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# French scientific cooperation 2007-2008 on the Trepča lead-zinc-silver mine and the gold potential of Novo Brdo/Artana tailings (Kosovo)

Final Report

**BRGM/RP-57204-FR**
October, 2009

TREPÇA

Geoscience for a sustainable Earth
brgm

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Study carried out as part of
Research activities of BRGM 2007

**J. Féraud, Y. Deschamps**

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(Front cover photo) Pseudo-stalactite (without axial feeder pipe) of rhodochrosite, galena, sphalerite, calcite, 5 cm wide, Stari Trg mine (old collection).

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Ore deposits; Tailing; Mining residue; Valorization; Skarn; Karst; Pb-Zn-Ag ore deposit; Hydrothermal-metasomatic; Low sulfidation; Gold; Indium; Hydraulic breccia; Hydrothermal breccia; Fluidised breccia; Maar volcanism; Phreatomagmatic breccia; Neogene; Museography; Kosovo.

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# Synopsis


The world-famous Trepča mine (also renowned as the Trepča Stari Trg or Stan Terg mine) has yielded 2 Mt lead and 1.5 Mt zinc, 2,500 t silver, 4,000 t bismuth and 9 t gold. After the war of Kosovo, the mine has resumed Pb and Zn-concentrates production since September 2005 and is currently offered to foreign investment. exploration restarts on promising deposits like Novo Brdo as well.

A close cooperation between BRGM and Trepča has developed. In 2007, it partly benefited of a grant from the Research directorate of BRGM (project n° PDR07REM06 entitled “valorization of the high-tech metals of the Balkans”). The present report aims at presenting an overall summary of the results currently obtained from this cooperation, within the global advances of knowledge presently reached by the Trepca geologists and mineralogists and by the other scientists who are working in the area.

The Trepča Stari Trg ore deposit was the main focus of the 2007-2008 cooperation. New data and observations now available lead to a geological appraisal of the deposit, concerning its geodynamic setting, its geological controls and metallogenic model, and its trace elements and particularly precious (silver, gold) and rare metals content (bismuth, indium, etc.). The valuable elements in the ore concentrates and flotation tailings of Stari Trg and some other mines have been investigated as well. Finally, concerning mineralogy, geological heritage and museography, a close cooperation has been settled in view of helping the famous Crystal Museum of Trepča to recover the world rank it deserves.

From the geodynamic point of view, the Trepča Stari Trg ore deposit is located in the western branch of the Alpine-Balkan-Carpathian-Dinaride belt (ABCD belt), in the External Vardar Subzone (EVSZ of the current authors). It belongs to the carbonate replacement deposits type, but it may also be considered as the polymetallic root of an eroded low-sulphidation epithermal type system as well. It comprises a series of manto orebodies and mineralized skarns within the Jurassic sedimentary carbonate platform known as the Stari Trg series. These orebodies form a hose shaped envelope at the contact with an Oligo-Miocene dacitic volcanic conduit partially brecciated.

Within this envelope, the deeper parts of the ore deposit visible at present have led both Trepca and BRGM geologists to identify hydraulic brecciation by hydrothermal explosions within the marmorised limestones hosting the mineralisation. A phreatomagmatic breccia is evidenced in the conduit (diatreme).

Therefore, within the regional frame of Oligo-Miocene volcanism with ignimbrites and calderas, the existence of maar-type hydrovolcanic deep explosions along the Trepča volcanic diatreme, connected with its plumbing system acting as a hydrogeological trap for the mineralised mantos and skarns, is evidenced.

The age and role of the karstification itself in the metallogenetic process is discussed in the light of new observations.

Finally, the analyses performed on the run of mine of Trepca Stan Terg, on the ore bodies of the lower levels and on three batches of Zn and Pb ore concentrates assessed significant contents of Ag, Bi, Cu and Au, with indications of In, Te, Ga and Tl. The increasing abundance of In together with other rare metals downdip suggests that valorisation of selective mining of elevated grades could be profitable in the next years.

The other focus of the 2007-2008 cooperation was the Novo Brdo (Artana) ore deposit. It has enlightened in particular the (relative) abundance of indium in this deposit (200 g/t In within the zinc-concentrate). Moreover, the high grade in the old tailings of Artana/Novo Brdo particularly of gold, already identified by the geologists of Trepča, is confirmed (possibly up to 2.5 g/t Au). They represent a potential target the order of magnitude of which could reach 21 Mt ore containing hypothetically around 30 t Au and 300 t Ag. According to the last BRGM laboratory scale tests still currently in progress, this target appears hampered by the lack of free gold and by its location within the iron sulphides (pyrite, pyrrhotite).

Additional studies of these tailings (and of the other tailings dams and slags heaps not yet sampled in the whole Trepča district) are recommended.

Thus the mining activities of this historical district could be developed, whereas the environmental impacts of its old tailings dams could be reduced.

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# 1. General framework and scope of the cooperation

## 1.1. TREPCA MINE AND TREPCA ORE DISTRICT : MAIN FEATURES, IMPORTANCE

In the middle of Eastern Europe, Trepča *(pronounce Treptsha)* is the most famous Zn Pb (Ag) old mine of the Balkans. It is located near Stari Trg village in Trepča Valley, Kosovo.

### 1.1.1. Exact name of the ore deposit

The United Nations currently considers the official Kosovo name of the mine to be "Trepca, Stan Terg." The previous name of the mine under Serbian administration was Trepča, Stari Trg, which is the designation still used in all mineralogical treatises and museums specimens of the world. Therefore, both terms will be used in the report.

### 1.1.2. Location

The mine is located in the lead-zinc mining district of Kosovo. This district (fig. 1) groups several mines : to the North (in the Kopaonik Mounts) Črnac and Belo Brdo (the ore of which is treated in the Leposavic concentrator), Koporic and Zuta Prlina which are under exploratory works ; in the centre, Trepca - Stari Trg (and the Tuneli i Pare concentrator) ; to the South and to the South-East (towards Priština) Artana-Novo Brdo, Hajvalija, Kišnica-Badovac (and the Gračanica concentrator).

### 1.1.3. Importance and interest

The whole district has yielded the astronomical figure of 60.5 millions tons run-of-mine ore at more than 8 % Pb+Zn, the half of which only in Trepča. It is one of the largest Pb-Zn ore districts in Europe, with a metal tonnage produced of nearly 3 Mt lead and 2 Mt zinc. Its silver production is assessed at more than 4,500 t. Its geological reserves are impressive (ITT Kosovo Consortium Ltd 2001). The reserves figures formerly calculated based on criteria of state-controlled and centrally planned economy must today be drastically recalculated on the basis of profitability and free-market economy but remain very attractive (Strmić-Palinkaš, Diehl *et al.* 2007).

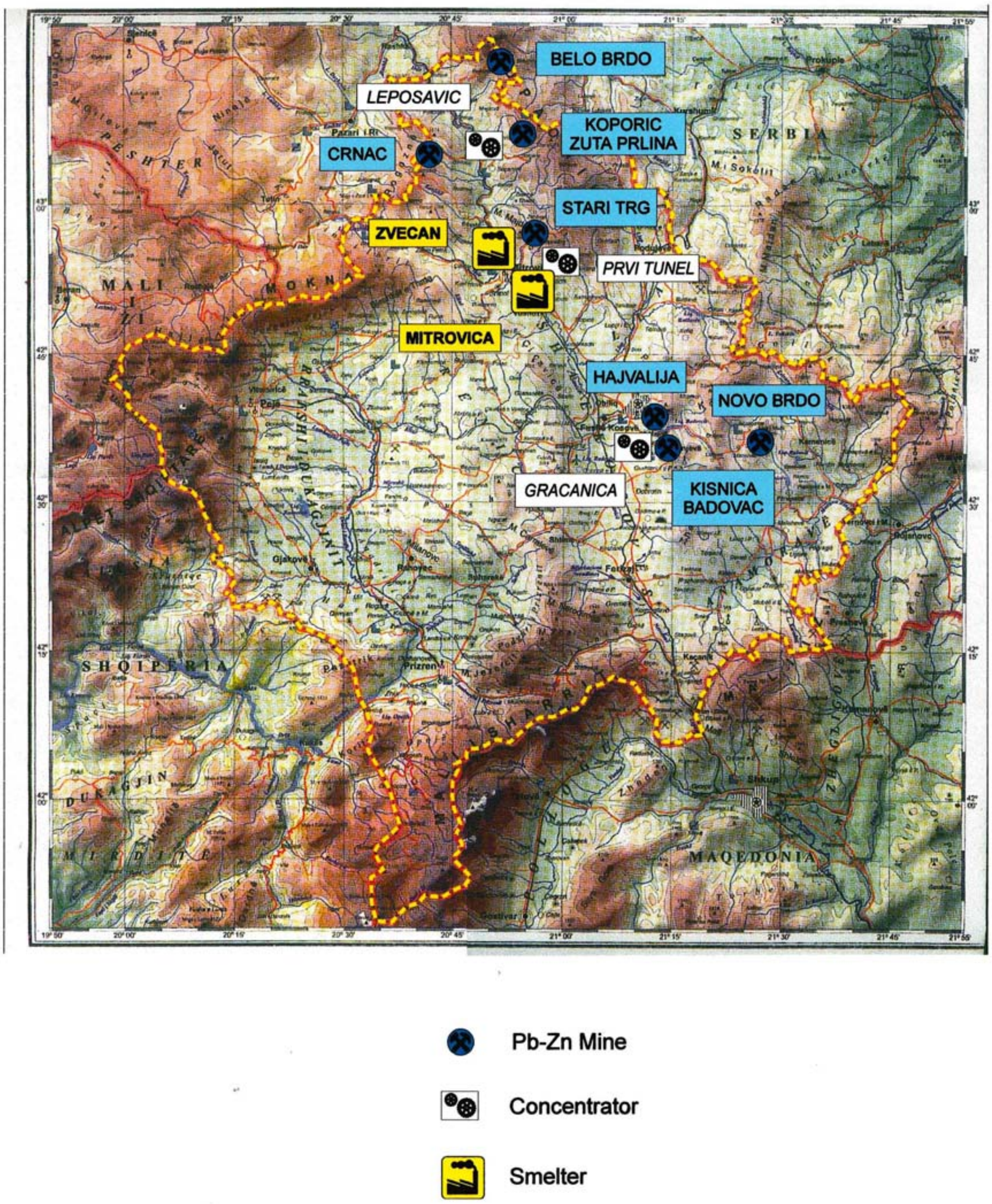


*Figure 1 - Location map of the various mines and concentrators of the Trepca district (Monthel et al. 2001)*

Together with a few others mines and factories located further North in Serbia and South in Macedonia, all these facilities were ruled from 1930 to 1999 by the Rudarsko Metalurški Hemijski Kombinat Olova i Cinka Trepča (Mining, Metallurgical and Chemical Kombinat of Lead and Zinc Trepča), one of the most important mining complexes of the Balkans.

The mine is renowned among the geoscientists of the whole World for four main reasons (Féraud et al. 2006, 2007):

- its total production (fig. 2) ranks it among the major European Pb-Zn deposits, being estimated at 34,350,000 t of run-of-mine ore having grades of 6% Pb, 4% Zn, 75 g/t Ag and 102 g/t Bi; the total metal tonnage produced was 2,066,000 t Pb, 1,371,000 tonnes Zn, 2,569 t Ag and 4,115 t Bi;

- its mining history is long and rich, although nearly unexplored;

- its mineralogical assemblage is particularly rich in various Pb-Zn sulphides and sulphosalts, and in Mn-Fe-Ca-Mg-carbonates and silicates; innumerable geodes of very large crystals of all these species confer a Worldclass museological interest to the deposit;

- its geological setting, although well defined, remains still intriguing because of the shape of the orebodies (both skarns, mantos and karstic fillings at the contact between limestones, schists and a volcanic pipe).

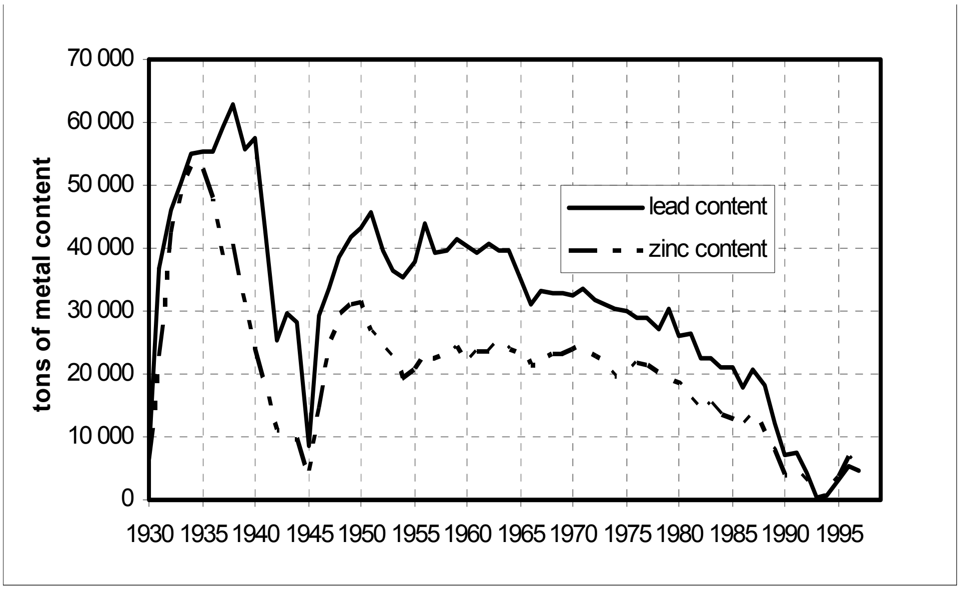


*Figure 2 - Stari Trg output 1930-1997*

Source data from Tiosav Lazarević, *a brief History of Trepča* (Trepča internal document p. 3). After 1997, the figures will collapse, because of the growing tension.

Concerning the production, on behalf of the United Nations Interim administration Mission in Kosovo (UNMIK), the Kosovo Trust Agency (KTA) has conducted an intensive programme to enhance the value and viability of the existing Pb-Zn mines (among which Trepča) and to attract mining companies to discover and develop new deposits (Ceku, 2005). Within that frame, KTA has just resumed the production of Zn and Pb ore concentrates in the Stari Trg mine, in September 2005. Exploration is in progress to increase the reserves. In the light of the recent findings about their content of precious and rare metals, investigations were recently carried out by the authors on the ore concentrates, and their results will be developed hereunder. There is no doubt that the Privatisation Agency of Kosovo will pursue the KTA program in order to better attract private investors despite the present World crisis effects.

Concerning mineralogy, besides the more than 60 mineral species already inventoried in the ore deposit, mineral species new for the deposit are still sporadically discovered, such as lastly kutnohorite (Féraud et al., 2007, Žigovečki et al. 2007) which confirms the “Mn-carbonate” epithermal geochemical signature of the ore deposit. Moreover, much progress was very recently recorded concerning geochemistry and temperatures of ore deposition. The “historical” data of Smejkal (1960, 1962) and Janković (1968) are being deeply revised and upgraded. A doctoral thesis is under progress on this topic (S. Strmić Palinkaš, University of Zagreb). Numerous preliminary results of this work have just been issued (Strmić Palinkaš et al. 2006, 2007a,b,c,d; Nelles and Diehl, 2007), which the reader is invited to refer to.

Concerning the understanding of the geological setting of the mine, since the historical publications of Forgan (1948) and Schumacher (1950) much progress was very recently recorded, at both regional and local scales. Between 1950 and today, the known extent of the orebody along the dip has doubled. The workings now reach 900 m below surface (down to +15 m above the sea level), and extension of the mineralization downdip is proven by underground drilling. The doctoral dissertation of Maliqi (2001) was followed by a run of publications, immediately applicable to improve the exploration in and around Trepča and to restart the various mines of Kosovo (Monthel *et al*. 2001, 2002; Barral 2001; ITT Kosovo consortium 2001; Hyseni et al. 2003; Anonymous 2003, 2005; Nelles and Diehl 2007). In the meanwhile, the concepts of regional metallogeny were renewed (Naftali 2003, Cassard et al. 2004). Nonetheless, a few shadow cones of noteworthy interest remain.

This report is therefore presented as a much-needed contemporary review of the geological setting and metal content of the ore deposit, based on the published results of the Geological Survey of Trepča after the Stari Trg mine reopened, supplemented by new data and observations (this study). Citations of some of the advances reached by the others scientists of Zagreb currently surveying the area will be quoted for information. The other topics of collaboration (museography) in which BRGM is partly involved, alone or in association with other partners, are exposed.

## 1.2. HISTORY OF THE COOPERATION OF FRENCH INSTITUTIONS WITH TREPČA MINE AND ITS PEOPLE

Amazingly, the curator of the mineralogical museum of Paris University, Pierre Bariand (1958), reminds that, during the Middle Ages, the mines belonged to a French princess : *Helen of Anjou* or *Hélène d'Anjou* (in Serbian : *Jelena Anžujska* ; 1230-8 February 1314). She was a Serbian queen, wife of Serbian king Stefan Uroš I and mother of kings Dragutin and Milutin, whose names are tightly associated with the mines of Kosovo which financed their kingdom.

### *The pioneers*

In 1836 and 1838, Ami Boué, the founder of the French Geological Society, visits Serbia, Kosovo and Albania together with his colleague Auguste Viquesnel. The granitic intrusion of Mt. Kopaonik is featured on the geological map of Visquenel dated 1842.

After 1924, when Serbia opens to foreign capital, many French and English geologists are sent by foreign private companies to explore Serbia and Kosovo. Whilst the English develop Trepča, the French develop Bor but a few French geologists (like P. Jourdaine in 1936) investigate some other ore deposits of Kosovo like Ajvalija and Kižnica.

### *The international congresses visit Trepča mine*

After the Second World War, Eugène Raguin (professor at the School of Mines of Paris) and later on Pierre Bariand (curator of the mineralogical museum of Paris University) are among the most prominent French scientists to come back to Trepča. Bariand comes two times in 1958 and negotiates with the Crystal Museum of Trepča some exchanges of mineralogical specimens for the mineralogical museum of Paris. The visit of Eugène Raguin will be followed by exchanges of geologists between France and Yugoslavia. One of the few French trainees who will be assigned for a short period in Stan Terg is Jean-Claude Besombes in 1962. The Stari Trg mine is one of the stops of most of the metallogenic field trips of the international geological congresses held in the Balkans, among which the 1980 international geological congress of Paris.

### *BRGM awards the Crystal Museum of Trepča in 1972*

BRGM, the French national Geological Survey created in 1959, initiates cooperation with Trepča in 1965, when its general director, Claude Guillemin, sends his assistant at the Mineralogical Gallery of the School of Mines of Paris, Joseph Mantienne, to visit the Crystal Museum of Trepča and to negotiate exchanges of mineralogical specimens. At his return, the specimens are exhibited in the Gallery in Paris, where they are still admired by the public as some of the masterpieces of this museum.

Claude Guillemin, in his famous “Guinness books of minerals” published by BRGM in 1972 and reedited with Joseph Mantienne in 1989, ranks the crystal museum of Trepča among the “Top-100” of the World mineralogical museums, as will be confirmed by the book of another renowned mineralogist, Peter Bancroft (1988).

### *The “magic” of Dinarides*

In 1970, the French Geological Society publishes the paper “Geology of Dinarides and Hellenides” (in French) by professor Jean Aubouin and his disciples, which has a great influence on many young French geologists. A collaboration is settled between the French Universities and Branislav Ririć. Jean-Paul Rampnoux focuses his doctoral dissertation (at the Orleans University) on transects through Montenegro, southern Serbia and Kosovo, whereas the other parts of the belt are surveyed by René Blanchet, Jean-Paul Cadet, Jacques Charvet, Jean Chorowicz and Michel Cousin.

In 1972, one of the students of J. Aubouin in structural geology and in metallogeny in the University of Paris, Jean Féraud, who is 24 and is a trainee in BRGM, discovers a great personal attraction by the geology and metallogeny of Southern Serbia and Kosovo, in particular by the renowned crystals of Trepča. He takes the opportunity of his holidays in Yugoslavia to contact the Trepča mine management in Zvečan, asking for an authorised visit of the famous ore deposit. He is warmly welcome and he benefits of a full visit underground, guided by the chief geologist of Trepča, Aleksandar Topalović. He renews this mine visit in 1973 and in 1975. Those three visits result in a report (Féraud 1975) and in a scientific paper (Féraud 1979) where the karstic features of the mineralization (already pointed out by Forgan and Schumacher in 1950) are discussed for the first time in the light of the recent discovery of stalactites of calcium carbonates, galena and sphalerite (with an empty axial feeder-pipe) in an active lead-zinc mine of Tunisia (Rouvier 1971). No axial feeder pipe being found within the stalactites of Trepca, the author concludes that the mineralised karstic cavities of Trepča were made within a totally drowned environment during ore deposition.

### *The Rozan’s episode*

Jean-Pierre Rozan was a French private trader. His activities in Kosovo had no link with the French institutions but are worth to be reminded here.

On 13 January 1996 and possibly earlier, Trepča entered negotiations with the Paris based, private company “Société de Commercialisation des Métaux et Minéraux” (SCMM). This episode is reported in details in M. Palairet (2005). SCMM was already involved in mineral trading with various African countries, Zambia in particular. Leading the negotiations at Zvecan for SCMM was its manager, Jean-Pierre Rozan, together with his son Jean-Marc Rozan, who jointly owned a firm in Belgrade called Komeksim together with Dr. Milan Dvojaković. Rozan's primary interest in Trepca is for the supply of silver and his first contracts on silver deliveries from the Trepča group are signed in early 1998. He buys on the basis of “tolling contacts” (pre-financing Trepča production, either by money or by the supply of metallurgical equipment to the smelter of Zvečan). Nonetheless, rapidly, Trepča fails to complete its obligations and its debts increase. Thus Rozan seems to have, in guarantee, received rights over one part of the stockpiles of zinc concentrates as well, even becoming (possibly) one of the shareholders of the group (but, later, the French government did not support his claims about that).

His commerce with the Serbian management of the Trepča Group is interrupted by the closure of the plants in August 2000 by UNMIK. He will die in France on December 19th, 2005.

