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WATER RESOURCES
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Hydrogeological Conditions of Submarine Groundwater Discharge in the Crimea

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Abstract—A structural hydrogeological model of the Crimea based on the assumption of the leading role of faults in groundwater distribution is discussed. Areas with intense submarine groundwater discharge are outlined. The existence of water streams related to the faults in the area of the Chernaya River, Mramornaya Gully, Varnautskaya Depression, Batiliman Bay, and Nikitskii Cape is substantiated. The sites for drilling hydrogeological wells are recommended.

The results of multipurpose geological, hydrogeological, and engineering geological surveys as well as the data on specialized geological structural surveys carried out by the author of this paper over the period of 30 years made it possible to study in detail the fault tectonics and to specify a hydrogeological model of the zone of active water exchange within the Crimea [3].

All geotectonic formation complexes composing the Crimea are dissected by a system of dislocations with breaks in continuity, among which deep faults, deep crustal faults, and local dislocations with breaks in continuity are distinguished. Orthogonal and diagonal systems are clearly seen among faults. Diagonal dislocations with breaks in continuity have a dominating role in structure formation and control. As a rule, faults of the Crimea have well defined rectilinear forms. In addition to this, deep faults and deep crustal faults are rather long and tend to recur at definite intervals. Respectively, the dimensions of blocks limited by faults of different sizes are fully coordinated. In most cases, tectonic movement is inherited [1, 2].

The significant role of faults in groundwater distribution was discussed before [6]; however, this idea was more consistently upheld by B.N. Ivanov [12] and V.N. Dublyanskii [7, 8] in studying the conditions of formation and distribution of karst and karst water of carbonaceous formation composing the Main Ridge of the Crimean Mountains. The results of multipurpose surveys during the construction of the Yalta water supply tunnel [13] showed that the hydrogeological characteristics of the Main Ridge were governed by the block structure of calcareous strata. The surface runoff is transferred into the subsurface runoff through fractured zones stripped by the erosional and hydrographic network. The system of crossing tectonic dislocations favors the redistribution of the subsurface runoff in depth and the variation in the direction of subsurface streams.

Water availability in the zone of faults and fractures of the volcanogenic (andesite) formation is evident and generally recognized [5]. The rest lithological–stratigraphical complexes can be classed either as water-impervious, practically waterless (flysch, flyschoid, and flyschlike formations; marly Aptian–Albian and partially Upper Cretaceous deposits; Maikopian clay stratum, clayey layers in Sarmatian and Pliocene deposits), or as slightly water-bearing (certain layers of limestone and sandstone in Cretaceous, Paleogene and Neogene rocks) complexes.

Detailed studies at field stations (in the course of reconnaissance surveys, analysis of geophysical data and the results of drilling numerous core and hydrogeological wells) make it possible to revise the regularities of groundwater distribution in most lithological–stratigraphical complexes composing the Crimean geosystem.

First of all, certain knowledge of the areas of groundwater recharge, transit, accumulation, discharge and, hence, the location of water intakes, needs to be corrected. The analysis of regularities of water exchange in the Pontian–Meoptis–Sarmatian water-bearing complex (with no regard to man-made factors) can be taken as an example. The Tarkhankutskoe Plateau and Piedmont are assumed to be the areas of recharge of this complex [5, 17]. Not denying this fact, we note that, in recent years, dozens of wells were drilled south of Piedmont; they revealed the zones of faults and fractures in rocks of different age, whose water migrated from the Main Ridge to the north, northwest, and northeast thus replenishing the groundwater resources and having a considerable influence on the hydrogeological conditions in the flatland part of the Crimea.

