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ARTICLE

Some Results of Direct FR Technology Applied to Study Methane Seepage Areas in the Arctic Region

Mykola Yakymchuk[1], *Ignat Korchagin*[2], *Valery Soloviev*[2*]

[1] *Institute of Applied Problems of Ecology, Geophysics and Geochemistry, Kyiv, 03126, Ukraine*
[2] *Institute of Geophysics, NAS of Ukraine, Kyiv, 03680, Ukraine*

ABSTRACT

The experimental study of the seepage processes' sources formation in structures of the Arctic Region was carried out using modified methods of frequency-resonance (FR) processing and decoding of satellite images and photographs with the vertical scanning of the cross-sections. The newly obtained results show that the intensity and dynamics of the methane seeps and pockmarks fields' formation depend on active deep degassing processes in the continental margin structures. The use of direct FR-sounding technologies allows for determining the probable origin and depth of geological sources of gas migration at marginal migration centers in Greenland, and Norwegian and Barents Seas. New results confirm the crust-mantle gas fluids' influence on the nature and degassing processes features in the scan points of polar marginal structures. These data are important arguments in favor of the "volcanic model" of various structural elements formation in this and other regions. The FR technologies data also showed a possibility of seeps use as shallow and deep hydrocarbon field indicators in gas emission areas. These independent data can be used in compiling models of the deep lithosphere structure and possible mechanisms of abiogenetic hydrocarbon formation in Arctic margin structures. The authors suppose that hydrocarbons through deep channels migrate (from 57 km deep) to the upper crustal horizons where their fields can form. During this migration, gas seeps and pockmarks are formed on the sea bottom and part of the gas can migrate into the atmosphere. Data show that basaltic volcanoes in Greenland scan points can be the real channels through which hydrogen migrates to the upper crustal horizons and further into the atmosphere. Active gas migration in Arctic seepage areas can be an important factor in the global climate change processes.

Keywords: FR mobile technologies; Active hydrocarbon seepage; Greenland; Spitsbergen; Polar Arctic

*CORRESPONDING AUTHOR:
Valery Soloviev, Institute of Geophysics, NAS of Ukraine, Kyiv, 03680, Ukraine; Email: solvalera@ukr.net

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1. Introduction

The idea of the Earth's deep zones degassing is an important factor in the development and evolution of our planet [1]. It allows us to reconsider the interconnected processes of global volcanism and the intrusion of deep fluids, mud volcanism, and local and long-lived gas seeps—zones of the anomalous release of carbon dioxide, methane, hydrogen, helium, nitrogen, and other gases.

These processes are realized due to the functioning of long-term active influence of localized flows of hydrocarbon fluids (mantle degassing products) on the rocks of deep and near-surface structures of various ages and genesis through the "gas pipes" (point channels) and deep linear fracture zones.

An important role in the inflow of deep fluids into the upper horizons of the earth's crust is played by the presence of a developed network of faults, as well as processes of tectonic activation, due to which degassing and concentration of gas emissions in emission centers occur.

New technologies for the interpretation of Earth remote sensing data (ERS-data) significantly complement the results of complex geological and geophysical research in hard-to-reach Polar marine areas and shelf structures of the World Ocean [2]. Special attention to the identification and study of modern methane-degassing sites in the Polar continental margins is connected with their important impact on the global climate change processes [3,4].

2. General principles and methods

Experimental studies were carried out using modified methods of frequency-resonance (FR) processing and decoding of satellite images and photographs, vertical scanning of the cross-section, and the method of integral assessment of hydrocarbon potential prospects areas [5-8].

These methods use the principles of the "substance" paradigm of geophysical research, the essence of which is to search for a specific substance in the sections- oil, gas, gas condensate, water, metals, hydrogen, etc. They are based on the experimentally proven assumption that a large amount of a homogeneous substance creates an electromagnetic field characteristic of a given substance, the radiation power of which is proportional to the concentration of the substance [5-8].

A separate method of this technology allows within the contours of detected anomalous zones (at the resonance frequencies of gas) to estimate the maximum value of the fluid pressure in the reservoirs at different intervals (depth including) of the cross-section.

According to the new paradigm of conducting geophysical research, the focus is not on the selection of certain structural elements in the section and the determination of their physical properties, but on the detection of the specific substances in the section [2,5-8].

Databases of chemical elements, minerals, oil, and condensate samples, as well as sedimentary, igneous, and metamorphic rocks, are classified and divided into separate types and groups, the resonance frequencies of which are used in the processing satellite images and photographs, and became important components in the modifications of direct search methods.

The developed methods are based on the analysis of standing electric wave distribution, discovered by Nikola Tesla in 1899 in the deep horizons of the Earth. In modified versions of the methods of frequency-resonance processing of satellite images and photographs, as well as vertical sounding (scanning) of the cross-section, existing databases (sets, collections) of sedimentary, metamorphic, and igneous rocks (http://rockref.vsegei.ru/petro/), minerals and chemical elements are used. The peculiarities and potentialities of the methods used, as well as the technique of instrumental measurements, carried out [2,5,6,8].

In the process of performing experimental studies of a reconnaissance or detailed nature (carrying out instrumental measurements!) within the blocks and areas of the survey, the following sequence of procedures (graphs) for processing an individual satellite image (or its local fragment) is used.