### *The post war revival of Trepča and BRGM involvement*

At the end of 2000, BRGM is involved in an expert assessment of the entire complex of Trepča mines financed by the United Nations Mission in Kosovo (UNMIK). The aim is to contribute to the reconstruction of the industrial fabric of the country, from the mining, metallurgical and environmental standpoints. The objective of the assessment is to conduct a financial viability analysis to determine whether some or all of the components of the TREPCA Complex could be restored to an operational level that would not require an operating subsidy, and to determine the capital investment needed to restore various levels of unsubsidized operation.

This expert assessment is carried out in the context of a joint venture between TEC-Ingénierie of France, Boliden Contech of Sweden and Morrison Knudsen International of the USA. It involves some 40 engineers in the fields of geology, mining, ore processing, metallurgy and environment. BRGM participates as a partner of TEC-Ingénierie for the reserves assessment of the Novo Brdo, Ajvalija, Kišnica and Črnac ore deposits. Therefore BRGM assigns his mining geologist Jacques Monthel to the mission in Kosovo from 12 November to 20 December. His report (Monthel *et al.* 2001) is issued on January 25th, 2001.

During 2001 and 2002, BRGM builds a Geographical Information System (G.I.S.) of the ore deposits of Central Europe. The part of this work corresponding to Serbia, prepared with the cooperation of the Ministry of Mining and Energy of Serbia and with Geoinstitut, is published as a BRGM report (Monthel *et al*., 2002) and accessible free on the Website http://giseurope.brgm.fr

In September 2005, the Trepča Enterprise under KTA/UNMIK-Administration restarts production in the mine and in the zinc and lead concentrator of Trepča Stan Terg.

### *French volunteers back up the Crystal Museum*

In the meanwhile, since 1999, bad news had been spread on Internet, according to which the Crystal Museum of Stan Terg would have been plundered during the war (news which much later turned to be false, by chance). This bad fate which seemed to have collapsed over a so famous museum decided few French experts in mineralogy and museography, belonging to various organisms or independent (among which one BRGM geologist, J. Féraud) and Trepča friends in France to volunteer in order to go and bring help, at their own cost, to the Trepča mine Directorate and to the curator of Trepča museum. This team is entitled “the Supporting Committee for the Crystal Museum of Trepča” (address : B.P. 8, F-68311-Illzach cedex, France). As a first step, the aim of this team was to make an assessment of the local situation and, upon agreement of the authorities in Kosovo, to provide their advice and assistance in the hope to help the museum recover its means, its collections (if stolen) and its worldwide influence.

An exploratory journey to Kosovo was the first action decided and was done from September 11$^{th}$ to 18$^{th}$ 2005. The team comprised Joël Balazuc, Carole Frima, Pierre-Christian Guiollard, Benjamin Larderet, Skender Plakolli, Michel Schwab, Jérôme Schwab, Jocelyn Vendel and Jean Féraud. This journey got a very warm and efficient welcome from the authorities in Kosovo and from the scientists of Trepča. In agreement with the managers of Trepča under UNMIK administration, it resulted in a report (Feraud et al. 2005) emphasizing the importance, the significance and the needs of the museum. This report was widely distributed to the authorities, institutions, UNESCO and other potential donors, on Internet and in the media.

Since this time, the cooperation between this Supporting Committee and the directorate and scientists of Trepča has been "non stop". It has resulted in several exhibitions in Europe, numerous webpages issued on Internet and numerous papers published in specialized magazines, many of them written in close cooperation with the scientists from Trepča (Féraud et al., 2005, 2006, 2007; Guiollard, 2005, 2007).

In January 2006, on demand of J. Féraud, the General Manager of Trepča Group in the Kosovo Trust Agency/UNMIK, Charles Carron Brown, agreed to send to BRGM two representative samples of zinc and lead concentrates for analyses in the laboratory of Orleans. They were prepared by Michael Diehl and Shyqri Kelmendi and they arrived in Orleans in September 2006. The results (delivered from the lab in January 2007) and forwarded to Trepča, yielded attractive information on the potential of the area in "high-tech" metals such as indium, which convinced BRGM experts to offer to Trepča to pursue the scientific collaboration with more means.

## 1.3. ORGANISATION OF THE 2007-2008 COOPERATION

Early 2007, the scientists conducting the scientific research BRGM project n° PDR07REM06 entitled "valorisation of the high-tech metals of the Balkans" decided to include southern Kosovo (with the authorities of which the collaboration was thus already tightly engaged) in their annual program.

On receipt of the agreement of the General Director of Trepča under UNMIK administration, Mr Nazmi Mikullovci, dated March 15th 2007, BRGM commissioned his Drs Yves Deschamps and Jean Féraud for a field visit in Kosovo from 21 to 29 July 2007. Later on, the samples collected were analysed in the BRGM laboratory in Orleans, where this report was written.

The very warm welcome received from the team of Trepča is worth to notice.

### *Experts met in Kosovo*

(during this field visit and previously) :

- Ferat SHALA, General Manager of Trepča under UNMIK administration ;
- Nazmi MIKULLOVCI and Charles Carron BROWN, former General Managers of Trepča under Kosovo Trust Agency/UNMIK administration ;
- Miftar HYSENI, Manager of the Stan Terg mine ;
- Beqir MALIQI, Deputy-manager of the mine ;
- Shyqri KELMENDI, chief engineer in Trepča and (later on) assigned in the Ministry of Energy and Mining of Kosovo ;
- Rizah VRAJOLLI, Manager of the site of Kishnitsa/Ajvalija/Badovac and of the concentrator of Gračanica ;
- Gani MALIQI, chief geologist in Trepča and professor of geology in the University of Prishtina and in the Fakulteti i Xehetarise dhe Metalurgjise, Mitrovice ;
- Michael DIEHL, German consulting engineer, chief geologist assigned in the United Mission in Kosovo for the reorganization of exploration in the Trepča mines ;
- Vjollca MEHA, Curator of the mineralogical museum of Trepca ;
- Halil QELA, chief of the drilling department ;
- Feriz MALIQI, junior geologist ;
- Abdullah BERISHA, junior geologist ;
- Xhemajl TUPELLA, junior geologist ;
- Naser PECI, Deputy Manager of the Independant Commission for Mines and Minerals of UE/UNMIK ;
- Xhelal SMAKIQI, General Secretary of the Faculty of Mining of Mitrovica ;
- Festim KUTLLOVCI, preparing a diploma of mining geology in the Fakultet of Mitrovice.

### *Acknowledgements*

Special thanks are indebted to other contributors among which : Skender Plakolli ; the Direction de la Recherche of BRGM, as well as Patrice Christmann, Jack Testard, Thierry Augé and Laurent Bailly, who have granted one great part of this collaboration with Trepča ; all the members of the Supporting Committee for Trepča Crystal Museum, particularly its president Michel Schwab, Jocelyn Vendel and Frank Wierich and Christiane David of Marburg University and the others we forget ; eventually, Nigel Cook, Andor Lips and Ladislav Palinkaš, as reviewers.

## 1.4. WORK PERFORMED

The BRGM cooperation focused on 7 topics :

- assessment of the geodynamic setting of the Trepca ore deposit ;

- assessment of the geological controls and metallogenic model of the mineralisation;

- ore composition, trace elements, precious and rare metals of Stan Terg;

- valorisation of the tailings of Stan Terg for rare and precious metals (one test sampling);

- potential of the Artana/Novo Brdo ore deposit for rare and precious metals (one test sampling);
- valorisation of the tailings of Badovac (one test sampling);
- mineralogy, geological heritage and museography.

# 2. Geodynamic setting of the Trepča/Stan Terg ore deposit

## 2.1. STRUCTURAL FRAMEWORK

From a metallogenic viewpoint, according to the definition of Neubauer (2002), Heinrich and Neubauer (2002) and Neubauer et al. (2005) and to the figures of those three papers (reproduced here as our fig. 3), Trepča is located, within the Alpine-Balkan-Carpathian-Dinaride belt (ABCD belt), in the Oligocene-Miocene Serbomacedonian-Rhodope belt, being stated by these authors that this belt comprises two very different branches: the one (to the East) hosting porphyry Cu-Au-Mo and epithermal Au mineralisations (Rhodope belt, not concerned by this report) and the second one (to the West) hosting epi- to mesothermal Pb-Zn (Ag-Au) vein and carbonate replacement deposits like Trepča. It extends from Bosnia, through Serbia and Macedonia, to Greece and southern Bulgaria. From a geotectonic viewpoint, Trepča is located within the "Vardar Zone".

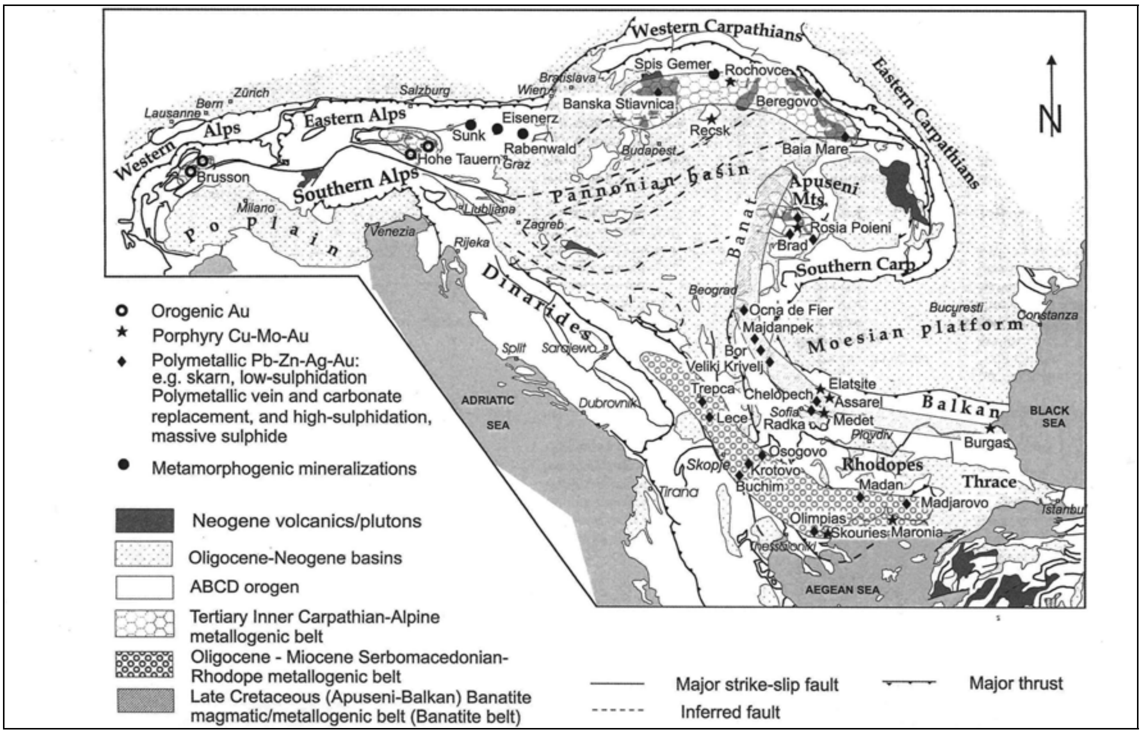


*Figure 3 - Simplified tectonic map of Neubauer et al. (2001) dispaying the distribution of major tectonic units and ore deposits in the ABCD region.*

The "Vardar zone" (Fig. 4) is the ophiolitic suture zone between the Serbo-Macedonian Massif (overlapping late Proterozoic metamorphics) to the East, and the Dinarides (constituted of folded and overthrust Mesozoic units with typical Alpine style in nappes) to the West (Karamata, 2006). Some authors include it within the Dinarides (Marroni et al. 2004). It is a composite terrain consisting of both oceanic- and continental-derived slices (Robertson & Karamata, 1994; Resimić-Šarić et al., 2000; Karamata et al., 2000; Dimitrijević, 2001). It is the relic of the main oceanic domain of the Balkans, the Vardar Ocean, which formed the NW part of the Neo-Tethys.

As mentioned by Dimitrijević (2000) and Sudar et al. (2006), its internal organization in three parallel subzones (internal, central and external) is differently conceived by the geodynamicians, according to the position they devote to an important unit of this zone, the "Kopaonik Block and Ridge area", which outcrops in Kopaonik Mt, north of Trepča and includes several Pb-Zn-(Ag) ore deposits like Belo Brdo (Veselinović-Williams et al., 2007). Nonetheless, this block narrows in the South in the direction of Mitrovica and, in the Trepča area, its deposits are covered by younger sediments and pyroclastites, which has led to locate the Trepča mine without ambiguity as in the External Vardar Subzone (EVSZ).

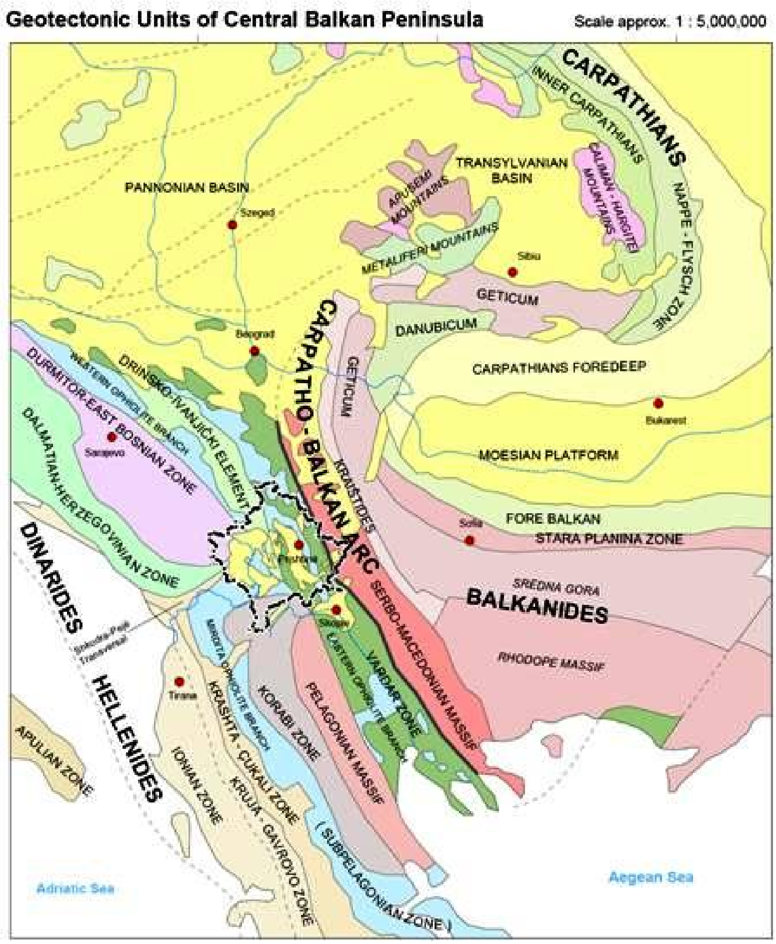


*Figure 4 - Geotectonic setting of Kosovo (Dimitrijević 2001)*

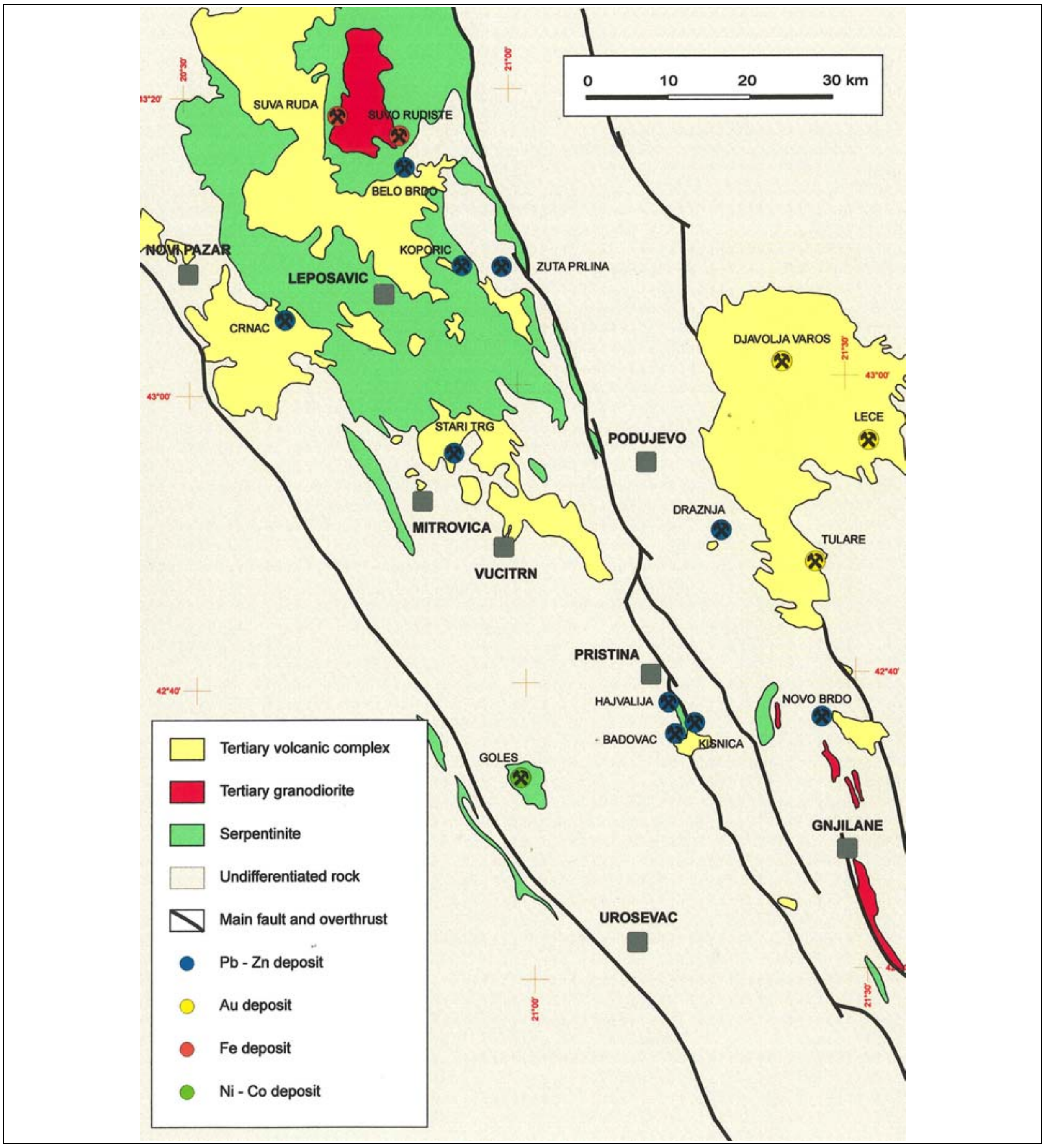


*Figure 5 – Location map of the Trepca ore belt (Monthel et al., 2001).*

## 2.2. STRATIGRAPHIC EMPLACEMENT OF THE ORE DEPOSIT, METAMORPHISM

The EVSZ consists of a Palaeozoic basement made of sericite schists and marmorised limestones (equivalent to the Veles Series of the Eastern Kopaonik), a Jurassic carbonate platform (the Stari Trg Series, beginning, inside the mine, with pebble-bearing conglomerates and sandstones transformed into quartzites), and overthrust Cretaceous, more or less serpentinised ultrabasic rocks, gabbros, diabase and sediments of the ophiolite association.

In detail, this picture is much more complex. Until 1972, geologists assumed that the Stari Trg metamorphic Series were Silurian-Ordovician, but in that year, Yugoslavian geologists found fossils (conodonts) in the sequence suggesting that some of the limestones are of Late Triassic age, partly Carnian (Kandić 1970; Klisić et al. 1972, interpreted by Štrucl 1981). Bogdanović (1978) thus proposed a new stratigraphic succession of the Trepča series. Nonetheless, twenty five years later, the identification of olistostromes and “melange” formations was to change completely the figure. It is now stated (Dimitrijević et al. 2003, Sudar and Kovács 2006) that the long evolution of the EVSZ oceanic realm from the Late Triassic to the Latest Cretaceous, with long and complex closing, was accompanied by the genesis of island arcs, obduction of ultramafic bodies and development of very large olistostromes. These olistostromes are both masses of sandstones, basalts and cherty formations Upper Triassic and younger in age, and olistoliths of limestones Middle-to-Late Triassic, Late Jurassic and Late Cretaceous in age.

A chlorite facies metamorphism episode dated as Early Tertiary has transformed all these terranes in marmorised limestones and in sericite schists. A foliation affects the whole litho-stratigraphic pile. At least two folding phases are visible within the schists, which are considered by Grubić and Protić (2000) as equivalent of the so-called “schistes lustrés” of the Western Alps and Corsica.

The “Metamorphic Trepča Series” defined by Klisić et al. (1972) thus covers an area of 30 $km^2$ between Smrekovnica (near Mitrovica) and Trepča. Its lower part comprises argillaceous schists, calcschists, actinolite-chlorite-epidote-sericite schists, metasandstones, cherts, gneisses, feldspathic micaschists, amphibolite and amphibole schists, and the middle part of the series, the Smrekovnica limestones partly Lower and Middle Norian in age (Sudar and Kovács 2006).

## 2.3. MAGMATISM AND ITS REGIONAL METALLOGENIC ROLE

The whole Series is interlayered with basaltic sills and spilitic lava flows (Maliqi, 2001).

Post-tectonic magmas, comprising granodiorite (particularly in Kopaonik Mt) and dacite-andesite, intruded this assemblage during the Oligocene-Miocene. They are largely calc-alkaline, acidic and in part highly potassic. They are interpreted as of collisional type, formed, in part, by melting of continental crust. The northwestward oriented, active margin processes and subduction beneath the Hellenic trench related to the closure of the Vardar Ocean has recently been proposed as a trigger for this magmatism, the hypothesis of slab break-off being more speculative (Lips, 2002; Neubauer, 2002; Heinrich and Neubauer, 2002; Neubauer et al., 2005).

The available datations by K/Ar method give a range of congruent ages from 50 to 25 Ma (Pamić, 1993; Pamić 2000; Cvetković et al. 2000; Pamić et al. 2000, 2002; Memović 2004; Kovács et al. 2006). In the Trepča area, two samples of latites were dated by the K/Ar method at respectively 26 and 27 Ma (Janković 1978) whereas the dacite pipe in the mine has just been dated at 16.6 +/- 0.5 Ma by the same method (Maliqi et al. 2006).

