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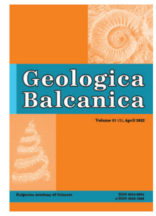

Comparison between the geological settings of the Varbitsa (NW Bulgaria) and Bure (SE France) sites for geological disposal of radioactive waste

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Abstract. Geological settings are of major importance in selecting appropriate environment for disposal of high-level radioactive waste from nuclear power plants. Clay rocks are preferred in a number of countries as a suitable host rocks due to their insulating properties and ability to self- seal cracks and other disturbances. In Bulgaria, on the basis of multi-criterion comparative analysis, several prospective sites have been selected for further consideration. One of them is the Varbitsa site located in the Fore-Balkan Unit. The marls of the Sumer Formation are the host rock. Similar clay host rocks for high-level radioactive waste disposal have been extensively studied in France, Switzerland and Belgium. In this context, the experience gained in these countries is particularly valuable for the further development of the geological disposal in Bulgaria. The current paper presents a comparison between the geological settings of the Varbitsa site (NW Bulgaria) and the Bure site (SE France), whose argillites are similar to the Bulgarian marls. The outcomes of this comparison would be useful for planning and conducting future research activities, as well as for the public acceptance of the geological disposal.

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Keywords: Varbitsa (NW Bulgaria) and Bure (SE France) sites, geological disposal, high-level radioactive waste.

INTRODUCTION

In Bulgaria, based on the so-called stepwise approach and multi-criterion comparative analysis, several prospective sites with their respective host rocks have been selected for consideration. The site selection for geological disposal of high level radioactive waste (HLW) from nuclear power plants (NPP) has reached the end of regional explorations. One of them is the Varbitsa site located in the Fore-Balkan Unit (NW Bulgaria). The Lower Cretaceous marls of the Sumer Formation are the host rock. Similar clay host rocks for HLW geological disposal have been extensively studied in France, Switzerland and Belgium. In this context, the experience gained in these countries is particularly valuable for the further development of the geological disposal in Bulgaria. This paper presents a comparison between the geological settings of the Varbitsa site in Bulgaria and the Bure site in France, where the Callovian–Oxfordian (COx) argillites in the area of Meuse/Haute-Marne are selected for host rock for

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HLW disposal. These argillites were chosen for comparison due to their great similarity with the marls of the Sumer Formation. The geological settings of both formations (lithostratigraphic, tectonic and neotectonic, seismic, geomorphological and hydrogeological) are discussed first, and then a comparison between them is made. The outcomes of this comparison and established similarities would be useful for planning and conducting future research activities, as well as for the public acceptance of the geological disposal in Bulgaria.

GEOLOGY OF THE REGION OF THE VARBITSA SITE

Lithology and stratigraphy

The Sumer Formation is among the preferred lithostratigraphic units for host rock for HLW disposal due to its significant thickness (about 1200 m), large lateral distribution and homogeneous lithology (Evstatiev and Kozhoukharov, 1998, 2001; Karastanev *et al*., 2011). The Lower Cretaceous marls of the Sumer Formation are spread in the West Fore-Balkan Mts region, where the Mesozoic strata are represented by diverse Triassic, Jurassic and Cretaceous terrigenous and carbonate rocks. Here, the Triassic consists of alternating sedimentary and volcanogenic rocks, and the Lower and Middle Jurassic by gravelstones, limestones, siltstones and argillites, as well as clayey limestones with marly intervals. The Upper Jurassic sediments are composed mainly of limestones. The relations of the Lower Cretaceous lithostratigraphic units in the West Fore-Balkan Mts are presented in the Fig. 1. In this area, the carbonate rocks of the West-Balkan Carbonate Group (the Glozhene and Brestnitsa formations) are overlain by the Salash and Mramoren formations. The Salash Formation is built of limestones, clayey limestones and marlstones, predominantly in the upper part of the section. In a southwest direction, the unit gradually wedges out into the reefal limestones of the Brestnitsa Formation. The Salash Formation was also considered as a potential environment for deep disposal by Evstatiev and Kozhoukharov (1995). The Mramoren Formation lies, with a gradual transition, above the Salash Formation and grades, with a rapid lithological transition, into both the organogenic and detritus limestones of the Cherepish Formation and the marls of the Sumer Formation (Monov and Nikolov, 1991; Fig. 1). The carbonate and terrigenous-carbonate sediments of the Vratsa Urgonian Group, the clay marls of the Sumer Formation, and the siltstones and marls of the Malo Peshtene Formation are developed in the middle and upper parts of the section. In a large part of the West Fore-Balkan, the Lower Cretaceous ends with the Sumer Formation, which, in turn, covers either the Lyutibrod or the Mramoren Formation.

