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Evidence of a high quality barite in Drâa-Tafilalet region, Morocco: a non-upgraded potential

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Abstract

With production exceeding 2/3 (between 2010 and 2016) of the national production of barite, Drâa-Tafilalet region is an outstanding mining region especially for this industrial mineral. However, the mining activity of the barite in the region suffer many problems and dysfunctions related to exploration, exploitation and treatment. This situation decreases the economic value for the barite. Thus, strike and dip analysis of several vein deposits have been done; also, microscopic and chemical analysis were carried out. Results indicates a high quality ore (mean density = 4.30 g/cm^3, $SrSO_4$ = 2.35%, SiO_2 = 2.04%, Fe_2O_3 = 1.03% and low levels of clays and carbonates), that should be used in industries rather than petroleum drilling. Many technical actions must be taken at the three stages of mining activity. Three objectives aimed of this study : i) increase the participation of the barite mining activity in the regional and national economy ii) preservation of the potential of the region's barite deposits iii) safeguard the region's naturel landscape.

1. Introduction

Fuelled by the rapid expansion of the economies of developing countries such as Brazil, China, and India, the demand for oil and gas has risen rapidly. This increase in demand, plus improvements in technology, has resulted in a substantial increase in worldwide exploration for oil and gas and with it an increase in production and consumption of barite.

Mining activity in Morocco is very old. Its first known development dates back to the 9th century. Taking advantage of a favourable geological context, the mining industry plays a very important role in the economic and social development in Morocco. The importance of this sector is reflected by its Gross Domestic Product (GDP) contribution of 5% in 2015, and its weight in the national exports which was for nearly 27% in 2015 (Moroccan Ministry of Economy and Finance). The number of direct jobs created by this sector is over 67700, i.e. 0.6% of the employed population (Moroccan Ministry of Economy and Finance).

The Kingdom of Morocco is a country that has a long mining tradition [1]. This strong mining activity is explained by the richness and diversity of its mineral resources. Thus, Morocco contains 3/4 of the world's phosphate reserves, it is also the third largest producer and the first exporter of this substance in the world, and it is the world's leading exporter of phosphoric acid with a share of 50% of the international market [2]. In addition to phosphates, many minerals are mined: coal, silver, gold, zinc, copper, cobalt, manganese, antimony, iron, barite, gypsum, fluorite, salt, clays, pyrophyllite, talc, feldspar, mica and calcite [3-10].

Morocco is also one of the world's leading producers of certain minerals. Therefore, it is the Africa's 1st and the world's 14th largest producer of silver. It is also the Africa's first and the world's 11th lead producer, the 2nd largest producer in Africa and the 16th the world for zinc, and the world third largest producer of barite [2].

Drâa-Tafilalet region is administratively the eighth region of Morocco (Figure 1); it contains five provinces, which are Errachidia, Midelt, Ouarzazat, Tinghir and Zagora. This region occupies a very favourable geological position in Morocco, and its subsoil revealed numerous mineral deposits. It has always been considered a region with a great mining vocation. For a long time, it has been the site of an appreciable silver-cobalt-zinc-lead-barite production. Several hundred of zinc-lead-barite deposits are known and have been the subject of mining works.

Artisanal mining activity or "Artisanal and small scale mining activity" carried out in this region is governed by the Dahir (Royal decree) of 1st December 1960. This which also created the "Centrale d'Achat et de Développement de la région minière de Tafilalet et de Figuig" (CADETAF), that is a public institution with a financial autonomy, it is under the supervision of the Ministry of Mines.

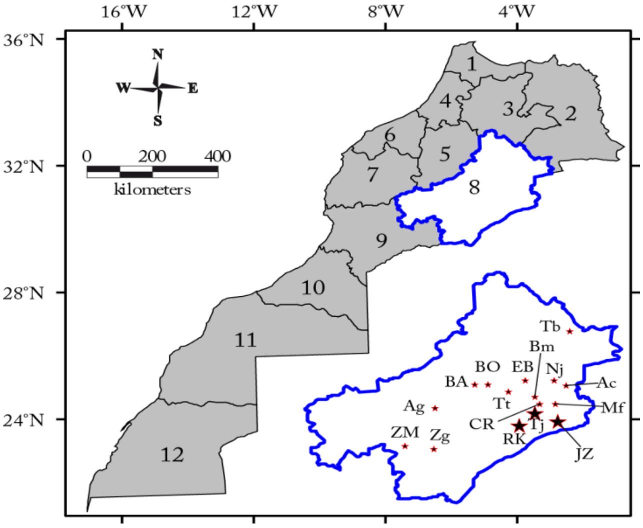

Figure 1: *Geographical position of Drâa-Tafilalet region in Morocco (Moroccan map), and position of some studied mines into the region (map of the region in blue). 1- Tanger-Tétouan-Al Hoceïma, 2- L'Oriental, 3- Fès-Meknès, 4- Rabat-Salé-Kénitra, 5- Béni Mellal-Khénifra, 6- Casablanca-Settat, 7- Marrakech-Safi, 8- Drâa-Tafilalet, 9- Souss-Massa, 10- Guelmim-Oued Noun, 11- Laâyoune-Sakia El Hamra, 12- Dakhla-Oued Ed-Dahab, Ac- Achguig, Ag- Agdz, BA- Bou Adil, Bm- Boumaiz, BO- Bouizriri Ouest, CR- Chaib Ras, EB- Erfoud Boulaagadi, JZ- Jbel Zorg, Mf- M'fis, Nj- Njakh, RK- Ras Kammouna, Tb- Tabouaroust, Tj- Tijjekht, Tt- Tikertouchène, Zg- Zagora, ZM- Zagora Milha.*

A number of opencast workings and underground mines show a clear evidence of extensive of artisanal and small mining activities for barite subject of this work, because this substance has an outcrop and subcrop character, and easy to exploit. Despite the socio-economic contribution of this mining activity in the local and national development, a numerous of problems have been recorded; they are materialized by some dysfunctions in terms of geological exploration, mining exploitation and processing. In generally the mines workings show no modern mechanised mining techniques. All vein barite deposits are exploited archaically (Figure 6A) without using any geological preparation and the use of non-adapted exploitation technics. Another source of the lack of in-depth preliminary prospecting, this is essential in mining industry but in the context artisanal mining activity for barite in this region is limited some time to "intuition". Consequently, the miners follow the visible mineralization vertically and laterally without having a clear idea of the location and grades of the mineral reserves. This exploitation method makes unacknowledged the deposits, and makes impossible their exploitation with respect to the international standards. Finally, despite of facility of the treatment of barite ore, this activity is very rare or absent in this studied region. This situation decreases the economic value of the ore and increases the transport costs.

This paper presents the situation of the artisanal and small mining activity of barite ore in Drâa-Tafilalet region, and a contribution to suggest some thoughts for a better management of the barite ore for the improvement of the mining activity, and this in order to create the conditions of its sustainable development.

2. General points

2.1. Properties of barite mineral

Barium sulphate have a chemical formula $BaSO_4$. It's a highly water insoluble sulphate salt; s = 2.448 mg/l (20°C), $Ks = 1.0842 \times 10^{-10}$ (25°C).