The conditions of groundwater accumulation in the Pontian–Meotis–Sarmatian water-bearing complex were analyzed in detail in [4, 12], where the tectonics was considered as one of the many factors (along with geomorphological, soil and botanical, and other fac-

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tors) responsible for the increased fracturing and porosity. It is no mere chance that many large water intakes (Vorontsovskii, Dzhankoiskii, etc.) have been sited at points of crossing of differently oriented faults. Clearly, such points are considered promising for the discovery of considerable groundwater reserves. The recent data testify that relatively thin zones of fractures and faults can also accumulate and carry large volumes of groundwater. According to the results of pumping out from numerous wells, the water conductivity of fractured zones in Neogene deposits may exceed 10 000 m/day.

The situation is different in some areas of occurrence of Neogene deposits. The comprehensive surveys in the Gerakleiskoe Plateau near Sevastopol carried out in 1992–1994 make it possible to state that there are no continuous aquifers in this area. This was proved by the fact that most drilled hydrogeological wells were virtually waterless. Groundwater of the Neogene stratum can be formed not only due to the infiltration of atmospheric precipitation but also due to the groundwater drained by faults coming from the Main Ridge. Groundwater mainly concentrated in zones of faults and fractures. In this case, water sometimes spreads over layers of slightly cemented sandstone or cavernous limestone at a distance not exceeding 20–30 m from the zone of fault. In specific cases, water "caps" are formed in the base of limestone over buried faults.

Faults in Neogene rocks and more ancient rocks may serve as water conduits. A well drilled in 1995 in the village of Novozhilovka of the Belogorskii raion may serve as an example. The hydrogeological conditions of this area are extremely unfavorable. The Neogene–Paleogene stratum was taken to be practically waterless and water of the Neocomian horizon occurring at a depth of about 400 m was alkaline. This water is not suitable either for drinking or for domestic needs. On the author's recommendation, a new well was located with regard to the revealed regularities; at a depth of 75 m a fractured zone 1–1.5 m wide with a yield of more than 2 l/s (the upper limit was not found) was met in the Paleogene limestone. It should be noted that the hydrodynamics of zones of fault does not depend on the geomorphological, soil, and botanical factors.

The results of multipurpose surveys carried out in many areas of external ridges of the Crimean Mountains and interridge valleys prove that the above mentioned regularities, with rare exception, are typical of all lithological–stratigraphic complexes from Early Cretaceous to Pliocene inclusive. Particular attention should be given to the hydrogeology of the strata, which are considered to be waterless or slightly water-bearing.

The flysch formation of Triassic and Early Jurassic periods is composed of such water-impervious rocks as argillite, aleurolite, seldom compact quartz-like sandstone, which theoretically excludes the presence of water-abundant zones of faults and fractures. However, the results of drilling a deep well in Yalta [5] during the construction of the Yalta water supply tunnel [13] as well as the availability of wells and shallow water springs are indicative of the possibility of revealing local sources of water supply.

If the question of the water-bearing capacity of flysch formation is still an open question, the perspective nature of Middle Jurassic flyschoid and Upper Jurassic flyschlike formations is the fact beyond question. For example, the engineering and geological surveys on landslide slopes of the Laspinskaya Bay composed of the flyschoid formation have revealed water-abundant zones of faults and fractures, whose water is partially discharged to the sea in the form of submarine springs and partially is spent to recharge near-base areas of landslide bodies.

More accurate data have been obtained during the surveys in search of water supply sources in the eastern part of the Crimea in the rocks of the Upper Jurassic flyschloid formation. Groundwater of this area falls in the category of fissure or stratal fissure water [5] mainly confined to a carbonaceous terrigenous stratum and characterized by a diverse chemical composition and often by increased salinity. Intense folding of rocks and the predominance of clayey deposits in the geological section hamper the free groundwater circulation; this does not contribute to the formation of considerable water reserves and results in the situation of local stagnation regime.

