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DEPTH DISTRIBUTION OF INTERNAL FRICTION COEFFICIENT AND COHESION IN SEDIMENTARY ROCKS OF SAKHALIN ISLAND

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Abstract. The paper is devoted to evaluation of geomechanical parameters of sedimentary rocks on the basis of empirical expressions found for different kinds of deep borehole logging.
Using the data of acoustic logging for Polyarninskoe oil and Aniva gas fields we estimated cohesion and internal friction coefficient. The maximum possible value of horizontal tectonic stresses is determined.
The results are applicable to *in situ* evaluation of stress-strain state of rocks around oil and gas deposits and to construction of their geomechanical models.

Keywords: geomechanics, geomechanical parameters, stress, cohesion, internal friction coefficient.

Introduction

Knowledge of the stress-strain state parameters of the medium is crucial for understanding the deformation processes in zones of tectonic plate interaction, such as Sakhalin island situated on the boundary of Amur and Okhotsk plates. The practical interest to this question is due to development and exploration of oil and gas deposits in seismic dangerous regions. In this case it requires modern technologies that use information about stress distribution in geological medium and correlation between vertical and horizontal stresses. Consideration of characteristics of the stress state of rocks is needed, in particular in drilling and operation of horizontal and inclined wells.

In most cases, the relationships between horizontal and vertical stresses are known for depths up to 1 km and are based mainly on unloading method data. For depths more than 5 km these correlations are set according to the data on focal mechanisms of seismic events [*Kropotkin, Efremov, and Makeev,* 1987; *Leont'ev,* 2001; *Rebetsky,* 2008; *Kozyrev and Savchenko,* 2009]. The depths interval from 1 to 5 km remains insufficiently known.

Due to active development of shelf drilling, a new opportunity to study the parameters of the rock state at depths of 1.5-3 km using *in situ* methods appears. Estimations obtained using these methods are also of interest for the regional geodynamics because they are a substantial addition to the traditionally used areal methods that provide data on mechanisms of earthquake sources, distribution of GPS velocities, etc [*Wei and Seno,* 1998; *Saprygin,* 1997]. Compared to the estimates obtained by traditional methods, the estimates considered have obvious advantages: they differ by the higher density of data (number of measurements per length unit) and wider range of the research depth [*Ali et al.,* 2002].

It should be noted that estimation of geomechanical parameters of sedimentary rocks has a practical significance for the drilling due to the following reasons. In most cases, a specialist that has to provide the stability of borehole walls, has no opportunity to obtain the main geomechanical parameters on the basis of laboratory data, since, for example, in a drilling of terrigenous rocks a cave-in mainly occurs in intervals composed of clay shale. However, for operators these intervals are of no interest and coring is performed rarely.

Therefore, the only way to obtain the geomechanical parameters is according to geophysical studies.

Unfortunately, experts that deal with stability of borehole walls rather rarely have a high quality material of combination logging, first of all, of multiwave acoustic logging and borehole images built on its basis. Modern acoustic sounders allow implementation of the multiwave logging that provides the key geomechanical parameters, but still a large amount of logging material on acoustics contains only longitudinal wave travel times. Besides, many types of logging, including acoustic, usually are held in producing zone of the well rather than in its upper sections. Therefore, empirical methods based on geophysical studies of wells are very popular in oil and gas industry. The use of their results compensates for the lack of more complicated and expensive logging methods and also laboratory data.

Initial data

In the present study, the logging data are used as a main basis for *in situ* estimates of geomechanical parameters. In their selection preference was given to exploratory wells where complex logging: acoustic logging, gamma-ray logging, and resistivity survey was performed and the data were representative (a uniform step of well coating, amount of data). Data obtained in the study of wells in Polyarninskoe oil field (Lunskaya depression, northern part of Sakhalin Island) and Aniva gas field (southern part of the island) fully comply with these requirements; location of these fields is shown in Fig. 1 *a*.