The crystal structure of orthorhombic sulphates $BaSO_4$ ($Ba^{2+}[SO_4]^{2-}$) was first determined by [11]. Since it has been refined many times using conventional X ray [12, 13]. More recently, [14] refined structures of isostructural orthorhombic sulphates: celestite ($SrSO_4$), anglesite ($PbSO_4$) and barite ($BaSO_4$) by Rietveld methods using synchrotron high-resolution powder X-ray diffraction (HRPXRD) data. Structural model was refined in space group Pnma. The unit-cell (Z= 4) parameters for $BaSO_4$ are a = 8.88101 Å, b = 7.15505 Å, c = 5.45447 Å, and $V=346.599 Å^3$ (Figure 2A). The average <M-O> distance is 2.953Å and average <S-O> distance is 1.471 Å. X-ray powder pattern for a synthetic barite show 3.445 (100), 3.103 (95), 2.121 (80), 2.106 (75), 3.319 (70), 3.889 (50), 2.836 (50). Barite mineral have perfect cleavage on [001], less so on [210], and imperfect on [010] (Figure 2B).

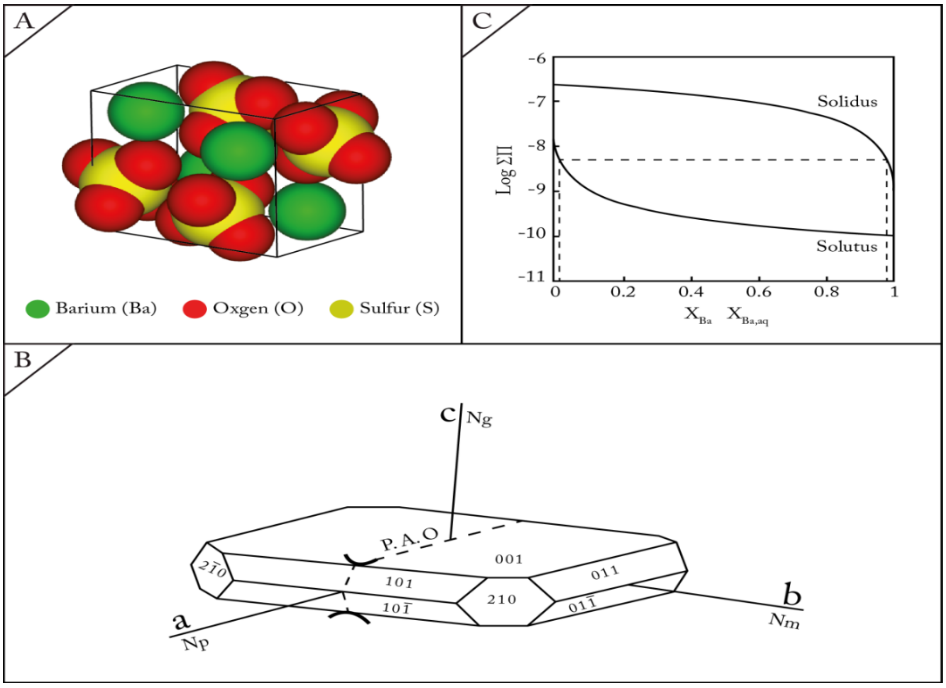

Figure 2: *Barite conventional cell (A), main crystal plans of barite (B) and Lippman diagram for an ideal (Ba,Sr)*SO_4 *solid solution (C).* $\Sigma\Pi$ *is the total solubility product defined as* $[SO_4^{2-}]([Ba^{2+}][Sr^{2+}])$*, where* $[SO_4^{2-}]$,$[Ba^{2+}]$ *and* $[Sr^{2+}]$*, are the activities of this ions in the aqueous phase.*

Strontium is by far the most common impurity in natural barite [15-17]. Strontium occurs as celestite $SrSO_4$. Most natural barite contains less than mol 7% ($SrSO_4$) and most celestite contains less than mol 4% ($BaSO_4$) [17-19]. Intermediate composition are very rare. Lippman diagram is a powerful tool to study aqueous solutions – solid solutions equilibrium. Figure 2C illustrate such diagram for an ideal (Ba,Sr)SO_4 – solid solutions. This shape of the diagram is a result of large ratio between $BaSO_4$ and $SrSO_4$ solubility products log Ks = -10.05 for Barite and log Ks = -6.63 for celestite. Horizontal lines can be drawn between solutus and solidus curves thereby giving solid phase and aqueous phase compositions of possible thermodynamic equilibrium states. According to this diagram, an aqueous solution (dashed lines) even with very small barium to strontium ratio will be at equilibrium with a weakly substituted barium solid phase (almost pure barite). Therefore, at equilibrium, a large fractionation between strontium and barium exist. This explains bimodal distribution of natural barite and celestite composition.

2.2. World, Moroccan and Drâa-Tafilalet production of barite

In descending order of production, China, India, Morocco, and the United States were the leading producers of barite. These four countries accounted for 79% of estimated world barite production, where Morocco is the third world producer of barite after China and India. According to recent data published by the United States Geological Survey (USGS), the Moroccan barite production between 1998 and 2016 has exceeded 11.5 Mt after China (70.3 Mt) and India (19.8 Mt) and before the United States of America (9.8 Mt) (Figure 3A). During this period, Moroccan production experienced stagnation between 1998 and 2005 (an average of 0.36 Mt), followed by continued growth from 2006 to 2014 (from 0.56 to 1.2 Mt) (Figure 3B). The productions of 2015 and 2016 are respectively 1 and 0.7 Mt. (Data synthetized from the USGS).

On the scale of the Kingdom of Morocco, Drâa-Tafilalet region is a leader in term of barite production. Thus, according to data provided by the energy and mines department of the region (Moroccan governmental institution), the region provided 68% of barite produced in the country between 2010 and 2016 (60% in 2010, 74% in 2011, 71% in 2012, 55% in 2013, 65% in 2014, 93% in 2015 and 56% in 2016) (Figure 3C). These figures clearly show the mining potential of the region and its contribution to the regional and national economy.

2.3. Uses of barite

The Barite is a mineral substance whose particular characteristics enable it to be used in several fields. Its high density and chemical inertness – highly insoluble even in high concentrated acidic medium [17] – make it an ideal mineral for many applications. Worldwide, about 80% of the barite is used for oil drilling (weighting agent), 10% as a mineral filler (paints, brake pads, soundproofing for cars) and in the construction industry (baritic bricks and heavy concrete), and 10% in barium chemistry (mainly specialty glasses) and metallurgy. The US is the largest consumer country, around 3 Mt / year (2.7 Mt in 2013), ahead of China (1.45 Mt) and The Gulf states (0.7 Mt) [20].

