ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 415A, No. 6, pp. 979–983. © Pleiades Publishing, Ltd., 2007.
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GEOPHYSICS

Accumulation of Gas Hydrates and Compaction of Accumulated Sediments: The Problem of Interrelation between the Processes

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Presented by Academician A.O. Gliko September 11, 2006

Received September 13, 2006

DOI: 10.1134/S1028334X07060335

Heating of sediments and their compaction accompanied by filtration of pore fluids to the surface are the basic processes of heat-and-mass transfer, which occur during formation of sedimentary sequences on the geological time scale. However, filtration of pore fluids containing dissolved gas to the surface, many cases of which are described in the scientific literature, leads to the formation of layers saturated with gas hydrates at different depths in the sedimentary column, because pressures and temperatures favorable for the formation and stability of gas hydrates are widespread in the structures of the ocean floor. If the amount of gas is sufficient, gas hydrates are formed [1].

Accumulation of gas hydrates in the sedimentary column depends on the course of basic processes of heat-and-mass transfer, which govern *PT* conditions of the stability of hydrates and the transfer of fluid and gas into the the hydrate stability zone. In turn, accumulation and decomposition of gas hydrates in the pore space should influence the development of these basic processes: the gas hydrates create additional sources and sinks of fluid and gas, because they change porosity and permeability in the zones of their localization; thus, they influence the dynamics of the basic process of compaction of sediments and filtration of the pore fluid to the surface.

In the papers dedicated to the modeling of hydrate formation in the sedimentary sequences, as well as in the studies of compaction of sediments, the problem of the mutual influence of the processes mentioned above was not studied. Several papers devoted to modeling of the accumulation of gas hydrates in the sediments have been published. The authors of [2] presented a model of gas hydrate accumulation in a porous saturated half-space, where temperature T at the initial moment was greater than the equilibrium temperature of gas hydrate–gas saturated fluid. It was supposed that the half-space has constant porosity and is saturated with the gas–fluid mixture. An analytical solution was obtained for the displacement rate of the boundary of a gas hydrate layer in the case of two-phase equilibrium without advection of fluid and without account for the kinetics. It was shown that the boundary growth rate decreases with an increase in the Stephan number, i.e., a decrease in the difference between the initial temperature of the medium and the cooling boundary. The model predicts that up to 1 vol % of the share of hydrates would be accumulated during a time of $2 \cdot 10^5$ yr. In 1999, the authors of [3] studied the role of diffusion and advection of pore fluid in the formation of methane hydrates in the ocean floor. The model system included the equations for the fluxes of pore fluid q_f, methane q_m, and energy q_e in the porous medium of sediments. The authors of [2] concluded that if advection dominates, the gas hydrate layer is usually accumulated rapidly to make up a thick hydrate layer. If the velocity of the fluid is constant and exceeds 1.5 mm/yr, the concentration of gas hydrate appears greater near the base of the zone of gas hydrate stability than at smaller depths. The authors of [2] showed that, if diffusion dominates, gas hydrates are deposited more uniformly in the stability zone, but the accumulation rate is one order of magnitude smaller than in the case of the predominance of advection. In 2004, the authors of [4] presented a numerical model of the formation and accumulation of gas hydrates in sediments. The problem was solved with respect to the evolution of concentrations of dissolved methane in pore fluids and hydrate concentration in pores. Organic material transported with the accumulated sediments was the source of the gas (methane). The balance equations of hydrate accumulation and evolution of dissolved gas concentration in pores were solved for stationary sedimentation, constant rates of pore fluid filtration, and distribution of porosity with depth. The model

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calculations illustrated the formation of the gas hydrate layer in time. The model calculations showed that a prominent hydrate layer appears during a period of ~2.5 Ma and reaches a stationary position after 10 Ma under conditions of constant sedimentation (22 cm/ka) and filtration rates. The proportion of hydrate in pores was approximately 6%, and the maximum was located near the base of the gas hydrate layer.

