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GEOLOGY

The Role of Nappe Tectonics in the Development of Abnormally High Formation Pressure and Economic Metalliferous Brines: A Case Study of the Southern Siberian Craton

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Worldwide experience in the exploration of oil-and-gas (hereafter, petroleum) fields shows that drilling deep wells in thick saliferous caprock above the petroleum pools often becomes problematic, or even becomes impossible, due to high-pressure spouts generated by abnormally high formation pressure (AHFP) of fluids [1] that develops in virtually all large petroliferous basins (Fig. 1). At the Siberian Craton, the AHFP phenomenon has received too little attention, although considerable hydrocarbon and hydromineral resources of Russia are located in this region. For example, the giant Verkhnechonskoe (Upper Chona) oil- and gas-condensate field, the Kovykta gas condensate field, and the Znamensky economic brine field have been discovered and explored. Three main geological factors determine the prospects of further development of the Siberian rare-metal brines (in essence, liquid polycomponent ores): (1) very high concentration of useful elements (Br, Li, Mg, and others); (2) reservoir rocks with high (locally, abnormally high) conduction; and (3) abnormally high formation pressure. The study of interrelations between the aforementioned factors and localization of brines in the sedimentary cover are crucial in minerageny of economic brines at the Siberian Craton. Therefore, the models of the distribution of high-quality reservoir rocks in a geological section serve as a basis for forecasting, prospecting, and exploration of hydromineral resources. This communication is devoted to the possible role of nappe tectonics in the development of AHFP and in the formation of industrial pools of rare-metal brines on the Siberian Craton.

The in-depth and system analysis of nappe–fold structural features of East Siberia is based on the morphokinematic model of zonal distribution of nappe belts at the southern margin of the Siberian Craton [2]. This model is permanently upgraded and replenished by new factual data [3–7]. It becomes clear that the nappe dislocations not only control spatial distribution of petroleum fields, but also govern the formation and localization of economic pools of rare-metal brines at the southern margin of the platform. This allows us to reappraise the resources of the Siberian brines from a principally new view.

The Siberian Craton is a large petroliferous province with widely developed AHFP. Flows of economic brines and hydrocarbons under AHFP are everywhere confined to the relatively thin carbonate reservoir beds within a thick saliferous sequence of the platform sedimentary cover [8]. Two large AHFP zones—the Northwestern and the Southeastern (Fig. 2)—are outlined by deep exploration wells. The Northwestern zone was

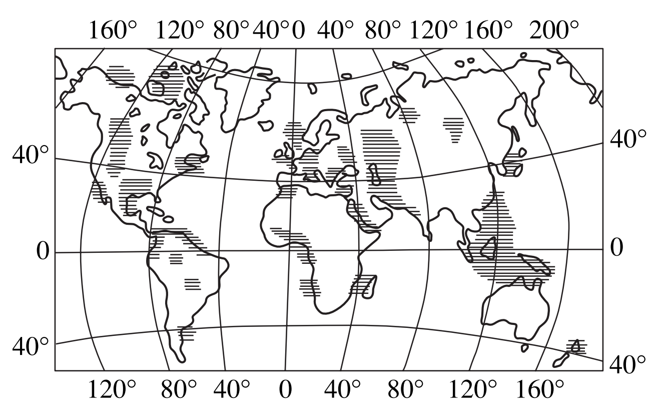

Fig. 1. Worldwide distribution of abnormally high formation pressure [1].

