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Problèmes de Sécurité et d'Environnement en Mécanique des Roches

Sicherheits- und Umweltsfragen im Felsbau

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Roof failure mechanisms in Greek underground bauxite mines

Mécanismes de rupture du toit dans les mines de bauxite en Grèce

Bruchmechanismen des Hangenden in griechischen Bauxitbergwerken

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ABSTRACT: Bauxite in Greece is usually mined by the room and pillar method. Stability of the hangingwall is of paramount importance for the safe exploitation of the deposits. Various types of failures have been observed during the operation of the mines and have been grouped according to their mode. The knowledge of the involved mechanisms will undoubtedly lead to the mitigation of the risk of failure.

RESUME: L' exploitation des mines de bauxite en Grece est d' ordinaire effectuee en suivant les methodes de depilage par chambres et piliers. La stabilite du toit est un objectif fondamental pour la securite d' exploitation des gisements. Divers types des ruptures sont observes pendant l' operation des mines et sont groupes conformement a leur mode. La connaissance des mechanismes participants va nous guider a la mitigation du risque des ruptures.

ZUSAMMENFASSUNG: Der Bauxit in Griechenland wird meistens nach den Verfahren der Raume und Seulen abgebaut. Die Stabilitat des Hangendes ist die grundlegende Bedingung fur den sicheren Abbau der Erzschicht. Verschiedene Bruchtypen sind wahrend des Betriebes des Bergwerks beobachtet und sind auf Grund ihrer Art gruppiert. Die Kenntnis der mitwirkenden Mechanismen wird uns anleiten das Risiko der Erfolglosigkeiten zu vermindern.

1 INTRODUCTION

Greece is the only EEC bauxite producer and holds approximately 2.75% of world's total proven reserves. Mining activities expand within the geosyncline of Parnassos - Giona - Helicon - Oiti mountains, the main axis of which has a northwest-southeast orientation. Rock formations overlying the bauxite deposits consist of white, usually non crystalline Maestrichtian limestones. They are usually thin-bedded with the exception of the upper strata, which are thick-bedded, with occurrences of hornfels nodules.

Three main bauxite stratigraphic horizons may be distinguished in the region, the deepest called the first, the intermediate the second and the top the third. The mineral composition of the bauxite deposits varies substantially with respect to their content of boehmite and diaspore. The two upper horizons and especially the uppermost third one are nowadays intensively mined. The rock of the immediate roof of the deposits is dark-coloured and consists of Turonian, roudists bearing, bituminous limestones. The footwall of the deposits of the third bauxite horizon consists of lower Cretaceous white limestones which establish a characteristic angular unconformity with the limestones of the hangingwall.

Due to the impermeability of the bauxite orebodies, groundwater, percolating through the limestone of the hangingwall, lays down clayey muddy sediments, particularly in areas of high joint density. These sediments have formed, at the contact of the bauxite deposits with the limestone hangingwall, a relatively thin yellow clayey marl layer, which is usually within the range of 20 to 50 cm thick and is completely distinguished from the deposit and the hangingwall.

Mechanized room and pillar mining is used as the main underground exploitation method. The task of roof control depends on the unmined mineral which forms the pillars and to the self supporting ability of the rock mass of the roof, which is reinforced by intense, mechanized rock bolting. Pillars are designed on the assumption that acting stresses on any member should not exceed pillars' strength. This should hold till the completion of the gradual reduction of pillars' dimensions during the depillaring stage.

2 ROCK MASS PROPERTIES OF THE HANGINGWALL

Extensive laboratory tests evaluated a uniaxial compressive strength of the limestone rock mass of about 100 MPa, a Young's modulus between 9 and 14 GPa, a Poisson's ratio of 0.25, a unit weight of 26.5 kN/m^3 and a Point Load Index of about 4.