Thus, in all the papers mentioned above, accumulation of gas hydrates was modeled at constant values of the filtration rate and porosity. However, investigations of compaction of accumulated sediments demonstrate that the porosity and filtration rate of pore fluids are not constant and depend on time and depth [5, 6]. Compaction of accumulated sediments includes interrelated mechanical and hydrodynamic processes, which depend on physical and hydrodynamic characteristics of the sediments and conditions of their accumulation. Filling of pores with gas hydrates potentially creates a hydrodynamic barrier for the filtration of fluids and can influence the process of compaction. In order to perform quantitative investigations of the regularities and peculiarities of the interrelation of gas hydrate accumulation and compaction of the accumulated sediments, an integrated mathematical model is formulated below and the results of model calculations for the typical values of the geophysical parameters of the problem are given.

FORMULATION OF THE PROBLEM

Compaction of a porous saturated medium of sediments and accumulation of gas hydrates in their stability zone are modeled during the formation of a basin. This process includes sedimentation and subsidence of the basin basement. In the case of compensated sedimentation, this means that the thickness of sediments increases, while the upper boundary of the domain remains at rest. The evolution of the distribution of porosity and accumulation of gas hydrates would be obtained as the solution of the equation system in partial derivatives, which connect porosity, pressure, pore fluid velocity, and hydrate accumulation. Compaction of accumulated sediments is considered under the assumption of viscoelastic rheology of sediments of the Maxwell type [7].

The flow of pore fluid to the surface is described by the Darcy equation

$$V_f - V_s = -\frac{k}{\mu(m-gh)}\left(\frac{\partial p_f}{\partial z} + \rho_f g\right), \qquad (1)$$

where p_f is fluid pressure, V_f is the velocity of pore fluid, V_s is the velocity of the sediment matrix, t is time, z is depth coordinate (directed upward), m is porosity, ρ_f is density of fluid, k is permeability, μ is the viscosity of the fluid, g is acceleration due to gravity, and gh is hydrate saturation of pores.

The equations of mass balance for a saturated porous medium are written as

$$\frac{\partial \rho_f m(1-gh)}{\partial t} + \frac{\partial \rho_f V_f m(1-gh)}{\partial z} = -J_{gh}\rho_f, \qquad (2)$$

$$\frac{\partial \rho_s(1-m)}{\partial t} + \frac{\partial \rho_s V_s(1-m)}{\partial z} = 0, \qquad (3)$$

$$\frac{\partial \rho_{gh} mgh}{\partial t} + \frac{\partial \rho_{gh} V_s mgh}{\partial z} = J_{gh}\rho_{gh}, \qquad (4)$$

where ρ_s is the density of sediments. The source terms in Eqs. (2) and (4) (volume velocity of fluid absorption and increment of hydrate formation under the assumption of local thermodynamic balance) are written in accordance with [4], in which they are considered in detail.

The gas contained in the pores is absorbed during the growth of gas hydrates. Modification of the conservation equation for gas [2] in the case of not constant porosity gives

$$\frac{\partial \rho_f m(1-gh)c}{\partial t} + \frac{\partial \rho_f V_f m(1-gh)c}{\partial z} = -\rho_h(c_h - c)\frac{\partial gh}{\partial t}, \qquad (5)$$

where c is concentration of methane in pore fluid and c_h is concentration of methane in hydrate.

Compaction of a saturated sediment medium obeying the rheological Maxwell law, which is modified with the account of the Bio-Terzaghi principle of effective stress in a porous medium [5], can be written as

$$\frac{dm}{(1-m)dt} = -\frac{m}{\eta}p_e - \frac{m}{K_p}\frac{dp_e}{dt}, \qquad (6)$$

where p_e is the effective pressure $p_e = p_{\text{tot}} - p_f$ (p_{tot} is total pressure). Here, we assume that external pressure is equal to zero and $p_{\text{tot}} = p_s = -\rho_s gy$; p_s is the pressure of the solid phase, η is the effective viscosity of the medium, and K_p is the volume modulus of elasticity. Owing to the assumption of viscoelastic rheology of the medium, the value inverse to K_p is pore elasticity $\beta = -\frac{\partial m}{\partial p_e}\frac{1}{m}$.

