THE STRUCTURAL GEOLOGICAL APPROACH IN THE EVALUATION OF THE GEOLOGICAL LOSSES IN THE DEPOSITS OF CARBONATE ROCKS – LIMESTONES, DOLOMITES AND MARBLES

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ABSTRACT. The losses represent this part of the geological reserves, which cannot be extracted, or for one or another reason, cannot be sold for a profit. The amounts of the losses in all deposits are different, because of differences in the geological situation and in the technology of extraction and processing. The errors in the evaluation of the losses can result in shortening the life of the deposits. Via the concession contracts, the concessioners are obliged to make payments to the state, which they may not afford to do if the losses are too significant. This paper presents a short review on the problem with the evaluation of the losses in the carbonate deposits. An evaluation approach is described, which is based on structural geological mapping of the karst-controlling fractures and faults. An example is shown of computer modeling of the karst in a real deposit.

Keywords*:* economic geology, limestone, karst, solution cavity, structure, reserves

СТРУКТУРНОГЕОЛОЖКИЯТ ПОДХОД ПРИ ОЦЕНКАТА НА ГЕОЛОЖКИТЕ ЗАГУБИ В НАХОДИЩАТА НА КАРБОНАТНИ СКАЛИ – ВАРОВИЦИ, ДОЛОМИТИ И МРАМОРИ

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РЕЗЮМЕ. Загубите представят тази част от геоложките запаси, която не може да бъде иззета или поради една или друга причина, не може да бъде икономически реализирана. Загубите във всички находища се различават количествено, поради различията в геоложките особености и технологичната схема на извличане и преработване. Погрешното оценяване на загубите може да съкрати значително живота на находищата. Чрез концесионния договор концесионерът се задължава да направи плащания на държавата, които могат да се окажат непосилни, ако загубите са твърде големи. В тази работа е направено кратко ревю на проблема с оценката на геоложките загуби в находищата на карбонатни скали. Описан е подходът за оценяване на загубите чрез структурногеоложко картиране на контролиращите карста пукнатини и разломи. Показан е пример на компютърна моделиране на карста в реално находище.

Ключови думи: икономическа геология, варовици, карст, структури, запаси

Introduction

The reserves of pure carbonate rocks in Bulgaria are fast declining, because of the increased demand caused by the desulfurization installations in the coal TPP. In spite of the demand, there is a tendency for the investors to face financial losses, because of poor evaluation of the projected losses of the geological reserves. In case of underestimated losses of the geological reserves, via the concession contract the investor is obliged to pay royalty fees, which he may not afford to pay simply because he is not making enough profit. The geological losses of the reserves are usually caused by the tectonics and karstification. In this paper, the current state of affairs in Bulgaria is exposed and an approach is presented for tackling the problem with the proper evaluation of these losses based on structural geological mapping and modeling of volumetric bodies of karst domains using modern software.

Short economic and geological evaluation of the carbonate deposits

The limestones and marbles comprise of the mineral calcite ($CaCO_3$) and less commonly the minerals dolomite ($CaMg(CO_3)_2$), magnesium calcite and aragonite. The limestones are biogenic sedimentary rocks, which are formed in various environments that is why they contain undesired components. The chemically pure limestone contains more than 98% $CaCO_3$ and almost always was deposited in reefs (Walker and James, 1992). The reefal bodies are massive and without primary bedding or with slightly detectable bedding. The pollutants in otherwise chemically pure carbonate deposits are found in solution cavities or karst. The karst caverns are partially filled with the residual material from the karstification and represent a mixture of SiO_2, Al_2O_3, Fe_2O_3(SAF), as well as negligible amounts of CaO, MgO,TiO_2 and other oxides and hydroxides.

The residual products accumulate is the form of yellowish or reddish clays with varying consistency. Some clay is oily in palpation and water saturated. It can be easily detached from the cavern walls. Other has a bauxite like appearance and is firmly attached to the cavern walls. During blasting the latter tends to stick to the rock fragments and pollutes the product with clay, sometimes making it completely unusable.