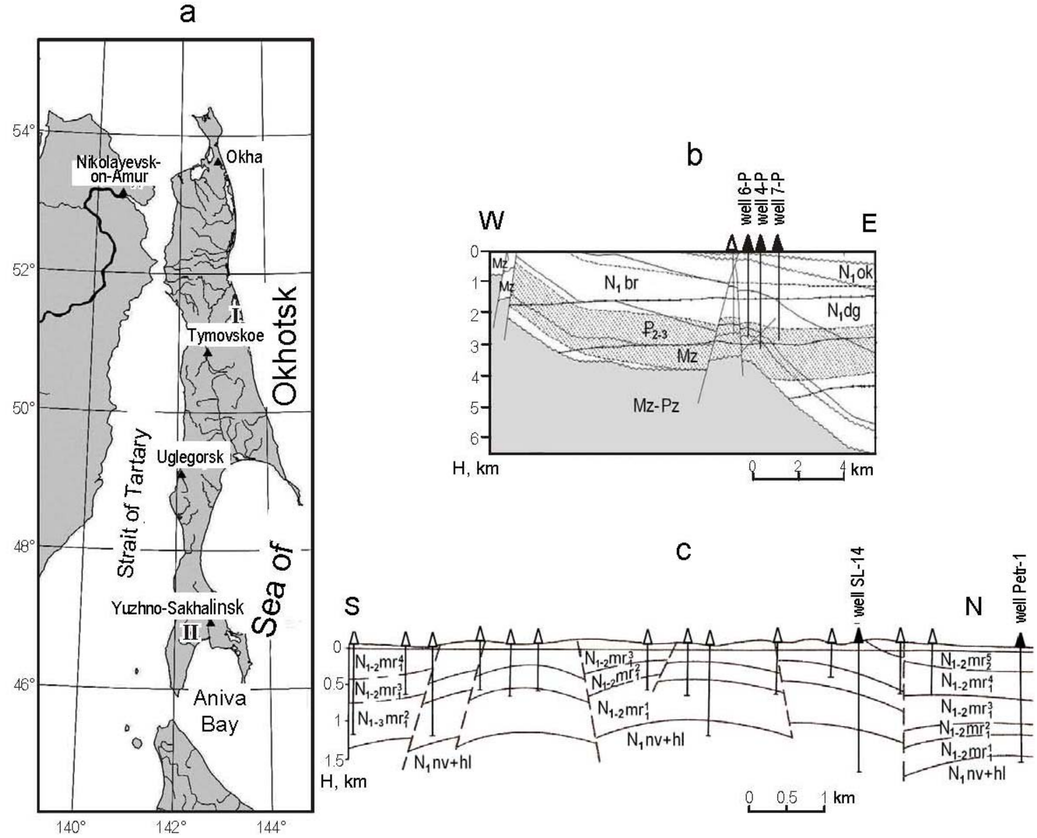

Fig. 1. (*a*) Sakhalin Island and location of (I) Polyarninskoe oil and (II) Aniva gas fields, (*b*) sublatitudinal geological cross-section of the Polyarninskoe field and (*c*) submeridional geological cross-section of the Aniva field. Black triangles in *b* and *c* indicate wells, whose data were used in the study. Stratigraphic sections are constructed according to [Geologiya …, 1970; *Tytrin and Dunichev,* 1985; *Isaev,* 2010]

The choice of the method

The most developed and widely used methods of estimation geomechanical parameters described by the Mohr-Coulomb law are based on the assumption of monotonic increase of rock compaction with the depth. The most well-known methods are developed for terrigenous sedimentary rocks, mainly clay shale, although some of them can be applied in case of carbonate rocks, in particular, for limestone.

Let us turn to the estimation of geomechanical parameters of the medium described by the Mohr-Coulomb law:

$$\tau = C_0 + \sigma_n \mathrm{tg}\varphi, \quad (1)$$

where τ is a shear strength; C_0 is cohesion, MPa; φ is an angle of internal friction; σ_n is an effective stress (stress in the rock matrix) acting normal to the plane of rupture, MPa.

Angle of internal friction φ and cohesion C_0 were determined using the Lal method [*Lal,* 1999] by formulas obtained in summarizing data of acoustic logging:

$$\sin\varphi = (V_P - 1)/(V_P + 1), \quad (2)$$

$$C_0 = 5(V_P - 1)\cdot(V_P)^{-1/2}, \quad (3)$$

where V_P is velocity of longitudinal waves, km/s.

To control the obtained values of φ and C_0, another empirical method can be applied, namely the Horsrud method [*Horsrud,* 2001, Knowledge…, 2001] with the further comparison of results with those obtained by formulas (2 and 3). According to the Horsrud method the angle of internal friction (in degrees) is described by the formula

$$\varphi = 11.0 V_P - 10.2. \quad (4)$$

To calculate C_0 in frames of this method, we should previously determine the ultimate strength under uniaxial compression without lateral support σ_{max} using the formula

$$\sigma_{max} = 0.77(V_P)^{2.9}, \quad (5)$$

and apply the expression

$$C_0 = \sigma_{max}(1 - \sin\varphi)/2\cos\varphi. \quad (6)$$

It is known the more popular representation of φ via tgφ called the coefficient of internal friction f. For convenience, we chose this method of representation in analysis.