The limestone has an RQD value within 50 and 75 and an average spacing between the joints of the main sets between 0.3 and 1.0 m. The usual condition of the discontinuities may be characterized by the relatively rough surfaces, the separation of no more than 1 mm, the soft filling gouge material and the weathered wall rock. Most of the joints dissecting the rock mass, are characterized according to CSIR (Bieniawski, 1979, 1984) as fair to favourable for the majority of the underground openings, provided they are aligned properly.

In general, groundwater appears as interstitial with the exception of water under moderate pressure appearing during winter periods. The overburden of the mining excavations exceeds 300 m, which creates a gravitational stress field of more than 8 MPa.

Rock Mass Rating of the limestone rock mass according to CSIR is evaluated to be in the range of 55 to 70, which characterizes it as fair to good rock. This suggests a mean stand up time of about 6 months for a 4 m span. Rock support interaction analyses (Economopouloset al., 1992) with rock mass strength parameters m and s, as suggested by Hoek and Brown (1980), having values in the range of 2.0 - 0.5 and 0.05 - 0.0005 respectively, predicted satisfactorily the stability of the openings.

3 GROUND CONTROL

Initial development (advancing) of the deposit involves the extraction of the ore by excavating 5 meter wide rectangular rooms and leaving 8 meter wide square pillars of ore. During the retreating stage, pillar sidewalls are reduced to 5 meters in each direction.

The soft clay sediment layer between the hangingwall and the ore is very soft and is completely separated from the hangingwall. This layer is always completely scaled, by mechanical means.

The Turonian limestones of the hangingwall, which lay above the afore- mentioned soft layer, are relatively competent rocks. Hence the mine layout and the reinforcement system selection is highly dependent on the persistence and the frequency of the main joint sets. However, despite the frequent crossing of the limestone hangingwall by bedding planes and discontinuities, it generally appears to behave satisfactorily.

Indications of disintegration and instability of the hangingwall are given in the form of noise, fall of small size particles, bolt failure and changes in the mode and sound of drilling. Unfortunately these warnings are distinguished in the last stages, prior to a roof failure, at almost incipient collapse.

In most of the underground mining openings, the roof of the excavation coincides with the bedding planes. The analysis which concerns the behaviour of the thin bedded layers of the limestone roof is based on the application of elastic or "Voussoir" beam and plate theories. According to these concepts a relieved zone is formed in the crown, bedding planes are separated and the roof sags. This sag may clearly be observed in situ. The almost zero tensile strength and the relatively low shear strength compared to the corresponding of the intact rock, are the two main engineering properties of the bedding planes of the Turonian limestone.

In almost all Greek underground bauxite mines

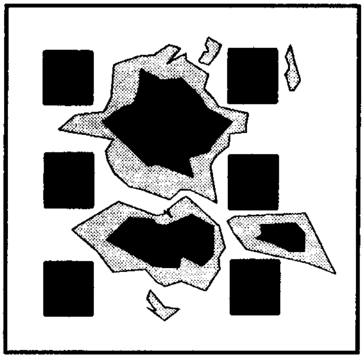


Figure 1. Controlled roof falls during the depillaring stage.

the immediate roof is reinforced by expansion shell or resin grouted rockbolt systems. This establishes a massive and strengthened rock beam which prohibits roof failure and falls. Ground control is applied in such a manner that is based on field observation of roof failure modes, in situ testing, performance monitoring and careful evaluation of the excavation's stability, especially during the depillaring stage.

Intense and systematic rockbolting provides tensile and shear strength to the bedding planes and hence increases considerably the safe excavation spans. Magnitudes of spans are influenced by the pretension, length, spacing, stiffness etc., of the rock bolting system.

The presently applied anchoring scheme is successful for most of everyday conditions, since roof failures are associated with only extraordinary rock mass conditions, for which alternative stability measures and exploitation methods have to be developed. These would include changes in the production schedule, secondary scaling, intensification of anchoring (Habenicht,1982), installation of timber or steel sets, stress and deformation monitoring and improvement in the layout of the room and pillar arrangement.

