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Underground innovative mechanized bauxite mining under difficult conditions due to the existence of karstic voids

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ABSTRACT : This paper presents a case of innovative underground mining of a bauxite deposit where, due to a random distribution of various karstic voids, the each time prevailing mining conditions are quite unpredictable and changeable. Therefore, essential considerations concerning mechanization as well as use of innovative prediction systems must be employed, in order to enhance safety and minimize production costs.

1 INTRODUCTION – THE "AGIOS PANTELEIMON No4 MINE"

Bauxite deposits are abundant in the Greek mainland and are considered to be of prime importance for the Greek economy, together with the other mineral reserves of the country. Proven and probable reserves exceed 200 and 600 millions tonnes respectively. Greece holds approximately 2,75% of world bauxite reserves and is the only EEC bauxite producer, since French production comes almost to an end. Mining activities expand within the geotectonic belt of Parnassos-Giona in the district of Central Greece, particularly in the geosyncline of Parnassos-Giona-Helicon-Oiti mountains, the main axis of which has a northwest-southeast orientation.

The prevailing rocks in these regions ordinarily consist of white, usually non crystalline limestones which stratigraphically belong to the Maestrichtian period. Apart from the upperstrata which is massive and rather blocky, the underlying rock formations are usually thinly bedded. There are three main bauxite horizons (the third, the second and the first, which is the deepest one) that belong to the existing stratigraphic structure in which the content of the minerals boehmite and diaspore varies within the bauxitic mass. Nowadays, the upper two horizons are intensively mined and especially the uppermost third one, which underlies dark coloured rudistid bituminous limestones of the Touronian-Senonian period and overlies white limestones of the lower Cretaceous. The latter form a stratigraphic unconformity which is in angular discordance with the hanging wall of the bauxite deposits. The main characteristic of the limestone formations is their karstification, which in several sections of the bauxite bearing region is more or less intense.

Due to the random distribution of various karstic voids, the confronted mining conditions are rather difficult and quite subjected to unexpected incidents and changeable factors. A most characteristic exploitation facing the above mentioned conditions is the "Agios Panteleimon No 4 Mine", owned by the "Greek Helicon Bauxites -G.L. Barlos Industrial & Mining Co. S.A.", which is one of the three largest private enterprises of bauxite mining in Greece. Mechanized room and pillar is the usually applied underground mining method. Mining excavations are supported by abandoned ore pillars. Pillars' layout and dimensions are designed under the general assumption that stresses at any point within the surrounding rocks should not cause, under any circumstances, roof or pillar failure, at least until the end of the depillaring stage (gradual reduction of pillars' dimensions).

The bauxite deposit under exploitation is located approximately 750 m above sea level, in a depth of 450 m , with an average dip of 20°, a W-SW/N-NE strike and an average thickness of 5,6 m. The orebody belongs to the uppermost (third) bauxite

Photo 1. Typical karstic void with stalactites.

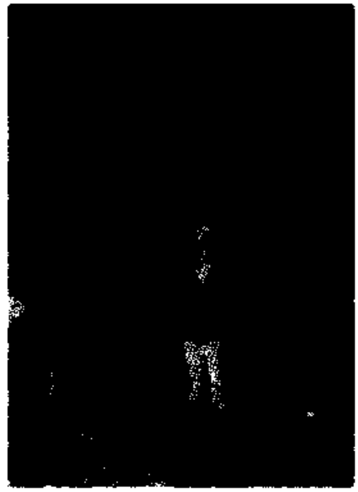


Photo 2. Typical karstic void with stalagmites.

horizon and is surrounded by fully stratified, microcrystalline limestones of relatively high values of physical and mechanical properties. Its typical chemical analysis shows that it consists of 60% Al_2O_3, 19,5% Fe_2O_3, 3% SiO_2, 2,5% TiO_2, 1,5% CaO and 13,5% CO_2+H_2O.

2 THE KARSTIFIED LIMESTONES SURROUNDING THE DEPOSIT

As well known, karst is produced by the process of leaching out soluble and relatively fractured rock formations by active underground waters as well as waters occurring between the ground surface and the water table. The main morphologic results of the above mentioned process is (rather rarely) a peculiar closed depression on the surface relief and (more often) the formation of caves and river channels deeper down. The term "karst" derives from the name of the Karst Plateau near Trieste (on the northern coast of the Adriatic Sea).