The numerous Pb-Zn deposits known in the Vardar Zone are attributed to this magmatism. They have a diverse range of styles from simple vein systems (Zletovo in Macedonia, Črnac in Kosovo) to skarns and hydrothermal, metasomatic (Sasa and Toranica in Macedonia, Novo Brdo, Ajvalija and Trepča in Kosovo), and even porphyry style and stockwork in Kišnica (in Kosovo ; pronounce “kishnitsa”). At the end of the collisional processes, in two places of the Vardar Zone, a basaltic ultrapotassic magmatism occurred: it is dated at 30 Ma in Rudnik (in Serbia, 100 km north of Trepča, near the Rudnik Pb-Zn mine which is very similar to Trepča mine) and at 6.9 and 3.9 Ma respectively in Kosovo south of Priština (Cvetković et al. 2004). It is attributed to a collapse or relaxation phase. The authors stress that it was very rarely able to reach the surface but acted as a heat source for various crustal melts. In Rudnik, both types of magmatisms are present (Tosović 2000). In the Trepča area, only the calc-alkaline one is known (Maliqi, 2001).

On the summit of the mountains all around Trepča (Fig. 6), a very important period of extrusive felsic Oligocene-Miocene volcanism is represented by a large, nearly flat sheet of pyroclastic rocks, especially ignimbrite and volcano-sedimentary deposits.

The Trepča/Stari Trg ore deposit outcrops at the bottom and on the flank of a narrow valley which crosscuts the whole of that litho-stratigraphic and volcanic pile (Fig. 6).

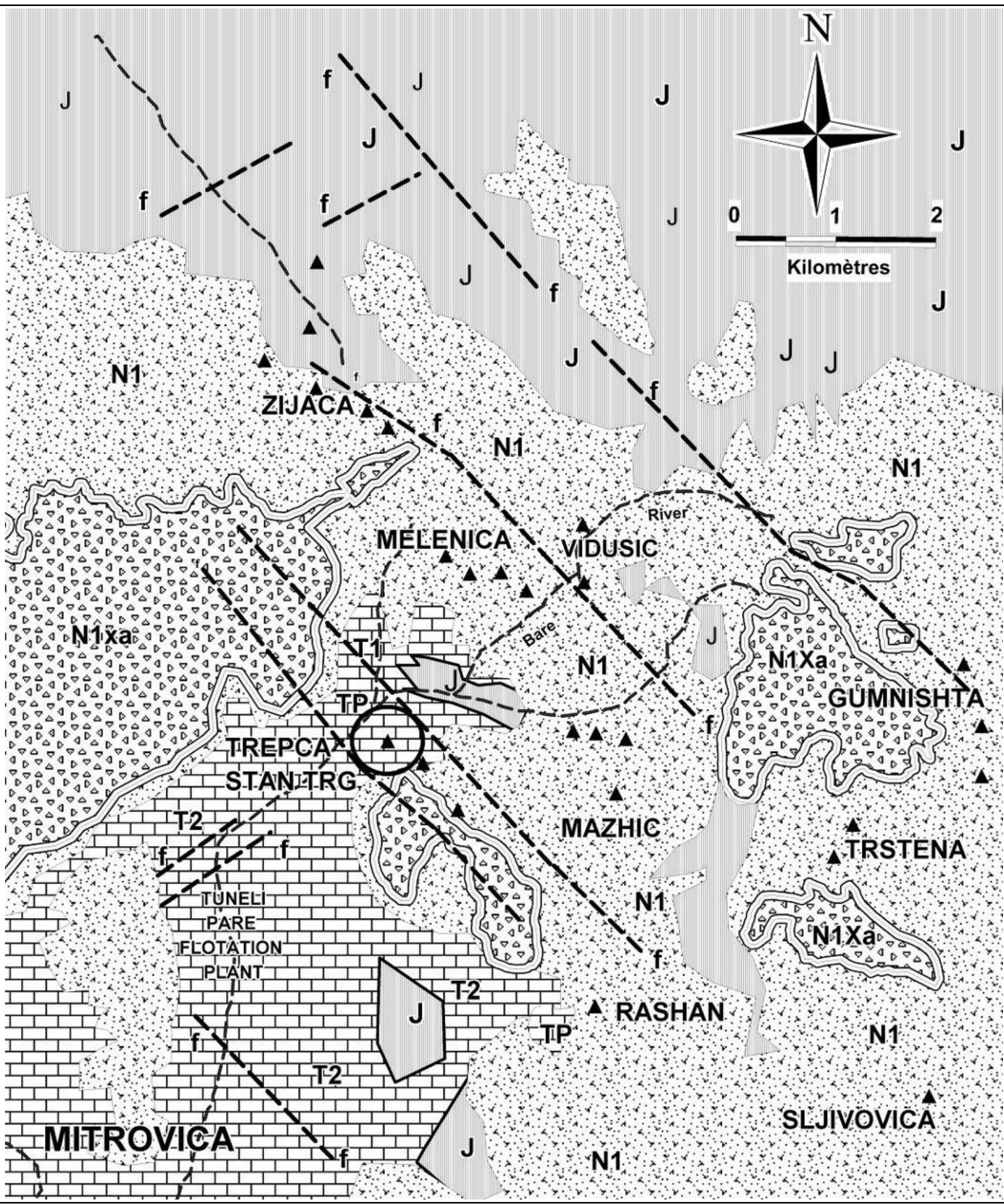


*Figure 6 - Geological map of the Trepca zone (simplified from various authors)*

**Legend:** N1Xa= quartzlatite, volcanic breccia and pyroclastites of the Miocene. N1= andesites-dacite and pyroclastites, ignimbrites of the Miocene. J=Jurassic diabase and associated series. T2=Triassic metamorphic series (limestones with Conodonts, diabase, metagabbro, quartzose conglomerate. T1=Triassic limestones and dolomites, metamorphosed. TP=Triassic and/or Paleozoic limestones (undifferentiated) of the Trepča Series, metamorphosed. ff=faults. Black triangles: Pb-Zn prospects. Dashed lines: rivers. Original scale of mapping: 1/50 000.

# 3. Geological controls on mineralisation and metallogenic model

From the beginning of mining in Trepča, the constant geological follow-up of the mine development has led to a perfect knowledge of the geometry and controls of the various orebodies (Brammal *et al.* 1930; Titcomb et al. 1936; Forgan 1948; Schumacher 1950, 1954; Smejkal 1960, 1962; Janković 1978, 1984; Janković and Petković 1982; Topalović, 1966, 1971, 1980; Bogdanović 1978; Kurtanović 1985; Maliqi 2001; Nelles and Diehl 2007).

## 3.1. GEOMETRY OF THE ORE DEPOSIT, MINERAL ASSEMBLAGE, HYDROTHERMAL ALTERATIONS

The Trepča mine ore deposit consists (Forgan, 1948 ; Schumacher, 1950) of a series of 11 manto orebodies and mineralized skarns within the sedimentary carbonate pile known as the Stari Trg Series, at the contact with an Oligo-Miocene volcanic conduit (fig. 7 to fig. 10). As a whole, it is hose-shaped.

The 11 orebodies are intercalated between thick marmorised limestones at the footwall (Mazhiq limestones, at least 300 m thick) and thick sericite schists at the hanging wall. In some places along the stratigraphic contact, there is an intercalated layer of quartzite and quartz-micaschists, from 5 up to 100 m thick, that Štrucl (1981) interpreted as metamorphised sandstones corresponding to the base of the Jurassic transgression over the Palaeozoic schists. The contact between limestones and schists is folded in an asymmetric anticline, the northwest-southeast axis of which plunges 40° towards the northwest. The southern limb of the anticline dips 65° SW whereas the northern dips 35° N (Fig. 8).

Along the crest of the anticline, at the contact between the schists and the limestones, the volcanic conduit was emplaced, having a pitch 40° NW. It has an irregular, roughly oval cross-section measuring about 100 x 200 m (Fig. 8, 9 and 10). It has a sharp, clean, slickened contact with the limestones whereas the upper surface of the pipe merges into brecciated and broken schists. It consists of a core of altered dacite measuring 60 to 80 x 120 m in oval cross-section, surrounded by an "explosion breccia". The section of the lava core diminishes gradually from the top of the mine, partly removed by brecciation; its root seems to disappear below the 610 m level (or it may be so narrow that it has not been intersected by galleries or drilling). It is this conduit which controlled the distribution of most of the mineralization, which consists in a lenticular "manto" of ore, between 30 and 60 m thick, intercalated in the schist/limestone contact along the sides of the volcanic pipe (Fig. 3 and 4). Within the contact, the manto expands as a network of at least eleven coalescing mineralised columns, each one stretching parallelly to the volcanic conduit along the plunge of the anticline axis (Fig. 6). A few oreshoots are discordant over this contact but located at a short distance in its footwall (from a few meters to a few tens of meters).

Four directions of fractures are inventoried at Trepča and around, the two principal ones being N40 to 60°E and N100 to 130°E. The former is parallel to the plunging hinge of the mineralised antiform, to the axis of the volcanic pipe, to secondary fold hinges (over-ride crenulations already noticed by Forgan, 1948) plunging NW which affect both limbs of the antiform, and to the axis of the mineralised columns. The latter corresponds to a network of transversal fractures which played an important role within the limestones to locate karstic ore fillings.

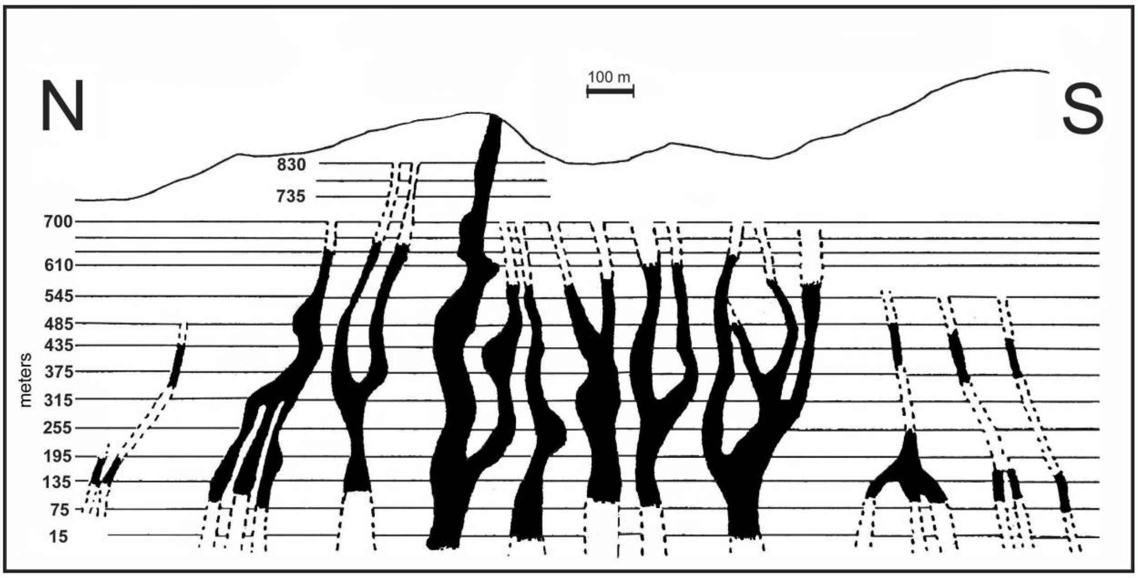


*Figure 7 - Map of the unfolded contact between schists and limestones in Trepca, showing the elevations of each mining level and the 11 columnar-shaped orebodies (in black) coalescing downdip (modified from Kurtanović 1985)*

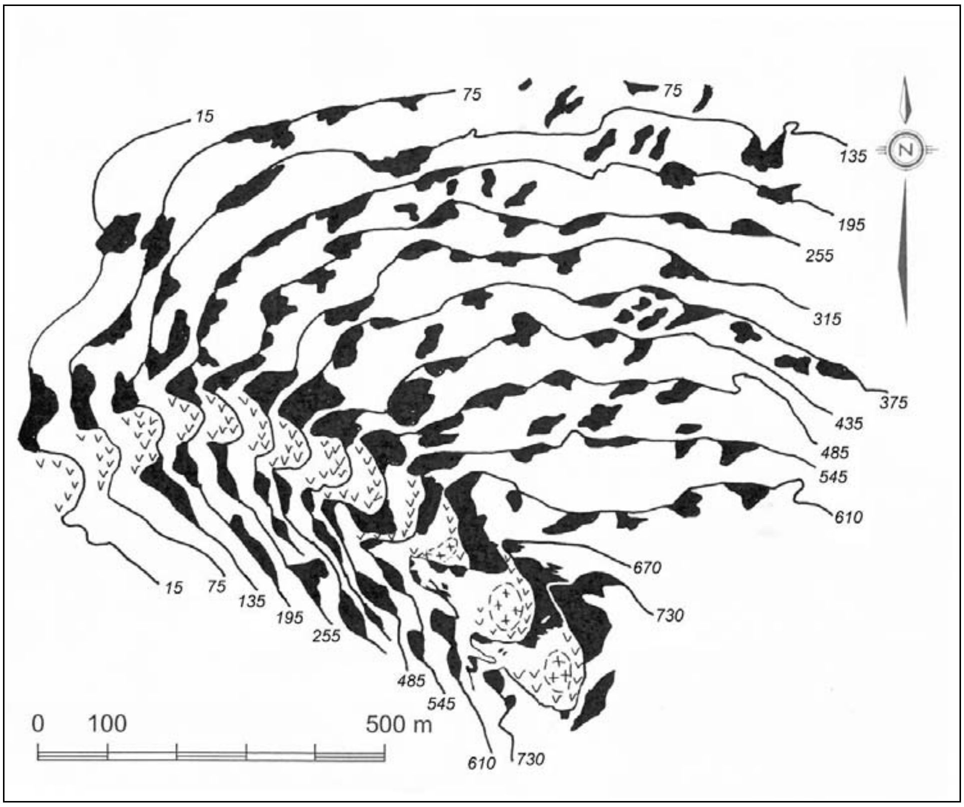


*Figure 8 - Vertical projection of the 11 Trepca ore bodies (in black) on an horizontal plane, updated successively by Forgan (1948) and Schumacher (1950), Topalovic (1971), Kepuska (1998) and Maliqi and schematized.Ore bodies currently mined in the +75 level are added but not to scale. At each mining level, the contact of the schists (outside) over the limestones (inside) is indicated by a continuous line, with its elevation (in* m*). The projection shows the NW pitch of the volcanic conduit (dacite +++ ) surrounded by the breccia (vvv) along the axis of the mineralized anticlinal hinge.*

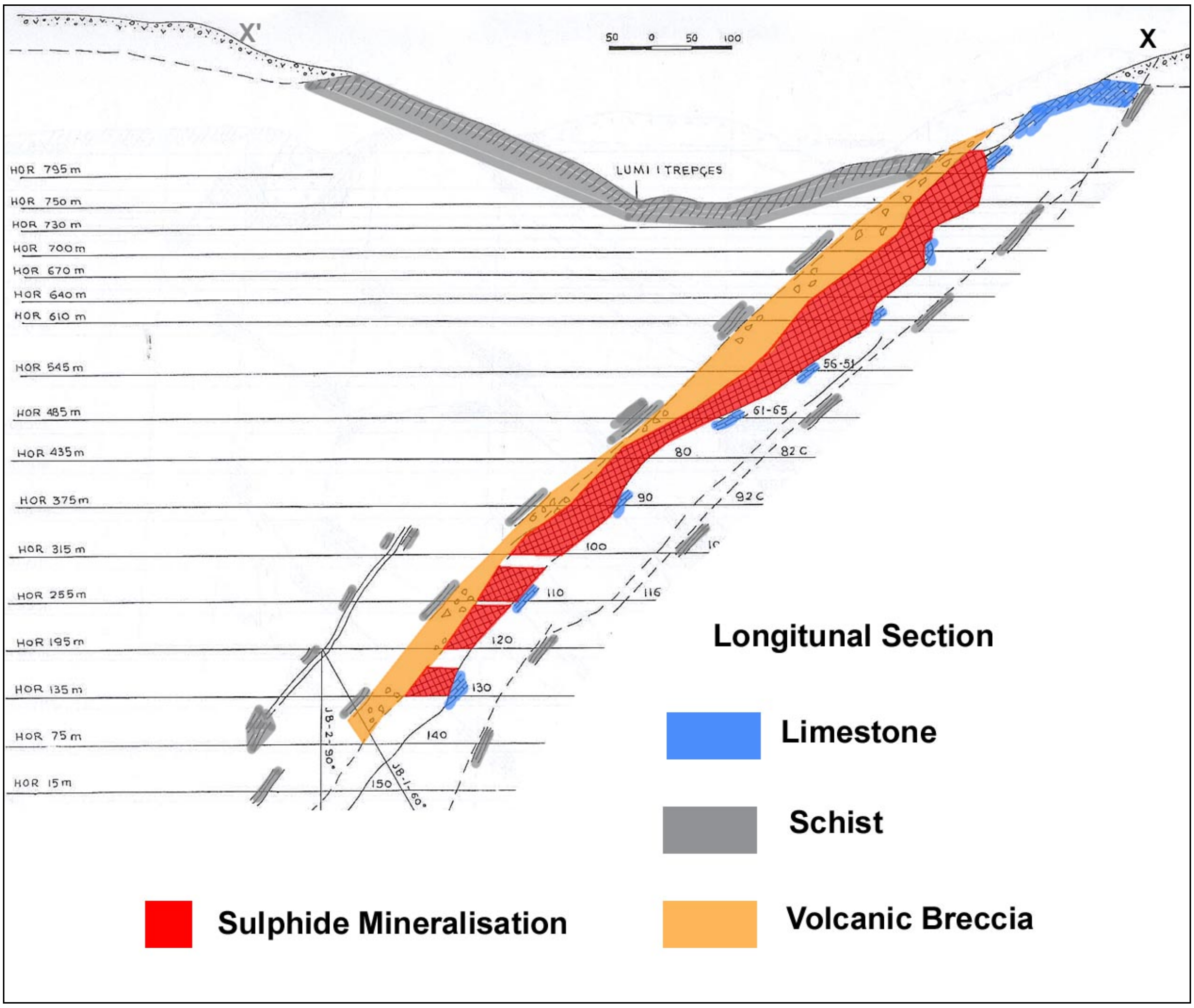


*Figure 9 - Transverse cross-section along the Trepca antiform hinge axis, showing the mineralized skarn at the contact between the volcanic breccia and the limestones (initiated by Titcomb and Forgan 1936 and completed by the geologists of the mine till Maliqi 2001*

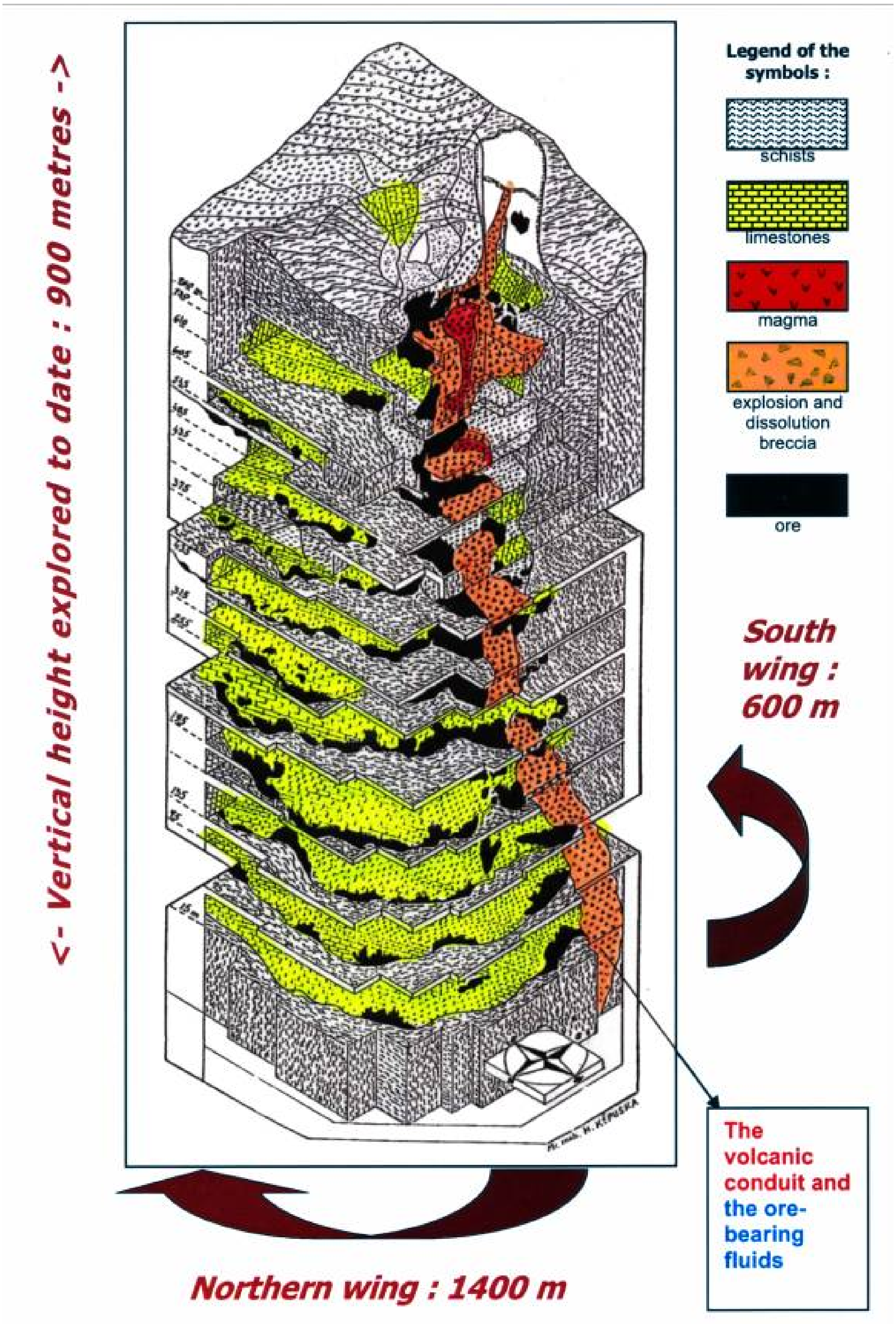


*Figure 10 - Geological bock diagram of the Trepca ore deposit, from H. Këpuska (1998, modified). The projection used increases the apparent pitch of the volcanic conduit and the axis of the mineralised anticlinal hinge*

The mineralisation both consists of skarn and hydrothermal parageneses (photos 1 to 4). The hydrothermal paragenesis mostly includes pyrrhotite, pyrite, arsenopyrite, argentiferous galena, sphalerite, boulangerite, with minor amounts of bournonite, chalcopyrite, tetrahedrite, stibnite, stannite, enargite, in a gangue of carbonates (calcite, rhodochrosite, dolomite, ankerite, siderite) and minor quartz. In the larger orebodies close to the volcanic conduit and at its footwall occurs a skarn paragenesis which replaces the limestones of the footwall over up to 70 m. It comprises the minerals listed above, together with ilvaite, hedenbergite, actinolite, garnet and magnetite.

