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Simulation of the Offshore Permafrost and Gashydrate Stability Zone: Mathematical Solution, Numerical Realization and Preliminary Results

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THEME 12: Gashydrates and Permafrost, Onshore and Offshore

Summary: A two-dimensional finite model for differences in conductive heat transfer with phase change was applied to investigate the dependence of the formation and evolution of both the offshore permafrost layer and the gashydrate stability zone (GHSZ) on two essential exterior conditions. The first one is the long-term temperature variation on the surface of the lithosphere, the second is the variable hydrostatic pressure due to sea level regression/transgression. The model was used to estimate the Laptev Sea shelf permafrost and the GHSZ evolution during the late Pleistocene and Holocene.

INTRODUCTION

The shelves of the Arctic seas are characterized by the occurrence of permafrost and hydrates of natural GASES (MELNIKOV & SPESIVTSEV 1995, MARINE SCIENCE ATLAS 1987, SOLOVIEV et al. 1987, OSTERKAMP & FEI 1993). The evolution of the offshore permafrost and the behavior of marine gashydrates in relation to paleogeographic events on the shelf is a new topical problem. The solution of this problem is greatly supported by numerical modelling incorporating both paleogeographic scenarios and geological models adopted for the simulation.

The main goal of this work is the mathematical modelling of the formation and evolution of both onshore\offshore permafrost and the gashydrate stability zone (GHSZ) under the influence of the long-term temperature fluctuation on the surface of the earth and under regressions and transgressions of the sea. The model takes into consideration (i) the processes of heat transfer and phase transitions both between water and ice and between water + gas and hydrates of natural gases of the methane series, (ii) the thermobaric conditions of natural gas hydrate formation.

The model permits to study the space variability of temperature fields determined by the influence of heat transfer between gas and gashydrate bodies.

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The initial step of the study was the investigation of the interaction between ice-bonded permafrost, gas deposits, and the gashydrate stability zone on the shelf during the last 120 Kyr, when the Laptev Sea shelf was under the influence of variations of the land surface temperature and dynamic changes of the level of the World Ocean.

PALEOGEOGRAPHICAL SCENARIO OF THE PLEISTOCENE-HOLOCENE GLACIOEUSTATIC CYCLE

Contemporary relict ice-bonded permafrost on the Laptev shelf was formed in the course of a glacioeustatic sea regression in the Late Pleistocene. The Laptev Sea shelf (L SS) was dried up to where the actual isobath of -120 m is situated. (ROMANOVSKII et al. 1997a, 1997b). During this time, the formation of gashydrate-saturated deposits took place in areas with permafrost and gas-bearing bodies. The transformation between gas and gashydrate deposits led to the formation of temperature field anomalies and changes in permafrost thickness (ROMANOVSKII & TIPENKO 1998), particularly on lowlands and the sea shelf.

The lowering of the sea level with concomitant general climate cooling started at the end of the Kazantsevo Interglacial, i.e. about 112 Kyr B.P. (CHAPELL et al. 1996). The sea regression reached its maximum in the Sartan cryochron (22-18 Kyr B.P.). During this period, the permafrost was also characterized by a maximum thickness. About 18 Kyr B.P., the glacioeustatic sea level rise began as a result of increased melting of ice sheets on the globe. Flooding of the shelf induced the degradation of permafrost under the influence of seawater with temperatures ≥-2°C and the impact of geothermal fluxes. The zone of gashydrate stability and gashydrate-bearing deposits could be preserved during this period, since the rise in temperature was compensated by the increase of pressure due to the additional load from the sea water column.

