Role of Mineralogy and Geochemistry in the Beneficiation of Jajarm Bauxite from North East Iran: Comparison with some other Bauxite Deposits of the World

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Abstract

Two types of bauxite occur in the Jajarm Bauxite deposit, the first one is the hard bauxite and the other is the shaly bauxite or soft bauxite. The Al_2O_3 content ranges from 30% to 60% and SiO_2 varies between 5% to 39%.The total tonnage is more than 22 million tons with a mean value of Al_2O_3 content between 47% to 48% , SiO_2 around 10% and Fe_2O_3 ranges between 6.95 to 27% . The Jajarm bauxite deposit shows high concentration of active SiO_2 and Fe_2O_3 in comparison with other bauxite deposits of the world. Efforts have been made in this research to delineate the characteristics of the Jajarm monohydrate bauxites, consisting of a diaspore and chamosite mixture, to improve their chemistry by different beneficiation techniques and optimize their processing, grinding and digestion conditions for alumina production The Jajarm bauxite shows politomorphic and micro- granular texture with several secondary textural elements. The size of diaspore grains (which is the main mineral component) are generally below 10 microns, with a homogeneous matrix. In addition, for the very hard bauxite we can not do any separation between the crystal grains and the matrix because of similar hardness for both with closely packed space filling and in consequence of the absence of well-defined grain boundaries. Based on the above studies, the Jajarm bauxite can be enriched neither by grain analysis nor by magnetic separation. In this research hard bauxite was crushed between 2 to 3 inches and then samples were washed with 5% HCl. The result of this laboratory studies shows that the silica modulus has improved from 1.05 to 2.56 which indicates an increase of 29% in the Al_2O_3 content. Jajarm laboratory s study shows that Jajarm bauxite deposit partially can be improved only by water treatment.

Keywords*: Mineralogy, Bauxite Deposit, Bauxite mineralogy, Beneficiation, Jajarm, Iran.*

1. Introduction

Bauxite ores in Iran have characteristics of diasporic type with high content of aluminum and iron and low Al_2O_3 to SiO_2 mass ratio. In diasporic bauxite ore processing, silicates are easily over-ground and the fine silicate slimes are harmful to direct and reverse flotation beneficiation of bauxite. The actual beneficiation processes adopted are determined by the nature and physical properties of ore and gangue minerals, their mode of association with each other, the method of exploiting the deposit and the end-use of the beneficiated product. In the small scale mining operations selective mining is supplemented by hand-sorting whereby ferruginous or siliceous impurities like laterite, quartz, etc, are separated from bauxite on the basis of megascopic characteristics like color, texture ,specific gravity etc. In large scale mechanized mining the upgradation of ore by sampling, mineral dressing, sorting, screening, and washing is not practicable, the bauxite becomes inventible particularly when the ore body is mixed with deleterious constituents. The mechanical beneficiation method for upgrading such bauxite can only be effective if the impurities are easily liberated from the ore. Metallurgical grade bauxite is beneficiated by mechanical screening and washing. In most of the countries bauxite is subject to mineral dressing operations before being dispatched to the consuming industries. The various processes used (apart from crushing which forms the first stage in all the flow sheets) are: 1- Screening, Scraping and Washing 2- Magnetic separation and 3- Drying and Calcination. Beneficiation by magnetic separation of iron is practiced on a limited scale, primarily on ore mined for abrasive and refractory industries. The bauxite is usually dried and calcined before magnetic separation because the heating converts siderite ($FeCO_3$) to magnetite (Fe_3O_4), leaves pyrite (FeS_2) as a magnetite residue and makes hematite (Fe_2O_3) and other paramagnetic minerals strongly magnetic. Today's demand for aluminum in Iran is more than 140,000 tons per year. The capacity and actual production of aluminum in Iran by IRALCO is close to 45,000 tons per year which requires an alumina feed of about 90,000 tons per year, all of which is being imported. At the present time the exact demand of bauxite for IRALCO is about 240,000 tons alumina powder per year but the maximum feed is only about 120,000 tons alumina powder which is exactly fifty percent of IRALCO requirement. The Jajarm alumina plant has adopted the Bayer process to produce

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alumina from diasporic bauxite. The alumina produced has fully met the standards of metallurgical sandy alumina and each index has achieved or surpassed the planned capacity. The trial operation has been very successful, saving 80 million US$ for Iran and creating thousands of jobs for the local population. This project has been acclaimed by the aluminum industry for advanced Alumina technologies, thus laying a foundation for the expansion of aluminum market.

We can compare Jajarm bauxite deposit with the other bauxite deposits like those from China and [1] and Italy [2]. But in Iran we are faced with two problems, the first one is that the Jajarm deposit is a very hard diasporic bauxite with a very fine texture and the second point is that the SiO_2 and Fe_2O_3 contents in this bauxite are very high. Therefore the improvement of this bauxite is very important and the aim of this research is to improve its chemistry by different beneficiation techniques and to optimize the processing, grinding and digestion conditions for alumina production.

2. Previous Investigations in the Region

The Alburz Range of mountains in general and the Shemshak Formation in particular have been studied by a number of Iranian and foreign geologists because of their economic importance . Most of this work has been listed by Harb in his PhD thesis, who studied the stratigraphy and tectonics of the area [3]. The Jajarm bauxite was identified as a black layer by N. Valeh when he studied the aerial photograph of the area and verified as bauxite in the field by Samimi and Mallakpoor [4] who have analyzed hundred samples, which showed Al_2O_3 between 41.3 to 62.2 % and SiO_2 between 4 to 19.3 %. Balkay and Samimi [5] summarized the status of bauxite exploration in Iran and Jamshidpoor, [6] carried out research on the Alburz Range with special reference to the Shemshak Formation. The feasibility and techno-economical studies were carried out by Alluterv-FKI [7]. Mollai et al. have published a paper on the geochemistry of Jajarm bauxite [8]. Davoodi et al. [9] presented a paper on the characterization of Alborz, Zagros and Central Iranian Plateau bauxites for the Tube Digestion Process. Exploration and technology of Jajarm bauxite for alumina production were studied by Mollai [10]. Jafarzadeh did his MSc thesis on mineralogy, geochemistry and genesis of Jajarm Bauxite deposit [28]. Ataei et al. and Mollai, and Sharifiyan [11, 12 and 13] also published papers about geological and exploration characteristics and textures of different phases of Jajarm bauxite deposit respectively. Karstification of Jajarm bauxite was studied by Mollai [14] .Petrography and geochemistry of Jajarm karst Bauxite was studied by Esmaeli et al. [15]. As the above summary shows, a number of papers and research reports are available on various aspects of the Jajarm bauxite deposit, but there is no research reported on the beneficiation of Jajarm bauxite.

3. Regional and Geological setting of Jajarm Bauxite Deposit

From the tectonic point of view, Iran can be divided into two marginal active fold-belts located in the NE (Kopeh Dagh) and in the SW (Zagros) resting on the Hercynian terrain and the Precambrian Arabian plate respectively (Fig.1). Between these marginal fold belts are the Central Iran, Alborz, Zabol-Baluch and Makran units [18]. In more detail, according to Stöcklin [16, 17] and Nabavi [18] Iran can be divided into ten major litho-tectonic domains: Makran, Lut Block, Eastern Iran, Kopet Dagh, Alborz Mountains, Central Iran Block, Urumieh-Dokhtar zone, Sanandaj-Sirjan zone, Zagros fold belt, and Khuzestan plain. The boundaries of these units are usually marked by faults or in some cases by depressions (mainly tectonic).

