IDENTIFICATION OF ZONES AND AREAL EXTENT OF WEATHERING CRYSTALLINE BASEMENT IN THE ARCHEAN-LOWER PROTEROZOIC CRUST OF THE SOUTH TATAR ARCH

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Abstract. Based on the data of geophysical surveys and deep drilling the depth to the crystalline basement and its weathering upper layer at the eastern flank of the South Tartar Arch varies from 1650 to 2500 m. Against the ongoing depletion of hydrocarbon reserves in the Paleozoic reservoirs of the region the basement becomes a promising exploration target. However the study of its architecture, composition and areal extent is largely hindered by so far very limited coring in this interval. In previous research correlation of core data and wireline logs was used for petrophysical characterization and identification of zones in a vertical profile of the upper weathering layer of the basement in the deep parametric test wells 50 Novournyak and 2000 Tyimazy with most complete core recovery. These characterization criteria have been utilized for analysis of 750 deep wells drilled in Bashkortostan within the South Tatar Arch which is bounded in the south by the Serafimovsko-Baltaevskiy Graben. In 340 wells based on wireline and production logs the upper weathering layer of the basement revealed certain distinct features of vertical zonation. The analysis resulted in thickness maps for Zone B and combined thickness maps for Zones B + C where the weathering basement is characterized by two morphological types – linear-areal and linear-fractured. The findings support the initial assumption that the obtained petrophysical characteristics may be applied to identify the weathering crystalline basement in wells with no core.

Key words: basement, crystalline rocks, hypergenesis, weathering crust, zone, core, areal extent
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The productivity of the weathering crust, both ancient and young platforms, has been proved in many oil and gas basins of the world, including the West Siberian (fields of Shaimsky swell and Krasnoleninsky arch), the South Mangyshlak (Oymasha), the northern side of the Dnieper-Donetsk avlakogen (Yuliyevsky, Khukhrinsky, and others). The presence of this geological formation in the sections of wells drilled in the western areas of the Republic of Bashkortostan was indicated in the 50s of the last century (Timergazin, 1951). The crystalline basement lies at depths of 1650-2500 m within the most hypsometrically elevated part of the eastern slope of the South-Tatar arch, and under the conditions of a sustainable reduction in the resource base of hydrocarbons in conventional Paleozoic complexes, its weathering crust may represent an undoubted petroleum search interest. However, the study of its structure, material composition, and specific features of the areal development is complicated by a small selection of cores from a given interval of the section.

In the paper (Amelchenko, Ivanova et al., 2016) on the example of parametric wells 50 Novournyak (NUN) and 2000 Tyimazy (TMZ), zones of weathering crust are identified using field geophysical data. Based on the comparison of the core material and logging data, a vertical profile of the weathering crust of the South-Tatar arch basement was constructed, in which the zones of successive changes in crystalline rocks under the influence of hypergenic factors from the initial disintegration of the original substrate to the final products of its decomposition are traced from below and their logging characteristics are outlined. The indexing of the zones is accepted by (Syungeevsky, Khafizov, 1999).

Zone "A" – unchanged in the ground surface mother rocks of the basement, which are characterized by high values of apparent resistance – 625 Ohm*m (lower in the section they can significantly increase, for example, in the silted intervals or decrease in zones of tectonic dislocations). In the well 50 NUN (the most representative complex of logging is performed here), the roof of the zone is clearly identified from the depth

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of 2462 m also from the sidewall log, which differs uniformly in different patterns, varying in the range 550-7000 Ohm*m; neutron gamma-ray logging – the values reach 7 cu; microprobe readings (micropotential and microgradient sondes) reflecting tight rocks. The acoustic logging curve is kept near 160 μs/m, and the induction curve is kept at 90 Ohm*m.