MATHEMATICAL MODEL AND DIFFERENCE APPROXIMATION

As a mathematical model we used the quasi-linear heat conductive equation, which expresses the energy conservation law:

$$(1) \quad \frac{\partial H(x,t)}{\partial \tau} = div(\lambda(x,t)\nabla t(x,\tau)), \quad x \in \Omega$$

Depth m	Composition	W %	Density	Cv, J/(m³•K)		γ, J/(m•K)		Q_F,J/m³	t_F °C
			g/cm³	u	f	u	f		
0-10	clay	80	1.6	$3.09 \cdot 10^6$	$1.97 \cdot 10^6$	$6.25 \cdot 10^7$	$8.39 \cdot 10^7$	$4.39 \cdot 10^8$	-2
10-500	clay, sylt	26	1.5	$1.99 \cdot 10^6$	$1.65 \cdot 10^6$	$4.86 \cdot 10^7$	$5.87 \cdot 10^7$	$1.11 \cdot 10^8$	-2
500-750	sand, clay	12	1.5	$1.59 \cdot 10^6$	$1.35 \cdot 10^6$	$3.31 \cdot 10^7$	$3.66 \cdot 10^7$	$6.29 \cdot 10^8$	-2
750-3000	sandstone	0.8	1.6	$1.21 \cdot 10^6$	$1.21 \cdot 10^6$	$9.72 \cdot 10^7$	$9.72 \cdot 10^7$	$4.39 \cdot 10^8$	-2
400-600	hydrate-bearing deposits			$2.07 \cdot 10^6$	$2.07 \cdot 10^6$	$6.48 \cdot 10^7$	$6.48 \cdot 10^7$	$1.44 \cdot 10^8$	-2

Tab. 1: Composition and properties of deposits taken for modeling of permafrost and gashydrate stability zone (GHSZ) evolution

where Ω is the geometrical model domain and H(x,t) is the enthalpy:

(2) $$H(x,t)=\int_0^t c(x,s)ds+Q_F\,\Theta(t-t_F)+Q_G\,\Theta\left(t-t_e(x_2,\tau)\right)$$

t is the temperature, $c(x,t)$ is the heat capacity, $\gamma(x,t)$ is thermal conductivity and $\theta(t)$ is Heavyside's function. The last two components in equation (2) take account of the latent heat of phase transitions water (ice Q_F and (water + gas) (gashydrate Q_G. It should be noted that the temperature of phase transition (water + gas) (gashydrate varies with depth and time in conformity with the dependence

(3) $$t_e(x_2,\tau)=R_1 Ln\left(h(\tau)+x_2\right)+R_0$$

where x_2 is the depth and $h(\tau)$ is the function describing the dynamics of ocean level changes, R_1,R_0 is a constant. Equation (1) is complemented with boundary and initial conditions. We used a rectangle with sides' l_1 and l_2 as the domain (. The domain öw occupied by a gas/gashydrate deposit has the form of the upper half of an ellipse with semi-axes a, b (Fig. 1A). We consider the case of axes symmetric problem, so Neuman's conditions were set at the lateral boundaries:

(4) $$\frac{\partial t(x,\tau)}{\partial x_1}=0, x_1=0, l_1$$

A geothermal gradient was set at the lower boundary:

(5) $$\frac{\partial t(x,\tau)}{\partial x_2}=g, x_2=l_2$$

On the earth surface, a variation of temperature was set: $t(x,t) = t_s(\tau), x_2 = 0$. During the periods, when the ocean level rose above the onshore surface level, the temperature was assumed to be -2°C. The initial temperature distribution was regarded to be linear, dependent on depth $t(x,0) = gx_2$.

For numerical modeling of the processes described by equation (1), a smoothing of Heavyside's function was performed. An implicit, absolutely stable, locally one-space-dimensional scheme on irregular grids was used as the difference model (TIPENKO et al. 1990). The resulting system of difference equatiops is non-Jinear, and to solve it, the method of simple iterations was employed at each time step.

