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Local pressure lows as possible sinks of fluids in geologic structures

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Abstract

Local pressure lows in layered sections perturbed by anticlinal structures are studied analytically using equations for pressure change across interfaces. They are simple equations of pressure difference for low-angle structures and boundary integral equations for steeply dipping anticlines. Pressure may decrease locally near the crests of anticlines, as well as away from them at distances commensurate to the anticline height. Predicting stress patterns, which are specific for different groups of geologic structures, is a difficult task. However, some components of the stress field, such as low-pressure zones which may act as sinks for fluids, are relatively easy to constrain. Stress in these zones depends on the dip of anticlines and their curvature at each surface point. Negative curvature causes additional lateral extension and promotes further decrease of overburden pressure around the crests.
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Keywords: pressure change across interface; layered-homogeneous medium; pressure low; boundary integral equation

Introduction

Simulations for 3D fluid dynamics often remain beyond the conventional reservoir modeling tasks. Seismic inversion resolves mostly the boundaries of geologic structures but fails to constrain stress and strain patterns. Meanwhile, shear stress (second stress tensor invariant) correlates with porosity and permeability, and tangent stress highs may be indicator for porous rocks; the stress tensor also has implications for preferable orientations of fractures (Sibiryakov et al., 2004). Of course, stress can be only tentative guides to the distribution of fluids because flow requires some transport system.

Pressure is another important indicator of fluid patterns. Local pressure lows may act as natural pumps of fluids accommodated by pores and cracks in fractured reservoirs. Stress estimates are inferred from velocity of *P* and *S* waves and density of rocks. Approximate estimates of stress in low-angle anticlinal structures can be obtained with an algorithm presented by Sibiryakov et al. (2004). Note that stress in these structures is not hydrostatic even in the case of horizontal layering (Sibiryakov et al., 2004): vertical stress equals the overburden pressure *P*, while horizontal stress is much lower, being $P(1-2\gamma^2)$, where $\gamma = v_S/v_P$ or the *S*-to-*P* velocity ratio. *P*-wave interval velocities are evaluated from 3D seismic data, while densities and *S* velocities are extrapolated from well logs.

In this study we estimate stress in a way even simpler than in (Sibiryakov et al., 2004): approximate values are obtained via interface pressure change for low-angle anticlines, and boundary integral equations are used for high-angle structures.

Layered structures

Constraining stress in 3D structures requires integrating the equilibrium equation with boundary conditions on the layer surfaces. In terms of stress, a layered medium with low-angle structures fits a zero approximation of horizontal layering. Stress is not hydrostatic even in this simplest case. Namely, the vertical stress $\sigma_{zz} = -\rho g z$ equals the overburden weight, where g is the acceleration due to gravity and ρ is the density. With Hooke's law given by $\sigma_{ik} = \lambda\,\theta\,\delta_{ik} + 2\mu\, e_{ik}$, the principal stress components are $\sigma_{xx} = \sigma_{yy} = \lambda\, e_{zz}$, $\sigma_{zz} = (\lambda + 2\mu)\, e_{zz}$, while all other components of the stress tensor are zero. The stress ratio is related to the *S*-to-*P* velocity ratio as

$$\frac{\sigma_{xx}}{\sigma_{zz}} = \frac{\lambda}{\lambda + 2\mu} = 1 - 2\gamma^2,\ \tau = \frac{\sigma_{zz} - \sigma_{xx}}{2} = \gamma^2 \sigma_{zz} = \gamma^2 \rho\, g z,$$

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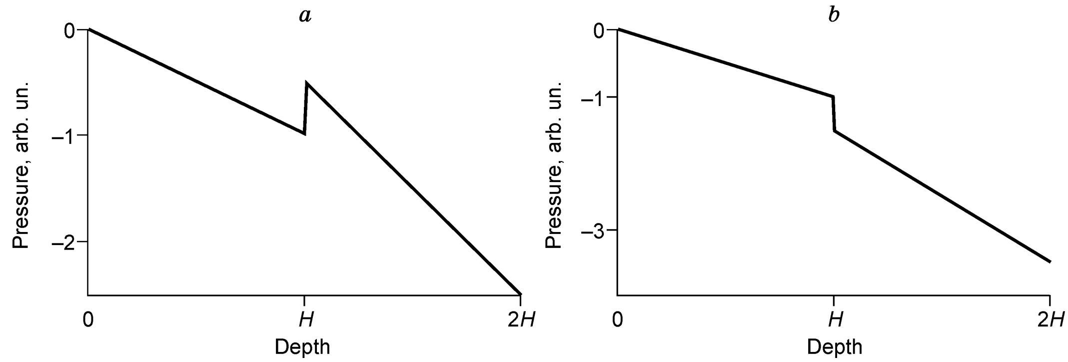

