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GASES AND GAS HYDRATES IN THE EARTH'S CRYOSPHERE

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METHANE AND CARBON DIOXIDE HYDRATE STABILITY ZONES IN THE SEDIMENTARY COVER OF THE VILYUI SYNECLISE

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Results of determining the gas hydrate stability zone boundaries for methane and carbon dioxide hydrates at 46 sites within the Vilyui syneclise sedimentary basin are presented. The geothermal data and phase diagrams representing hydrate formation conditions in the CH_4–H_2O and CO_2–H_2O systems were used as the basis for the proposed methods for calculating positions of the gas hydrates stability zone boundaries. These data allowed constructing schematic representation of the lower boundary of methane hydrates stability zone within the entire Vilyui syneclise and its position along the latitudinal profile through the Khapchagai megaswell. The research results convincingly demonstrated that there are favorable conditions for the gas hydrates formation (e.g. sandy sections, high concentrations of dissolved methane in groundwater throughout the section, and considerable thicknesses of gas hydrates stability zones) in the sedimentary cover of the Vilyui syneclise.

Vilyui syneclise, permafrost zone, methane and carbon dioxide hydrates, gas hydrate stability zones

INTRODUCTION

Gas hydrates (methane, carbon dioxide, etc.) are widely distributed in nature. The formation and preservation of natural gas hydrates occur in sediments under specific thermodynamic (P–T) conditions, given a sufficient amount of water and free gas (or water dissolved gas is present). Such conditions may occur in substantially cooled permafrost and in deep-sea and sub-bottom sediments [*Istomin and Yakushev, 1992*]. Methane (CH_4) hydrate which is viewed as a potential energy resource has recently attracted much research interest [*Makogon et al., 2007*]. Carbon dioxide (CO_2) hydrates have received increasing attention, due to its revealed potential for: (i) sequestration of this greenhouse gas in a hydrate form; and (ii) liquid CO_2 for production of methane from the hydrate accumulations [*Duchkov et al., 2009*].

The prospects of methane hydrate deposits discovery in the Siberian region where permafrost zone is widespread have long been estimated as high. However, presently, we have to admit that even the most exhaustively explored northern portion of the West Siberian plate can claim to have only indirect evidences (geophysical anomalies, gas flows into production well after pressure drop, etc.), which have not been confirmed anywhere in Siberia by direct observation of hydrates in drill cores (this is also true for the Messoyakha gas field) [*Yakutseni, 2013*]. These indirect evidences have provided grounds for numerous projections containing optimistic estimates of methane resources in gas hydrates on the territory of the Russian Federation [*Combustible ice..., 2018*]. After all, this situation typifies other permafrost underlain areas. To date, only a few methane hydrate deposits have been discovered in the areas of North American Arctic (coastal areas of Canada and the United States) [*Dallimore and Collett, 2005*], as well as in high-altitude Tibet [*Song et al., 2014*]. Hydrate-focused searches in bottom sediments of seas and deep lakes by drilling and sample collection by pressure coring resulted in locating over 200 accumulations of methane hydrates in deep sea and sub-bottom sediments, including those in the Siberian region (Sea of Okhotsk, Lake Baikal) [*Mazurenko and Soloviev, 2003*].

Gas hydrates are known to form and persist only within competent layers of rocks termed gas hydrate stability zones (GHSZs) localized at depths to 1–2 km, with no clear lithological boundaries. The existence of such zones implies conditions favorable for the formation of gas hydrates (generally described as moderately high pressure and moderately low temperature) in this the part of the section. Once the studied part of the geological section falls within a GHSZ, this is interpreted as a major indirect indication of its potential for gas hydrates.

Inception of modern gas hydrate stability zones on the continental margins of the Northern Hemisphere was prompted by climate cooling and formation of permafrost during the Pleistocene. The evolution of GHSZs on the continents largely correlates with their permafrost history, inasmuch as changes in its extent will entail alterations in the GHSZ parameters.

Hydrate stability zones can form within any sections with low subsurface temperature, however searches for gas hydrates are focused only on water-saturated sedimentary basins. The resource potential of GHSZs is very high, inasmuch as it is only within their limits that gas can accumulate and persist as gas hydrate (relict permafrost associated gas hydrates, which can exist outside the GHSZ limits [*Yakushev, 2009*] are beyond the scope of this research). Accordingly, accurate estimation of the GHSZ parameters is critical when predicting and exploring gas hydrate accumulations.