The upper boundary of the Sumer Formation is sharp and transgressive. It is covered by Neogene and Quaternary sediments. The unit mainly consists of gray to dark gray marls, in some places with in-

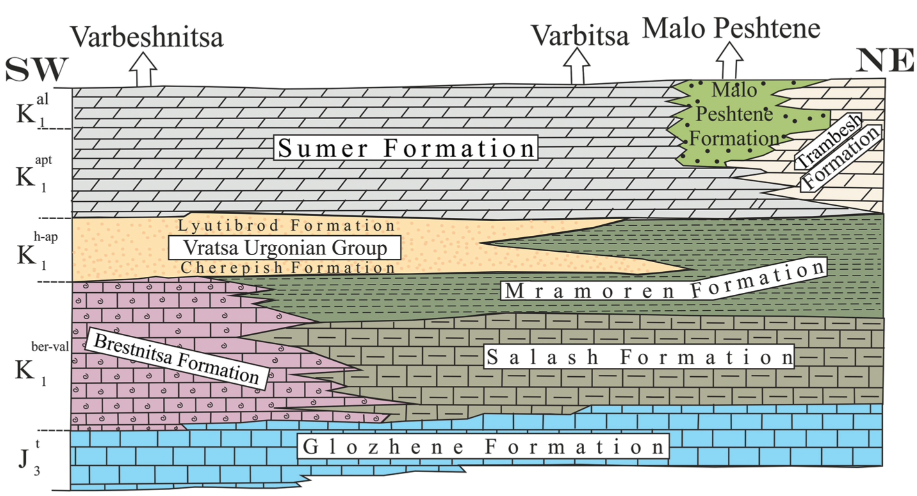

Fig. 1. Relations between the Lower Cretaceous lithostratigraphic units in the West Fore-Balkan Mts. area (after Monov and Nikolov, 1991).

tervals of micritic limestones or fine- to medium-grained sandstones and siltstones. The thickness of the Sumer Formation varies from 950 m to 1200 m. To the northeast, it passes laterally to the Malo Peshtene Formation, which consists of glauconite sands, siltstones and glauconite-bearing marls (Monov and Nikolov, 1991). To the northeast, the Malo Peshtene Formation grades into the Trambesh Formation, which is widespread in the central and eastern parts of the Moesian Platform. The Trambesh Formation is represented by clays and marls with rare sandstone intervals.

The Upper Cretaceous rocks in the region of the Varbitsa site crop out mainly to the east and south of it. They consist of varied carbonates that belong to the Novachene, Darmantsi, Kunino, Mezdra and Kaylaka formations (Campanian–Maastrichtian) (see Fig. 2). The Neogene is represented by the terrigenous sediments of the Dimovo Formation (lower Sarmatian). In the region of Trifonovo, the Sumer Formation is covered in places by the lower–middle Badenian conglomerates, sandstones and clays of the Blagovo Formation (Fig. 2). The Quaternary sediments consist of alluvial-deluvial clays, gravels and sands.