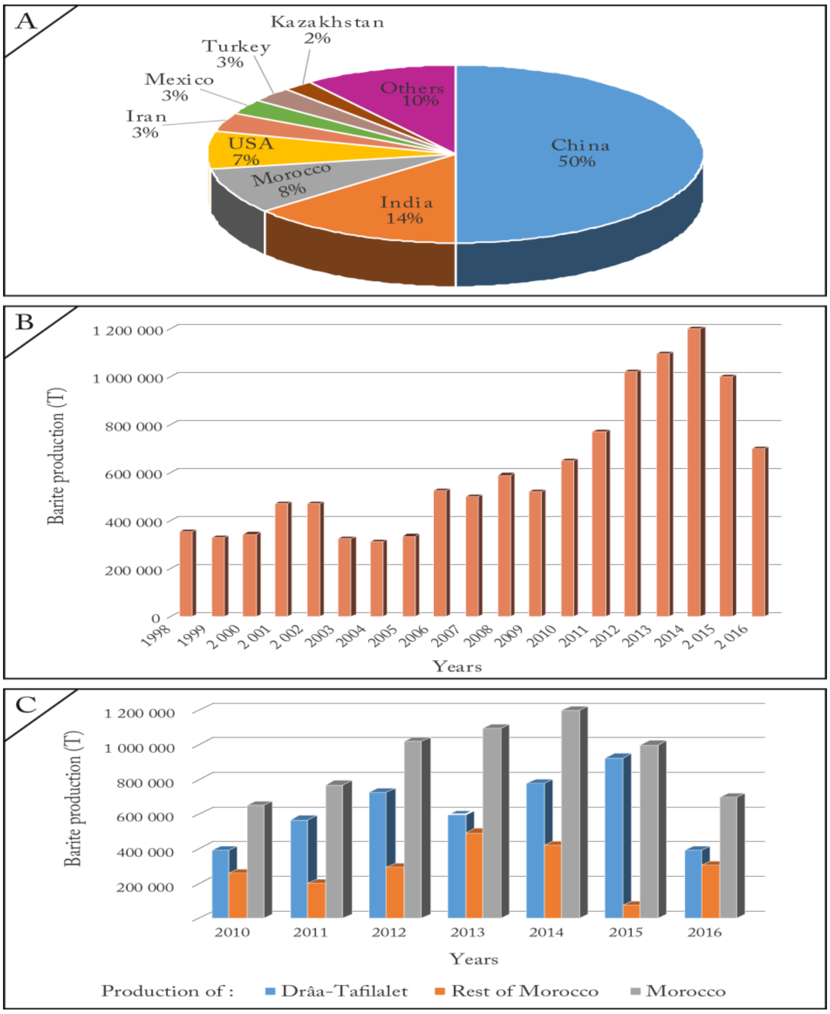

Figure 3: *World and Moroccan production of barite between 1998 and 2016 (A) and (B) respectively, and detail of Moroccan production between 2010 and 2016 (C) (Source: USGS).*

So, most barite produced in the world is used as a weighting agent in drilling muds. These high-density muds are pumped down the drill stem, exit through the cutting bit and return to the surface between the drill stem and the wall of the well. This flow of fluid cools the drill bit and the high-density barite mud suspends the rock cuttings produced by the drill and carries them up to the surface.

Barite is also used as a pigment in paints and as a weighted filler for paper, cloth and rubber. The paper used to make some playing cards has barite packed between the paper fibers. This gives the paper a very high density that allows the cards to be "dealt" easily to players around a card table. Barite is used as a weighting filler in rubber to make "anti-sail" mudflaps for trucks.

Barite is the primary ore of barium, which is used to make a wide variety of barium compounds. Some of these are used for x-ray shielding. Barite has the ability to block x-ray and gamma-ray emissions. Barite is used to make high-density concrete to block x-ray emissions in hospitals, power plants, and laboratories.

Barite compounds are also used in diagnostic medical tests. If a patient drinks a small cup of liquid that contains a barium powder in a milkshake consistency, the liquid will coat the patient's esophagus. An x-ray of the throat taken immediately after the "barium swallow" will image the soft tissue of the esophagus (which is usually transparent to x-rays) because the barium is opaque to x-rays and blocks their passage. A "barium enema" can be used in a similar way to image the shape of the colon. Thus, it is used in the manufacturing of medicine and chemical derivative.

Finally, barite is also used in a wide variety of other applications including plastics, clutch pads, rubber mudflaps, mold release compounds, radiation shielding, television and computer monitors, sound-deadening material in automobiles, traffic cones, brake linings, paint and golf balls.

It should be noted that barite can be substituted with other materials. Therefore, possible substitutes for barite, especially in the oil drilling industry, include other similar minerals, such as celestite (strontium sulphate, $SrSO_4$)

and iron ore. A German company is producing synthetic iron ore (hematite) which is proving a good substitute for barite. However, these alternatives have yet to be widely used in the oil industry, and barite continues to be the preferred commodity for this application as long as barite production remains strong.

2.4. Methods of mining and processing of barite

The type of the ore deposits (vein, stratabound or residual) and their morphology conditions the exploitation of barite. It is therefore made either underground or in open-pit. In industrialized countries, since underground mining is expensive, this type of exploitation has generally ceased and replaced by open-pit method. However, in countries with large and cheap labour force, artisanal and semi-industrial exploitation methods are used. In addition, when vein-type deposits are small, the underground exploitation is chosen.

According to [21], barite processing is relatively simple and does not require very expensive means. Several processes have been developed and used; each method has its own unique requirements and limitations. The processes that can be used are hand selection, screens, washing, jigs, tables, spirals, and flotation. One or a combination of several different methods may be required to separate the waste from the barite.

Hand Selection can be done in areas where the cost of labour is low and/or where hand selection will achieve the desired quality of barite. In some areas of the world, the cost of labour is low enough that the barite deposit can be mined and the barite separated from the waste by manual labour. The labourers must be able to easily identify the ore and determine quality. To aid in the separation, the waste and ore should have different colours or other physical differences that are easily discernible by eye. A deposit of high -purity white barite flanked by brown sandstone would be easy to separate by hand. There are optical sorters that can remove off-white product, but nothing is better than the human eye and hand; because two properties must be taken into account: color and density.

Screening or the combination of crushing and screening can remove some clays, fine-grained waste, or other waste with different breaking characteristics than barite. Screens are ideal for removing some clay and subsoil, with the barite produced as oversize and the waste as fines. This removes the lower specific gravity material and raises the specific gravity of the final barite product. In some cases, screening has been used to raise the specific gravity of ore from a deposit that consists of shale and barite.

Washing the ore with a dewatering screw, barrel screen, or logs removes special types of clays and subsoils where material is hard to break up. A washing-type system is used mainly with residual type deposits, but can be used on other deposits as well. The object of this method is to remove large amounts of clay from the rock material. The material can be either ore-bearing material that will be sent to an additional process to complete the separation or material that will meet specifications without any additional work.

Jigs are used all over the world to separate barite from other rocks and minerals. Jigs use pulsating water to separate barite from the waste by gravity. The feed must be crushed finer than a predetermined liberation size, namely the size to which the ore must be crushed to liberate the barite from the waste. The feed size also must be the size that the jig can handle. Several different brands of jigs and several different jig configurations are available. The pulsating water lifts the feed material, allowing the heavy barite to sink to the bottom. The lighter waste stays at the top and is washed off the end of the jig. The barite is removed from the bottom by what are called "cups". A cup is a pipe about 1 cm above the screen to the top of the jig. The barite fills the pipe from the bottom. The material is then removed by a series of pipe or slides. In some cases, jigs are used in series to upgrade the material. There must be a difference in the specific gravity between the waste product and the barite for this method to work.