In 1973, the author in collaboration with S.V. Pivovarov (State Geological Enterprise Krymgeologiya) found in the course of structural geological surveys that all operation wells of the area of Sudak were confined to faults. The new data permitted us to recommend several locations of drilling; the drilling resulted in the fact that one well in the settlement of Novyi Svet stripped a zone of faults and fractures with fresh water at a depth of 130 m and the other well, which was drilled at the southeastern foot of the Perchem Mountain, tapped hydrogen sulfide solution with a yield of 8 l/s. A well drilled at the sanatorium of "L'vovskii Zheleznodorozhnik" stripped a well washed fractured zone with fresh water at a depth of 220 m. The dissolved helium content of that water was three orders of magnitude higher than the background value, which was indicative of a considerable depth of the fault occurrence. In 1991–1992, zones of fractures and faults were revealed and mapped in the area of the settlement of Novyi Svet; two of the zones were traced up to the sea shore [16]. Perspective zones were also revealed in the areas of Solnechnaya Dolina, the settlement of Planerskoe, the Dvuyakornaya Gully; some of the data indicated that the water supply of these zones was more intense than at the settlement of Novyi Svet. The mode of groundwater movement in these strata is more complicated than in Neogene deposits. The zones of faults become narrower within the layers with prevailing clay and argillite, their water supply being relatively low. The