Tectonics

The Sumer Formation is distributed within the western area of the Fore-Balkan Unit, which is a part of the Balkan Zone of the Alpine orogen in Bulgaria (Dabovski and Zagorchev, 2009). The boundary of the Balkan Zone with the Moesian Platform is drawn by the Nivyanin (Deventsi) fault that takes part of the Fore-Balkan fault (*sensu* Bončev, 1971). The western area of the Fore-Balkan Unit is conditionally divided into two subareas: southern and northern. The southern subarea is characterized by a pronounced fold structure, while the northern one has a fold-block structure (*ibid*.). The amplitude of

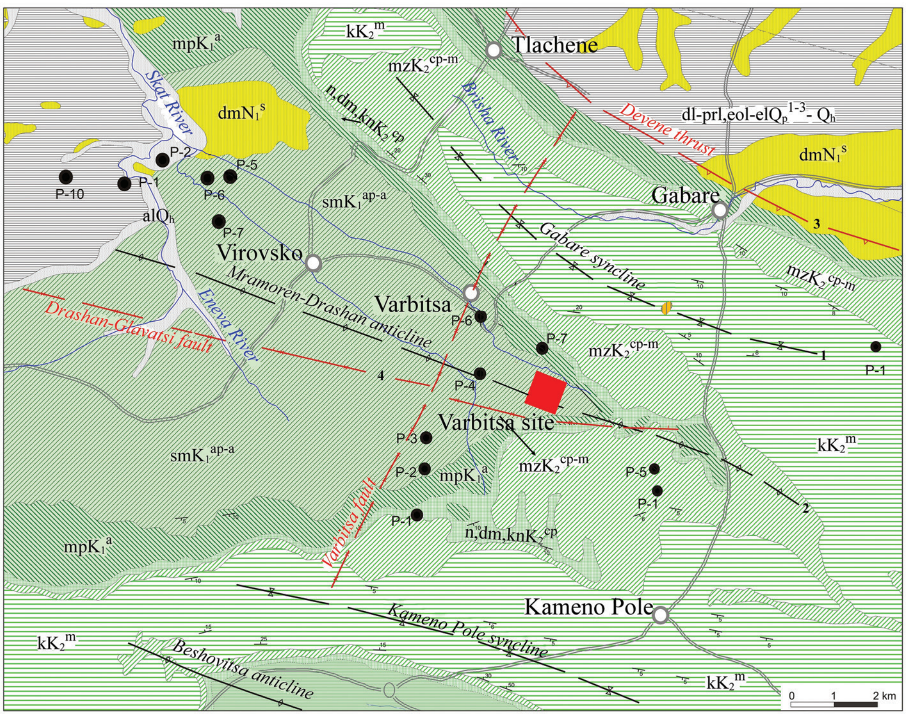

Fig. 2. Map of the region of the Varbitsa site (modified from Evlogiev, 2019).
1 – syncline axis; *2* – anticline axis; *3* – thrust; *4* – fault. P-1 – deep structural drilling; Drashan-Glavinitsa and Varbitsa faults – active till the Aptian; Deventsi thrust – active till the Pliocene; Lower Cretaceous: $smK_1^{ap\text{-}a}$ – Sumer Formation (marls); mpK_1^{a} – Malo Peshtene Formation (marls and glauconitic sandstones); Upper Cretaceous: n, dm, knK_2^{cp} – Novachene, Darmantsi and Kunino formations (limestones with marl intervals); $mzK_2^{cp\text{–}m}$ – Mezdra Formation (limestones with flint concretions); kK_2^{m} – Kaylaka Formation (organogenic thick-bedded limestones); Neogene: dmN_1^{s} – Dimovo Formation (sands, sandstones and detritus limestones); Quaternary: dl-prl, eol-el $Q_p^{1\text{-}3}$–Q_h – deluvial-proluvial clays with terrigenous materials covered with clayey loess, loess-like clays and extant humus soil; alQ_h – alluvial deposits in riverbeds.

the folds in the northern subarea is much smaller compared to the southern one, and its building layers, on a larger scale, are sub-horizontal

The Varbitsa site is located in the Mramoren anticline. The Sumer Formation is widely exposed in its core, its limbs being built of the limestones of the Mezdra and Kaylaka formations (Evlogiev, 2019; Fig. 2). The Mramoren anticline is limited to the west by the Varbitsa fault, to the south by the Drashan-Glavinitsa fault, and to the north by the Deventsi fault.