1) The procedure for fixing responses (signals) from the surface at the frequencies of the following set of substances: oil, condensate, gas, amber, bacteria (methane-oxidizing bacteria), shale, gas hydrates, ice, coal, anthracite, hydrogen, living (deep) water, dead water, diamonds, potassium magnesium salt, sodium chloride salt;

2) Graph of responses from the groups of sedimentary, metamorphic, and igneous rocks in the cross-section registration;

3) Procedure for determining the presence of the deep channels (volcanoes) in a survey area that is filled with various groups of rocks; assessment of depths of the roots of volcanoes location;

5) Graph for determining groups of rocks (or individual samples of groups), from which signals are recorded at frequencies of oil, condensate, gas, and water;

6) The procedure for recording responses of oil, condensate, gas, and phosphorus at the surface (depth) of 57 km—the boundary of the hydrocarbons synthesis in deep channels (Volcanoes and Faults), filled with certain groups of rocks [6];

7) Graph of signals registration from water on the surfaces of 11, 46, 57, and 68 km—the predicted boundaries of water synthesis in volcanoes of a certain type [6];

8) The procedure for scanning a cross-section with different steps from the surface up to 15 km to determine the depth intervals, within which responses are recorded at the resonant frequencies of oil, condensate, and gas. Refinement of the depths of the location of the most promising hydrocarbon intervals of cross-section during additional scanning with a finer step;

9) Graph for assessing the depth of the upper boundary (edge) of basalts, as well as the depths of the beginning of fixing responses at the resonant frequencies of hydrogen and living (healing) water from basalts. It is implemented in case of fixing responses from the 6-th group of igneous rocks (basalts) in the surveyed area.

3. Results

Previously, examples of the developed direct universal FR-sounding technologies used for solving a wide range of geological and geophysical problems were shown [2,5,6,8]. They include: 1) determining the composition and the main features of the deep structure of the studied structures; 2) assessment of the prospects of territories for the most important types of minerals; 3) determination of the volcanic structures composition and their formation depth; 4) detection and mapping of deep fluid migration vertical channels; 5) identification of local areas of gas emission into the atmosphere and assessment of the sources of degassing processes depth.

The use of the universal "substance" paradigm in the study of pockmarks, seeps, gas hydrates, and mud volcanoes as a result of frequency-resonance studies, makes it possible to obtain new and independent data on their composition, formation depths, and position in the section, to reveal the presence of gas emissions from bottom structures.

The data obtained can be used to assess the manifestation of degassing processes in local structures, as well as to establish their possible connection with deep accumulations of hydrocarbons.

Detection and mapping of gas hydrates in the sections of sedimentary strata make it possible to assess their origin and the degree of their participation in the processes of migration of "greenhouse" gases into the atmosphere. Special attention to the identification and study of modern methane-degassing places is connected with the assessment of their impact on the processes of global climate change [4].

Some results of the use of these technologies on modern methane seepage sites in various structures of the Polar margins are considered below (**Figure 1**).

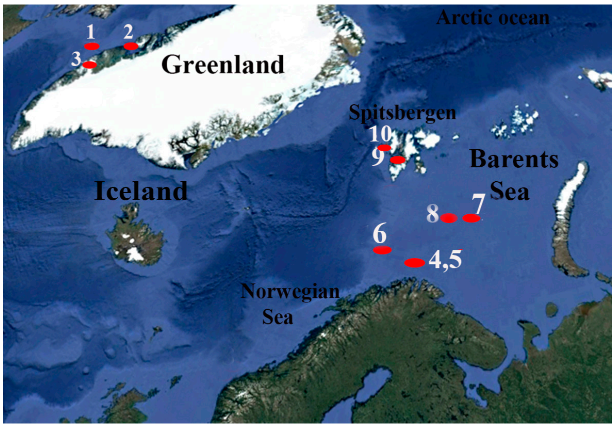


Figure 1. FR-scanning points (SP) position in the Polar Region, and their coordinates (1: 68°24.148 N, 55°43.383 W; 2: 69°12.762 N, 51°27.541 W; 3: 65°15' N, 51°50' W; 4: 71°36'00" N, 21°10'00" E; 5: 71°26'25" N, 20°47'10" E; 6: 72°00.05 N, 14°43.5 E; 7: 75°09'20" N, 32°05'00" E; 8: 75°00'00" N, 28°00'00" E; 9: 78°20'00" N, 15°27'00" E; 10: 78°39'12" N, 09°25'48" E.

3.1 Seepage areas in the central West Greenland margin

In the central part of the Western Greenland margin (Disko Bay region), two FR scanning points (PG2011-12 and PG2012-03), located within fields of pockmarks and seeps were selected for research [9-11].

Sounding point PG2011-12 (Ilulissat area) is located at the south-western flank of the Nuussuaq Basin, and near the mouth of the Isfjord **(Figures 2A and 2B)**, at a depth of 433 m, inside the largest pockmark, the width of which reaches 200 m, and the depth is 23 m. No acoustic indications for hydrocarbons within the Mesozoic strata have been reported for this distal part of the Nuussuaq Basin [9].

Seismic data showed that the pockmarks resulted due to expulsing fluids, neo-tectonic faulting, and crustal uplift [11]. Active modern gas migration in pockmarks was not observed, and it can be supposed that the pockmarks are the result only of neo-tectonic activity and gas hydrate was not involved in their formation in this area [9].

Our FR-sounding data of the PG2011-12 satellite image confirmed the modern active migration of gas but there are no signals from gas hydrates. Salt signals are recorded in the range of 435-882 meters. The joint signal of gas and salt is fixed in the interval of 468-742 m. FR data fixed the salt volcano presence with the root at 99 km. A hydrocarbon synthesis signal is recorded at a depth of 57 km.

Scanning point site PG2012-03 is located in the deepest part of a pockmark-like structure with a large diapir in the upper sediment unit where gas/fluid escape features lie close to the seabed [9]. The seismic data show that in an elongated depression (20 × 35 km large, 575 m deep) on the inner shelf west of Disko Bay younger sediments (**Figure 2C**) cover the Cretaceous-Paleocene strata with gas-hydrates and a bottom simulating reflector (BSR) below seabed [9].