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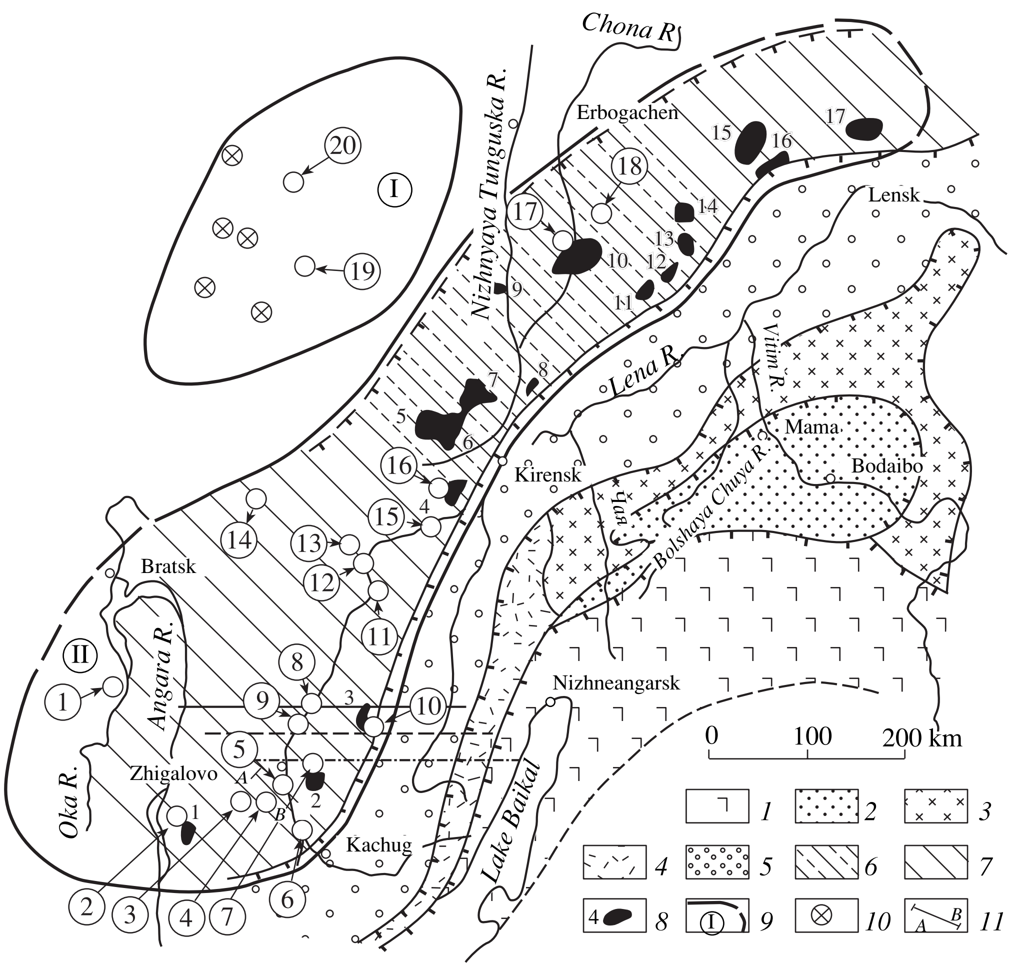

Fig. 2. Allochthonous structural features, oil-and-gas fields, and deep wells with AHFP at the southeastern margin of the Siberian Craton at the boundary with Baikal–Patoma Highland (modified after [2]). (*1*) Baikal–Muya Ophiolite Belt (the root zone composed of packets of detached tectonic nappes consisting of island-arc and ophiolitic complexes); (*2*) Mama–Bodaibo zone filled with shelf sequences of passive margin characterized by nappe–fold structure; (*3*) Chuya–Tonod–Nechera zone consisting of megaslabs of lithotectonic complexes that represent fragments of the reworked basement of the Siberian Craton; (*4*) Akitkan Megaslab; (*5*) Baikal–Fore-Patoma underthrust zone; (*6*) Nepa–Botuoba frontal anteclise (megaslab); (*7*) frontal zone of reflected folding in the platform sedimentary cover; (*8*) petroleum fields; (*9*) AHFP zones; (*10*) deep wells with brine flows; (*11*) geological profile *A*–*B*. Petroleum fields (numerals in figure): (1) Atovo, (2) Tutura, (3) Kovykta, (4) Markovo, (5) Yarakta, (6) Ayan, (7) Dulis'ma, (8) Pilyudino, (9) Danilovo, (10) Verkhnyaya Chona, (11) Taran, (12) Central Talakan, (13) Lower Khamakan, (14) Ozernoe, (15) Middle Botuoba, (16) Khotogo-Murbai, (17) Upper Vilyuchan. AHFP zones (numerals in circles): (I) Northwestern, (II) Southeastern. Areas and deep wells with highyield flows of industrial brines (numerals in circles): (1) Krakhun, Well 2; (2) Balagankino, Wells 2 and 3; (3) Balykhta, Well 5; (4) Znamensky, Wells 3 and 3A; (5) Rudovsky, Well 176; (6) Upper Lena, Wells 100 and 131; (7) Tutura, Wells 1 and 5; (8) Gruznovka, Wells 1 and 134; (9) Zharkovo, Wells 3 and 133; (10) Kovykta, Wells 3, 18, 52, 60, 61, and 64; (11) Omoloi, Well 13; (12) South Ust-Kut, Well 3; (13) Ust-Kut, Well 1; (14) Ilim, Wells 4 and 5; (15) Kazarkino, Well 2; (16) Markovo, Wells 1, 4, 5, 28, and 49; (17) Upper Chona, Well 900; (18) Vakunai, Well 3; (19) Tetere, Wells 278 and 279; (20) Altyba, Wells 244 and 250

