea sedimentary basin and the Siberian platform.

The presence of a currently operating seismic station on Severnaya Zemlya has made it possible to record low-magnitude earthquakes occurring within the archipelago and the Taimyr Peninsula. Most of the recorded local earthquakes occurred in the estuary of the Khatanga Gulf, within the Khatanga graben, and in the east of the Taimyr Peninsula [97,98].

At present, practically nothing is known about the seismicity of the East Siberian Sea—only individual earthquakes have been recorded, mainly in its western part within the so-called Novosibirsk Trough [99]. On the Chukchi shelf, only the southern and southeastern parts have increased seismicity [100]. Most of the events are associated with the western part of the Kotzebue Ridge. In addition, individual epicenters of weak earthquakes can be traced from the western part of the Kotzebue Ridge along the near-axial zone of the South Chukchi Trough [101]. The few geological and geophysical studies of tectonic activity on Wrangel Island revealed the presence of seismotectonic scarps, which are planes of active faults along which repeated modern movements have occurred [102]. Most likely, the small number of registered events in most of the shelf of the East Siberian and Chukchi Seas is due to the fact that the fault zones there are ancient and are currently inactive [103]. It should also be borne in mind that individual on-land seismic stations are probably not sensitive enough to register weak earthquakes there.

The seismicity of the White, Barents, and Pechora Seas has been better studied due to the presence of the NORSAR seismic array in the region as well as the network of seismic stations of the Federal Research Center for Integrated Arctic Research and the GS RAS located on the coast, including on the islands of the Spitsbergen and Franz Josef archipelagos. In particular, in the western part of the White Sea region, most epicenters are located outside the Kandalaksha graben to the west and southwest of it. In the eastern part of the region, two earthquakes were recorded in the White Sea–Dvina region and one was recorded in the White Sea Throat area. In the central part of the White Sea region, weak earthquakes have not been recorded over the past ten years [104,105].

In the western sector of the Russian Arctic, the greatest seismicity is observed at the boundaries of large crustal blocks, for example, in the vicinity of the Novaya Zemlya and Severnaya Zemlya archipelagos, the Pai-Khoi-Novaya Zemlya folded system, and the Trollfjord–Rybachy–Kildin ligament. The shelf of the Barents and Kara Seas is characterized by rare and scattered seismicity [106]. However, in the outer part of the Barents–Kara shelf and on the slope, in particular in the area of the Franz–Victoria, Orly, and Voronin troughs, seismic activity is observed, which is associated with both modern tectonic activity and isostatic compensation processes [60,61].

3.3. Areas of Landslide and Gas Seep Concentration in the Russian Sector of the Arctic Seas

The processes of underwater landslide generation and active gas release from marine sediments are of interest as important types of geohazards. Nevertheless, they, as a rule, accompany active tectonic processes, since dynamic effects from earthquakes are one of the main triggers in the formation of landslides [107–109], and also affect the permeability of rocks and pore pressure, thus changing the filtration properties of the geological environment [110]. This, in turn, can affect the intensity of gas discharge and other geofluid components, manifest itself in hydrate destabilization, massive methane emissions, the formation of funnels of various diameters (from meters to hundreds of meters), soil subsidence, and other potential geohazards [111–115]. Figure 5 shows the spatial distribution of areas of gas seep concentration and areas with high risks of underwater landslides in the Russian sector of the Arctic Ocean.