The presence of gas hydrates is significant for future petroleum exploration offshore Greenland but gas hydrates there are mainly in sectors with a thin young sediment cover. The new geochemical data point to methane migration from a deeper-lying petroleum system [9].

These data are confirmed by the FR-sounding results at point PG 2012-03, where the signals of synthesis of oil, gas condensate, and gas at a depth of 57 km are recorded, and there are no signals of gas hydrates. It has been established that the signals at the resonant frequencies of oil, condensate, and gas are recorded only in areas, where the channels (volcanoes) are filled with certain groups of sedimentary and igneous rocks. In the survey areas, the responses from the Hydrocarbons are recorded at a boundary of 57 km within the central parts of the channels (volcanoes) of the deep fluid migration. Below this boundary, the responses are recorded at the frequencies of hydrogen and carbon, above that of oil, condensate, and gas.

The salt signal is fixed in the interval of 588-810 meters, and the joint signal of salt and gas is fixed in the interval of 590-766 meters (**Figure 2C**). The signals of dolomites (0.81-1.3 km, 2.0-99 km) and the ultramafic magma group (1.3-2.0 km, 99-470 km) are recorded. A degassing process with gas migration from the surface to the atmosphere is fixed though no sign of present-day gas seepage was found in the area [9].

These results support previous predictions that

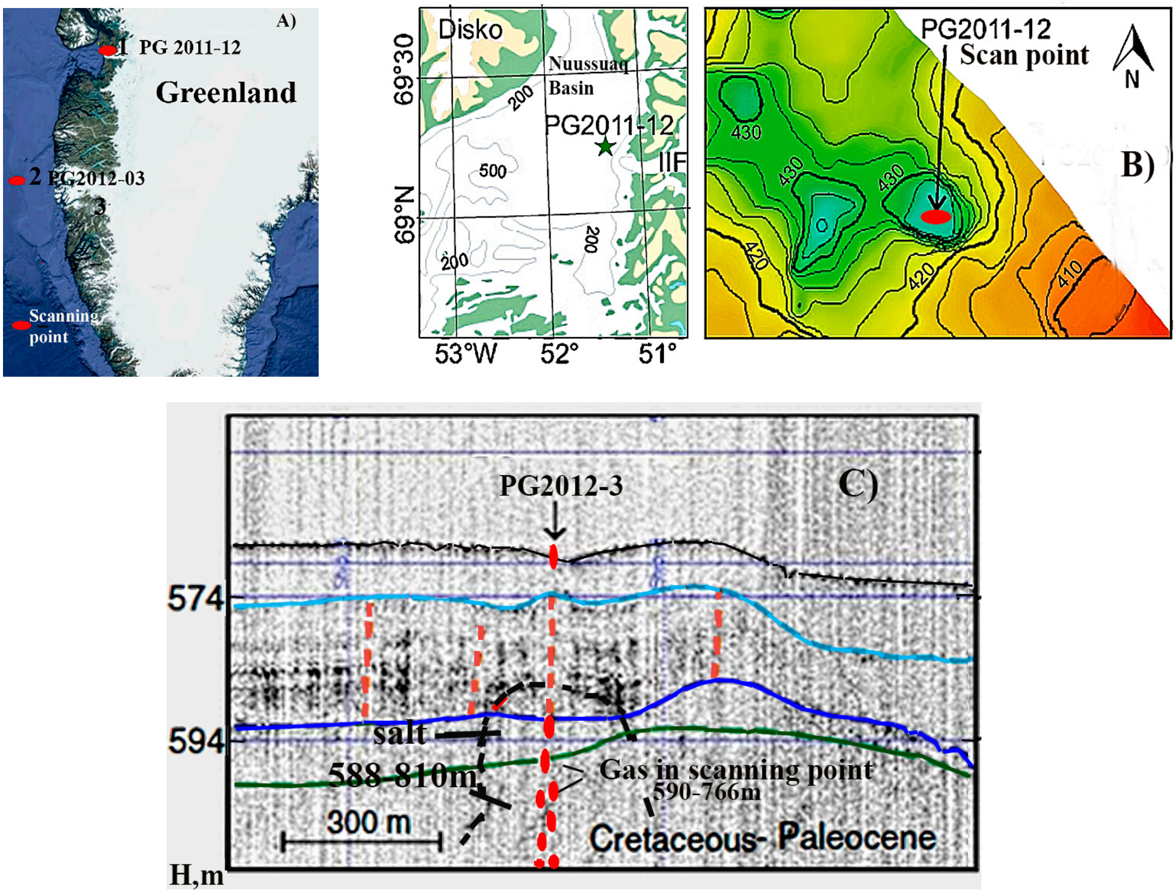


Figure 2. Seepage areas in central West Greenland continental margin (A); B: bottom relief in Nuussuaq Basin (Disko Bay) and PG 2011-12 scan point position off the mouth of Ilulissat Isfjord (IIF) [9]; C: high-resolution seismic profile structure across PG 2012-03 point. In (C) the light blue, dark blue, and green lines are the units in a 40 m thick sediment sequence; the orange lines are gas-fluid escape features [9].

Mesozoic sedimentary basins in the central West Greenland margins could hold high quantities of oil and gas but the processes of mature source rocks in the subsurface, their transformation, and the vertical and lateral migration of hydrocarbons into traps are enough debatable [12]. We suppose that gas originated not only from gas hydrates and the Cretaceous-Paleocene sediments because our data showed the possible realization of the abiotic hydrocarbon crustal-mantle generation mechanism in this as in other Arctic areas.