The Jajarm Bauxite deposit is part of the eastern Alburz Range in the north of Iran The northern chain of the Alborz represents a branch of the Alpine-Himalayan Orogenic system and runs for 960 km separating the Caspian Lowlands from the Central Iran Plateau. The Alborz Mountains, form a gently sinuous E-W range across north of Iran. The Jajarm bauxite deposit occurs in the Zoo mountain 600km north-east of Tehran, 400km west of Mashhad and 15km northeast of Jajarm town which is part of eastern Alborz , which includes the main part of Iran and Caucasia in the north and Arabian plate in the south. Figure 2 shows the outline structural setting of the Jajarm area. The oldest formation in the area is the Padha Formation (Devonian) and the youngest is the Lar Formation which belongs to the Late Jurassic [3]. The bauxite deposit strikes E-W for about 16km. In addition, the major tectonics have divided the Jajarm mine into four deposits, from west to east which are called ***Golbiny, Tagoei, Zoo,*** and ***Sangterash*** deposits respectively. There are a number of minor north-south faults that have displaced the ore body some times up to two hundred meters. Two horizons of bauxite occur in the Zoo mountain, which are called **A** and **B** horizons. The B horizon constitutes the Jajarm bauxite deposit. Prospecting and exploitation have been carried out on this deposit, which has a late Triassic age (Fig. 3). This deposit underlies the dolomitic rocks of the Elika Formation and overlies the sequences of shale, sandstone and coal seams of the Shemshak Formation. The dolomite of Elika Formation steeply rises from the Jajarm plain to an elevation of 800-900m. The Kisijin bauxite in the Hamedan Province shows the same stratigraphy [19] whereas the Gushkamar bauxite is of Devonian age [37]. This rock is well- bedded, fine grey crystalline, compact and hard with a thickness of about 200m of dolomite and subordinate limestone bed.

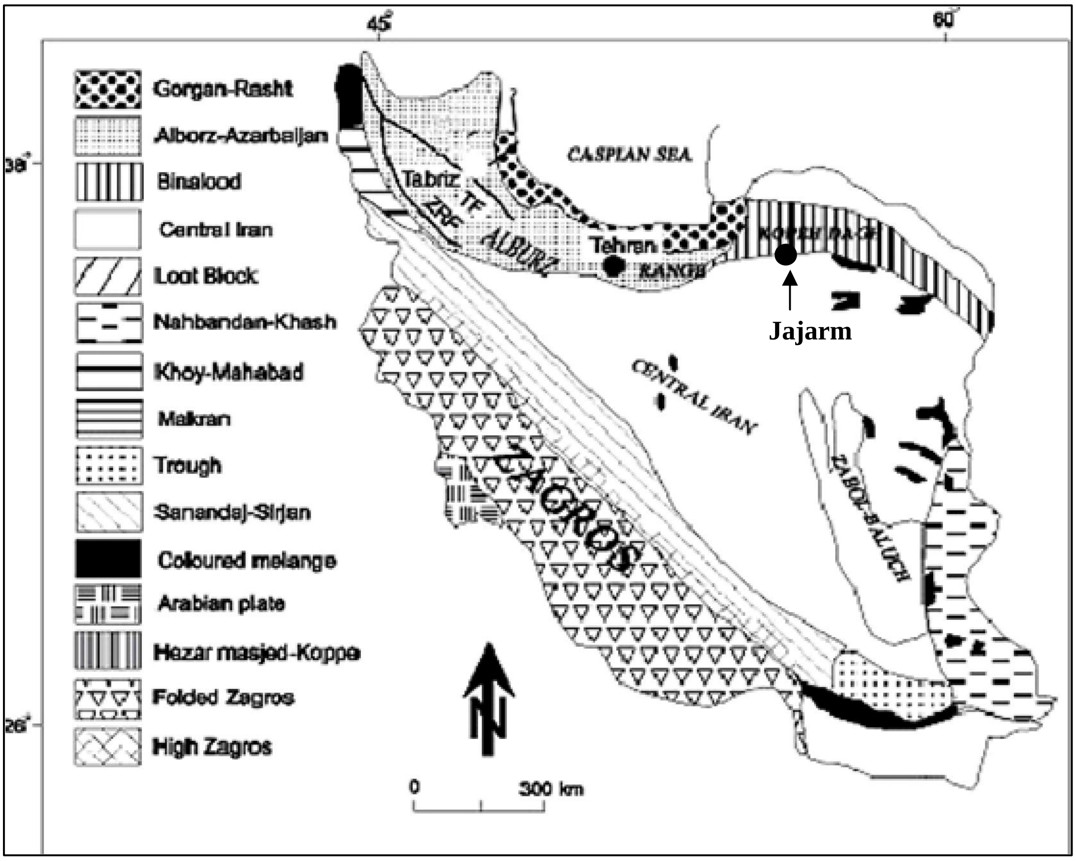


Fig. 1. Regional tectonic map of Iran showing location of area under study [18].

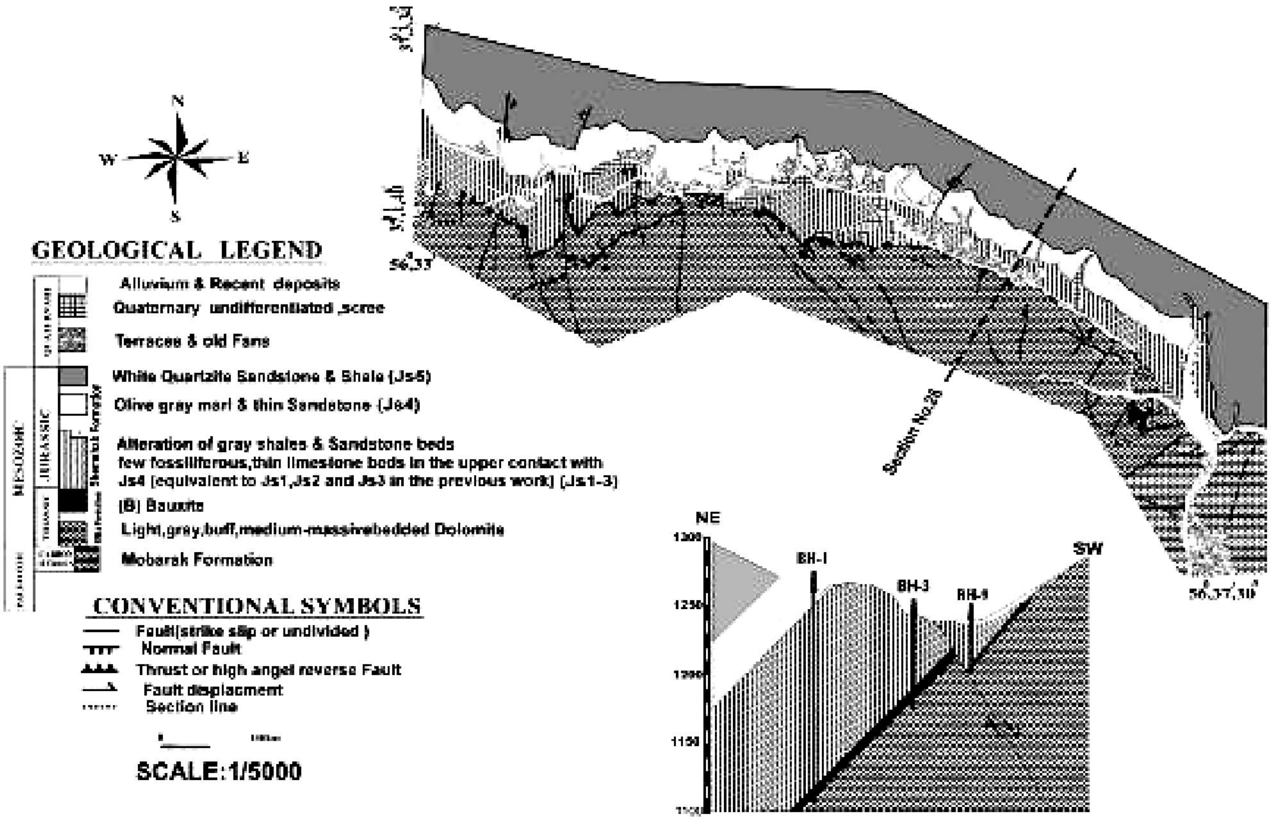
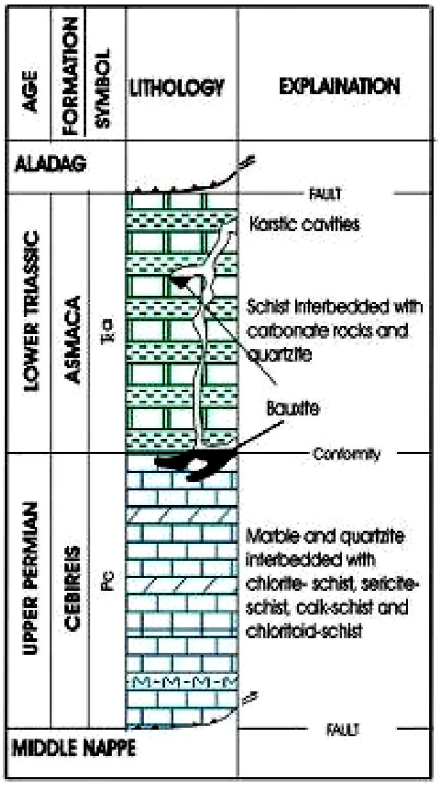


Fig. 2. Outline structural setting of the Jajarm Bauxite deposit and its cross section.



