

Classification of anomalous methane fields in the Sea of Okhotsk

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Abstract: An original classification of anomalous methane fields according to the vertical structure of the water column in the Sea of Okhotsk is proposed. Basic types of anomalous methane fields are described: penetrating, near-bottom, deep, intermediate, subsurface, surface, and combined. Anomalous methane concentrations are greater than background values, sometimes by 1–3 orders (up to 30000 n/l above methane hydrates). Spatial and quantitative varieties of anomalous methane fields have genetic relations with different hydrocarbon sources. These varieties suggest a high permeability of active fault zones and geochemical activity in marginal areas, especially along the western Sea of Okhotsk.

key words: anomalous and background methane fields, water mass, methane venting, hydrocarbon accumulations, methane hydrates

1. Introduction

Methane in marine sediments (up to 90–98% vol. of natural combustible gases) and in the water column is an important subject for research. This research intends mainly to elucidate the considerable influence of methane-saturated fluids on geochemical (*e.g.*, authigenic minerals and gas hydrate formation), biological (*e.g.* breeding of microorganisms and macroorganisms), and ecological (*e.g.* increase of greenhouse gas content in the atmosphere) processes (Rehder *et al.*, 1998; Suess *et al.*, 1999; Elvert *et al.*, 2000; Bohrmann *et al.*, 2002; Paull *et al.*, 2003; Greinert and Derkachev, 2004). Methane, concentrated in the submarine gas hydrates, is considered to be a future energy supply (Max, 2000; Matsumoto, 2001). Furthermore, the presence of commercial oil and gas deposits in the marine realm gives recent investigations a special focus: they are aiming at solving problems that are connected with hydrocarbon energy resources. In this aspect, methane anomalies caused by gas release from hydrocarbon deposits are consid-

ered to be informative and interesting natural phenomena in the western Pacific (Abrams, 1992; Lammers *et al.*, 1995; Dafner *et al.*, 1998; Rehder and Suess, 2001).

Active methane venting was observed in the second largest marginal sea of the Pacific Ocean—the Sea of Okhotsk. Submarine methane emissions were explored mainly using measurements of huge anomalous methane concentrations in the water column (Obzhairov, 1996) (expressed as anomalous methane fields (AMFs) in space). Methane leakage to the seawater from active gas-venting sites within the thick Cenozoic sediment basins (up to 10 km) is linked to multiple hydrocarbon accumulations: oil and gas deposits (Kharakhinov, 1998), and gas (methane) hydrates (Obzhairov, 1992). Leaks are also likely to occur from coal-bearing complexes (Kudelkin *et al.*, 1986).

Onshore, the geospatial features of anomalous methane fields, realized particularly by their classifications, are well explored (Starobinets and Petukhov, 1993). These results are applied efficiently, particularly for hydrocarbon prospecting. Consequently, knowledge of AMF in detail is extremely important for applications. Attempts to develop methane spreading patterns in the water column have been made from the 1970s to the present (Geodekyan *et al.*, 1979; Rehder *et al.*, 1998; Obzhairov *et al.*, 2002; Yoshida *et al.*, 2004). However, classifications of anomalous methane fields in the water medium, based on systematic measurements, have not yet received careful scientific attention. This study is intended to elaborate a transparent approach for generalizing the background methane distribution and to classify its anomalous fields which are caused by gas emission from the geological hydrocarbon sources in the Sea of Okhotsk.

2. Materials and methods

This study bases upon a data set obtained within the scope of the Russian-German joint project KOMEX—Kurile Okhotsk Sea Marine EXperiment—subproject *Methane monitoring*, during 1998–2000. Results from six surveys of Russian research vessels were examined: RV *Akademik M.A. Lavrentyev* Cruise LV28 (3 Aug.–12 Sept. 1998); RV *Professor Gagarinsky* Cruise Ga25 (23 Sept.–6 Nov. 1998); an Ice Expedition by helicopter MI-8, (ICE1; 22–29 Mar. 1998); MV *Utyos* cruise Ut99 (19 May–15 June 1999); RV *Marshal Gelovany* cruise Ge99 (22 Aug.–5 Oct. 1999); and RV *Professor Gagarinsky* cruise Ga28 (2 June–16 June 2000).

Surveys were concentrated along the northeastern, eastern and southern shelves and slopes of Sakhalin Island, in the central part of the sea and in the Derugin and Kurile Basins. Additionally, data of methane content in the Sea of Okhotsk, along with data collected by the POI FEB RAS during 1984–1996 is used. Figure 1 shows locations of those surveys.

Positions of oceanographic stations were chosen to analyze methane distribution in water masses all over the sea. In total, 116 stations (1132 water samples) were analyzed. Sampling was performed in different layers of the water column according to temperature, pressure, density, and other hydrological profiles. The probes were a MARK-IIIC WOCE (General Oceanics Inc., Miami, FL, USA), a 3" MICRO-CTD (Falmouth Scientific Inc., Cataumet, MA, USA), and a Seabird 911 CTD (Seabird Electronics Inc., Bellevue, WA, USA). Additionally, 113 water samples obtained from