INPUT PARAMETERS AND ASSUMPTIONS

The modeling procedure assumed horizontal layering of depo-

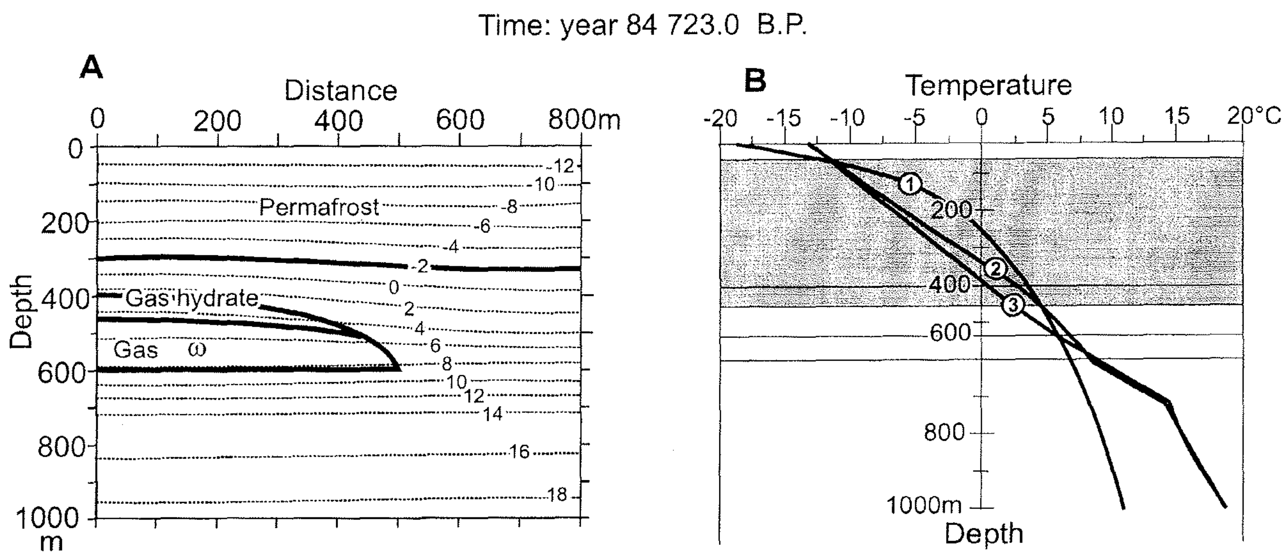

Fig. 1: Scheme of investigation domain Ω (A) and impact of gashydrate body on the thickness of the gashydrate stability zone (GHSZ) (B); (1): curve of gas + water ↔ gashydrate equilibrium; (2): distribution of temperature versus depth in case of an existent gas body; (3): the same in case of an absent gas body.

sits. The composition of deposits was chosen in conformity with the seismostratigraphic scheme developed for the Laptev Sea by DRACHEV et al. (1995). A gas body was taken as upper part of an anticlinal fold. The properties of the deposits were assumed on the basis of literature data (ERSHOV 1984) and results of the studies carried out in the Baidaratskaya inlet of the Kara Sea (Tab, 1). Thermophysical properties of gas/gas-hydrate bearing deposits (sandstone) were taken from GROISMAN (1985). Coefficients R_1 and R_0 were taken equal $R_1 = 8.027599$, $R_0 = -44.635899$. Due to the values of these coefficients in equilibrium with t = O °C, the value of function $t_c(x_2) = R_1 Ln(x_2) + R_0$ is 26 atm.

It was assumed in this model that the tectonic regime was stable on the Laptev Sea shelf for the last 120 Kyr. The pattern of temperature variations on the surface (t_s) of deposits on the shelf was assumed in accordance with the most recent paleogeographic reconstruction for this region (ROMANOVSKII et al. 1997).

The influence of pore water salinity on gashydrate formation was neglected. The curve of glacioeustatic sea level oscillations reported by CHAPPEL et al. (1996) and FAIRBANKS (1989) was used as the function describing changes in the World Ocean sealevel. The geothermal gradient at the lower boundary of the model domain was set by analogy with continental geostructures and corresponded to the heat flux of 50 mW m-2 (BALOBAEV 1991, CATALOGUE 1985).

Computations were performed for shelf areas situated at different latitudes and sea depths. Results of the computation are presented in Figures 1 through 3.

CONCLUSION

1) The mathematical model permits to investigate the behavior of permafrost and the GHSZ for the condition of the Arctic Ocean shelf not affected by glaciation for both cases, the