Empirical equations (2) - (6) are based on experimental data obtained in laboratory tests of clay shale cores that were carried out together with acoustic studies [*Lal,* 1999; *Horsrud,* 2001; Knowledge…, 2001]. It should be noted that using the empirical expressions (2) – (6) is caused by the fact that the classical theory of elasticity allow determination of neither the medium characteristics (density and elastic moduli), nor their geomechanical parameters (angle of internal friction and cohesion) based on the velocity of elastic waves

Indeed, although the number of unknown parameters of the medium is not less than three (for example, density, bulk modulus, and the Poisson's ratio) there are only two equations expressing through them the velocity of longitudinal and shear waves. In this regard seismic prospecting is usually confined to construction of velocity cross-sections. However, the physical meaning of the coefficient of internal friction is similar to normalized value of indicator of sound wave damping in granular medium if the wavelength significantly exceeds the grain size. Empirical formulas for a number of sedimentary rocks with similar texture and structure allow us to reduce the complicated dependence of the absorption coefficient on a set of parameters to the single dependence on V_P. This dependence corresponds to the fact that the more consolidated are the rocks of the named series, the higher are V_P values in the rocks, strength and, consequently, parameter f (or tgφ).

We will analyze the validity of applying equations (2) – (6) from [*Lal,* 1999; *Horsrud,* 2001] for the studied region and the possibility to transfer estimations from characteristic sizes of order of the well diameter to rock scale.

Phenomenological approach to estimation of geomechanical parameters of terrigenous rocks using the combination logging data of deep wells was proposed in the works of Lal and Horsrud and in several other studies. On the one hand, this approach covers a wide class of sedimentary rocks: clay shale, argillaceous and silty sandstones with percentage of clay particles from 25 to 99 %. This opens the possibility of its application in regions with similar lithology and stratigraphy of sediments. Due to the similarity of composition and dispersed characteristics of sedimentary rocks of the Polyarninskoe and Aniva fields [*Skorikova,* 1965; *Tikhomirov,* 1970; Spravochnik…, 1983; *Isaev,* 2010] and rock samples studied in [*Horsrud,* 2001], equations (2) – (6) can be applied to terrigenous rocks in the North and South of Sakhalin. It should also be noted that the most Sakhalin deposits are characterized by the smooth change of lithological composition. Sandstones of the formations studied here are mainly aleurolitic and argillaceous, and argillites and aleurolites are sandy. Lithological characteristics are conditional since there is no single granulometric classification system of terrigenous rocks in Russian literature, as well as in foreign [Spravochnik…, 1983; *Wentworth,* 1922; *Swanson,* 1981].

On the other hand, it is known that longitudinal wave velocity significantly depends on the composition and structure of rocks rather than on frequency range. So, V_P values are 1.5–4.5 km/s in case of elastic waves with frequencies of 50 kHz (acoustic logging), as well as in case of waves with frequencies from tens to hundreds of Hertz (range of near-surface seismic prospecting). Values of V_P obtained in acoustic logging of wells of the Polyarninskoe and Aniva fields [*Kamenev,* 2014] correspond to the range of V_P values for the depths of 1-3 km as compared to considered in [*Lal,* 1999; *Horsrud,* 2001] that also determines the applicability of phenomenological equations (2)–(6).

Note that *Lal* [1999] and *Horsrud* [2001] did not discuss the frequency dependence of internal friction and cohesion defined with formulas (2) – (6). The absence (or irrelevance) of such dependence is equivalent to constancy of parameters φ and C_0 at different scales. This allows the transfer the estimates obtained for the area around the well with sizes from tens of centimeters to meter (areas of wave propagation excited during acoustic logging with frequencies of 15-50 kHz) on the whole massif.

It is interesting to check experimentally applicability of (2) – (6) for waves with seismic logging frequencies. The experiment requires a powerful source comparable in amplitude of pressure with vibrators described in [Aktivnaya…, 2004] that can cause block boundary sliding (actually, repacking) at distances of tens and even hundreds of meters. However, the discussion of such experiment is beyond the frames of this work.

The results of the research

The results of calculations of the internal friction for the wells 4-P, 6-P, and 7-P of the Polyarninskoe field and for the wells SL-14 and Petr-1 of the Aniva field obtained using the methods of Lal [1999] and Horsund [2001] are shown in Fig. 2.

For the Polyarninskoe field (Fig.2, *a*) values of the internal friction coefficient f obtained by different methods increase monotonically with the depth. The same increase is also characteristic for the Aniva field (Fig.2, *b*). The well SL-14 displayed the largest spread of f values obtained by different methods. f coefficient increases up to 0.3–0.5 from the depths of 1400-1450 m.

The values of the internal friction coefficient f are almost constant with depth at the Petropavlovsk well Petr-1 (Fig. 2 *b*). Here the values calculated by different methods show the best fit. The plots of f values at both fields indicates that calculations using the Lal method give the higher values of f compared to the calculations using the Horsrud method. In all wells both methods give similar results when approaching the bottom while in the upper intervals there is a greater discrepancy of data obtained by different methods. Therefore, f values obtained by both empirical methods become more stable with the increase in rock density and the degree of their consolidation.