4 COMMON MODES OF ROCK FAILURE

The mechanized initial, as well as secondary, scaling performed in proper time and the regularly applied efficient rock bolting, have spectacularly decreased the number of big scale roof falls at the existing large span roof surfaces. Nevertheless a certain number of controlled roof failures still occur (Fig.1), mainly during the gradual increase of the room dimensions at the depillaring stage.

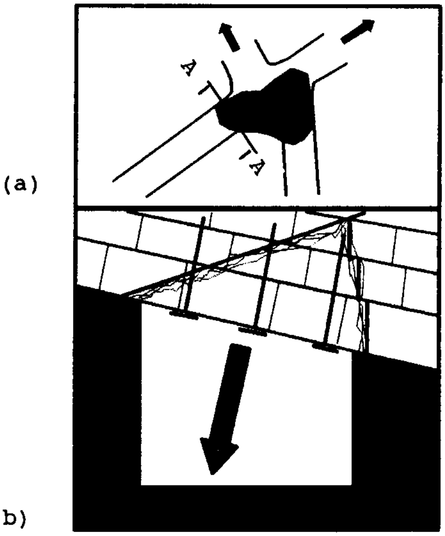


Figure 2. Roof failure due to critical joints (a. Plan view, b. Cross section A-A).

Experience is gained by observing, collecting (Sofianos, 1992) and analyzing various types of failures (Sofianos et al., 1992), such as overbreaks, fallouts, roof slabbing, rock movement and support destressing. Most roof failures in the underground bauxite mines are related to tectonic events, weak or soft rock, strata separation, clayey joint filling, high residual local stress field, high permeability, karstic erosion as well as to delayed installation or improper selection of the rock reinforcement system.

The various observed modes of failure have been grouped into nine types and are briefly presented below.

4.1 *Critical joints*

Unstable joints appear to be a main cause of roof failures that occur in the bauxite underground

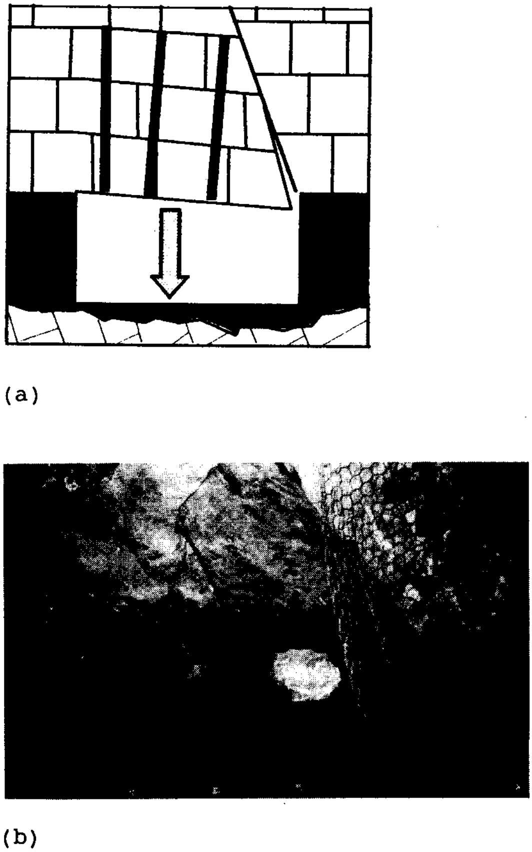


Figure 3. Roof fall due to steeply dipping joints.

excavations. The most critical joints are usually these which are flat dipping and their angle with the roof surface is below 30° (Fig. 2b). These are not always recognized by the mining crew because the entire visible roof is regularly lineated by some at random running intersections of joints and stratification planes. Hence most joint planes causing roof falls do not distinguish themselves from the usual "harmless" ones. The unstable joints have a dense spacing and are usually filled with clay gouge, which causes detachment from the intact stable rock mass.