Neotectonics and seismicity

Currently, the northern zone of the Fore-Balkan Unit and the adjacent part of the Moesian Platform have been subjected mainly to positive vertical movements. In a southern direction, these movements are more pronounced, which has led to the inclination of the platform to the north (Vaptsarov *et al.*, 1993). Two denudation planes were formed as a result of the uplifting during the Miocene. The vertical processes continued also in the Late Pliocene (late Romanian), forming an erosion surface with an absolute height of 200–350 m in the marls of the Sumer Formation, as well as in the Sarmatian clays to the north. The subsequently accumulated deluvial-proluvial and aeolian-eluvial clays are an indication for reduction of the velocity of uplifting. The width of the floodplain terrace of the Ogosta River in Montana District (Late Pleistocene–Holocene) reaches up to 3 km and it is between 1.5 km and 2 km in the remaining part of the river valley. This is a sign of decreased rising during the last 8,000–10,000 years (Evlogiev, 2019).

There are different opinions about the last activity of the Deventsi fault, which is closest to the Varbitsa site (see Fig. 2). According to Nakov (2009), separate segments of this fault, especially the southern ones, have been active during the Quaternary. Radulov (2013) found tectonic deformations reflected in the contemporary relief along the Ogosta River, between the villages of Vladimirovo and Gromshin (about 40 km from the Varbitsa site), and interpreted them as evidence of movements that occurred during the last 71,000 years.

According to historical and instrumental data (Bončev *et al.*, 1982), the Varbitsa site falls within a relatively calm seismotectonic area, where no local earthquakes with magnitude exceeding 4.0 have been documented. The main sources of seismic hazard are earthquake zones outside the region, such as the Vrancea area in neighboring Romania, where earthquakes with magnitude >7 have occurred.

According to the national application of Eurocode 8 (2012), the area of the site has a reference maximum acceleration α in the range of 0.10–0.13 g for a recurrence period of 1000 years.

Geomorphology

The area of distribution of the Sumer Formation encompasses a system of low hills located in the transition area between the fold structures of the Balkan Zone and the subhorizontal strata of the Moesian Platform. The hills are incised by transverse gorges with distinctly outlined ridges. In the Fore-Balkan Unit, between the Iskar and Ogosta rivers, there are a number of north-vergent anticlines and synclines. The relief in its present form is influenced by tectonic movements during the Pliocene and the Quaternary.

The marl composition of the Sumer Formation is a prerequisite for the formation of hilly relief with flat ridges and slanting slopes of river tributaries. The anticline cores are deeply denudated and their limbs represent monoclinal ridges, which are also the most widespread secondary structural form. Since Cretaceous times, the terrain has been subjected mainly to uplifting, and, as a result of erosion, the cores of the antiforms, including that of the Mramoren anticline, have been exposed. This erosion does not impose a hazard for potential surface exposure of the repository, which is located at a depth of several hundred meters. Some fault structures (*e.g.*, Deventsi and Vratsa faults) also exert effect on the relief.

The relief forms between the villages of Varbitsa and Drashan are influenced by the compact limestones of the Campanian–Maastrichtian lithostratigraphic units. Their presence has contributed to the formation of wide and almost horizontal plateaus. The Miocene denudation surface, which is formed on the Upper Cretaceous limestones in the high parts of the relief, is also similar to the horizontal plateau in lithostratigraphic features and morphometry (Evlogiev, 2019).

The Pliocene denudation surface is developed in the lower part of the relief, in the marls of the Sumer Formation and the Sarmatian clays. In the area of the Varbitsa site, this surface has an absolute height of 200–350 m and is surrounded by erosion valleys. The Pliocene denudation surface is covered by Quaternary clays with angular gravels (up to 2 m thick), sandy yellowish-red clays with rock fragments (6.40 m thick), followed by loess-like clays (2.40 m thick).