Above the surface of the basement, its weathering crust has been exposed in the sections of the wells, in the vertical profile of which, from below upwards the following zones are identified:

Zone "B" is the zone of initial disintegration, which corresponds to the first stage of rock discontinuity. The effect of factors of physical weathering leads to the emergence of multidirectional fracturing and microcracking, the degree of their occurrence increases from the bottom up. With the penetration of surface waters containing oxygen into cracks, the processes of hydration and oxidation begin. Mechanical changes in the state of the rocks are reflected in the logging by the reduction of the apparent resistance diagrams (from 625 to 125 Ohm), sidewall logging (in the well 50 NUN from 25,000 to 100 Ohm*m), the increase in the interval time of the longitudinal waves. In the lower part of the zone, tight rocks are still recorded on the microprobe, but intervals of discrepancy between the micropotential and microgradient sondes are already observed above.

Zone "C" is continuation zone of disintegration and initial decomposition. Further mechanical destruction leads to an increase in the reaction surface and intensification of geochemical processes that ensure the decomposition of silicates and aluminosilicates, and leaching of sodium and calcium. On the logs, the bottom of the zone corresponds to the apparent resistance value-125 Ohm*m; up the section, the values of the apparent resistance drop off step-by-step up to 40-50 Ohm*m and lower. The interval travel time of longitudinal waves increases (in the well 50 NUN up to 240 μs/m), in the lower half of the zone the cavernogram is usually kept near the face value, at the top – it can show an increase in the well diameter characteristic for coarse clastic rocks.

Zone "D" is the zone of final decomposition. It is composed of clay minerals of hydromica-kaolinite composition, which are a product of weathering of acidic metamorphic rocks – plagiogneisses and granite-gneisses, discovered in most wells of the South-Tatar Arch; in the clay mass fragments of undecomposed crystalline rocks are noted. According to the logging, it is distinguished by deep cavities, abnormally low apparent resistance readings (U-shaped recording is observed), lowering of neutron gamma-ray logging to 1-1.3 cu; the increased values of natural gamma activity from the spectral gamma-ray logging data are explained by the presence of thorium and potassium.

Zone "E" is a residual zone, represented in various degrees by washed clastic material (fragments of source rock, grains resistant to weathering of minerals). It is allocated in well 50 NUNs in the range of 2443-2427 m according to the increased content of thorium and potassium, which indirectly indicates its connection with the underlying "D" zone and belonging to the weathering crust.

Using the revealed logging characteristics of the weathering crust zones, we studied materials on 750 deep wells drilled in the territory of the South-Tatar Arch, confined by the Serafimovsko-Baltaevsky graben from the south; in 340 of them, the weathering crust was identified.

The crystalline rocks unchanged by hypergenesis, the roof of which is indicated by the readings of the apparent resistance at 625 Ohm*m, were installed only in 147 wells out of 340. The passage through zone "A" was from less than 1 to 69 m and only in two wells – wells 50 NUN and 2000 TMZ – the basement rocks were penetrated to a depth of 538 and 2204 m, respectively.

The raised core is mainly represented by the differences between biotite plagiogneisses and granite-gneisses; amphibolites, quartz diorites, granodiorites, plagiogranites, and gabbro-diabases were more rarely encountered.

Zone "B", with which the profile of the weathering crust itself actually begins, is penetrated in 271 wells. It should be kept in mind that it is certainly present in the sections of those 69 wells that were stopped by drilling in the overlying zone "C". The wide areal distribution of the zone of initial disintegration is explained by the fact that the occurrence of fracturing in crystalline rocks is ensured by the establishment on the territory of continental conditions and does not depend directly on the climate and the relief. In contrast to it, the formation of zones of initial and final decomposition of the vertical weathering crust profile ("C" and "D") takes place against the background of a warm moist climate and a relatively leveled but dissected basement surface.