The solutional cavities form in stages depending on the level of the nearby rivers' erosional bases. Following the geological epochs of warming and cooling the karst cavern climb up section or down section in relation with the change in the sea level, which changes the river bases and the ground water level. Stage formation may occur also because of tectonic reasons. In the geological evolution of the rock massif, karst caverns of different age are superimposed one upon another. This results in redeposition of the residual material that fills them.

Apart from the stage formation the karst caverns do not follow some pronounced spatial regularity in its distribution and for this reason are difficult to be prospected. In spite of this, some slight regularity still exists, which is expressed in the fact that the movement of ground waters is facilitated by weak zones in the rock massif, predestinated by fractures, joints and faults (Fig.1). The joints and faults of course have systematic and more or less predictable position.

Fig. 1. Tectonized limestone from the Slivnitsa formation in West Bulgaria. Angular rock fragments are visible on the photograph, included in grinded mass with predominantly clay composition. In the absence of industrial washing installation this rock represent 100% loss from the reserves for production of products of higher technological grade.

During the exploitation, the preferred distribution of caverns along fractures is evidenced by the fact, that the karstificaton visible in a blasting front, which is developed perpendicular to the fractures looks very different than the karstification visible is a front developed parallel to the predominant joints and faults.

In the deposits of marbles the problem of karstification is usually more aggravated than in the limestone deposits, because the marbles are usually older and reflect longer periods of karst superposition. The marble deposits have been elevated to surface level and depressed under sediments more times and longer in the geological history, so the residual material in the caves is more mature, denser and firmer. In the marbles even the slightest traces of primary bedding have been obliterated by the foliation formation so the observed fabric of the rock is not related to the primary sedimentary fabric and with the spatial distribution of the carbonate body.

Another problem related to the assessment of marble and limestone deposits is the significant difference in the physical properties, structure and texture of the rocks from different deposits. Some finer grained (micritic) limestones have uniaxial compression strength in the range of 1200 kg/sm^2, while other barely reaches 400 kg/sm^2. In relation to this, gas permeability during roasting and chemical reactivity with sulfuric gasses substantially vary not only between deposits but between the various parts of one deposit. These variations of course can also result in geological losses.

As a whole, the following specifics are valid for the Bulgarian deposits:

The Paleogenic (litotamnium algal type) deposits are very cavernous and porous. They have low density but very high specific reactivity with acids even in rocks with relatively low content of $CaCO_3$. Unfortunately the pollutants are evenly distributed in the entire rock volume on meso and microstructural level, so selective extraction is difficult and the total mined mass rarely exceeds 98% of $CaCO_3$. It is beneficial for this rock to be stored in open piles for longer periods, so the rains partially wash them and allow usage in drier periods of the year. The Paleogenic limestone is frequently intercalated with marl layers and volcanic tuffs, which may not be described in the primary prospecting reports and may result is serious economic losses.

Cretaceous limestone the type of Mezdra formation. This limestone has good chemical composition and mechanical properties but it is located far from the large industrial consumers and this hinders its usage.

Jurassic micritic limestone the type of Slivnitsa formation. It is pure, very strong mechanically and moderately cavernous limestone, however it is located in west Bulgaria and so far it is inaccessible in southeast Bulgaria where the large TPP are located. Its reserves are still substantial but declining because of exclusion of some deposits for environmental and other social reasons.

The Triassic limestones are nearly universally dolomitized, which results in decline of the quality for chemical application. In East Bulgaria these limestones were also metamorphosed and turned into various types of marbles or slightly marbalized limestones, which affect negatively their chemical reactivity although it improves their usage as a construction stone.

Precambrian limestone of the Dobrostan formation was deposited in two sedimentary facies – reefal facies and lagoonal facies (Dimitrov, 2009). In the lagoonal facies dolomitic zones and intercalations are common, which leads to decline of the chemical reactivity and other industrial qualities.