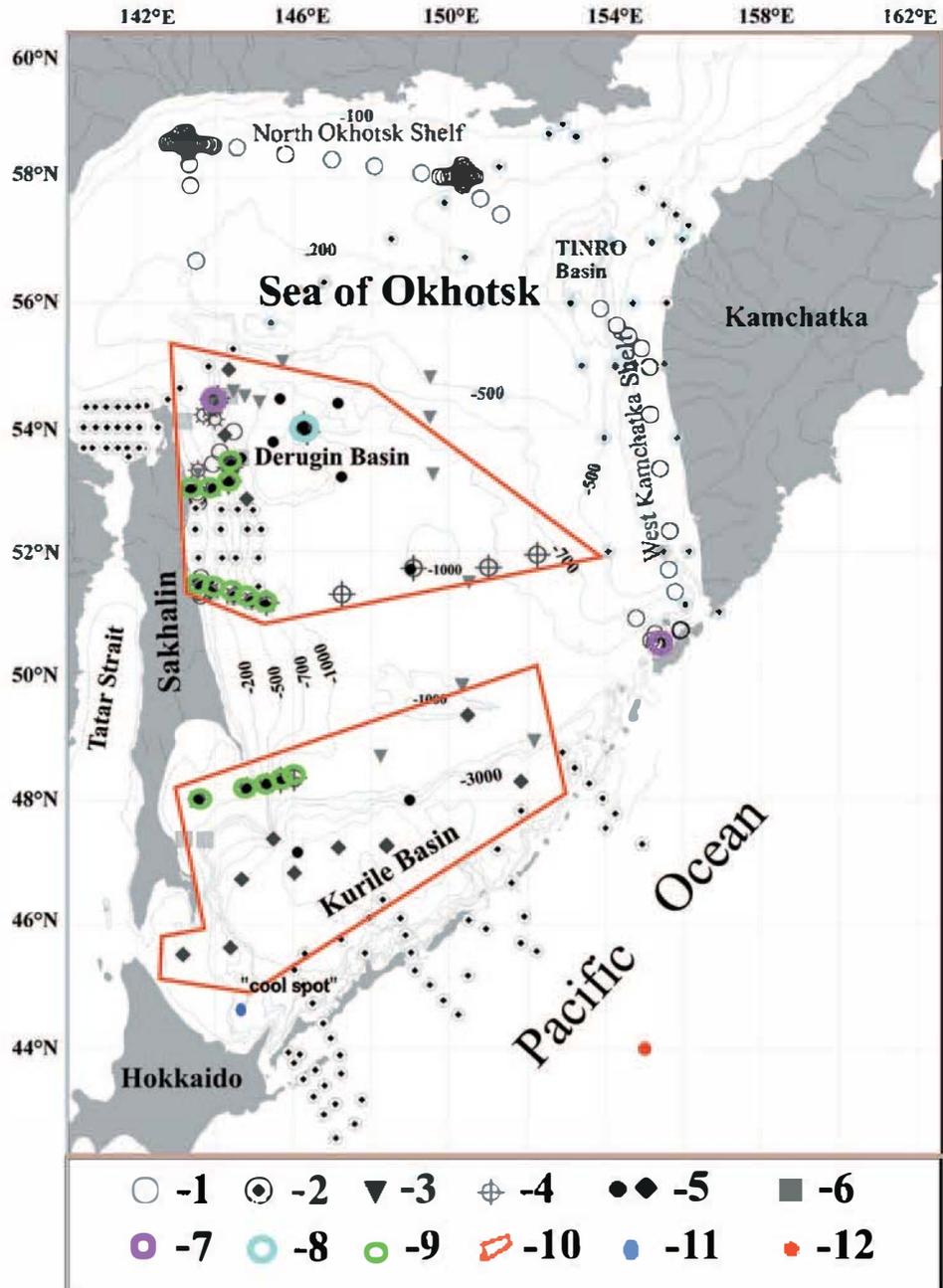


Fig. 1. Map of the basic gas geochemical surveys in 1989–2000. 1: methane hydrate site monitoring, 1998–2000; 1: 1988; 2: 1993; 3: 1996; 4: 1998; 5: 1999; 6: 2000; 7: gas hydrate findings; 8: “Barite Mounds” area; 9: interannual monitoring stations; 10: KOMEX investigation areas; 11: “cool spot” (Sasaki *et al.*, 2002); 12: Station KNOT (Tsurushima *et al.*, 2002). Bathimetry: Svarichevsky (2001).

RV *Akademik Nesmeyanov* (1993) in the Pacific Ocean near the Kurile Island area were included in this study. Those water samples were collected using a *Rosette* (Sea Bird 32 12-position system; Seabird Electronics Inc.) and NISKIN-type bottles. The sampled water was taken from bathometers in non-contact with the atmosphere using soft pre-vacuumed samplers. The analytical method for methane content determination in water samples (unit: n/l) is described in Obzhirov (1993).

3. Results and discussion

3.1. Background methane distribution

All varieties of gas geochemical fields are classifiable into two general types: background and anomalous (Starobinets and Petukhov, 1993). Background concentrations of the fields' components and features of their spatial dispersion should be clarified a priori for studying any anomalous geochemical field. Moreover, knowledge on background gas geochemical fields within the hydrocarbon bearing sediment basins is an important goal for hydrocarbon deposit prospecting.

The authors have analyzed the background methane content in each basic water mass of the Sea of Okhotsk. Vertical intervals corresponding to the general Okhotsk water mass structure (Moroshkin, 1966; Terziev, 1998) were chosen for the background methane values computation (Table 1). The subsurface layer was excluded because high methane concentrations were constantly registered inside it (subsurface maximum). In addition, two points for the deep-water layer were computed because of the great vertical pressure change that occurred there.

Background values were established separately for each water mass using a normal

Table 1. General vertical water structure of the Sea of Okhotsk (after Moroshkin, 1965; Terziev, 1998) and corresponding anomalous methane fields.