Mapping the stability zones of gas hydrates (dominantly, formed from methane and carbon dioxide) for the Siberian sedimentary basins was initiated quite a long time ago [*Makogon, 1974; Istomin and Yakushev, 1992*]. This required the knowledge of geothermal information and phase diagrams that represent the conditions for hydrates formation in gas–water systems. The level of detail of the GHSZ schemes is largely determined by the quantity and quality of the geothermal data. Relatively recent estimates of the parameters of carbon dioxide and methane hydrate stability zones (CO_2–HSZ and MHSZ) in the sedimentary cover of the West Siberian basin were inferred from the extensive geothermal database (thermograms for 500 wells drilled to a depth from 100 to 4000 m within 380 sites) [*Duchkov et al., 2009*]. This allowed to infer that in the northern portion of West Siberian plate, where the permafrost thickness reaches 500–600 m, lower limits of GHSZ occur within the 700–900 m depth interval, on a level with the tops of Cenomanian deposits. This paper sets out to locate the limits of stability zones of hydrates formed from the said gases in the sedimentary cover of the Vilyui syneclise, and provides analysis of the results obtained.

GEOLOGY OF THE VILYUI SYNECLISE

The Vilyui Mesozoic basin situated in the eastern part of the Siberian Platform, is one of Russia's major regions with concentration of large natural hydrocarbon resources [*Sitnikov et al., 2017*]. The upper part of its sedimentary cover 1–2 km in thickness is composed of Upper Jurassic-Cretaceous terrigenous deposits dominated by sandy-silty facies. A number of multi-layered gas and gas condensate fields have been discovered in the area. The uppermost gas pool (depth: ~1 km) is attributed to the Middle Vilyui site. Within the syneclise, Cretaceous and Upper Jurassic sediments occurring in a subpermafrost interval are pervasively saturated with fresh water. Groundwater salinity tends to grow (35–100 g/L) with increasing sediment occurrence depth (Lower Jurassic, Triassic, Permian deposits). The entire hydrogeological system of the syneclise is water-dissolved gas saturated (primarily, methane). Variations in the chemical composition of gas enabled detection of reservoir fluid cross-flows (along joints and fault zones), which, under favorable conditions, have prompted the formation and evolution of new gas fields, including those sitting in Upper Jurassic-Cretaceous sedimentary sequences "immediately overlain by permafrost ... above the previously identified conventional gas pools" [*Sitnikov et al., 2017*]. Specifically, such strata are expected to ensure necessary conditions for gas hydrate formation. This hypothesis can be tested by finding an answer to the question as to where MHSZ and CO_2–HSZ are located in the sedimentary envelope of the Vilyui syneclise, using the available geothermal data and pertinent phase diagrams.

SEDIMENTARY ROCK TEMPERATURE IN THE VILYUI SYNECLISE

The temperature regime in the upper sedimentary cover of the Vilyui syneclise has been systematically studied by the staff of the permafrost geothermics laboratory at Melnikov Permafrost Institute, Siberian Branch of the Russian Academy of Sciences (MPI SB RAS) since the 1970s. This has resulted in extensive material on the geotemperature field and permafrost strata parameters accumulated to date for the area [*Balobaev and Devyatkin, 1983; Balobaev, 1991; Semenov and Zheleznyak, 2013, 2018; Semenov, 2018; Zheleznyak et al., 2018*]. The geothermal studies enabled estimation of average depth of the zero isotherm (H_0) and, accordingly, permafrost thickness for 46 sites within the syneclise [*Semenov, 2018*]. Their location map and schematic representation of the lower limit of permafrost (depth of zero degree isotherm) are shown in Fig. 1. On average, permafrost thickness varies from 0.06 to 0.82 km within the studied sites (Table 1), showing an increasing trend northward and westward, and significant (up to 0.2 km) variations in the local geologic structures.