Spirals and Tables are used infrequently because of the cost to operate the units. Both methods use specific gravity and the material movement to separate the waste from the ore. The mineralurgical enrichment based on the principle of magnetic separation is used when the barite is associated with ferromagnetic minerals.

Flotation is used when the liberation size is finer than what a jig or other equipment can handle. Normally, the feed for a flotation cell is 40 mesh or finer. The flotation method uses a chemical to float either the barite or waste into a froth. The separated barite is normally called a filter cake, because a filter is used to remove the excess water from the barite.

3. Results and discussion

Mining activity related to the barite deposits in Drâa-Tafilalet region know many problems in the three steps of production: exploration, exploitation and processing. However, a high quality of the barite in many deposits of the region is devalued as a result of numerous dysfunctions. Thus, based on field data, microscopic observations and chemical analyses of ore samples taken from numerous deposits of the region, we note a set of malfunctions and offer valid solutions for a real development of the mining activity in the region. These solutions would allow the increase of the economic value of the barite, whose Drâa-Tafilalet region is by far the main producer in Morocco.

3.1. Geological setting

Drâa-Tafilalet region covers various geological domains; i.e. a large part of the Anti-Atlas domain and a large portion of the central and eastern High Atlas chain. i) The central and oriental high Atlas are characterized by Mesozoic series structured by alpine orogeny. ii) The south-atlasic basin and Hamada are formed by tabular Cretaceous and Cenozoic series. iii) The middle and oriental Anti-Atlas belt are formed by the inliers of Siroua, Zenaga, Bou Azzer, Saghro and Ougnat made of Precambrian bed-rock and their Palaeozoic cover represented mainly by the Tafilalet, Maider and Drâa plains (Figure 4). To the north, the region extends on the Ahouli-Mibladen Variscan inlier and on the Mesocenosoic formations of the Moulouya basin, and a small portion of the southern border of the Middle Atlas.

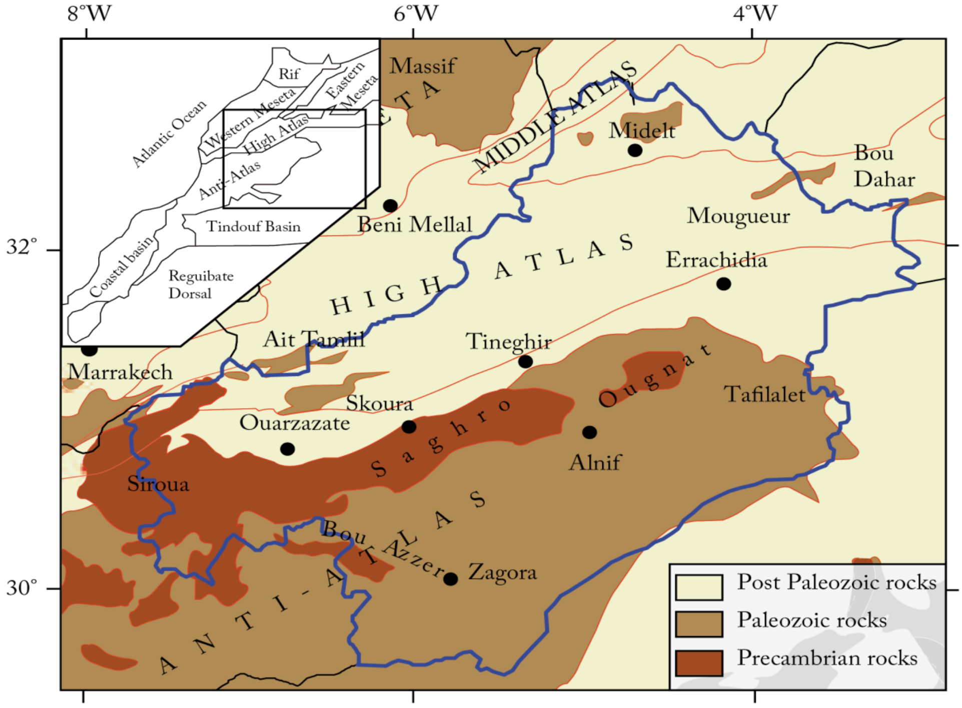

Figure 4: *Geological map of Drâa-Tafilalet region (extracted form[22]).*

3.2. Exploration, mining and processing

Most of barite veins deposits are hosted in the Anti-Atlas part of Drâa-Tafilalet region (Figure 1 & 4). No barite deposits have been found in the Hamada and Ouarzazate-Boudenib basin. Only, a few deposits are located in the Jurassic series of eastern and central High Atlas and in the Variscan inlier of Ahouli-Mibladen.

In our study area covered by Drâa-Tafilalet region, a big number of barite deposits are visited. These deposits are illustrated in Figure 1. The exploration and exploitation of barite deposits are usually realized by persons (artisanal miners). Only a few companies are active in the sector. Neither the companies, nor the persons active in the sector make a real exploration such as mapping, geological cross-section, geophysical prospection and drilling. In order to get an idea of the general orientation of the different barite veins studied, a measurement campaign was carried out. The stereographic projection of 206 measures of various structures is established using the "Dips" software. The results are illustrated in Figures 5A & 5B. These Figures show clearly a dominance of the NE-SW directional family (Figure 5A) with a significant concentration of poles indicating a vertical-dipping; the average pole of the projected veins is oriented N135°,00° (Figure 5B). It is obvious that the direction of a vein does not influence its method of exploitation, but the value of the dip plays a principal role in the choice of the method of exploitation to be adopted.

As shown in Figures 5A & 5B, the barite mineralization of Drâa-Tafilalet region principally occur in the form of veins with a NE-SW orientation and showing a rectified dip. In the central and eastern Anti-Atlas, these veins are hosted in Precambrian and Paleozoic terrains. The main deposits are located on the Zagora-Taouz axis and are hosted mainly in cambro-ordovocian series (sandstone, siltstone and pelites) such as Jbel Zorg, Tijjekht and Ras Kammouna deposits (Figure 1). Only a few barite deposits are hosted in the calcareous Mesozoic series at the High Atlas. In this case, the deposits are vein or karstic type.