Formarion	Period	Lithology
Lar	Up.Jurassic	massive fossilferous limestone
Delychay	Md.Jurassic	marl and limestone
Shemshak	Low.Jurassic	nine members, 2025m, thick, sequences of shale, sandstone and coal, red ron stone as base layer
BAUXIT	Upper Triassic	B. Horizon
Elika	Middle Triassic	1-uper part 200m. thick well bedded dolomite. 2-lower part, 95 thick limestone and dolomite.
Sorkhshale	Low - Triassic	Quartizitic sand and thin layer of red shale inter bedded with 9m dolomite.
BAUXIT	Permian	A . HORIZON
Mobarak	Carboniferous	115m massive, pores Oosoparite, ridge forming dolomite
Khoshyeilagh	Up.Devonian	98m. thick of fossiliferous lim. dolo. shale, sand.silt and basic volcanic rocks
Padha	Low.Devonian	492m. thick catclastic, evaporate and carbonate rocks

Fig. 3. Stratigraphy and lithology of Jajarm Bauxite deposit in comparison with Masatdagi diasporic bauxite, Alanya, Antalya, Turkey [20]. Both deposits have almost similar mineralogy as well as the bed rock with the same age.

Dolomite rocks show disconformities with overlying Sorkhshale Formation where the lower limestone is absent. From Figure 3 one can see that the Jajarm bauxite is very similar to the bauxite of Masatdagi diasporic bauxites, Alanya, Antalya, Turkey [20] from the geological and lithological point of view. The carbonate bed rock on the surface does not show any significant karstification and seems to be flat. However, in some cases significant karstic depressions and deep sink holes were exposed during drilling and exploitation. The bedrock shows sharp contacts with bauxite. The bed rock in the Golbiny deposit is inter-bedded with layers of bauxite of the so called B′ horizon, which is part of the B horizon; this repetition has taken place due to an E-W thrust in the area.

The bauxite deposit is covered conformably by shales and sandstones inter-bedded with thin coal seams of the Shemshak Formation. The basal member is a red ironstone bed in many parts of the country; consisting of pockets of weathered argillaceous and ferruginous material that has been variously described as lateritic bauxite. Volcanic activities also have been reported for this basal member [3, 5, 9 and 15]. The trace of volcanic rocks in the basal member of Shemshak Formation can be seen on the western side of the Jajarm region in the Shahmirzad area. From the above discussion one may conclude that the source of this bauxite could be a volcanic rock with a carbonate rock as the bed rock. Figure 4 shows various field views of bauxite deposit along with their cover and bed rocks respectively.

4. Description of Bauxite

In the Jajarm region there are two horizons of bauxite, each with a different stratigraphy and mineralogy, which are called A and B Horizons. The A-horizon bauxite overlies the massive Oosparite ridge forming dolomite of Mobarak Formation (Carboniferous age) and underlies the Sorkhshale Formation (Lower Triassic age).

This formation in the Jajarm area is very thin, but due to its color contrast with the overlying and underlying formations it becomes a very significant unit. It consists of white to pink quartzitic sandstone and thin layer of red shale with interlayers of yellowish dolomite (9m).The main prospecting and investigation is concentrated on the B horizon which constitutes the Jajarm bauxite deposit, and is so far the biggest known bauxite deposit in Iran. The bauxite deposit overlies the dolomitic rocks of Elika and underlies the Shemshak Formation, striking E-W for more than 12km.

The strata of the ore are bordered by the Elika Formation in the south and limited by the shearing zone of a thrust fault in the east; to the west and southwest the bauxite is covered by alluvium. The bauxite layer is constant neither in the horizontal nor in the vertical direction. It is interrupted by non-industrial bauxite or clay strata. In general, the thickness of bauxite varies between 2 to 40m but in some cases it may reach up to 100m.

The deposit is filled with smaller or larger dolines; significant karstic depressions and deep sinkholes were exposed during drilling and mining activities (Fig. 4). The various types of depressions which host the Jajarm bauxite occur in the upper part of dolomitic Elika Formation.

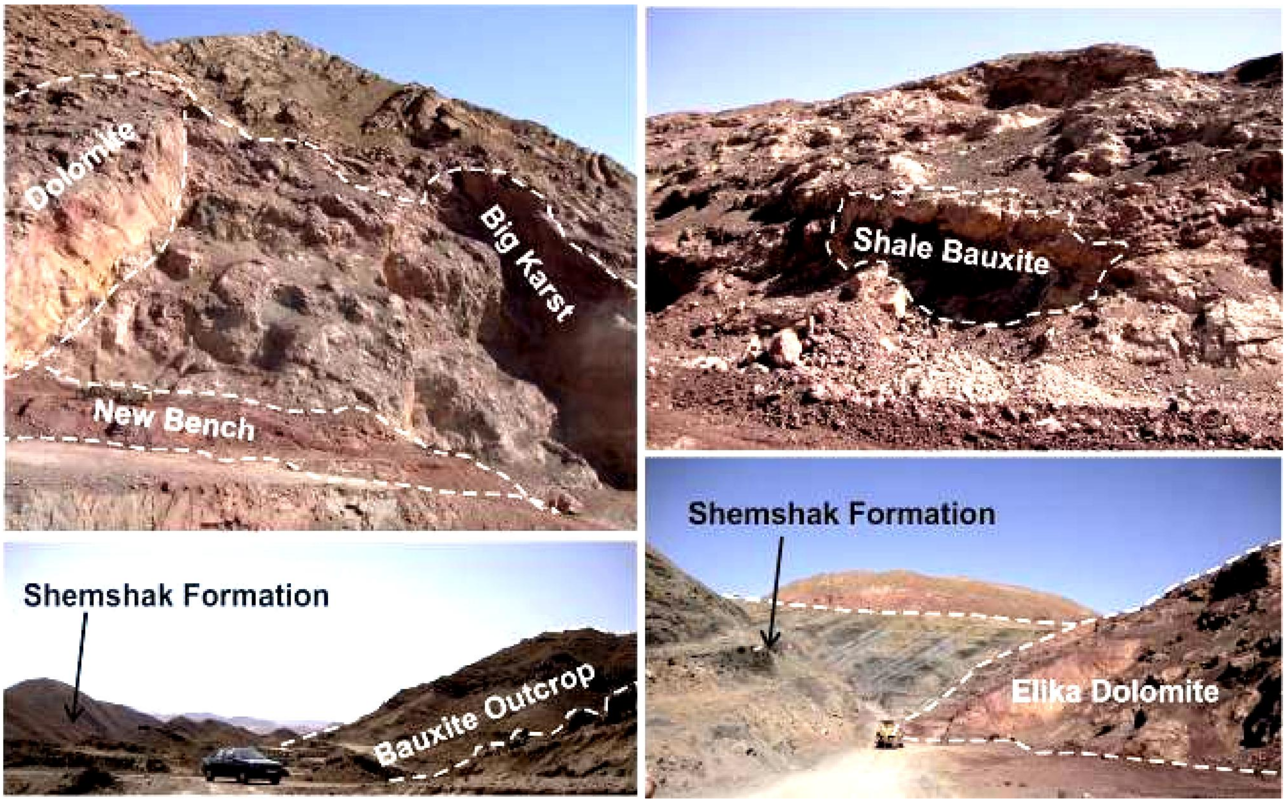


Fig. 4. Field photographs showing big karst as the best place for high quality bauxite deposit. The Elika Dolomite occurs as the bed rock and the Shemshak Formation as the covering rock.