Within the host rocks, the hydrothermal alterations are important (Forgan, 1948; Schumacher 1950). The dacite core is considerably kaolinised. Its ferromagnesians are altered into chlorite, sericite, limonite and silica. The dacite is slightly pyritised and carbonatised suggesting propylitisation. The matrix of the breccia is argillised, carbonatized and pyritised. The limestones are silicified. The dark schists are altered into much clearer sericite schists and in some places silicified into quarzites.

## 3.2. GEOMETRY OF THE OTHER PB-ZN PROSPECTS AROUND TREPČA

The Trepča mine ore deposit is surrounded (Fig. 2) by a few Pb-Zn prospects exposed nearby, hosted within various geological settings as noted by Titcomb et al. (1936), Forgan (1948), Schumacher (1950), Topalović (1966a, 1971) and Maliqi (2001).

The Melenica ore deposit consists of Pb-Zn ore shoots at the contact between limestones of the Trepča Series and Oligo-Miocene sediments (Tmava and Koliqi, 2003). A volcanic breccia pipe similar to the one of Trepča was crosscut by the mine workings but it is not mineralised.

The Mazhiq (Mažic) ore deposit consists of six well delineated ore lenses located along the contact between limestones and volcanic tuffs (probably pyroclastic flows) and separated by irregular and more disseminated ore zones. A careful ore sampling totalising 300 analyses has yielded for the six mineable orebodies an average of 8 % Pb, 5 % Zn and 225 g/t Ag (Schumacher, 1950).

The Zijača ore deposit hosts two styles of mineralization. The first one consists of Pb-Zn sulphides associated with a siliceous-carbonate mass (stockwork type) occurring within Jurassic serpentinites and gabbro-amphibolites capped by about 100 m of Oligo-Miocene volcanics and siliciclastics. The second one is vein-like, occurring in the same stratigraphic position.

The Vidušic ore deposit, in the Bare river, is linked with a big quartz vein (Schumacher, 1950).

Promising mineralisations found in Djidoma-Mažic, Rashan-Trstena (Simić 2000; Lydian Res. Co. 2007) and Gumnishta-Gropava, together with numerous past mine workings and slags, seem to reflect the same geological diversity (their exploration is still under progress by the Geological Survey of Stan Terg).

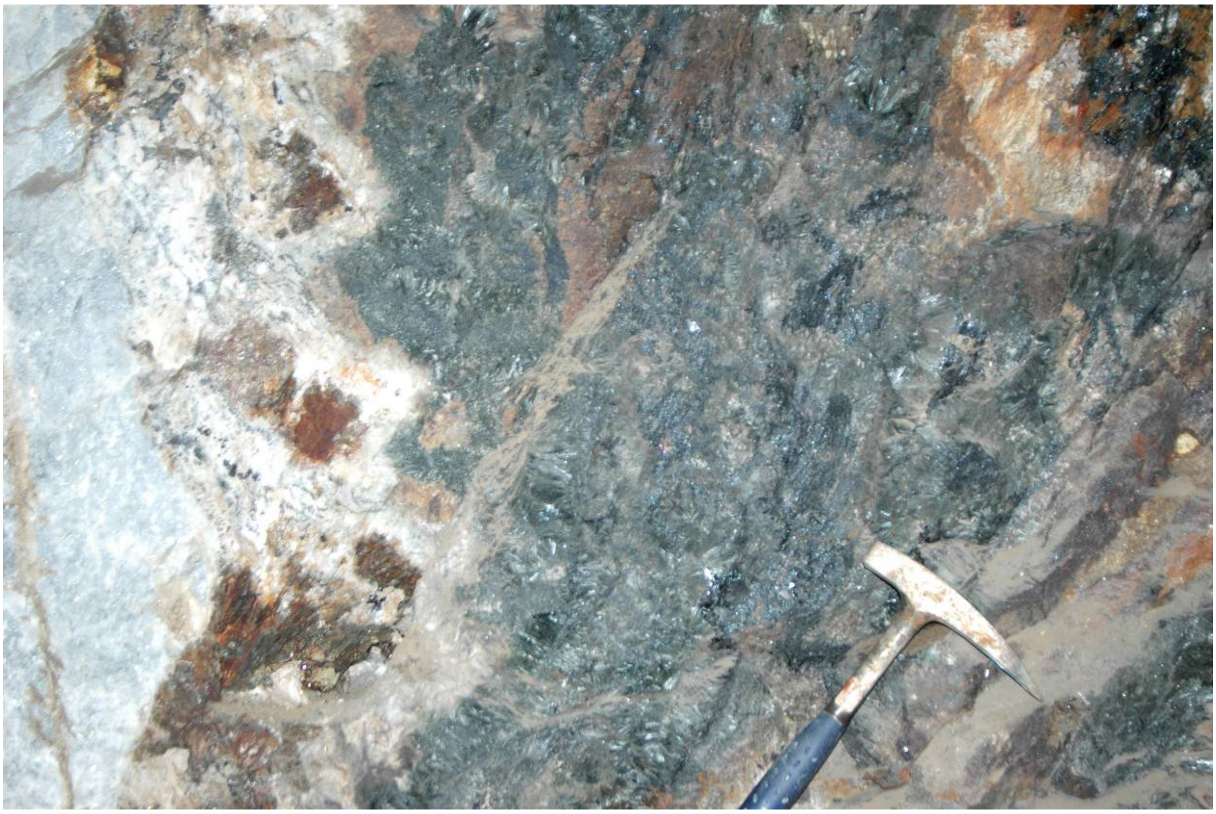

*Photo 1- Skarn mineralisation with ilvaïte and hedenbergite (Level +75)*

*Photo 2- Mineralisation in the skarn zone (Level +75)*

*Photo 3 - Karstic pipe dug within the marbles and filled with banded calcite and dolomite (oligonite) followed by sphalerite, galena and pyrite (Level +75)*

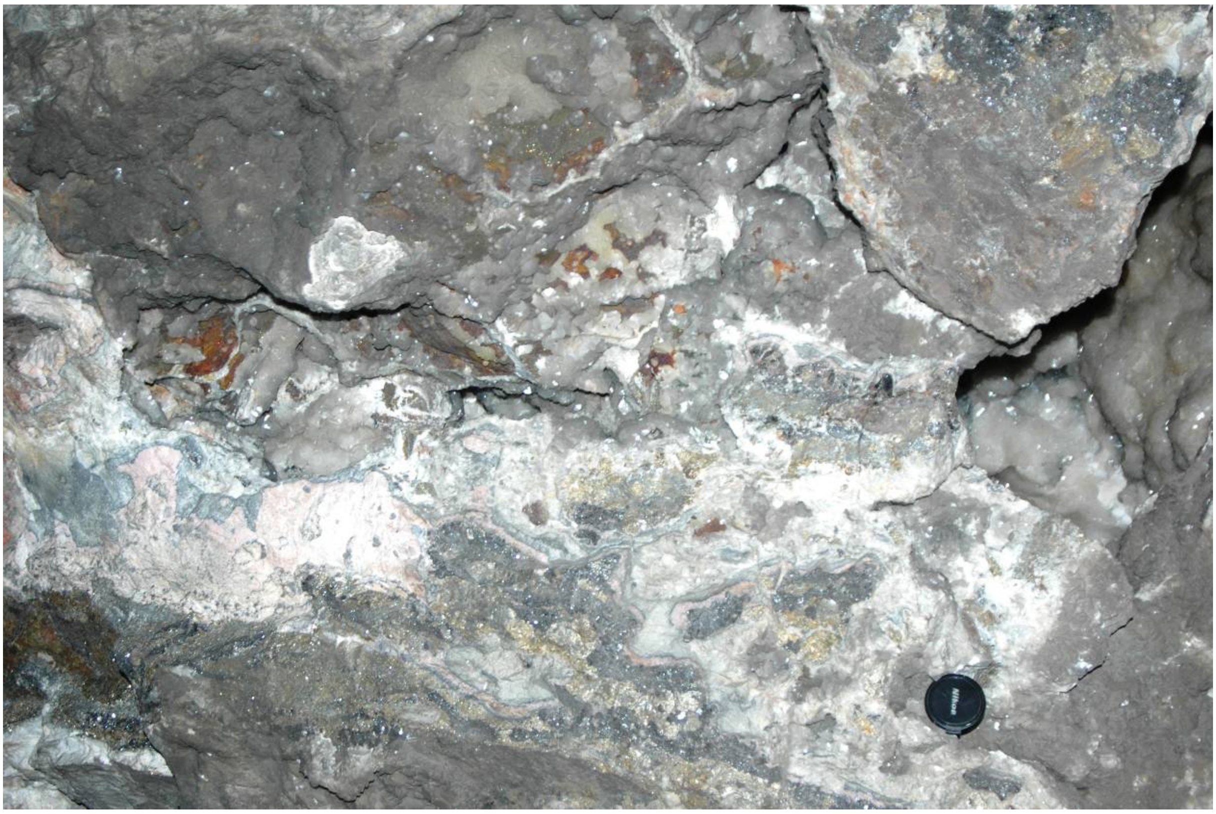

*Photo 4- Mineralisation in karstic environment with rhodochrosite and other carbonates (Level +75)*

## 3.3. AGE AND METALLOGENIC CLASSIFICATION OF TREPČA

Trepca is classified as a carbonate replacement deposit (CRD) according to the definition of Titley (1996). Since Titcomb et al. (1936), it has been defined as of Oligo-Miocene age, related to calc-alkaline magmatism, as reminded by Rajavuori and Heiljlen (2001). It was generated by a geothermal system where a prominent role in locating the major ore deposit was played by the structural trap represented by an anticline and a volcanic pipe. The contact of waterproof schists over limestones made a hydrogeological trap and focused a manto-type deposit (made of 11 ore bodies at least) rich in Ca-Mg-Mn-carbonates, whereas the volcanic pipe focused a more skarn-type mineralisation.

The presence, in the neighbourhood of Trepča, of several other Pb-Zn mineralisations scattered at different levels of the lithostratigraphic pile and belonging to various types (stockwork, vein, replacement, dissemination…) as was stressed by Tmava et al. (2003) for Melenica, suggests that these mineralisations resulted from an ore-bearing plume linked to volcanism. Titcomb et al. (1936) report cinnabar in veinlets crosscutting the pyroclastites. The whole Trepča district thus appears as a huge plumbing system, mineralised at various stratigraphic levels corresponding to various structural traps, and intersected at various depths by erosion. Trepča mine is a CRD type ore deposit, but in its neighbourhood are both to be found other CRDs, epithermal Au-Hg deposits, porphyry deposits etc.

In Trepča, the abundance of manganocalcite (the “oligonite ore”), together with rhodochrosite, silver and gold in a context of fractures and brecciated volcanic rocks, reminds the signature of low-sulfidation epithermal deposits as well.

### 3.3.1. Role of magmatism and volcanism

As stressed by Serafimofski (2000) and Naftali (2003), many Miocene ore deposits of the ABCD belt are related to volcanic activity and are structurally controlled by shallow volcanic edifices. For Trepča, the role of volcanic centres was underlined by all the previous authors among which Forgan (1948) and Schumacher (1950), Smejkal (1962), Topalović (1972), Maliqi (1999a-b, 2001).

#### *Indications from Pb isotopes*

Using the ratios $Pb^{204}$ versus $Pb^{208}/Pb^{204}$ and $Pb^{206}/Pb^{204}$ from 11 galena samples collected at the 610, 375 and 135 m levels, Janković (1978) concluded that, concerning the relative ages of ore emplacement in the Vardar Zone, Trepča is ranked in a rather medium position among the other deposits. The Črnac, Koporić and Rudnik deposits seem slightly older, Zijača might be younger. In Trepča, Janković presumed the source of ore lead is nonhomogenous, on account of the significant variations in $Pb^{204}$ values and of the variations of ratios in $Pb^{208}/Pb^{204}$ that are greater than variations of $Pb^{206}/Pb^{204}$. Eventually, these results suggested to Janković (1978, 1982, 1984) and Topalović (1980) that domes ascending from anatexis zones within the lower crust and the upper mantle exerted strong thermal and structural influence (they employed the word *ring structures*, a rather misused term for possible hidden granitic cupola). However, Janković stressed that ore deposition occurred at the subvolcanic level and at shallow depth below the ignimbritic horizons. This hypothesis of crustal melting is congruent with the recent results of Avanitidis et al. 2006 on Greek mineral deposits, and with the ones about sulphur isotopes of Serafimovski et al. (2006). On the basis of analyses of 5 magmatic rocks from Trepča, which are supposed to be genetically related to Pb-Zn deposits (latites, granodiorites and a quartzlatite), Janković (1978) concluded that the rock lead has characteristics similar to those of the ore lead. Therefore he considered the sources to be the same, as well as the time of their origin close to the one of magmatic complexes of granodioritic magma and Pb-Zn deposits.

### *Calderas and ignimbrites*

During the last three years, the Trepča mine geologists M. Diehl and G. Maliqi recognized several ring structures corresponding to Upper Oligocene to Miocene calderas (Anonymous, 2005; Nelles and Diehl, 2007; M. Diehl and G. Maliqi, oral comm. 2007). In many places, these ring structures are spatially linked with mineralised showings, ancient dumps and slags. The hilltops of Trepča area are capped by horizontal remnants of pyroclastic tuffs and flows obviously resulting from caldera huge eruptions. No author identified any precise geometric connection yet between these pyroclastites and the volcanic conduit of the mine. Nonetheless, within the frame of plinian eruptions, genetic relations between them are highly probable.

## 3.3.2. New observations: identification of hydraulic explosion breccias

In this paragraph are developed observations which we did in September 2005 and which we submitted for publication in 2006 in cooperation with the Trepča geologists G. Maliqi and V. Meha who had guided our visit of the mine. This paper (Féraud et al. 2007) was edited in July 2007. Later on, we discovered that the same observations had been done by M. Diehl and published by him with other authors working on Trepca simultaneously : Anonymous (2005), Nelles and Diehl, 2007; Strmić Palinkaš et al., 2007).

In the ancient open pit, all the fragments of the volcanic breccia (mostly schists and very few fragments of limestone or dacite) are mixed, tightened together nearly without matrix in-between. The size of the blocks varies from a few centimetres to one metre. The matrix is an argillaceous, grey brown rock flour. Within the mine, the breccia was the focus of great attention as early as Forgan (1948), and Schumacher (1950). From their observations, it results that, in the upper half portion of the conduit, the breccia is mainly composed of blocks and subangular fragments of the hosting rocks: dark phillites (85-90 % of the mass), quartz-sericite schists (5-7 %), quartzite and white pyritised quartz (5 %), limestone and some calcite (1 %), together with, in the upper mine levels, rounded fragments of the central dacite (2 % only). In the lower zone, limestone diminishes and dacite fragments are absent. The larger fragments are set in a clayey matrix or paste modified by hydrothermal alteration and slightly impregnated with pyrite, silica and carbonates.

Schumacher (1950) already identified this breccia as of phreatomagmatic origin, but the specificities above described are fairly uncommon in breccias resulting from simple conduit brushing explosions (“vulcanian” steam blast eruptions). They remained unexplained until we made the following discoveries in 2005, particularly in the 10$^{th}$ mining level (+75 m above the sea level) along the crosscut which links the main shaft to the stopes currently mined.

### *Hydraulic breccia*

First, in the *in situ* marmorised limestone hosting the volcanic breccia pipe, hydraulic brecciation is common (Photo 5) :

- blocks of limestone 20 to 50 cm on edge on average are fractured but their fragments, just disjointed, remain at a distance of a few cm one from the other (jig-saw-fit or puzzle structure) ;
- among these blocks, rotational breccia structures are frequent ;
- the cement between these stockworked blocks is rare ; it is made in some places of calcite, elsewhere of goethite-limonite, but mostly of a very fine grained, tuffaceous, brown matrix where smashed fragments of black schists a few centimetres on edge can still be identified ;

- vugs are totally absent, contrarily to the mineralised zone crosscut nearby. No block of ore reworked within the breccia has yet been found.

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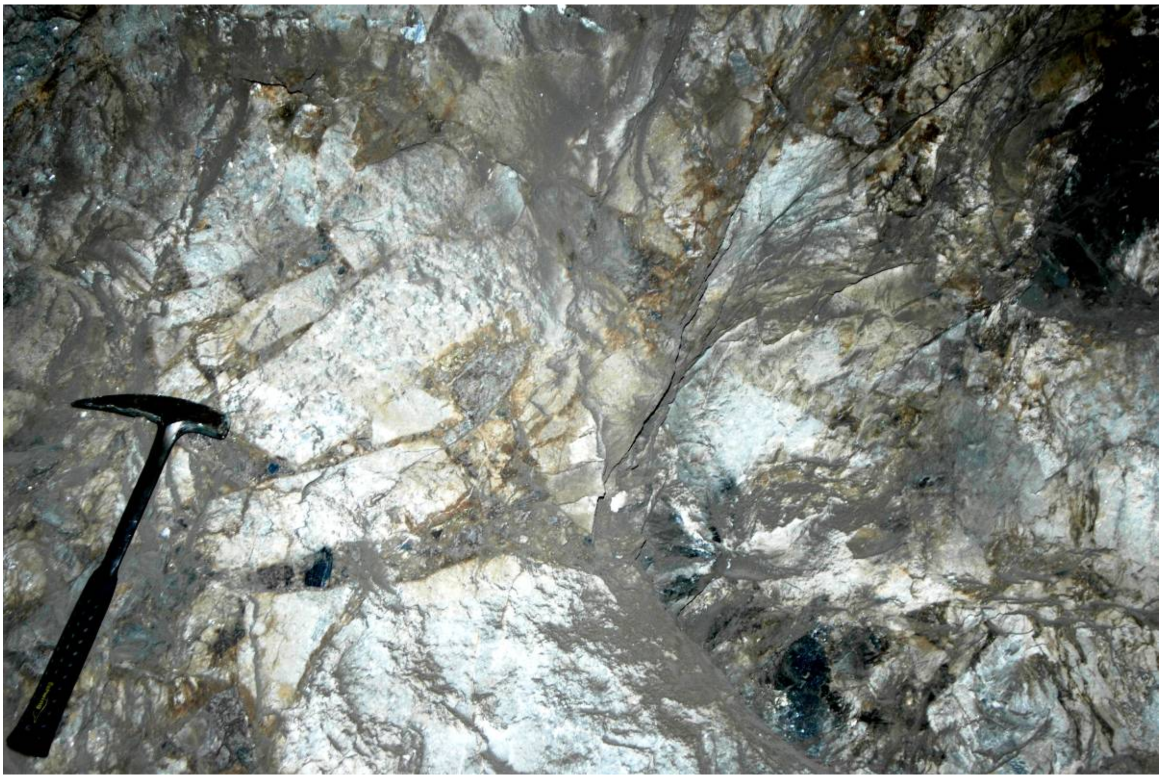

*Photo 5 - Hydraulic breccia in marmorised limestones hosting the mineralisation, close to the volcanic breccia. To the right of the handle of the hammer, smashed schists fragments (in black), clay, phyllites and minute fragments of dacite constitute the matrix*

### *Phreatomagmatic hydrothermal breccia*

All the features of hydrothermal phreatomagmatic fluidised breccias are encountered as well. Within the volcanic breccia pipe, the matrix varies from 50 up to 90 % from one place to the other. It is a comminuted, brown rock flour in which an attentive observation by the naked eye succeeds to recognize minute clasts of black schists and white limestones in an argillaceous, soft cement. Fluidisation structures are common. The blocks of black schists are abundant and their size varies considerably, from a few centimetres up to three metres on edge (Photo 6). Some big blocks of limestone are angular, others are rounded. A few blocs of schists look partly outburst, exfoliated. In some places, late veinlets of pyrite, galena and sphalerite crosscut both the blocks of limestones and the matrix, without being displaced by the brecciation, which suggests mineralization postdates the breccia. Schumacher (1950) mentioned disseminations of galena and sphalerite as well. He mentioned also (in his plate XI) a few isolated breccia pipes (entirely made of brecciated schists) hosted within the schists of the hanging wall. He interpreted them as apophyses of the main breccia pipe. It is possible to compare them to the satellite, vein-like branching structures described by Tamaş and Milesi (2003).

*Photo 6 - Phreatomagmatic breccia. Level +75. Fragments of limestones and black or brown schists, cemented by clay, phillites and smashed schists.*

## *Maar structure*

These observations led us to publish with the geologists of Trepča who had guided our visit of the mine (Féraud et al. 2007) the conclusion that the breccia mantle around the dacite pipe is a hydrothermal breccia of phreatomagmatic origin, and that the marmorised limestones hosting it have been brecciated hydraulically, within a diatreme structure, according to the model described by Tamaş and Milesi (2002).

Hydraulic breccias linked with diatremes were identified for the first time in the Vardar Zone by Tosović (2000) in the Rudnik Pb-Zn ore deposit.

Such hydrothermal brecciation fits well with the "maar"-type explosions at the bottom of dacitic eruptive pipes when they encounter the water table. In that hypothesis, the central core of dacite which is visible in the centre of the breccia in the upper levels of the mine may be the remnant of the last release (discharge) of viscose magma before the lava eruption stopped. Pyroclastites emission is the first phenomenon, with which caldera collapse (the second phenomenon) is linked. The third phenomenon is phreato-magmatic explosions, shortly preceding the extrusion of dacite domes on the caldera floor or outside, as described in many places like in Turkey (Féraud, 1994).

These observations totally confirm those of the Trepca/UNMIK geologist M. Diehl published by him with other authors working on Trepca simultaneously : Anonymous (2005), Nelles and Diehl, 2007; Strmić Palinkaš et al., 2007).

### 3.3.3. Role and place of karstification

On account of the location of the ore at the contact of schists presumed Palaeozoic in age and limestones dated Triassic, the metallogenetic classification of Trepča as a "CRD" is funded but not complete. In the hypothesis of Štrucl (1981), this contact is underlined by a layer of quartzites (former sandstones) corresponding to the transgression of the Mesozoic sea over the discordance capping the Palaeozoic basement. Therefore the Trepča deposit should also be classified in the karst ore deposits trapped under an unconformity.