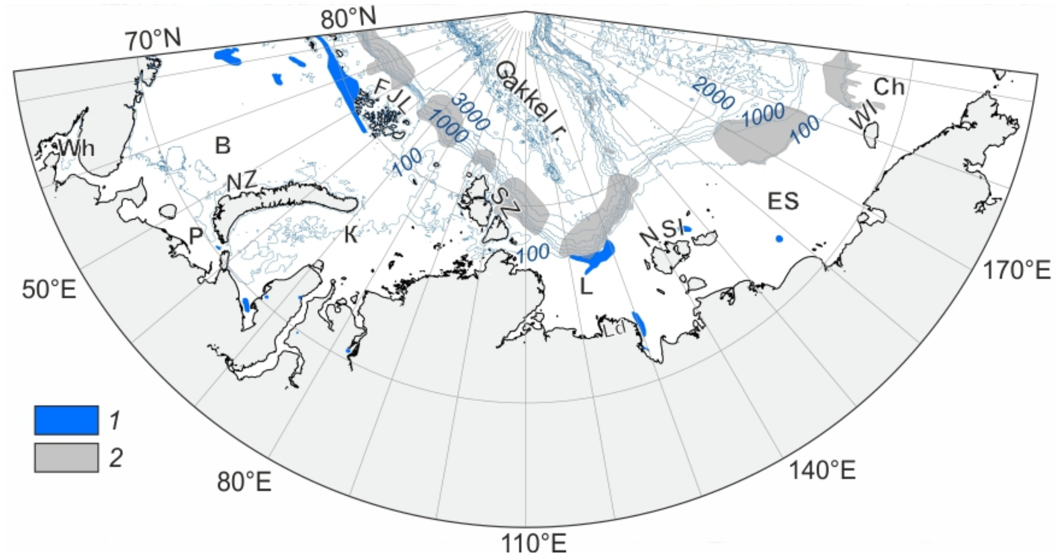

Figure 5. Distribution of gas seep provinces (1) and areas at high risk for underwater landslide formation (2) in the Arctic seas of Russia. Compiled using data from works cited in the text. Seas: B—Barents; Wh—White; P—Pechora; K—Kara; L—Laptev; ES—East Siberian; Ch—Chukchi. Ld—Lena Delta.

Manifestations of massive gas releases are widespread in Russian Arctic waters and are described in a series of publications [41,116,117]. In particular, data on the distribution of massive fluid discharge fields in the western sector of the Russian Arctic were summarized by the VNIIOkeangeologiya in the form of a corresponding map [118].

Areas of intense methane bubble discharge are recorded by echosounders as hydroacoustic anomalies (gas flares), which are one of the main indicators of the presence of gas seeps [41,119]. Gas seep fields are most widespread in the Laptev Sea. A large province of gas seeps, called the "mega-seep", is located on its outer shelf and continental slope near its junction with the Gakkel Ridge [41,49].

The province of gas seeps is confined to the troughs of the northwest and west of the Barents Sea [55,58,117]. In the central and eastern parts of the East Siberian Sea, traces of powerful discharges of bubbly methane were discovered in 2008 [120], which have been intensively studied in recent years. In the southeastern part of the East Siberian Sea [121] and within the Chukchi [122] and Kara Seas [123,124], only scattered gas flares were detected.

There is almost no information on underwater landslides in the Russian Arctic sector. At the same time, the environmental conditions existing on the continental margins of the Arctic Basin give reason to assume that underwater landslides are quite widespread in the Russian Arctic sector.

The areas with high risks of underwater landslide formation are identified based on the IBCAO (GEBCO) bathymetric bases, geological data, CDP and seismoacoustic profiling, seismicity, and the distribution of gas seep fields. The above studies revealed individual signs of underwater landslides on the continental slope in the Laptev Sea area [125,126], in the East Novaya Zemlya Trough, on the sides of the St. Anna Trough, east of Severnaya Zemlya, on the outer shelf of the East Siberian and Chukchi Seas, and on the slopes of the Lomonosov Ridge [117,118,127,128].

According to [129], the most important factors determining slope instability are as follows: high sedimentation rates and the accumulation of large volumes of loose sediments, seismicity and fault activity, relief character and slope values, and the gas saturation of sediments. It is known that in conditions of gentle slopes (less than 5°) due to the accumulation of large volumes of sediments in a calm environment, large landslides can form. The most likely trigger mechanisms for the region are as follows: earthquakes and releases of large volumes of natural gas from marine sediments.

It should be noted that glaciomarine sediments are widespread in Arctic seas. According to [118,130], these sediments are distinctive of the outer shelf and shelf break, grading to declivial slope sediments including turbidites on the slope.

A large amount of gas in arctic sediment increases failure risks by decreasing effective stress. It is noted that the presence of gas hydrate may increase sediment cyclic resistance, but dissociating gas hydrates deliver an abundance of free gas and water, forming weak layers in the top and in the bottom of the stability zone [131].