Depth, m Water mass /Anomalous methane field	Area					
	Sakhalin Shelf		Sakhalin Slope	Deep areas (central sea, basins)		
	0–100 m	100–200 m	200–700 m	700–1000 m	1000–2000 m	2000–3500 m
Surface layer / Surface AMF	0–5 bss	0–5 bss	0–10 bss	0–50 bss	0–50 bss	0–50 bss
Subsurface layer / Subsurface AMF	—	5–50 bss	10–100 bss	50–200 bss	50–200 bss	50–200 bss
Intermediate layer / Intermediate AMF	—	—	100 bss–50 asf	200 bss– 100 asf	200–1000 bss	200–1000 bss
Deep layer / Deep AMF	—	—	—	—	1000 bss– 100 asf	1000 bss– 100 asf
Near-bottom layer / Near Bottom AMF	0–5 asf	0–5 asf	0–50 asf	0–100 asf	0–100 asf	0–100 asf

bss—below sea surface; asf—above sea floor

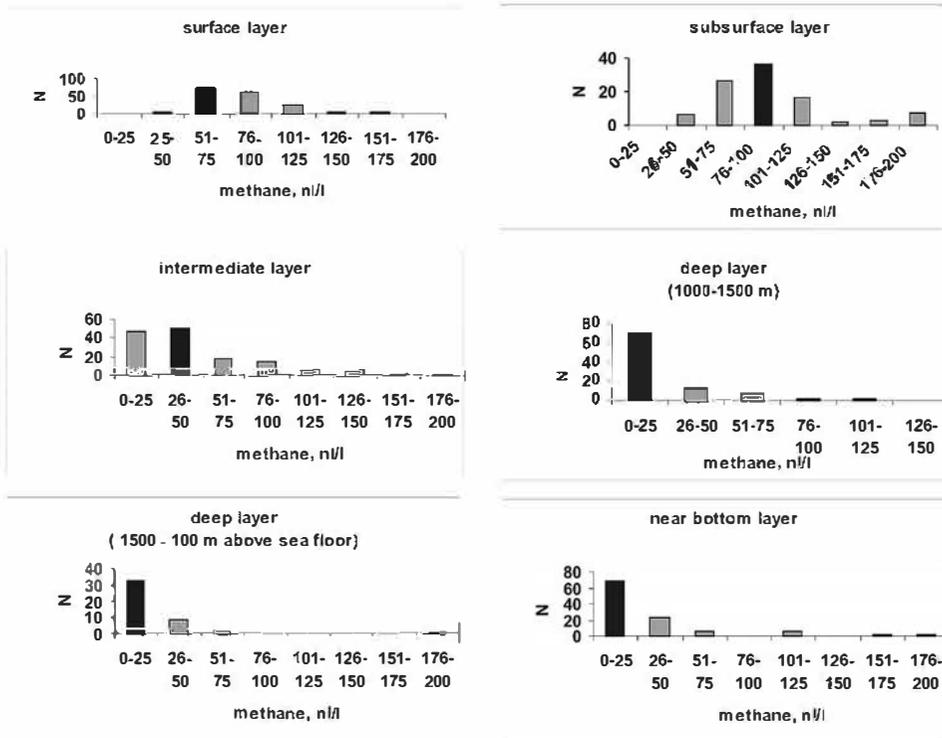


Fig. 2. Gaussian histograms of methane concentration value frequencies in Okhotsk water masses.

distribution (Gaussian) function. Areas with extremely anomalous values (>400 n/l), which were detected everywhere at the eastern Sakhalin shelf and slope, were not included. The total representative data collection comprised 955 samples. Gaussian histograms, showing frequencies of methane concentrations for definite water masses, are depicted in Fig. 2. The average (modal) values obtained for the most frequently occurring concentrations, as a first approximation, were considered the methane background values.

The background methane profile for the Sea of Okhotsk (the Okhotsk Background Curve) is shown in Fig. 3a. The curve has a characteristic vertical pattern that closely resembles major diagrams of methane distribution in areas where submarine gas venting does not occur. The maximum values of background concentrations were limited to the 50–200 m layer below the sea surface in all cases. Below 200 m, methane concentrations decreased gradually toward the seafloor. Above the methane maximum toward the sea surface, background values decreased close to the equilibrium with atmospheric values of 60–70 n/l.

Vertical background methane distribution for the Pacific Ocean near the Kurile Islands (“Pacific Background Curve”) was analyzed using the same methodology for verifying previous results. It is noteworthy that analyses of the available data have shown an almost equal vertical background methane distribution to 1000 m below the