Let us write equation of heat conductivity as

$$\frac{\partial f}{\partial t} + A_1\frac{\partial m V_f f}{\partial z} + A_2\frac{\partial(1-m)V_s f}{\partial z} = \kappa\frac{\partial^2 f}{\partial z^2}, \qquad (7)$$

$$A_1 = \frac{\rho_f C_f}{\rho C}, \quad A_2 = \frac{\rho_s C_s}{\rho C},$$

where f is temperature; κ is the thermal diffusivity of sediments, C_f, C_s, and C are heat capacity of the fluid, sediment matrix, and medium, respectively [8]. The term describing the source caused by the formation of hydrates is absent in Eq. (7) because the authors of [4] showed that accumulation of hydrates does not introduce notable perturbations to the temperature profile in sediments. System (1)–(7) becomes complete and closed after formulation of the following boundary conditions: at the lower impermeable boundary of sediments $z = b(t)$, the velocities of the solid V_s and fluid V_f phase are equal to V_1, the velocity of the basin basement subsidence. Porosity at the upper (drainage) boundary is constant $m((z = 0), t) = m_b$; the temperature at the upper boundary is maintained constant and equal to 0°C; at the lower boundary, a constant temperature gradient is specified. Dependence c_{eq} (equilibrium methane concentration in the pore fluid) on pressure and temperature is also specified. It is used for determining the thickness of the layer of gas hydrate stability: $c_{eq}(T) = c_{eq}(T_3(P))\exp\dfrac{T - T_3(P)}{\tau}$, where $\tau \sim 10°\mathrm{C}$ [9, 10]. The natural condition of zero hydrate content in pores below (beyond) the stability boundary is specified for gas hydrate.

PHYSICAL PARAMETERS OF THE PROBLEM AND SOLUTION

Equations (1)–(7) include coefficients that are physical parameters of the model. Permeability, which is a nonlinear function of porosity according to the experimental data, is usually considered in models as a power function of porosity, and the exponents vary from 2 or 3 [11] to 8 in [12]. In the works carried out within the “Basin modeling,” permeability is assumed as a logarithmic function of porosity and the problem of the form of the permeability–porosity dependence is an object of research. In this work, we follow [5] and assume a cubic dependence of permeability on porosity $k = k_0m^l$, $l = 3$. The k_0 value depends on the type of sediments. Experimental values of permeability for sediments can range from 10^{-12} to 10^{-21} m^2 [13]. In this work, we assumed the value equal to 10^{-14} m^2. The influence of gas hydrates formed in pores on permeability of sediments is not practically studied at present and remains a debatable issue [13, 14]. Therefore, we shall consider below that the formation of hydrates can influence permeability only by means of the decrease in the free pore space. This is one of the most likely mechanisms of the influence of hydrate formation on permeability. The next model parameter is the effective viscosity of the sedimentary medium, which usually varies in the range 10^{19}–10^{22} Pa s [11, 12, 15]. Parameter β is estimated as 10^{-10}–10^{-9} Pa^{-1} [6]. The subsidence rate of the basement of sediments is not constant in the general case. In the model, the rate varies from 10^{-10} to 10^{-11} m/s. Such values are typical according to the literature data [12]. Under the assumed condition of compensated sediment accumulation, the sedimentation rate appears slightly greater but the order of its magnitude remains the same [5]. The other assumed parameters of the model are as follows: $\mu = 2.6 \cdot 10^{-3}$ Pa s, $\rho_f = 1.0 \cdot 10^3$ kg m^{-3}, and $\rho_s = 2.65 \cdot 10^3$ kg m^{-3}. The calculations were carried out for a finite thickness of sediments equal to 6 km and constant porosity at the surface of sediments equal to 0.3.

The boundary condition for the thermal problem corresponds to the supposed value of the temperature gradient at the base of the sedimentary layer equal to 40 K/km, which is widespread in the scientific literature. In [8], the author showed that accumulation of sediments, their compaction, and associated filtration of pore fluids do not introduce any significant distortions to the temperature distribution in the sediments at low and medium rates of sedimentation corresponding to the majority of the sedimentary structures. Taking into account the results of these studies, it seems possible to simplify system (1)–(7) by excluding the equation for heat conductivity and use the linear distribution of temperature corresponding to the parameters of the problem for calculating the values depending on temperature and the boundary of gas hydrate stability. The *PT* conditions of hydrate stability and the values of the equilibrium concentration of dissolved gas as a function of depth and temperature needed for the calculations were taken from [9, 10].

After reducing system (1)–(6) to dimensionless form, it was solved numerically according to [5] using semi-implicit schemes with a time-variable step and stability control on the basis of two Courant–Gilbert criteria.