The sediment temperatures suggest significant heterogeneity for equal depths within different studied sites of the syneclise. At this, most of the sites with permafrost thickness in excess of 0.2 km, show a very close type of thermograms (temperature distributions with depth). The lowest temperatures (–3...–5 °C) are reported at a depth of about 0.1 km. Deeper down, temperature gradually increases up to 0 °C at the lower boundary of permafrost (permafrost base), below which sediment temperature increases with depth at a rate dictated by the geothermal gradient (G) varying in some sections from 1.0 to 3.6 °C/100 m, on average. Temperature variations in

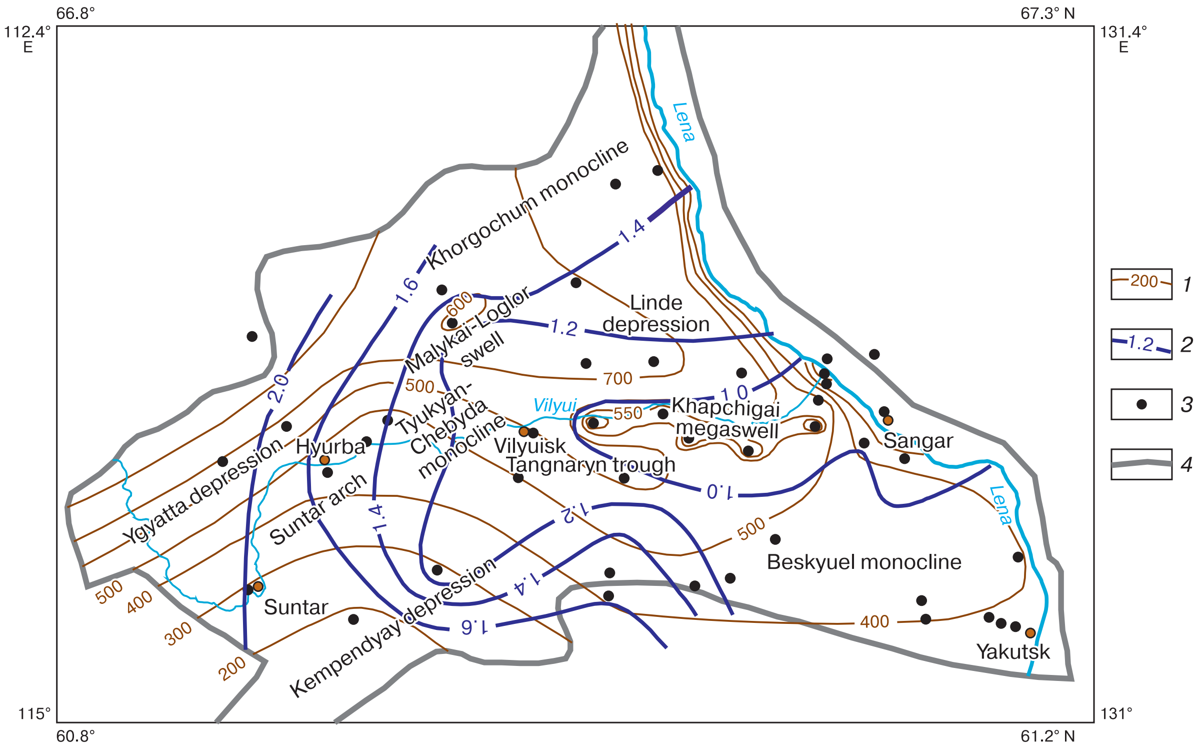

Fig. 1. Schematic location of lower boundaries in the sedimentary cover of the Vilyui syneclise:

1 – permafrost zone (digitized isolines, m) [*Semenov, 2018*]; *2* – methane hydrate stability zones (boundary H_{2p}, digitized isolines, km); *3* – investigated exploration sites (see Table 1); *4* – syneclise boundary.

unfrozen sediments can be additionally characterized by the mean temperature values for each section at depths of 1 km (T_1), 1.5 km ($T_{1.5}$) and 2 km (T_2). Most of the studied sites in the Vilyui syneclise are characterized by the mean temperature values described as T_1 = 15–20 °C and T_2 = 25–45 °C. Note that in the northern parts of the West Siberian plate, temperatures grow warmer much more rapidly within the subpermafrost layer: T_1 = 20–30 °C and T_2 = 50–70 °C [*Duchkov et al., 2009*]. Specifically, these differences in temperature regimes can cause the formation of a more extensive GHSZ within the sedimentary cover of the Vilyui syneclise. The obtained geothermal data (average values of H_0, G, T_1, $T_{1.5}$, T_2) are listed in Table 1. At this stage of research, the authors set out to reveal the main distinctive features of MHSZ and CO_2–HSZ localization in the Viluyi syneclise. When delineating the extent of GHSZ, we therefore used thermograms averaged over individual sites, rather than relying on numerous real available thermograms from separate wells. Such thermograms were constructed for each site from several points: a) T = –5 °C at a depth of 0.1 km for all sites; b) T = 0 °C at the permafrost base depth averaged over a site (Table 1); c–e) mean temperature values for each site at depths of 1, 1.5 or 2 km (Table 1).