Two floodplain and four non-floodplain terraces are established along the Ogosta River. In the area of the Fore-Balkan Unit, the Skat River has six terraces, including one floodplain and five non-floodplain ones. The incision of the river in the Fore-Balkan Unit is about 60–70 m, which gives an idea of the intensity of the vertical neotectonic movements (Evlogiev, 2019).

Hydrogeology

The Sumer Formation, and the Varbitsa site in particular, is a part of the Fore-Balkan division of the Moesian Artesian deep basin and, more precisely, of the Skat River watershed (Karastanev *et al*., 2011). The following hydrogeological section is observed in depth:

1) Near-surface slightly permeable temporary aquifer developed in the weathered zone of the marls, with an insignificant thickness (up to 10 m). The water in this zone recharges by the precipitation and discharges in the closely situated gullies with low flow rate;

2) Lower Cretaceous (Aptian–Albian) regional aquiclude built of the marls of the Sumer Formation. The unit is considered completely impermeable. Hydraulic conductivity is assumed in the order of 10^{-11} m/s. Fine cracks are also observed, most often parallel to the stratification, the greater part of which is filled with clay material. An indirect, but very important, proof of the insulation properties of the unit is that, in the area, it encapsulates a gas deposit;

3) Lower Cretaceous regional aquifer developed in the karstified Urgonian limestones, located below a depth of 1000–1100 m.

Beyond the boundaries of the area, there are karst basins (Gradeshnitsa–Vladimirovo, Mezdra and Kameno Pole), which are far from the Varbitsa site.

GEOLOGY OF THE REGION OF THE BURE SITE

Similarities have been established between the geological settings, structure and composition of the Callovian–Oxfordian argillites (COx) of the Bure site and the marls of the Sumer Formation (Tsvetkova, 2022). France is a country with many years of experience in HLW disposal in clay host rocks and the acquired knowledge is very important for the site selection and the stakeholders' acceptance in Bulgaria.

Lithology and stratigraphy

The COx unit is located in the northeastern part of the Paris Basin, which is situated in the western part of the European Platform. The Paris Basin is made of local Carboniferous–Permian, Mesozoic and, to a lesser extent, Cenozoic sediments lying, with an unconformable contact, over a Cadomian–Variscan basemen (Beccaletto *et al*., 2011, and references