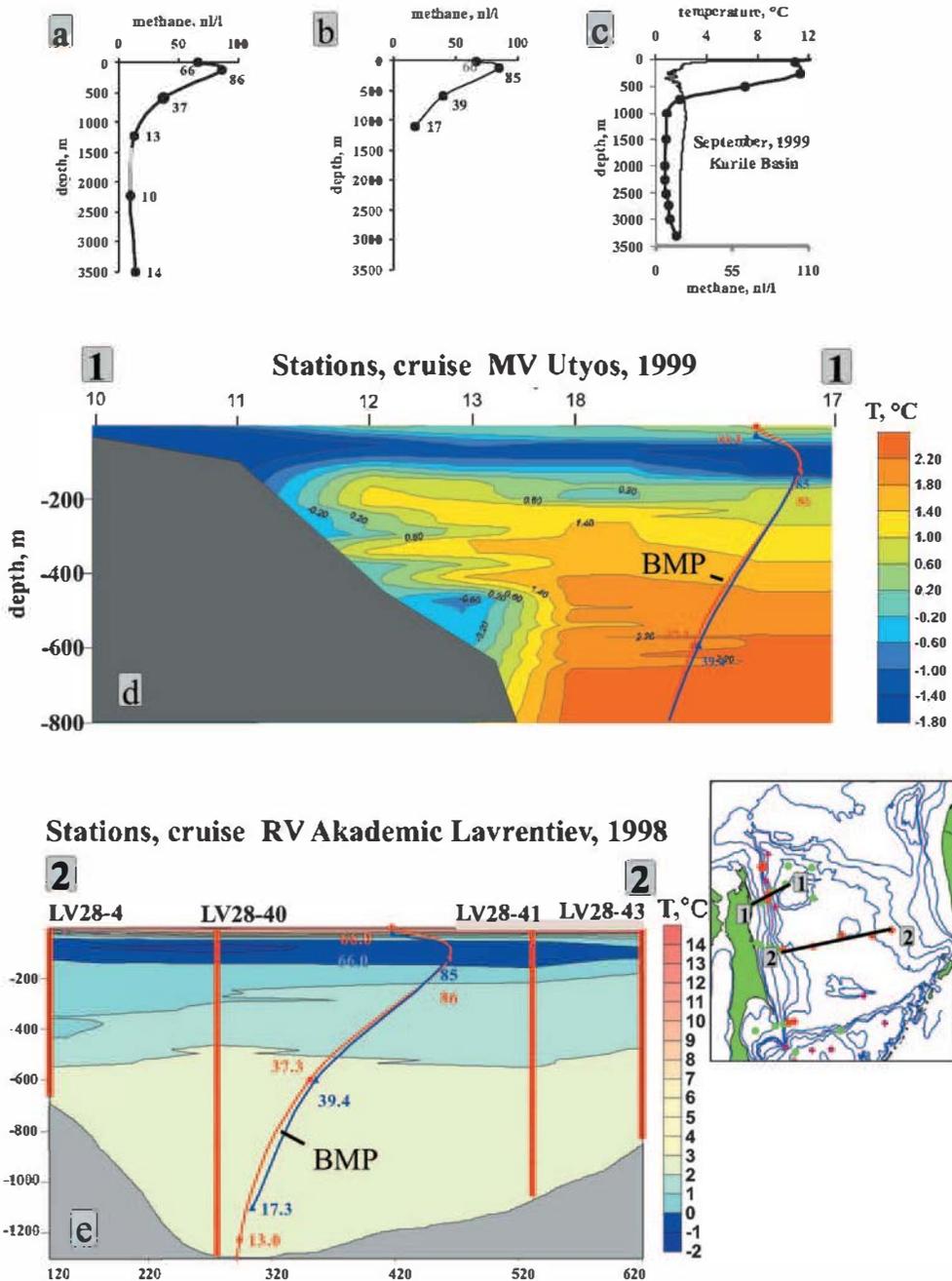


Fig. 3. Background methane distribution in the water column. a: Sea of Okhotsk; b: Pacific Ocean near the Kurile Islands; c: example of the background methane distribution and temperature in the Kurile Basin water column; d–e: temperature sections for late spring 1999 and early autumn 1998 (see map location, BMP: background methane profiles).

ocean surface (Fig. 3b). Unfortunately, sampling under this level was not performed.

It is presumed that the subsurface methane maximum results from biological production (Geodekyan *et al.*, 1979; Tsurushima *et al.*, 2002). An additional reinforcing feature for the subsurface maximum in the Sea of Okhotsk might be the slight suppression of methane dispersion in the cold subsurface layer, which probably results from growth of its solubility at low temperatures at 50–200 m below the ocean surface, which are constant year-round (Figs. 3d and 3e).

Comparison has shown that the “Okhotsk Background Curve” and “Pacific Background Curve” are almost identical to the first general type of methane distribution in the seas and oceans examined by Geodekyan *et al.* (1979). Moreover, they correspond

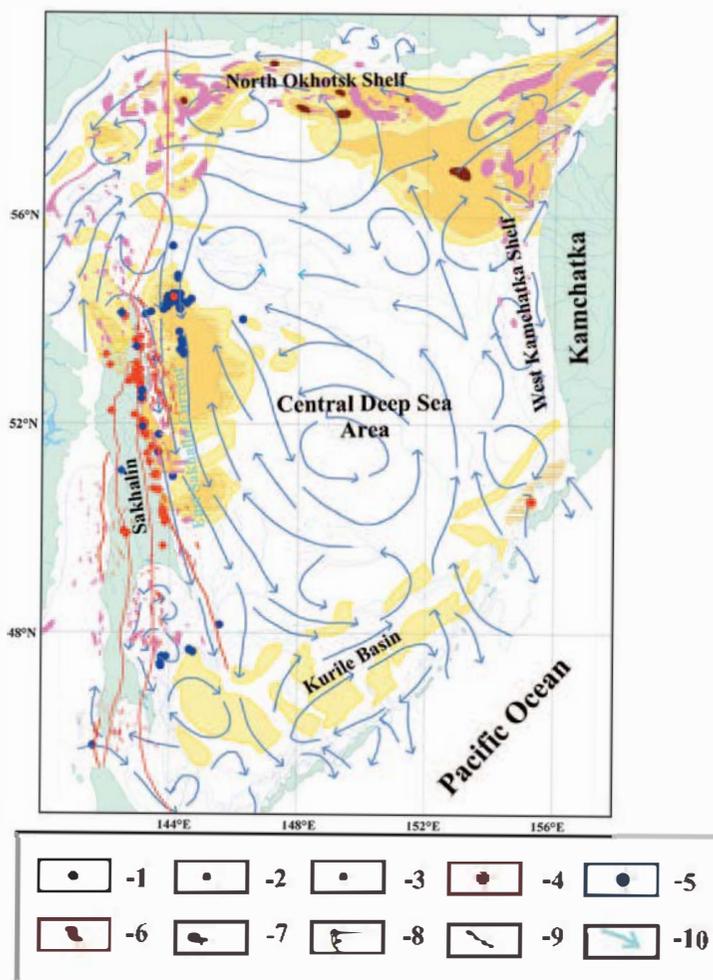


Fig. 4. Distribution of hydrocarbon sources and methane vents in the Sea of Okhotsk. Legend; 1: fields; 7: local structures; 8: isopachits (sediment cover thickness); 9: faults; 10: currents; 11: concentrations in the near-bottom water layer (1 m above sea floor); 13: charts of methane con-