In a first approximation, the combination of high slope values and high sedimentation rates and the accumulation of weak glaciomarine sediments determines the environmental conditions characteristic of the continental slopes of Eurasia [119,130,132]. Seismicity, active faults, and the saturation of sediments with natural gas are most clearly manifested on the continental slope of the Laptev Sea. The combination of these factors is also characteristic of the northern part of the Barents Sea, especially in areas where troughs are located. On the outer shelf of the East Siberian and Chukchi Seas, environmental conditions favorable for the formation of underwater landslides are characterized by a thick sediment layer formed under stable hydrodynamic conditions and the saturation of sediments with gas [119,133].

3.4. Tsunami Hazard Assessments for the Russian Arctic Ocean Coast

At present, there is no information on the observation of tsunamis of either seismic origin or any other types of tsunamis (e.g., landslide, rockfall, and meteorological origin) for the Arctic seas of Russia, including the Barents, Kara, and Laptev seas. In the case of tsunamis of seismic origin formed as a result of underwater earthquakes, based on data on earthquakes in the 20th and 21st centuries, it can be assumed that tsunamis with a wave height of more than 0.5 m have not occurred in the seas of the Russian Arctic [134,135]. The occurrence of tsunamis, associated with earthquakes indirectly, rather than directly, in this part of the World Ocean is an open question that requires special research. Tsunamis of landslide, rockfall, and meteorological origin are practically impossible to predict, and information about their occurrence and spread can only be obtained through measurements at coastal and bottom tide gauge stations.

In [134,135], probabilistic estimates of the maximum heights of tsunami waves of different recurrences on the Arctic coast of Russia and an overview scheme of its tsunami zoning were obtained for the first time (Figure 6). Due to the lack of reliable information on tsunami manifestations in the Arctic, a probabilistic approach was used, based on a statistical seismicity model developed from data on the structural features and historical earthquakes of the region. From the analysis of seismological data, it follows that the potential tsunami hazard for the Arctic coast of Russia is posed by earthquakes with a magnitude of $Mw \geq 7$ from three zones of increased seismic activity: the Gakkel Ridge, the Laptev Sea, and the Chukchi Sea with the Bering Strait.

In [134,135], a catalog of probable tsunamigenic earthquakes for a time interval of ~300 thousand years was constructed based on a seismicity model, containing more than 2000 events with a magnitude of $Mw \geq 7$ and more than 250 events with $Mw \geq 7.5$, although such strong events were not observed in the specified zones during the period of instrumental seismological observations. The synthetic catalog of model earthquakes made it possible to perform mathematical modeling of synthetic tsunami waves and assess the characteristics of waves in the Arctic waters. Recurrence graphs of the estimated maximum tsunami heights were constructed for the entire Arctic coast of Russia.

The most tsunami-hazardous area turned out to be the western part of the Laptev Sea coast, where the maximum tsunami heights on the seacoast, with a probability of 10^{-3}/year, can reach 30–50 cm. The most protected part of the Arctic coast is located in the Kara Sea, where the tsunami height for a recurrence period of 10^{-3} years does not exceed 5 cm.

In some Arctic bays and gulfs, local increases in tsunami heights can occur due to resonant amplification. Earthquakes can also cause tsunamis indirectly, for example by triggering landslides. For example, the catastrophic Palu-Sulawesi tsunami in September 2018 was not directly related to the Mw 7.5 earthquake, but to the local submarine landslide in Palu Bay [136]. On 17 June 2017, a massive subaerial landslide entered the Karrat Fjord on the west coast of Greenland and generated a tsunami wave with a runup height exceeding 90 m, close to where the landslide occurred [137]. This tsunami flooded several villages, killing four people and destroying 11 houses in the village of Nuugaatsiaq (32 km from the landslide site), where the tsunami height was 1–1.5 m [138]. In September 2023, a rock–ice avalanche on the east coast of Greenland (the Dickson Fjord) triggered a tsunami with an initial backsplash with a runup height of 200 m and subsequent waves up to 110 m high [139]. A possible source of tsunamis in the Arctic region could be icebergs calving into a water body [140]. However, in the Russian sector of the Arctic seas, such events have not been described in the scientific literature.