3.2 Maniitsoq structure, central West Greenland

The Maniitsoq structure in the North Atlantic Craton of West Greenland (**Figure 3**) has been proposed to host a ~3 Gyr old impact crater, allegedly the oldest on Earth but these interpretations have been challenged [13,18].

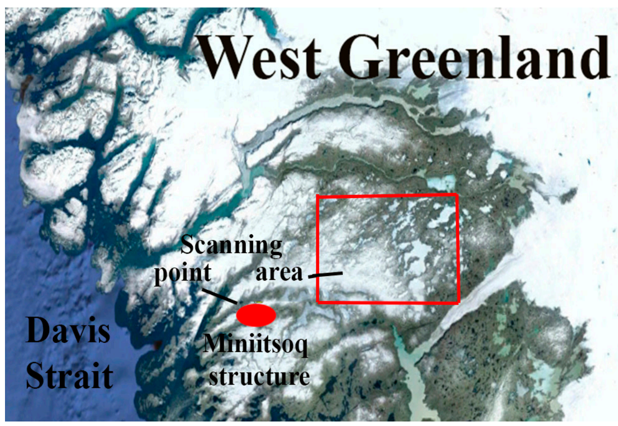


Figure 3. FR-scanning point in Maniitsoq structure position in West Greenland (65°15’ N, 51°50’ W) and scanning area with the possible process of hydrogen degassing position (red square).

Many geological features in the Maniitsoq region associated with impacts (from microscopic structures at the mineral scale to macroscopic structures at the terrane scale, as well as the age and geochemistry of rocks) can be explained by endogenous (non-impact) processes that are related to magmatism, metamorphism, and deformation associated with tectonometamorphic reworking and stabilization of the North Atlantic Craton in the late Archean [13].

During the processing using the FR methods of satellite images within the Maniitsoq structure (scanning point position in **Figure 1**), a volcanic complex filled with ultramafic rocks was discovered with a root at a depth of 723 km. It is an additional argument in favor of the endogenous nature of its origin. A volcano with a root at a depth of 99 km and an upper boundary at a depth of 15 m was discovered in the surveyed hydrogen-degassing area located to the East of the Maniitsoq structure (**Figure 3**, red square). Responses at hydrogen frequencies are recorded here from 25 m. The results of the study of areas of active hydrogen degassing were found according to the data of FR-scans in various regions of the world [8].

Thus, the results of experimental studies using the FR scanning method provide new independent information indicating the endogenous (non-impact) nature of this structure, which is confirmed by the materials of modern geological and geochemical studies [13].

3.3 Barents Sea areas

We used the FR methods to study the nature and determine the degassing processes' sources origin, and the depth of their formation in various structures of the Barents Sea, including in areas where large gas fields are located, and hydrocarbon fluids migrated from deep-seated reservoirs (**Figure 1**).

Southwestern Barents Sea, Hammerfest Basin

The SW Barents Sea is located between Norway and the Svalbard archipelago. There are large seeps and pockmarks areas, gas chimneys, and leaking faults systems that show hydrocarbon leakage and fluid migration in structures of this Region.

The known Snøhvit and Albatross fields are located in the SW Barents Sea, in the Hammerfest Sedimentary Basin (**Figure 4**).

FR methods were used in this area where the sub-bottom hydrocarbon fluid-flow process and leakage were discovered by seismic data that included zones of chaotic low-amplitude seismic, discontinuous reflections in the seismic records, areas of high amplitude anomalies, vertical fluid flow features and shallow gas accumulations [14].

Active methane seepage in the study area may be due to the thermogenic and abiogenic oil and gas source, the negative effect of global warming on the ice sheet, permafrost, and gas hydrate stability, some mechanisms of the influence of deep faulting tectonics and tectonic deformation system in the lithosphere-asthenosphere. Other factors such as neotectonics, glaciation history, and deep and shallow degassing processes from hydrocarbon reservoirs of the petroleum system that includes multiple source rocks from the Carboniferous to the Cretaceous are the major factors too [14].

The major deep-seated faults are the main hydrocarbon migration pathways from the deep source rocks and the reservoirs; further leakage to the seabed was through the smaller Paleocene to Early Eocene faults. The major gas chimneys in the southwestern and northeastern parts of the field originated from the Triassic source and reservoir rocks [15,16].

As a result of FR scanning at a point near 7121/4-1 well (Snohvit Field) the gas signal is fixed in the intervals: 362-496 m, 515-673 m, 769-879 m, 896-1027 m.

Obtained data can confirm the fact that natural shallow gas is discovered in some deep hydrocarbon layers of reservoir rocks stacked vertically in the scanning points and formed gas chimneys, pockmarks, and fluid escape pipes in this area.

At the surface, a signal of degassing is recorded, and their gas migrates to the atmosphere (**Figure 4B**).