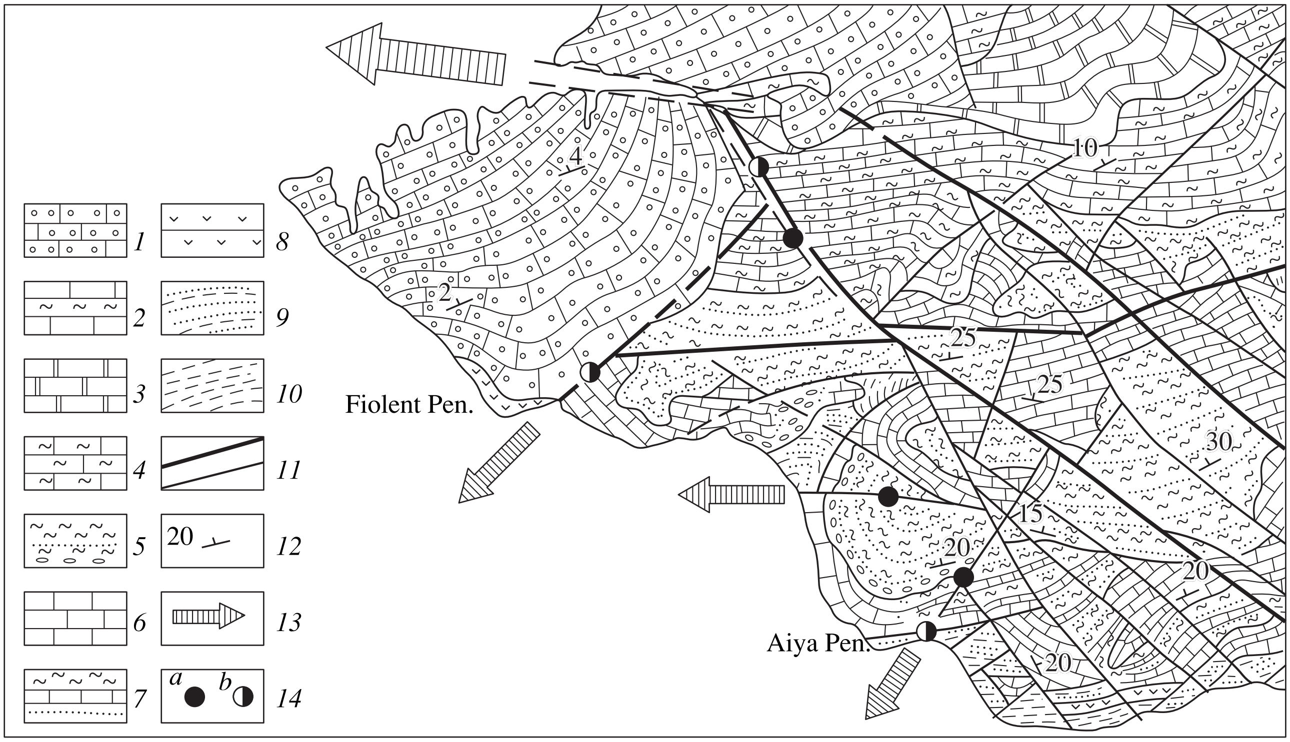

Fig. 1. Geological and structural features of the southwestern part of the Crimea with elements of hydrogeology (prepared on the basis of the data of the State Geological Enterprise Krymgeologia with the author's supplements). (*1*) Neogene oolitic limestone; (*2*) Paleogene marl and clay; (*3*) Paleogene limestone; (*4*) Upper Cretaceous marl; (*5*) Lower Cretaceous clay with intercalations of sandstone and gritstone; (*6*) Upper Jurassic limestone; (*7*) Upper Jurassic clay with intercalations of limestone; (*8*) Middle Jurassic volcanite; (*9*) Middle Jurassic clay with bands of sandstone; (*10*) flysch of Taurian series; (*11*) dislocations with breaks in continuity of different magnitude; (*12*) rock position; (*13*) zones of proposed submarine groundwater discharge; (*14*) wells: (*a*) drilled; (*b*) recommended for drilling.

thickness and water supply of zones increases at places of crossing of zones of faults and fractures with sandstone bands; in this case, groundwater flows to fractured sandstone.

One more important aspect of the problem under study is the possibility of vertical water exchange. Similar phenomena were recorded in other regions. For example, it was proved that vertical water exchange played an important role in the formation of natural resources in areas of recharge, transit, and discharge of individual aquifers or complexes within the limits of the Dnieper artesian basin [17]. Vertical groundwater migration occurs, even if there are water-impervious layers in some areas. Intense fracturing, drastic facies variation, and rather significant amplitudes of recent tectonic movements make it possible to maintain hydraulic connection between individual aquifers (clearly, at considerable differences in the pressure). The circumstantial evidence of this process in the Crimea was noticed long ago [15]. Undoubtedly, the increased concentrations of methane and helium in some local areas suggest the possibility of groundwater flow from lower to upper horizons.

More definite information was obtained in the course of comprehensive studies of lakes of the Perekop group. The extreme diversity of chemical composition of water of Quaternary and Pliocene aquifers can be explained by the impact of zones of faults and fractures. For example, water is quite fresh (against the background of total high mineralization) in a series of wells located in the zone of faults; this is due to the vertical migration of water of the Pontian–Meotis–Sarmatian aquifer. This fact also explains the occurrence of fresh water gryphons observed in the 1930s in the lakes of Krasnoe and Staroe.

Thus, the revealed regularities make it possible to have a somewhat different view of the principles of hydrogeological zoning and to improve the strategy of groundwater prospecting and rational use. It is apparent that the radical solution of the problem of water supply of the Crimea is impossible; however, the available reserves should be used to their full effect.

The hydrogeological situation in the southwestern part of the Mountainous Crimea is extremely complicated but it is most promising (Fig. 1). Water budget calculations have shown that the subsurface runoff makes up more than 30% (110 000 m^3/day) in the output parts of the budget of this area [18]. Some portion of groundwater is drained through faults in the northern direction to the flatland part of the Crimea; however, this flow is limited, because the Crimean deep fault stretching from Sevastopol to Simferopol serves as a natural barrage.