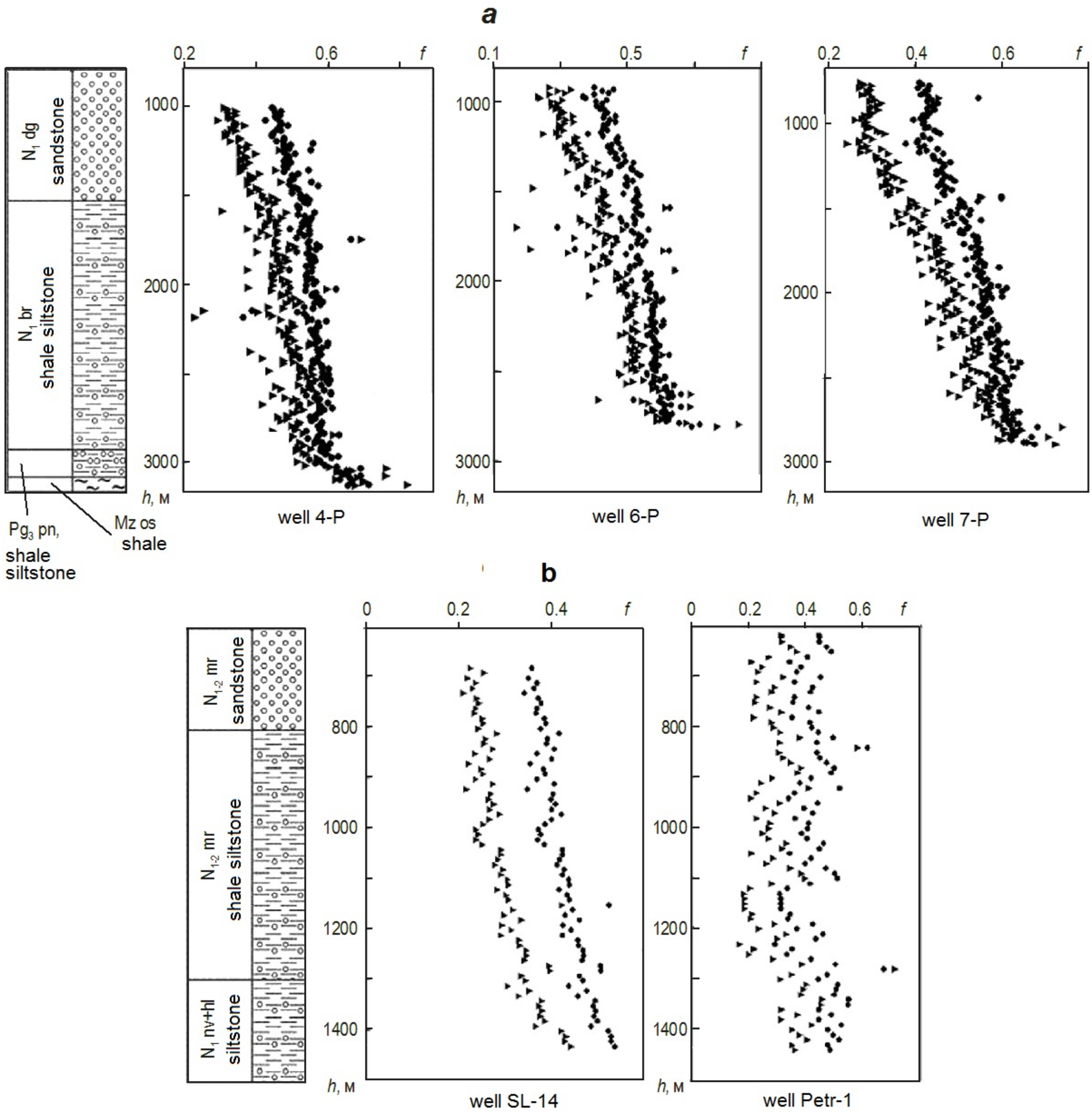

Fig. 2. The results of calculations of the internal friction coefficient f obtained using the methods of (*circles*) Lal and (*triangles*) Horsrud for the wells of (*a*) Polyarninskoe (wells 4-P, 6-P, 7-P) and (*b*) Aniva (wells SL-14, Petr-1) fields. The lithological and stratigraphic sections here and in Fig.3 are constructed according to [Geologiya …, 1970; *Tytrin, Dunichev,* 1985; *Isaev,* 2010]

The cohesion value C_0 calculated for the Polyarninskoe field wells (Fig. 3 *a*) changes with depth from 2 to 10 MPa; besides several point maximums are noted up to 18 MPa. The best fit of C_0 values obtained by different methods is observed in the depth interval between 1700 and 2200 m. Results obtained by the Horsrud method show the larger scatter. Values of C_0 defined by this method sharper increases with the depth.