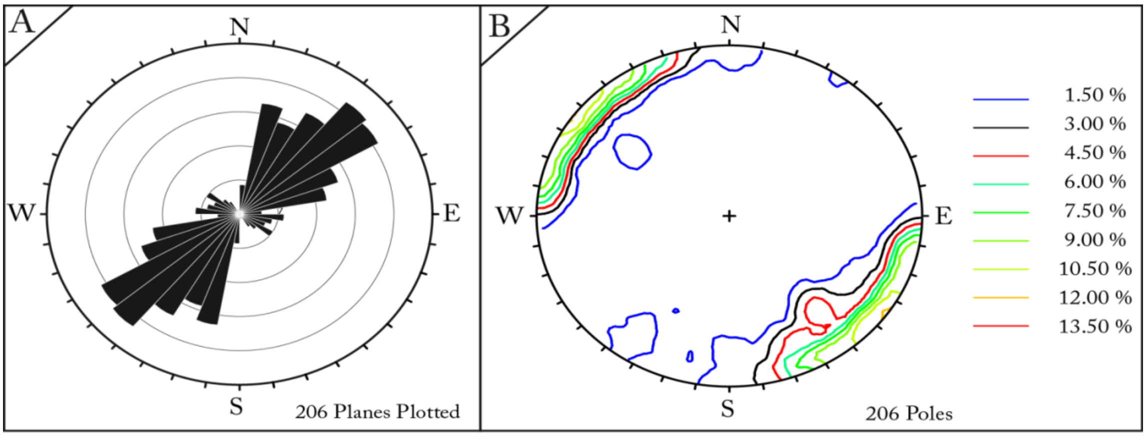

Figure 5: *Statistical orientation (A) and stereographic projections (B) of studied veins (equal angle, lower hemisphere).*

Most of the barite veins are exposed on outcrop; therefore, the artisanal miners use trenches to extract barite, they rarely use wells and galleries. This extraction method was observed in most of the sites presented above (Figures 1 and 6A).

Figure 6: *Exploitation of barite vein used in Drâa-Tafilalet region (A, d and E), appearance of barite after manual sorting, example of Tinejdad barite ore (B and C).*

Consequently, the deep part of the barite veins is abandoned as soon as the extraction becomes delicate and expensive. Three other problems arise because of trench extraction methods that operate from top to bottom: i) the contamination of barite ore by the sterile that fell as a result of explosive shocks and as a consequence of the activity of the big engines (machines). ii) The opening trenches to weather conditions result in their use by meteoric water and the filling of the mine by the water and the mud, and iii) the risks on miners working in the mine. On another side, barite veins exploitation by trenches has a terrible impact and irreversible changes in the natural environment of Drâa-Tafilalet region. The principal effects have been observed concerned the natural landscape and the security of humans and animals [23].

The mined ore of barite is not subjected to any type of valuation. Only the manual sorting is carried leading to a low enrichment of the barite. There is no type of enrichment as washing, jig, flotation, crushing or micronization. For a good choice of the appropriate processing method of the barite ore in studied deposit, deep microscopic and chemical studies are necessary.

3.3. Petrographic study

Macroscopically, barite minerals are colourless or white, often tinged with yellow, pink, black or bluish. The barite ore is usually massif with fine grained, it is sometimes in orthorhombic form with three cleavages or in crested form. Figures 6B & 6C show some examples of white barite ore.

The observation of the mineralization was made in the field and using an Olympus BX41 polarising microscope of the department of the geology (Faculty of Science and Technic of Errachidia). Thin sections are made in the petrography workshop of the department. The observation of thin section made at different barite ore from several mines shows that the barite minerals are associated in massive texture (Figures 7A & 7B). The barite minerals has usually a great size (upper of 1 mm) and are often arranged in the sheaf form (Figures 7A & 7B).

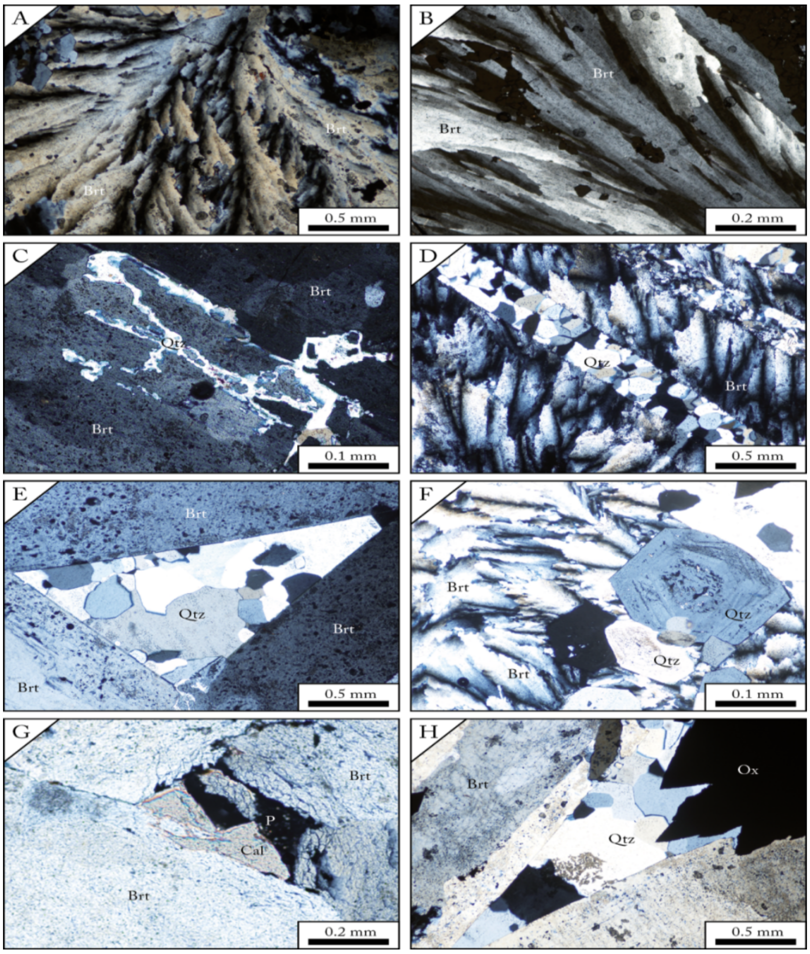

Figure 7: Photomicrographs of thin sections of barite ore derived from different deposits (transmitted light and crossed nicols). Sheaf structure of barite (A), elongated barite cristals (B), quartz within the barite (C), barite crossed by quartz veins in mosaic form (D), quartz in mosaic form within barite (E), automorphic cristals of quartz within barite (F), note the areas of hexagonal growth in quartz, barite-calcite-iron oxide association (G) and barite-quartz-iron oxide association (H). Brt: barite, Cal: calcite, P: pore, Qtz: quartz, Ox: iron oxides.

Several thin section of ore barite shows the presence of the quartz minerals who is often present in xenomorphic mosaic form, by filling small veins (Figures 7C & 7D) or by filling triangular spaces between phenocrysts of barite (Figure 7E). Euhedral quartz minerals are also observed (Figure 7F). Carbonates are rarely present in the form of the small xenomorphic minerals (Figure 7G). This carbonate is principally observed in the Tijjekht and in the High Atlas deposits of barite. Ferrous minerals are also present mainly in the M'Fis ore deposits (Figure 7H).

3.4. Chemical analyses and barite qualities

In order to get an idea of the quality of the different barite ores mined in Drâa-Tafilalet region, a representative quantity of barite samples from different sites have been analysed for chemical analyses and density measurements. The main data are given in Tables 1, 2 & 3. Density measurements were carried out using classical volumetric techniques. Chemical analysis of major elements Ba, Sr, Si, Al, Fe, K, Na, Ca were made using an UNICAM 929 atomic absorption spectrometer (FAAS), equipped with quadeline background correction. Colour parameters and heavy metals analysis (gratefully offered by Geomex sarl and Gem Alliance companies) listed in Tables 2 and 3 concern commercial samples.