Some authors [6] thought that the most favorable area for groundwater transit and submarine discharge was the area from the Cape Aiya to the Mramornaya Gully. In fact, the thick limestone stratum sinking below the sea level, the occurrence of faults and intense karsting favor the conditions for submarine discharge. In recent years, comprehensive surveys have been completed in the area of the Cape Aiya [19–21]. The studies involved above-water and underwater operations with the help of skin-diver equipment, reconnaissance survey description, water temperature measurement in surface and near-bottom layers, and hydrochemical observations. According to these data, the localized groundwater discharge is observed in a 500-m-long shore line area west of the Cape Aiya. The shore line represents a rocky cliff about 300 m high with the sea depth at the edge of water equal to 25 m. Groundwater outflows to the sea from numerous fractures located in submerged or semisubmerged caverns and from individual fractures, which dissect the carbonaceous rock mass into blocks. The depth of caverns varies from 10 to 41.5 m, the slope ranges from 20° to 42°. The inlet to submerged caverns is 0.5–1.5 m below the edge of water. The maximum water availability in fractures is observed in dead end zones and in eastern walls. During low-flow periods, the total freshwater flow rate in the area of the Cape Aiya amounts to 3000–7000 m^3/day [20].

In 1974, a powerful gryphon was observed after heavy rains 80–100 m away from the shore, north of the Cape Aiya in the Megalo-Yalo Bay. The ascending flow raised silt, organic matter, and fine sand to the surface. The gryphon was observed on the extension of the Kuchuk–Muskam’inskii strike–strip fault passing through the Varnautskaya Depression. In 1981, a well was drilled 700 m northwest from the settlement of Reservnoe; the well was meant to reveal the said fault and to assess its water availability. A water-abundant zone was found in fractured brecciated limestone within the depth interval of 654–1171 m, the established level being 230 m. There were no resistivity measurements and hydrogeological testing. Most likely, it would be necessary to open up the well and carry out all necessary tests. The geological and structural conditions in the area of the Kuchuk–Muskam’inskii strike–strip fault differ insignificantly from the conditions in the area of the Cape Aiya. Hence, the total fresh–water flow rate here may also be 3000–7000 m^3/day.

In the same year 1981, a well 1005.6 m deep was drilled in the zone of the Batilimanskii strike–strip fault in the Khaitu Valley 1.4 km southwest from the settlement of Tylovoe. Water abundant, cavernous fractured limestone was met within the depths of 372–704 m, the established level being 345 m. The inflow was not determined. In 1995, the Batilimanskii strike–strip fault was observed up to the sea shore. On the sea shore slope, the fault is controlled by a zone of crush in the Middle Jurassic stratum and by numerous swampy hollows. Fragments of Upper Jurassic limestone with numerous gliding planes and gouges of fault breccia are impregnated in the zone in the upper part of the slope. The availability of access roads make it possible to recommend the drilling of a relatively shallow (150–200 m) prospecting hydrogeological well in the Batilimanskii amphitheater. However, it should be taken into consideration that in a certain area, groundwater moves through the Batilimanskii strike–strip fault in a fractured Middle Jurassic sandstone stratum. It means that the flow rate exceeding 2000 m^3/day can hardly be expected here. It is worth mentioning that groundwater of the Kuchuk–Muskam’inskii and Batilimanskii faults is of local importance and can be used for water supply of farms and boarding houses. Water drained by the Georgievskii and Chernorechenskii faults is of particular value for Sevastopol.

The Georgievskii fault, which stretches from the Mramornaya Gully to the Chernaya River valley, is characterized by inversion movements of conjugate flanks at considerable amplitudes. The southeastern flank in the area of the Mramornaya Gully is composed of Upper Jurassic limestone, whose base dips below the sea level. Middle Jurassic vulcanite occurs in the northwestern flank; the vulcanite is sequentially overlain with Early Cretaceous sandstone and clay as well as with Neogene limestone armoring the Gerakleiskoe Plateau. As suggested in [6], considerable submarine groundwater discharge is quite possible in this area. Over the past 35 years, there was no information, which could support or invalidate this assumption. The results of analysis of the geological conditions support the possibility of groundwater discharge through the Georgievskii fault. In this case, the fresh groundwater flow rate may be equal to the total flow rate through faults in the area of Batiliman, the Cape Aiya and Megalo-Yalo Bay. The drilling of one prospecting well in limestone in the immediate vicinity (20–30 m) of the main tectonic suture is sufficient to assess water supply of the fault (Fig. 1).