#### *Age of the karstification*

The age of this karst is debatable. The metamorphism makes any verification difficult. Till now, no trace of reworked stalagmitic floors, breccias, roof-collapse structures were found in the mineralised cavities.

Therefore, this huge plumbing system should not be considered as a "palaeokarst", i.e. found empty by the mineralised brines when they invaded the favourable structural and hydrogeological trap, but as a karst dug by dissolution caused by the hydrothermal fluids during or just before the mineralizing process following the schists/limestone contact.

Naturally, other periods of karstification without ore transportation probably occurred at various periods in Trepča, and karstification is still in progress. Forgan (1948) quoted the numerous difficulties encountered during mining because of intersection of active karstic conduits. Presently, many karstic cavities are found empty (because of pumping or natural drainage) and coated with white calcite, but others are crosscut full of water, even of hot waters, as those at 47° C quoted by Forgan (1948) in the upper levels of the mines.

#### *Interpretation of the travertine*

The travertine which outcrops between the Saxon church ruins and the breccia forming the northern flank of the volcanic pipe is questioning.

It was mapped by Titcomb (1936) and by Forgan and Schumacher (1950). It partly covers the outcrops of the volcanic conduit and its mineralised contacts, at an altitude from 775 to 830 m. Travertines usually spot a point where an active karst communicated (or communicates) with the open air or where springs (hot or cold) come out. We assume that this one is much later in age than mineralisation, and even contemporaneous with the late Quaternary erosion phase which created the present valley. It is located at a much lower level than the tabular pyroclastites which cover the iron cap of the Trepča ore deposit at an altitude from 890 to 920 m, at the top of the hill were no travertine is known (Titcomb et al. 1936). Therefore we presently interpret this travertine as the result of a recent, barren karstic vent, distinct from the mineralising event.

#### *Stalactites or pseudo-stalactites*

The karstic shape of a great number of the orebodies was pointed out by Forgan (1948), Schumacher (1950, 1952), in particular the abundance of stalactites and stalagmites of Ca-Mg carbonates mineralized in various sulfides. Therefore, during the present study, much attention was paid to examine the inner structure of the stalactites (both inside the mine and in various museums) and to search for sedimentary features (breccia, graded of criss-cross bedding) which are typical of intra-karstic fillings.

As was already stressed (Féraud, 1979), none of the common Trepča specimens showing stalactites of carbonates overgrown by sulfide crystals have so far shown axial pipes (feeding canals) in the stalactites to give evidence of water dripping from ceilings of caves, as they were described in other karstic ore deposits in the world such as (Rouvier 1971, Mansouri 1985) in the Jebel Hallouf zinc-lead deposit (Tunisia), which is of roughly similar age than Trepča (and was visited by one of the authors). This implies that, during the whole duration of ore deposition, the karst was totally flooded and that the walls of the karstic (geodic) cavities were overgrown by sulfides not in void spaces but under a water table.

For the time being, neither sedimentary ore bedding nor typical ore collapse blocky structures have been found, but investigations are still attentive with these revealing structures.

Such a geological setting, with a hydrothermal plume of magmatic origin mineralizing carbonate host rocks within favourable hydrologic and tectonic traps, looks very similar to the Kipushi model and to some ore deposits of the Dalnegorsk district in Russia (Moroshkin and Frishman 2001), to Zletovo in Macedonia (Serafimovski et al. 2006) or to Madan in Bulgaria (Vassileva et al. 2005). Amazingly, these last deposits are, like Trepča, renowned for their abundance of magnificent geodes of sulphides.

| TREPCA STARI TRG / STAN TERG | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample Number | A.th. | Unit | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Nature/Year | | | Run of mine ore 1948 | Run of mine ore 2007 | Zn concentrate 1999 | Zn concentrate 2006 | Zn concentrate 2007 | Pb concentrate 2006 | Tailings |
| Laboratory | | | Trepca/Zvecan | BRGM | S.G.S. | BRGM | BRGM | BRGM | BRGM |
| SiO2 | 1 | % | 12.10 | 7.2 | 0.39 | 1.2 | <1 | <1 | 16 |
| Al2O3 | 1 | % | 2.51 | <1 | 0.04 | <1 | <1 | <1 | <1 |
| K2O | 0.5 | % | | <0.5 | 0.005 | <0.5 | <0.5 | <0.5 | <0.5 |
| CaO | 1 | % | 3.40 | 14.4 | 0.56 | 1.6 | 1.6 | <1 | 22.4 |
| Fe2O3 t (total Fe expressed as Fe2O3) | 1 | % | 11.02 | 42 | 4.65 | 22 | 19.2 | 8.8 | 23.2 |
| TiO2 | 0.01 | % | | <0.01 | 0.02 | <0.01 | <0.01 | <0.01 | 0.04 |
| MgO | 1 | % | 0.45 | <1 | 0.030 | <1 | <1 | <1 | <1 |
| MnO | 0.01 | % | 2.33 | 1.88 | 0.56 | 0.68 | 0.72 | 0.04 | **4.08** |
| P2O5 | 100 | g/t | | 820 | | 980 | 980 | 3340 | 770 |
| S | 0,1 | % | 28.93 | 23.8 | 32.8 | 31.6 | 32.6 | 17.7 | 12.1 |
| Pb | 0.1 | % | **7.12** | **3.55** | **3.71** | **2.88** | **1.16** | **74.3** | 0.374 |
| Zn | 0.1 | % | **5.50** | **3.65** | **46.79** | **46.8** | **46.2** | **1.17** | **1.29** |
| Ag | 0.2 | g/t | 85.8 | 70 | | 66 | 37 | **1260** | 10 |
| As | 20 | g/t | **5100** | **5430** | **400** | 2970 | 760 | 2850 | **5020** |
| Au | 0.005 | g/t | <0.2 | 0.195 | | 0.140 | 0.066 | 0.349 | 0.210 |
| Bi | 10 | g/t | 87 | 80 | 100 | 184 | 92 | **1300** | 60 |
| Cd | 2 | g/t | 200 | 168 | 2300 | **2090** | **2220** | 72 | 52 |
| Cu | 5 | g/t | 800 | 1172 | 2700 | **6420** | **5000** | **4740** | 468 |
| Ga | 0.1 | g/t | | 5.3 | | 17 | 25 | 0.5 | 6.1 |
| Ge | 0.1 | g/t | | 9.1 | | 4.6 | 2.4 | 3.5 | 7.2 |
| Hg | 0.1 | g/t | | | | 1.42 | | 0.34 | |
| In | 0.1 | g/t | | 6.8 | <20 | **45** | **70** | 1.4 | 3.3 |
| Sb | 10 | g/t | traces | 268 | | 124 | 136 | **1380** | 100 |
| Se | 1 | g/t | | <1 | <20 | <1 | <1 | 2.3 | <1 |
| Te | 1 | g/t | | <1 | <20 | 4.5 | <1 | **19** | <1 |
| Tl | 0.1 | g/t | | | <20 | 0.8 | | **4.9** | |
| B | 10 | g/t | | 12 | | <10 | <10 | <10 | 24 |
| Ba | 10 | g/t | | <10 | | 28 | 16 | <10 | 44 |
| Sr | 5 | g/t | | 56 | | 32 | 28 | 28 | 76 |
| Be | 2 | g/t | | <2 | | <2 | <2 | <2 | <2 |
| Li | 10 | g/t | | <10 | | <10 | <10 | <10 | <10 |
| Ce | 10 | g/t | | 24 | | 12 | 28 | 12 | 24 |
| La | 20 | g/t | | <20 | | <20 | <20 | <20 | <20 |
| Y | 20 | g/t | | <20 | | <20 | <20 | <20 | <20 |
| Nb | 20 | g/t | | 20 | | <20 | <20 | <20 | 24 |
| Zr | 20 | g/t | | <20 | | <20 | <20 | <20 | <20 |
| Co | 5 | g/t | | 8 | <20 | 8 | 8 | 12 | 8 |
| Cr | 10 | g/t | | <10 | | 24 | <10 | 20 | 24 |
| Ni | 10 | g/t | | 44 | <20 | 44 | 48 | 16 | 60 |
| V | 10 | g/t | | <10 | | <10 | 20 | <10 | <10 |
| Mo | 5 | g/t | | 12 | | **60** | 48 | **120** | 8 |
| Sn | 10 | g/t | | 36 | 50 | 84 | **200** | **120** | 20 |
| W | 10 | g/t | | **104** | | **72** | <10 | <10 | **64** |

*Table 1 - Analyses of run of mine ore, ore concentrates and tailings of the Trepca Stari Trg ore deposit (AT=analytical threshold)*

# 4. Ore composition, trace elements, precious and rare metals of Stan Terg

Before 2002, the only figures available about the trace elements, precious or rare metals of Trepča concerned Ag, Cd, Au and Bi (Table 1, sample n° 1). Very briefly, however, the presence of W, Ga, Ge, In, Se, Te and Tl was reported (Table 2) at the microscopic sample scale by Këpuska (1998, 2000) and Këpuska et al. (2001). Nonetheless, data were still lacking at the scale of the run of mine ore of the whole ore deposit and at the scale of the concentrates treated in the smelters of Kosovo or (after 2000) sold to the traders who buy the concentrates of Trepča.

In 2004, one first analyse by Trepča under UNMIK administration started to fill this gap. When the new staff resumed the mining activities, they discovered in the Tuneli Pare concentrator a stockpile of zinc-concentrate dating back to the last treatment in 1999 of the Stan Terg mine ore. They had analysed it in the SGS laboratory. The results listed in Table 1 (sample n° 3) do not provide information of the rare and precious metals included, particularly In, Se, Te and Tl the grades of which were below the detection limit of the laboratory. The Sn grade revealed as of 50 g/t.

Therefore, in a both scientific and economic objective, we have collected in the Tuneli Pare (Prvi Tunel) concentrator and analysed four Trepča samples, 2 kg each, corresponding to the orebodies presently mined in the +75 m level: the first one (sample n° 2) is run of mine ore sampled at the exit of the primary crusher (<24 mm), and the three others (samples n° 4 to 6) are Zn or Pb concentrates (sampled by random coring of the saleable heaps of concentrates) Each sample weighed about 3 kg. The analyses were done in BRGM laboratory by the inductively coupled plasma atomic emission spectroscopy (ICP/AES) method for 34 elements, and by the inductively coupled plasma mass spectroscopy (ICP-MS) method for the traces of Ga, Ge, In, Se and Te.

The results are listed in Table 1, together with analytical data from bibliographical source (Schumacher, 1950) for the run of mine ore of Trepča collected in 1948 (sample n° 1). The grades encountered for the various metals contained are reported and commented hereafter.

## 4.1. ZINC, LEAD, SILVER

On average, the grades of the run of mine ore in the past production of Trepča were 6 % Pb, 4 % Zn and 75 g/t Ag respectively (statistics of the mine reproduced by Monthel et al. 2001, 2002). Now they are 3.65 %, 3.55 % and 70 g/t respectively (Table 1, sample n° 2). These grades are similar to those recorded in the other Pb-Zn ore deposits of the Vardar metallogenic province.

During the 1930-1950 period, they were rather higher in Trepča. For the period 1930-1935, at the very beginning of the British mining, calculations using the data of Titcomb et al. (1936) yield average grades of 9.46 % Pb, 8.54 % Zn and 87 g/t Ag. For 1948, Schumacher (1950) reports of 12.6 % Pb+Zn and 86 g/t Ag (Table 1, sample n° 1). That run of mine ore had a high $SiO_2$ and a rather high $Al_2O_3$ content; therefore it obviously came from the skarn ore typical of the upper levels mined. Concerning more precisely the Ag grades, Forgan (1948) and Schumacher (1950) published figures recorded from 1930 to 1944, of 91 to 143 g/t Ag (106 on average). Our analyses of the Pb-concentrate (Table 1, sample n° 6) show that silver is linked with galena (probably in solid solution or as pyrargyrite, as discovered by Smejkal, 1960).

| (in g/t or ppm) | Minimum | Maximum | Average | Mine levels hosting the highest grades |
|---|---|---|---|---|
| **Cd in sphalerite** | 1210 | 7800 | 2640 | |
| **Cd in galena** | 0 | 326 | 51 | |
| **In in sphalerite** | 40 | 602 | 97 | +75 and +15 (220 to 602 ppm) |
| **In in galena** | 0 | 720 | 55 | +375 down to +75 |
| **Te in pyrrhotite** | 0 | 12 | | |
| **Ga in sphalerite** | 0 | 28 | 10 | +15 (more than 16 ppm) |
| **Ge in pyrite** | 3 | 180 | | +255 |
| **Tl in galena** | 0 | 285 | 32 | +485 (285 ppm), +135 |
| **Se in sphalerite** | 125 | 250 | | |
| **Hg in sphalerite** | 0 | 54 | 22 | |
| **Bi in galena** | 17 | 11,080 | 342 | |

*Table 2 -Rare metal content of Trepča sulfides (from H. Këpuska 1998 and Këpuska et al. 2001).*

Three causes can be identified for the decrease of the Zn, Pb and Ag grades since 1930. First, the cut-off grade was higher than now. Moreover, the dilution was lower because mechanisation was not so developed as now. Finally, the thickest orebodies mined in the 1930-1950 period were those of skarn ore around the volcanic pipe (the highest in grade) whilst the orebodies more distant from the pipe at the same levels were much thinner (and of lower grade), as can be seen in Schumacher's plates XII to XIV (1950). The influence of these distant ore bodies on the overall grade mined was thus weak. Nowadays, the run of mine ore (sample n° 2) is a blending from the several orebodies inventoried in the +75 m level that are simultaneously mined, both of high grade skarn type and of lower grade "oligonite ore" type.

In the lower levels of the mine currently reached, a large geographical dispersion of the grades from one orebody to the other has just been discovered. Therefore Trepča/UNMIK is now conducting a project for introducing selective mining. For the calculation of the proven reserves, it seems (according to Strmić Palinkaš *et al.*, 2007a) that the average Pb+Zn grade has now been fixed at 10.2 % and it is obviously a cut off grade, as usual in free market economy mining.

## 4.2. COPPER

The Cu grade of the run of mine (currently 0.1 %) has got a 50 % increase from 1948 to now (from 800 g/t in sample n° 1 up to 1172 g/t in sample n° 2), from which it results that the concentrator usually produced 2,000 t/y Cu on average in the 1990's. The Zn- and Pb-concentrates currently sold contain 0.5 % Cu (Table 1, samples n° 4, 5 and 6). According to Smejkal (1960), the carriers are bournonite, chalcopyrite, enargite, tennantite, tetrahedrite, as well as stannite, bornite, cubanite and covellite.

## 4.3. BISMUTH

After silver and copper, bismuth is the following component of economic interest in Trepča. Forgan (1948) and Schumacher (1950) published a figure recorded from 1930 to 1944, of 87 g/t Bi on average in the run of mine ore. Monthel *et al.* (2001, 2002), reproducing more modern statistics got from the Trepča company, report of 102 g/t Bi on average. Our sample n° 2 of 2007 yielded 80 g/t Bi. These grades are similar to those recorded in the other Pb-Zn ore deposits of the Vardar metallogenic province.

Bismuth in Trepča is obviously linked with galena (Bi raises 0.13 % in the Pb-concentrate sample n° 6). According to Smejkal (1960), it occurs at least as native bismuth and cosalite.

The recent mineralogical studies (in Bulgaria) of Bonev (2007) devoted to galena crystals from Madan (which is an ore deposit similar to Trepča), following older general observations, have shed light to the positive relation between the abundance of bismuth and the tendency of galena in this ore deposit to crystallize in the octahedral and cuboctahedral habitus rather than in cubes. This tendency is strong in the galena crystals in Trepča. Këpuska (1998) reminded that, in Trepča, bismuth is present within galena mostly as bismuthinite and native bismuth. He recorded an average grade of 964 g/t Bi in the galena crystals he assayed. Therefore, concerning mineralogy, we suggest as a hypothesis that the prevailing cuboctahedral habitus of the galena in Trepca is caused by the high grade of this mineral in bismuth.

## 4.4. CADMIUM

Cadmium in the run-of-mine ore of Trepča is reported (sample n° 1 Table 1) at a grade of 0.02 % in 1948 (Schumacher 1950) and its production is estimated at 1,655 tonnes from 1968 to 1987. Our analyses indicate a grade of 200 g/t in the run of mine ore (sample n° 2) and 0.2 % in the Zn-concentrate (samples n° 4 and 5).

## 4.5. GOLD

Gold was first reported by Titcomb et al. (1936), as traces in the run of mine ore, that could not be recovered (Schumacher, 1950, quoting grades lower than 0.2 g/t in 1948) and later by Dokič (in Janjušević 1974) as a by-product recovered in the lead smelter of Zvečan together with indium and thallium, without any carrier being identified. The report of Monthel *et al.* (2002) records, from 1950 to 1985, a total production of 8.7 t gold at the lead smelter, i.e. 250 kg per year. At an average output rate of 600,000 t/y run of mine ore, the grade would thus be in the order of 0.4 g/t Au in the ore.

In the Vardar metallogenic province, the presence of gold was recorded in the Roman times and it was mined in the Lece area. In the recent period, run of mine grades from 3 to 4 g/t Au have been reported in Novo Brdo, from 1 to 2.7 g/t in Belo Brdo (with 7 t Au reserves at 1g/t), from 4 to 6 g/t in Lece (2 on average), and minor indications of gold in Dražnja, Rudnik, Rudnica (Rudnitsa ; a new ore deposit discovered in 2004 in the western margin of Mt Kopaonik), Gokčanica, Plavkovo, Sijarinska Banja (Popović 1992, 2000; Simić 2000; Serafimovski 2000; Monthel et al. 2001, 2002; Kozelj et al. 2007). These various occurrences belong to various metallogenic types (from porphyry to low sulphidation) but all can be considered as manifestations of the same mineralizing phenomenon connected with the Oligocene-Miocene volcanism and intersected by different levels of erosion, as developed in 3.3.

In Trepča/Stari Trg ore deposit, our analyses yielded 0.195 g/t Au in the run-of-mine (sample n° 2). The current process used in the Tuneli Pare concentrator does not permit to recover all this gold in the zinc-concentrate (Table 1, samples n° 4 and 5). It is probably linked with pyrite and pyrrhotite, because (according to our test) it is found intact in the tailings (sample n° 7 of table 1, which will be discussed in the next chapter). Nonetheless, according to our test, this concentrator raises gold in the Pb-concentrate (up to 0.349 g/t Au in sample n° 6). This grade is low but it can be valorized at the smelter level, as was done till 1999 in Zvecan (the Trepča concentrates are now sold to traders for foreign smelters).

## 4.6. TUNGSTEN AND TIN

The presence of tungsten, in the form of scheelite, is another renowned feature of Trepča (Smejkal, 1960). Our analyse of the run of mine ore (sample n° 2) yielded 104 g/t W. Scheelite having a density (4.4) lower that the other metal carriers, only one part of it (when present) is recovered as W in the Zn-concentrate (sample n° 4) whilst Sn arises from 36 g/t in the run of mine ore (sample n° 2) up to 84 and even 200 g/t in the Zn-concentrate (samples n° 4 and 5) and 120 g/t in the Pb-concentrate (sample n° 6). According to Smejkal (1962) the carrier is stannite. Within the same context and the same belt, scheelite is abundant in the Pb-Bi-W ore deposit of Rudnik (Stojanović 2006).

## 4.7. INDIUM AND OTHER RARE METALS

Indium is another metal of great interest for the current market of Zn-concentrates like the Trepča one. Traces of Ga, Ge, In, Se, Te and Tl in the run-of-mine ore have been reported as extracted at the local smelters. Nonetheless, no data about Trepča had ever been published before the works of Këpuska (1998), Këpuska and Fezja (2000) and Këpuska et al. (2001). They collected 128 ore samples at various depths in the deposit and, through electron probe microanalysis and atomic absorption spectrometry, assayed the rare metals present in sphalerite, galena, pyrrhotite and pyrite crystals (Table 2). They describe In as becoming increasingly abundant as investigation proceeds downdip in the orebody (based however on small mineralogical hand specimens and not batch samples representative of noteworthy ore tonnages). Unfortunately, data were still lacking concerning the Ge content of sphalerite (the mineral which is the usual Ge and Ga-carrier in world zinc deposits). For Ge, besides the maximum 180 ppm in pyrite, Këpuska (1998) reported 3 ppm in rhodochrosite, 1 ppm in dolomite and 2 ppm in skarn.

Our analyses (Table 1) confirm the relative interest of Trepča for indium. The Zn-concentrate of 2006 (sample n° 4) yielded 45 g/t In and the one from 2007 (sample n° 5) yielded 70 g/t (starting from a run of mine ore grading 6.8 g/t In in sample n° 2). The presence of indium seems in relation with the grade in tin, since the highest indium grade (70 g/t) is found in the Zn-concentrate highest in tin (200 g/t), probably in relation with the abundance of stannite reported by Smejkal (1960) in the sphalerite. The corresponding run of mine ore (sample n° 2) contains 36 g/t Sn.

The indium content of Trepča Zn-concentrates is noteworthy, but low if compared to the 200 g/t In found in the Zn-concentrate of Novo Brdo of 1999 (see Table 3, which will be discussed later), a concentrate which was also rather rich in Sn (110 g/t). Nonetheless, these figures reflect only the grade of the orebodies that were mined when the ore concentrate was sampled. They are representative neither of the whole ore deposit, nor of other orebodies which may be exploited further downdip or on strike.

In Trepča/Stari Trg, tellurium is rather abundant (19 g/t Te) in the Pb-concentrate analysed (Table 1, sample n° 6).

Germanium, present in the run of mine ore (sample n° 2) at an order of magnitude of 9 g/t, is amazingly not upgraded in the concentrates either of zinc or lead (2 to 4 g/t only in samples n° 4, 5 and 6). This means that the beneficiation process of the ore (when the samples were collected) was not adapted to its recovery.

Gallium is upgraded up to 17 to 25 g/t in the Zn-concentrate (samples n° 4 and 5).

These figures and tendencies seem of great importance for the future, in the case the market of some of these rare metals would increase.