Zone "B" is found most confidently by logging, as it is located in the range of apparent resistance values from 625 to 125 Ohm*m. The revealed thickness varies considerably (from 1 to several tens of meters); the largest value – 112 m – is marked in the well 12 BLT. From the bottomhole part of the section (interval 2367-2370 m, core 2.0 m) dark gray and dark red differences of biotite plagiogneisses, slightly weathered, with numerous formless cracks; on the fractures there are chlorite, kaolinite spots (drilling log). Dark gray, fractured sillimanite-biotite plagiogneisses were removed from the overlying interval (2296.2-2300.9 m, core 2.0 m). Micro-study shows that the rocks are changed – sillimanite is replaced by fibrous and flaky kaolinite (forms pseudomorphs in sillimanite), and

Fig. 1. Fractured core from well 181 VIU. Interval 1864-1869 m

plagioclases – with sericite; cracks are made of limonite and chlorite (Timergazin, 1959).

In the well 181 VIU zone "B" has a thickness of 29 m and is penetrated in its upper part, since the interval 1840-1869 m is characterized by relatively low readings of apparent resistance – from 210 to 125 Ohm*m. Fractured garnet-biotite plagiogneisses are raised from the bottomhole zone (Fig. 1).

In view of the fact that zone "B" is located at the very bottom of the vertical profile of weathering crust, it can continue to develop even with erosion of the upper zones, reaching significant thicknesses. In addition, if the well is located near tectonic faults, hydrothermal fluids are imprinted on its formation (Razumova, 1977). Under their influence, the rock-forming minerals of crystalline rocks change with the formation of scapolite, quartz, calcite, microcline, etc.

Zone "B" is established in sections of all 340 wells. In 271 of them it is completely covered and its thickness is 3-65.5 m. In 69 wells completed by drilling in the zone of initial decomposition, the penetrated thickness varies in significant ranges – from 1 to 25-30 m; in fact, it can be much larger. The core and sludge raised from the upper part of the zone are often characterized in drilling logs as crystalline eluvium or deluvium, in the lower part there are markedly fractured rocks.

The bottom of the zone is clearly identified by the apparent resistance value of 125 Ohm*m; upward along the section, the apparent resistance diagram is reduced to 40-50 Ohm*m and lower (often step-like, sometimes sharply within 2-3 m). Roof is identified by standard logging uncertainly, especially when the substance is well developed and the upper part of the section is represented by small clastic rocks. In this case, it is difficult to distinguish it from the overlapping terrigenous deposits of the Paleozoic or pre-Devonian, even in the presence of core descriptions. As a rule, the position of the roof in the "C" zone is recorded by the rise of natural gamma activity in the spectral gamma-ray logging, caused by an increased content of potassium and thorium. The method of gamma spectrometry until recently was not included in the compulsory complex of logging and was performed only in wells 50 NUN and 181 VIU. Zone "C" in the first well was described in detail in the paper (Amelchenko, Ivanova et al., 2016); in the section of well 181, roof is clearly identified at a depth of 1818 m by a high total content of potassium and thorium.

In the well 12 BLT zone "C" is allocated by logging in the interval 2246-2258 m and is composed of polymictic gravels with large fragments of pink feldspar and meat-red color (drill log). Gravelites overlap with sediments of the Kaltasinskian formation of the Lower Riphean. The thickness of zone "C" is 12 m; it is disproportionate in comparison with the underlying zone of initial disintegration (> 112 m), which suggests an intensive erosion of the upper part of the weathering crust in the Pre-Kaltasinskian.

As for the "D" zone, its establishment in sections with a sufficient degree of certainty is possible only by rock material and spectral gamma-ray logs, which records the continental character of clay formations (Ferthl, 1983). The diagram of apparent resistance is characterized by typical values for clay rocks with low values (up to 10-20 Ohm), and cavernogram – by a significant increase in the diameter of the well.

In the well 28 TMK the allocation of zone "D" according to logging is confirmed by sludge: from the interval 1777.5-1788 m the clay is red-brown with grains of quartz and feldspar. This well is one of the few where the successive changes in crystalline rocks from the source substrate (zone "A") to the clay zone have been established based on the rock material (Fig. 2). The total thickness of the weathering crust is 124 m, of which 69 m are in zone "B" and 43 m – in zone "C", marked by deluvium of crystalline rocks. The vertical profile ends with a 12-meter clay zone. The increased thickness of the weathering crust is explained by the well location in the contact zone of the main intrusion (in the magnetic field it corresponds to an anomaly with an intensity of more than 1200 nT) with the host rocks.