Failure of the rock mass is rather the result of shearing of pre-existing joints, than fracture of the intact and undisturbed rock mass, with the exception of areas of extremely weak rock. Wedges or blocks are formed in the crown of the

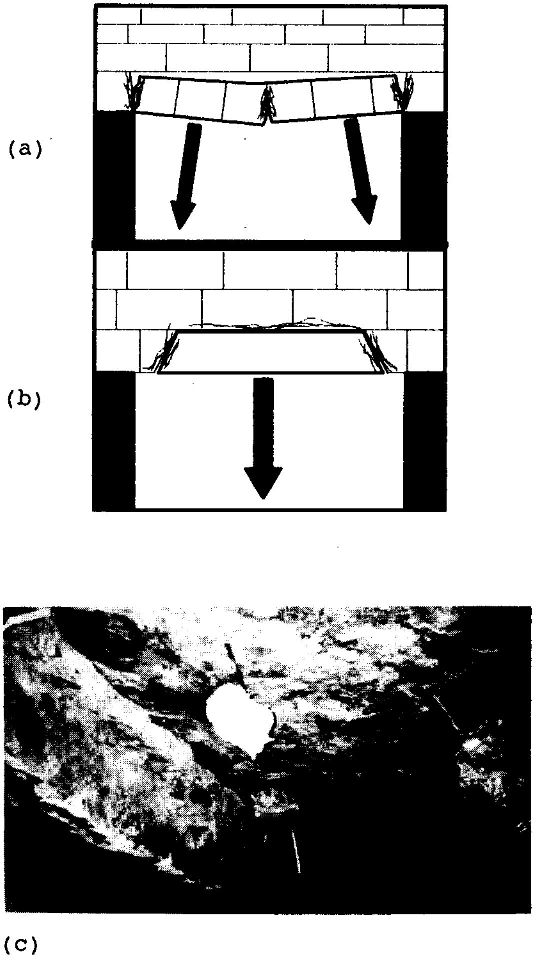
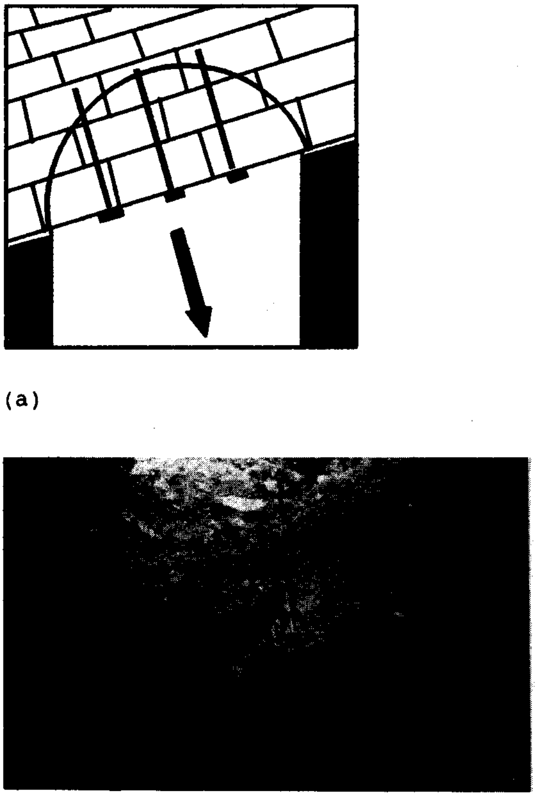


Figure 4. Voussoir beam roof failure.

room by two continuous intersecting joint sets that dip 25° - 35° or 75° - 110° respectively.

The stability of the steeply dipping joints (Fig. 3a) is dependent on the lateral stress field (Sofianos, 1986). Fig. 3b shows a roof fall due to sliding of such a steeply dipping joint plane. This local stress field of the limestone rock mass of the area has been rearranged, from the initial gravitational one, by the tectonic forces that have caused folding, faulting and jointing and by the nearby mining activity. This local stress field causes further deformation of the rock mass around the openings during mining.


(a)

(b)

Figure 5. Roof failure due to insufficient bolt length.