Water saturated with carbon dioxide dissolves limestones and dolomites many times faster than chemically pure water, by seeping through and along the joints, the fissures and any other kind of discontinuities of the carbonaceous rocks. While dissolving limestones on its way (in the alteration zone) it becomes saturated with calcium carbonate according to the following chemical reaction :

$$CaCO_3 + H_2O + CO_2 \longleftrightarrow Ca(HCO_3)_2$$

When this water percolates through the roof of the karstic cave, it liberates some of the carbon dioxide, thus resulting in that the above chemical equilibrium becomes unstable and the reaction shifts to the left. In this way, bicarbonate changes into calcium carbonate which precipitates while water drops are still on the roof of the cave.

Under this process, water drops seeping through the roof of the karstic cave or channel give rise to downward growing sinter or pendant like formations, called stalactites (photo No 1). At the same time, water drops falling down on the floor release residues of calcium carbonate, resulting to the formation of stalagmites, with an upward orientation (photo No 2).

Among the underground karstic forms existing in the hanging wall as well as in the footwall of the Agios Panteleimon No4 bauxite deposit, these of paramount importance are the voids, caves and channels of various shapes and dimensions, especially if they have not been identified during the surface exploration drilling and are located in critical or "strategic" regions of the specific room and pillar layout to be applied in the mine. The caves constitute a system of horizontal or near-horizontal channels, irregularly branching and interconnected by narrow passages, suddenly widening out into great voids or passing into narrow, almost impassable "pipes". In most cases, they are characterized by recurrent zig-zags and bizarre shapes, mainly due to the quite complex system of joints and faults dissecting the limestones and probably to the variety of the chemical composition of the latter.

An extensive karst is also prevailing in areas adjoining fractured zones which can act as underground drains as well as in the vicinity of the main tectonic faults of the deposit.

In underground mining operations, it is very important to estimate in time and correctly the inflow of abundant karst-fissure waters in order to prevent the water inrush and the eventual flooding of the mine.

The larger karstic voids that have been identified after almost three years of intensive mining are more than twenty and they are located in both the hangingwall (H/W) as well as the footwall (F/W) of the deposit. Of prime importance for the mining design are listed in table 1. Figure 1 presents a simplified typical cross section of the bauxite deposit exploited by room and pillar mining.

3 THE DIFFICULT CONDITIONS CREATED DUE TO THE EXISTENCE OF THE KARSTIFIED SURROUNDING LIMESTONES

During the execution of the various exploitation stages, a variety of serious problems and essential difficulties appear, the most remarkable of which are stated below :

1. The general mine layout must be modified on a continuous basis, according to the voids found in the everyday advances of the development and production excavations.
2. Due to the difficulty in locating the specific position and estimating the exact dimensions of the voids, serious problems come on stream during the depillaring stage, affecting the design of the pillars' layout.
3. Many pillars are lying above, below or nearby the karstic features thus influencing the geostatical stress field, as well as the response of the rock mass, due to the redistribution of loads.
4. The largest voids exist in the vicinity of faults and are associated with noticeable water inflows, which cause – quite often – production problems and necessity of pumping.
5. Additional precaution and safety measures must be considered and taken during the design and the excavation of the main access openings, in order to prevent them from passing through, over or under the voids.

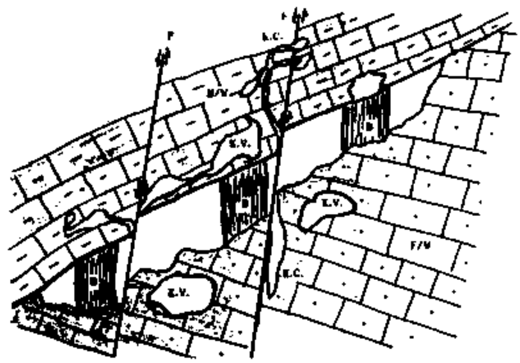


Figure 1. Non-scaled simplified typical cross section of the deposit and the surrounding rocks (B: bauxite pillar, H/W: hangingwall, F/W: footwall, K.V.: karstic void, K.C.: karstic channel, F: fault).