lowest potential of hydrocarbon generation $<5 \times 10^6$ t/km² (Fig. 4).

The potential of hydrocarbon generation (PHG), used in this work, is a complicated parameter that was developed based on the content and composition of dispersed organic matter, rock's associations, thermodynamic conditions, and the quantity and quality of generated hydrocarbons in marine sediments studied over a long term in the Sea of Okhotsk (Gretskaya, 1990; Gretskaya *et al.*, 1992).

Subsequent sections describe anomalous methane fields in water layers caused by gas emission from hydrocarbon sources (areas, characterized by highest PHG), especially in the western part of the sea.

3.2. *Anomalous methane fields (AMF)*

3.2.1. Methane sources

It is reasonable to infer that the initial source of most large submarine hydrocarbon accumulations is dispersed organic matter submerged in the sediments. Because of organic matter maturation and transformation in different thermobaric and geologic states and following migration and accumulation of liquid and gaseous hydrocarbon compounds, the formation of primary accumulations such as oil and gas deposits occurs. Seismo-tectonic activity can cause intensive upward migration of methane, ethane, propane and other gases from these deposits, generating secondary accumulations as gas pockets or gas hydrates in the upper sediments. Biogenic production of methane in surface sediments is also an important factor of organic matter degradation. When gas saturated fluids migrate through the upper sediments and penetrate the sea floor, particularly through fault systems, pockmark-like structures and gas vents can originate, accompanied by acoustic anomalies in the water column, deformations of the Bottom Simulating Reflector (BSR), mud volcanoes, and even gas-hydrothermal springs.

The compiled map shows that the distribution of discovered sites of methane emissions is located within zones of the highest density of PHG and is related geologically with hydrocarbon deposits, local structures, and recent faulting along the sea margins (Fig. 4).

It is necessary to note that gas seeps are widespread on the inner slopes of trenches (subduction zones) and are connected with the existing fault pattern and tectonic stress, for example, in the Japan and Nankai Trenches (Kaiko-Tokai Project, 1998). The eastern Sakhalin offshore region, including the island's slope, is related to another type of plate boundary—the transform boundary (Biebow and Huetten, 1999). Modern high seismic activity (Karp and Bessonova, 2002) and active faults that break through the sea floor (Baranov *et al.*, 1999) create a perfect gas-permeable state along this border. Anomalously high ambient methane concentrations in the water column reflect that situation geochemically.

3.2.2. Classification of anomalous methane fields (AMF) and their origin

The common scheme of the Sea of Okhotsk vertical water mass structure (Table 1) was applied to classify anomalous methane fields (AMF). The title of AMF corresponds to a water mass title (*e.g.* near-bottom water mass—near-bottom anomalous methane field). If AMF is proved in some, but not all, water masses, they are called *Combined*. We used the term *Penetrating* AMF if the anomalous content of methane was found throughout the water column. By their term variety, only two types of AMF are

