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GEOLOGY

Structural Features of the Earth's Crust and Petroleum Potential: First Results of CMP Deep Seismic Survey along the Geotraverse across the Volga–Ural Petroliferous Province

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Deep CMP seismic surveys carried out in petroliferous regions of Tatarstan (since 1993) and other regions of the Volga–Ural petroliferous province in the later period revealed that time sections of large oil fields are underlain by intense dynamic anomalies [1 and others]. Although the nature of these anomalies is unclear, their presence has demonstrated the principle possibility to elaborate methods for predicting large hydrocarbon fields based on the CMP method. The above fact simulated similar seismic studies in the Kirov, Samara, Orenburg, Bashkir, and Udmurt regions, as well as prospecting in Tatarstan. However, due to the specific character of planning of geological–prospecting works, exhausted regional profiles were not always properly located in different administrative units. Moreover, they did not coordinate with some profiles in the adjacent regions. This made it difficult or even impossible to study comparative characteristics of large tectonic structures and petroliferous and poorly studied regions.

In order to obtain qualitatively new information and additional data, we substantiated the accomplishment of the NW–SE-trending geotraverse across the Volga–Ural petroliferous province including the giant Romashkino oil field (Fig. 1). The main purpose was to examine the structure of the sedimentary layer and the entire crust in the North Tatar Arch, Kazan–Kazhim Aulacogen, Kotel'nich Arch, and southeastern Moscow Syneclise and to compare these structures with the South Tatar oil-bearing arch.

The Tatseis-2003 geotraverse (more than 1000 km long) crossed the Nizhni Novgorod and Kirov regions, as well as the Marii-El, Tatar, and Bashkir republics.

In the southeastern part near Sterlitamak, the profile was coordinated with the Uralseis-1995 geotraverse by correcting Profile VIII (Bashneftegeofizika Open Joint-Stock Company). In the future, this will provide integrated information on the ~1600-km-long profile extending from the Urals to the Moscow Syneclise.

We used the following technique in field works [2]: asymmetric observation system; array length 12 000 m; 240 active channels; maximal source/receiver distance 10 000 m; distance between receivers 50 m; distance between source points 100 m; and multiplicity factor 60.

The telemetric system INPUT/OUTPUT SYSTEM TWO was used as recording equipment. The length of a useful record was 20 s with a quantization step of 4 ms. Powerful seismic vibrators Hemi-50 with the maximal propulsive force of 23 t were used as excitation sources. The vibrators were applied in a group of 5–6 pieces at the base 50–55 m long, and 5–8 vibration actions were performed at each source point. The sweep parameters specified in the course of trial works were as follows: initial frequency 14 Hz; final frequency 70 Hz; sweep duration 20 s. It should be noted that the applied technique and equipment provided high-quality results, which served as the basis for solving the formulated geological tasks.

The Tatseis-2003 geotraverse crossed 12 oil fields. Among them, the Romashkino, Novoelkhovo, and Tuimaza are attributed to the category of giant and unique fields. Many of these fields incorporate several productive beds with the main productive horizon represented by Devonian terrigenous formations. The southeastern slope of the North Tatar Arch also hosts oil fields, but their number and reserves are substantially lower as compared with the South Tatar Arch.

In the Kazan–Kazhim Aulacogen, insignificant oil seeps were recorded in the Syr'yan structure of the northern Kirov region and in Well 1-Ilet in the Marii-El Republic [3]. The latter oil show is of particular importance from the point of view of deep seismic survey, because the Ilet area is located not far from the geotraverse.