Table 1. The largest karstic voids of "Agios Panteleimon No4" mine.

VOIDS	ADIT (ELEVATION)	LOCATION	WIDTH (m)	LENGTH (m)	HEIGHT (m)
1	+680	F/W	25	30	70
2	+779	F/W	20	30	20
3	+814	F/W	*	*	15
4	+780	F/W	3	70	30
5	+720	F/W	*	*	15
6	+739	H/W	*	*	10
7	+728	H/W	*	*	20
8	+798	H/W	5	13	15
9	+805	F/W	2	*	7
10	+780	F/W	*	*	*
11	+788	H/W	3	4	5
12	+712	H/W	2	3	15

* : CHANGEABLE OR INDETERMINABLE DIMENSIONS.

6. A great deal of work is needed for the localization and estimation of the voids in proper time.
7. A considerable amount of the intake air is subjected to undesirable leakages through the karstic network, or to adverse recirculations, thus causing changes of the main parameters of the ventilation system.
8. The roof bolting -point anchored-systems, used for the rock reinforcement and the support of the mine openings, are often gradually slipping or completely failing in the cases where the contact area of the expansion shells and the rock mass is muddy or jointed due to the karstic alterations (photo 3).
9. The presence of the big volume karstic voids underneath the orebody causes considerable losses of bauxite and

obviously influences the total amount of the pre-calculated mineral reserves.

10. The production scheduling under the existing conditions should always take into account noticeable delays because of the additional work needed, the supplementary safety measures that have to be taken and the reasonable reservedness of the mine workers.

All the above mentioned parameters, in conjunction with the prevailing conditions in the international ore trade markets, renders absolutely necessary to exploit the orebody by employing fully mechanized room and pillar mining systems, in order to extract safely a mineral product with a competitive cost. Furthermore, use of modern geophysical techniques for effective surveying and recording the underground karstic features had to be tried. On the other hand, in order to inverse the adverse role of the karstic voids and use them efficiently, various procedures have been followed (i.e. internal dumping of refuse in the empty karstic volumes, water drainage through the hydraulic network, use of karstic openings as winzes or raises and utilization of water inflows for everyday production needs).

Since 1988, when mining operations started, due to the complete mechanization of the applied room and pillar mining systems and the careful mine design and production planning, no accidents or operation failures have occurred.

4 INVESTIGATION METHODS FOR DETERMINING THE LOCATION AND DIMENSIONS OF KARSTIC VOIDS

4.1 *Geophysical methods*

The first use of geophysical methods in karst dates back almost 40 years. The basic scope is the investigation of those particular volumes in the rock mass (karstified carbonate rocks) that are not feasible to observe directly, containing discontinuities which include all underground voids and channels, karstified zones and tectonic features.

The geophysical methods commonly used in the karstified formations are geoelectrical, gravimetric, seismic and georadar. The relative techniques are based on the physical characteristics of the karstified limestone as well as of the bauxite ore, and especially on their specific electrical resistance, electrochemical activity, density and rock wave velocity.

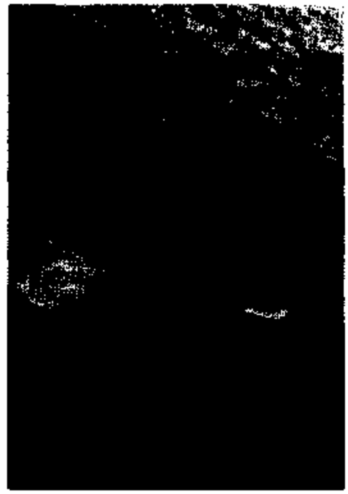


Photo 3. Failure of rock bolts due to karstic alterations.

Table 2. Values of electrical resistance of the bauxite and the surrounding rocks.