## 4.8. URANIUM

Amazingly, the presence of uranium in the ore of Stari Trg/Trepča was tested by Yugoslavian geologists in the 80's (Kostić *et al.*, 1985-86). The reason at the origin of these tests is unknown from us.

The concentration of uranium in the mineral samples tested (sphalerite-marmatite, pyrite, quartz, calcite and barite) ranged between 2.66 and 1.18 ppm. From an economic viewpoint, these grades have no interest at all. From a metallogenic point of view, these grades are very low but worth to notice.

The presence of uranium in the form of pitchblende, assessed within other lead-zinc ore deposits belonging to the CRD type, is not widespread but known, for instance in :

- the Zletovo Pb-Zn ore deposit in Macedonia (Serafimovski et al. 2006) ;

- the small French ore deposit which is in France the most similar to Stari Trg, the late-Hercynian-age one of the La Rabasse Zn-Pb mine, in Cambrian dolomites (Lescuyer *et al.* 1987, 1988).

## 4.9. PERSPECTIVES AND RECOMMENDATIONS

At the scale of the ore deposit, the exploration of the Stan Terg ore deposit and neighbouring prospects is well conducted by Trepca/UNMIK teams and no specific recommendation has to be made.

At the scale of the ore, further studies are recommended as the ore concentrates coming from the Trepča ore deposit are abundant in precious metals (Ag and at a lesser extent Au) and rare metals (Bi, Cd). They contain relatively attractive grades in the so-called "high tech metals" (on account of their role in the high-tech industry) such as indium and possibly gallium, selenium, tellurium and thallium. Concerning these 5 last elements, the figures assessed up to now on the Trepča samples are low, possibly because the ore processing method currently used in the plant is adapted to the best recovery of zinc and lead and not to the recovery of these by-products, the carriers of which are not identified yet.

As stressed by tables 1 and 2, among the most probable carriers of these precious and rare metals, are galena for silver and bismuth, sphalerite for cadmium, indium, mercury, germanium and gallium (indium being probably linked with stannite, genetically if not also spatially). Most of the gold "goes" with galena, as well as silver, bismuth, tellurium, selenium and thallium.

For comparison, the mineralogical Zn-concentrates obtained by Arsenijević (1992-98) from the Žuta Prlina ore, close to the Belo Brdo mine and similar to Stari Trg ore, yielded up to 80 g/t In, 130 g/t Ag and 35 g/t Ge.

Therefore, all the various orebodies of the other ore deposits such as those of Trepča warrant testing, in order to seek for criteria that could find the most promising targets for selective mining focused on special metals.

Mineralogical studies are recommended to better identify the various carriers. In Kosovo, no particular indium mineral has been found yet as the carrier of indium. Beside sphalerite, stannite, which has been identified by Smejkal (1960) in Stari Trg, is usually renowned as a possible host. In Stari Trg, the indium grade seems according to our analyses in a positive relation with the tin grade.

# 5. Valorization of the tailings of Stari Trg for rare and precious metals: one test sampling

## 5.1. VOLUME AND TONNAGE SUBJECT OF INTEREST

From its beginning in 1984, the flotation plant of Trepča Stan Terg (named Tuneli i Pare or Prvi Tunel) has rejected (Deissmann *et al.* 2007; Mattich and Seitz, 2005) nine to eleven millions tons tailings covering an area of 20 ha, named Zharkov Potok. It is located near the Kelmendi village, about 2.5 kilometres southwest of the processing plant of Tuneli Pare. The road from Mitrovica to Belgrade passes below (Photos n° 7 to 12).

These tailings have filled an old valley with gentle slopes. One part of the surface is occupied by a pond, where isolated cattle and beasts come to drink. The internal structure and dimensions of the tailing mass are described in details in the MonTec report (Deissmann *et al.* 2007). The environmental problems caused by this accumulation of waste containing high grades in Pb, Zn, Cd and As are huge. There is currently a rehabilitation program (Bektashi, 2008) to reduce its environmental impact by reinforcement of the dam crest, greening, re-cultivation and settling an anti-dust programme.

*Photo 7- Tailing dam of Zharkov Potok seen from the West, with the Belgrade road below*

*Photo 8- Tailing dam of Zharkov Potok*

*Photo 9- Tailing dam of Zharkov Potok*

*Photo 10- Tailing dam of Zharkov Potok*

*Photo 11 - Tailing dam of Zharkov Potok: location of the sample collected (sample n° 7 of Table 2)*

*Photo 12 - Tailing dam of Zharkov Potok: location the sample collected (sample n° 7 of Table 2)*

## 5.2. TREATMENT METHOD AND ELEMENTS ALREADY POINTED OUT AS VALUABLE

In the flotation plant at Tuneli i Pare (Prvi Tunel) the treatment method is conventional (anonymous, 2005). The pulp (grainsize: 200 microns) is conditioned with zinc sulphate and sodium-cyanide to depress the zinc, and lead is floated using a xanthate collector and alcohol frother. Lime is added to the tailings from lead flotation to raise the pH and depress pyrite. Zinc is reactivated by the addition of copper sulphate before xanthate and frother are used to float the zinc.

The plant provides for the tailings from zinc flotation to be pumped by hydrocyclones, whose underflow is distributed to wet drum, low intensity, magnetic separators. The cyclone overflow goes directly to the tailings pumps. The magnetic products gravitate to the pyrrhotite thickener and the thickened pyrrhotite is pumped to a vacuum disc filter. The non-magnetic product is pumped to a hydrocyclone ahead of the pyrite flotation circuit.

The pyrite flotation circuit is very similar to the lead flotation circuit. The pH is lowered and xanthate and copper sulphate is used to promote the flotation of pyrite.

Both pyrrhotite circuit and pyrite circuit are currently not used. In the past, it seems that they were used rarely or even never (Anonymous, 2005).

The coarse rejects of the flotation (sands) are sent to backfill the stopes in the mine, whereas the fine tailing is pumped to a pump-station to the tailings dam at Zharkov Potok, a valley 2 km west of the concentrator.

The team of Trepča under UNMIK administration already pointed out (table 5.2 in Anonymous, 2005) grades of 0.33 % Pb, 0.26 % Zn, 49 g/t Bi and 0.019 % Cu remaining in these tailings.

Therefore, within the frame of the French cooperation, special attention was paid to the possibility to eliminate or reduce the environmental impact of this tailing dam, by means of its valorisation as an ore.

For that purpose, BRGM sampled the tailings located at the crest of the dam, according to the chip sampling method, after having dug the material over a depth of 50 centimetres in order to avoid the weathered and drained superficial crust of the tailings. The analyses were done in BRGM laboratory by the inductively coupled plasma atomic emission spectroscopy (ICP/AES) method for 34 elements, and by the inductively coupled plasma mass spectroscopy (ICP-MS) method for the traces of Ga, Ge, In, Se and Te.

The three kilogram-sample (n° 7 in Table 2) yielded the following results.

## 5.3. ADDITIONNAL VALUABLE ELEMENTS DISCOVERED

It must be stressed that BRGM sampling was just a test. Obviously, the tailings are far to be homogenous. The grade of the run of mine ore and the cut off grades having much changed from the beginning of the concentrator (1981-1982) to now, the tailings are composed of various layers. Anyway, the results of the test are remarkable. They must be examined by comparison with the run of mine ore samples n° 1 and 2. Their contents in the most important elements are as follows :

Ag : 10 g/t (instead of 70 g/t in the run of mine);

Zn : 1.29 % (instead of 3.65 % in the run of mine);

Pb : 0.37 % (instead of 3.55 % in the run of mine);

Cu : 468 g/t (instead of 1172 g/t in the run of mine);

Bi : 60 g/t (instead of 80 g/t in the run of mine);

Ge : 7.2 g/t (instead of 9.1 g/t in the run of mine);

Ga : 6.1 g/t (instead of 5.3 g/t in the run of mine);

In : 3.3 g/t (instead of 6.8 g/t in the run of mine);

Au : 0.210 g/t (instead of 0.195 g/t in the run of mine).

## 5.4. PENALIZING ELEMENTS :

Besides the high grade of these tailings in pyrite which could hamper their re-treatment because of environmental impacts, two elements are penalizing:

As : 0.502 % (instead of 0.543 in the run of mine ore);

Cd : 52 g/t (instead of 168 g/t in the run of mine ore).

## 5.5. RECOMMENDATIONS

Our analyses, although being not representative, suggest that the losses in Ag, Pb, Zn, Cu, Bi, Ge, Ga, In and Au during the flotation process are important.

A study of the flow sheet of the Tuneli Pare concentrator is recommended in order to improve the flow sheet and to reduce these losses.

The 9 to 11 Mt tailings of Zharkov Potok contain rather attractive grades in these elements, a part of which could be valorized.

Therefore further tests are recommended, among them a mineralogical study to identify the minerals carrier of lead, zinc, silver, gold etc. ; systematic augerdrilling to assess the grades and tonnages ; chemical analyses ; reserve calculation ; laboratory-scale and (in case of favourable results) pilot-scale beneficiation tests.

# 6. The potential of the Artana/Novo Brdo ore deposit in rare and precious metals: one test sampling

During our field visit, we had not time enough to go and visit the Artana or Novo Brdo mine (both names are used for this mine) which is located south of Trepca Stan Terg (fig. 5). In the same area, we visited quickly the old open pit of Kišnica, which warrants no particular comments in this report because no mineralization could be observed during our visit. Nonetheless, we could sample the heaps of ore concentrates resulting of the beneficiation of ore from Novo Brdo in the Badovac concentrator. We could visit the corresponding tailings nearby. Both operations were to yield very attractive results.

## 6.1. MAIN GEOLOGICAL FEATURES OF THE ORE DEPOSIT

Many studies were devoted to the geology of the Artana/Novo Brdo ore deposit, the exploitation of which goes back to about 3,000 years. The Trepča geologists have stressed (fig. 11) that it is CRD type Pb-Zn-Ag-Au ore deposit composed of eight orebodies, all of which are irregular in morphology but clearly fault-controlled (Cirić and Grubić 1956 ; Smejkal, 1960 ; Barjaktarević, 1995 ; Simić, 2000 ; Anonymous, 2005).

Most of the mineralization is hosted by marbles within the metamorphic series. The mineralogical composition of the various orebodies is similar to Stari Trg except the particular abundance of microscopic gold. According to Smejkal (1960), gold is present as free crystals. No particular gold telluride was identified by Smejkal or by Barić (1977), contrarily to what happens in other ore deposits of the district (Kišnica and Kopaonik) where krennerite and calaverite are known besides gold.

Another particularity is the presence of a massive mono-mineralic layer of halloysite (kaolin group) one to 6 m thick along the footwall contact of the Pb-Zn orebody with the gneissic country rock, representing more than 2 Mt resources regarded as a potential by-product.

## 6.2. GRADES IN LEAD, ZINC, SILVER AND GOLD ALREADY REKNOWNED

A preliminary reserve assessment was done by Monthel et al. (2001) and revised by the Trepca/UNMIK team (Anonymous 2005; Nelles and Diehl 2007 compiling data of A. Wheeler 2002 and of M. Diehl and S. Kelmendi July 2005).

The reserves and resources are thus estimated at 4,748,000 t run of mine ore, with an average composition varying from one orebody to the other, as follows :

Pb : between 3.7 and 4.4 % Pb ;

Zn: between 4.8 and 5.4 % Zn ;

Ag: between 104 and 140 g/t Ag ;

Au: between 0.8 and 1.4 g/t Au.

These figures are synthetised as a virtual sample n° 8 in Table 3.

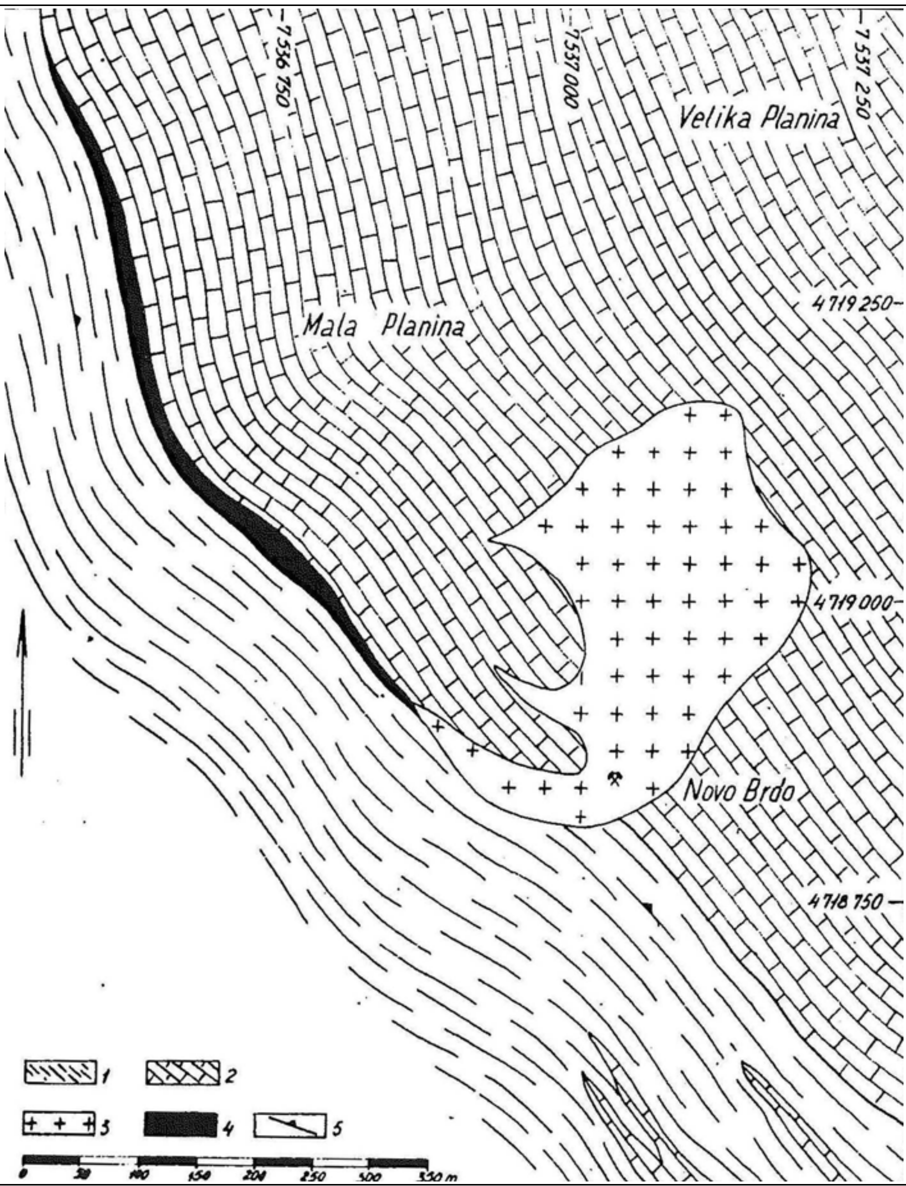


*Figure 11 – Geological map of the main orebody of Artana/Novo Brdo mine (Smejkal, 1960). Legend: 1=schists of the Veles series; 2=marmorised limestones; 3=andesite; 4=ore; 5=schistosity direction and dip.*

## 6.3. THE TREPCA/UNMIK TESTS

In 2004, when the new staff of Trepča under UNMIK administration resumed the mining activities, they discovered in the Badovac concentrator a stockpile of zinc-concentrate. It was assessed that this zinc-concentrate came from the treatment in 1999 of the ore of Novo Brdo/Artana mine (Ch. Carron Brown, Trepca manager, written communication 20.01.2006). The concentrate was assayed by the SGS laboratory. The results are listed in Table 3 (sample n° 9) and suggest the main following remarks : high grades in copper (nearly 0.5 % Cu), in bismuth as usual in the district (120 g/t) but in indium as well (200 g/t In). This figure is the highest found to date in the district, which enlightened the possibility to find attractive ore bodies permitting the valorisation of this rare metal as a by-product of zinc and lead.

## 6.4. THE BRGM SAMPLING OF CONCENTRATES

Being aware of this indium grade, we intended to test this discovery by new analyses.

A little time before our visit in 2007, the concentrator of Badovac had treated a few tons of ore coming from the pyritous orebodies No. 1 and No. 2 of Artana/Novo Brdo mine which is under reactivation, thus producing a few tons of zinc-concentrate and of lead-concentrate.

The Badovac concentrator had also been used for re-treating experimentally a few tons from the old tailings of the Marevc concentrator (tailings resulting from the processing of the Artana/Novo Brdo ore before 1978) because they reportedly (Anonymous 2005) contain about 1.3 g/t Au.

BRGM thus sampled the 4 corresponding concentrates (Table 3) :

- sample n° 10 = zinc concentrate of Artana ;

- sample n° 11 = lead concentrate of Artana ;

- sample n° 13 = zinc concentrate from the retreatment of the tailings of Artana/Marevc ;

- sample n° 14 = lead concentrate from the retreatment of the tailings of Artana/Marevc.

The samples were collected within the saleable heaps of concentrates, by core-sampling by means of a sampling pipe in iron. Each sample weighed about 3 kg.

The analyses were done in BRGM laboratory by the inductively coupled plasma atomic emission spectroscopy (ICP/AES) method for 34 elements, and by the inductively coupled plasma mass spectroscopy (ICP-MS) method for the traces of Ga, Ge, In, Se and Te.

| | | | ARTANA/NOVO BRDO OREBODY | | | | | RETREATED TAILINGS OF ARTANA/NOVO BRDO/MARECV | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | A.th. | Unit | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Nature/Year | | | Run of mine ore | Zn concentrate 1999 | Zn concentrate 2007 | Pb concentrate 2007 | Tailings at Badovac | Zn concentrate 2007 | Pb concentrate 2007 | Residual tailings 2007 |
| Laboratory | | | Trepca/UNMIK | S.G.S. | BRGM | BRGM | BRGM | BRGM | BRGM | BRGM |
| SiO2 | 1 | % | | 1.46 | 2.4 | 1.6 | 6.4 | 1.2 | 2.4 | 9.6 |
| Al2O3 | 1 | % | | 0.44 | <1 | <1 | 1.2 | <1 | 1.2 | 1.6 |
| K2O | 0.5 | % | | 0.058 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| CaO | 1 | % | | 0.78 | 3.2 | 1.2 | 1.6 | 3.2 | 2 | 2 |
| Fe2O3 t (total Fe expressed as Fe2O3) | 1 | % | | 7.79 | 23.2 | 18.8 | 56.8 | 27.2 | 39.6 | 55.6 |
| TiO2 | 0.01 | % | | 0.01 | 0.04 | <0.01 | 0.04 | <0.01 | 0.04 | 0.08 |
| MgO | 1 | % | | 0.38 | 1.6 | <1 | <1 | 1.6 | <1 | <1 |
| MnO | 0.01 | % | | 0.39 | 0.48 | 0.12 | 0.28 | 0.4 | 0.2 | 0.56 |
| P2O5 | 100 | g/t | | | 1200 | 2800 | 900 | 1040 | 2140 | 1090 |
| S | 0,1 | % | | 37.51 | 31.1 | 26.5 | 43.9 | 32.7 | 34.5 | 41.3 |
| Pb | 0.1 | % | **3.7 to 4.4** | **2.20** | **4.3** | **47.7** | 0.59 | **2.81** | **23.5** | 0.52 |
| Zn | 0.1 | % | **4.8 to 5.4** | **30.53** | **32.3** | **4.21** | **1.35** | **31.1** | **2.95** | **1.06** |
| Ag | 0.2 | g/t | **104 to 140** | | 130 | **1000** | 26 | 105 | **655** | 19 |
| As | 20 | g/t | | **1400** | **3900** | **4700** | **5630** | **3200** | **4400** | **5450** |
| Au | 0.005 | g/t | **0.8 to 1.4** | | **1.146** | **3.908** | **2.338** | 0.957 | **2.755** | **2.547** |
| Bi | 10 | g/t | | 120 | 104 | **736** | 52 | 136 | **684** | 44 |
| Cd | 2 | g/t | | 1600 | **1590** | 288 | 76 | **1550** | 272 | 52 |
| Cu | 5 | g/t | | 4500 | **4300** | 2920 | 568 | **6200** | 2420 | 380 |
| Ga | 0.1 | g/t | | | 21 | 4.2 | 11 | 23 | 6 | 15 |
| Ge | 0.1 | g/t | | | 6.2 | 6.2 | 9.9 | 6 | 6.9 | 9.9 |
| Hg | 0.1 | g/t | | | | | | | | |
| In | 0.1 | g/t | | **200** | **63** | 7.4 | 6.6 | **177** | 12 | 3.9 |
| Sb | 10 | g/t | | 200 | 276 | **1630** | 116 | 212 | **868** | 124 |
| Se | 1 | g/t | | <20 | 2.6 | 14 | 10 | 2.2 | 24 | 13 |
| Te | 1 | g/t | | <20 | 3 | 7.4 | 5.4 | 1.6 | 5.2 | 6 |
| Tl | 0.1 | g/t | | <20 | | | | | | |
| B | 10 | g/t | | | <10 | <10 | 28 | <10 | <10 | 48 |
| Ba | 10 | g/t | | <50 | 28 | 28 | 192 | 20 | 76 | 236 |
| Sr | 5 | g/t | | | 48 | 40 | 36 | 48 | 40 | 40 |
| Be | 2 | g/t | | | <2 | <2 | <2 | <2 | <2 | <2 |
| Li | 10 | g/t | | | <10 | <10 | <10 | <10 | <10 | <10 |
| Ce | 10 | g/t | | | 16 | 16 | 24 | 12 | 20 | 24 |
| La | 20 | g/t | | | <20 | <20 | <20 | <20 | <20 | <20 |
| Y | 20 | g/t | | | <20 | <20 | <20 | <20 | <20 | <20 |
| Nb | 20 | g/t | | | <20 | <20 | <20 | <20 | <20 | <20 |
| Zr | 20 | g/t | | | 24 | <20 | <20 | <20 | <20 | <20 |
| Co | 5 | g/t | | 25 | 16 | 16 | 16 | 16 | 20 | 16 |
| Cr | 10 | g/t | | 100 | **132** | **100** | 48 | 64 | 64 | 56 |
| Ni | 10 | g/t | | 66 | 76 | 92 | 64 | 24 | 88 | 68 |
| V | 10 | g/t | | <50 | <10 | <10 | <10 | <10 | <10 | <10 |
| Mo | 5 | g/t | | <50 | 44 | 28 | 8 | 36 | 20 | 8 |
| Sn | 10 | g/t | | **110** | **184** | **124** | 32 | **112** | 80 | 32 |
| W | 10 | g/t | | | **192** | 36 | 16 | **172** | 28 | <10 |

*Table 3 - Analyses of run of mine ore, ore concentrates and tailings of the Novo Brdo/Artana ore deposit (AT=analytical threshold)*

## 6.5. MAIN RESULTS

As illustrated by Table n° 3, the remarkable figures are as follows.