Methane and carbon dioxide hydrate stability zones in the sedimentary cover of the Vilyui syneclise

The most common approach to determining the limit of the extent of hydrate stability zones is to use the graphical method, in particular, by comparing depth and temperature dependent thermograms and phase diagrams, which would represent gas hydrate localities under changing *P*,*T*-conditions and different salt concentrations (water salinity). The parameters of methane and carbon dioxide/HSZs in the Vilyui syneclise were analyzed using plots of phase diagrams for the CH_4–H_2O and CO_2–H_2O systems discussed in [*Duchkov et al., 2018*]. Figure 2 provides an example of the graphical method application for delineating the boundaries of MHSZ distribution. The top point of the intersection of a well thermogram with phase diagrams (and the upper boundary of MHSZ, accordingly) lies within the 240–250 m permafrost interval, while the lower boundary is reported in the unfrozen sediments at a depth of 1100 m and is determined from the thermogram and phase diagrams intersection point for water with salinity 40 g/L that saturates sediments in this section at a given depth. Judging from the lithologic log, hydrate formation also ceased at a depth of 1100 m.

Table 1. **Estimates of the occurrence depth of lower and upper boundaries of carbon dioxide and methane hydrate stability zones and geothermal data from 46 exploration sites of the Vilyui syneclise**

