GEOCHEMICAL PROPERTIES, FORMATION MECHANISMS, AND INDUSTRIAL APPLICATIONS OF BARITE ($BASO_4$): A REVIEW

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Introduction

The chemical formula of barium sulfate, commonly known as barite, is $BaSO_4$, with a theoretical composition of 34.3% sulfur trioxide (SO_3) and 65.7% barium oxide (BaO). It is also referred to as barytes or heavy spar. When strontium substitutes for barium in the crystal lattice, the resulting mineral is celestite (strontium sulfate, $SrSO_4$). According to Clark and Washington [1924], barium is the fifteenth most abundant element in the Earth's crust, comprising approximately 0.05% of average igneous rock. Its highest concentrations are found in acidic igneous rocks, particularly in alkalic types such as syenite and nepheline syenite. Barium is also prevalent in sedimentary rocks, with shale exhibiting the highest content [Rankama & Sahama, 1950].

Barite ($BaSO_4$) forms under a broad range of pressure and temperature conditions (1–2000 bar, up to approximately 400°C) and is relatively resistant to weathering and secondary alteration processes. As a result, it is commonly distributed in igneous, metamorphic, and sedimentary geological environments. In sedimentary sequences, barite frequently occurs as massive beds, laminations, rosettes, or nodular structures [Hanor, 2000; Bonny & Jones, 2008].

In present-day marine geological environments, barite formation can be categorized into four genetic types based on strontium (Sr) and sulfur (S) isotopic compositions:

1. Pelagic/marine,
2. Cold seeps,
3. Hydrothermal, and
4. Diagenetic.

Pelagic barite forms in microenvironments within the water column that become supersaturated with respect to barite due to the decomposition of organic matter. Cold seep barite precipitates at the sediment–water interface along active and passive continental margins, driven by tectonic or hydrological expulsion of Ba-enriched fluids. Hydrothermal barite is typically associated with submarine volcanic activity, though it may also form where meteoric waters interact with late-stage hydrothermal fluids [Hanor, 2000; Paytan et al., 2002; Griffith & Paytan, 2012; Rye, 2005].

Barite occurrences have been identified on all continents except Antarctica. The leading global producers include China, India, the United States, and Morocco, with confirmed reserves concentrated in China and India (Asia), Algeria and Morocco (Africa), and the United States and Russia. As of 2020, global barite reserves were estimated at 3.0 billion tons. China held approximately 12.0% of global reserves, followed by India (17.0%) and Iran (8.0%), while China alone accounted for 30.53% of the world's total production.

Although elemental barium has limited industrial usage, its sulfate form—barite—is a widely utilized industrial mineral. Its high specific gravity (4.5 g/cm^3) significantly enhances its commercial value, particularly in petroleum and gas exploration, where approximately 90% of barite consumption in the United States is dedicated to drilling mud, weighting agents, and mud additives [Brobst, 1970; Johnson et al., 2017]. Barite also serves as a component in mold-release compounds for the metal casting industry and is employed in automotive manufacturing for metal protection, paint primers, and friction materials such as brake and clutch pads. Due to its opacity to gamma and X-rays, barite is widely used for radiation shielding in nuclear facilities and medical radiology [Fortier, 2022]. Additionally, it is used as a contrast agent in gastrointestinal radiographic imaging [Horton, 1963].

1.Geochemistry and Mineralogy of Barite

Barium commonly occurs in the geological environment as the divalent cation Ba^{2+}. Due to its relatively large ionic radius compared to most other divalent cations, barium is not readily incorporated into common rock-forming minerals. During the fractional crystallization of silicate magmas, barium becomes increasingly concentrated in the residual silicate melt. Similarly, it is enriched in silicate liquids generated through partial melting processes. The average barium content of the upper continental crust is estimated to be approximately 0.0624 wt.%. Granitic rocks generally contain higher concentrations of barium than the average continental crust, while basaltic rocks tend to have lower levels. Shales, on the other hand, exhibit barium concentrations comparable to those found in granitic rocks.