Rock type	Resistivity Ohm m
Older upper Jurassic footwall limestones	3000 - 6000
Bauxite (second Bauxite horizon)	500 - 900
Upper Jurassic and middle Cretaceous hangingwall limestones	2000 - 6000
Immediate footwall limestones of the third Bauxite horizon (Cenomanian age)	5000 - 20000
Bauxite (third Bauxite horizon)	100 - 700
Upper Cretaceous hangingwall limestones (Turonian-Senonian age)	8000 - 2000

The specific electrical resistance (electrical resistivity) is an important rock parameter, which depends on mineral composition, porosity, moisture, rock structure and temperature. Whereas compact, non-karstified, limestones have homogeneous and rather high and constant electrical resistance, on the contrary, bauxite seems to have much less resistivity value. Data concerning the electrical resistance of the bauxite orebodies of "Agios Panteleimon" area as well as of the overlying and underlying limestones are given in table 2.

As indicated above, the "contrast" between Bauxite and limestones is characterized by considerable margin, so that geoelectrical resistances may well be used as an indicative parameter during bauxite exploration.

Furthermore, the difference of the electrical resistance of the karstified limestones is the consequence of different

Photo 4. The georadar model SIR-3 of Geophysical Survey Systems, Inc.

porosity, fracturing and saturating characteristics, which means that in case of intense karstification, the water content inside the rock mass is being increased and the electrical resistance is being reduced. These changes are clearly visible on figure 2, representing a certain graph of an electrical recorder.

The electrochemical activity of the rock is the cause of its self polarization, resulting to the formation of a natural electrical field. The above parameter depends on the chemical composition of the rocks and also on the composition and concentration of the electrolytes dissolved in the ground water with which they are in contact. Upon it depends the magnitude and sign of the voltage developed when the rock material is in equilibrium with an electrolyte.

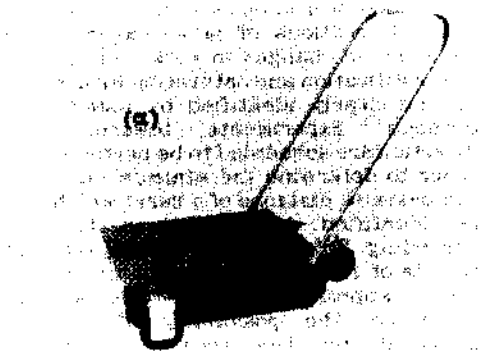
Occurrence of these fields in karsts is related to the influence of underground water filtration in such a way that negative anomalies occur at water sinking locations and positive anomalies at the points of water emerging locations, creating a signal of usually less than 100 mV. Due to the low value of the electric fields these electrical anomalies can not be used in order to inform us about the hydrogeological characteristics of the rock mass and the existence of karstic voids.

Some experimental efforts for direct detection of single caves and karst channels, located at great depths, by using such methods of natural electrical potential, have failed, in cases where the thickness of the overburden was considerably greater that three times the radius of the voids, due to the fact of deformations in the electric field that were practically impossible to measure. Therefore, satisfactory results may be obtained in the cases where the investigation extends to a relatively small distance.

The density of a rock mass is a very important characteristic when gravitometric methods are applied. Lack of mass at locations of large caverns and channels or changes in rock density due to karstification and saturation with water can be clearly identified by using such methods. Experiments towards this direction are scheduled to be performed in order to determine the minimum void and the maximum distance of a karst which can be identified from a given location. According to theoretical analysis and results of recent investigation on similar cases, appearing in the international literature, the possibility of success provided by the method of micro-gravimetry, for the direct detection of relatively shallow and large karstic voids is greater than the possibility provided by methods of electrical resistivity.

A relatively new method, called georadar, was extensively used in "Agios Panteleimon No 4" Bauxite mine, for the determination of discontinuities into the rock mass. Georadar uses the time-of-flight technique to determine the range of a karstic channel by measuring the time it takes for a pulse of energy (electromagnetic) to travel from a transmitter to the karstic channel, and reflect back to the receiver. The range can then be calculated by multiplying the velocity of the pulse by one-half of the time required to travel the distance. It is very important to note that the time-of-flight sensors maintain reliable as long as the return signal is received and detected, which is depending on the distance of the karstic channel, the strength of the transmitted signal and the characteristics of the reflective surface. Therefore, as the range of the channel increases, the intensity of the return signal decreases.