No.	Exploration site	H_0, km	G, °C/100 m	T_1, °C	$T_{1.5}$, °C	T_2, °C	CO_2–HSZ boundaries, km		MHSZ boundaries, km		
							H_1	H_2	H_1	H_{2p}	H_{2m}
1	23rd km of the Vilyui highway	0.36	–	11.4	20.5	29.6	0.10	1.0	0.24	1.20	1.02
2	40th km of the Vilyui highway	0.36	–	11.4	20.5	29.6	0.10	1.0	0.24	1.20	1.02
3	Andreevo	0.48	2.13	11.1	21.8	32.4	0.08	1.01	0.21	1.16	1.01
4	Andalakh	0.72	2.44	6.8	19.0	31.2	0.08	1.20	0.18	1.40	1.25
5	Badaran	0.53	2.01	18.0	29.5	39.0	0.09	0.82	0.18	0.84	0.76
6	Balagacha	0.70	3.17	9.5	25.8	41.2	0.05	1.05	0.16	1.14	1.05
7	Bappagai	0.46	1.90	10.3	19.8	29.3	0.08	1.06	0.23	1.26	1.06
8	Byrakan	0.47	2.20	11.7	22.7	33.7	0.07	0.99	0.20	1.10	0.96
9	Bakhynai	0.64	2.14	7.7	22.0	29.1	0.07	1.19	0.19	1.42	1.25
10	Berge	0.37	2.11	18.6	26.0	39.7	0.08	0.74	0.24	0.70	0.60
11	Borulakh	0.60	–	13.3	24.0	34.4	0.10	0.96	0.24	1.0	0.91
12	Upper Linde	0.70	2.76	7.0	20.3	34.0	0.06	1.18	0.18	1.35	1.22
13	Upper Sinyaya	0.50	1.60	8.3	14.4	24.3	0.08	1.19	0.23	1.51	1.27
14	Vilyui	0.57	2.48	10.2	22.5	34.9	0.07	1.04	0.20	1.18	1.04
15	Kenkemen	0.39	1.80	11.4	20.5	29.6	0.09	1.0	0.24	1.17	0.97
16	Kitchan	0.16	1.70	25.0	~40	>60	0.10	0.52	0	0	0
17	Kedepcha	0.29	1.88	14.3	23.2	33.1	0.10	0.84	0.25	0.90	0.70
18	Kederge	0.17	1.06	10.8	15.1	21.4	0.12	1.10	0.31	1.80	1.20
19	Linde	0.70	3.11	9.3	25.1	40.4	0.05	1.06	0.16	1.16	1.06
20	Mastakh	0.57	3.60	17.1	28.2	53.1	0.05	0.83	0.16	0.85	0.79
21	Meik	0.69	1.45	4.5	13.1	19.0	0.08	1.45	0.20	1.84	1.68
22	Namy	0.48	2.18	11.3	27.3	33.7	0.08	1.0	0.21	1.14	0.99
23	Nyurba	0.48	1.88	9.8	19.7	28.6	0.08	1.10	0.23	1.32	1.12
24	Nedzheli	0.46	2.58	17.0	29.6	42.8	0.07	0.82	0.20	0.84	0.74
25	Lower Vilyui	0.56	–	22.5	35.0	48.0	0.06	0.78	0.16	0.77	0.72
26	Lower Tyukyan	0.47	1.70	12.2	20.4	29.2	0.09	1.0	0.23	1.15	0.92
27	Oloi	0.38	2.45	15.2	27.5	39.7	0.08	0.83	0.23	0.86	0.72
28	settl. Magras	0.40	1.86	14.4	22.0	30.0	0.08	0.86	0.23	0.92	0.78
29	settl. Orto-Surt	0.48	2.19	11.4	22.3	33.3	0.08	0.97	0.21	1.09	0.94
30	Sabo-Khaya	0.06	3.23	29.0	40.8	61.3	0	0	0	0	0
31	Sangar	0.07	2.75	25.6	39.8	53.1	0	0	0	0	0
32	North Linde	0.70	2.04	6.2	11.8	26.5	0.06	1.23	0.18	1.45	1.31
33	North Tyung	0.70	1.94	5.8	11.2	25.2	0.08	1.30	0.18	1.56	1.40
34	Sinskaya	0.44	1.35	8.3	16.0	24.3	0.10	1.20	0.24	1.60	1.34
35	Middle Vilyui	0.55	3.38	15.3	32.6	49.1	0.06	0.87	0.18	0.90	0.83
36	Middle Markha	0.82	0.95	2.0	7.0	11.5	0.08	>1.9	0.20	2.84	2.60
37	Middle Tyung	0.60	3.21	11.6	27.8	43.7	0.06	1.0	0.18	1.09	0.99
38	Suntar	0.28	1.13	10.1	15.1	21.4	0.10	1.14	0.26	1.80	1.34
39	Tolon	0.56	1.70	15.0	30.0	45.0	0.06	0.88	0.18	0.93	0.85
40	Uorang	0.62	–	10.0	22.0	35.0	0.05	1.03	0.18	1.15	1.03
41	Uordakh	0.40	2.40	11.4	22.0	33.0	0.09	1.0	0.24	1.16	0.97
42	Ust'-Vilyui	0.15	3.38	28.3	42.0	62.1	0.11	0.43	0	0	0
43	Ust'-Markha	0.49	–	9.5	18.0	27.4	0.08	1.10	0.22	1.34	1.14
44	Ust'-Meik	0.70	1.21	3.6	10.2	15.8	0.08	1.68	0.21	2.32	2.10
45	Khailakh	0.60	2.23	11.7	22.9	33.7	0.06	0.99	0.18	1.08	0.98
46	Eksenyuakh	0.29	–	15.0	26.0	36.0	0.10	0.81	0.26	0.84	0.62

Note. H_0 shows location of the zero isotherm; G is average geothermal gradient in the sub-permafrost sediment layer; T_1, $T_{1.5}$, T_2 are average sediment temperatures at depths of 1, 1.5 and 2 km [*Semenov and Zheleznyak, 2013, 2018; Semenov, 2018*]. CO_2–HSZ boundaries, km – Boundaries of the carbon dioxide hydrate stability zone in the case of fresh-water saturated sediments: H_1 – upper, H_2 – lower. MHSZ boundaries, km – Boundaries of the methane hydrate stability zone: H_1 – upper, H_{2p} – lower (for fresh-water saturated sediment), and H_{2m} – lower (for salt water (~35 g/L) saturated sediment). Dash indicates the unavailable data.

The pioneering determinations of the parameters of hydrate formation zones within 11 sites of the Vilyui syneclise were made using the available geothermal data, which were rather scant back in 1960–1970 [*Makogon, 1974*]. Results of the calculations showed that there is an extensive MHSZ in the sedimentary cover, with the lower boundary occurring at depths of 0.8–1.4 km.