Table1: Major elements analyses and density mesurments of some barite samples from Drâa-Tafilalet region (NA: not analyzed)

Sample's number	Sample's Code	Chemical composition (%)								
		BaSO4	$SrSO_4$	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Density
1	Zg-a	96.41	2.90	0.00	0.11	0.01	0.03	0.00	0.02	4.34
2	Zg-b	96.46	3.18	0.00	0.08	0.03	0.03	0.00	0.02	4.35
3	Ag-a	97.70	1.68	0.11	0.20	0.038	0.03	0.01	0.01	4.36
4	Ag-b	95.90	1.42	1.79	0.06	0.321	0.06	0.01	0.01	4.32
5	Tj-a	93.32	3.62	1.44	0.14	0.89	0.07	0.01	0.02	4.29
6	Tj-b	92.70	3.19	1.61	0.11	0.32	0.06	0.00	0.02	4.27
7	Tj-c	92.36	3.57	2.19	0.07	0.52	0.07	0.01	0.02	4.27
8	Tj-d	91.68	3.50	1.83	0.15	0.57	0.06	0.00	2.00	4.26
9	Tj-e	90.22	3.45	1.95	0.13	0.50	0.07	0.01	0.03	4.23
10	Tj-f	91.22	3.41	3.01	0.25	1.89	0.07	0.00	0.03	4.29
11	RK-a	89.34	2.00	4.68	0.35	1.78	0.77	0.13	0.04	4.23
12	RK-b	88.59	2.39	5.49	0.37	1.64	0.57	0.12	0.04	4.21
13	RK-c	89.11	2.71	3.06	0.25	3.73	0.33	0.05	0.03	4.29
14	RK-d	84.23	2.42	3.84	0.26	7.23	0.71	0.08	0.03	4.30
15	RK-e	92.14	2.17	3.29	0.26	1.22	0.32	0.08	0.03	4.27
16	Tj-g	96.98	2.03	0.24	0.07	0.03	0.03	0.00	0.03	4.34
17	Tj-h	98.20	1.10	0.10	0.10	0.10	0.10	0.11	0.01	4.38
18	Tj-i	98.30	1.20	0.05	0.10	0.01	0.05	0.05	0.02	4.40
19	Tj-j	97.20	1.20	0.75	0.10	0.32	0.10	0.10	0.00	4.39
20	Tj-k	98.40	1.10	0.10	0.10	0.10	0.10	0.12	0.04	4.40
21	Tj-l	96.40	1.50	1.70	0.05	0.01	0.10	0.40	0.01	4.40
22	Tj-m	90.90	1.80	3.20	0.10	1.20	2.30	0.30	0.02	4.31
23	Tj-n	94.40	1.30	1.50	0.10	1.70	0.50	0.02	0.00	4.35
24	Tnj-a	96.27	2.29	0.62	0.12	0.11	0.03	0.01	0.00	4.33
25	Tnj-b	94.01	5.21	0.27	0.00	0.17	0.03	0.20	0.05	4.33
26	Tj-o	89.90	1.40	7.40	0.21	0.28	0.17	0.06	0.02	4.18
27	Tj-p	97.70	1.20	0.20	0.10	0.16	0.09	ND	ND	4.36
28	Tj-q	95.60	2.60	0.40	0.15	0.65	0.07	0.02	0.00	4.35
29	Tj-r	95.20	3.50	0.30	0.10	0.29	0.09	0.02	ND	4.33
30	Tj-s	86.60	2.50	8.10	0.21	0.65	0.68	0.15	0.03	4.14
31	Tj-t	93.30	2.60	2.80	0.25	0.29	0.16	0.04	0.02	4.28
32	Tj-u	94.50	2.50	1.10	0.24	1.00	0.09	0.05	0.01	4.35
33	Tj-v	91.30	1.90	4.50	0.24	1.06	0.20	0.00	ND	4.25
34	Tj-w	97.10	1.70	0.20	0.10	0.24	0.09	ND	ND	4.34
35	Tj-x	87.50	2.10	6.20	0.18	1.33	0.97	0.07	0.01	4.16
36	RK-f	92.30	1.80	2.10	0.10	2.91	0.04	0.04	0.01	4.32
37	RK-i	85.40	1.90	3.90	0.25	6.20	0.65	0.11	0.03	4.29
38	Tj-y	76.80	1.40	0.80	0.39	0.46	19.80	0.30	0.11	3.96
39	Tj-z	91.30	1.90	4.50	0.24	1.08	0.45	0.25	0.12	4.25
40	Tnj-c	94.86	3.95	0.17	NA	0.26	NA	NA	NA	4.33
41	Tnj-d	95.34	2.74	1.04	NA	0.06	NA	NA	NA	4.32
42	Tnj-e	94.19	3.23	0.88	NA	2.40	NA	NA	NA	4.37
43	Tnj-f	96.69	1.88	0.47	NA	0.40	NA	NA	NA	4.35
Average		92.98	2.35	2.04	0.16	1.03	0.77	0.08	0.08	4.30

The domain of use of barite depends mainly on its physicochemical properties. So, according to the USGS, during 2003, approximately 95% of all the barite mined and processed in the United States was used by the petroleum industry. The industrial market and the medical field used the remaining 5%.

The American Petroleum Institute (API) has set specifications for the barite used in the oil industry [24]. These specifications primarily deal with specific gravity, particle size, and maximum quantities of some impurities. The barite must have a minimum specific gravity of 4.20 g/cm^3. It must also be ground to a powder where at least 97% will go through a 200 mesh sieve. The amount of water-soluble alkaline earth metals must be below a prescribed amount, 250 mg/kg. Barite deposits useful for oil and gas drilling must have barite that can be separated to give a minimum specific gravity of at least 4.20. However, the colour of the barite is not a factor.

As showed by barite analysis performed on several samples derived from different mines of Drâa-Tafilalet region, there is different qualities of barite in this region (Table 1). Concerning density, there are some samples with low, medium and high densities, but the majority of the analysed samples show densities greater than 4.3. As mentioned above, a specific density of 4.20 is sufficient for use in the petroleum industry. We can also easily note that the majority of sampled have a density greater than 4.35 and a percentage of $(Ba,Sr)SO_4$ greater than 97%, this category should not be wasted in petroleum uses; it would be more cost-effective to use it in the automobile industry.

The barite specifications for industrial products also involve specific gravity, particle size, and quantities of impurities. Some of these products have an additional specification for brightness or whiteness. The barite specifications vary depending on the needs required by the final product. For example, the barite in automobile brake lining normally has a specific gravity of 4.35 or higher. In addition, many of the industrial products have a specification on maximum particle size. The maximum particle size is important in some products such as brake pads and sound-deadening sheets that have a particular thickness.

Colour (surface colour parameters "a" and "b") and whiteness parameter ("L") (see Table 2) can also be a factor to a paint manufacturer. In paint applications, a very white barite with a high brightness is preferred because it is easier to tint or control the final colour of the product. In the paint industry, grind size of the barite is also important because particle fineness will affect paint gloss. An instrument used in the paint industry, a Hegman gauge, is used to determine the maximum size and fineness of the ground barite.