FR scanning shows that gas signals of high intensity are fixed up to 10 km. We think that the roots of this petroleum system originated not only in source rocks from the Carboniferous to the Cretaceous [14]

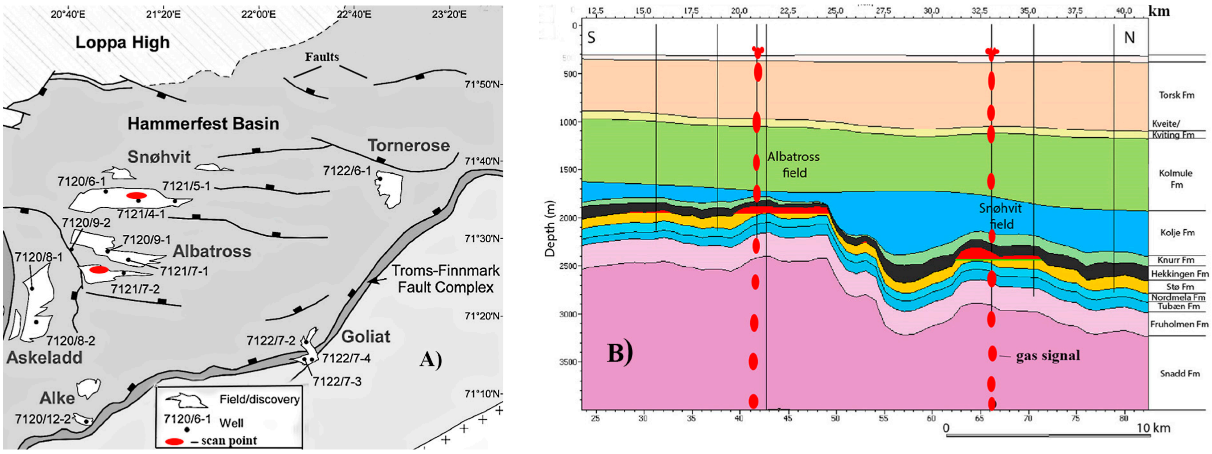


Figure 4. Schematic map (A) of the Hammerfest Basin (SW Barents Sea) with structural elements, Fields and wells [15,16]; B: a well section profile across the Snøhvit reservoir with the results of FR scanning and the depths of the reservoirs [17].

but much deeper, at a depth where a hydrocarbon synthesis signal is recorded [5-8].

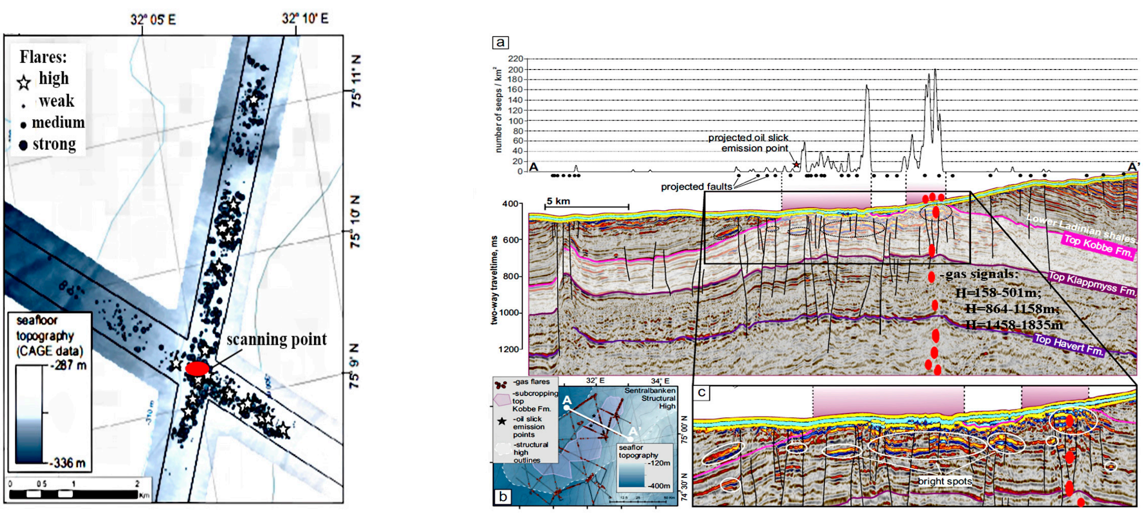
The Haakon Mosby mud volcano

Seafloor mud volcano Haakon Mosby (72°00.05 N, 14°43.5 E) with a diameter of 1.5 km is located in SW Barents Sea at a depth of 1250 m in the area between the coast of Norway and Bear Island (**Figure 1**).

It was discovered in 1995. The main products of its eruptions are mud and gases, of which more than 99% is methane. Under the mud volcano, there is a 1- to 2-km-wide disturbed zone with free gas which extends to a depth of > 3 km [18]. Reconnaissance scanning showed that oil and gas signals were found in the section of the mud volcano, and the emission of gases into the water column was also confirmed.

Northern Norwegian Barents Sea, Sentralbanken high area

Methane fluxes from > 7000 seeps in the Arctic significantly deplete seawater, but nevertheless, reach the sea surface and may transfer to the atmosphere [19,20]. 4,137 acoustic 'flares' diagnostic of bubble emission sites (seeps) were identified at the Sentralbanken area with the highest gas flare density in the central part of this structural high (**Figure 5**).



A

B

Figure 5. Gas flares location (A) in the Sentralbanken high area [20]; B: correlation of gas release and sub-cropping reservoir Kobbe Formation and faults. a: seepage density, faults, and sub-cropping Kobbe Formation along transect A-A'; b: transect A-A' location; c: bright spots distribution within the apex of Sentralbanken structural high [20]. There is also a possible depth of gas signals by FR scanning (B, a, c).

The results of FR scanning in the Sentralbanken area show that the signal of old granites is recorded from 470 km. The signals of oil, gas, and gas condensate are recorded at a depth of 57 km. The gas signal is fixed in depth intervals: 158-501 m, 864-1158 m, 1458-1835 m, further probing was not carried out. The gas signals are recorded in the depth range of 1,835-10 km. The signal of gas hydrates is fixed in the interval 0-400 m. The degassing process from the water surface into the atmosphere is recorded.

These obtained data indicate the existence of additional sources and processes of deep degassing that can explain the magnitude of the formation and manifestation of seep and pockmark fields in various structures of the Barents and other seas of the Arctic region.

