The role of the leading formations of crystalline basement in the generation of clay minerals of weathering crust (East of the Russian plate)

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Abstract. The studied weathering crust on the basement rocks of the central part of the Volga-Ural anteclise lies at great depths under thick sediments of sedimentary cover. A diversity of initial basement rocks, features of formation and secondary changing processes of weathering crust determine interest for this geological formation and its uniqueness. Clay minerals play a major role in the composition of the weathering crust and determine its features. A change in the associations of clay minerals by the weathering profile allows distinguishing different zones, which confirm the zonal structure of this formation.

1. Introduction

For a long period, the problem of studying the deep horizons of the East of the Russian plate and, in particular, one of its large tectonic structures – the Volga-Ural anteclise, has attracted great attention of researchers [1-3]. The largest Romashkinskoye oilfield is localized within this structure, the development of which is in the final stage. Within the Volga-Ural anteclise and smaller tectonic structures included in its composition - the South Tatar and North Tatar arches [4] (Fig. 1), deep and exploratory drilling revealed the widespread development of the weathering crust on the crystalline basement rocks of the Archean-Proterozoic age. The weathering crust was formed in the continental period before the formation of deposits of sedimentary cover of the Devonian period and occurs at sufficiently great depths under their thick mantle.

According to morphological features, this weathering crust is divided into the following types: areal, linear (fractured) and fractured-areal [1, 2, 5]. Within the studied region, the most developed areal weathering crust with zonal structure of the weathering profile, which consists of several zones (bottom-up): disintegration, cementation, hydration and leaching, oxidation, and secondary hydration. The thickness of the areal weathering crust varies from several meters to 20-25 m. At the same time, the highest thickness values are characteristic for the peripheral parts of the basement arches and aulacogens. The linear weathering crust provides a significant increase in thickness (up to 50 m and more). It has a limited distribution and fixes in the zones of basement faults. In the weathering crust of this type, distinct zonality is not observed, but a material characteristic is traced that is distinctive for typical weathering crust [6].
At the present stage of research, the problem of identifying and studying non-traditional reservoir zones with possible industrial accumulations of hydrocarbons in deep horizons, such as crystalline basement rocks of the platform and weathering crust, is noteworthy. It is known, that the formation of the weathering crust of the basement is oil-bearing in many oil and gas regions of the world. Most of the identified hydrocarbon deposits are often confined to the upper parts of the section of platform basement, where they can be overlap by sedimentary cover of different thicknesses [3, 7].

2. Methods

The geological, geophysical, and core materials of most deep wells that uncovered the formation of the weathering crust of the foundation of studied area allow us to characterize the conditions of formation and types of weathering profiles, the features of the material composition, the void-pore space, and the prospective potential of the weathering crust.
An integrated approach and the use of various methods for studying of core material can provide to describe in detail the mineralogical and geochemical features of weathering products of various rocks of the crystalline basement, and to compile a generalized profile of weathering, and to determine the filtration-capacitive parameters of the weathering crust of the basement of the North Tatar and South Tatar arches. This work presents the results of studies using the following methods: optical microscopy (polarization microscope Leica DM/LP), scanning electron microscopy (microscope Merlin Carl Zeiss), X-ray fluorescence spectral analysis (spectrometer Bruker S2 Ranger), X-ray analysis of the clay fraction (diffractometers Dron-3M and Bruker D2 Phaser). The method of nuclear magnetic resonance (NMR analyzer Proton 20M) was used to study the filtration-capacitive characteristics of the rocks of the weathering crust formation.

3. Results and discussions

The main criterion for identifying weathering crust in well sections is the transition from unchanged basement rocks to weathered rocks with an increase in the degree of change up the section and, accordingly, the presence of mineralogical and geochemical zoning in weathering profiles. The material composition of the weathering crust and the features of the development of finely dispersed and clay minerals during hypergenesis over various areas of the basement are variable and largely associated with the mineralogical and petrographic features of the initial rocks of the crystalline basement [5].

The basement rocks of the South Tatar and North Tatar arches are represented by metamorphic (gneisses, amphibolites, crystalline schists, etc.) and, to a lesser extent, igneous (gabbro-diabases, gabbro-norites, etc.) complexes. According to the quantitative relationship of the main rock-forming minerals, metamorphic rocks are divided into two formations - mafic-silicate and high-alumina [5]. The mafic-silicate formation is characterized by the predominance of femic minerals (ortho- and clinopyroxenes, amphiboles and biotite); cordierite, sillimanite, garnet, and biotite are widely developed in the rocks of the high-alumina formation. The leucocratic mineral component of these two formations is the same.

The variety of initial basement rocks largely determines the characteristics of the weathering profile and the composition of newly formed hypergenic mineral associations, and, first of all, the composition of clay mineral associations. Based on the quantitative ratio of the main clay minerals of this weathering crust - kaolinite, chlorite, illite and the mixed-layer illite-smectite phase, the leading paragenetic associations of clay minerals were identified and their distribution was established both according to the weathering profile and within the studied areas [6]. It should be noted, that in the lower zones of the weathering profile at the initial stages of hypergene changes in the basement rocks, the composition of clay mineral associations is the most complex and diverse.

In the majority of studied weathering profiles, kaolinite prevails in the composition of clay mineral associations and, as the final product of the clay component evolution; it composes the most altered upper zones of the profile. Chlorite is developed in subordinate quantities, with the exception of individual weathering profiles for igneous rocks. The significant content in the composition of igneous and metamorphic rocks of femic minerals determines the formation of associations with the predominance of a mixed-layer illite-smectite phase with different contents of smectite interlayers with a decrease for kaolinite. The formation of illite is associated with a hypergenic change in biotite; in some cases, illite plays a significant role in the composition of clay associations.