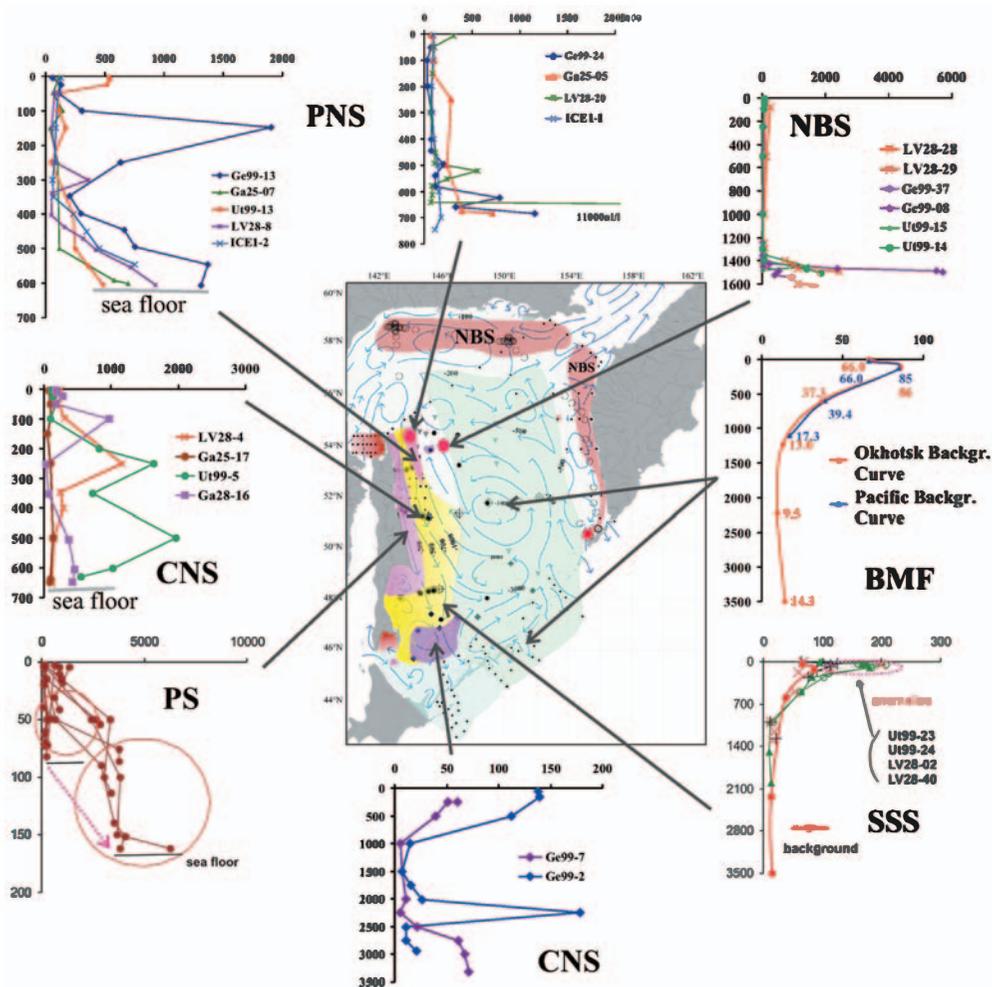


Fig. 5. Distribution of the most typical anomalous methane fields in the Sea of Okhotsk water column. PS: penetrating-steady, red arrow indicates an increase of methane anomalies values from shallow shelf toward shelf break (NE, E and SE shelf of Sakhalin Island); PNS: penetrating non-steady; NBS: near-bottom steady (NE-flank of the Derugin Basin, “Barite Mounds” site); SSS: subsurface steady (E and SE Sakhalin slope’s foot); CNS: combined non-steady (E-Sakhalin slope); BMF: background methane field. Diagrams; axe X: methane concentrations (nl/l), Y-axis: depth (m).

discussed in this work. The *Steady* type is a constant-in-time field of anomalous methane concentrations proved in all surveys. The *Non-Steady* type was registered in several, but not all, methane monitoring surveys.

The most widespread vertical types of AMF following this scheme are illustrated in Fig. 5 because a detailed discussion of the AMF spatial and term oscillations is beyond the scope of this study.

Penetrating Steady AMF occurs along the eastern shelf of Sakhalin Island, includ-

ing the inner part of Terpeniya Bay (Fig. 5, PS). Its distribution implies that such an AMF is a characteristic feature for shallow waters (<200 m) of the eastern oil-gas bearing Sakhalin shelf. Notably, average values of the near bottom methane anomalies increase from the shallow waters toward the shelf edge. Consequently, methane concentrations of 500–2000 nl/l are mostly registered at depths of 50–100 m and of 3000–4000 nl/l at 100–200 m depths.

The East Sakhalin Shelf is dominated by the East Sakhalin Basin, which contains almost all oil and gas deposits discovered in the Sea of Okhotsk (Fig. 4). The sediment cover in the study area is up to 7–10 km thick (Margulis *et al.*, 1979; Gretskeya *et al.*, 1992); numerous active faults controlled by the large shear zones are conduits for the steady methane release to the water column. Several shallow flares, which mark sporadic gas escapes, mud volcanic manifestation, and anomalous CH₄ content in surface waters (up to 1000 nl/l), identify the eastern shallow shelf of Sakhalin as an important source of atmospheric methane.

Penetrating-Non-Steady AMFs are developed particularly along the northeastern Sakhalin shelf break and slope (Fig. 5, PNS). The highest anomalous methane concentrations (up to 30000 nl/l) in the water column of the Sea of Okhotsk were measured constantly in this area, particularly above near-surface gas hydrates (usually 1–3 m below the sea floor). Methane concentrations decreased sharply to values of 300–400 nl/l toward the sea surface. In the near-bottom and intermediate water layers concentrations of 5000–10000 nl/l were observed that are 2–3 times higher than background values. In gas hydrate-bearing sediments (Dullo *et al.*, 2004), the methane concentration reached 1100 ml/l.

Apparently, the anomalous methane field in this area originated from an active gas escape from gas-hydrate bearing sediments (Fig. 4). Numerous gas vents emit methane and are accompanied by acoustic anomalies—flares—which were mapped along northeastern Sakhalin in the longitudinal direction at a distance of about 170 km. Their biggest accumulation (>250 flares) was observed by different surveys in a *ca.* 875 km² area.

A highly representative *Near-Bottom Steady* AMF was observed in the northeastern flank of the Derugin Basin in the “Barite Mounds” area (Biebow and Huetten, 1999). Methane concentrations of 900–5700 nl/l were measured in the near-bottom, 70–100 m thick, water layer (Fig. 5). Around this area, only a background methane distribution was found. The source of methane and barium rich fluids is probably connected with remnant postmagmatic low thermal processes within the rift zone (Kulinich and Obzhirov, 2003).

Another example of a *Near-Bottom Steady* AMF is a small cluster of flares at the slope off Paramushir Island. The 500–1000 nl/l AMF was investigated repeatedly in the near-bottom water layer above gas-hydrate accumulations discovered after registration of flare-like acoustic anomalies in the water column by a fishing vessel (Avdeiko *et al.*, 1984; Ginsburg and Soloviev, 1994). This area is located in the zone with heightened PHG 5–10 t/km² (Fig. 4). This region is influenced by modern volcanic activity that could dictate another fluid-temperature regime of dispersed organic matter transformation, yielding lower values for the AMF (<1000 nl/l) than for the northeastern Sakhalin Slope.