More accurate data were obtained for the Chernorechinskii fault, which was likely the main water stream responsible for groundwater drainage from a large area. In this particular case, by the Chernorechinskii fault is meant a system of dislocations with the valley in the near–mouth part of the Chernaya River. The southeastern fault branches into several dislocations: the Baidarskii, Kuchuk–Koiskii, and other strike–strip faults, one of which, stretching from Simeiz to the Chernorechenskii canyon, is called in some publications as the Chernorechenskii strike–strip fault.

This fault is of particular interest, because it is connected with the Skel’skii spring, along which the Chernorechenskii canyon is located. From here on, the terminological misunderstanding will be eliminated. It is essential that groundwater drained by the above mentioned strike–strip faults forms one stream, reaches Inkerman, and discharges into the water area of the Black Sea through faults, which surround the graben of the Severnaya Bay. In 1975, tracer tests were carried out [9]. Today, it is possible to take a fresh look at the results of these tests given the tectonic base. The dye, which was introduced into the Beshtekne polje, emerged in the Skel'skii spring as well as in the upper and lower parts of the channel flow in the Chernorechenskii canyon, i.e. the subsurface flow was under the control of one fault. The emergence of the dye in the Chernorechenskii canyon channel is indicative of the pressure groundwater nature. To capture the main water stream it is recommended to drill a well in the zone of crush at the foot of the right slope of the Chernaya River to the southeast of Inkerman. The well depth can easily be calculated. In the 1960s, a well 604.7 m deep was drilled in the area of the settlement of Shturmovoe. The well did not strip the zone of crush but it provided information on the mode of geological structure of that area. The upper part of the section (to a depth of 340 m) is represented with a nearly impervious stratum of Upper Cretaceous marl. Then follows a stratum of interbanded sandstone and conglomerate–like limestone of Cretaceous and Upper Jurassic stages. Intense fracturing in the zone of fault impact and quite probable karsting of limestone intercalations favor the conditions for transit of considerable amount (30 000–40 000 m^3/day) of water. Because the marl base slope to the north is 5°–7°, water may be tapped at depths of 400–420 m. Artesian flow is possible due to the pressure nature of water and the piezometric level much higher than the sea level.

It is suggested that there is one more area of considerable submarine groundwater discharge in the western part of the Mountainous Crimea and this is the Nikitskii Cape. Groundwater of this area is collected by a thick stratum of solid limestone with poorly defined layers, the stratum being located to the north of Massandra. The rock dip is southwestern, the floor is rather abruptly sloping to the sea. The stratum is broken by a system of strike–strip faults, one of which intercepts all the water accumulated in limestone and drains it to the Black Sea. A zone of intense fracturing in dominating sandstone band confined to the base of the Middle Jurassic flysch-like stratum serves as a water conduit south of the limestone massif. Sandstone is exposed on the surface in the area north off the Nikitskii Botanical Gardens; then it gently slopes in the southwestern direction; sandstone occurs at depths of 180–250 m in the area of the above mentioned strike–strip fault. Hence, the recommended well (Fig. 2) will tap an aquifer at depths of 120–200 m. The geological and structural conditions are similar to the conditions of the Batilimanskii amphitheatre and, therefore, the flow rate will not exceed 2000 m^3/day.

It is reasonable to suppose that the submarine discharge occurs (at different intensity) throughout the shore line from Tarkhankut to Feodosiya. Preliminary values of the total and specific (per 1 km) intensity of discharge were obtained by [14] using the method of water budget calculations as well as hydrodynamic and geothermal methods. The values indicated that intense water exchange occurred in many areas of the sea shore from Yalta to Tarkhankut. In particular, the intense water exchange results in demineralization in near–bottom water layer south of Sudak and Feodosiya. True enough, the submarine discharge of alluvial water in river fans with well developed U-shaped valleys plays an important role here. The discharge belongs to the area type at sea depths of 1–5 m. Discharge focuses are from 150 to 800 m^2 in size, the total flow rates varying from hundreds to thousands m^3/day [21].