Presently, the availability of an extensive geothermal database allowed the authors to conduct a more comprehensive and detailed study of GHSZs within the entire Vilyui syneclise. As it was discussed above, it was heavily based on the geothermal data (Table 1) which allowed constructing average thermograms for each of the 46 studied sites within the syneclise. Later, these average thermograms were validated by comparison with the phase diagrams provided in [*Duchkov et al., 2018*]. This enabled determinations of depths of the upper and lower bounds of methane and carbon dioxide hydrate stability zones for each site. The latter (CO_2–HSZ) received two lower boundaries to conform with varied groundwater salinities: 0 and 35 g/L. The calculation results (Table 1) show that the upper boundaries of MHSZ and CO_2–HSZ are located in the upper portion of the permafrost interval at depths of 0.05–0.11 and 0.16–0.30 km, respectively. The occurrence mode of the lower boundaries of GHSZs attracts the most interest. Thus, the lower boundary of CO_2–HSZ (H_2) is located at depths between 0.5 and 1.6 km, averaging around 1.1 km.

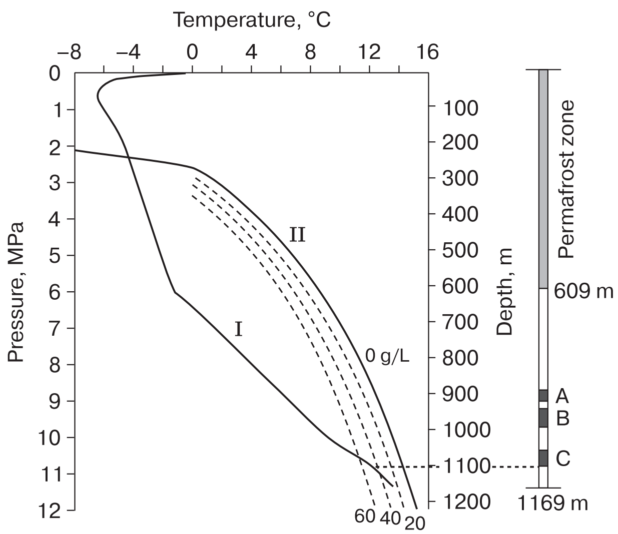

Fig. 2. Results of MHSZ determination from Mallik 5L-38 well (Arctic coast of Canada) [*Dallimore and Collett, 2005*].

I – well thermogram; II – phase diagrams for the "methane-water" system with different groundwater salinities: 0, 20, 40, 60 g/L. The image on the right shows a simplified geological column for the same well: A, B, C – intervals containing methane hydrates. The dashed horizontal line (depth: ~1100 m) shows the lower boundary of MHSZ at salinity of 40 g/L.

Given that the sediment is saturated with fresh water, the occurrence depth of the lower boundary of MHSZ H_{2p} is 0.8–2.8 km, depending on the permafrost thickness and the value of the subsurface heat flow (average $H_{2p} \approx 1.2$ km). In the case of sediment saturation with saline water (about 35 mg/L), the lower boundary H_{2m} is located 0.15–0.20 km higher, at depths of 0.6–2.6 km, at average value of H_{2m} is ≈1.1 km. Hydrate stability zones MHSZ and CO_2–HSZ are generally more extensive within the Vilyui syneclise, against Western Siberia [*Duchkov et al., 2009*].

The obtained estimates of the parameters of GHSZs can be utilized to generate diagrams or profiles illustrating positions of the lower boundaries of GHSZs (variations in the upper boundaries are negligible). Note that although occurrence depths of the lower boundaries labeled H_2, H_{2p} and H_{2m} may differ considerably (Table 1), their distributions over the area tend to have very similar configurations. At this, the boundaries H_2 and H_{2m} occur approximately at the same depth: 0.10–0.15 km higher than H_{2p}. Here, the authors confined themselves to constructing and analyzing schematics of the boundary H_{2p} (Fig. 1) superimposed on the map of permafrost base in the Vilyui syneclise, which is discussed in [*Semenov, 2018*]. The diagram shows that the lower boundary of MHSZ rises to the maximum (0.8–0.9 km) in the central part of the syneclise which is accentuated by the minimum thickness (0.6–0.7 km) within the Khapchagai megaswell. In most of the sites located outby this megaswell, the H_{2p} boundary descends to 1.0–1.4 km. However, the lack of geothermal data for the area lying to the east of the Lena river precludes the lower boundary of GHSZ from its delimiting or extrapolating eastward. Maximum thicknesses of the MHSZ are anticipated in the western part of the syneclise, where H_{2p} is located at depths below 1.6–2.0 km. Distribution of the lower boundary of MHSZ in the sedimentary cover of the syneclise often differs markedly from the position of permafrost base (Fig. 1), however it agrees well with lateral variations in heat flow [*Semenov and Zheleznyak, 2013; Semenov, 2018*]. This accounts for the fact that the GHSZ parameters are affected by the permafrost thickness and in equal measure by the value of geothermal gradient (heat flow) in the subpermafrost layer, with the latter being a major control in this case. This can be illustrated by the data for the Suntar (No. 38) and Eksenyakh (No. 46) sites (Table 1). Average thicknesses of permafrost within their sites are fairly uniform and average 0.28–0.29 km, while temperatures in the subpermafrost layer differ significantly, which results in different estimates of the lower boundary position of MHSZ: $T_2 = 36$ °C and $H_{2p} = 0.84$ km for Eksenyakh site and $T_2 = 21.4$ °C and $H_{2p} = 1.8$ km for Suntar site.