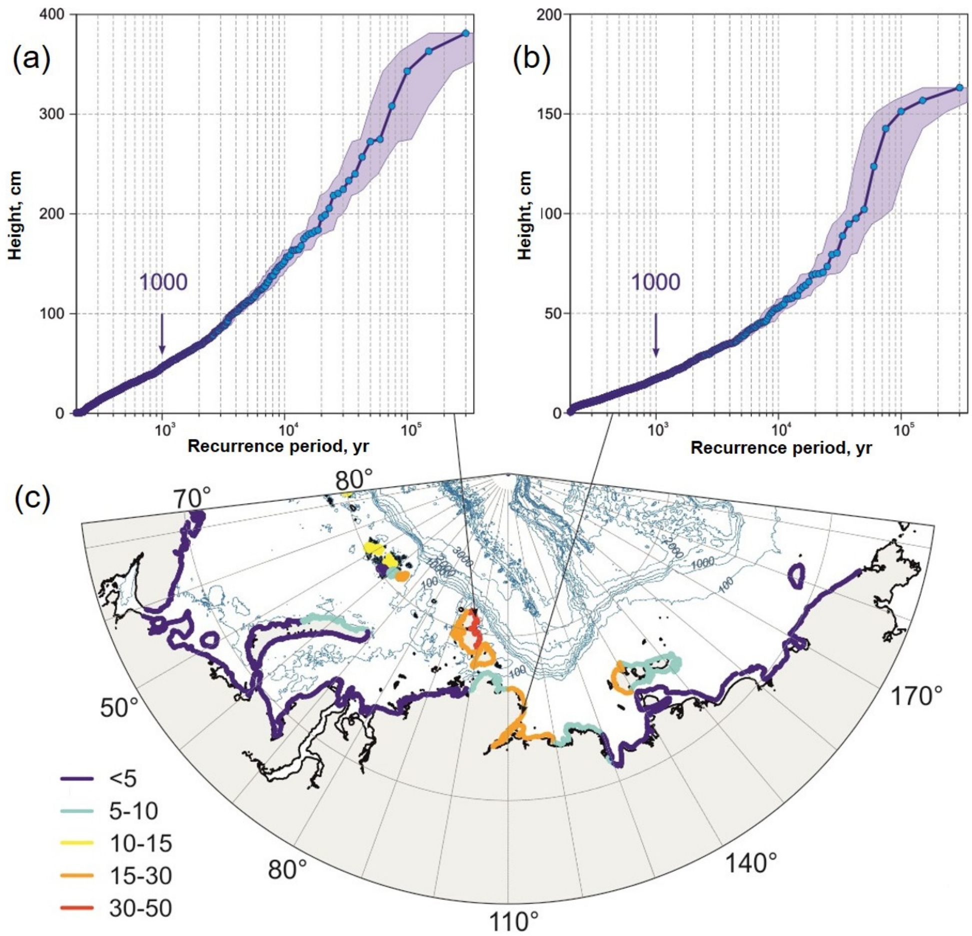

Figure 6. Recurrence periods of maximum tsunami heights on the coast of Severnaya Zemlya (**a**) and the Taimyr Peninsula (**b**), calculated using the synthetic catalog of model earthquakes [135]. The 95% confidence interval for recurrence period estimates is shown in purple. Overview map of tsunami zoning of the Russian Arctic coast (**c**) for a recurrence period of 1000 years (according to [135]). The color scale shows gradations of coastal tsunami hazard in units of expected maximum tsunami wave height (in cm).

The Great Chilean Earthquake of 22 May 1960 generated a tsunami wave that was observed in the Chukchi Sea at Point Hope on the northwest coast of Alaska, but no wave height was reported [141]. In [142], the tsunami hazard in the Bering and Chukchi seas was examined by determining whether trans-oceanic Pacific tsunamis penetrate through the Aleutian Islands and Bering Strait based on numerical modelling, and the study concluded that tsunami penetration into the Arctic Ocean from remote sources in the Pacific is unlikely. Even tsunamis generated in the Alaska–Aleutian subduction zone have a relatively small impact on the Bering and Chukchi seas [142,143].