On the Aniva field (Fig. 3 *b*) the results of C_0 calculation by two methods differ more than on the Polyarninskoe field, which is particularly characteristic to the well SL-14. The coincidence of C_0 values obtained by different methods is observed from 1500 m to the bottom; the best fit is observed at the well Petr-1 (see Fig. 3 *b*).

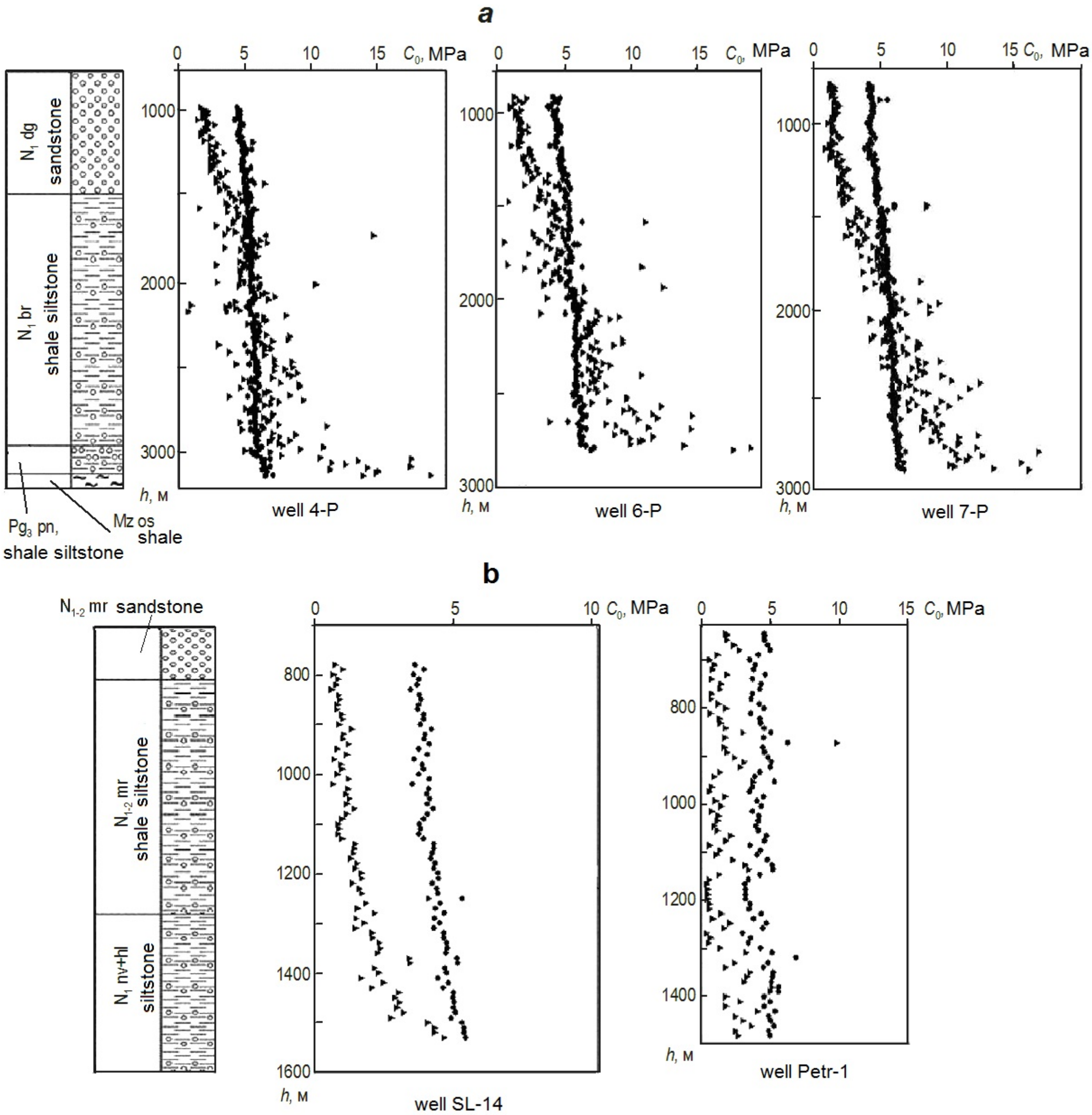

Fig. 3. Results of calculations of cohesion by the method of (*circles*) Lal and (*triangles*) Horsrud for the wells of (*a*) Polyarninskoe and (*b*) Aniva fields.

There are two main change intervals of changes in stratigraphy and lithology on the Polyarninskoe field: 1400–1600 m and 2900–3100 m; Aniva field also has two intervals: 700–900 m and 1200–1400 m. The table below gives the average values of the internal friction coefficient f and cohesion C_0 for these intervals.

The average values of the internal friction coefficient f and cohesion C_0 calculated for the main intervals of stratigraphy and lithology changes on Polyarninskoe and Aniva fields.