Table2: Chemical composition and physical parameters of some barite samples from Drâa-Tafilalet region.

Sample's number	Sample's Code	Chemical composition (%)		Physical parameters			
		$BaSO_4$	$SrSO_4$	a	b	L (%)	Density
1	Zg-a	96.41	2.9	**	**	91.82	4.34
2	Zg-b	96.46	3.18	**	**	94.4	4.35
3	Ag-a	97.7	1.68	2.69	5.43	86.7	4.36
4	Ag-b	95.9	1.42	8.79	11.6	72.2	4.32
16	Tj-g	96.98	2.03	1.79	3.51	92.91	4.34
24	Tnj-a	96.27	2.29	0.2	7.16	72.81	4.33
25	Tnj-b	94.01	5.21	0.85	4.18	85.33	4.33

Table3: Heavy metal content of some barite samples from Drâa-Tafilalet region.

Sample's number	Sample's Code	Chemical composition (ppm)											
		As	Cd	Cr	Fe	Co	Cu	Hg	Pb	Mg	Mn	Ni	Zn
1	Tj-A	<2.7	<0.14	<13	3900	<0.9	5.9	<0.04	<5	88	5	<2	<11
2	Tj-B	<2.5	<0.13	<13	1400	<0.8	60	<0.04	<5	87	8	6	<10
3	Tj-C	5.6	<0.14	<0.15	2600	2.50	34	<0.04	<5	140	77	37	<11
4	Tj-D	8.7	0.14	<14	3600	2.00	52	4.20	86	420	240	2	40

In the Table 2 three samples (1, 2 and 16) have a specific density of exceeding 4.34 (4.34, 4.35 and 4.34 respectively), and a white colour (91.82, 94.4 and 92.91 respectively) and a big percent of $BaSrSO_4$ (99.31%, 99.64% and 99.01% respectively), it can be used in paint industry. Their densities also allow them to be used in the automobile industry.

The medical industry uses barite that has been through a special process that produces a very high-purity barite. Therefore, not all barite deposits are suited for every barite use. If one is looking for barite for use in the paint industry, one would need to locate a deposit that has a high whiteness and brightness. The material would need to have a specific gravity exceeding 4.35 and also a low calcium and silica content. The deposit should not have minerals or contaminates that would cause the barite to become discoloured. Therefore, the value of paint-grade barite is much higher than drilling fluid-grade barite because of these requirements.

A barite with a specific gravity that exceeds 4.35 but has an associated mineral that results in a lower brightness or whiteness may be ideal for the brake industry. This material, however, would also need to be low in silica and calcium content to be usable in the brake industry.

Many industries require the absence or presence of very small quantities of metals, especially the medical uses. Four samples are analysed and reported in Table 3. Someone of these samples (Tj-A and Tj-B) show very low levels of metals, which may allow them to be used in this type of industry.

Compilation of mineralogical and geochemical data shows that the high content of SiO_2, Fe_2O_3 and rarely CaO in some samples reflect the presence of minerals observed in thin section (quartz, iron oxides and calcite). The small size of these minerals relative to barite shows that these impurities can be eliminated by simple washing, and by gravimetric or magnetic separations. These processes must be carried out after hand selection. The product resulting from this simple treatment will be enriched with barite and free from impurities like quartz, iron oxides, calcite and clays. Thus, density, whiteness and $BaSrSO_4$ amount will increase. The product obtained will have physicochemical properties appropriate for using in various industrial fields.

4. Recommendations

According to this study, it is obvious that Drâa-Tafilalet is an outstanding mining region, especially for barite ore. However, despite the large-scale production of this substance and the abundance of the high qualities barite ore, it remains undervalued. The dysfunctions in the three stages of production (exploration, mining and treatment) lead to the commercialization of the raw barite ore. The improvement of the production chain would make it possible to reduce the "lack of profit" and increase the participation of this mining activity in the regional and national economy.

First step, the geological exploration: before starting a mining exploitation, a number of steps will be done. Therefore, geologist will follow some steps to have a good knowledge of the future exploited ore. After [25], when a prospect has been identified, assessing it involves advancing through a progressive series of definable exploration stages. Positive results in any stage will lead to advance to the next stage and an escalation of the exploration effort. Negative results mean that the prospect will be discarded, sold or joint ventured to another party, or simply put on hold until the acquisition of fresh information/ideas/technology leads to its being reactivated. Thus, prospect exploration will generally go through four stages [25]; i) target generation: this includes all exploration on the prospect undertaken prior to the drilling of holes directly targeted on potential ore; ii) target drilling: This stage is aimed at achieving an intersection of ore, or potential ore. The testing will usually be by means of carefully targeted diamond or rotary-percussion drill holes, but more rarely trenching, pitting, sinking a shaft or driving an adit may be employed; iii) resource evaluation drilling: This stage provides answers to economic questions relating to the grade, tones and mining/metallurgical characteristics of the potential ore body. Finally, iv) feasibility study which the final stage in the process, is a desktop due-diligence study that assesses all factors-geological, mining, environmental, political, economic-relevant to the decision to mine. This procedure will make it possible to clearly define the morphology of the deposit, and therefore choose the best technique to extract it.

In our case, where most of barite deposits are exposed on outcrop, and they are in the form of subvertical veins, it is necessary before starting the mining exploitation to define the thickness, depth and lateral extension of the vein structure. In addition, it is recommended to define the geochemical parameters and the fracturing properties of the surrounding rocks. Therefore, it is necessary to realise the geological mapping and cross-geological sections before starting drilling. The main objective of this work is to choose the optimal exploitation method to use.

Second step, the mining: As shown in Figures 5A & 5B, the ore deposits of Drâa-Tafilalet region have a vertical dip. So, the exploitation of these ore deposit in artisanal way from top to bottom is not adequate. Follow an exploitation technic well adapted to the morphology of the ore deposit. The chosen method must consider the different geometric and geotechnical parameters of the mineralization. Since the majority of deposits are vein-type with high dip and competent surrounding rock, it is recommended to use the method of cut-and-fill mining (Figure 8A) and sublevel stopping (Figure 8B) [26].