Slight Near-Bottom Steady AMFs occur on the North Okhotsk Shelf (100–200 nL/l) and on the West Kamchatka Shelf (70–150 nL/l) above local structures that might bear hydrocarbon accumulations that can originate from sediment sequences characterized by the highest PHG (up to 25×10^6 t/km²) among the Sea of Okhotsk sediment basins (Fig. 4). No flares or huge anomalous methane concentrations were observed there because of minor seismo-tectonic activity of those areas and a certain lack of gas geochemical investigations. A comprehensive gas geochemical study in the North Okhotsk Shelf and West Kamchatka Shelf could support hydrocarbon-source prospecting, as it did on the East Sakhalin Shelf (Obzhirov, 1996).

From the shelf toward the slope of Sakhalin Island, the *Steady-Penetrating* AMF transforms into the *Intermediate* and *Combined Non-Steady* types (depths 200–800 m, Fig. 5). These AMF changed mutually at different observation times. The anomalous methane concentrations are markedly varying through the seasons, especially at intermediate depths along the East Sakhalin slope. For example, the values of an Intermediate AMF observed in late spring were much greater than the last one in autumn at 51°08.417'N and 145°17.195'E (Fig. 5). Methane concentrations of 140 nL/l in the intermediate water layer (500 m below sea surface, temperature +2°C, depth 650 m) were measured in late October 1998 (station Ga25-17). Increased values to 1970 nL/l (500 m below sea surface, –0.72°C) were registered at the same location in May 1999 (station Ut99-05). These oscillations are likely to reflect seasonal variability of hydrological properties and water dynamics in this area—waters with the lowest temperatures retain the highest methane concentrations. Sosnin *et al.* (2002) proposed a pattern of diapycnal entrainment of the shelf waters to intermediate depths on the East Sakhalin Slope. Following that scheme during the winter-spring season, relatively cold and dense waters (max 26.84 δ_θ), which have been enriched in methane discharged from the shelf's oil-gas deposits, intrude into the slope area and create AMFs with the highest annual values at intermediate depths. Described intrusions are visible on the Fig. 3d.

Combined Non-Steady AMFs, the most widespread type of AMF, were observed also in the western side of the Kurile Basin. It is noteworthy that slight methane anomalies < 500 nL/l (*e.g.*, Ge99-02, 180 nL/l, 2250 m below sea surface) were detected there during several surveys in the near-bottom and deep water layers (Fig. 5). In our opinion, slight AMFs in deep and near-bottom layers might reflect a sporadic methane release because intrusions of shelf or intermediate waters to depths of 1500–2250 m below the sea surface are unknown and impossible according to the vertical density stratification in the Sea of Okhotsk. The thickness of sediment strata, 2–4 km, promises hydrocarbon generation; Geodekyan *et al.* (1979) proposed slight mud volcanic processes in this area based on heightened hydrocarbon gas contents in sediments. Nevertheless, the source of CH₄ anomalies in the deep-water layer of the Kurile Basin remains unclear and must be confirmed by further surveys.

A *Subsurface Steady* AMF was observed in the subsurface cold layer along the eastern and southeastern foot of the Sakhalin slope (Fig. 5, 900–1500 m depth). In this zone, a slight but constant excess by 70–150 nL/l above the background values was recognized in all observations. Tidal currents and the longitudinal East-Sakhalin Current (average velocity in southern direction is 1–1.2 m/s along Sakhalin Island) probably delivers methane that is released from seeps on the eastern Sakhalin shelf and