4. Patterns of Spatial Distribution of Geohazards and Their Relationship with the Geodynamic Situation of the Arctic Region

The distribution of active fault zones, earthquake epicenters, and possible maximum tsunami heights in the Russian sector of the Arctic seas is very uneven. The main seismic belt is the Gakkel spreading ridge, which is the main active geodynamic and volcanic structure in the Arctic Ocean and one of the segments of the boundary of the Eurasian and North American lithospheric plates. When passing to the Laptev Sea shelf, the clear spreading axis and plate boundary disappear; however, the stretching of the lithosphere is still present, manifested in the formation of the extensive Laptev Sea rift system, with less intense but more diffusive seismicity.

The seismic activity of the Gakkel Ridge, near its junction with the shelf, also indicates that the most tsunami-hazardous area is the western part of the Laptev Sea coast, especially the eastern part of the Severnaya Zemlya coast. At the same time, the most protected part of the Arctic coast is located in the Kara Sea.

In addition to the described seismically active zones associated with the boundary of lithospheric plates, earthquake epicenters are confined to deep faults marking the boundaries of large crustal blocks, such as the Siberian platform (Lena–Anabar fault), the Baltic shield (Trollfjord–Rybachy–Kildin folded system) or the Pai-Khoi-Novaya Zemlya folded system. In addition, marginal shelf rises (Spitsbergen, Franz Josef Land, and Severnaya Zemlya) and troughs in the outer part of the Barents–Kara shelf (Franz–Victoria, Orly, Voronin, etc.) are characterized by a lower degree of seismic activity.

Thus, the distribution of active faults and earthquake sources in the Arctic region is primarily determined by the position of active geodynamic zones associated with already formed or still forming segments of the boundary of the Eurasian and North American lithospheric plates. Intraplate seismic activity is less manifested, apparently associated with the influence of active tectonic processes in the spreading axis on ancient suture zones between large crustal blocks and with the rejuvenation of the corresponding faults. In particular, this is observed within the Barents–Kara shelf. In the western sector of the Russian Arctic, isostatic processes may also be superimposed. In the eastern sector, in the main part of the shelf of the East Siberian and Chukchi seas, the existing rift structures are no longer tectonically active.

A study [144] attempted to quantify the influence of geodynamic processes in the Arctic mid-ocean ridge systems on intraplate seismic activity. A correlation was found between the released seismic energy in the vicinity of the Gakkel, Mona, and Knipovich ridges and the seismicity of the Novaya Zemlya archipelago region, with a certain time lag. In addition, modeling showed that lithospheric stress disturbances from the Gakkel ridge reach Novaya Zemlya in 3 years.

It is generally recognized that studying the mechanism of methane emissions from sediments of the Eastern Arctic seas, as well as assessing the possible climatic consequences of this process, is a priority area of research regarding the Arctic climate system [145]. Large gas seep fields in the Russian sector of the Arctic seas are also located in the most tectonically active zones. In particular, the largest seep province in the Eastern Arctic seas is located on the outer shelf and slope of the Laptev Sea, near the junction with the Gakkel Ridge [40–42]. Another large province of seeps is located in the outer part of the Barents Sea shelf to the west of the Franz Josef Land archipelago, where the epicenters of the strongest earthquakes of the Barents–Kara continental margin are located. Apparently, this pattern is associated with the increased permeability of the geological environment for geofluids in extended and disturbed active fault zones. Seismic waves from earthquakes themselves can serve as a trigger for a breakthrough or a regulator of the intensity of geofluid release from marine sediments [42,111,113,146].

Active fault zones are also characterized by increased heat flow, which promotes the thawing of underwater permafrost and the flow of deep geofluids to the surface of the seabed [147,148]. In [41], it was proven that the intensity of methane-containing geofluid discharge can differ by 5 orders and is determined by the state of underwater permafrost and the formation of gas emission pathways associated with submarine sublake taliks–their formation is caused, among other things, by seismotectonic processes [49,51]. The migration of deep gas along tectonic faults and zones of anomalous heat flow also causes the formation of explosive degassing in the north of Western Siberia, manifested by the formation of gas-saturated cavities in underground ice massifs, frost heave mounds, emissions, and spontaneous gas ignition with the formation of giant craters [149,150]. In particular, as a result of comprehensive aerospace studies on the Yamal Peninsula, about 5000 zones of powerful gas emissions (explosions) in the form of craters (pockmarks) were discovered. In addition, about 700 more zones of explosive degassing were identified in the coastal zones of the Kara Sea [151].