Problems of the geological prospecting of the Bulgarian deposits of carbonate rocks

Most of the significant carbonate deposits in Bulgaria were prospected prior to the 10th of November 1989 (the official date of overthrow of the centralized communist system) by state owned specialized companies, such as Zavodproekt, as the geological reserves were accepted after examination in the state commission for the geological reserves (DKZ), which still exists in a modified form named SEC – Specialized Expert's Commission. During the privatization concession contracts were made with new private owners. These concession contracts were based on rather superficial evaluation of the residual reserves. During the prospecting of these deposits frequently but not always *the coefficient of cavernosity* was found. This coefficient represents the ratio between the intersected lengths of the caverns and the total drilled length of the drill hole multiplied by 100 to achieve percentage. Obviously, if the number of the drills is small or insufficient, the evaluation is far from realistic. This coefficient can give reliable evaluation of the caverns only in perfect drilling with 100% of retrieved core. However, nearly universally the drilling was made by a single tube technology, using the simplest and cheapest materials so the percentage of the retrieved core varied significantly. It is then, highly doubtful that 3% or 5% of caverns, as stated in the reports, are a proper estimate. In addition, the fault zones in the limestone are heavily brecciated and saturated with clay, so practically limestone core cannot be extracted from the fault zones (Fig. 2).

The new prospecting after "10th of November" is rarely reliable. The protracted bureaucratic procedure, overburdened with environmental assessment and social compliance assessment activities lead to nearly unavoidable financial losses and the investors become impatient in the process. The environmental assessment and social compliance procedures offset the emphasis of the prospecting away from the assessment of the reserves. In general they cost more than the actual geological prospecting. At the end, the investor acquires legally a deposit, which only in his mind is ready for development.

Although, to some degree the examination of the geological reports by the specialized state commission SEC improves the quality of the prospecting it cannot protect the investor from false or poor geological evaluation of the deposit.

Fig. 2. Core of tectonically reworked limestone nearly completely converted to a clay.

As a result of the abovementioned practices in Bulgaria concession contracts were made, and are presently made, based on prospecting, which does not offer enough information about the quantity of the losses from the geological reserves in the deposits. The author of the paper has observations that for some of the largest deposits in these contracts at average 5% losses were envisaged, while in reality they appear to be 3 to 4 times larger.

Comment on the meaning of the terms reserve, loss, dilution

Reserves

In the text below, a brief review is made on the meaning of the conceptual terms of the economic geology, following Petrinsky (1960).The source dates back to the centralized economy as these concepts were integral part of the practical deposit evaluation at that time. They are still used in defining the terms of the concession contracts in Bulgaria in the absence of better substitutes. Although there is well-specified international terminology in this aspect, and in sense these terms correspond to this terminology, they are listed here as being relevant to the discussion on the losses in the carbonate deposits in the Bulgarian context.

Geological reserves. These are all reserves of valuable material at the stage of the geological report, which were found to exist in a given volume of geological space. The geological reserves are divided into *in balance* and *out of balance*.

The *in balance reserves* are these reserves, which correspond to the industry requirements and the demand of the market.

The out of balance reserves are these reserves, which cannot be mined at a profit given the present state of technology and market.

The in balance reserves are the industrial reserves minus the projected losses. These are the industrial reserves that are taken into account when the extraction process is planned. The industrial reserves are divided into: *Uncovered (exhumed) reserves* – the reserves, for which expenses for removing the barren cover were made and *Prepared reserves,* which represent this part of the uncovered reserves ready for immediate mining.

The temporary inactive or blocked reserves are the reserves, which for some reason cannot be mined immediately.

The extinguished reserves are all mined reserves in a given part of the deposit (block, horizon, etc.) after the exploitation stage have passed. These are the exploited and sold for a profit reserves as well as the part of the reserves that went for the losses.

Losses

To mine out completely all known reserves in a deposit is impossible and such a task is never undertaken. What is generally desired is to mine the deposit with minimal losses of the geological reserves and with minimal total cost of the extraction. The losses at the end represent the difference between the extinguished and the properly utilized reserves.

Fig. 3. Dilution. Mixing of pure limestone blocks with lamps of clay after the blasting so the clay cannot be separated from the limestone.

Three types of losses are recognized. These are *the project losses*, *the planned losses* and *the factual losses*.

The project losses are these parts of the reserves, which are envisaged in the overall long term mine project to be left in the earth with regard to mine safety and minimization of the cost of extraction.

The planned losses are envisaged in the annual mining plan and they depend on the accepted mine exploitation system and various technical decisions taken daily after the acceptance of the overall mine project.