For example, in the Golbiny deposit a big karstic depression with about 30m depth was exposed surrounded by almost vertical walls; sometimes these depressions may reach up to 70m in width, 80m in length and 100m in depth. The best quality bauxite can be found in such depressions (Al_2O_3 >50 % and SiO_2<9 %). The quality of ore shows a positive relation with its thickness. Some of these depressions in the area are accompanied by tectonic activities and faults. Although most of the fault planes are filled with kaolin, in general, these tectonic activities have played a positive role in improving the quality of ore deposit. The following layers can be traced in most of the drilling and mining sites:

1. Kaolinitic clay which is blue, grey, grayish green and white
2. Hard bauxite which varies from very hard, compact, dark brown to grayish white which is considered as industrial bauxite.
3. Clayey soft, red to dark brown bauxite with a soapy touch
4. Kaolinitic layer.

Bauxite development requires certain chemical, physical and geological conditions: tropical climate above 20°C, alternating wet and dry seasons, high-porosity rock with high alumina content, a vegetation cover with bacterial activity, low topographical relief on higher ground, long periods of stability and weathering [21,22 and 23].The Jajarm Bauxite deposit indicates that suitable conditions for formation of bauxite deposit like shallow water table, topography, organic activities and tropical climatic conditions were available . Some of the previous workers [24,25 ,26, 27and 28] believe that during the Triassic and Jurassic the oceanic lithosphere of the Neotethys began to subduct beneath the Eurasian plate and the movement of the Afro-Arabian plate toward the Eurasian plate (i.e. Central Iran and Alborz) resulted in tropical conditions. In addition, the dominance of shallow–water carbonate environment is one of the main features of the Tethys Basin. The hosting of bauxite deposits in different places of Iran like Jajarm and Abe Garm by the thick bedded and fine grained dolomite of Elika Formation, is the result of the same conditions [15 and 19]

5. Methods of Study

Atomic Absorption Spectrometry (AAS) and Flame Spectrometry (FS) were selected for chemical analysis of main oxides of bauxite. The phase analysis of bauxite and red mud was based on XRD combined with Thermogravimetry and sometimes combined with Infrared Spectroscopy as well. Jajarm Bauxite phase analysis was done in three central research laboratories. Most of the daily samples were analysed in Karaj Research Center in Iran. Some of the samples were sent to the Jawaharlal Nehru Aluminum Research

Development and Design Centre at Nagpur, India. In this centre the samples were analysed using Philips PW 183 Automated Powder Diffractometer equipped with PW1820 high precision vertical goniometry. CuKα radiation was used for the analysis and the current settings were 45 kv and 35 mA. The instrument was microprocessor controlled and fitted with automatic divergence slit arrangement and curved crystal graphite monochromator.

The diffraction patterns were evaluated by the full profile match technique, using the XDB software. After reaching a phase composition, the corresponding theoretical diffraction pattern was simulated and compared to the measured diffraction pattern. Additional independent information (like chemical composition, preferred orientation, grain size, influence etc.) was also used in the refinement of results. Use of additional information helped us to give a coherent solution of the phase composition. The results of these analyses are given in Table 2 and 3. Phase analysis and technological tests as well as Techno-Economic feasibility were carried out on 120 samples.

These tests included XRD investigation in the Aluterv-FKI laboratory carried out by Philips PW 1730 dual generator with a goniometer supplied with graphite monochromator, using CuKα radiation at 1.35kv/45kv/30mA. For the thermoanlytical investigation, a Derivatograph Q-1500D/made by MOM/system was used with a heating rate of 10°C/min with a one gram bauxite sample. Table 4 shows the result of some of these phase analysis.

Table1. Important characteristics of Jajarm bauxite in comparison with some Iranian and other bauxite deposits of the World.

Name of Dep.	Age	Main Mineral	Bed rock	Cover Rock	Reference
Jajarm, Iran	Late Triassic	Diaspore, chamosite, kaolinite and hematite	Elika (Dolomite)	Shemshak (shale, sandstone and coal)	[12]
Bukan, Iran	Permo-Triassic	Diaspore, bohemite, hematite	Ruteh (carbonate)	Elika (Dolomite)	[32]
Hangam, Iran	Late Cretaceous	kaolinite, geothite and gibbsite	Sarvak (carbonate)	Ilam (carbonate)	[33]
Aghadjari Iran	Permo-Triassic	Bohemite,diaspore, and kaolinite	Ruteh	Elika (Dolomite)	[34]
Zagros Mountain Belt, Iran	Late Cretaceous	Boehmite, gibbsite, Kaolinite, diaspore and goethite	Sarvak (carbonate)	Ilam (carbonate)	[35]
Parnassos-Ghiona Greek	Late Jurassic Late Cretaceous	diasporic or boehmitic	Dolomitic limestone	dark coloured bituminous limestone	[36]
Gushkemar, Iran	Devonian	Bohemite, kaolinite and hematite	carbonate	limestone	[37]
Timan, Russia	Devonian	diaspore–crandallite–svanbergite	Riphean dolomite	shale	[38]
Los Pijiguaos, Bolivia, Venezuela	Middle Proterozoic	Gibbsite, hematite and goethite	Igneous rock (Laterite)	Alluvium	[39]
Antalya, Turkey	Late Permian	Diaspore, bohemite, gibbsite	Cebireis Formation (carbonate and schist)	Asmaca Formation (Carbonate, quartzite and schist	[20]

Table 2. Results of phase analysis and the Alumina and Silica percentages in different minerals.

	Silica In Various Minerals				Alumina In Various Minerals			
Sample	Topaz	Illite	Quartz	Kaolinite	Topaz	Illite	Kaolinite	Diaspore
3278	0.55	0.50	*	0.47	0.94	-	0.39	68.84
3274	0.55	1.36	*	5.59	0.94	1.15	4.74	59.49
Sc14	0.55	-	2.00	3.49	0.94	-	2.96	55.25
Sc15	0.55	-	1.50	3.79	0.94	-	3.16	54.39
606A	0.28	-	1.50	7.91	0.47	-	6.71	43.34
3070	0.55	2.72	*	5.59	0.94	2.31	4.74	41.64
Sc16A	-	-	*	24.67	Trace	-	20.93	13.60
3036	Trace	-	0.50	16.29	Trace	-	13.82	7.65
1550	0.28	-	*	28.86	0.47	-	24.49	6.80
30.41	Trace	-	*	18.62	Trace	-	15.80	5.95

Table 3. Percent of Oxides in different minerals resulting from Table 2.

Mineral Phases	Topaz	Quartz	Rutile	Kaolinite	Goethite	Diaspore	Anatase	Hematite	Calcite	Sum
	2.00	1.50	1.00	8.00	3.00	64.00	5.00	12.00	1.00	97.50
$Fe_2O_{3\%}$								12.00		14.70
TiO_2%			1.00				5.00			6.00
CaO%									0.56	0.56
SiO_2%	0.55	1.50		3.72						5.78
Al_2O_3%	0.94			3.16		54.39				58.49
F%	0.36									0.36
CO_2%									0.44	0.44
	0.17			1.12	0.30	9.61				11.20
				1.12	0.30	9.61		0.00	0.44	11.47