Deposit	Depth, m	$F_{av.}$	$C_{0av.}$, MPa
Polyarninskoe oil	1400	0.2–0.5	2–5
	1600	0.2–0.6	1–5
	2900	0.4–0.7	4–15
	3100	0.6–0.8	5–15
Aniva gas	700	0.2–0.4	1–5
	900	0.2–0.5	1–5
	1200	0.2–0.5	0.5–4
	1400	0.3–0.5	2–5

The interval of 3000-3100 m on the Polyarninckoe field needs a special attention because the values of cohesion coefficient and of the internal friction significantly increase there due to the transition to the bedrocks of Mesozoic.

Thus, both fields considered display only a slight change in coefficients of internal friction and cohesion when changing the lithological composition and stratigraphy in sediments. In selected intervals, their values change only by 6–7 % without any sudden jumps. As noted above, this is due to relative homogeneity of dispersed composition of sediments; besides, the thickness of the transition layer significantly exceeds the wavelength used in acoustic logging.

Kamenev [2014] analyzed in detail distribution of longitudinal wave velocity depending on the depth and their changes with the change of lithological composition of sedimentary rocks in the Polyarninskoe field. Smooth variations in V_P in transition layers determine the same character of changes in the parameters f and C_0.

There is a number of approaches to estimate the changes in lithostatic pressure with the depth h. One of them employs an empirical formula from [*Bell,* 1969]:

$$\sigma_3 = 0.018h - 0.9. \tag{7}$$

Such relations are used if the data on rock density are absent. The more traditional approach to estimation of lithostatic pressure uses the total densities and thicknesses of corresponding layers of rocks:

$$\sigma_3 = 9.8 \cdot 10^3 \sum_i \rho_i h_i , \tag{8}$$

where ρ_i is density of rocks of the i-th layer, g/cm^3; h_i is the thickness of this layer, m.

In the study we used both equations (7) and (8) together with results of density calculations from [*Kamenev,* 2014].

According to the data on lithostatic stress and coefficients of internal friction and cohesion we calculated the maximum horizontal stress using the criterion of Mohr-Coulomb. We assume that lithostatic pressure corresponds to the smallest of principal stresses determining the normal and shear components in (1). This assumption is based on geodynamic conditions determining the predominance of sublatitudinal compression as a result of interaction of the Okhotsk and Amur plates [*Saprygin,* 1997; *Steblov et al.,* 2010; *Wei and Seno,* 1998].

In the studies on the project "The World Stress Map" [*Zoback,* 1992], the stress map of the north-eastern Eurasia shows the prevalence of horizontal compression regime that is manifested mainly in thrust slips in earthquake sources determined by fault plane solutions [*Poplavskaya et al.,* 2011].

Data of caliper measurements of wells of the Piltun-Astokhskoye field located in the North-East of Sakhalin Island given in [*Ali et al.,* 2002] also demonstrate the prevalence of horizontal stress (sublatitudinal compression) over vertical in the depth interval of 1800–2000 m. According to the named work, the walls of the studied well indicate clear caving in two diametrically opposite angular sectors coinciding with directions of maximum compression (or tension). All this confirms the ratio of principal stresses $\sigma_1 > \sigma_2 > \sigma_3$, where σ_1 is a maximum horizontal stress (compression), σ_2 is the smallest of two components of horizontal stress, and σ_3 is a vertical stress.

The theory of faulting [*Turcotte and Schubert,* 1985] implies that the maximum possible value of horizontal compression is determined by the law of Mohr-Coloumb (1), written for the shear stress τ on the plane inclined to the horizon at an angle β in the form of $\mathrm{tg}2\beta = \pm 1/f$. As known, the orientation of this plane distinguishes among others because for this plane, the criterion (1) is reached for the minimum difference between σ_1 and σ_3 (i.e. tectonic component of horizontal stress). However, in the theory of faulting developed by Anderson for rocks with brittle type of fracture, cohesion wasn't considered [*Turcotte and Schubert,* 1985]. In our case, according to equations (2) – (6) and plots given in Fig.3, cohesion is not a negligible factor.

To derive the general expression for the maximum horizontal stress σ_{1max}, we use expressions to recalculate the stress in the coordinate system rotated at an angle β. If the fracture plane considered is inclined ("rotated") at an angle β relative to the horizontal plane, i.e. σ_1 direction, then expressions for the normal σ_n and tangential τ_n stresses on it take the form:

$$|\tau_n| = \tfrac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta, \;\; \sigma_n = \tfrac{1}{2}(\sigma_1 + \sigma_3) - \tfrac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta \,. \quad (9)$$

To estimate the limit stress σ_{1max}, the value $|\tau_n|$ can be equaled to the maximum tangential stress τ from expression (1).