The factual losses are the summed amounts of valuable resource left in the earth notwithstanding the reasons. The factual losses never coincide with the project losses and the planned losses. There are several categories of factual losses. Losses because of the geological and hydrogeological reasons; losses in protecting benches and rock blocks left to support the underground integrity; losses depending on the exploitation system; losses resulting in erroneous management of the mine works etch.

The error in the evaluation of the losses can result in the depletion of a mine in 10 or 15 years instead of the originally projected 20 years, which will distribute unevenly or even prevent the repaying of the main investment or lead to total bankruptcy.

In the case of quarries for limestone, marble and dolomite two main types of losses are common: *geological losses from karstification,* and *technological losses during the blasting and crushing,* usually because of the overgrinding of the rocks.

The losses caused by the karstification are formed in various in size caverns and brecciated zones filled entirely or partially with clay and other karst filler.

All carbonate deposits in the world have such losses, which may comprise between 20 and 30% of the total rock volume. In principle, the losses depend on the technology of processing and on the application of the material. For example, if the limestone is not suitable for production of quicklime it may still be usable for construction stone or cheap filler, of course at lower market price, so this limestone will be considered as a loss for the quicklime production but as an asset for the cheaper construction applications.

Dilution

The dilution is a process of mixing of a valuable material with waste or poor quality material, which is below the application standards. Because of the mixing, the overall quality of the mined mass declines. In the environment of the limestone deposits, the dilution results from mixing of high-grade limestone with clay from the solution cavities (Fig. 3).

In the fault zones, because of the tectonic grinding, the limestone is brecciated and clay was introduced between the fragments by the ground waters. The tectonically reworked rocks are naturally impoverished in valuable components and are usually not suitable for better priced applications, unless the blasted rock is washed or otherwise purified.

Methodology for assessment of the geological losses

There is no universal, widely accepted approach for evaluation of the losses in the carbonate deposits and in fact in any deposit. The article proposes an approach, which is based on geological mapping and structural geological investigation of the fault zones and joint sets; drilling and evaluation of the core; visual expert evaluation of the degree of overall tectonic fragmentation and the amount of residual clay with the aid of CAD and GIS software such as Autodesk Civil 3D, ArcGIS or other, which allows modeling of volumetric rock bodies.

As already mentioned above, the karst caverns do not follow some geometric laws in their development other than the predefined orientation of the fractures and to some extent the path of more soluble rocks as the latter may not be valid in lithological homogeneous massif. Here is the opportunity to geometrically characterize the karst network. For the purpose astructural geological mapping of the deposit is needed for gathering of detailed information for the statistical distribution of the fractures and faults. It is of particular importance to determine the number of the joint sets, the density of the joints in each set and the relative age of the joint sets with relation to the age of the solution cavities. During the mapping it will become evident that some joint sets are particularly prone to facilitate karst formation. While other joint sets are less likely to be affected by solution and deposition of karst products.

The mapping of the faults has the same purpose that is to find which individual faults and fault sets contain karst and to what degree they are affected by it. The orientation of the large faults with relation to bedding, the width of the deformation zones and the intensity of brecciation have to be classified. There is a general rule that faults intersecting the bedding at higher angles have wider deformation zones with abundant brecciation and clay deposition, while faults that are nearly parallel to bedding accommodate shear without much deformation and may not contain substantial amount of clay. Because both joints and faults are predetermined by the tectonic stress directions in the massif their formation is characterized by symmetry and regularity.

The quality of the structural geological mapping must satisfy the following requirements: The deposit should be subdivided into large enough domains that allow sufficient number of structural geological measurements. The structural data should be processed with stereographic software using all geometric techniques that the stereographic method allows, including kinematic analysis. The measurements have to be positioned on the field with GPS receiver or geodetic stations and the data have to be transferred on up to date surveying plan of the mine. The mapping has to be extensive in time, in order to follow the uncovering of various faults and karst zones in a series of several consecutive blasting activities. Data for the chemical composition of the products of the karst caverns have to be integrated with the lithological and structural data to form spatial database of the deposit. Some fault zones have to be drilled in order to finds the percentage of clay in them. The purpose of the drilling is not to delineate the tectonic or karst zones, because the delineation is better done by mapping. Its purpose is to clarify the content of the clay in the tectonic zones and karst cavities, so they can be classified according to their degree of pollution. The intersections between the fault zones have to be geometrically delineated, because they are a preferred location of karstification. An overall classification scheme has to be built for the deposit, in which the domains have to be classified according to their degree of pollution with SAF. Because the process of pollutant's assessment includes combination of precise methods and subjective judgments it cannot be considered accurate. It is desirable that the final results of the calculations are checked with the data for the amount of waste deposited on the depots or sold.