6. Mineralogy

The mineralogical constitution depends on the Eh-pH conditions and paleorelief, which is determined by the position of the area of bauxite formation /accumulation which varies as a function of the oscillating karst or ground water table [29]. Two types of bauxite with two different sets of physical and chemical properties occur in the Jajarm mine**:** one is industrial bauxite which is called ***hard bauxite***, the other one is non- industrial bauxite which is called shaly or ***soft bauxit***e. The soft bauxite is shale bauxite with Al_2O_3 between 20 to 40 % and SiO_2 between 15 to 35 %, with a high percent of iron. It is well distinguished from hard bauxite in the field by its color, trace of layering, soapy feeling and low resistance to weathering and crushing. After explosion and exposure in the atmosphere the shale bauxite loses its moisture and starts weathering to fine grains and fragments which break up very easily in the hand, whereas this is not the case with hard bauxite. The hardness of hard bauxite is about 7 on the Moh's Scale and it is very rough and dense with variations in colour from dark brown to light cream colour (Fig. 5). In comparison Jamaican bauxite is considered to be 'young' in that it is un-compacted and soil-like in nature, with deposits filling sinkholes or depressions in a karst limestone topography [29]. In the Masatdagi bauxites, Antalya, Turkey, four types of ore can be defined based on outcrop appearances: black, earthy, clayey, and Fe and Mn-bearing bauxites. Oölitic textures are common in all ore types, except the earthy ones. Bauxites are represented by a mixture of diaspore and clay in varying proportions [20]. The white cream ore is very high quality bauxite, with Al_2O_3>55 % and SiO_2<9 %. The greenish color can be seen when chamosite is predominant. The thin layers of iron which are the result of leaching process can be seen with high quality ore**;** such a leaching sometimes develops significant zonation. Figure 5 shows the hand specimens of these bauxites. The spheroidal, oölitic, pisolitic texture and nodules of rich iron are very common in this deposit. The study of texture and different phases has been carried out to understand the degree of crushing, particle size, condition of formation, degree of crystallization, distribution of constituent elements for the purpose of digestion and to evaluate the potential of physical beneficiation. The textural studies of Jajarm bauxite show, a politomorphic, micro-granular texture with several secondary textural elements. The individual crystallite size of diaspore is mostly below 10microns. Silica is mainly present in kaolinite, which forms very thin stacks (≤ 0.1 micron thickness) of crystal platelets. The studied samples were mostly very compact; they had closely packed space filling, and only the fine-grained aggregates of Fe minerals were more loosely packed (Fig.7). Where as in the Dinarides region of Montenegro bauxite deposit**,** the uppermost part of the column is made of pisolitic or pisolitic-oölitic bauxites, with pisolites up to 5 mm in diameter, rarely up to 1.0 cm[31] .No doubt this bauxite is much better than Jajarm bauxite for beneficiation. The phase analysis indicates that the Jajarm bauxite is a typical diasporic one accompanied with chamosite as minor and boehmite as trace constituent. Kaolinite as reactive silicate is a dominant mineral and every time shows negative relation with diaspore; free quartz can be seen as a trace constituent. Hematite is the only primary iron ore associated with goethite and siderite as secondary minerals. The main titanium mineral is anatase accompanied by a minor amount of rutile. Table 4 shows that berthierine (chamosite B) is the main chamositic mineral accompanied by chamosite A. Replacement of 2 to 6 % Fe by Al leads to the formation of aluminous goethite and aluminous hematite as the other secondary iron minerals. Table1 shows the comparison of Jajarm bauxite with the other bauxites in Iran and other parts of the world.

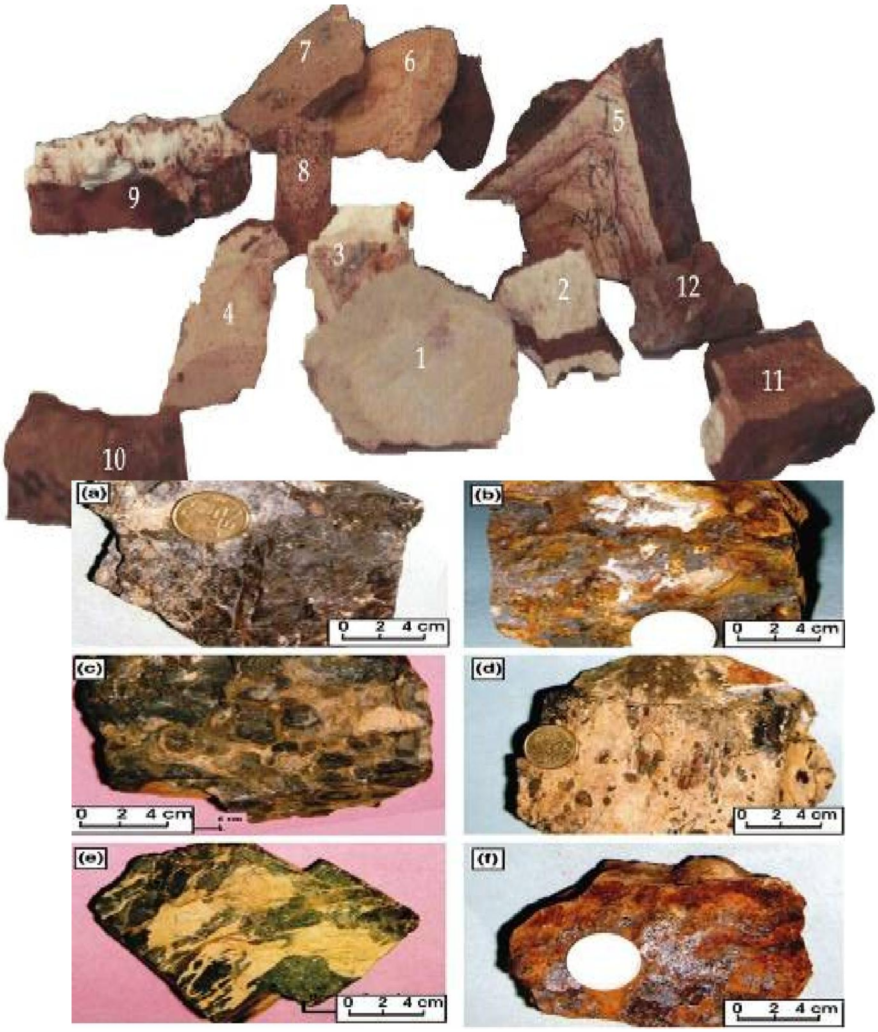


Fig. 5. Photographs of hand specimens from Iran and Turkey :Figure 5-1 to 5-11 show various characteristics samples from Jajarm bauxite.Fig.5-1 to 5.4 show various shades of cream colour for bauxite, which indicate very good leaching of iron minerals and formation of very high quality bauxite. Fig. 5-5 shows very good zonation. Fig.5-6 to 5-10 shows various shades of brown colour. All of these samples are very fine- grained without clear boundaries between the grains. Figures 5a to 5f are from the Masatdagi diasporic bauxites, Alanya, Antalya, Turkey [33] Structural and textural properties of bauxite samples: (a) Blocky bauxite-bearing sparse oölitic grains and kaolinite coated fractures; (b) Limonite (yellow–brown) and kaolinite (white) in the iron–manganese bauxite samples; (c) and (d) Hematite and diaspore oölites and pisolites in yellow–green clayey bauxite; (e) Lateral and vertical transitions between light clayey bauxite and black bauxite; (f) Limonite (yellow–brown), amorphous aluminum hydroxide (black) and clay (white) in earthy bauxite.(For interpretation of the reference to colours in this legend, the reader is referred to the web version of this article).