Clay zone in the well 377 SRF according to logging data is recorded at depths of 2974-3012 m. According to (Timergazin, 1959), greenish-gray kaolin-sericite rocks are raised from the bottom part, consisting of a "finely scaly-fibrous bulk containing relics of strongly altered plagioclase, biotite, grains of quartz and a fairly fresh microcline". The upper part of this interval is represented

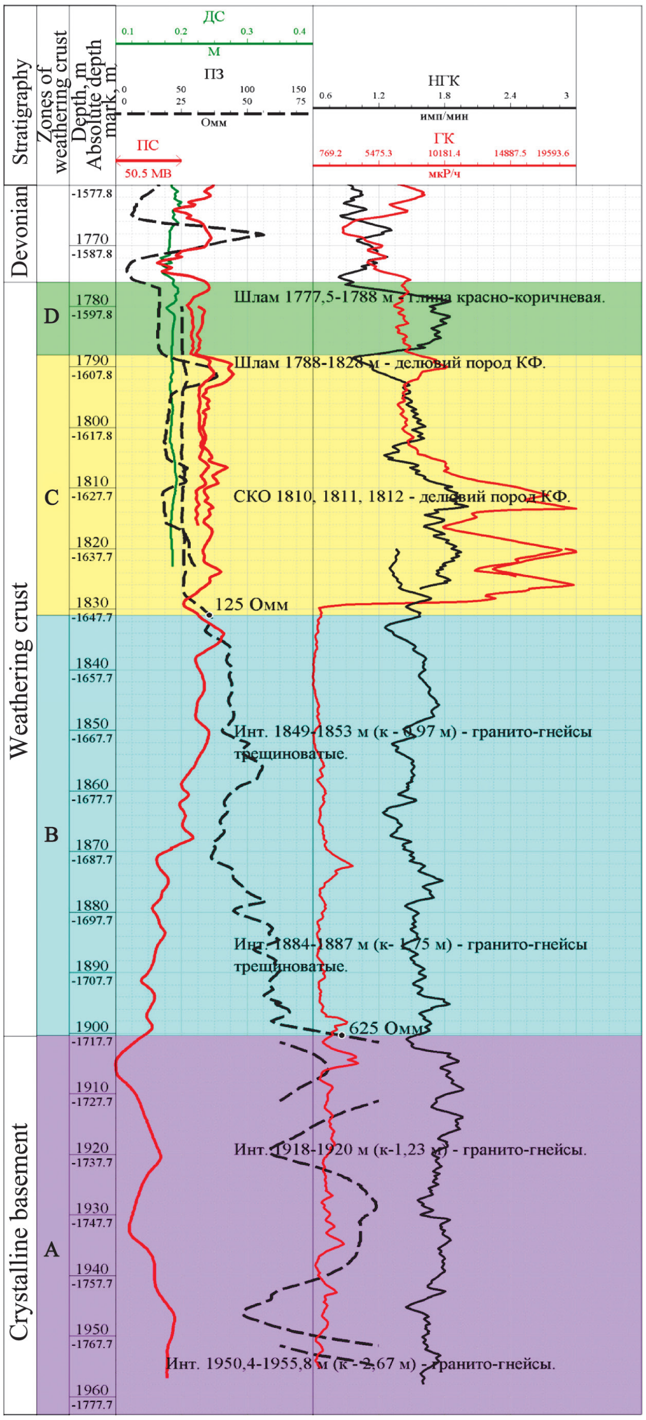

Fig. 2. The weathering crust of the South-Tatar Arch basement in the well 28 TMK

by a red-brown tight rock with rare inclusions of grains of gray quartz, pink feldspar and dark green biotite. Micro-study showed the presence of a fine-fibrous-scaly kaolin-sericite material, which amounts to 75% of the rock; it is thinly permeated with brown iron oxides and contains grains of microcline and strongly fractured quartz.