RESULTS AND DISCUSSION

Figures 1 and 2 present results of calculations of sediment compaction and gas hydrate accumulation using model (1)–(7) carried out for representative physical parameters of the sediments described above and two typical values $V_1 = 10^{-10}$ and 10^{-11} m/s, respectively. A comparison of the results shows that, if the sediments have equal final thickness, a greater amount of hydrates (~9%) is formed in the case of faster sedimentation and greater gradient c_{eq}. During slow sedimentation and smaller gradient c_{eq} at the same final thickness of sediments, the saturation with hydrates is smaller (~2–3%). Compaction at given physical parameters of the model does not lead to anomalously high pore pressure in the subsurface zone, and the fluid velocity in the surface zone in the absence of hydrates is greater in the case of faster sedimentation. The influence of accumulation of hydrates on the pore fluid velocity was found in both cases, but it is more prominent in the case of faster accumulation of sediments and greater gradient c_{eq}, which reflects the interrelation of these processes. It is interesting that the process of hydrate formation lacks any influence on the compaction of sediments and the pore pressure determined by compaction in the range of the representative physical parameters of sediments considered here, which is probably due to the small percentage of hydrate and its near-surface localization.

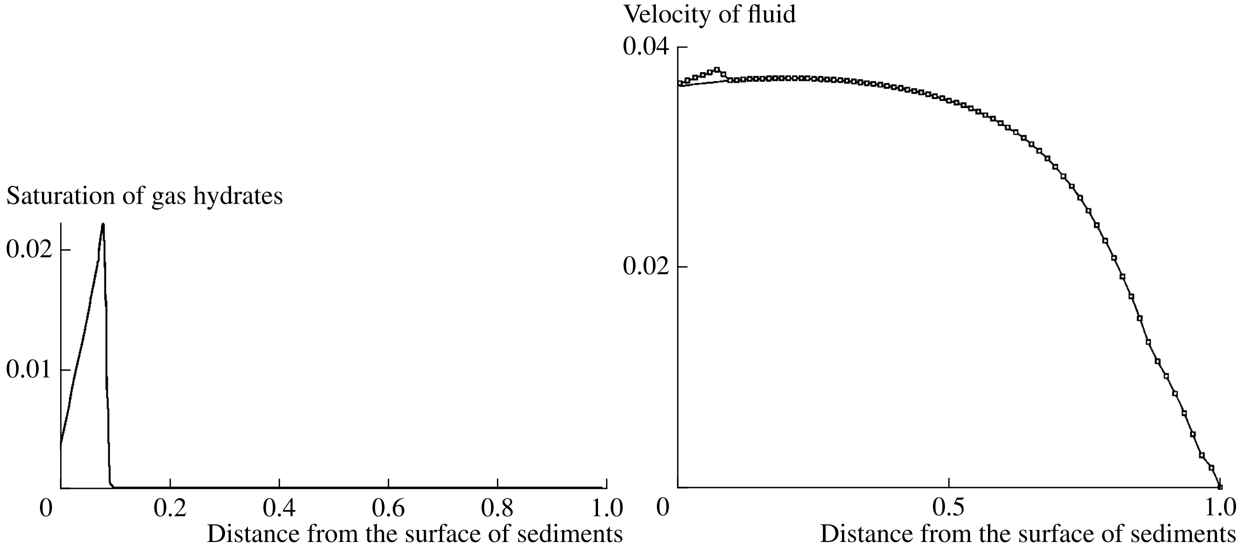

Fig. 1. Results of calculations of the distribution of hydrate saturation and velocity of pore fluid over the depth of the sediments for $V_1 = 10^{-11}$ m/s and final thickness of sediments (6 km) presented in dimensionless form. The solid curve reflects velocity in the absence of hydrate accumulation; the curve with boxes shows the velocity in the case of gas hydrate accumulation.