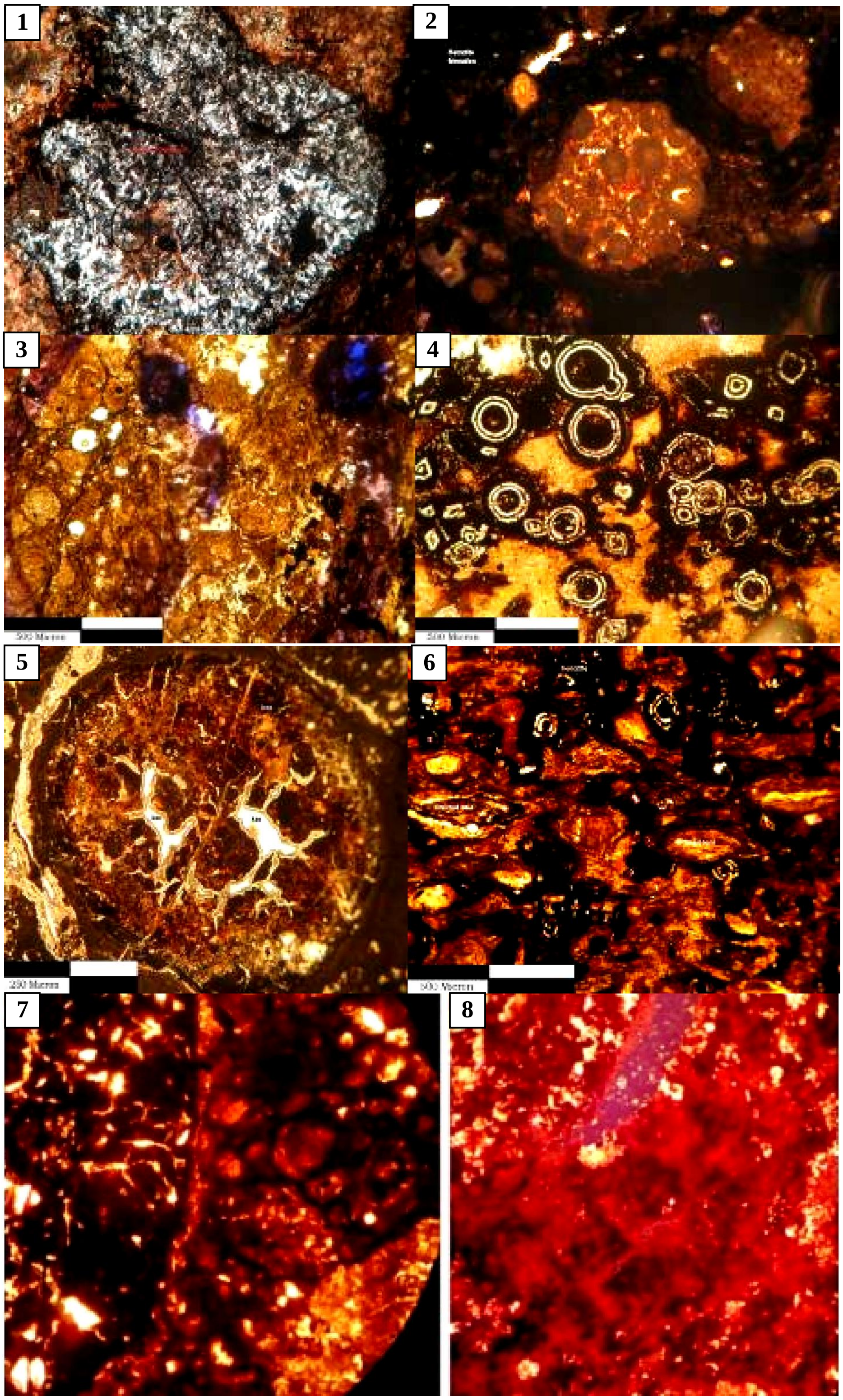


Fig. 6. Photomicrographs of Jajarm bauxite showing politomorphic and micro-granular texture with closed space packing: (1) fine grains of silicate as the remnant of parent rocks are observed (2) shows the initial stage of bauxitization with formation of iron oxide (3) uniform and homogeneous ground mass of bauxite (4) Well-rounded oölite composed of diaspore cemented intraclasts. It shows several phases of cementation and reworking of bauxitic material, during and after bauxitization. (5) Grain-bounded epigenetic fractures in a pisolite grain from red bauxite horizon and micro-fractures that cross-cut the matrix of red bauxite sample (6) Oölitic texture with reworking features and fine grained diasporic and iron oxy-hydroxides matrix from the red bauxite horizon (6) Pressure-solution fabric in the reworked diasporic clasts formed during burial. (7 and 8) Diaspore cemented bauxite with very fine and homogeneous texture.

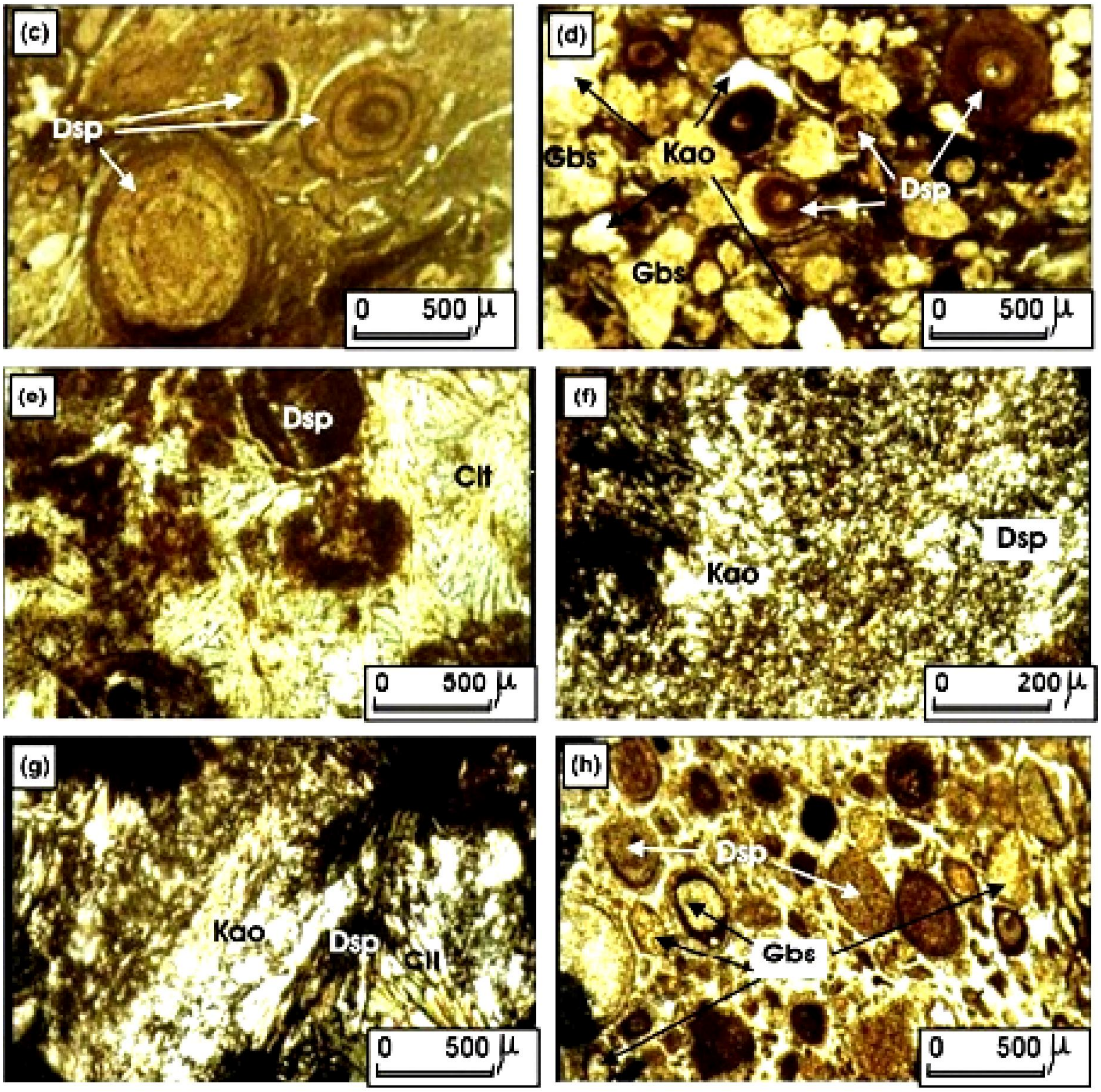


Fig. 7. Photomicrographs of Jajarm bauxite and its comparison with other bauxite deposits.
Thin section views of bauxite[20] ; (c) Diaspore (brown) and clay (white) matrix filling the space between euhedral diaspore (Dsp) oölites in black bauxite; (d) Diaspore (Dsp), gibbsite (Gbs) and kaolinite (Kao) filling the space between euhedral diaspore (Dsp) oölites in black bauxite; (e) Diaspore (Dsp) oölites among chloritoid grains in clayey bauxite; (f) and (g) kaolinite (Kao) aggregates scattered in chloritoid (Clt) filling the space between diaspore (Dsp) grains in clayey bauxite; (h) Kaolinite and other silicate minerals (white–yellow) filling space between diaspore (Dsp) and gibbsite (Gbs) oölites in clayey bauxite.(For interpretation of the reference to colour in this legend, the reader is referred to the web version of this article) [20].