Generally, the hydrogeological conditions of the Crimean coastal area can be compared with the conditions of the coastal area of the Mediterranean Sea. As to the structural and hydrogeological conditions, the European coastal area of the Mediterranean Sea represents an alternation of hydrogeological blocks confined to mountainous structures and small artesian basins connected with tectonic basins [10]. The hydrogeological blocks are usually composed of intensely karsted carbonaceous rocks of Mesocenozoic age. In some areas, groundwater is also confined to fractured volcanogenic formations. The degree of karsting and fracturing of water-containing rocks depends on the intensity of subsurface runoff the high modulus of which reveals good washing conditions of aquifers. Hence, the mineralization of groundwater of hydrogeological blocks is below 1 g/l. The total subsurface outflow to the Mediterranean Sea makes up 24% of the river water inflow [10].

The detection and, moreover, sampling of submarine water is an extremely complicated problem, particularly when it is considered that submarine discharges are possible not only in the shelf zone but in the continental slope as well. The present infiltration recharge per unit time is several hundred times larger then the extrusion recharge. Therefore, under favorable conditions, tongues of infiltration water may intrude far into the sea water area and reach the continental slope displacing sedimentation water on their way [11]. The probability of detecting submarine sources in the area of the continental slope is higher, when the groundwater migration is regulated by faults or related karst caverns. One of the largest submarine sources with a flow rate of 43 m^3/day was found at the coasts of Jamaica 1600 m away from the water edge at a depth of 256 m. There are some sources at considerable depths in the Mediterranean Sea: near Cannes at a depth of 165 m, near San Remo at a depth of 190 m, in the Saint Martin Bay at a depth of 700 m [10]. The submarine fresh groundwater discharge on the continental slope in the Black Sea is possible north of the Severnaya Bay and south of the Nikitskii Cape.

Hence, it is more reasonable to carry out surveys in the seaboard area. Most dislocations with breaks in continuity, i.e. natural drains, are revealed in the course