### 6.5.1. Zn concentrate (sample n° 10)

The zinc concentrate obtained directly from the ore contains 4.30 % Pb. Attractive are the figures for silver (130 g/t Ag), gold (1.1 g/t), copper (0.43 % Cu) and indium (63 g/t In).

### 6.5.2. Pb concentrate (sample n° 11)

Very attractive figures are those for silver (1000 g/t Ag) and mostly gold (3.9 g/t Au), copper here again (0.292 % Cu), bismuth (736 g/t Bi).

### 6.5.3. Zn concentrate from retreatment of tailings (sample n° 13)

The grade in zinc recovered is satisfactory (31.10 % Zn, like in the concentrate of sample n° 10 obtained directly from the ore). The concentrate obtained from the retreatment of the tailings contains 2.81 % Pb and 0.62 % Cu. As a result of the pyritous nature of the tailings, it is particularly high in iron and in total sulphur. Amazingly, the grade in silver is nearly as high here (105 g/t Ag) than in the zinc concentrate directly obtained from the ore (130 g/t Ag) which is very satisfactory. Gold reaches nearly one ppm (0.9 g/t Au) whereas indium reaches here its second highest value recorded for the time being in the area (177 g/t In).

### 6.5.4. Pb concentrate from retreatment of tailings (sample n° 14)

As a result of the pyritous nature of the tailings, it is particularly high in iron and in total sulphur. The grade in silver is very attractive (655 g/t Ag) together with that of gold (2.7 g/t Au) and that of copper (0.242 % Cu).

For selenium, a grade of 24 g/t Se is recorded, which is relatively high for the district.

## 6.6. RECOMMENDATIONS

The Artana/Novo Brdo ore deposit has always been considered by the Trepča geologists as of particular interest because of its high gold and silver contents. The new analyses moreover stress focus on indium on account of its relative high grade in the Zn-concentrate (63 to 200 g/t In). Its presence would seem in parallel with the relative abundance of Sn (up to 184 g/t Sn in the Zn-concentrate of sample n° 10). Nonetheless, the analyse of the Pb-concentrate of sample n° 11, rather low in indium (4.4 g/t In), yielded 124 g/t Sn.

Apart from a mineralogical study to identify the minerals carrier of gold, silver and indium, an assessment of the potential of the ore deposit is recommended, possibly orientated by a few geological drill-holes.

The presence of Sn was already pointed out in the same area by D. Barjaktarević (1995) in the Glama Silver medieval mine, between Novo Brdo and Gnjilane. This ore deposit is located in the Upper Jurassic limestones and seems of a type similar to the others. Its ore is rich in Pb, Zn and Mn and has yielded grades of 300 to 1200 g/t Sn, 3 to 23 g/t Au and 12 to 77 g/t Ag.

# 7. Valorization of the tailings of Artana Novo Brdo in the Kishnica/Badovac dam : one test sampling

The tailings of Badovac area and Novo Brdo area seem of high interest. They are of various origins. In the flotation plant at Badovac (Kishnica), built in 1968 upstream of the historical city of Gračanica, have been both treated (sometimes successively, sometimes simultaneously) the ores coming from five different mines and four different ore deposits, although belonging all to the same CRD type as Trepča-Stari Trg deposit :

- ore from the Kishnica underground mine ;
- ore from the Badovac underground mine ;
- ore from the Hajvalija underground mine ;
- ore from the Kishnica open pit ;
- ore from the Artana/Novo Brdo mine (located a few kilometres to the East) during the 1978-1988 period when this mine was reopened. Previously, the ore from Artana Novo Brdo was processed in the Marevc concentrator close to the Artana/Novo Brdo mine ; this concentrator has been abandoned since 1978).

From all these activities, resulted four groups of tailings (Table 4 and Fig. 12 and 13).

The first historically tailing dam (site n° 1 of fig. 12, photos 13 and 14) is located on the right bank of the river coming from the dam of Lake Gračaničko. It has a reddish brown colour. It has not been used for 20 years or more. It is partially a heaped tailing, covering the alluvial plain, and partially a side-hill tailing. It is rather larger than thick. Its height is about 15 m only, and his longest side is about 500 m. Its 11 Mt (Deissmann *et al*. 2007) result of the treatment of the ores from all the mines very near Gračanica/Badovac (Hajvalija, Kižnica, Badovac).

We did not sample this tailing yet. Nonetheless it should be of interest for gold, because Smejkal (1960) reported the presence of microscopic gold in all the mineralogical associations of the ore deposits which he investigated in the area (Hajvalija, Kišnica etc.).

*Photo 13 – Old tailings from the Hajvalija mine (site n° 1 of fig. 12)*

*Photo 14 - Old tailings from the Hajvalija mine (Site n° 1 of fig. 12)*

The second mass of tailings (site n° 2 of Fig. 12, photos 15 to 18) is located in the hills on the left bank of the lower part of the river coming from Lake Gračaničko. It has completely filled a small valley with rather steep slopes which was a tributary of left bank of the Gračanka river. No vegetation has grown. It has a grey colour. It is still used.

*Photo 15 - Old (left side) and new tailings (right side) near the Badovac concentrator, sampled by BRGM (Site n° 2 of fig. 12)*

*Photo 16 - Old tailings near the Badovac concentrator (site n° 2 of fig. 12), sampled by BRGM on the crest of the dam (sample n° 12 of Table 3); on the right, at the bottom of the dam can be seen the new tailings of sample n° 15 and photo 18*

*Photo 17 - Old tailings near the Badovac concentrator (site n° 2 of fig. 12), sampled by BRGM on the crest of the dam (sample n° 12 of Table 3)*

*Photo 18 - New tailings (from the retreatment of the old tailings of the Marevc concentrator) near the Badovac concentrator (site n° 2 of fig. 12), sampled by BRGM down the crest of the dam (sample n° 15 of Table 3)*

This tailing dam has focused all BRGM attention for the time being.

Its 8 Mt (Deissmann *et al.* 2007) result from the treatment of the ore of Artana/Novo Brdo mine after 1978. The ore was crushed at the mine and delivered by an aerial ropeway to the Badovac concentrator where it was processed.

The last two tailings (site n° 3 and site n° 4 of fig. 13) are located 2 km north of the village of Artana/Novo Brdo, close to the mine of Novo Brdo and downstream of the old Marevc concentrator, now abandoned. They amount at 0.4 and 1.6 Mt respectively (Deissmann *et al.* 2007). They have just been the subject of a remediation programme conducted by the UNDP country office in Kosovo funded by the Netherlands government (Bektashi 2008). They were visited and sampled by BRGM during the Tec-Ingenierie 2001 economic assessment of Novo Brdo mine (Monthel *et al.* 2001) but they not visited during the present BRGM cooperation programme.

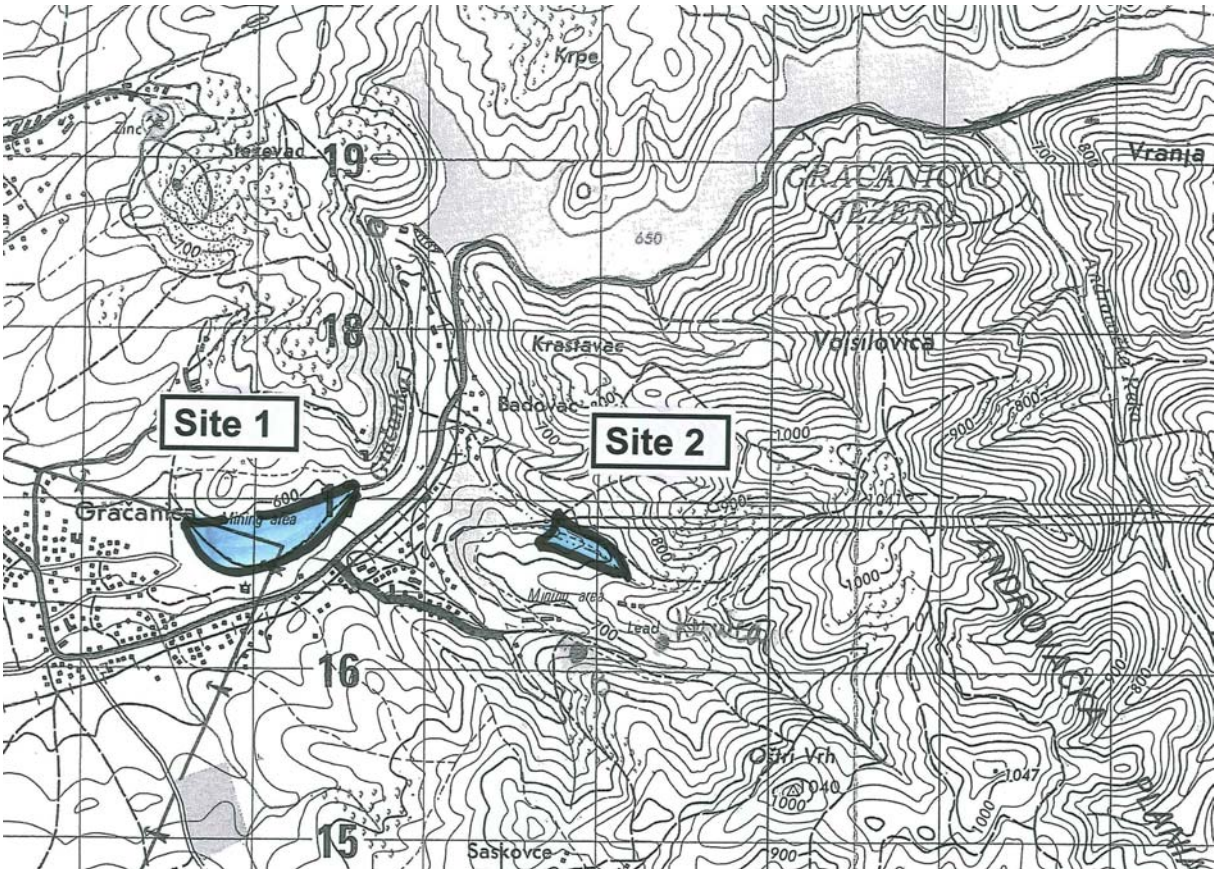


*Figure 12 - Location map of tailings site n° 1 and n° 2 of the Gracanica/Badovac area*

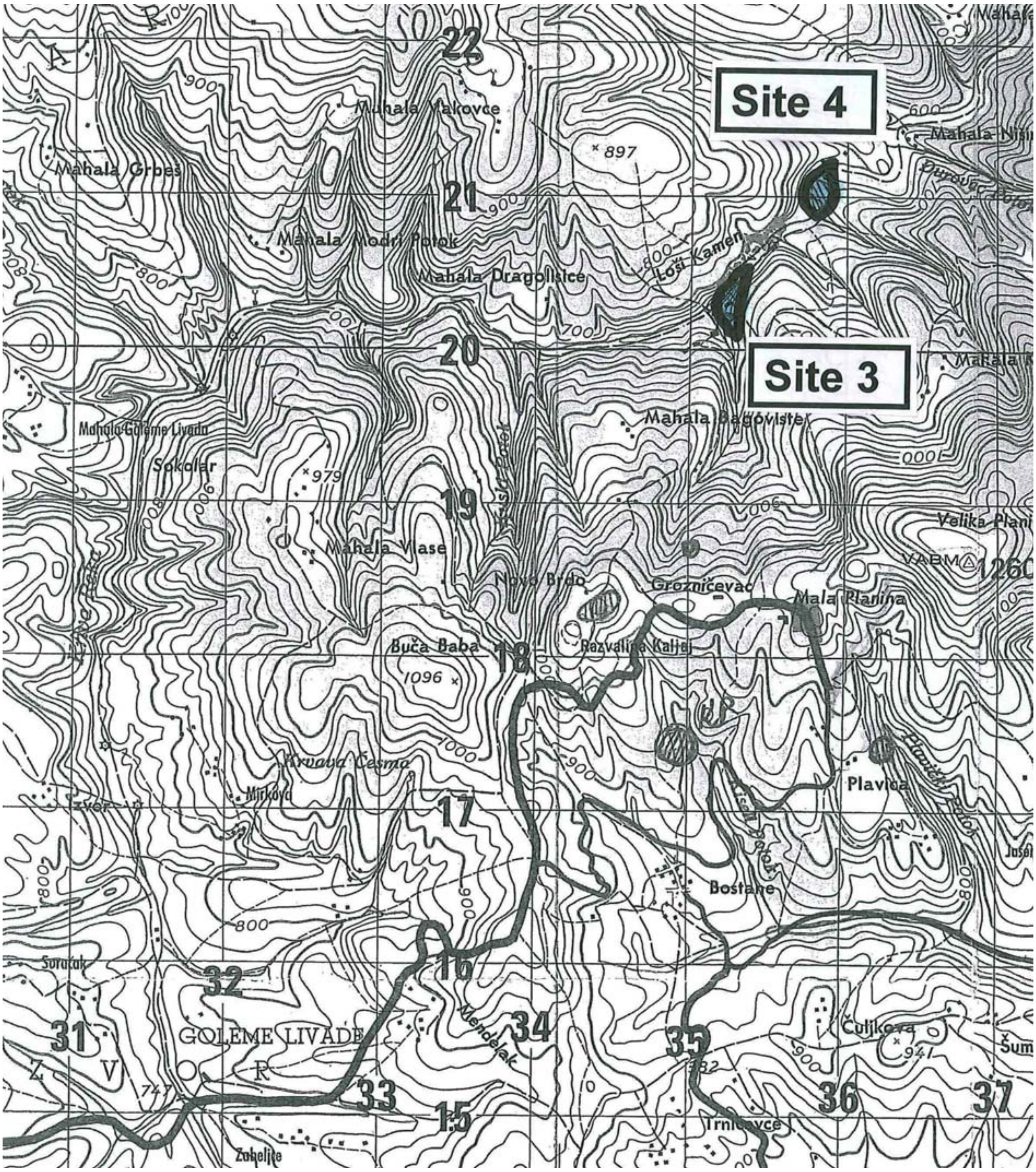


*Figure 13 - Location map of tailings sites n° 3 and n° 4 of the Artana/Novo Brdo area*

## 7.1. TONNAGES SUBJECT OF INTEREST

The 4 sites and the corresponding tonnages (in a preliminary assumption) subject of interest are listed in Table 4 below.

| **Identification of the site** | **Origin of the tailings** | **Tonnage presumed prior to the current survey** | **Location on fig. 12 and fig. 13 and work performed** |
|---|---|---|---|
| 1. Hillside reddish tailings from the Hajvalija mine and possibly of the Kishnica mine, on the right bank of the Gračanka river flowing down from the Gračanička Lake dam | Very old tailings from ore treatment in the Kishnica/Badovac concentrator | 11.5 Mt according to Deissmann *et al.* 2007; | Site n° 1 of Fig. 12<br><br>Photos 14, 15 from the asphalted road |
| 2. Grey tailings on the left bank of the Gračanka river coming from Lake Gračaničko, at the western foot of the Androvačka Plania hills | Old tailings from ore treatment of Novo Brdo mine (and of the Kisnica mine or other mines,) in the Kishnica/Badovac concentrator.<br><br>Locally: new tailings resulting from retreatment of old tailings described hereunder | 8 Mt<br><br>according to (Deissmann *et al.* 2007; | Site n° 2 of Fig. 12<br><br>Photos 16 to 19<br><br>One test sampling,<br><br>2 chemical analyses |
| 3. Grey tailings dam n°1 of the Marevc concentrator in the upper stream of the Krivareka river | Old tailings from the treatment of the ore of Artana/Novo Brdo mine in the Marevc concentrator | 0.4 Mt | Site n° 3 of Fig. 13<br><br>Bibliographical compilation |
| 4. Grey tailings dam n°2 of the Marevc concentrator in the upper stream of the Krivareka river | Old tailings from the treatment of the ore of Artana/Novo Brdo mine in the Marevc concentrator | 1.6 Mt | Site n° 4 of Fig. 13<br><br>Bibliographical compilation |
| **Total tonnage** | | **21.5 Mt** | |

*Table 4 - Main features of the 4 tailings dams of the Gračanica/Badovac and Artana/Novo Brdo areas*

## 7.2. TREATMENT METHOD AND ELEMENTS ALREADY POINTED OUT AS VALUABLE

### 7.2.1. Historical data about the treatment process

The treatment method of the Artana/Novo Brdo ore is conventional (Anonymous, 2005). The pulp is conditioned with zinc sulphate and sodium-cyanide to depress the zinc, and lead is floated using a xanthate collector and alcohol frother. Lime is added to the tailings from lead flotation to raise the pH and depress pyrite. Zinc is reactivated by the addition of copper sulphate before xanthate and frother are used to float the zinc.

For the ore coming from Artana/Novo Brdo between 1978 and 1988, a pyrite flotation circuit was also installed to produce a pyrite concentrate from the zinc tailings. For some years, pyrite was sold for acid manufacture but the arsenic content of the pyrite finally made it unmarketable. This pyrite circuit has not been operated for many years (Anonymous, 2005).

The tailings are now pumped from the concentrator to a pump-station and poured in the tailings dam of the Site n° 2 which fills the small valley at the western foot of the Androvačka Plania hills. This valley located 1 km north of the concentrator is a tributary (of left side) of the Gračanka river.

### 7.2.2. Volume and grade

The team of Trepča under UNMIK administration already pointed out (table 5.2 in Anonymous, 2005) grades of 0.60 % Pb, 0.56 % Zn, 12 g/t Ag, 18 g/t Bi and 0.032 % Cu remaining in these tailings. They estimate the tonnage of tailings in Site n° 2 at 8 Mt.

### 7.2.3. Rehabilitation in progress

On the old tailings sites n° 3 and 4 of the Marevc concentrator in the Krivareka river (the eldest tailings from Artana/Novo Brdo), there is currently a rehabilitation program (Bektashi, 2008) to reduce the environmental impact but there is no program for Badovac sites 1 and 2.

Therefore, within the frame of the French cooperation, special attention was paid to the possibility to eliminate or reduce the effect of the tailing dam of Badovac (site 2), by means of its valorisation as an ore.

## 7.3. THE BRGM TESTS IN SITE 2

For that purpose, BRGM did two test-samplings:

- the first one (sample n° 12 of Table 3 and Photos 15 to 17) was done in the tailings located at the crest of the dam, corresponding to the treatment of ore from Hajvalija mine (ore that was probably mixed with some ores from the other mines);

- the second (sample n° 15 of Table 3, Photo 18) was done at the inner bottom of the dam, at the top of the wet pond, in the tailings currently produced by the retreatment of the tailings which are transported by trucks from the tailings of the Marevc concentrator, corresponding to the treatment of the ore of the Artana/Novo Brdo mine.

The samples were collected according to the chip sampling method, after having dug the material over a depth of 50 centimetres in order to avoid the weathered and drained superficial crust of the tailings. The analyses were done in BRGM laboratory by the inductively coupled plasma atomic emission spectroscopy (ICP/AES) method for 34 elements, and by the inductively coupled plasma mass spectroscopy (ICP-MS) method for the traces of Ga, Ge, In, Se and Te.

Each 3 kg-sample yielded the results given below.

## 7.4. ADDITIONNAL VALUABLE ELEMENTS DISCOVERED

It must be stressed that BRGM sampling was just a test. Obviously, the tailings of Site 2 are not homogenous. The grade of the run of mine ore and the cut off grades having much changed from the beginning of the treatment of Novo Brdo ore in the Badovac concentrator (1978) to 1988 (and till the current recycling of old tailings), the tailings in Site 2 are composed of various layers.

Anyway, the results of the test are remarkable. They must be examined by comparison with the run of mine ore of Novo Brdo/Artana (Anonymous 2005) and with the various concentrates now produced with the material of Novo Brdo/Artana (samples n° 9, 10, 11, 13 and 14 described in chapter 6 and in Table 3).

Their contents in the most important elements are as follows :

Ag : 26 g/t (instead of 100 to 140 g/t in the run of mine ore, according to Anonymous 2005);

Zn : 1.35 % (instead of 4.8 to 5.4 % in the run of mine ore);

Pb : 0.59 % (instead of 3.7 to 4.4 % in the run of mine ore);

Cu : 568 g/t

Bi : 52 g/t

Ge : 9.9 g/t

Ga : 11 g/t

In : 6.6 g/t

Te : 5.4 g/t.

Gold is particularly remarkable : the test samples yielded 2.3 g/t Au in the old tailings, and 2.5 g/t Au in the tailings resulting from the re-treatment of the Marevc concentrator tailings. The Trepca/UNMIK team had reported (Anonymous 2005, and BRGM analyses made by Monthel *et al.* 2001) 1.3 g/t Au in the tailings of Artana (tailings of the Marevc concentrator). In the run-of-mine ore, gold grade is 0.8 to 1.4 g/t, according to Anonymous 2005 and to Bektashi 2008). Therefore it appears that gold is entirely or nearly entirely lost during the ore concentration, possibly because it is linked mineralogically with pyrite and pyrrhotite which are rejected within the tailings.

## 7.5. PENALIZING ELEMENTS

Besides the pyritous nature of the tailings, the two samples are particularly high in :

As : 0.563 %, and Cd : 76 g/t.

## 7.6. RECOMMENDATIONS

The BRGM test samples, although of poor representativeness, suggest that the current treatment in the Badovac concentrator is not adapted to a suitable recovery of gold. The previous tests (Anonymous 2005) proved the same, by pointing out 0.8 to 1.4 g/t Au in the ore of Artana and 1.3 g/t Au in the one million tons tailings of Artana.

Obviously, the losses in Ag, Pb, Zn, Cu, Bi, Ge, Ga and In during the flotation are important as well.

In conclusion, the 21 Mt tailings of the 4 tailing dams of this area warrant further tests (a mineralogical study to identify the minerals carrier of gold, systematic augerdrilling to assess the grades and tonnages, chemical analyses, reserve calculation, laboratory-scale and then pilot-scale beneficiation tests) in view of valorising a substantial part of their content in Zn, Pb, Cu as well as possibly in rare and precious metals among which gold seems very promising.