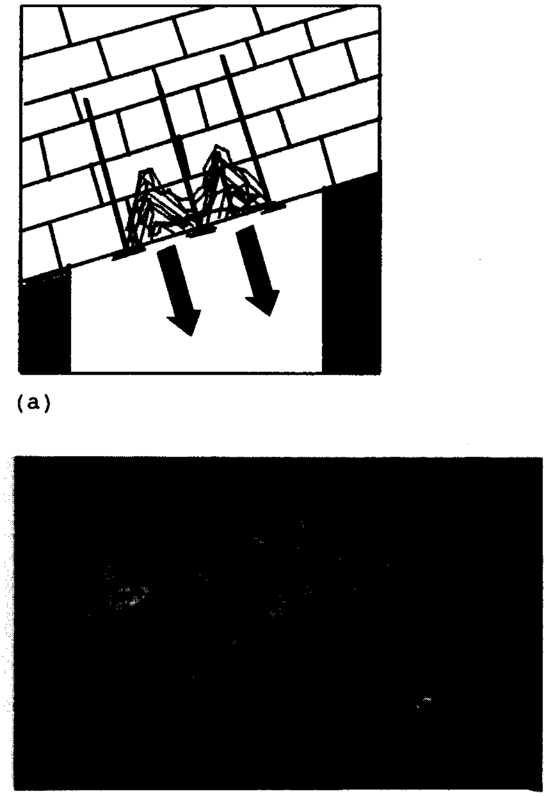

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Figure 6. Local roof failure due to insufficient rock confinement.

4.2 *Voussoir beam*

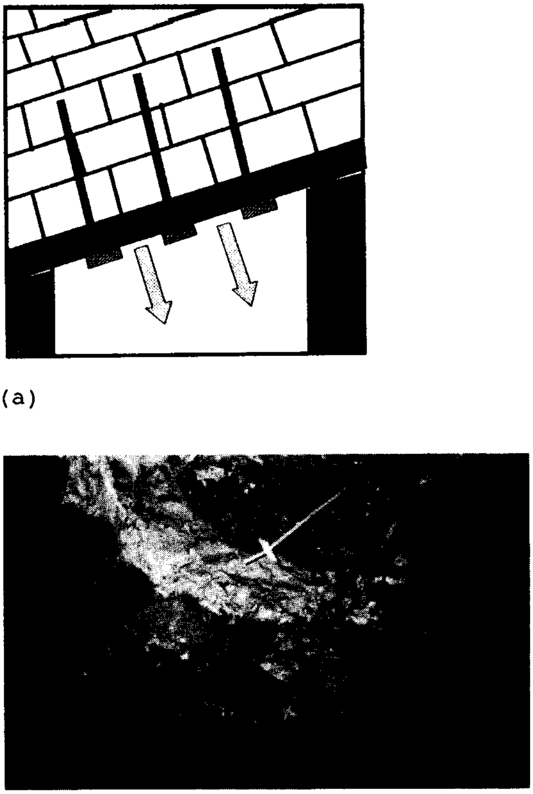
The limestone of the hangingwall is usually thin-layered. Gradual sagging of the immediate layers, opening of critical fractures and squeezing of rock (Fig. 4a), and shearing at the abutments (Fig. 4b), makes the immediate roof to behave like a Voussoir beam (Beer and Meek, 1982).

When the beam is relatively thin it will break through. In areas where the lateral stress is insufficient and the vertical load on the roof beam high, the lower stratum is subjected to high tensile stress and fractures. This may also happen when the roof beam consists of soft rock and the abutments may not provide adequate lateral stress. In areas where the upper part of the roof beam consists of soft rock, the rock over the crown yields under the applied compressive stress (Fig. 4a) and causes also failure.

The arch action of the beam (Wright,1972) and any gradually growing weight of the lower detached strata cause the rockbolts at the middle of the opening to overstress and to act as "drawbolts", thus encouraging further separation. Fig. 4c shows a characteristic Voussoir beam failure that corresponds to Fig. 4b.