The calculation stage of the assessment includes the following activities: delineation of zones of brecciating, fracturing and pollution using digital surfaces, which confine the volumes of these zones (Sachkov and Dimitrov, 2012; Sachkov, 2015). Examples of such digital surfaces are as follows: the terrain of the quarry (benches) at present, the surface separating the cover rocks from the resource at present, the lower confining surface of the resource at present, the surface of the projected situation of cover rocks and resources in the quarry at a given date in future according to the overall mine project, confining surfaces of the mapped fault zones and karst domains. The delineated larger domains are subdivided into smaller domains, which are also delineated as zones of certain category of resource, according to the degree of pollution and expected application. These may be individual fault zones, intersections of fault zones, fracture zones with moderate, less moderate or intense karstification, etc. The goal is a volumetric model of the deposit, using structural data and data from the sampling coeval with the exploitation, which subdivided the deposit into volumes of rocks with different industrial application. A question may be asked why this was not done at the stage of the original prospecting. And the answer is, because it cannot be done at that stage for many reasons. Visualization of such model for a limestone deposit polluted along fault zones is shown on Figures 4 and 5.

Conclusion

It is obvious that in deposits, which have not been developed yet, the mapping of the structure in such a detail that allows delineation of the karst caverns is not possible, because the exposed surfaces of the benches are missing and the overall accumulation of data is still low. It implies that the evaluation of the losses must be done continuously after the concession contract is made. If this is to have sense, it has to be envisaged in the concession contract so that further evaluations of the losses are easily effected in the contract. At present this is not the case in Bulgaria. After the contract is made, the state will demand payment of royalties based on the amount of losses written in the original contract. Changes of