One part of these tests is in progress in the BRGM ore treatment department. They were launched as the logical follow-up of the investigations reported there. They will be the conclusion of the current scientific cooperation programme between Trepča and BRGM. They consist in laboratory scale gravimetric beneficiation tests of gold on the tailings samples n° 12 and 15 of table 3. These tests aim at identifying the minerals which host the gold. The first results suggest that the recovery of gold in this target would be hampered by the lack of free gold and by its location within the sulphides (pyrite, pyrrhotite etc.). The final results (expected for December 2009) will be communicated to the Director of Trepča and, upon his agreement, they will be, later on, published in a scientific paper signed by the scientists of both institutions.

# 8. Mineralogy, geological heritage and museography

These topics did not enter in the official agreement of cooperation between the authorities of Trepča and BRGM for 2007-2008. Nonetheless, they were permanently kept in mind by both parties.

Concerning the huge geological heritage represented by Trepca and by its mineralogical museum, the efforts of the Supporting Committee of Trepca Museum to promote interest and subsidies from international funding organizations have been pursued in 2007-2008 and the BRGM scientists have involved themselves (as previously) within the actions carried out and by personal contacts taken in Kosovo and elsewhere.

Nonetheless, no results are worth to be reported at the time this report is edited.

The posters of the exhibitions organized in 2006 in Sainte-Marie-aux-Mines (France) and in Munich (Germany) by the Committee and Euromineral Concepts with the back-up of Trepča and BRGM scientists, are still available free upon request for any further supporting action. For any inquiry, any help to suggest, or just to join the crew, the volunteers can write Email to musee-trepca@hotmail.fr or j.feraud@brgm.fr

Concerning mineralogy, a rather important discovery was simultaneously done in BRGM and in the Croatian Museum of Natural History in Zagreb : the discovery of kutnahorite within the carbonates of Stan Terg.

Both parties were independently assaying various mineralogical samples in their rock and mineralogical library.

In fact, in all the samples studied in Zagreb and in the one of BRGM, kutnahorite was not identified as an isolated mineral phase but within an association of several mineralogical carbonates of the same isomorphic group.

This discovery was published, as concerns the museum of Zagreb, in Žigovečki, Bermanec and Rajić Linarić (2007) and in Gobać, Zebec and Bermanec (2008), whereas Trepča and BRGM scientists published it jointly in Féraud, Maliqi and Meha (2007).

# 9. Conclusions

The new data and observations now available lead to a contemporary geological appraisal of the Trepča/Stari Trg deposit, concerning its geodynamic setting, its geological controls and metallogenic model, and finally its trace elements and particularly precious (silver, gold) and rare metals (bismuth, indium, etc.). The analyses done on the ore concentrates and of the flotation tailings of the Novo Brdo (Artana) ore deposit seem promising as well. Finally, concerning mineralogy, geological heritage and museography, a close cooperation has been settled in view of helping the famous Crystal Museum of Trepča to recover the world rank it deserves.

From the geodynamic point of view, the Trepča ore deposit is located in the western branch of the Alpine-Balkan-Carpathian-Dinaride belt (ABCD belt), in the External Vardar Subzone (EVSV of the current authors). It belongs to the carbonate replacement deposits type but on account of many features it belongs to the low-sulphidation epithermal deposits as well. It comprises a series of manto orebodies and mineralized skarns within the sedimentary carbonate platform known as the Stari Trg series. These orebodies make a hose shaped envelope at the contact with an Oligo-Miocene dacitic volcanic conduit partially brecciated.

Concerning the understanding of the controls of ore emplacement, within this envelope, thanks to the resumption of exploration and mining in the deepest levels of Trepča, interesting findings have been done in the "marmorised" limestones hosting the massive sulfide ore bodies. They point out the importance of carbonate dissolution phenomena at high temperature and the formation of hydraulic breccias within the host rocks of the ore deposit around the conduit. As had been presumed by Schumacher (1950), a phreatomagmatic brecciation is evidenced within the volcanic conduit. These findings suggest the role of maar-type explosions in the formation of the volcanic central pipe of Trepča and in the percolation of the metal-bearing hydrothermal solutions along the litho-stratigraphic contacts or cross-cutting them. The majority of schists in the fragments composing the breccia around the lava pipe, as originally noticed by Forgan (1948) and Schumacher (1950, 1954), resulted probably of the greater ability of schists to be fragmented by such steam explosions compared to the marbles and the chilled dacite. We suggest to particularly seek for maar ring volcanic features (base surge structures, bomb sags etc.) within the Tertiary volcano-sedimentary deposits and ignimbrites overlying the Trepča area, to verify this hypothesis.

Concerning the karstic model of one part of the ore deposit, in the light of these observations, the age and role of the karstification itself in the metallogenetic process is debatable. It must be understood more as a dissolution process at hot temperature contemporaneous with the progress of hydrothermal fluids than as the karstic fillings of pre-existing, empty or watered cavities observed in the usual Pb-Zn ore deposits under unconformity that are common in the Jurassic carbonate platforms of the Tethys belt.

Concerning the grades in rare and precious metals of the ore, the analyses performed on the run of mine ore and on three new lots of Zn and Pb ore concentrates assessed significant contents in Ag, Bi, Cu and Au, with indications of In, Te, Ga and Tl. The increasing abundance of In and some of these rare metals downdip suggests valorisation of selective mining of elevated grades, profitable for the high-tech industry in the next years. Special attention must be paid to identify and locate the mineral species that may bear the various rare metals (Au, In etc.) ; according to the results, selective mining could be recommended for the orebodies of higher grade in these by-products. As a whole, Trepča as well as other Zn-Pb ore deposits of the same type in Kosovo, like Novo Brdo and Kišnica, warrant further detailed investigations concerning the high-tech metals (these studies are currently in progress within the frame of a further step of collaboration between the Trepča Geological Survey and BRGM).

South of Trepča, the rather important grade of indium in the zinc-concentrate of the Novo Brdo zinc-lead mine, identified by Trepca/UNMIK in 2004, is confirmed (up to 200 g/t In). Moreover, the particularly attractive grade of the old tailings of Artana/Novo Brdo in gold, already identified by the geologists of Trepča, is confirmed by the present study (possibly up to 2.5 g/t Au). They represent a potential target the order of magnitude of which could reach 21 Mt ore containing around 30 t Au and 300 t Ag (these figures being currently hypothetic).

Therefore additional studies of these tailings (and of the other tailings dams and slags heaps not yet sampled in the whole Trepča district) are recommended. One part of them is already in progress in the BRGM ore treatment department, as a follow-up of the investigations reported there. They consist in laboratory scale gravimetric beneficiation tests of gold on the tailings samples n° 12 and 15 of table 3. These tests aim at identifying the minerals which host the gold. The preliminary results suggest that this target would be hampered by the lack of free gold and by its location within the iron sulphides (pyrite, pyrrhotite).

From a scientific point of view, the studies should be extended to a comprehensive mineralogical study of the mineral association of the whole Trepča ore district : since the pioneer important works of Strahinja Smejkal in 1956-60, this modern study has ever been warranted to better valorise the ores of this worldclass, still very promising district.

From an economic and sustainable development point of view, further investigations are warranted as well, to assess the valorisation possibilities of all the tailings, the related environmental issues and the tonnage. Thus could be developed the mining activities of this historical district whereas the environmental impacts of its old tailings dams could be reduced.

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# Appendix 1

# The discovery of kutnahorite in Stari Trg

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## *RAPPORT D'ESSAIS 06-6-037-C sur l'échantillon de Trepca n° JF1 désigné comme « kutnahorite présumée » par le demandeur J. Féraud*

1 **Nature de l'essai :**
L'échantillon provient d'une collection minéralogique ancienne privée ; il était étiqueté par une pastille en papier collée, ancienne, jaunie, libellée (à l'encre) « kutnahorite Trepca »
La fraction cristallisée de l'échantillon est déterminée par diffractométrie des rayons X à partir de son diagramme de poudre. Cette technique est surtout qualitative et ne peut donner qu'une indication semi-quantitative. Le seuil de détection est de l'ordre de 5%, mais peut largement varier en fonction de la nature des différentes phases.
Une phase dite « amorphe aux rayons X » peut être : une phase non cristallisée ou une phase cryptocristalline.
L'échantillon a également fait l'objet d'une étude au microscope électronique à balayage.

2 **Appareillage et conditions expérimentales :**

**Analyse par D.R.X. :**
Appareillage : Diffractomètre SIEMENS D5000 automatisé
Conditions expérimentales :
- Balayage de 4 à 84°2θ
- Vitesse de balayage de 0,02°2θ/seconde
- Temps de comptage : 1 seconde par pas
- Echantillon tournant

Traitement des diagrammes : Logiciel DIFFRAC$^{plus}$

**Analyse par M.E.B.** :
L'échantillon a été examiné par microscopie électronique à balayage (MEB, JEOL 6100) associée à un dispositif d'analyse chimique ponctuelle par spectrométrie des rayons X dispersive en énergie (EDS, KEVEX Quantum), à 25 kV après métallisation au carbone afin de rendre l'échantillon conducteur.

3 **Résultats d'analyse**

Echantillon Trepca n° JF1 (« kutnahorite présumée »

L'échantillon a été observé sous binoculaire et fait l'objet de photos (figure n°1). On a pu observer un empilement de rhomboèdres face gauche.

**Figure 1, photos numérique de l'échantillon n° JF1 analysé.**

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## *RAPPORT D'ESSAIS 06-6-037-C sur l'échantillon de Trepca n° JF1 désigné comme « kutnahorite présumée » par le demandeur J. Féraud*

Un prélèvement a été effectué afin d'opérer à une analyse par diffractométrie des rayons X (DRX) sur poudre, et une analyse au microscope électronique à balayage (MEB, sur poudre et sur échantillon brut).
Les résultats de l'analyse par DRX (diagrammes en annexe) indiquent la présence de rhodochrosite (le pic majeur étant légèrement décalé sur la gauche) et d'une phase à structure dolomitique donc le pic majeur est situé entre celui de l'ankérite et celui de la kutnahorite. Les observations au MEB ont permis de mettre en évidence que la rhodochrosite contenait du calcium dans sa structure (figure n°2), et que la phase dolomitique était un carbonate à Ca, Mg, Fe et Mn. Ceci confirme les informations obtenues par la DRX.

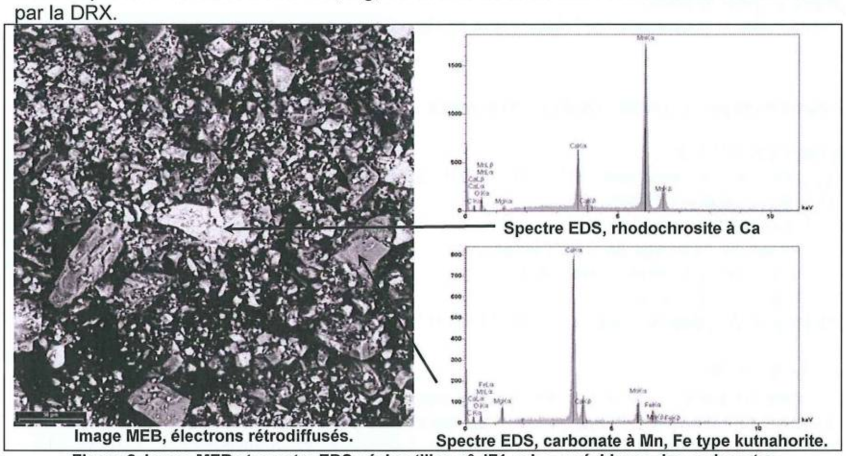


**Figure 2, image MEB et spectre EDS : échantillon n° JF1, mise en évidence des carbonates.**

On a pu également bien voir l'empilement des structures dolomitiques sur un cœur de rhodochrosite (figure n°3).

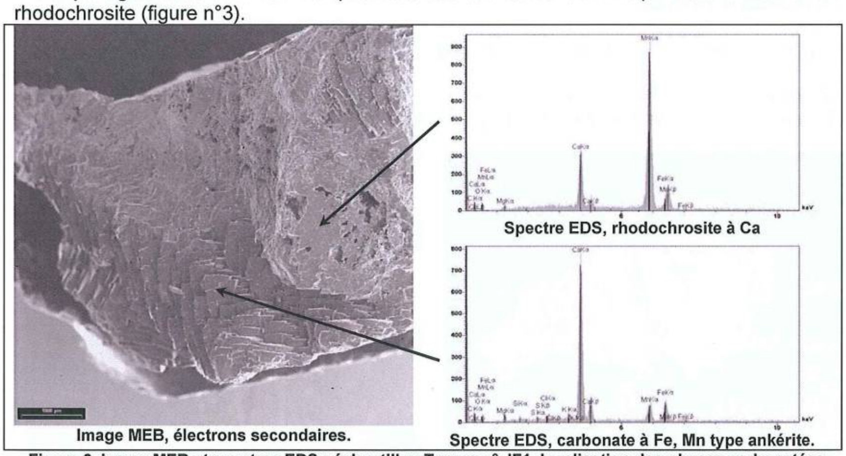


**Figure 3, image MEB et spectres EDS : échantillon Trepca n° JF1, localisation des phases carbonatées sur l'échantillon « brut ».**

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Cependant, les spectres EDS ne permettent pas de distinguer strictement si on est en présence d'une kutnahorite à Fe ou d'une ankérite à Mn, le ratio Fe/Mn semblant se rapprocher de 1, parfois légèrement favorable à Mn et encore parfois légèrement favorable à Fe. On distingue même une autre composition Fe/Mn plus riche en Mg (figure n°4).

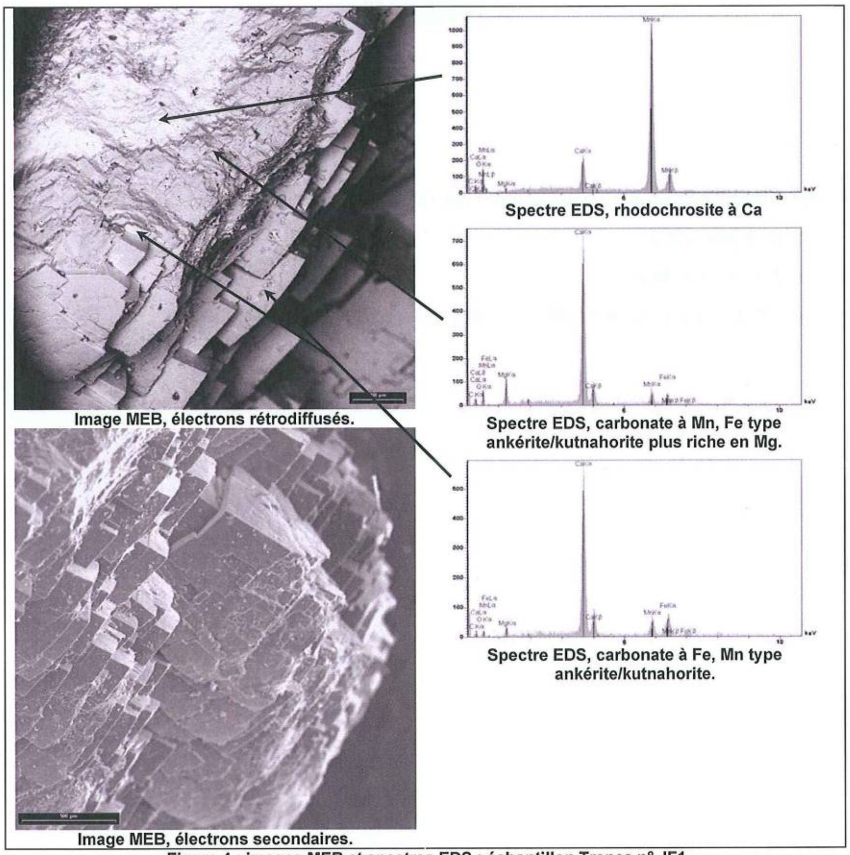


**Figure 4 : images MEB et spectres EDS : échantillon Trepca n° JF1.**

### 4 Observations

Des analyses complémentaires quantitatives sur le fer, le manganèse et le magnésium présents dans les carbonates dolomitiques, pourraient permettre un classement statistique des phases en présence afin de voir la représentativité ankérite/kutnahorite/dolomite dans l'échantillon.

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# ANNEXE

- Le diffractogramme interprété avec les références internationales J.C.P.D.S. (mise à jour 2003)
- Le diagramme brut
- Le diffractogramme avec les valeurs (en Å) attribuées à chaque pic

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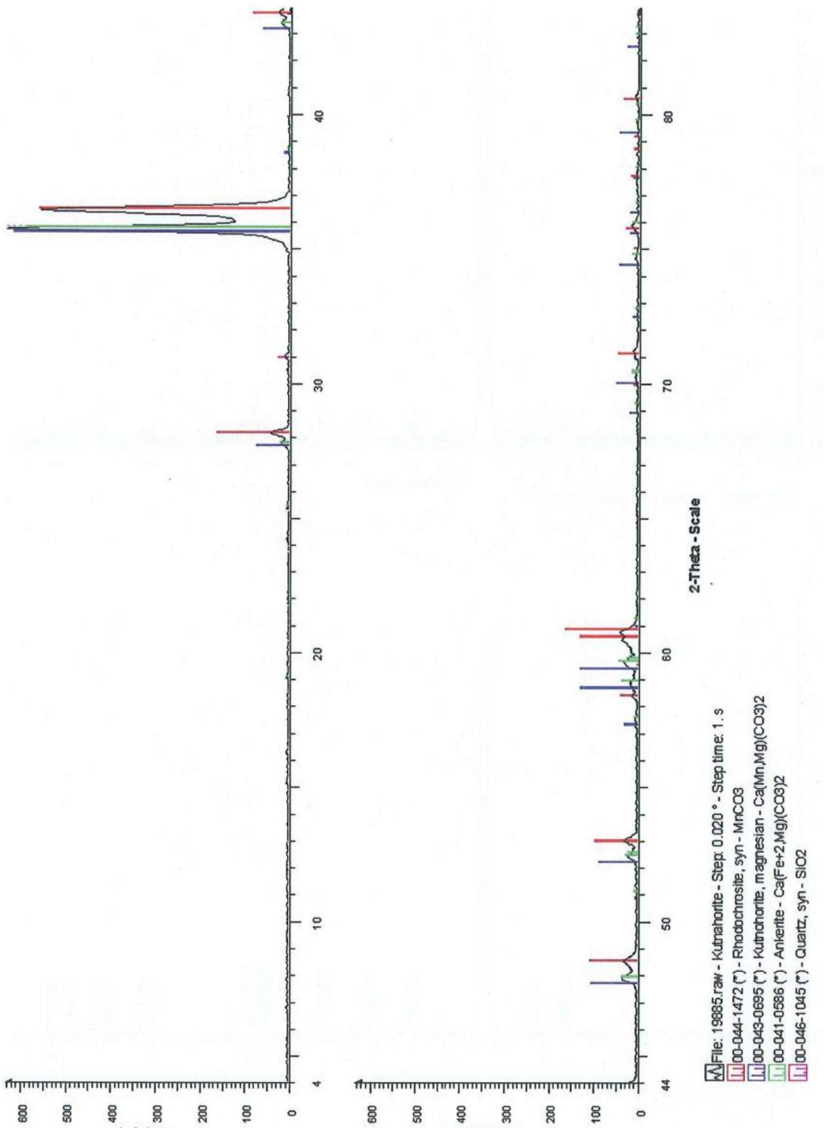


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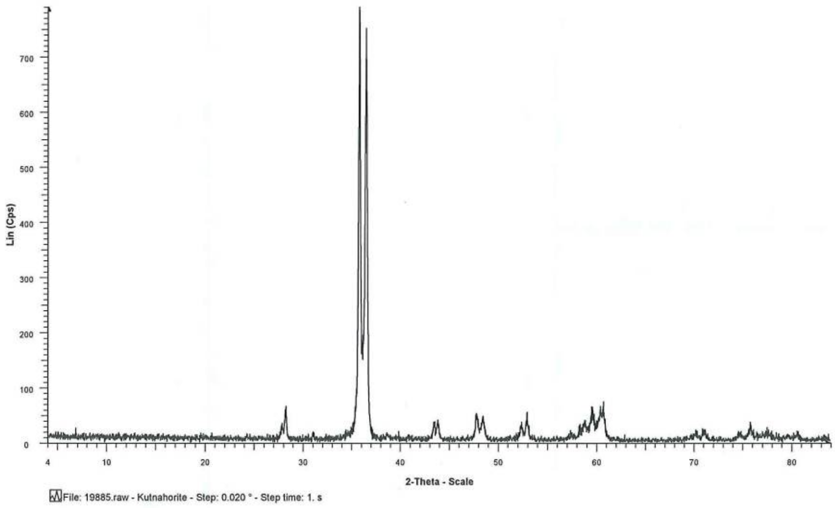
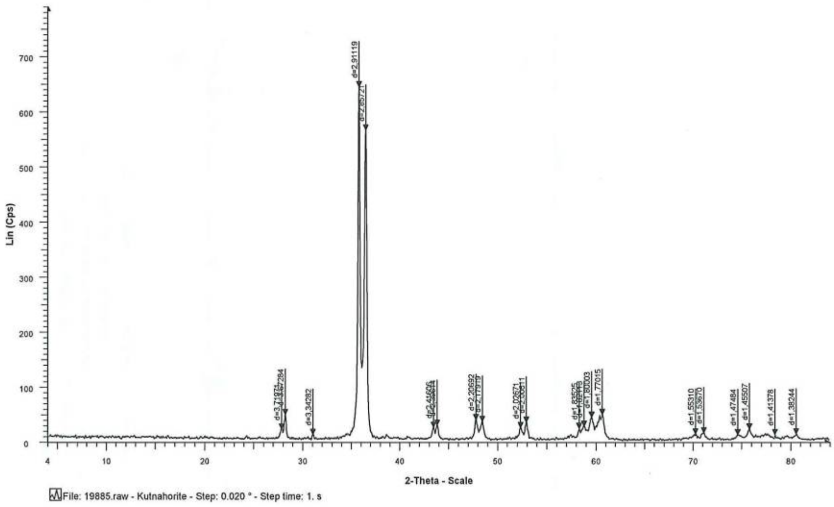
**RAPPORT D'ESSAIS 06-6-037-C sur l'échantillon de Trepca n° JF1 désigné comme « kutnahorite présumée » par le demandeur J. Féraud**

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