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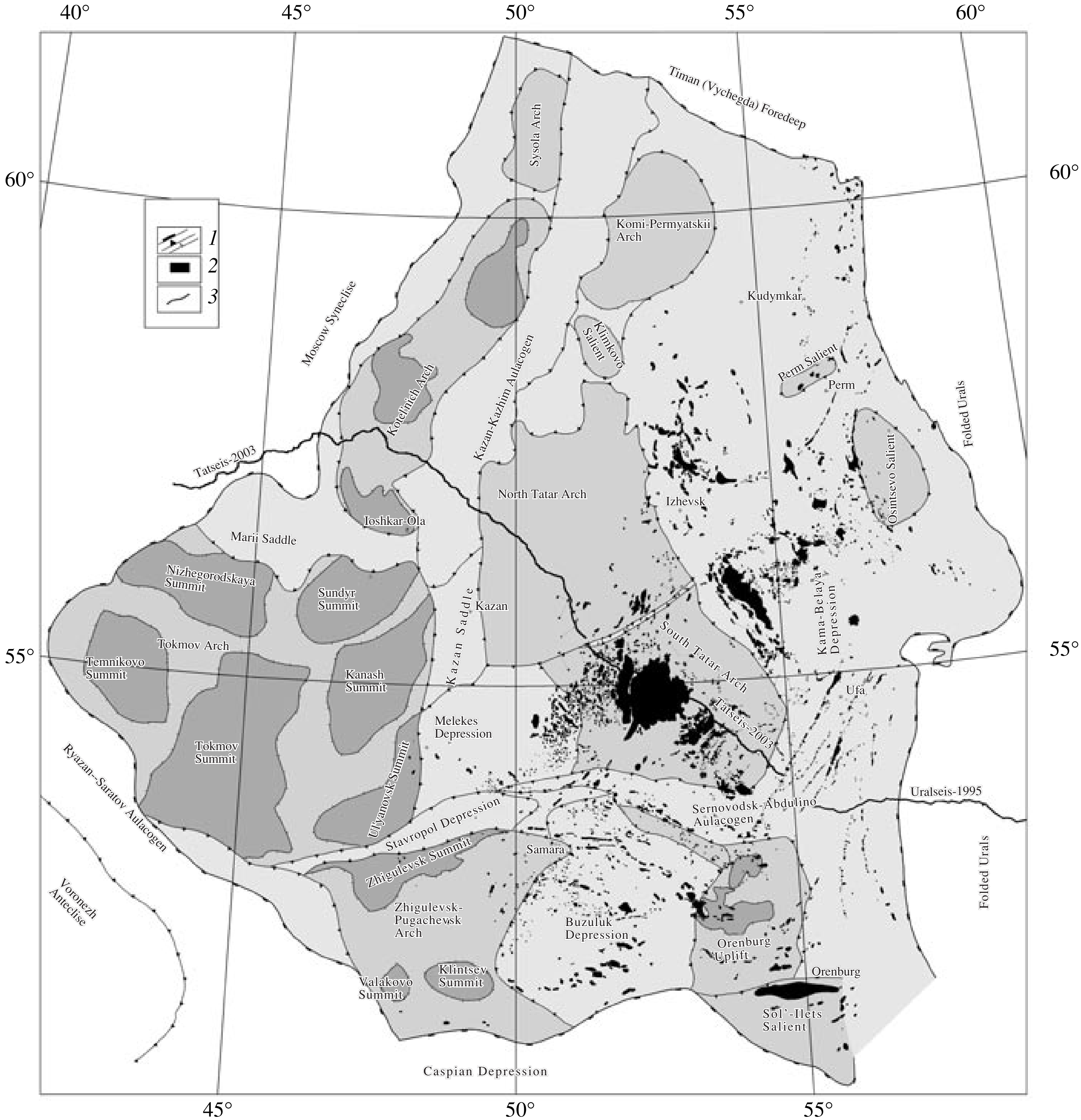

Fig. 1. Location of the Tatseis-2003 geotraverse and the schematic tectonic structure of the Volga–Kama Anteclise basement. (*1*) Boundaries of tectonic structures; (*2*) oil fields; (*3*) Tatseis-2003 and Uralseis-1995 geotraverses.

Oil pools and shows are unknown so far in the Kotel'nich Arch and eastern flank of the Moscow Syneclise. Deep drilling data on the petrography and structure of the basement are given in [4–6 and others].