In bauxite the Al^{3+} ion is smaller than the Fe^{3+} ion, thus when aluminium substitutes for iron in the goethite structure, the average size of the unit cell decreases. Generally, the substituted species is regarded as a solid solution of the isostructural goethite and diaspore, with a linear relationship between unit cell volume and degree of substitution. The same can be said for aluminium substitution in the hematite/ corundum system, and iron substitution within the boehmite–lepidocrocite system. Deviations from the linear relationship with substitution for hematite have been noted and attributed to structural water. Generally for Jamaican bauxite ores, the higher the goethitic content, the more difficult the bauxite ore is to process, with exceptions to this general trend usually accounted for by the presence of very fine or amorphous phases [31]. Triangular diagram shows that Jajarm bauxite is a bauxitic ore as only about 2 % of samples are located in the ferriferous field [14]. Minerals like calcite, mica, dolomite, pyrite, illite, halloysite, gypsum, and crandallite can be found as traces. Boehmite was identified in small quantities in some samples.

The occurrence of a mixture of clay-minerals like kaolinite, illite, halloysite and chamosite is characteristic in some of the borehole samples. Siderite was also found in some samples. Consequently, the occurrence of siderite is irregular; occasionally pyrite was identified in samples of BH19-10 and BH 20, 1, 26, only. The most interesting feature of these samples is the distribution of silica –bearing minerals. Although the amount of the reactive kaolinite in some samples is very high, the presence of less reactive chamosite is also characteristic, mostly in the lower–grade samples with an average module of about 4. Chamosite is an alumino-silicate containing Fe^{2+} and Fe^{3+} in the octahedral layer which cannot be characterized by a standard composition because of the very wide substitution of ions in its lattice. The exact determination of the composition of a given chamosite sample needs very sophisticated chemical and mineralogical investigation. Chamosite is an alumino silicate, i.e. half of the silicon in the tetrahedral layer is replaced by aluminum in fourfold coordination. The SiO_2 content of kaolinite is 46 per cent, that of the chamosite is 20 per cent and the octahedral “gibbsite" layer is filled by bivalent cations, mainly Fe^{2+} in addition to Mg^{2+}, Ca^{2+} [40] This chamosite contrary to kaolinite- can be completely or partially inert in the Bayer process even at 250-260° C and the presence of a catalytic additive like CaO is required for processing diasporic bauxites.

However, under more extreme conditions, part of the Fe^{2+} can be oxidized in to Fe^{3+} destroying the crystalline structure, thus increasing the reactivity of the chamosite in the Bayer process. Fortunately, the addition of lime to the slurry has a protective effect against the oxidation of chamosite.

Table 4. The result of Phase analysis of jajarm Bauxite in weight percent in addition the weight percent of main oxides are showing in different minerals

Al_2O_3 in	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Boehmite	1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diaspore	20.0	13.7	43.5	34.3	32.0	42.6	42.5	51.6	33.6	35.6	32.9	30.6	38.3	30.0	32.2	38.6
Kaolinite or Illite		25.4					4.8					7.5	4.8	7.8		4.5
Halloysite	23.8		3.9	5.9	8.1	2.5	-	6.2	6.2	8.1	10.0	-	-	-	10.1	-
Chamosite		-				4.7	2.8	-				3.4	3.4	3.7		3.4
Goethite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2
Hematite	-	0.2	0.4	0.5	0.4	0.2	0.3	-	0.4	0.3	0.3	0.3	-	0.2	0.4	0.3
Crandallite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	44.8	39.3	47.8	40.7	40.5	50.0	50.4	57.8	40.2	44.0	43.2	41.8	46.5	41.7	42.7	47.0
Fe_2O_3 in																
Goethite	1.3	1.3	1.3	2.0	2.0	-	1.0	2.6	1.9	3.3	2.4	2.6	3.0	2.6	2.6	3.3
Hematite	5.6	10.4	23.7	27.2	22.9	13.0	13.9	8.2	24.6	19.5	21.2	18.2	15.1	15.3	20.7	13.4
Illite or Halloysite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Siderite	-	-	-	-	-	2.0	-	-	-	-	-	-	-	-	-	-
Chamosite	-	-	-	-	-	8.6	5.2	-	-	-	-	6.4	6.1	6.8	-	6.1
Total	6.9	11.7	25.0	29.2	24.9	23.6	20.1	10.8	26.5	22.8	23.6	27.2	24.2	26.4	23.3	22.8
SiO_2 in																
Kaolinite		29.9					5.7					8.8	5.6	9.2		5.3
Illite or Halloysite	28.0	-	7.0	6.9	9.5	2.9	-	8.3	7.3	9.5	11.8	-	-	-	11.9	-
Chamosite	-	-				4.7	2.8	-				3.4	3.4	3.7		3.4
Total	28.0	29.9	7.0	6.9	9.5	7.6	8.5	8.3	7.3	9.5	11.8	12.2	9.0	12.9	11.9	8.7
TiO_2 in:																
Anatase	3.3	3.4	3.1	3.6	3.4	3.7	3.9	5.4	3.6	4.0	3.6	4.0	4.2	4.1	3.6	4.2
Rutile	1.6	0.7	1.7	1.0	0.7	14.6	1.6	1.7	1.3	1.3	1.2	1.2	1.4	1.0	1.3	1.5
Total	4.9	4.1	4.8	4.6	4.1	5.3	5.5	7.1	4.9	5.3	4.8	5.2	5.6	5.1	4.9	5.7
CaO in																
Calcite		0.7	1.8	4.6	5.7	0.5	1.2		5.5	4.1	2.6	0.8	0.7		1.8	2.2
Dolomite						-	-		-	-	-	-	-		0.6	-
Illite or Halloysite						-	-		-	-	-	-	-			-
Gypsum						-	-		-	-	-	-	-			-
Crandallite						-	-		-	-	-	-	-			-
Chamosite						-	-		-	-	-	-	-			-
Total		0.7	1.8	4.6	5.7	0.5	1.2		5.5	4.1	2.6	0.8	0.7		2.4	2.2

The oxidation process takes place on the surface; therefore, it is a real assumption that the deeper, unaltered part of the bauxite deposit could contain less kaolinite. We can also expect more non-reactive, non-oxidized type of chamosite and more diaspore, in the deeper parts [41]. For the quantitative evaluation of the chamosite it has been assumed that the weight ratio in the chamosite lattice for these bauxite samples is Al_2O_3**:** SiO_2= 1:1. The results obtained are in good agreement with the data of chemical analysis, thermo-analytical investigations and technological tests which confirm the applicability of our evaluation method.

7. Beneficiation of Jajarm Bauxite

It is well known that bauxite characteristics as chemistry, and especially texture and mineralogy play a significant role during digestion in the Bayer method [42]. To know the theoretical possibilities of ore dressing, textural investigation is necessary. Significant ore dressing is possible when the constituent minerals are hard and well developed with the grain size at least more than 100 microns within the soft cement matrix. Optical studies yield information concerning the size of the bauxite particles, the formation conditions of the bauxite and the degree of crystallization. Also, the electron micro-probe permits determination of the distribution of individual elements. From the texture, conclusions may be drawn regarding the crushability of the bauxite and the constituent minerals, the reactivity towards the digesting liquor and the potential of physical enrichment. In fact most of the authors have offered various methods for bauxite processing and refineries [42,44 ,45,46, 47,48 and 49**],**but Iannicelli [43] showed that Arkansas bauxite containing 11.3% Fe_2O_3 and 1.6 %TiO_2 could be beneficiated to less than 1.2% Fe_2O_3 and less than 0.7 % TiO_2.