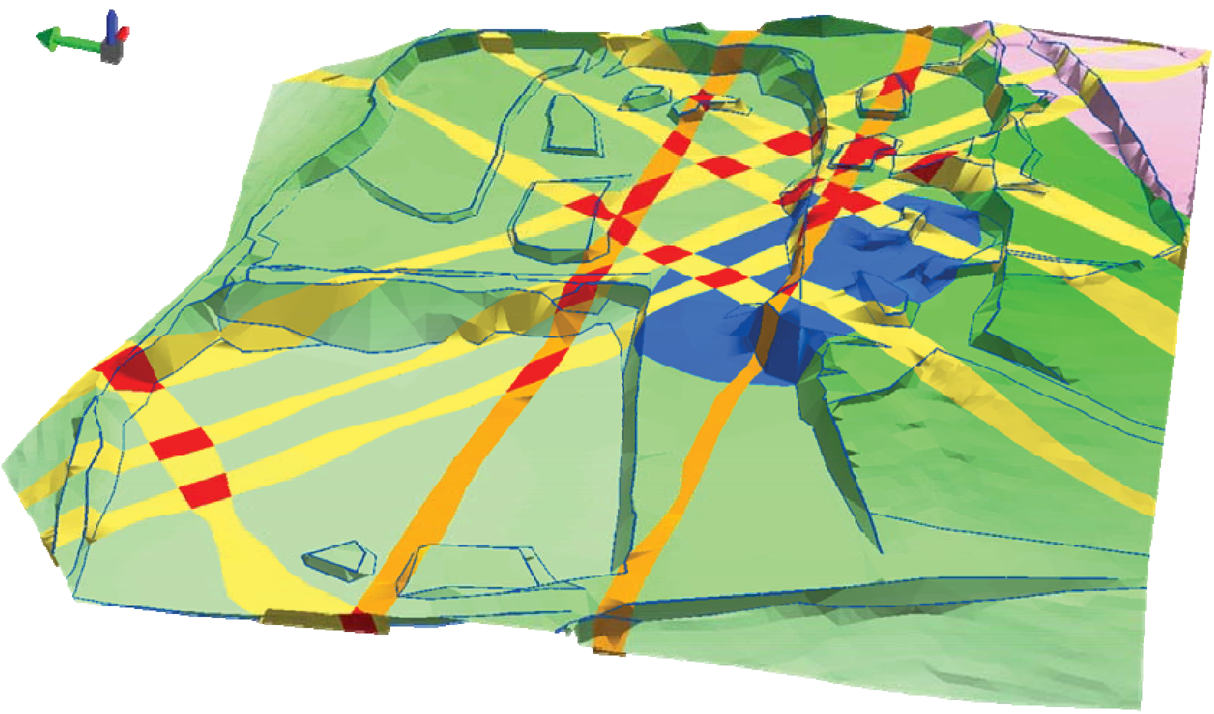

Fig. 4. Geological model of a deposit – map of the karst polluted zones. The traces of the fault zones are shown on the digital modelof the deposit's surface.

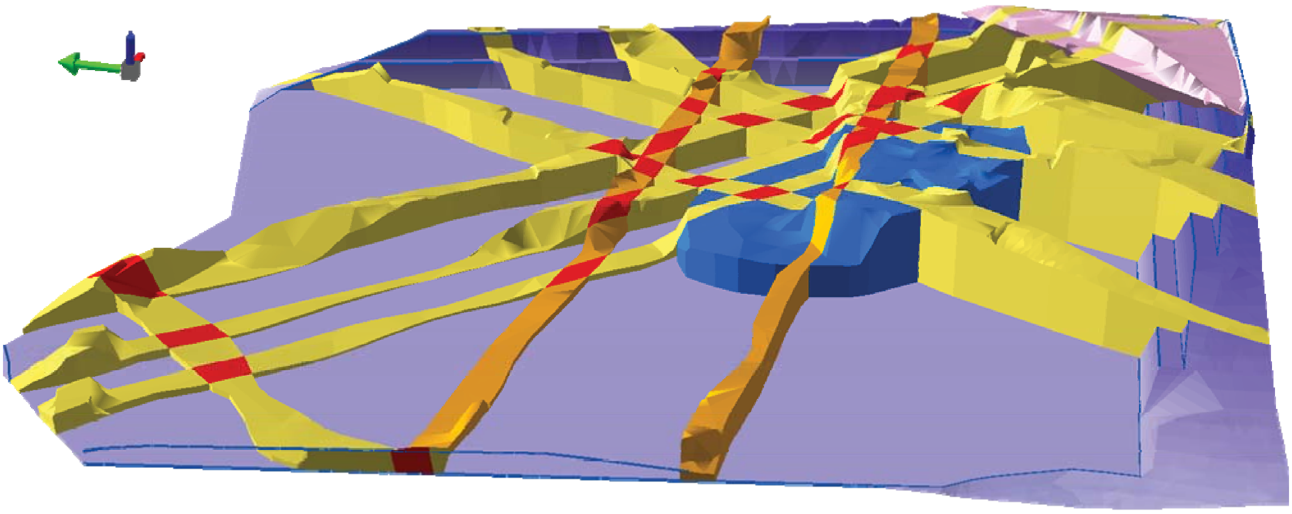

Fig 5. Geological model of a limestone deposit, which is lithologically homogeneous but transected by faults. View from west.

this are possible only after prolonged, expensive and tedious administrative procedure that involves signing of a new contract with all related to it legal requirements. No procedure for adjustment of the amounts of the losses based on data from the exploitation prospecting is envisaged in the regulatory framework or at least not clearly envisaged. The investors are discouraged to file complaints and to attempt readjustment of the contracts based on the flow of data that arrived after the deposit was developed. However, the problem with the losses is serous and if a flexible procedure to address this issue is not designed, the investors will rather abandon mining in some quarries, as it actually happens, instead of continuously investing in geology and production. It is also clear that the re-evaluation of the losses invokes nearly complete recalculation of the amount of the reserves.

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