The wave field in time sections obtained along the Tatseis-2003 geotraverse is substantially more informative as compared with CMP records of earlier profiles accomplished in this region. This became possible owing to the higher technical–methodical level of our works and optimal orientation of the geotraverse in most of its segments (the profiles were mainly oriented across the strike of tectonic elements and faults). Let us consider the major features of the wave field reflected in time sections.

The wave field at large time intervals is dominated by inclined (SE-rising) in-phase axes with distinct zon-

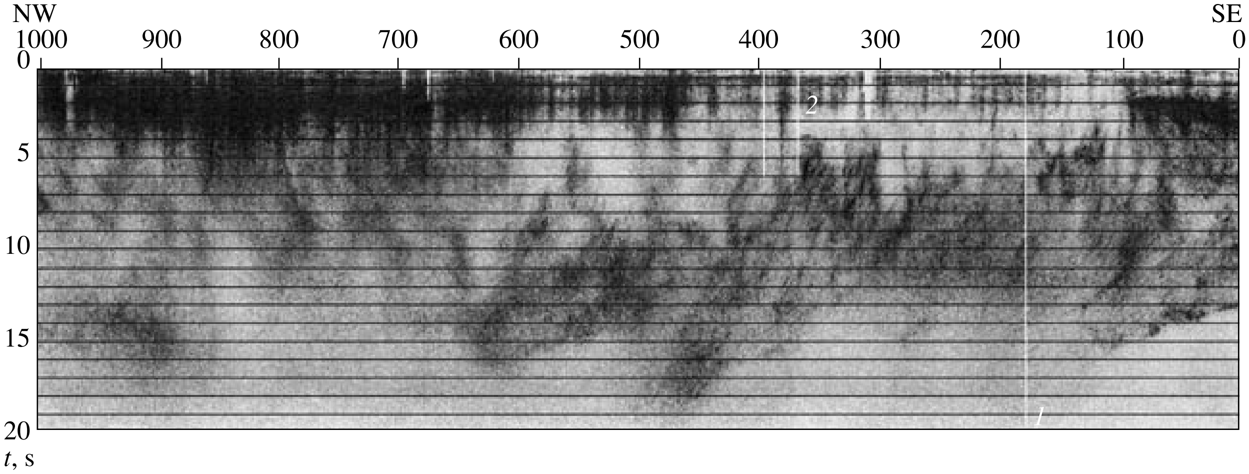

Fig. 2. General view of the time section along the Tatseis-2003 geotraverse.

ing: they are mainly observed in the southeastern segment of the geotraverse (interval 100–430 km) with oil fields (Figs. 2, 3).

According to previous studies [7–10 and others] and results of the complex analysis of geological–geophysical data based on superdeep boreholes drilled in Tatarstan [11, 12], the most intense reflectors in the basement have a tectonic origin. Therefore, the inclined reflectors can be interpreted as faults, which correspond to zones of destructed and fractured rocks. Judging from the reflection patterns, their flattening at deeper levels, and grading into near-horizontal stratified zones, one can assume that the reflectors represent reverse upthrust structures [12, 14] formed under conditions of horizontal compression. Recent tectonic activity in oil-bearing areas of Tatarstan suggests that these structures are still active.

The lower segments of inclined reflectors adjoin the lower near-horizontal stratified crust, cross it in some places, and flatten at the Moho (M) discontinuity (boundary) level. Locally, these reflectors cross the Moho boundary and penetrate the upper mantle. This is particularly distinct at the interval of 430–480 km (t_0 = 15–19 s).

In the time section obtained along the geotraverse, one can confidently trace the Moho boundary, which probably represents the base of the seismically stratified lower crust (Fig. 2). In the major portion of the profile, the Moho boundary shows a SE-oriented rise, particularly at the interval of 0–140 km, where its registration time decreases from 16 to 13 s (or from 52–53 to 42–43 km in the depth scale). The Moho boundary rises irregularly. For example, at 480, 280, and 120 km of the profile, the depth of the stratified zone changes in a stepwise manner. It is noteworthy that the thickness of the zone anomalously increases southeast of these points. Such areas are sometimes marked by the fan-shaped divergence of the most intense inclined reflectors from the stratified zone. Judging from the depth of the base of stratified intervals in anomalous zones (up to 60–65 km, 18–19 s in the time scale), they are located already in the upper mantle.