penetrated by deep wells on the western slope of the Nepa arch in the Tetere, Altyba, Eremino, Platonovo, and Pilyudino areas in carbonate rocks of the Ust-Kut bed. The Southeastern zone occupies a much wider territory in the Angara–Lena scarp with linear AHFP distribution shown on the figure. We can identify two types of AHFP flows in deep wells. The first type is penetrated by deep wells that recover traditional reservoir beds in the halogenic–carbonate sequence, e.g., the Bil'chir Unit in the Lower Angara Subformation or the Balykhta Unit in the upper part of the Lower Cambrian Usol'e Formation. The second type is unrelated to the known brine-bearing units and is represented by thin interbeds of the disintegrated dolomite (anomalous reservoirs, or AR) that do not serve as reservoir rocks in the adjacent areas. Flows of the second type show the following trend: if wells are located at a similar altitude, AR is penetrated at the same depth. It is evident that, if parameters of the AHFP coefficient are similar, different wells penetrate an actual near-horizontal fault plane approximating a thin (from tens of centimeters to 1–2 m) near-horizontal slab. The opening of an AHFP unit is indicated by the sudden collapse of a drilling tool, abrupt increase in drilling speed, and instant increase in bottomhole pressure. When deep wells (Fig. 2) located at a considerable distance from one another (tens of kilometers or more) but within the same interval of geological section, e.g., the Bil'chir Unit or the uppermost units of the Usol'e Formation (salt and dolomite), encounter AHFP zones in thin dolomite interbeds, this may indicate the presence of an imbricate fan-shaped thrust fault and associated secondary reservoir. Thus, the Cambrian sequence of the studied territory includes carbonate AHFP beds in fracture–pore space between saliferous rock beds. Pressure excess relative to the normal hydrostatic pressure, i.e., coefficient of anomalous pressure (K_a), is as much as 2.30–2.65.

At the first stage of research [9], we suggested that such interbeds were formed as a result of ancient multistage deep-seated salt or carbonate karst. The structural features indicate the subsidence of the overlying sedimentary beds, and this might be a cause of rock pressure transmission to the fluid. However, the karst process could start during the tectonic reactivation of the Earth's crust. Indeed, we have now come to the conclusion that the formation of superimposed geological features genetically related to the deep salt karstification may explain the local development of AHFP. At the same time, when the location of deep AHFP wells is compared with the contours of inferred thrust dislocations (Fig. 2) in the Fore-Baikal sector [10], one can see that the anomalous wells are grouped within a NE-trending linear regional thrust fault zone.

The hydrogeological filtration model based on the results of filtration tests [8] does not contradict the idea of near-horizontal zone of active fracturing. The widespread active fracturing within a detachment zone suggests the formation of a superimposed filtration structure that works during draining according to the Barenblatt model of media superposition. One of the authors of this paper included a geological model of regional thrust fault plane in a project of geological exploration of the Znamensky brine deposit (Fig. 3). The theoretical suggestion was fully confirmed by practice. The drilled brine zone with abnormally high yield (3000 m^3 in Well 3A, 7000 m^3 in Well 3R) and AHFP = 42 MPa at a depth of 1820 m has been documented as a near-horizontal active fracturing zone that consists of several thin carbonate beds hosted in salt in the upper part of the Usol'e Formation. It is appropriate here to draw the analogy to the localization of ore deposits in the thrust fault zones. As has been stated, "the fracturing subconcordant to bedding is also among the leading geostructural factors" [11]. In the course of drilling, the wells encounter AHFP–AR zones in the fracture system oriented parallel to the thrust fault plane and in the tensile fractures. Brines behave as a lubricant, and the overlying rock pressure is transmitted to the liquid that fills the fault plane.

Based on comparison of the maps of seismic activity, nappe tectonics, and AHFP distribution at the southeastern margin of the Siberian Craton from the deep drilling and CSD data, we point out that the AHFP zones are localized within the domains of the Sayan and Fore-Baikal–Patoma nappe belts [10], i.e., within the belt of frontal thrusts and reflected suprafrontal structures in the inner part of the platform [2]. This statement is supported by the following facts.

First, the brine flows with high discharge and AHFP values comparable in some objects with rock pressure should be regarded as an irrefutable indicator of the dynamic stress state of the middle (saliferous) portion of the geological section of the platform cover. Despite the seemingly mosaic AHFP distribution in the figure, the linear orientation of zones provides evidence in favor of the model of the front of nappe structures at several levels, i.e., the front of imbricate fan-shaped nappes (Figs. 2, 3).