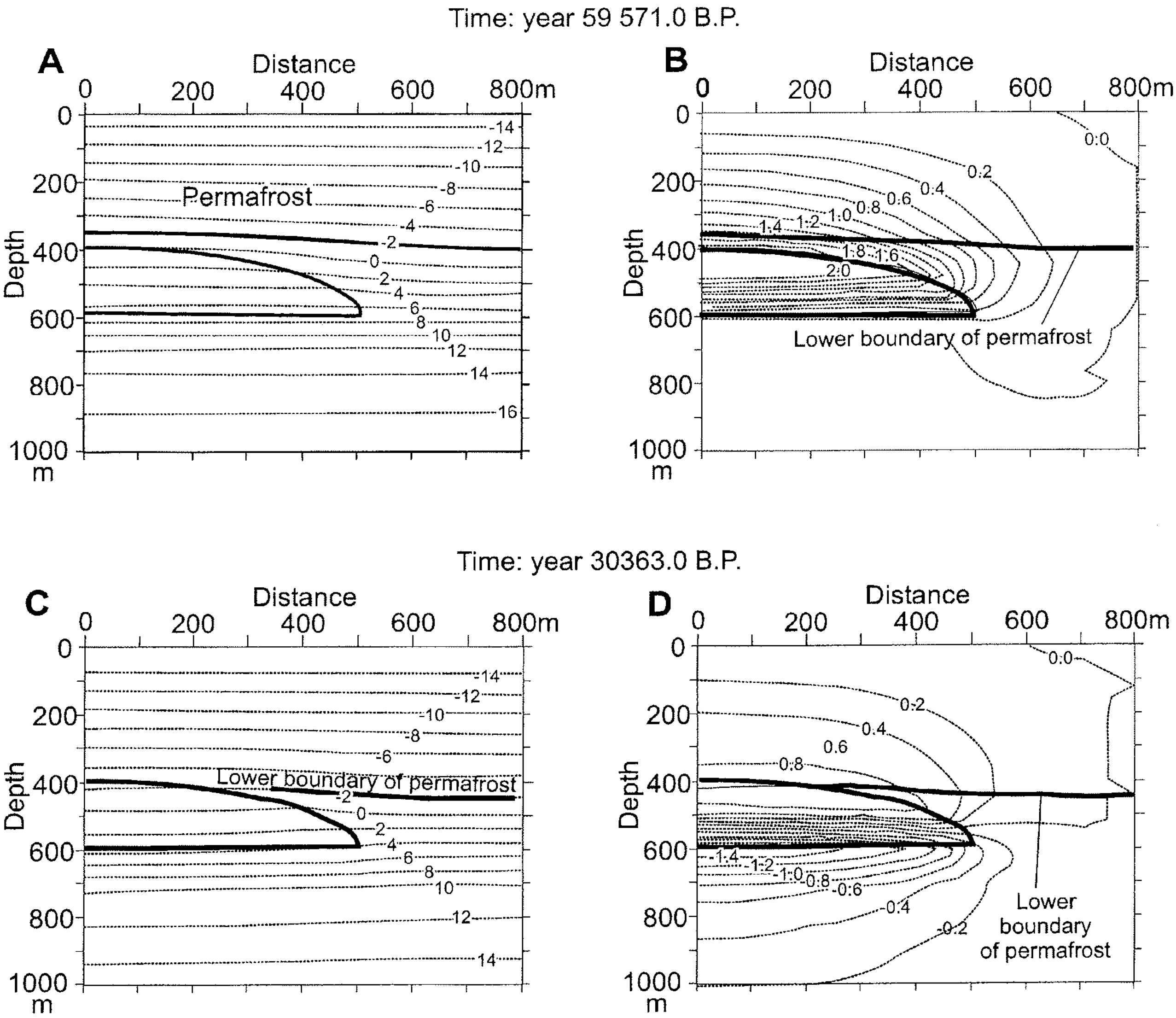

Fig. 2: Temperature fields (A, C) and their disturbances due to gashydrate formation (B, D). Two cases are distinguished: (a) the lower permafrost boundary is separated from the top of the gashydrate body (A, C), and (b) this boundary merges with the top of the gashydrate body (B, D). In the former case a positive anomaly is generated (A), and in the latter case both, a positive anomaly on top of the gashydrate body (solid lines) and a negative one at the bottom (broken line).