Detailed analysis of the time sections shows that the base of the stratified zone beneath some profile segments is extremely heterogeneous. For example, its initial part (interval 0–110 km) is characterized by alternation of very intense and weak in-phase axes of different shapes and inclinations.

Like in other areas of the Volga–Ural province, time sections of the Tatseis-2003 geotraverse demonstrate near-vertical dynamic anomalies, which locally are very intense, for example, at 382–383 km. The analysis of seismic records and sections of incomplete summation made it possible to conclude with a sufficiently high degree of confidence that near-vertical dynamic anomalies reflect real geological bodies, although their nature is unclear so far. According to [1], they are near-vertical zones of disturbed and fractured rocks. This assumption is most probable but unproven so far. In the future, it would be expedient to solve this question by conducting special geophysical and geochemical investigations and drilling. Although near-vertical dynamic anomalies are recorded beneath many oil fields crossed by the geotraverse, we shall not discuss them in this paper.

Thus, the crust and mantle structure beneath oil fields of the South Tatar Arch and southeastern slope of the North Tatar Arch (the profile segment between 50 and 360 km) differs cardinally from that in other regions.

First, their seismic records show reflections interpreted as deep upthrusts characterized by high values of reflectance. In the northwestern segment of the profile between 610 km and its end (Kotel'nich Arch, Moscow Syneclise), inclined reflectors are also traced, but they