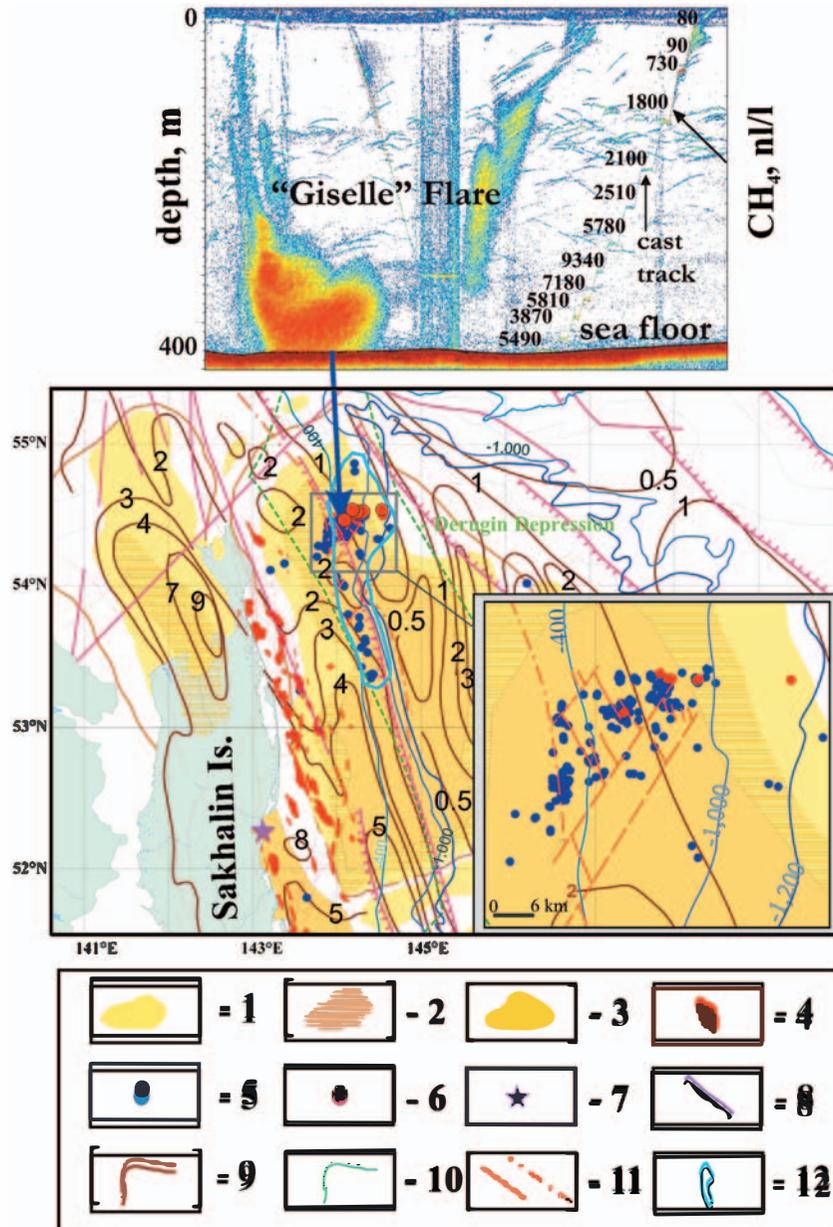


Fig. 6. Geological structure of the Northeastern Sakhalin Slope.

Legend; 1, 2, 3: potential of the hydrocarbon generation (see Fig. 5); 4: oil and gas deposits; 5: methane vent/flares; 6: methane hydrate findings; 7: mud volcano; 8: rift zones; 9: isopachits; 10: isobaths; 11: tectonic faults; 12: methane hydrates allocation proposed. "Giselle Flare": A.S. Salomatina, "Akademik M.A. Lavrentyev", Cruise 29, 2002 (Obzhirov *et al.*, 2004).

slope toward the southeastern and southern slope's foot. Following methane dispersion from the subsurface, the water layer was suppressed slightly by low temperatures similarly to the subsurface maximum of background concentrations in the central sea. The influence of currents on methane dispersion has been established in studies of other seas as well (Cynar and Yayanos, 1992; Rehder *et al.*, 1998).

Surface Non-Steady AMFs were observed many times in the surface waters of Eastern Sakhalin shelf and slope as a rule, not alone, but in combination with other AMFs (Fig. 5). The last fact explains well that surface methane anomalies in the eastern Sakhalin shelf and slope are related genetically to active methane venting, following gas dispersion up to the sea surface, especially in cases of bubbles streams from methane-hydrate bearing sediments and leakage from oil and gas deposits. It is noteworthy that concurrent studies conducted by Marty *et al.* (2001) show no direct relationship between methane concentration and production in surface seawater, suggesting that the dissolved gas is likely not produced *in situ*. Upwelling phenomena in the slope area off eastern Sakhalin are proposed as an additional means of transport of abundant methane to the sea surface (Biebow and Huetten, 1999).

Regarding the distribution of *Penetrating Non-Steady* AMFs, newest findings of flares and methane hydrates (Dullo *et al.*, 2004; Matveeva *et al.*, 2005) have spurred authors to collect additional data and conduct certain reviews of the geological state of the northeastern Sakhalin slope. Consequently, all of the following support the widespread forecasting (*ca.* 5000 km²) of methane-hydrate occurrence in the Derugin Depression, and especially toward the south from known gas hydrate findings (Fig. 6): analyses of PHG distribution up to 10–20 × 10⁶ t/km² (Gretskaya *et al.*, 1992); thickness of sediment strata up to 3–5 km; the rift system developed by Gnibidenko (1979); suitable water depths of 400–1200 m and temperatures of near-bottom water +2°C; BSR distribution and heat flux studied in detail through the KOMEX Project (Luedmann and Wong, 2003); and recent studies of tectonics patterns (Kharakhinov, 1998; Baranov *et al.*, 1999; Bogdanov and Khain, 2000). Additional geological surveys to examine this methane hydrate province are required.

Therefore, the proposed classification of anomalous methane fields reflects the interaction between geological hydrocarbon sources and hydrological water structure in the Sea of Okhotsk.

Numerous unexplained local surface and other sporadic methane anomalies were observed within background areas; their origin should be investigated separately. Methane oxidation rates in marine sediments and in the water column, estimation of methane flux, and clarification of its biochemical and thermogenic components are a special case. Isotope-geochemical and microbiological studies are required for satisfactory evaluation of these processes in the Sea of Okhotsk.

4. Conclusions

This study undertook simple statistical analyses of available methane content measurements and elaboration of observed vertical methane profiles in the Sea of Okhotsk water column. Interpretations of anomalous methane field phenomena were carried out based on geological features, such as the potential of hydrocarbon generation.

Almost equal vertical profiles of the methane background field in the Sea of Okhotsk and the Pacific Ocean (near the Kurile Islands) were obtained. Uniformly low methane contents in background areas were explained by the absence of active gas/fluid venting and insufficient values of the potential of hydrocarbon generation in those sediments.

Anomalous methane fields occur in all water masses of the Sea of Okhotsk, but their spatial and quantitative variety has genetic relations with different hydrocarbon sources.

It is possible to classify penetrating, near-bottom, deep, intermediate, subsurface, and combined steady and non-steady anomalous methane fields in agreement with the vertical water column structure of the Sea of Okhotsk.

Local venting on the sea floor and subsequent gas dispersion controlled by water dynamics and variability of hydrological properties can extend anomalous methane fields from hydrocarbon sources into a large water volume including surface waters.

The results presented herein constitute a first step toward developing comprehensive models that describe the detailed behavior of methane in these studied areas.

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