The Khapchagai megaswell, a huge geologic structure and major gas-bearing region of the Vilyui syneclise located in its central part (Fig. 1), has thus far been the best studied by drilling. The revealed large gas fields (Srednevilyuiskoe, Tolonskoe, Mastakhskoe, etc.) are indicated on the latitudinal profile (Fig. 3) crossing major studied sites within the megaswell (sites No. 8, 14, 35, 39, 20, 24, 5, 25, 42, 30, 16 from Table 1). Using the average data on individual sites from Table 1, the authors located the zero-degree isotherm, upper H_1 and lower H_{2p} boundaries of MHSZ in the section. Within the larger (western) part of the profile (a stretch between Byrakan and Lower Vilyui sites), the zero isotherm lies at depths of about 0.46–0.57 km, which is indicative of the availability of necessary geothermal conditions for existence of GHSZs in the section. In the eastern extremity of the profile (sites: Ust-Vilyui, Sobo-Khaya and Kitchan), where the heat flow shows an increasing trend [*Semenov and Zheleznyak, 2013*], the permafrost thickness has decreased dramatically to 0.10–0.15 km. The calculation results rule out the existence of any favorable conditions for the formation of a GHSZ here.

In the western part of the profile, the upper boundary H_1 runs parallel to the earth's surface at a depth of about 0.2 km, while the lower boundary H_{2p} (sediments saturated with fresh water) is located at depths of 1.1–1.2 km at the Byrakan and Vilyui sites, and gradually rises eastward to 0.8 km (the Lower Vilyui site). This change in the lower boundary position was most likely caused by the heat flow progressively increasing in the same direction [*Semenov and Zheleznyak, 2013*]. The MHSZ thickness varies along the profile from 0.95 km in the west (the Byrakan site) to 0.6 km in the east (the Lower Vilyui site), whose significant part is located below the permafrost base in Cretaceous deposits dominated by sand and silt in the composition. Specifically, in this part of the MHSZ that gas hydrates are most likely to form, given that natural gas is present in necessary amounts. Importantly, the lower boundary of MHSZ (H_{2p} = 0.9 km) is located close to the topmost gas pool (depth: ~1 km) of the Srednevilyuiskoe gas condensate field (Fig. 3). The thermodynamic setting in this part of the profile resembles the situation with the Messoyakha gas field (Western Siberia), where the presence of methane hydrates has been anticipated for a long time in its upper layers [*Makogon, 1974; Makogon et al., 2007*]. The most favorable conditions for the formation of gas hydrate accumulations are reported within the Khapchagai megaswell, particularly, in the interval of Middle Vilyui site. The upper gas pool of the Badaran field is located in close proximity to the GHSZ. Other gas-bearing areas of the syneclise also require testing.

Note that in the case when sediments are saturated with saline water, the lower boundary of the methane hydrate stability zone H_{2m} will be located 0.1–0.2 km higher, than H_{2p} and have the same configuration, which, accordingly, will lessen the MHSZ thickness by the same value.