The hypothesis of the seismogenic-trigger nature of the process of massive methane emission from the frozen rocks of the Arctic shelf and adjacent land permafrost areas is actively developing [50,152]. According to this hypothesis, massive methane emission is caused by deformation waves coming from the subduction zones located closest to the Arctic, the Aleutian and Kuril–Kamchatka, where the strongest earthquakes with magnitudes greater than 8 occur. The sharp onset of warming in 1979–1980 can be explained by deformation waves that arrived in the Arctic zone approximately 20–25 years after the occurrence of a series of strong earthquakes with magnitudes greater than 8.5 in the Aleutian zone and the northern part of the Kuril–Kamchatka subduction zone, which occurred in the interval of 1952–1965. Deformation waves caused by a series of strong earthquakes in the indicated island arcs traveled a distance of 2000–2500 km between them and the Arctic zone at an average speed of 100 km/year over 20–25 years, leading, due to the trigger mechanism of additional stresses, to massive emissions of methane from the sedimentary strata into the atmosphere and the corresponding greenhouse effect.

The distribution of high-risk areas for underwater landslide formation in the Russian sector of the Arctic is at first glance determined by the geometry of the continental slope of the Arctic Ocean. Despite the fact that seismicity is considered one of the most important factors for determining slope instability, there is no unambiguous correlation between the distributions of landslide areas and seismically active zones. In particular, on the outer shelf of the East Siberian and Chukchi Seas, which is characterized by a stable geodynamic state, the formation of underwater landslides is apparently associated to a greater extent with the accumulation of a thick layer of sediments, the nature of the relief, and the values of the slope slopes. However, it should be borne in mind that the configuration of the continental slope itself is determined by the evolutionary history of the Arctic region as a whole and the opening of the Eurasian and Amerasian basins in particular [153].

Thus, it can be concluded that the main patterns of mutual distribution of the main geohazards of the Russian sector of the Arctic seas, in particular, active faults, earthquake epicenters and possible tsunami waves, gas seep fields, and underwater landslides, in general, are determined by both the modern geodynamic situation in the region and the history of the geodynamic evolution of the Arctic, namely the formation of the spreading axis and deep-sea basins of the Arctic Ocean. Currently, one of the most substantiated theories of the geodynamic evolution of the Arctic is the model of upper mantle convection in the Arctic region [154]. The existence of this convection cell is probably due to the subduction of the oceanic lithosphere of the Pacific Ocean, in accordance with the model presented in [8,9].

5. Conclusions

The waters of the Russian sector of the Arctic Ocean have enormous economic potential due to the presence of large offshore oil and gas fields, as well as the prospects for new sea transport routes. The construction of production and transport infrastructure facilities and their subsequent operation require mandatory research and the mapping of possible geohazards to reduce the likelihood of negative impacts on infrastructure, population, and the environment.

First of all, this concerns seismic zoning, since in the Russian sector of the Arctic Ocean, especially in the Laptev Sea region, there are many earthquakes. Earthquakes are also the cause of tsunamis. Moreover, a tsunami can occur not only as a result of seabed movements, but also as a result of underwater landslides, primarily due to an earthquake.

An equally dangerous phenomenon associated with seismotectonics is gas seeps. Methane, when thermogenic, can come from great depths to the surface along faults. Weak earthquakes occurring in such zones indicate the activity and permeability of fault zones, and strong earthquakes, changing the permeability of rocks, can provoke an increase in geofluid flows. Emissions of explosive gas have already led to global accidents, for example, in the Gulf of Mexico.

It should be noted that, with global warming and decreasing permafrost, an increase in the scale of gas manifestations, gas seeps, and explosion craters, is expected. The increased gas saturation of marine sediments in some areas and conditions will also lead to an increase in landslide hazards.

In conclusion, it should be noted that the patterns of spatial distribution and cause-and-effect relationships between various hazardous geological phenomena have been little studied, especially in the remote and hard-to-reach Arctic seas of Russia. A radical expansion of the database on marine geohazards in the Arctic region is essential to solve the problem of their zoning.

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