Second, virtually all brine-bearing AHFP wells are confined to the hanging wall of thrust fault, or allochthon (imbricate fan). They are less common in the axial zone of salt arch, e.g., the Zhigalovo, Upper Lena, Omoloi, Markovo, and Tuba swells [2, 11, 12], where the updip angle of fault plane sharply changes on the eastern limb of a typical linear fold. If the AHFP zone is correlated with a thrust fault plane, then we analyze the results of deep drilling the similar suprathrust zones with the typical geological structure.

The principal mechanism of AHFP development in a thrust fault zone is described in [13]. The development of AHFP in the Upper Mota Subformation (Ust-Kut Unit) in the Tetere–Altyba zone in Well 900 of the Upper Chona field may be accounted for by the mobility of wedge-shaped basement blocks. The movement of one such block produced the Tetere Inlier [2]. This led to the development of a stress zone from below. Thereby, the sedimentary cover in the Tetere–Altyba zone has an additional roof (framework) in the form of trap rocks, which do not allow the sedimentary rocks to react adequately to vertical displacements of basement blocks. The carbonate framework of the Upper Mota Subformation (carbonate reservoirs localized near the basement) also takes up the stress in the cover. In total, five wells with AHFP and brine overflow (Altyba 244, Altyba250, Tetere 278, Tetere 279, and Eremino 243) are known in the Northern zone. The idea of Hubbert and Rubey [13] suggesting an important role of AHFP in formation of large thrust faults is gaining much recognition among Russian geologists [14]. This idea has been confirmed both by laboratory tests and field observations. In addition to the proposed mechanism of AHFP development, this process is explained by neotectonics (K.A. Anikiev), injection of deep fluids (P.M. Kropotkin and B.M. Valyaev), crossflow of deep fluids in saliferous rocks (N.Ya. Kunin), and so on. Although reality of the aforementioned mechanisms in the development of