As one of the upper zones of the vertical profile of weathering crust, it is more often subject to erosion; established in only 17 wells.

A well-developed profile of the weathering crust ends with a residual zone “E”, the formation of which is possible only under conditions of intensive drainage. It is composed, to varying degrees, of coarse-grained, poorly sorted sandstones with interbeds of pebbles and conglomerates washed from the clay material. The clastic material is represented by fragments of crystalline rocks and minerals most resistant to the action of hypergenic agents – quartz, microcline, zircon, rutile, magnetite, etc. The zone is difficult to distinguish from overlapping terrigenous sediments of Riphean-Vendian and Paleozoic, so it is distinguished by position in the section of established weathering crust and by correlated core and logging data. It is revealed only in well 50 NUN, where it lies on clays of zone “E”. Initially, the interval 2443-2427 m was referred to the basal pack of the Tyuryushevskian formation of the Lower Riphean. However, it is distinctly separated from the overlapping Riphean sandstones by increased gamma activity (7-8 vs. 3.5 mcr/h), in the spectral gamma-ray logging provided by thorium and potassium; by a significant decrease in the curve of the neutron gamma-ray logging, which increases from 3.6 to 5 cu under the transition to the Tyuryushevskian sandstones (from a depth of 2427 m). In the middle part of the interval, a supposedly porous layer 7 m thick is distinguished, marked by a sharp increase in the interval time to 280 μs/m against 180 μs/m in its bottom. Coarse-grained terrigenous rocks of the residual zone also differ from underlying clay by higher values of apparent resistance. Apparently, the preservation of zone “E” in the well 50 NUN was provided by its relatively early burial by the most ancient in the region sedimentary rocks – the Tyuryushevskian formation of the Lower Riphean.

Conditionally, its presence is assumed over the zone “D” in wells 377 SRF in the interval 2974-2943 m according to the increased values of natural gamma activity; The curve of the gamma-ray log is similar to the diagram of well 50 NUN.

Based on the zones of the vertical profile of the weathering crust identified by the logging, maps of the “B” zone thicknesses (as most confidently identified by the logging characteristics) and the total thicknesses of the “B”+“C” zones (Fig. 3, 4) were plotted. The completed constructions make it possible to outline the main features of the development of the weathering crust along the surface of the crystalline basement of the South-Tatar Arch.

As is known from the geological literature (Koronovsky, Yakushova, 1991; Zhuravlev, 2009; Kayachev, 2014), as a rule, two main morphological types of weathering crusts are distinguished: areal and linear (linear-fractured). The weathering crust of the first type is developed over vast areas in the form of a cover, which has isometric outlines. Geometrically it is represented by two elements – width and thickness; the width is determined by the magnitude of straight