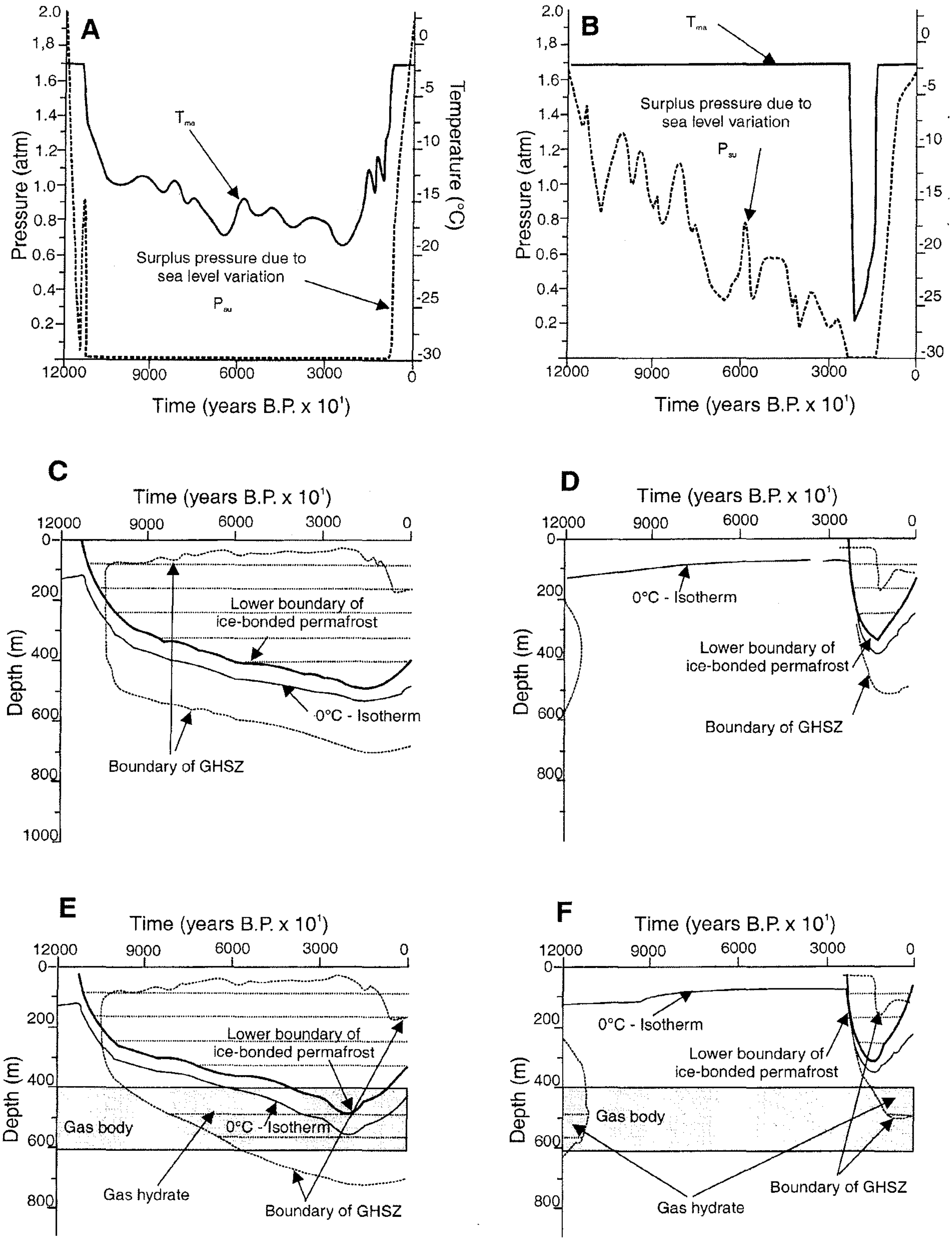

Fig. 3: Dynamics of permafrost and GHSZ on the Laptev Sea shelf during the last 120 Kyr for recent isobaths -20 m (I) and -100 m (II); A and B: dynamic of mean annual ground temperature (T_{ma}) and surplus pressure (P_{su}) due to sea level variation; C and D: dynamic of ice-bonded permafrost, isotherm 0 °C and boundaries of GHSZ versus time for the case of an absent gas body; E and F: the same for the case of an existent gas body.

existence and the absence of gas/gashydrate deposits. The model permits to carry out investigations on bilateral and multifold dependencies between components of the system and properties of the components. The model can be used for both reconstruction and prediction.