Norwegian Barents Sea

The first studies of pockmark fields in the Norwegian part of the Barents Sea [19-21] showed that the main part of the round or oval pockmarks found during the research had a diameter of 10 to 400 m and a depth of 2 to 15 m, and was found in the form of single structures, clusters, and extended chains.

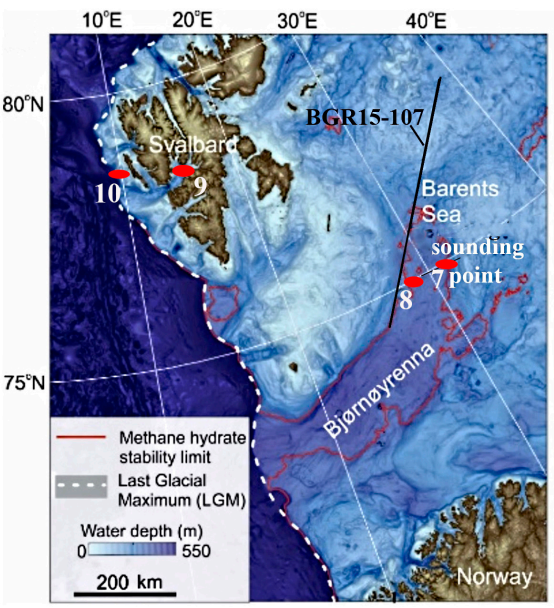


Figure 6. The sounding points in the degassing areas in the Barents Sea [19,20] and Spitsbergen [26,28], and the modeling profile position in the Norwegian part of the Barents Sea [22].

The formation of such accumulations of pockmarks could occur in various areas of the Barents Sea as a result of seepage of gases of deep or biogenic (in the case of thick sedimentary strata) origin [23].

Gas flares (more than 600), consisting of 97% methane and rising above the bottom to a height of up to 200 m, as well as numerous pingos (heaving mounds), the diameter of which reached 1100 m, were found at the research site, and the height is 20 m. Methane flares confirm the presence of modern degassing processes in this region, caused, according to the authors, by the decomposition of gas hydrates [19].

From our point of view, the formation of such gigantic (more than 1 km in diameter) pockmarks requires the involvement of additional sources of impulsive methane supply over a long period. The mechanism of deep degassing by "gas pipes" through accumulations of gas hydrates seems to be more reliable in explaining the formation of these large bottom structures. Such a mechanism was proposed for one of the sites (Hornsund Fault Zone) in the northwestern part of the Barents Sea [2].

The results of FR-sounding (up to 8.0 km) in the area of accumulation of giant pockmarks and pingos (**Figures 6 and 7**) showed that signals from hydrocarbons and the presence of gas accumulations are recorded here at depths: 1.3-2.0 km, 2.29-3.12 km, and 3.32-4.5 km. The intervals of these distinguished depths of gas accumulations are close to the depths of oil and gas—bearing Paleocene-Eocene and Middle Triassic horizons containing hydrocarbon source rocks enough for the formation of oil and thermogenic gas [22-24]. The presence of a fault system (**Figure 7**) makes it possible for deep gases to migrate to the upper horizons of the sedimentary strata, which creates additional conditions for the formation of pockmark and pingo fields in this area.

3.4 Spitsbergen area

Seep area in the Greenland Sea

On the continental margin of Svalbard (**Figure 1**), the field of seep accumulations was studied and the main factors of the formation and evolution of the gas hydrate stability zone were determined, as well

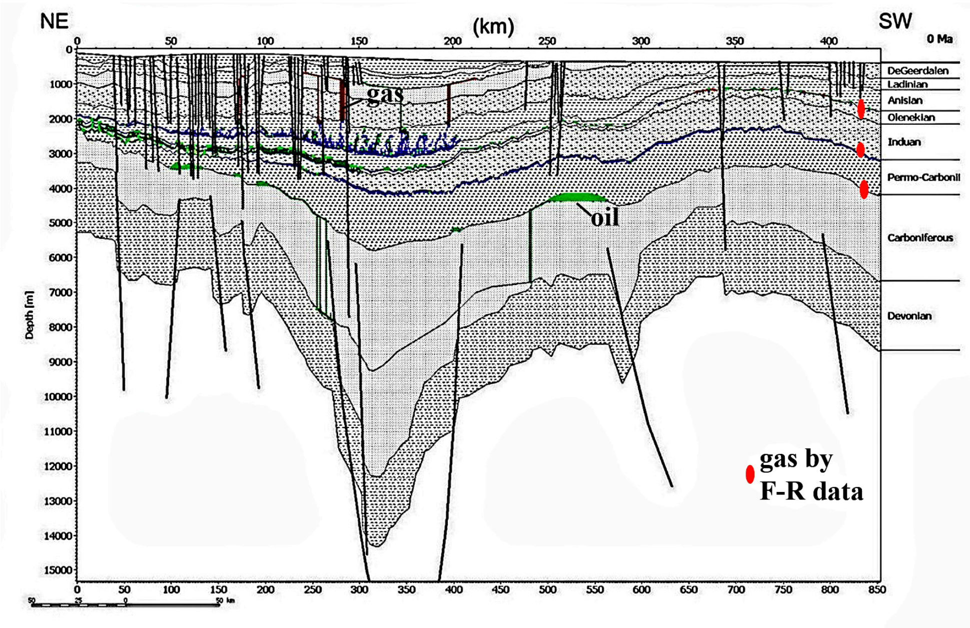


Figure 7. Modeling profile BGR15-107. The position of faults, accumulations of hydrocarbons, and the boundaries of oil-saturated (above the threshold value of 0.01%) sedimentary rocks are shown [22]. The position of gas accumulation zones according to FR-sounding data in the southwestern part of the section is also shown. The position of the profile is in **Figure 6**.

as the patterns of distribution of sources of methane plumes in the section [25,26].