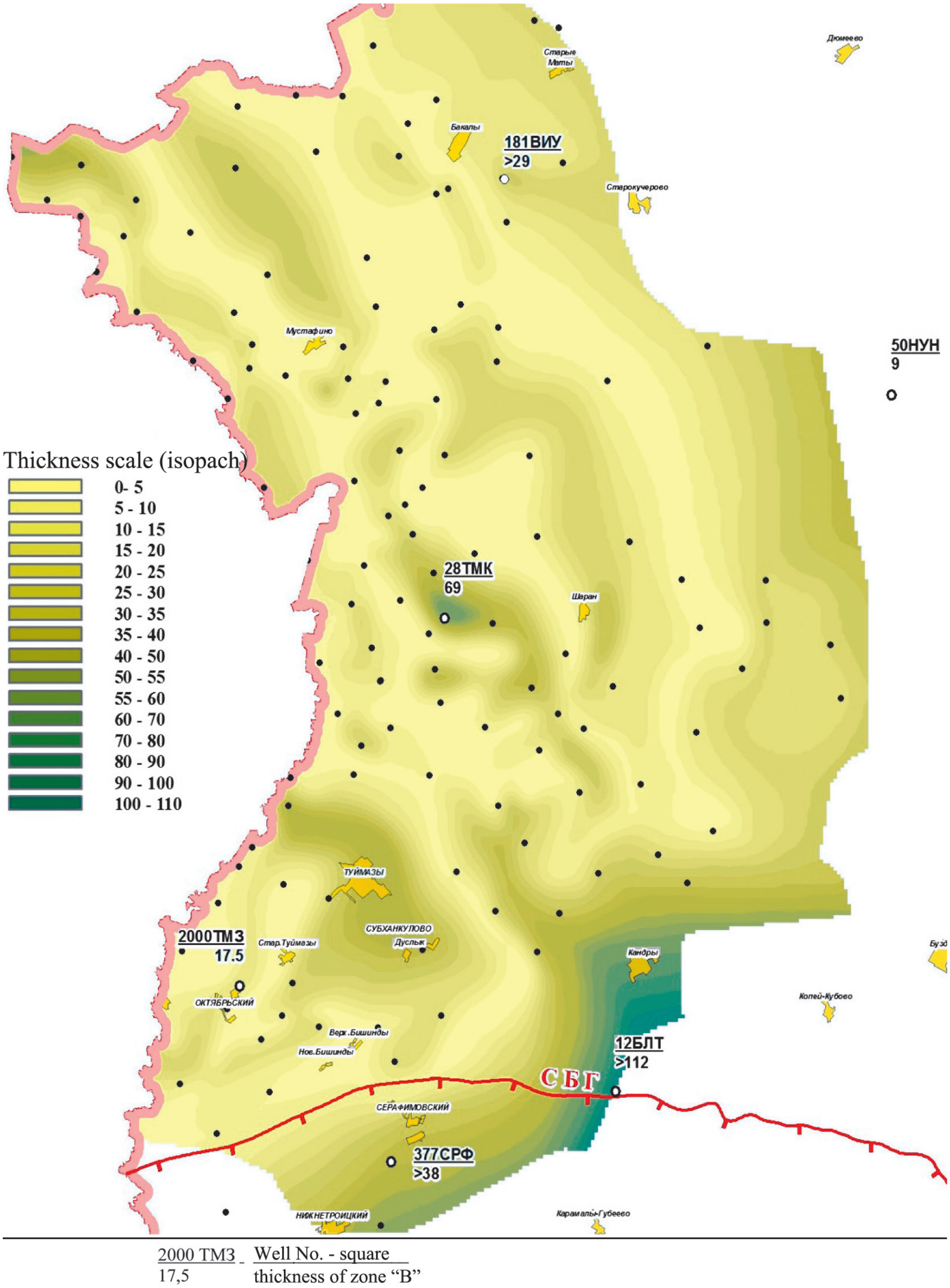

Fig. 3. Map thickness of zone "B" of weathering crust of the South-Tatar Arch (well spacing is rarefied)

lines drawn through the geometric center of the outline (Chetverikov, 2005).

The weathering crust of the second type has an increased thickness and is confined to areas of tectonic dislocation of a linear nature. There are three characteristics – length, width and thickness in the geometry of linear-fractured type of the weathering crust.

Analyzing isopachite maps, we come to the conclusion that within the investigated territory the weathering crust of the surface type in its classical sense (values of width relatively close to congruent) is not observed. The presented constructions testify to the dominance of the weathering crust of linear directivity, which is subdivided into linear-areal and