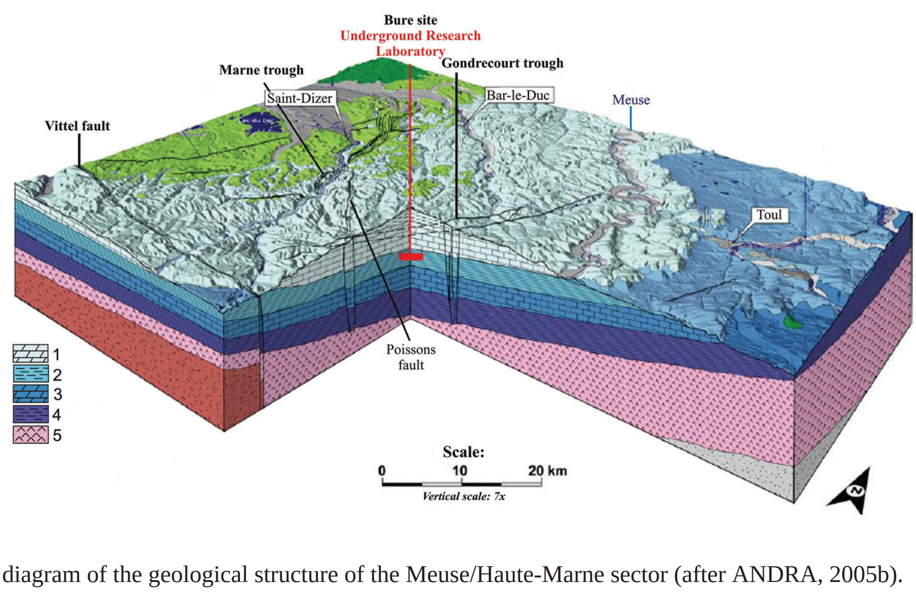

Fig. 3. 3D block diagram of the geological structure of the Meuse/Haute-Marne sector (after ANDRA, 2005b).
1 – Oxfordian (micritic and ooidal limestones); *2* – Callovian–Oxfordian (clays); *3* – Middle Jurassic (ooidal and bioclastic limestones and calcareous polypiers); *4* – Lower Jurassic (clays); *5* – Triassic (sandstones and evaporites).

therein). The stable tectonic conditions during the Jurassic were favorable for the deposition of horizontal and laterally extensive sedimentary rocks (*ibid*.). Uplifting of the edges of the Paris Basin, during the "Tertiary" and Quaternary, led to erosion of the sediments, thus reaching the Jurassic strata.

In the area of the Bure site, the lower part of the section (Fig. 3) consists of Lower Jurassic silty argillites, which are covered by Middle Jurassic (Aalenian–Bathonian) limestones (ANDRA, 2005a). They were deposited in a relatively shallow-marine paleotropic environment and are characterized by diverse facies (bioclastic, ooidal and reefal limestones) with a thickness of about 300 m. Above these limestones, the marls and silty marls of the COx unit lie, and argillites predominate in its upper part. The depth of its development starts from 420 m and reaches up to 600 m, gradually deepening to the north (*ibid*.). The thickness of the unit varies between 130 m and 160 m (Fig. 3).

Above the COx argillites, about 300-m thick Oxfordian limestones follow, lying at a depth between 400 m and 120 m. The Oxfordian strata are composed of calcarenites, ooidal and micritic limestones, in places interbedded with coarse-grained sands and clays. The Kimmeridgian strata cover the Oxfordian limestones and have a thickness of about 110 m. They represent an alternation of marls and clayey limestones, which separate the aquifer levels of the Oxfordian limestones and the Barrois limestones, (ANDRA, 2005a). The latter are Late Jurassic in age and are conditionally divided in two units: lower, with a thickness of about 30 m and poorly developed karst; and upper, with several meters of strongly developed karst (Fig. 4).

The sediments of the COx unit are predominantly clayey, with almost horizontal bedding and homogeneous composition. The unit is divided superpositionally in three parts based on their clay content. The maximum clay content is in the middle sequence and reaches about 60%. The upper one has higher carbonate content and the clay content is about 30–40%.

Tectonic conditions and seismicity

The eastern part of the Paris Basin, which includes the Bure site, is formed on a stable foundation of volcanic, low-metamorphic and granite Paleozoic rocks (Beccaletto *et al*., 2011). The basin has been insignificantly affected by tectonic movements over the last 65 million years (*ibid*.).

The area of the Bure site represents a monoclinal structure. To the southeast and southwest, it borders the Gondrecourt-le-Château graben, which is oriented in an east-southwest direction, and the Marne graben, which extends to the north-northwest. The northern border of the region is the Aulnois-Saint-Amande structure, built of layers gradually sinking to the west. Two fault zones restrict the region: the