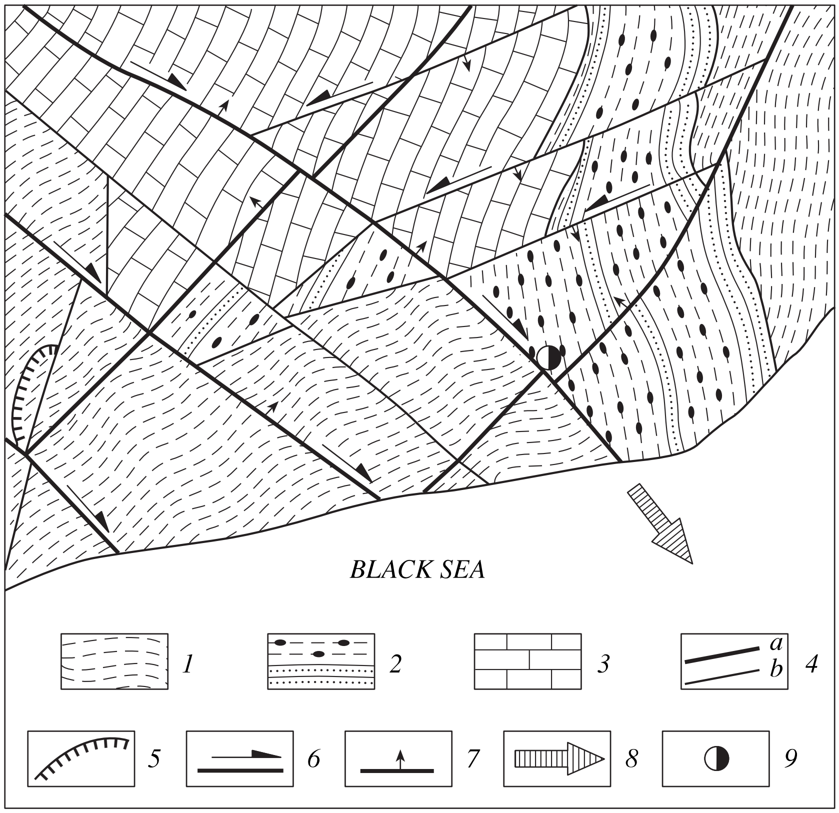

Fig. 2. Geological and structural features of the Nikitskii Cape and Nikitskii carbonaceous massif. (*1*) Flysch of Taurian series; (*2*) Middle Jurassic clay with siderite and sandstone band in base; (*3*) Upper Jurassic limestone; (*4*) faults: (*a*) main; (*b*) conjugate; (*5*) thrusts; (*6*) direction of dislocation of fault flanks; (*7, 8*) paths and zone of proposed submarine groundwater discharge, respectively; (*9*) recommended hydrogeological well.

of geological surveys. It is necessary to complete the geological survey of the coastal area, to specify the occurrence of faults, to assess the degree of their water supply, and to locate water intakes. Local geological organizations can cope with the solution of this problem.

The situation is more complicated in inland areas of the flat part of the Crimea, where groundwater reserves are nearly exhausted. Here, we would rather have to do with the rational use of groundwater and the system of water supply of economic projects. Many small settlements and farms use groundwater from remote water intakes. Therefore, considerable expenditures are needed to provide water pipelines and power supply lines. Moreover, water leakage losses should be taken into account. Numerous gardeners use imported water and this is associated with nonproductive fuel consumption and vehicle deterioration. It is more expedient to develop local sources of water supply, which should be under the control of the hydrogeological service.

Environmental and geological aspects of studying the fault tectonics should also be taken into consideration. Because of the increased permeability and water availability, zones of dislocations with breaks in continuity cause the anisotropy of the geological environment, which influences the origination and location of pollution sources as well as the migration of natural and anthropogenic pollutants. Endogenic and exogenic anomalies of elements and compounds affecting the environment and human health are formed within the area of these pollution sources. Local, linearly oriented natural anomalies of heavy metals, radon, etc. may serve as an example.

Faults, which act as migration routes of mobile phases, accumulate harmful substances and transport them in the form of concentrated streams. A source of pollution being detected, the regularities of fault formation and groundwater movement permit determining the paths of polluted water migration and making appropriate engineering decisions. In certain cases, the knowledge of the hydrogeology of the zone of faults and fractures will make it possible to forecast possible human-induced variations in hydrogeological conditions.

On the whole, there is enough new information, which allows the revision of principles of hydrogeological zoning. It has been found that faults of different magnitude play an important role in structure and dynamics of the groundwater system of the Crimea. The developed network of regularly oriented zones of faults and fractures is capable of draining subsurface runoff from large areas and may have considerable dynamic reserves of groundwater. Thus, along with continuous aquifers, zones of transit with a concentrated type of groundwater migration should be distinguished during zoning.

In addition to this, the revealed regularities make it possible:

to intercept water of zones of faults and fractures, which are discharged into the water areas of the Black Sea and the Sea of Azov;

to start regular prospecting of local water supply sources in the inland parts of the Crimea;

to purposefully chose water intake sites with due regard to environmental conditions, access roads, availability of water accumulation and distribution systems;

to redirect the network of observations at definite time intervals and pay main attention to the most water-abundant and promising zones;

to rehabilitate mineral water springs usually confined to large zones of faults and fractures, which are not used because of the environmental pollution or for any other reasons (the Area of Feodosiya).

And finally, the fault tectonics should be taken into consideration to a greater extent in working out the principles of ecogeological surveys, the measures meant to improve the environmental quality, and in ecogeological substantiation and administrative decision making.

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