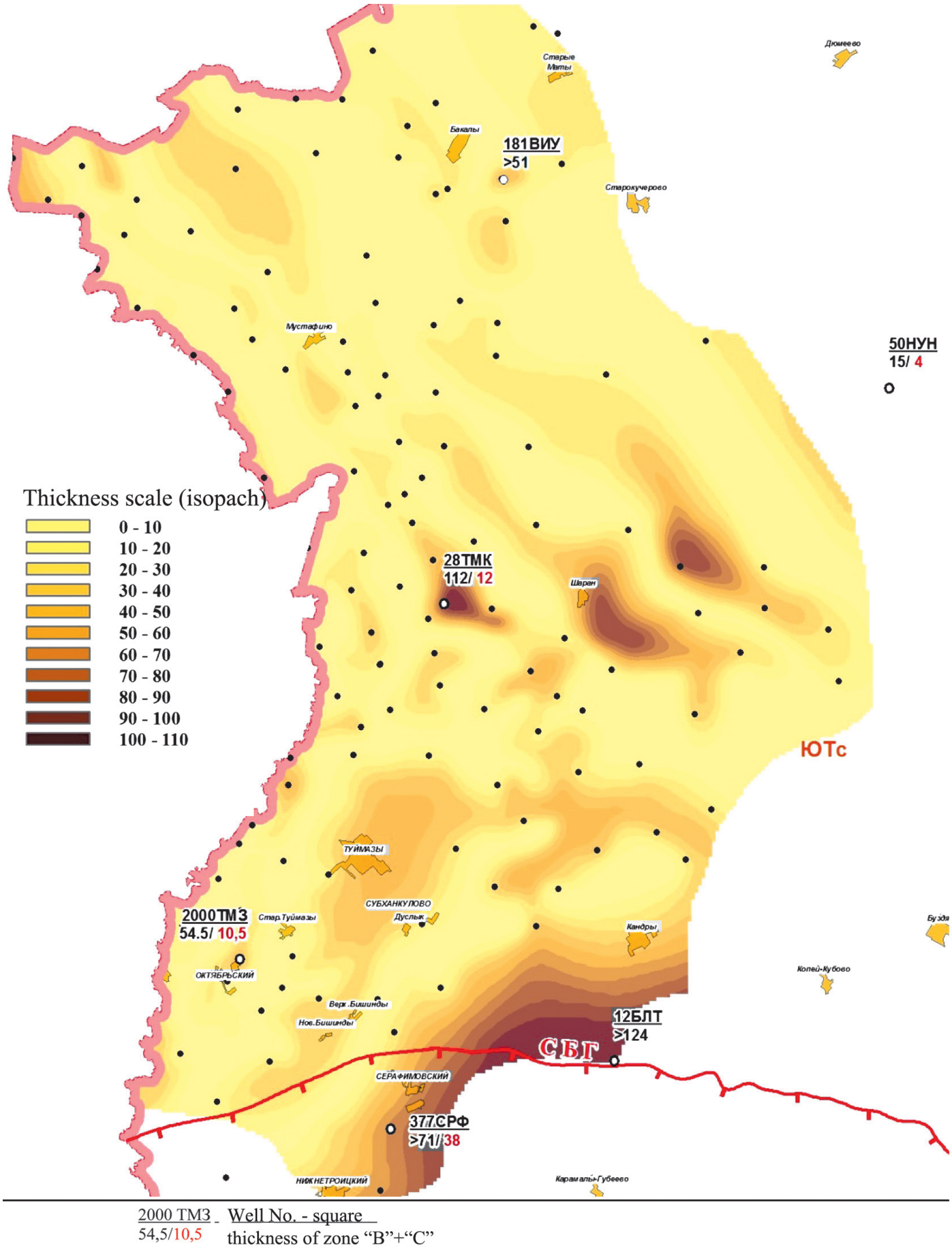

Fig. 4. Map of total thicknesses of zones "B" + "C" of the weathering crust of the South-Tatar Arch basement (well spacing is rarefied)

linear-fractured, having a thickness, width and much exceeding the last in length.