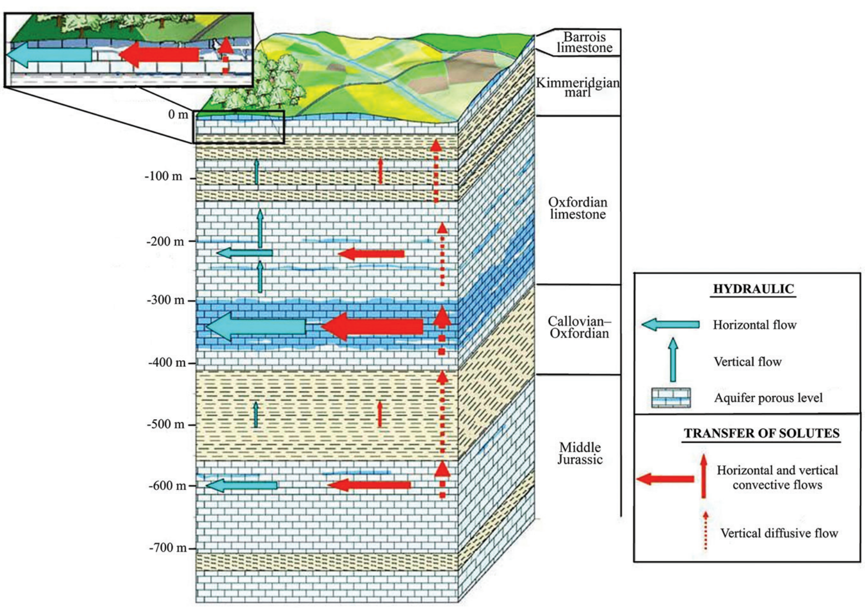

Fig. 4. Schematic representation of water flow and solute transport in the geological medium in its initial state at the Bure site (after ANDRA, 2005b).

Gondrecourt to the east and the Marne to the west (Fig. 3). The faults were formed before the Triassic, their last activity having been during the Miocene (23 Ma ago).

Seismically, the area of the site is stable. The greatest possible earthquake that could originate is related to the Marne fault or the Gondrecourt graben and its magnitude would be 6.1±0.4. At the same time, no evidence has been found for tectonic activity during the Quaternary. Analyses of the effects of possible earthquakes (and their return period) over the next million years show that earthquakes will have no deep impact either on the Callovian–Oxfordian or on the repository itself (ANDRA, 2005b).

Geomorphology

The present relief of the region is influenced by its tectonic development since the Cretaceous till now. The alternating glacial and interglacial cycles during the Quaternary exerted substantial effect on the relief formation (ANDRA, 2005b).

The alternation of clay and limestone layers exposed on the surface in the area of the Bure site is a prerequisite for the formation of a hilly relief, characterized by well-expressed elevations of carbonate rocks surrounding lowlands with clay and marl deposits of the COx unit and the Kimmeridgian strata (ANDRA, 2005b).

In the long term, due to the depth of the COx layers and the location of the site, the erosion activity will not exceed 40 m to 60 m in depth (ANDRA, 2005b).

Hydrogeology

The borehole investigations in the area of the Underground Research Laboratory prove that the limestones lying below and above the argillites of the COx unit have relatively low water permeability. The filtration coefficient of the Oxfordian limestones is between 10^{-9} m/s and 10^{-7} m/s, and of the Middle Jurassic ones is 10^{-10} m/s to 10^{-8} m/s. In addition, the limestones have undergone recrystallization leading to their compaction and low velocities of water flow. As a result, the vertical movement of fluids is restricted. According to the fluid migration models conducted with ^{36}Cl and ^{14}C, the velocity of their movement in the space around the repository would be 1 km for 100,000 years (ANDRA, 2005b). The low permeability is due to a great extent to the high content of clay materials (between 45% and 60%) and their homogeneous composition and texture. The vertical alternation of weakly permeable carbonate layers and clay layers limits the vertical flow. This predetermines the low velocity of water movement measured in the COx unit, which is 10^{-13} m/s to 10^{-14} m/s. The hydraulic gradient in the zone of water propagation (10^{-2} m.m^{-1}) is low and the groundwater movement is almost horizontal (Fig. 4).