Fig. 1. Depth dependence of pressure in a layered structure. *a*, Velocity ratio γ is higher below than above, absolute pressure drops at the interface; *b*, velocity ratio γ is lower below than above, absolute pressure rises at the interface.

where $\gamma = v_S / v_P$ and τ is the shear stress, i.e., the departure from hydrostatic stress. Pressure, in turn, is related to the stress tensor as

$$P = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3} = -\rho g z \left(1 - \frac{4}{3}\gamma^2\right) = P_0 \left(1 - \frac{4}{3}\gamma^2\right),$$

where P_0 is weight of rocks. Thus, pressure is lower than the weight of rocks; more so, if the velocity ratio changes, the pressure likewise jumps across the interface, the difference being $\Delta P = \frac{4}{3}(\gamma_1^2 - \gamma_2^2) P_0$. In the case when the ratio γ is lower in the upper layer than in the lower one, the pressure jumps at their boundary to become lower in the lower layer which thus becomes a potential sink for fluids. In the depth-dependent pressure pattern of a layered medium (Fig. 1) with an interface at the depth H, the pressure difference is either positive (Fig. 1*a*) or negative (Fig. 1*b*) at $\gamma_1 > \gamma_2$ and $\gamma_1 < \gamma_2$, respectively.

Low-angle anticlines

The system of equilibrium equations for a layered section containing an anticlinal structure implies stiff boundary conditions.

The assumption that the stress vector components at the interface $z = z_0(x, y)$ are

$$p_x = -\rho g z_0(x, y) n_x;\ p_y = -\rho g z_0(x, y) n_y;\ p_z = -\rho g z_0(x, y)$$

is valid because the contribution of Poisson's integral over the structure volume to the field of displacement (and stress) is vanishing relative to that of the overburden pressure. This condition is obviously unfeasible for shallow structures but works for depths below 1 km (the deeper the better) and for structures reaching hundreds of meters high or less. If the velocity ratio integral over the structure volume V_s is far less than that of the host rock volume V_1, the difference between the second and third integrals is negligible, and the field of vertical displacement is given by the simple equation

$$u_k^1 = \frac{1}{V_{s_1}^2} \int_{V_1} \Gamma_{kz}^{(1)}(x, y)\, dV_y + \frac{1}{V_{s_1}^2} \int_{V_s} \Gamma_{kz}^{(1)}(x, y)\, dV_y$$

$$- \frac{1}{V_{s_2}^2} \int_{V_s} \Gamma_{kz}^{(2)}(x, y)\, dV_y = \rho_1 g \frac{z^2}{2(\lambda + 2\mu)}.$$

Then the horizontal displacement components at the interface $z = z_0(x, y)$ are assumed to be related with the vertical components, to a good accuracy: $u_x = u_z \cos(n, x)$; $u_y = u_z \cos(n, y)$. This assumption is obviously inapplicable to steep structures, which is however quite reasonable (see below). It relates some stress elements with both rock physics and geometry (dip and curvature) of structures, while the role of these factors is surprisingly sensitive to depth. In an infinite space, the vertical displacement is $u_z = -\rho_1 g \frac{z_0^2}{2(\lambda + 2\mu)}$. The assumption implies that at the interface $z = z_0(x, y)$ the displacement field is approximately described by the equation $u_z = -\rho g \frac{z_0^2(x, y)}{2(\lambda + 2\mu)}$. Therefore,

$$e_{xx}\left[z_0(x, y)\right] = -u_{z,x} \frac{z_{0x}}{\sqrt{1 + z_{0x}^2 + z_{0y}^2}} - u_z \frac{z_{0xx}}{\sqrt{1 + z_{0x}^2 + z_{0y}^2}} \left(1 - \frac{z_{0x}}{1 + z_{0x}^2 + z_{0y}^2}\right), \qquad (1)$$

where $u_{z,x} = -\rho g z_0 z_{0,x} / (\lambda + 2\mu)$. Otherwise, equation (1) can be written as

$$e_{xx}\left[z_0(x, y)\right] = -\frac{\rho g z_0}{\lambda + 2\mu} \frac{z_{0x}^2}{\sqrt{1 + z_{0x}^2 + z_{0y}^2}} - \frac{\rho g z_0^2}{2(\lambda + 2\mu)} \frac{z_{0xx}}{\sqrt{1 + z_{0x}^2 + z_{0y}^2}} \left(1 - \frac{z_{0x}}{1 + z_{0x}^2 + z_{0y}^2}\right). \qquad (2)$$

Total dilatation strain (relative density increase or decrease) at the interface $z = z_0(x, y)$ is approximated by:

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