The linear-areal type is characterized by the hose-like development and insignificant thickness – 1-10 m. Three lengthy strips of weathering crust of this type are mapped on the thickness map of zone "B": western, central and eastern. They have sinuous outlines in the plan and strike with an azimuth of the order of 45-55° NW; at a considerable extent (60-70 km) they are characterized by extremely variable widths – from 1 to 6-10 km. A small submeridionally oriented fragment of linear-areal weathering crust (length 16 km, width – 2-4 km) is allocated in the outermost south-west of the territory.

From west to east, alternating strips of linear-areal weathering crust with the same elongated and narrow areas with increased thickness of hypergenically altered crystalline rocks (linear-fractured weathering crust) are observed.

Linear-areal type of the weathering crust, obviously, corresponds to areas with aligned and slightly dissected relief of the basement surface, which does not provide sufficient drainage, because of which the hypergenic factors did not have deep penetration into the crystalline rocks (thickness of the weathering crust is up to 10 m). The slopes of the peneplaines were characterized by an intensive washing regime, so here the weathering crust of a greater thickness – 11-25 m and more was formed.

Linear-fractured weathering crust marks axial zones of long-lived faults (well 12 BLT) and contact zones of rocks of various composition (well 28 TMK). The increased fracturing accompanying tectonically dislocated areas not only facilitates the penetration of hypergenic agents to a significant depth; hydrothermal solutions also rise along them. Thus, crystalline rocks are exposed to both exogenous and endogenous factors. According to a number of researchers (Leonov, Tsekhovsky et al, 2014), in the lower zones of the linear-fractured weathering crust, the transformation of crystalline rocks is dominated not by hypergenesis, but by "... processes associated with a tectonic or tectonic-hydro-thermal regime".

The weathering crust has a considerable thickness, 64 m, in the section of the parametric well 2000 TMZ, which is explained not only by the long period of its formation (taking into account the pre-Devonian age), but also by the location in the vicinity of disjunctive dislocation, as indicated by fracturing and fragmentation zones marked in the core, glide mirrors. In another parametric well 50 NUN, despite the confinement to the Neftekamsko-Sophyisky submeridional fault, the thickness of the full weathering crust profile is almost 2 times less – 35 m, which is apparently due to the early sealing of it by the Lower Riphean sandstones.

The maximum thicknesses of linear-fractured weathering crust are marked in well 377 SRF (> 109 m) and 12 BLT (> 124 m) located in the zone of Seraphimovsky-Baltayevsky graben. This is an penetrated thickness, since both wells were stopped by drilling in zone "B" and did not establish its lower limit. K.R. Timergazin indicates the change of rocks under the endogenous processes, in particular the appearance in well 377 SRF of such hydrothermal minerals as garnet, albite, quartz, calcite, pyrite, etc.

On the map of the total thicknesses of the "B"+"C", the northwest orientation of isolines also dominates and the alternation of the hose-like strips of the weathering crust of the linear-areal and linear-fractured type is preserved, although their configuration undergoes certain changes.

Comparison of thickness maps, in which, in general, the pattern of isopachitis is consistent, indicates a unified orientation of tectonic processes during the formation of weathering crust of the crystalline basement. The predominance of the northwestern orientation of isolines with an azimuth of 45-55° NW indicates on an earlier (probably pre-Riphean) age of tectonic faults of this strike.

The elements of the northeastern orientation (orthogonal to the above) appear on individual sections in the southern part and only on the map of total thickness, which allows us to assume a later laying of the corresponding disjunctive dislocations.

Conclusions

1. Based on the comparison of rock material and logging data, logging characteristics for zones of the weathering crust of crystalline rocks are determined.

2. Application of the revealed characteristics in consideration of materials on 750 wells drilled on the eastern slope of the South-Tatar Arch allowed to record vertical zonation of the weathering crust in 340 wells according to the field geophysical data.

3. The completed constructions made it possible to outline the main features of the development of the weathering crust along the surface of the crystalline basement and to establish linear-areal and linear-fractured types of it.

4. The results of the conducted studies prove the possibility of using the identified logging features to establish zones of weathering crust in the sections of wells even in the absence of core material.

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