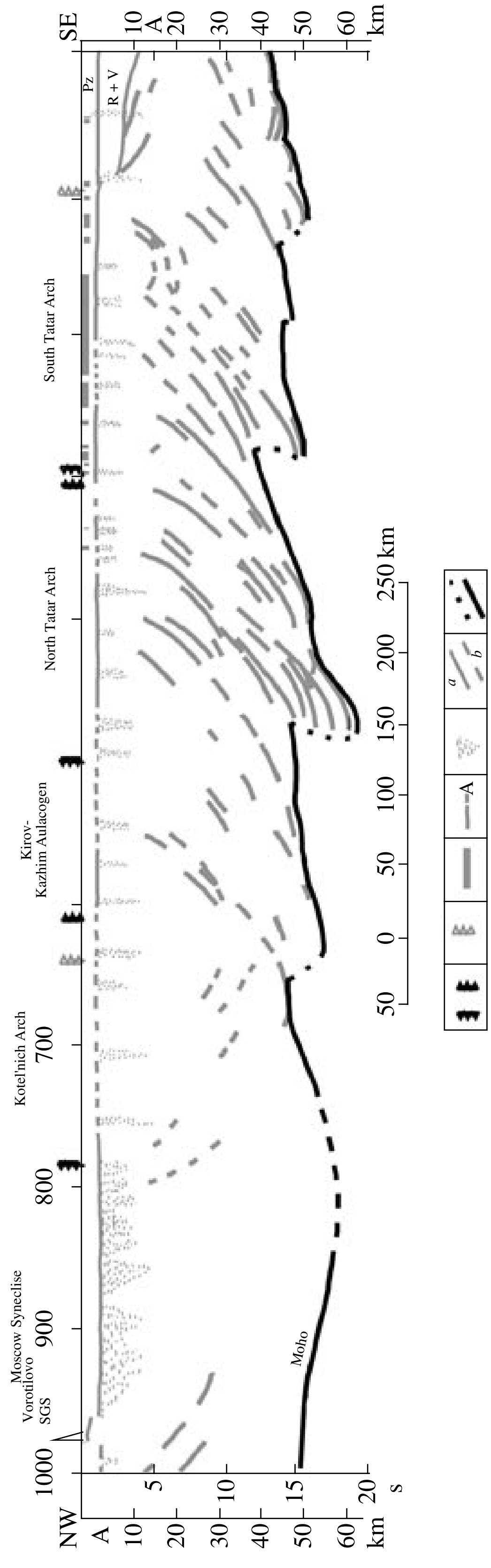

Fig. 3. Seismic–geological section of the crust along the geotraverse. (*1*) Boundaries of first-order tectonic structures; (*2*) specified boundaries of tectonic structures; (*3*) oil fields; (*4*) crystalline basement surface; (*5*) assumed near-vertical destruction zones; (*6*) reflectors in the consolidated crust: (*a*) proven, (*b*) inferred; (*7*) base of the stratified zone (probable Moho boundary).

are characterized by significantly lower reflectance and inclination in the opposite direction.

Second, inclined reflectors in this segment of the profile extend up to the Moho boundary and continue locally in the upper mantle (intervals 480–430, 280–240 km, and others). No such phenomena are observed in its northwestern part. Among the segments indicated above, of greatest interest is the first one, where time points 15–19 s (approximate depth 50–65 km) correspond to the local zone with a more intense and contrasting seismic record, as compared with the surrounding sequence. Several inclined reflectors diverging in the fan-shaped manner are recorded precisely in this zone.

Third, the behavior of the Moho boundary also changes: in the northwest, it is relatively flat and dips eastward from 48 to 54 km (profile interval 890–1000 km). In the southeast, the Moho boundary gradually rises, but it shows sharp changes in some places confined to the above-mentioned anomalous zones in the upper mantle.

All these features indicate the unusual, most likely disturbed, character of both the crust and the mantle beneath large hydrocarbon fields.

From this standpoint, the Kotel'nich Arch and Moscow Syneclise crossed by the profile at 610–1000 km are characterized by a low petroleum potential. However, we should state one reservation: the profile sharply changes its direction (approximately at 700 km) and crosses relevant tectonic structures, particularly the Moscow Syneclise, in an unfavorable direction.

Of particular significance for comparison of the structural characteristics of the crust and petroleum potential is the Kazan–Kazhim Aulacogen (in the recent tectonic scheme, profile interval 500–610 km). As in oil-bearing areas, this segment includes a relatively intense inclined reflector, which substantially increases the oil prospects of this area. Judging from the number (or density) of inclined reflectors in the crust, small oil fields can be discovered at intervals of 400–570 km.

These remarkable features of the crust and mantle beneath oil-bearing fields of the South and North Tatar arches (relative to the northwestern regions), as well as the presence of deep-seated listric faults rooted in the crust and mantle, provide sufficiently sound grounds to suggest that the specific features indicate the deep origin of oil. Moreover, it is expedient to use these features as criteria for the assessment of petroleum potential in poorly studied regions and for the exploration of large hydrocarbon accumulations.

Using these criteria, one can confidently draw the western boundary of the Volga–Ural petroliferous province along the Kazan–Kazhim Aulacogen (it corresponds to ~570th km of the geotraverse) and optimize the planning of oil prospecting works.

Thus, we can make the following conclusions:

(1) Processing of the unique >1000-km-long seismic profile across the nearly entire Volga–Kama Anteclise yielded highly informative materials indicating the correctness of target formulation and survey planning, as well as the optimal use of technical means and methodical approaches.

(2) The detection of relationships between the petroleum potential of sedimentary cover and the structure of the crust and mantle is of fundamental significance (deep origin of hydrocarbons). Specific features revealed in this region can be implemented for oil prospecting in the Volga–Ural and other regions, as well as for the assessment of oil prospects in poorly studied regions.

(3) Inclined reflectors in the crust and upper mantle have a tectonic origin. Near-vertical dynamic anomalies in the region are created by real geological bodies. Deep seismic studies carried out in the region have completely fulfilled the planned task. The results obtained made it possible to elaborate several recommendations concerning the direction and methodology of further research.

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