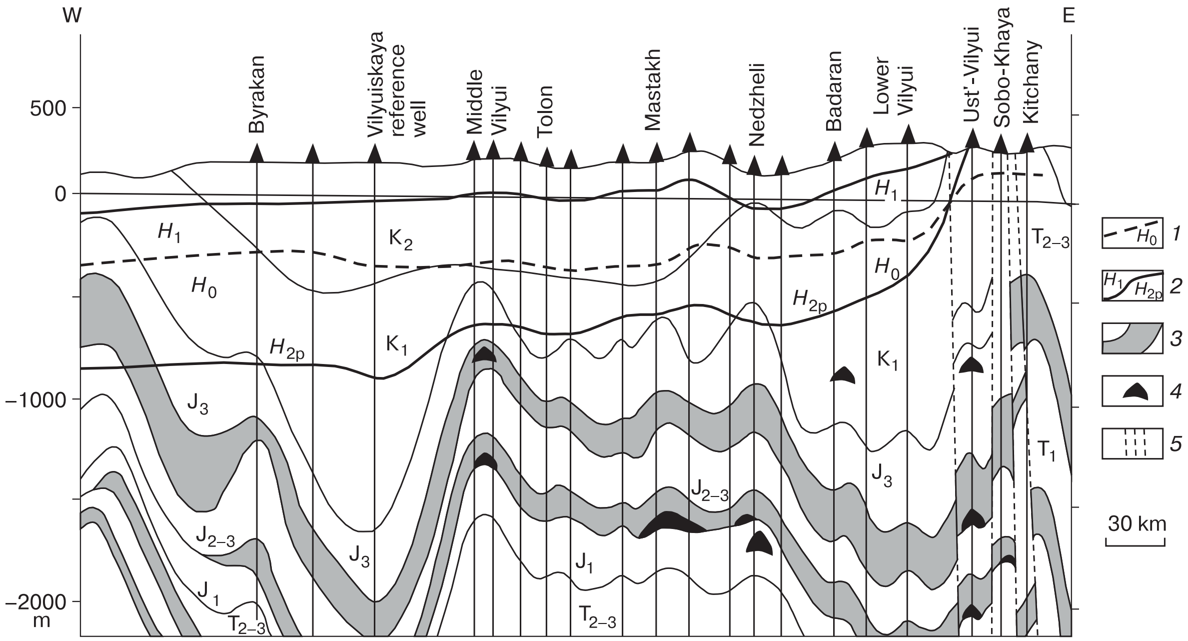

Fig. 3. Latitudinal permafrost-geological section through the Khapchagai oil and gas bearing region (geological data after [*Sitnikov et al., 2017*]).

1 – lower boundary of the permafrost zone H_0 (zero isotherm); *2* – upper H_1 and lower H_{2p} (fresh water-saturated sediments) boundaries of the methane hydrate stability zone; *3* – regional very clay-rich lithological screens; *4* – gas and gas condensate pools; *5* – tectonic faults. The section is composed of Cretaceous (K_1, K_2), Jurassic (J_1, J_{2-3}, J_3) and Triassic (T_1, T_{2-3}) deposits, dominantly sandy-silty in composition.

CONCLUSION

For the first time, the methane and carbon dioxide hydrate stability zones have been generally delineated within the entire Vilyui syneclise. This region is found to have favorable conditions for the formation of gas hydrates, among them: sanded section; higher levels of water-dissolved methane throughout the section; evidences of gas and water flows migration; considerable thicknesses of GHSZs (greater, than in Western Siberia), whose lower boundaries extend almost as far as the previously discovered gas pools (Sredneviluiskoe field).

It should be noted that the considered estimates of GHSZ parameters both within the entire syneclise and, in particular, within the Khapchagay megaswell (Table 1; Fig. 1, 3) need further testing. The parameters used in the calculations (which require greater detail) are: average permafrost thicknesses, subpermafrost temperatures, and groundwater salinity. A more comprehensive study of the parameters of MHSZ within individual, densely drilled sites (primarily within the Middle Vilyui site area). In this case, estimates of the depth of the GHSZ boundaries derived from real thermograms will enable updates of their location relative to the uppermost layers of gas fields.

Estimating the GHSZ parameters is a highly topical practical task, however not critical in the prediction and searches for gas hydrates. The results will provide insights about location of the sediment interval with the temperature-pressure conditions and amounts of water required for the formation of gas hydrates. The subsequent formation of gas hydrate accumulations will require a significant amount of natural gas which should have a long enough history of saturating this interval. Predicting the presence of gas or gas-saturated water flows and their migration paths, as well as potential locations of gas hydrate deposits, appears much more challenging. This issue should be addressed to the utmost attention in further searches for play areas with favorable conditions for the formation of gas hydrates in the sedimentary cover of the Vilyui syneclise.

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