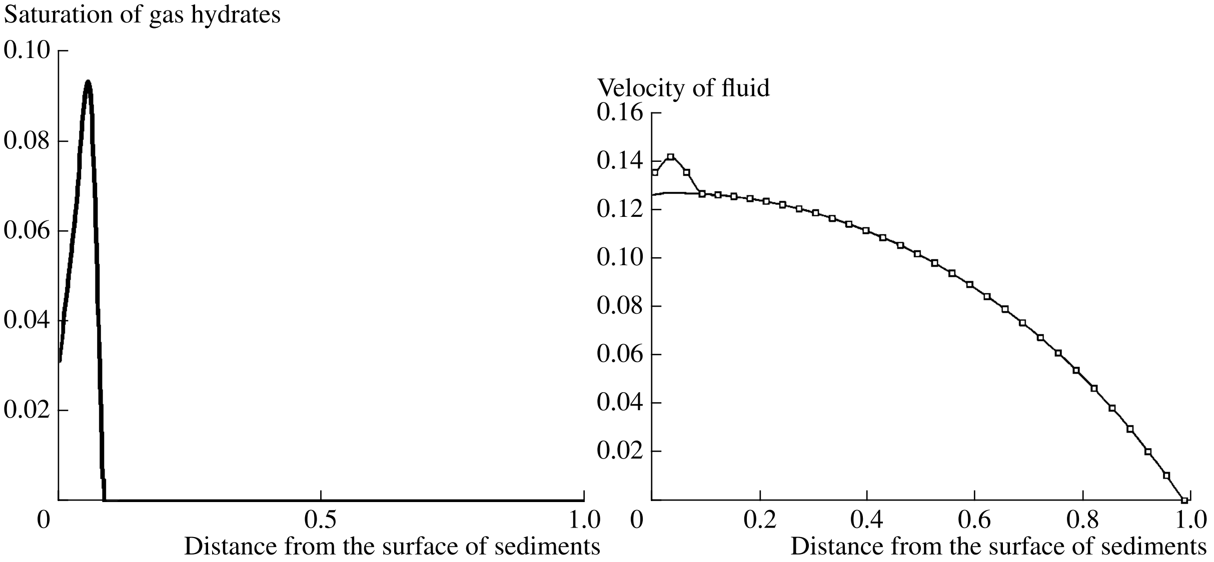

Fig. 2. Results of calculations of the distribution of hydrate saturation and velocity of pore fluid over the depth of the sediments for $V_1 = 10^{-10}$ m/s and final thickness of sediments (6 km) presented in dimensionless form. The solid curve reflects velocity in the absence of hydrate accumulation; the curve with boxes shows the velocity in the case of gas hydrates accumulation.

Thus, the results of the study showed that processes of the formation of gas hydrates from the gas dissolved in the pore fluid, compaction of sediments, and filtration of pore fluids influence each other. Integrated calculations are needed in modeling gas hydrate formation in specific regions to obtain a realistic estimate of the saturation of gas hydrates.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 06-05-65260.

REFERENCES

1. E. D. Sloan, *Clathrate Hydrates of Natural Gases* (Marcel Dekker, New York, 1998.
2. A. W. Rempel and B. A. Buffet, J. Geophys. Res. **102** (B5), 10151 (1997).
3. W. Xu and C. Ruppel, J. Geophys. Res. **104**, 5081 (1999).
4. M. K. Davie and B. A. Buffet, J. Geophys. Res. **106** (B1), 497 (2001).
5. E. I. Suetnova and G. Vasseur, Earth Planet. Sci. Lett. **178**, 373 (2000).

6. J. A. D. Connoly and Yu. Yu. Podladchikov, Tectonophysics **324**, 137 (2000).
7. A. Nadai, *Theory of Flow and Fracture of Solid* (McGrow-Hill, New York, 1963), Vol. 2.
8. E. I. Suetnova, Izv. Phys. Solid Earth **41**, 1005 (2005) [Izv. Ross. Akad. Nauk, Fiz. Zemli, No. 12, 53 (2005)].
9. O. E. Zatsepina and B. A. Buffet, Geophys. Res. Lett. **24**, 1567 (1997).
10. O. E. Zatsepina and B. A. Buffet, J. Geophys. Res. **103** (B10), 24127 (1998).
11. R. A. Birchwood and D. L. Turcotte, J. Geophys. Res. **99**, 20051 (1994).
12. A. C. Fowler and X. Yang, J. Geophys. Res. **104**, 12989 (1999).
13. R. L. Kleinberg, C. Flaum, D. D. Griffin, et al., J. Geophys. Res. **108** (B10), 2508 (2003). doi: 10.1029/2003JB002389.
14. J. Nimblett and C. Ruppel, J. Geophys. Res. **108** (B9), Cite ID 2420 (2003). doi: 10.1029/2001JB001650.
15. F. Schneider, J. L. Potdevin, S. Wolf, and I. Faille, Tectonophysics **263**, 307 (1996).