2) The following implications of the phase transition in a gas(gashydrate body are observed:
• formation of a positive temperature anomaly, in the upper part of the gas body (Fig. 2A);
• formation of a negative temperature anomaly at the moment, when the lower boundary of permafrost joins the gashydrate body, in the lower part and under the latter (Fig. 2B).
• increasing of the thickness of the GHSZ. (Fig. 1B).

3) The preliminary simulation shows that permafrost and GHSZ have formed on the exposed shelf during regression. Maximum values, both reached later, are 17 and 13 Kyr B.P. respectively, in relation to the Sartan cryochron termination (21-24 Kyr B.P.). After transgression of seawater on the main part of the Laptev Sea shelf (excluding the outer part), an intense decrease of permafrost and GHSZ started. Reduction in size took place both from above and from below. (Fig. 3).

4) In accordance with our calculations, on the outer part of the Laptev Sea shelf (recent water depth is about 100 m), the pressure increase due to sea level rise leads to an aggradation of the GHSZ (Fig. 3).

5) Recently, the GHSZ was found to occur on the whole shelf with relict permafrost. Its thickness decreases with seawater depth (Fig. 3).

For getting better results from simulation, it is extremely important to improve both, the paleoscenario and the geological model adapted for the numerical calculation and choice of proper input data.

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References

Balobaev V.T. (1991): Geothermy of the Frozen Zone of the North Asian Lithosphere.- Novosibirsk: Nauka, 193 pp (in Russian).
Byk S.Sh., Makogon Yu.F. & Fomin V.I. (1980): Gashydrates.- (in Russian).
Catalogue of Data on the Heat Flow of Siberia (1985): Novosibirsk: AN SSSR SO, Institute of Geology and Geophysics 82 pp, map (in Russian).
Chappell, J., Omura, A., McCulloch, M., et al. (1996): Reconciliation of late Quaternary sea level derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records.- In EPSL, 227-236.
Drachev S.S., Savostin L.A. & Bruni I.E. (1995): Structural pattern and tectonic history of the Laptev Sea shelf.- Reports Polar Res. 176: 348-366.
Ershov, E.D. (1984): Thermal properties of deposits.- Moscow, 204 pp. (in Russian).
Groisman, A.G. (1985): Thermophysical properties of gashydrate.- Nauka, Novosibirsk, 94 pp.
Melnikov, V.P. & Spesivtsev, V.I. (1995): Geological Engineering and Cryological Conditions on the Shelf of Barents and Kara Seas.- Novosibirsk: Nauka, 198 pp. (in Russian).
Osterkamp T.E. & Fei T.(1993): Potential occurrence of permafrost and gashydrates in the continental shelf near Lonely, Alaska.- In: Proceedings Six International Conference on Permafrost, China, Vol. 1.
Pelletier, B.R. (1987): Marine Science Atlas of the Beaufort Sea. Geology and Geophysics.- 41 pp.
Romanovskii, N.N., Gavrilov, A.V., Kholodov, A.L.,et al. (1997a): Occurrence of submarine permafrost on the Laptev Sea shelf.- Kriosfera Zemli 1: 9-18 (in Russian).
Romanovskii, N.N., Gavrilov, A.V., Kholodov, A.L., et al. (1997b) Reconstruction of paleogeographic conditions on the Laptev Sea shelf for the Late Pleistocene-Holocenic glacioeustatic cycle.- Kriosfera Zemli 1: 42-49 (in Russian).
Romanovskii N.N. & Tipenko G.S. (1998): Interaction regularities between frozen strata and gas deposits.- In: Kriosfera Zemli 2: 3-10 (in Russian).
Soloviev V.A., Ginsburg G.D., Telepnev E.V. & Mikhailyuk Yu.N. (1987) Cryogeothermy and Natural Gas Hydrates in the Arctic Ocean. - Leningrad: Nedra, 150 pp. (in Russian).
Tipenko, G.S., Ceregina, N.V., Romanovskii, N.N &Komapov, I.A. (1990): Mathematical simulation of permafrost and natural gas hydrate deposits interaction.- Vestnik MSU, ser. Geology 4(2): 73-84 (in Russian).