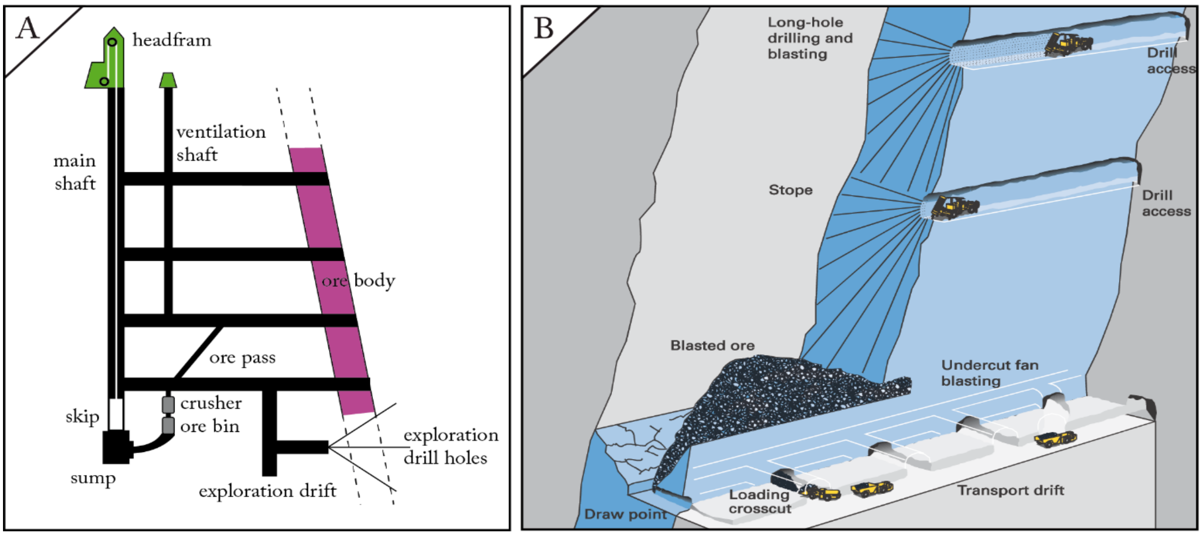

Figure 8: *Two underground exploitation methods adapted to redressed ore deposits. (a): cut-and fill stop layout and (b): Sublevel open stoping layout [26].*

It will allow a good ore recovery rate and avoid having long and deep trenches that alter the appearance of the area. Cut-and-fill mining is suitable for a steeply dipping mineral deposit contained in a rock mass with good to moderate stability. It removes the ore in horizontal slices starting from a bottom cut and advances upwards, allowing the stop boundaries to be adjusted to follow irregular mineralization. Sublevel stoping (SLOS) is used for mining mineral deposits with: steep dip where the footwall inclination exceeds the angle of repose; stable rock in both hanging wall and footwall; competent ore and host rock; and regular ore boundaries.

Third step, the ore processing: the analysis performed on several samples derived from different ore deposits of Drâa-Tafilalet region show different qualities of barite. Unfortunately, high quality of barite ore is marketed as barite for drilling mud. In order to increase its economic value, we recommend processing the ore before commercializing it, especially since the methods of processing are not very expensive. We propose two treatment methods, the first general (Figure 9) and the second chemical (Figure 10).

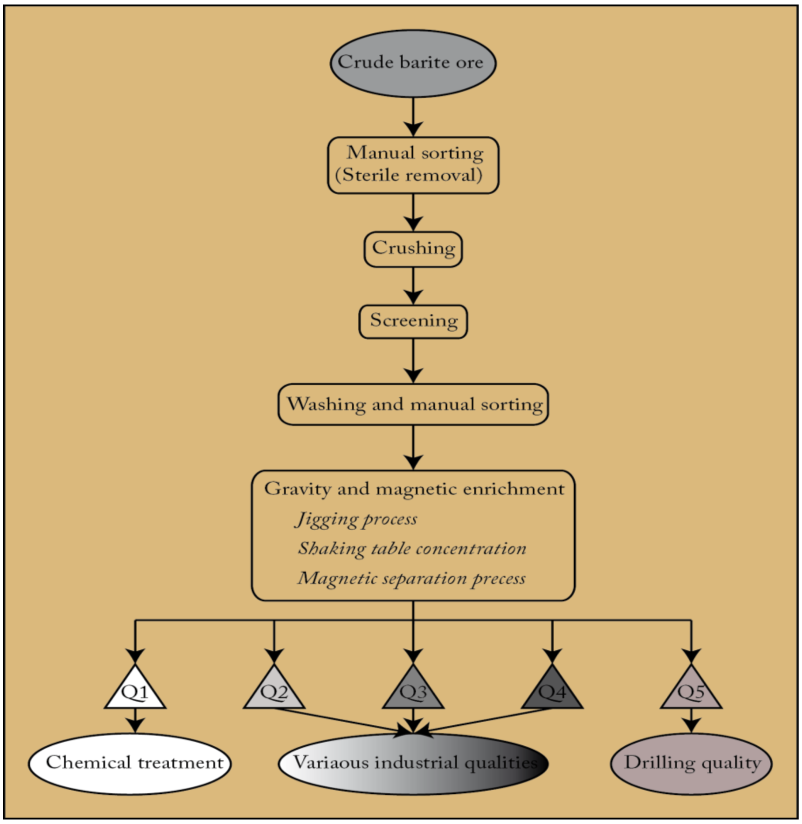

Figure 9: *Global flow-sheet of barite.*

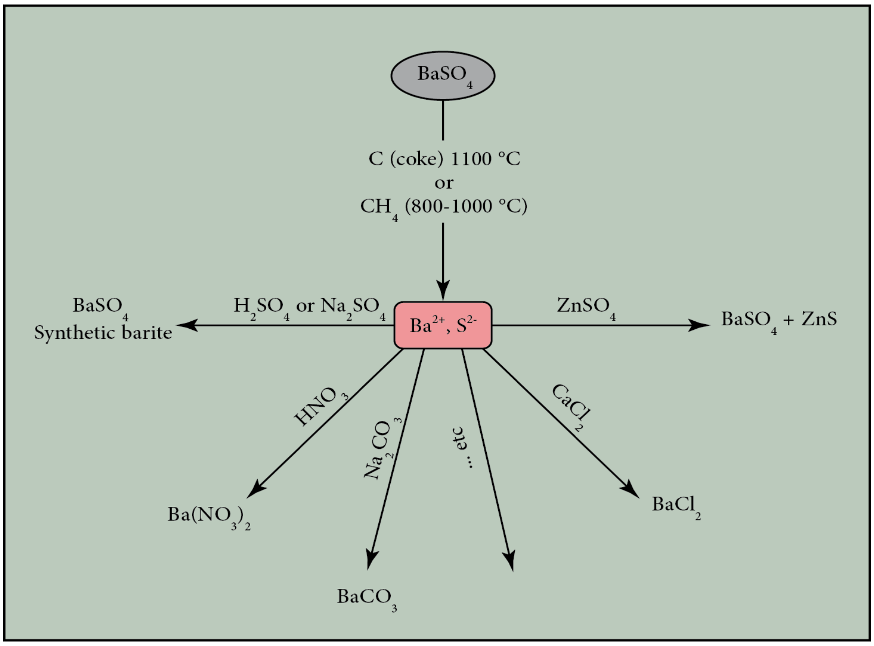

Figure 10 : *Chemical flow-sheet of barite.*

Conclusion

Mining reserves are exhaustible resources; therefore, their extraction must be optimal. Field studies of many barite deposits in Drâa-Tafilalet region, showed the i) absence of exploration ii) exploitation of the vein from top to bottom iii) lack of processing. Microscopic and geochemical studies of various samples indicate that the barite ore of this region is of high quality and can be used for many purposes. In addition, barite ore needs to be enriched. This will certainly enhance its commercial value. Economic, social and environmental benefits of the implementation of our recommendations will have big results.

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