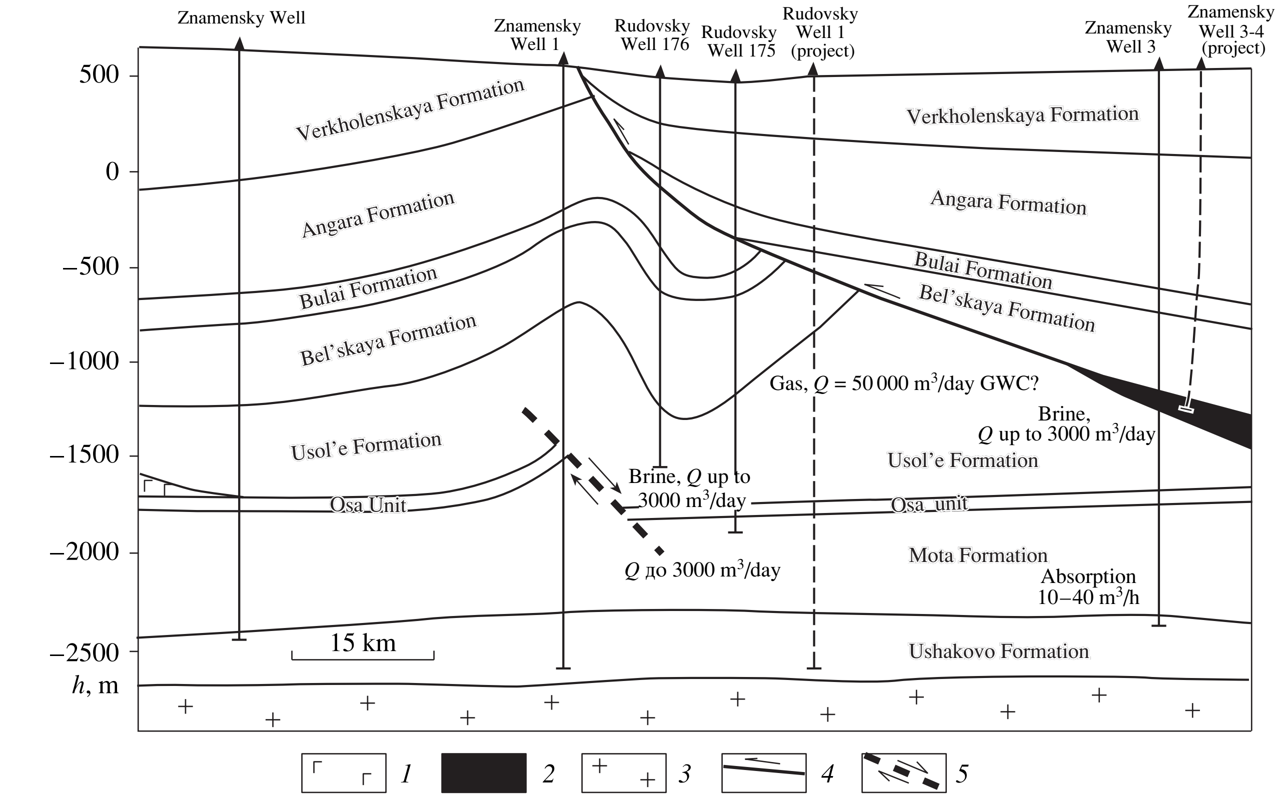

Fig. 3. Geological section across the front of thrust fault cut by deep AHFP wells and high-yield brine flows in the Znamensky (Wells 1–4) and Rudovsky (Wells 1, 175, 176) areas of deep drilling (modified after the materials of VostSibneftegazgeologiya State Geological Enterprise). (*1*) Trap rocks; (*2*) economic brines; (*3*) crystalline basement; (*4*) proved thrust fault; (*5*) inferred fault plane.

AHFP and economic metalliferous brines is possible, we give priority to the nappe tectonics.

Thus, issues of minerageny of the liquid polycomponent ore in the sedimentary cover of the southern Siberian Craton, i.e., the confinement of anomalous reservoir rocks, AHFP, and anomalously high concentrations of rare elements in brines, are considered within the framework of a common geological–genetic model in the present work. This view on the structural control of localization of economic rare metal brines substantially differs from previous concepts and allows the unique hydromineral resources of the Siberian Craton to be reappraised on a new basis.

REFERENCES

1. J. P. Mouchet and A. Mitchell, *Abnormal Pressures While Drilling*, 2nd ed. (Elf Aquitaine, Boussens, 1989).
2. V. I. Sizykh, *Nappe Tectonics of Ancient Platform Margins* (Sib. Otd. Ross. Akad. Nauk, Novosibirsk, 2001) [in Russian].
3. V. K. Aleksandrov, V. I. Sizykh, A. A. Bukharov, and V. D. Mats, Dokl Akad. Nauk **380**, 511 (2001) [Dokl. Earth Sci **380**, 815 (2001)].
4. V. K. Aleksandrov, V. I. Sizykh, A. A. Bukharov, and V. D. Mats, Geotektonika **37** (4), 35 (2003) [Geotectonics, **37**, 289 (2003)].
5. V. I. Sizykh, Vestn. MANEB **9** (1), 21 (2004).
6. Val. I. Sizykh, Vit. I. Sizykh, and Yu. I. Sizykh, Priroda, No. 12, 53 (2003).
7. V. I. Sizykh, A. A. Dzyuba, V. P. Isaev, and S. N. Kovalenko, Otechestvennaya Geol., No. 5, 8 (2004).
8. A. V. Baranov, A. G. Vakhromeev, N. P. Kotsupalo, et al. *Manufacture of Lithium Products from Siberian Brines for Environment Protection from Aluminum Production* (Irkut. Gos. Tekhn. Univ., Irkutsk, 2004) [in Russian].
9. A. G. Vakhromeev and G. A. Khokhlov, in *Technology of Drilling and Injection of Wells in East Siberia and Yakutia* (SNIIGGiMS, Novosibirsk, 1988), pp. 140–142 [in Russian].
10. A. V. Smetanin, *An Experience in Dynamic Interpretation of Gravity Anomalies* (Irkutsk, 2000) [in Russian].
11. I. S. Vakhromeev, in *Problems of Nappe Theory of the Continental Crust Formation* (Bashkir. Nauchn. Tsentr, Ufa, 1991), pp. 35–41 [in Russian].
12. A. A. Dzyuba, *Discharge of Brines at the Siberian Craton* (Nauka, Novosibirsk, 1984) [in Russian].
13. M. K. Hubbert, and W. W. Rubey, Geol. Soc. Am. Bull. **70** (2), 75 (1959).
14. E. V. Kucheruk and T. E. Lyustikh, *Geological–Geochemical Methods of Prospecting for Mineral Resources. Methods of Exploration and Evaluation of Mineral Deposits. Exploration and Industrial Geophysics* (Moscow, 1986), vol. 7 [in Russian].