4.3 *Ineffective rock bolts*

Some of the big scale roof falls that occur in the bauxite mines, comprise volumes of rock that extend beyond the anchor of the installed rockbolts (Fig. 5a). This insufficient length may



(a)

(b)

Figure 7. Roof failure due to low strength of the immediate roof layer.

concern only a portion of the fallen slab which involves incipient disintegration of the roof. Fig. 5b shows a characteristic fall where the rock bolt length was exceeded.

In cases of smaller fallen slabs where the anchor length is not exceeded, the jointed body has been tied to the back by too few bolts, occasionally by one or two only. There, the rockbolts may have slipped due to inadequate bond strength, may have broken due to overstressing or the jointed roof may have been split into pieces (Economopoulos et al, 1991).

4.4 *Junction drifts*

At the junctions of the drifts (Fig. 2a), any intersecting weakness planes may cause considerable roof falls. This happens without any warning due to the brittle elastic behaviour of the limestone rock.

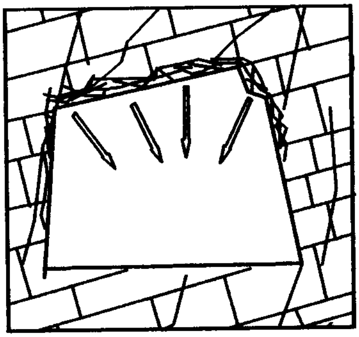


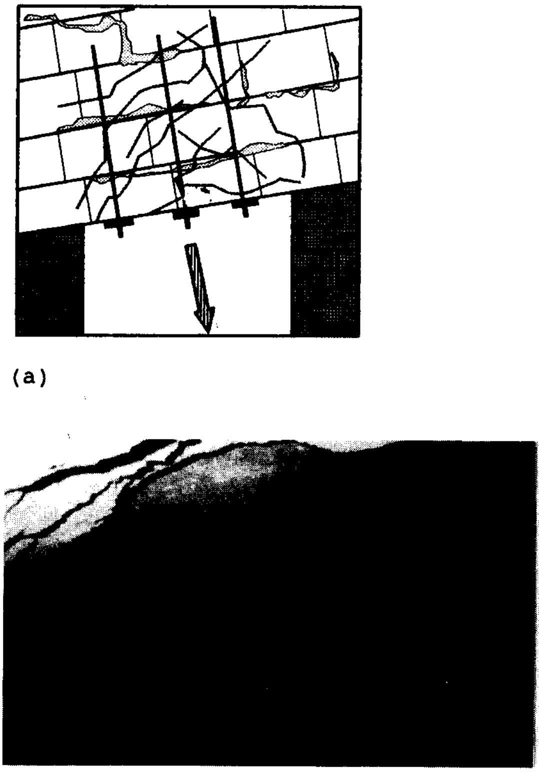
Figure 8. Peripheral spalling of main access drifts.

At these intersections the stressed volume, which is shown shaded in Fig. 2a, and the effective span are large, thus increasing the random defect probability and the stress level of the involved rock mass. These adverse conditions may be improved when the crosscuts are staggered. In the junctions of the drifts the sidewalls intersect each other and form corners, which have usually the shape of an acute angle. The rock mass at these corners, which forms an important pillar for the overlying immediate roof of the junction, is shattered twice by blasting vibrations. Whenever this pillar is weak and yields under the load of the overburden roof strata, the roof deflects according to the response of the pillar. This causes overstressing of the neighbouring pillars and of the hangingwall rock.

The ground control design is based on the assumption that the sidewalls of the junction and the individual drifts are going to suffer a certain damage. This ensures that rock support is acting only behind some depth of the external surface of the opening.