According to Papanastassiou and Solymar [42] the Greek monohydrate bauxite, consisting of a varying extent of diasporic and boehmite mixture are not readily amenable to cost-effective beneficiation, except for HMS (sink float) methods in order to remove the free or liberated limestone inadvertently contaminating the bauxite, especially during underground mining. With an appropriate solution–solid ratio, the gibbsite and kaolin in bauxites could be selectively dissolved in 5M NaOH containing dissolved Al(III) at 80 °C after 48 h without affecting the amounts and size of crystals of boehmite and other minerals. The amount of the boehmite in bauxites ranges from 0.5 to 20% (expressed as Al_2O_3) and this procedure when applied to the caustic digestion residues removed most of the iron oxides.

Hematite was more easily removed than goethite and goethite with lower levels of Al-substitution was more easily removed than highly Al- substituted goethite [43]. Commercial application of bauxite from Central India can yield high grade concentration with acceptable SiO_2 content and high recoveries thus dispensing with selective mining, screening and hand picking of bauxite for beneficiation of high silica bauxite ore [45, 46]. PAS (sodium polyacrylate) is a good flocculant for the beneficiation of diasporic-bauxite ore in combination with Na_2CO_3 as dispersant. The beneficiation of mixtures and diasporic-bauxite ore by selective flocculation can be done with Na_2CO_3 and PAS at pH about 9–10, but it is sensitive to the content of kaolinite. For the beneficiation of diasporic-bauxite ore a concentrate can be obtained with an Al_2O_3 recovery of 87.0% and Al_2O_3/SiO_2 ratio of 8.9. But in comparison, many efforts have not been expended in the past to delineate the bauxite dressing and beneficiation before alumina processing. This is same case for the Jajarm monohydrate bauxite deposit, consisting to a varying extent of a diaspore and chamosite mixture**.**

Optical study of Jajarm bauxite shows that the karstic diasporic bauxite of Jajarm region shows politomorphic micro-granular texture, and the submicroscopic size of the main minerals component (generally below 10 microns) with a homogeneous matrix with several secondary texture elements caused by the long, but slow alteration process of the original reductive type bauxite into more or less oxidized type. Kaolinite is the main silicate mineral, which forms stacks of very thin (<0.1 micron thick) crystal platelets. For these investigations the borehole samples were selected from the different bauxite regions. The selected samples represent different ore qualities and different mineralogical compositions.

In addition, the industrial ore in the Jajarm mine is very hard and compact with closely packed space filling. The similar hardness of minerals grains and its matrix material is another negative characteristic of this deposit for dressing. Only fine sized aggregates of iron minerals were comparatively loosely packed. Textural study shows there are no clear boundaries between the constituent grains and matrix materials that could allow us selective grinding and classification from the point of view of the possible enrichment and technological behavior of the bauxite samples. The following common conclusions are important: the individual crystallite size of diaspore is mostly below 10μm. Silica is mainly present in kaolinite, which forms stacks of very thin crystal platelets (≤ 0.1 μm thick). The samples studied were mostly very compact; they had closely packed space filling, and only the fine-sized aggregates of Fe minerals were more loosely packed.

7-1. Laboratory Tests for Beneficiation of the Medium Grade Jajarm Bauxite:

Although the results of the textural studies of the given bauxite samples were very negative from the point of view of ore dressing, laboratory test was carried out for justification, as well.

Table 5. Results of the laboratory test for magnetic separation of +25µm material.

Sample after separation	Magnetic field /Tesla/	SiO_2%	Al_2O_3%	Fe_2O_3%	Weight percent
1-magnetic	0.1	10.9	46.9	20.5	39.06
2-magnetic	0.5	11.2	45.3	21.4	23.66
3-magnetic	1.0	10.9	43.5	23.6	7.07
4-magnetic	2.5	11.3	42.1	24.5	6.26
5-Nonmagnetic	2.5	10.4	45.5	21.2	0.37
Total					76.42
Sieved before separation .–25µm		11.9	44.2	23.1	23.58

Table 6. Acid Water treatment of bauxite for beneficiation in Jajarm Laboratory.

Sizes	No. of Tests	UNTREATED BAUXITE			TREATED BAUXITE			
		Average oxide percent		Module	Average oxide percent	Module	Improvement Percent	W.L.%
SIZE>1″<2″	5	Al_2O_3	31.14	1.05	41.20	2.6	29.33	30.05
		SiO_2	29.74		14.10		47..80	
SIZE>2"<3″	4	Al_2O_3	31.14	1.05	40.19	2.56	29.06	31.40
		SiO2	29.74		15.69		47..24	
SIZE>3″	4	Al_2O_3	32.66	1.23	36.07	1.76	10.44	36.7
		SiO_2	26.45		21.34		19.43	

For this purpose 47 samples were selected and then the average sample was prepared by mixing the same amount from all the 47 samples in order to prepare the characteristic sample. First, this representative sample was ground down to 250 microns in a vibrating- mill. After removal of the –25µm fraction, wet magnetic separation was carried out by means of a Box-Mag-Rapid Plate-separator in a step-wise increased magnetic field, between 0.1–2.5 Tesla /1–25 A/. The slurry concentration for wet magnetic separation was 200 g/l solids, containing 1g/l sodium hexameta-phosphate. According to the results below, no significant improvement could be achieved (Table 5)

7-2. Wet Beneficiation Processes:

In certain bauxites removal of clay is only possible by scrubbing and wet screening after crushing to a particular size. Nodular bauxite associated or coated with Kaolinite clay are amenable to beneficiation by these processes. The bauxite is crushed in one or more stages by Jaw crushers to liberate the bauxite nodules. The crushed bauxite is then freed from the adhering sand and clay by scrubbing, screening and or washing according to a suitably designed flow sheet. Bauxite of Australia, Guyana, Indonesia, Surinam and Rumania are beneficiated in this manner to produce high alumina (50 t0 60 percent Al_2O_3) and low silica bauxite for metallurgical use.

In our test the Jajarm bauxite was crushed in two stages by Jaw crushers up to –3 and +3 inches to liberate the bauxite nodules. The crushed bauxite was then freed from the adhering sand and clay by scrubbing, screening and the samples were washed with 5% HCl solution in a mechanical mixture for 15 minute. After this process the samples were analyzed after drying. The results of these tests are given in Table 6 As Table 6 shows the result of beneficiation for the samples below 3 inches are much better, module of 1.05 has changed in to 2.56 which indicates about 29% increase in Al_2O_3 content. These studies indicate that practically the cause of this increase of Al_2O_3 is the removal of shale bauxite and other impurities which could not be separated from high quality bauxite during mining. Thus, after the Jajarm ore has been crushed to a particular size, most of the free clay can be removed by the washing, but not those silicates which are within the structure of clay or reactive silicates.

8. Conclusions

Based on the above studies the following points can be concluded:

- Jajarm bauxite is typical diasporic bauxite; therefore it will be digested under higher pressures and temperatures and would be least soluble. Its extraction would require long digestion times and large lime charges in comparison with gibbsite and boehmite.
- From the textural point of view it has politomorphic texture; generally, the grain size is below 10 microns with a homogeneous matrix whereas some other bauxites in the world are different with a larger grain size.
- High percent of kaolinite is present as the main reactive silicate mineral which forms stacks of very thin (<0.1 micron thick) crystal platelets. This reacts with the caustic to form an insoluble sodium aluminum silicate which results in a loss of NaOH.
- The advantage of this bauxite is the higher recovery of Al_2O_3 in comparison with the other bauxites. Therefore on the basis of the above investigation it can be declared that the Jajarm bauxite can be enriched neither by means of selective grinding and classification nor by magnetic separation. Only limited beneficiation is possible by scrubbing and wet screening, after it has been crushed to a particular size at which most of the free clay can be removed by the acid washing. Silicates which are within the structure of clay or reactive silica are not removed by this process.
- The following suggestion could be the best method for beneficiation: Removal of shale bauxite before exploitation of hard and high quality bauxite. Dry screening of mixed ore after exploiting the bauxite followed by hand-sorting of the low-grade bauxite in the mine and stocks. Shale bauxite after explosion and exposure in atmosphere will lose its moisture and start weathering and change in to fine friable grains and fragments, whereas this is not the case with hard bauxite. In this case by screening we can remove this low grade bauxite and enrich the industrial bauxite. This test has been already done by the author and it will be discussed in a separate paper.

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