The zone of stability of gas hydrates extends to a depth of 370-410 m (**Figure 8**), and the available results of seismic studies show the presence in this area of a system of "gas pipes" through which gas migrates into the sedimentary strata from deep gas "pockets" [25]. The authors suggest that the "gas pipes" do not reach the bottom surface.

The mechanism of gas transfer has not been sufficiently studied, since no extended, going to great depths, faults, which are considered to be the main

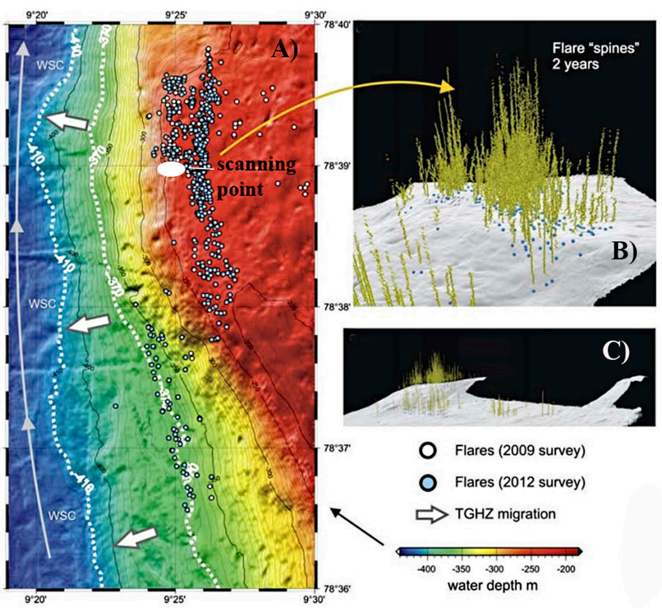


Figure 8. Bathymetric map (A) of the continental margin of the Spitsbergen area with a field of seeps (A) and their three-dimensional image (B, C) in the study area [26]. WSC, CC, and ESC are the dominant currents in this area (Western Spitsbergen; Coastal; East Spitsbergen Current). Arrows indicate the migration of the gas hydrate stability zone (TGHZ) over the past 30 years from a depth of 370 m to 410 m [27].

element of the influx of deep fluids into the sedimentary strata, have been found in the study area.

Studies of seep fields identified along the continental margin to the west of Svalbard at depths of 150-400 m showed that the released methane is due to the dissociation of gas hydrates due to a 1 °C increase in the temperature of the West Svalbard Current over the past 30 years. The presence of numerous additional flares at the shelf suggests that this particular region west of Prins Kalrs Forland is prone to hydrocarbon seepage and that gas seafloor emission unaffected by gas hydrate dissociation is common in the region [27].

It is assumed that such a relationship between the formation of methane seep fields and the processes of destruction of gas hydrates is also characteristic of other regions of the polar Arctic.

Based on the results of FR sounding at a scanning point in the central part of the seep field (**Figure 8**), gas accumulations were identified that form methane flares of this field, located in the upper part of the earth's crust.

Degassing processes occur from depths: 731-905 m, 1084-1141 m, and 1370-1471 m (deeper sounding was not carried out). In addition, gases emission into the water column and the atmosphere are recorded.

Spitsbergen, Isfjorden area

The Spitsbergen and its continental margins' cold seeps are the most studied by geophysical methods in the Arctic. The degassing processes investigation in this area contributed to a detailed study of the formation and evolution of gas hydrate and free gas accumulations, as well as the nature of their sources [2]. Particular emphasis in these works was placed on the study of the dynamics of the dissociation of gas hydrates and gas emissions associated with paleoclimatic changes in the region. Their important result was the identification of numerous fields of pockmarks, as well as associated "degassing pipes" and systems of tectonic faults extending to considerable depths [23-31].

The distribution of pockmarks in Isfjorden has a mosaic character [28], and their most actively expressed fields are spatially associated with known active fault zones of the Svalbard fold-thrust belt and other faults (Billefiorden, Isfiorden Fault Zones).

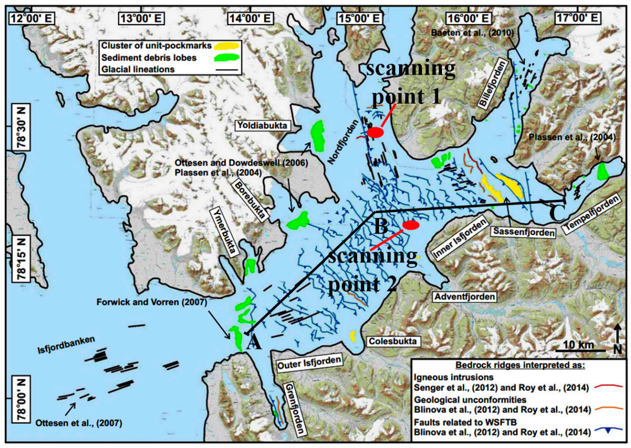


Figure 9. Satellite image of the Isfjorden in Spitsbergen [28] with the scanning points position; A-B-C: seismic profile [29] position.

One of the scanning points of the satellite image of the Svalbard archipelago (scanning point 1, SP1) is located in the north of Isfjorden, in Nordfjorden, in the central part of a large accumulation of pockmarks (**Figure 9**), formed on the southeastern continuation of the Blomesletta fault.