4.5 *Large rock bolt spacing*

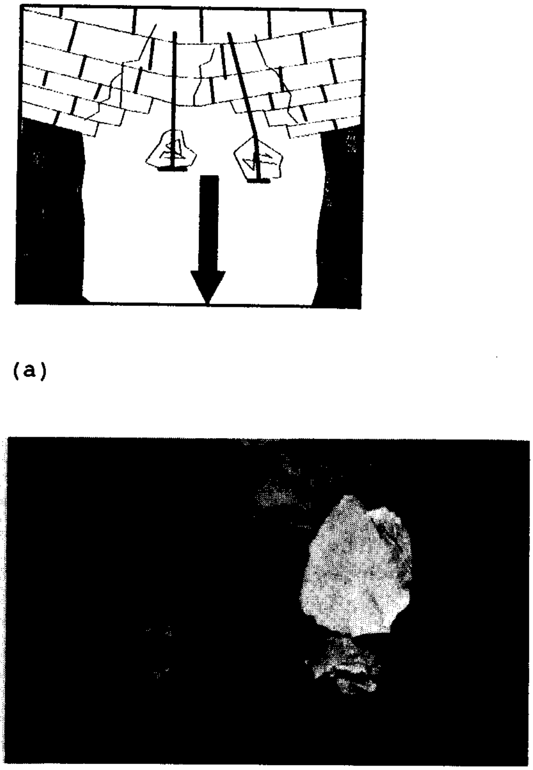
Tensioned expansion shell rockbolts are installed in order to form a highly stressed compression zone in the immediate roof of the opening. In



(a)

(b)

Figure 9. Roof failure due to karstic erosion.



(a)

(b)

Figure 10. Roof failure due to tectonically bent strata.

between the heads of the rock bolts, there are usually some considerable destressed bell shaped zones (Fig. 6a) of the rock mass. In such areas squeezing or breaking due to lack of confinement causes local failure of the roof and falling down of rock as shown in Fig. 6b.

4.6 *Low strength of the immediate roof*

In some areas, the bottom layers of the limestone hangingwall roof are characterized by extremely low strength, dense jointing, high clayey content and water inflows. Thus the rock layer becomes quite soft and muddy and behaves rather plastically. These layers cannot be scaled efficiently and tend to develop individual rock blocks, up to one cubic meter in volume, that may separate from the matrix rock.

Under these conditions, the performance of the installed rockbolts is influenced adversely by the softness of the rock mass and the consequent difficulty of load transfer from the head of the bolts to the rock mass (Fig. 7a). Fig. 7b shows a characteristic roof fall due to squeezing of the rock behind the bearing plates of the bolts.

4.7 *Peripheral spalling*

The main access and development drifts of the bauxite mines are usually driven into the limestone formations of the hangingwall or the footwall of the deposits.

Despite the quite satisfactory mechanical behaviour of the rock mass and the relatively long stand up time of the excavations, they often suffer from intense small scale spalling phenomena (Fig. 8). These are attributed to the local irregular stress field, the inappropriate support system and the inefficient scaling.

4.8 *Karstic erosion*

The limestone of the hangingwall is almost always karstified and its degree of karstic alteration varies widely. Usually the rock mass in such areas is muddy, intensively jointed and dissected by karstic features of various shapes (Fig. 9a). These cause gradual slip or complete failure of the expansion shell or resin grouted rockbolts respectively.

Karstic voids often overlie pillars, thus creating inefficient contact with the hangingwall. Fig. 9b shows a huge flat karstic void in the contact between the deposit and the hangingwall. Unloading of these pillars causes load transfer and overstressing of the nearby ones, whereas the increase of the effective excavation span causes further roof slabbing.

4.9 *Bent strata*

In certain areas the limestone layers of the hangingwall, are tectonically deformed and bent (Fig. 10a).

When the hangingwall roof is formed of such strata, these may not provide the arch action of a Voussoir beam and tend to failalmost immediately after the extraction of the underlying bauxite, as shown in Fig. 10b.

5 CONCLUSIONS

The various occurrences of failure during the operation of the Greek bauxite mines have been grouped into nine modes. Safety and feasibility of mining necessitates the proper selection of the mine layout and the reinforcement arrangement, considering the likelihood of such failures, in order to mitigate their risk.

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