Then substituting (9) in (1) and taking into account the relationship between the internal friction coefficient f and inclination of the plane of the easiest fracture in the case of low-angle thrusts $\mathrm{tg}2\beta = 1/f$, we obtain the expression

$$\sigma_{1\max} = \sigma_3 \frac{(1+f^2)^{1/2} + f}{(1+f^2)^{1/2} - f} + \frac{2C_0}{(1+f^2)^{1/2} - f}, \quad (10)$$

where for the brevity we use the internal friction coefficient f, although above we gave expressions for the angle of internal friction φ.

To obtain the dependence of maximum horizontal stress σ_1 on depth h, we substituted values of vertical (lithostatic) pressure $\sigma_3(h)$ obtained in our previous work [*Kamenev and Valetov,* 2011] into expression (10). Also we used the results of averaging the values of internal friction angle φ(h) and cohesion $C_0(h)$ at different depths according to equations (2)–(6). Figure 4 shows the plot of dependence obtained for the maximum horizontal stress together with the graph of vertical (lithostatic) pressure.

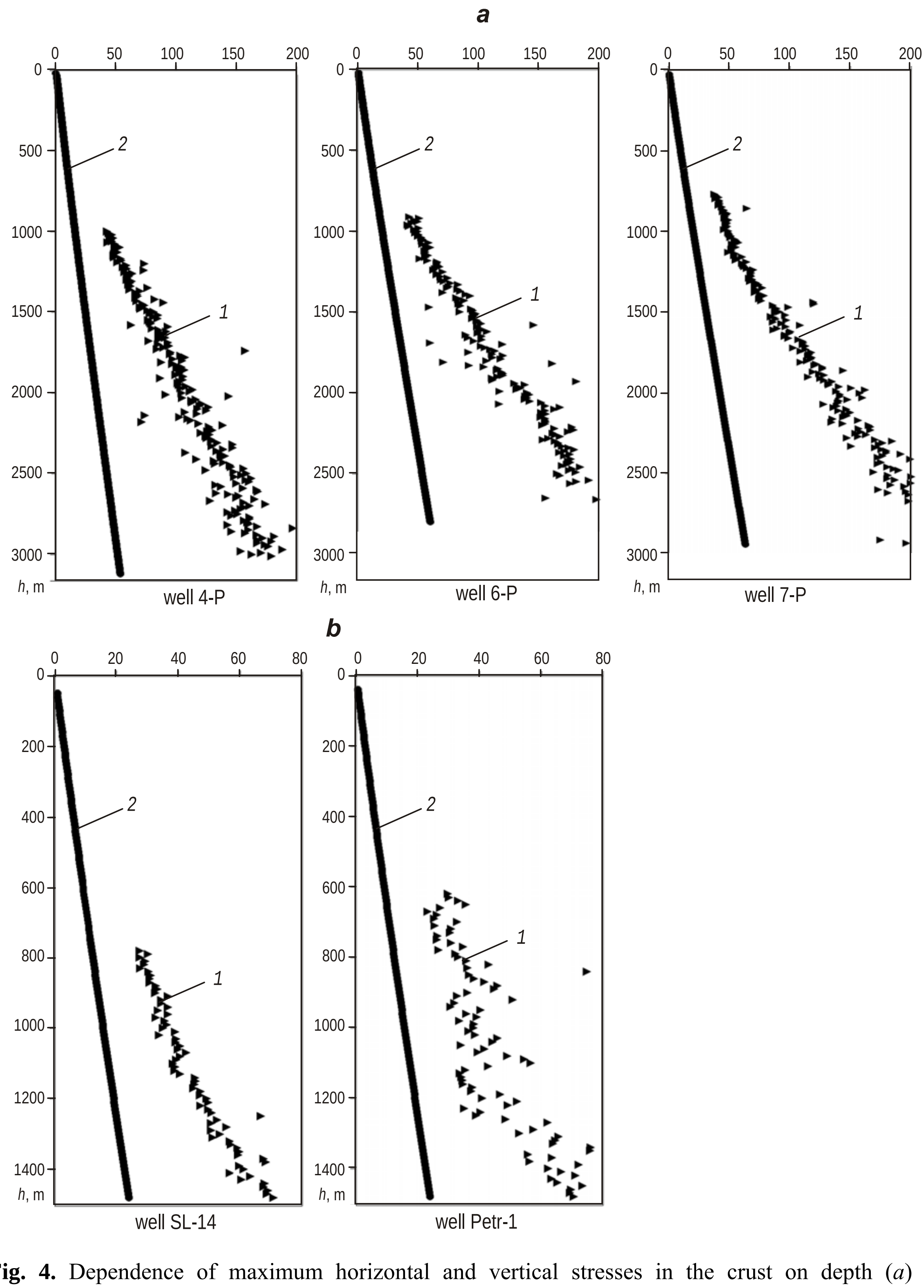

Fig. 4. Dependence of maximum horizontal and vertical stresses in the crust on depth (*a*) on Polyarninskoe and (*b*) Aniva fields near the described wells: *1* is σ_{1max} and *2* is σ_3