More than 1300 pockmarks (diameter from 14 to 265 m, depth from 1 to 11 m, and frequency of distribution up to 20 per km^2) were found in Isfjorden, and 535 pockmarks—in Nordfjorden [28].

Their genesis can be determined by the influx of hydrocarbon fluids (of biogenic or thermogenic origin), decomposition of gas hydrates, thawing of permafrost, and a number of other factors operating in polar latitudes. Geochemical analysis of hydrocarbon anomalies in the near-surface marine deposits of the fjords in the west and around Svalbard indicates a mixed (thermogenic and biogenic) nature of gases [28,30].

Detailed analysis of geophysical data in Nordfjorden showed the presence of gas flares only above a part of the pockmark fields (**Figure 10**), which may be due to the absence of modern degassing processes and sufficient gas accumulations under them, as well as to changes in the paths of deep fluid migration.

The complex filled with sedimentary rocks of groups 1-7 and 10 were identified at site SP1 (**Figure 10**), with a root at a depth of 470 km. Signals from oil, gas, gas condensate, carbon dioxide, methane-oxidizing bacteria, yellow phosphorus, oil shale, gas hydrates, anthracite, nitrogen, oxygen, carbon, and ice have been registered [2,5-8].

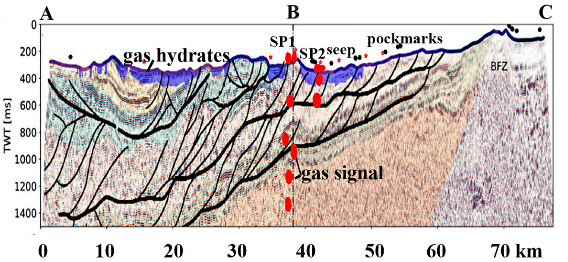


Figure 10. Geological cross-section with GHSZ extents of A-B-C profile [29]. The location of the seismic transect across Isfjorden is shown in **Figure 9**. Pockmarks and flares within 250 m of the transect have been projected onto the profile. BFZ: Billefjorden Fault Zone. SP1 and SP2: FR scanning points.

Responses at the gas frequency were obtained at depths: 1335-1932 m; 2459-3321 m; 3933-4467 m. The sounding in point (SP1) was carried out to a depth of 4789 m. FR instrumental measurements at this point confirmed the gas migration into the atmosphere (**Figure 10**).

The degassing processes and gas migration into the atmosphere at sounding point 2 (SP2) were fixed too. The gas signals were fixed there in intervals: 290-615 m, 996-1159 m, and 1198-1314 m but deeper sounding was not carried out (**Figure 10**).

In the central part of Svalbard, the flow of thermogenic gas along fault zones and large tectonic lineaments may be the main geological factor in the formation of seeps and pockmarks, and other factors (the presence of free gas accumulations, filtration processes, seismic activity, and etc.) may be also important. It is also noted that faults and magmatic sills play an important role in the formation of channels for the flow of fluids into the pockmark fields and the water column in many areas. The processes of active gases entering the water column and the atmosphere can change over time; they depend on many parameters, including the thickness of the water column, temperature, and wave dynamics [31].

4. Discussion

At present, the formation of extensive fields of seeps and pockmarks in the structures of the Polar Regions is mainly explained by the processes of decomposition of gas hydrates. In this case, the presence of sub-hydrate gas in the section and the inflow of deep gas fluids of various genesis is often assumed, partially migrating to the upper horizons of sedimentary strata along faults that disrupt the continuity of gas hydrates.

The study of the fields of methane seeps and pockmarks showed that the intensity and dynamics of their formation largely depend on the influx of gas fluids, the sources of which are located in the deep horizons of the crust and mantle.

The areas of degassing are located within the zones of the existence of volcanic apparatuses with a developed system of deep channels, along which gases migrate, as well as deep oil and condensate. The result of such migration is the formation of gas seeps, as well as oil slicks on the water surface - indicators of deep oil synthesis.

Our data confirm the significant but insufficiently taken into account influence of crustal-mantle gas fluids on the nature and features of degassing processes in the structures of the continental margins of various regions.

The obtained data show that in all the structures studied, the influx of fluids formed in the deep horizons of the lithosphere cannot be ignored [3,5,6,8].

5. Conclusions

The results of FR soundings of structures in the polar Arctic Regions showed that gas hydrates could be formed in various horizons of sedimentary and crystalline rocks of the Earth's crust due to degassing products of the Earth's deep geospheres.

The use of FR technology makes it possible to quickly assess the contribution of various geological sources of methane and other gases to the overall balance of greenhouse gases in the places of their greatest emission.

On the basis of the obtained results of using the technologies of FR-sounding of satellite images and photographs for the structures of the Polar regions, a conclusion was made about the possibility of remotely determining the material composition, structure, and probable depth of occurrence of sources of deep geofluides migration in various geospheres of the Earth.

The proposed volcanic degassing model for hydrocarbon formation can explain many features of both large-scale and local degassing processes on the Earth.

We believe that modern FR technologies can significantly speed up the processes of remote detection and mapping of numerous new volcanic structures of various types in the World Ocean, as well as similar structures on the planets of the Solar system [6].

The results of the research showed that the use of reference frequencies for various types of known rocks and minerals makes it possible to apply frequency-resonance methods to study the deep structure of our planet and solve the problems of searching for many types of minerals.

Author Contributions

M.Y. and I.K. carried out the experiments and developed the concepts of this research. V.D. collected the data and wrote this manuscript with contributions on discussion from M.Y. and I.K. All authors contributed to reading, manuscript revision, read, and approved the submitted version.

Conflict of Interests

The authors declare no conflict of interest.

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