Further, in the example of the description of several weathering profiles for wells located in different parts of the South Tatar and North Tatar arches, a variety of weathering products and the development of clay mineral associations for various types of basement rocks are shown.
Within the Chistopolskaya area (western slope of the South Tatar arch) in the interval of depth 1860.3-1868.7 m, the basement rocks are represented by alternating amphibolites and biotite-pyroxene gneisses of the mafic-silicate formation of the metamorphic complex. The presented weathering profile refers to an incomplete residual type of areal weathering crust with a thickness of 8.4 m. The leading rock-forming minerals of the initial rocks of biotite-pyroxene gneisses, according to which the disintegration zone is distinguished, are quartz, plagioclase, pyroxene (enstatite), biotite and potassium feldspars (orthoclase, microcline). Above the section of the well, biotite-pyroxene gneisses transform into intensely weathered amphibolites of the cementation zone and the hydration-leaching zone. The bulk of the rock is pelitized and kaolinitized; pseudomorphs of calcite, chalcedony, chlorite, and hydrochlorite, which develop along hornblende grains (Fig. 2a, b), are distinguished, which is accompanied by the release of iron oxides and hydroxides. The material composition of this weathering profile characterize by the development of two associations of clay minerals: illite-kaolinite (Fig. 2c) and kaolinite. Kaolinite is the main component of the clay material of rocks; the content of illite and chlorite is reduced. The quantitative content of kaolinite increases up the weathering profile starting from the lower zones, which is associated with the processes of intensive weathering of plagioclases and potassium feldspars, which prevail in the composition of the initial rocks. In general, upward in the profile, the illite-kaolinite association changes to kaolinite association.

On the territory of the Aktashskaya area (the central part of the South Tatar arch), garnet-sillimanite-cordierite-biotite gneisses of the high-alumina formation of the metamorphic complex are widespread in the interval of depth 1734.0-1740.5 m. The weathering profile (thickness 6.5 m) refers to the reduced residual of areal type with the allocation of disintegration and hydration-leaching zones. The mineral composition of gneisses (Fig. 2c) is represented by quartz, plagioclases, biotite, garnet, sillimanite, cordierite, potassium feldspars, single apatite grains were found among accessory minerals. The clay material of this weathering crust is characterized by other types of associations of clay minerals: illite-mixed-layer-kaolinite and illite-kaolinite associations with an admixture of chlorite (Fig. 2f). The dominant component in the composition of the clay substance of the profile of the weathering crust is also kaolinite. In this case, with an increase in the degree of weathering of the rocks, the illite-mixed-layer-kaolinite association undergoes a transition to the illite-kaolinite association.

An example of the development of the weathering crust by igneous rocks of the basement is the area of the central part and the eastern slope of the North Tatar arch. In well 47, strongly altered gabbro-diabases were discovered (Fig. 2d). The profile of the area residual weathering crust (thickness 6.2 m) includes disintegration and hydration-leaching zones. A characteristic feature of the development of clay mineral associations of rocks of this group is the predominance of a mixed-layer component of the illite-smectite type and, to a lesser extent, chlorite over almost the entire profile. Only in the oxidation zone, kaolinite can reach a significant content.

Weathering processes have led to a change in the physical properties of the basement rocks, which is reflected in an increase in the total and effective porosity [6]. The results indicate an increase in reservoir characteristics from bottom to top along the weathering profile, which is associated with an increase in the degree of weathering and the predominance of clay minerals in the composition of the rocks. The zones of weathering profile of the area type possess the best reservoir properties - disintegration zone (total porosity 9-17%, effective porosity 7-8%) and hydration and leaching zone (total porosity 21% and more, effective porosity - up to 10-15%). The geochemical zonality of the profiles of the areal weathering crust has a common pattern in the migration of individual components. In general, from bottom to top in the profile, it can be seen that the calculated values of the geochemical indices CIA, CIW and PIA [6, 8, 9] increase. This confirms the increase in the degree of weathering of the rocks up the profile, and speaks of the formation of weathering crust in a warm climate.
Figure 2. Optical micrographs (Nicole +): a) Pseudomorphs by grains of hornblende in biotite amphibolite, zone of hydration and leaching, Chistopolskaya area; c) Garnet-sillimanite-cordierite-biotite gneiss, zone of hydration and leaching, Aktashskaya area; d) Weathered gabbro-diabase, zone of hydration and leaching, Bondyuzhskaya area. Photograph of scanning electron microscope: b) formation of clay minerals by plagioclase and hornblende in amphibolite, Chistopolskaya area. XRD patterns of air-dried samples of clay fraction: e) Illite-kaolinite association, Chistopolskaya area; f) Chlorite-illite-kaolinite association, Aktashskaya area.
4. Conclusions

The studies indicate a change in the associations of clay minerals along the profile of the weathering crust, which allows distinguishing different zones and confirms the zonal structure of the weathering crust of the basement. The same type of orientation of weathering processes on various rocks of metamorphic formations and magmatic complexes was established, which leads to a similar final weathering product and leveling of the composition of the initial rocks.

The final product of weathering in most cases is kaolinite. An exception is the case when later secondary processes of change are superimposed on the formed weathering profile, occurring mainly due to percolation and infiltration of water from sedimentary cover deposits overlaying the weathering crust. In this case, a specific inversion type of profile is formed.

It is important to note that the degree of preservation and development of the full profile of weathering within the studying area is associated with a later history of the development of the region. Therefore, in the areas of basement elevations, the weathering crust can be completely or partially destroyed as a result of erosion while maintaining the lower profile zones, or it can be redeposited in areas of the basement depressions, or it may be subject to secondary changes, as noted above.

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