Plots in Fig.4 allow us to conclude that on Polyarninskoe field in the depth interval between 1000 and 2800 m, the maximum horizontal stress exceeds the vertical by about 1.5 times, which corresponds to regional stress character. According to the plot, at depths of about 3000 m the larger values of stress relationships are observed. The maximum horizontal stresses significantly increase up to the level exceeding the values of vertical stresses by 3.5-4 times. A similar situation is observed on the Aniva field. The values of horizontal stresses exceed the vertical ones on the average by 2-3 times in the same depth interval as on the Polyarninskoe field.

It should be noted that in the depth interval of 1200-1400 m, the maximum horizontal stress on Polyarninskoe field is several times higher than on Aniva. This fact may be related to the different fluid and gas saturation of fields at these depths corresponding to the producing horizon on Aniva field and to the interval of capping on Polyarninskoe field. Unfortunately, stress-strain state studies involving the instrumental methods were not carried out on Sakhalin.

The nearest field where such measurements were conducted is Nikolayevskoe field of polymetallic ores in the eastern Amur region situated in several hundreds of kilometers from Polyarninskoe [*Baryshnikov, Kurlenya and Leontev,* 1982]. This region is characterized by high seismic activity and high gradient of velocities of the newest vertical movements. There it was found the exceeding of horizontal stresses over vertical and, moreover, the anisotropy of horizontal stresses. Maximum compression stresses at depths to 850 m are oriented at azimuth 340° and do not exceed 40 MPa. Thus, our results in general coincide with the regional stress field.

Discussion of results

A number of projects of deep and ultradeep drilling carried out in geodynamic conditions similar to Sakhalin Island indicate the stress state with predominance of horizontal stress (thrust and shear regimes) that conserves with depth increasing [*Brudy, Zoback, and Fuchs,* 1997; *Zoback and Healy,* 1992; *Hickman, Zoback, and Healy* 1988]. A significant excess of horizontal stresses over vertical is natural for the crust of Sakhalin situated in the region of intense interplate interactions. To understand how this well-known fact is consistent with our estimates of maximum stresses, the following is important. Hypocenters of most earthquakes that occurred on Sakhalin Island are located at depths of 8-10 km [*Zlobin,* 2000; Nevel'skoe …, 2009]. The characteristic fault plane solutions for these earthquakes are thrusts; strike-slip and normal events are less frequent [*Zoback,* 1992]. According to *Turcotte* and *Schubert* [1985] and *Yunga* [1990], the very fact of the predominance of thrusts, particularly with small angles of overthrusts, indicates the ratio $\sigma_1 >> \sigma_3$.

Horizontal stresses are partially transferred from seismogenic layers (granitoids, basalts) in the sedimentary cover at depths of more than 5-8 km. This fact is confirmed by data on seismicity of Sakhalin Island: the depths of some events that happened on the Island were less than 8 km; earthquakes with hypocenters at depths of 2.5-5 km were also recorded [Katalog…, 2011].

Thus, horizontal stresses in near-surface layer of the crust on Sakhalin can be close to maximum according to criterion (1). Our estimates of maximum stresses σ_1 for depths of 1–3 km also indicate their increase with the depth (Fig. 4 *a*). It should be noted that on the Polyarninskoe field at the depths of about 2800 m, σ_{1max} is ~180 MPa exceeding the value of table (standard) strength of terrigenous rocks at these depths (sandstones, aleurolites, and argillites). If we transfer these estimates obtained *in situ* to the nearest fault zones, then such stresses can be associated with shallow earthquakes with hypocentral depths of 2.5–3 km.

Conclusions

The possibility of applying methods of estimation of geomechanical parameters of rocks using data of combination logging is demonstrated on the example of Polyarninskoe oil field and Aniva gas field, Sakhalin Island.

The detailed information about the internal friction coefficient and cohesion of terrigenous sedimentary rocks in near-surface layer of the crust on Sakhalin was obtained. The results demonstrate that maximum horizontal (tectonic) stresses increase with the depth.

It is shown that both in the north and south of Sakhalin Island, the maximum sublatitudinal compression can exceed the vertical stress on the average in 1.5-3 times.

The obtained estimates are useful for solving the problems of modern geodynamics as well as applied problems during the well drilling, perforations and hydraulic fracturing conducting. One of such tasks is the calculation of density of drilling mud (the so-called window of stability) which takes into account the values of the internal friction coefficient and cohesion.

Results of processing of logging data together with other geological and geophysical data create an innovative groundwork for the creation of geomechanical models to be used for drilling and operation of wells in oil and gas deposits on Sakhalin Island.

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