The system which was used to automatically record profiles of subsurface future is the SIR (Subsurface Interface Radar) of the Geophysical Survey Systems, Inc. The model SIR-3 (photo 4) consists of the PR-8304 profiling record system, the 38-VDU video display unit, a colour television and two different types of transducers. The first, type 3105-AP (photo 5a), is a general purpose transducer for medium resolution and depth of penetration, operating at a centre frequency of 300 MHz, with a 3 nanosecond pulse width, capable for detecting discontinuities at depth of 20 m. The second, type 3102 (photo 5b), has a central frequency 500 MHz and a 2 nanosecond pulse width, useful for moderately shallow investigations, up to 5-6 m depth. Figure 3 shows a typical output of the profiling record system which represents a small



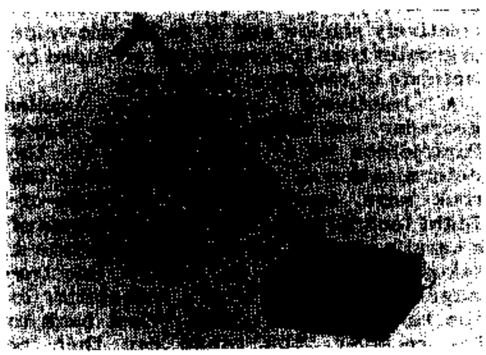


Photo 5. (a) type 3105-AR transducer, (b) type 3102 transducer.

karstic channel at a medium distance.

In conclusion, geophysical methods, and especially georadar techniques, seem to be a satisfactory solution for the determination of the location and geometrical characteristics (position, depth and dimensions) of the karstic channels, and is promising to be a useful tool for the mine engineer in order to prevent hazards due to the existence of large karstic voids.

4.2 *Drilling methods*

An old and successful method for identifying karstic structures is based on the technique of long-hole underground drilling. Drilling is the most common exploration method used in mine works and provides geological information pertaining to the karstified area, subject to examination. The location of drill holes needs careful consideration in order to maximize the information yielded and this does not necessarily mean arbitrarily space holes along an adit axis. For this purpose the ALIMAK BT-121 wagon drill was used, a flexible, light, four wheeled model which can be turned almost in any direction in narrow and dangerous passages, supplied with portable control panel and hose connection. Furthermore, during the production drilling, experienced miners can identify the existence of a nearby karstic void by means of peculiar dull sounds produced by the percussive drilling rod.

The information acquired from the underground drilling investigation program were combined with those from the preliminary surface drilling investigation program. The general aim of the preliminary geological and geotechnical investigation is that of identifying the geological types, determining the physical properties of rocks in karstified limestone terrains, providing data to evaluate probable support requirements and determining the geometry of the main karstic voids. For the preliminary investigation, two different types of surface wagon drills were used, the Hands-England 40CL and Joy Ramrod II. For special purposes it was necessary to use the Craelius Diamec 251/A underground exploration drilling rig in order to examine the geological and geotechnical conditions of future advances of production faces.

5 THE NEED FOR A FULLY MECHANIZED MINING

Due to the serious problems and the essential difficulties which have been described in chapter 3 it is obviously and undoubtedly necessary to access the production faces by using automatic remote controlled load-haul-dump units, equipped with digital address code Radio systems, thus increasing safety, productivity and reliability.

Furthermore, in an effort to attain quality control of the mine atmosphere and quantity control of the air movement through the mine openings, the Laboratory of Mining Technology of NTUA has developed a micro-processor based real time monitor and control system for bauxite mining applications. The system is capable of monitoring and controlling up to 48 transducers at a distance of 500 to 1000 meters from a central processor in a common four-wire cable. It can be used for continuous monitoring and displaying the ventilation system (especially the diesel equipment emissions and the distribution of the clean air), mainly in the areas of air leakages through the existing karstic

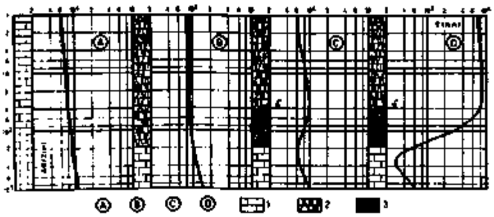


Figure 2. Diagram of electrical recording above a lithologically similar limestone formation (A: compact non-karstified limestone, B: karstified limestone where karstification is reduced with depth, C: same as (B) except limestone partially saturated with water D: same as (C) except limestone extensively karstified, 1: limestone, 2: karstified limestone, 3: karstified limestone saturated with water).