COMPARISON OF THE CONDITIONS FOR HLW DISPOSAL IN THE MARLS OF THE SUMER FORMATION AND THE CALLOVIAN–OXFORDIAN ARGILLITES

The comparative analysis of the marls of the Sumer Formation and argillites of the COx unit has been performed by juxtaposition of their lithostratigraphic, tectonic, geomorphological and hydrogeological settings. These are one of the most important factors, on which the long-term safety of HLW geological repository depends. The comparison of the geological conditions of the two clay formations leads to the following observations:

1) The rocks composing the Sumer Formation and the Callovian–Oxfordian unit are both situated into stable tectonic zones and, within their boundaries, they have homogeneous vertical and lateral distributions. The sedimentation in both regions proceeded for a long time under constant calm marine conditions. The Sumer Formation has a thickness of up to 1200 m, in some places the marls of the Mramoren Formation (thickness 800 m) underlie it. This contributes to the higher insulation properties of the medium. The thickness of the COx argillites is much smaller, reaching only about 160 m. However, the research carried out in the Bure site by the Underground Research Laboratory proves that this thickness is sufficient to prevent radionuclide migration in the limestones below and above for hundreds of thousands of years. The Sumer Formation, with its considerable thickness, provides more options for selecting an interval with the best parameters (*e.g.*, mineralogical, geochemical, mechanical) for safe disposal of radioactive waste and development of the repository system.

2) The marls of the Sumer Formation and the Callovian–Oxfordian argillites are lithologically homogeneous. The Sumer Formation is built of marls, which possess high insulation properties. The thin limestone and sand interbeds in its upper parts are not spatially sustained and practically do not influence the insulation properties. The COx argillites are dense, lithified and uniform and the investigations prove that their physico-mechanical

parameters are favorable for the construction of underground facilities.

3) The geological and tectonic conditions in the area of the French Bure site differ from those of the Varbitsa site. The first one falls within the Paris Basin formed in a platform area, while the second one is located in the transition zone between the Balkan Zone and the Moesian Platform. The French site has the advantage of being in a platform area. The Sumer Formation compensates to a great extent for its placement within a transition zone (between a platform and an orogen) with its large thickness, absence of strongly expressed folds and nearby-located faults. The layers in both units lie subhorizontally and are found in low-active tectonic zones. The seismicity of both sites is low. It has to be taken into account that the seismic forces exert less impact on deep structures than on surface ones.

4) The alternating glacial and interglacial cycles during the Quaternary have particularly influenced the relief at the Bure site. In the case of the Varbitsa site, the relief has been shaped mainly by the positive tectonic movements during the Miocene, Pliocene and Quaternary. The future development of the relief at both sites does not imply conditions for the origin of floods and surface dynamic processes. There are no conditions for the development of new deep valleys. The geomorphological processes do not provide prerequisites for the occurrence of unforeseen conditions in the modeling of radionuclide migration.

5) The hydrogeological settings in the two compared sites differ substantially, being more favorable in the Varbitsa site than in the Bure site. The aquifer in the Sumer Formation is deeply located (about 1000–1200 m) and the unit has been described as an impervious screen by previous oil and gas explorations. The COx argillites lie between slightly water-bearing limestone layers. The research carried out so far, and especially by the Underground Research Laboratory, proves that there is no risk of radionuclide migration to these layers. The hydraulic flow is mainly in horizontal direction and the argillites of the COx unit possess the necessary sorption capacity in order to ensure the safe long-term waste disposal.

CONCLUSION

The comparison of Varbitsa (NW Bulgaria) and Bure (SE France) sites for geological disposal of high level radioactive waste shows many similarities between both potential host rocks, *i.e*., the Lower Cretaceous marls of the Sumer Formation (Bulgaria) and the argillites of the Callovian–Oxfordian unit (France). Both sites are characterized by homogeneous lithology of the host rocks and are located within stable tectonic zones. At both sites, there are no conditions for the occurrence of deep erosion, floods or surface dynamic processes. The marls of the Sumer Formation at the Varbitsa site, however, are thicker, which is sufficient enough to prevent radionuclide migration, and the regional aquifer is located at greater depth compared to the Bure site. The Sumer Formation has also been indicated as impervious screen by previous studies. All this makes the Varbitsa site suitable for geological disposal of high level radioactive waste from nuclear power plants. The comprehensive research and investigation experience at the Bure site, from the viewpoint of the safe disposal of HLW in a deep geological repository, would be very useful for planning and conducting the future research activities as well as the public acceptance of the geological disposal in Bulgaria.

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