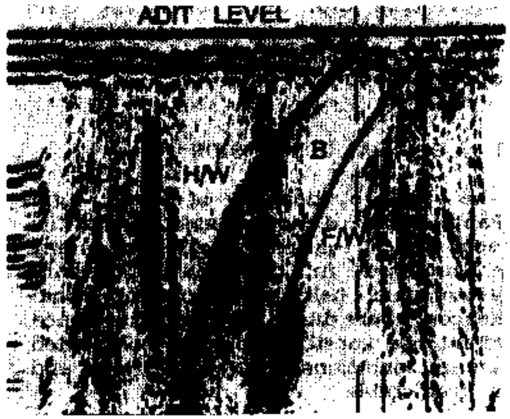


Figure 3. Typical output of the profiling record system.

channels. On the other hand, in order to achieve an effective ground control, this system can also be applied for real time convergence measurements during the depillaring stage provided that some proper technical modifications have been made.

Finally, georadar or similar relative techniques must be tried and used during the exploitation of the deposit for the identification of karstic structures in the surrounding limestones. The procedure must be properly scheduled and repeated following the advances of the production faces.

6 ALTERNATIVE USES OF KARSTIC VOIDS FOR INVERSING UNFAVOURABLE CONSEQUENCES

It is easily understood, that in any other case, the bauxite deposit under consideration, would have been abandoned or at least mined under controversial safety and economic conditions. The intense mechanization of all discrete stages during the mining process, as well as the innovative use of some characteristic properties of the karstic voids and channels, for inverting the aforementioned unfavourable consequences of their existence and for fulfilling various production requirements, have undoubtedly contributed to a less problematic exploitation of the mine.

It is necessary to point out, that the majority of the karstic voids were not identified during the surface exploration drilling program. Due to the above reason, it was indispensable to develop a variety of alternative choices in order to support the production decisions in proper time and take advantage of the karstic voids, thus minimizing operating costs.

Some of the most noticeable uses of the karstic caves and channels, are listed below :

1. The two main development drifts of the mine as well as the secondary transportation adits inside the deposit have length of more than 1000 meters and 500 meters, respectively. In order to reduce the relatively high transportation cost and the intense fatigue of the LHD units, almost all the quantities of extracted refuse during the mining operations are carefully disposed inside the largest karstic caves.

2. Some of the karstic channels are used as underground water sources, having such high flows that are quite sufficient for covering all the water requirements of the mine, thus eliminating the need for the use of special tank trucks. In most cases, special small and portable stations, including water tanks, pumps, pipes and control devices, are installed in critical points of the karst system.

3. Due to the hydrogeological conditions prevailing in the area, as well as to the complex tectonic system dissecting the orebody and the surrounding rocks, considerable water quantities must be handled through pumping and be disposed in proper places outside the limits of the deposit and the main access openings. For minimizing pumping and drainage costs, the network of the karstic channels serviced as gathering points and exhaust ducts.

4. Karstic channels having a vertical or

subvertical dip, thus connecting main sublevel haulage drifts, are used as winzes or internal raises for ore storage and draw points.

7 A GENERAL CONCLUSION

The bauxite deposit of the "Agios Panteleimon No4 mine" consists one of the most typical examples of adverse mining encountered in the bauxite bearing geotectonic belt of Parnassos-Giona-Helicon, where due to the drastic influence of intense karstification, the confronted mining conditions are quite difficult and unpredictable.

The problem of identifying reliably in proper time the location and the main dimensions of the existing karstic caves and channels has not yet been solved completely. More "in situ" research work must be done in order to increase the reliability and the detection distance of various suitable methods and techniques.

So far most of the difficulties, created by the existence of karstic voids, have been successfully confronted and this is due to the fully mechanized mining, the geophysical methods applied and the innovative mine design, by having always in mind that the most important thing for the miners is to come out from the mine.

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