In minerals, barium frequently substitutes for cations of similar size, such as Pb^{2+} and Sr^{2+}, and to a lesser extent for the smaller Ca^{2+} and K^{+} ions. Substitution for potassium requires coupled substitution to maintain charge balance. In igneous rocks, barium typically occurs as a minor or trace element in potassium feldspar and mica, where it replaces K^{+}. Less commonly, it substitutes for Ca^{2+} in amphibole, apatite, calcite, plagioclase feldspar, and pyroxene. In sedimentary rocks and hydrothermal systems, barium is predominantly present in the form of barite ($BaSO_4$) or associated with organic matter. The widespread presence of trace barite in sedimentary rocks reflects the thermodynamic stability of sulfate (SO_4^{2-}) under Earth-surface conditions and the high solubility product constant of barite. While barite is stable in oxidizing environments, it is readily dissolved under reducing conditions dominated by hydrogen sulfide (H_2S). This redox-dependent solubility has important implications for both barite deposit formation and the environmental behavior of barium during mining activities [Johnson et al., 2017].

Barium is naturally abundant in continental settings, primarily occurring in three minerals: barite ($BaSO_4$), witherite ($BaCO_3$), and hollandite ($Ba_2Mn_8O_{16}$). Despite its widespread use in industries such as drilling fluids, medicine, glass, ceramics, and paper, barite can exhibit toxicity in biological systems, potentially harming both human health and plant development [Kaur, 2013].

Barite typically appears colorless to white, reflecting its orthorhombic crystal symmetry through tabular and habitual crystal morphologies. It also occurs in massive, nodular, and fibrous habits. The mineral has a density of 4.48 g/cm^3, nearly double that of most common rocks, and a Mohs hardness of 3 to 3.5, comparable to that of copper. Barite is characterized by several prominent cleavage planes. Natural barite is relatively pure, with only minor substitution (typically <7%) of barium by lead or strontium. This high purity is economically favorable, as the physicochemical properties of barite, such as density and solubility, tend to remain consistent regardless of the deposit location. Barite commonly precipitates from aqueous fluids, and due to the strong partitioning of barium into sulfate phases over potential impurities like strontium and lead, the resulting deposits typically contain low levels of contamination. Similarly, the substitution of calcium for barium in natural settings is limited [Johnson et al., 2017].

Gangue minerals are frequently associated with barite deposits, although their identity and abundance vary depending on the deposit type. Common gangue phases include clay minerals, carbonates (e.g., calcite, siderite), sulfide minerals (e.g., galena, marcasite, pyrite, sphalerite), silica phases (e.g., quartz, chert, drusy quartz, jasperoid), and iron oxides. Additionally, organic matter can be present in concentrations of several weight percent.

Witherite is a barium carbonate mineral that is typically colorless and displays pseudohexagonal dipyramidal crystals. It has

a density of 4.3 g/cm³ and a Mohs hardness of 3.5. Its tendency to effervesce in cold acid helps distinguish it from barite. Witherite commonly contains trace levels of calcium and strontium, which substitute for barium. In sedimentary environments, witherite is generally found in veins with associated minerals such as galena, and less commonly with anglesite, barite, and barytocalcite. Furthermore, it can alter into barite under suitable geochemical conditions [Johnson et al., 2017].

Table 1 presents the average barium (Ba) and strontium (Sr) contents in various minerals found in felsic and mafic rocks, highlighting their geochemical distribution based on rock composition [Mason & Moore, 1985].

Table 1. Average Ba and Sr contents of minerals found in felsic and mafic rocks

	Granodiorite		Gabbro	
	Ba	Sr	Ba	Sr
Plagioclase	250	280	510	800
Microcline	3,7	250	810	1,2
Biotite	1,400	4	160	420
Hornblende	28	13	440	600
Titanite	2	48	-	-
Apatite	-	120	6	700

[in ppm, Mason & More, 1985]

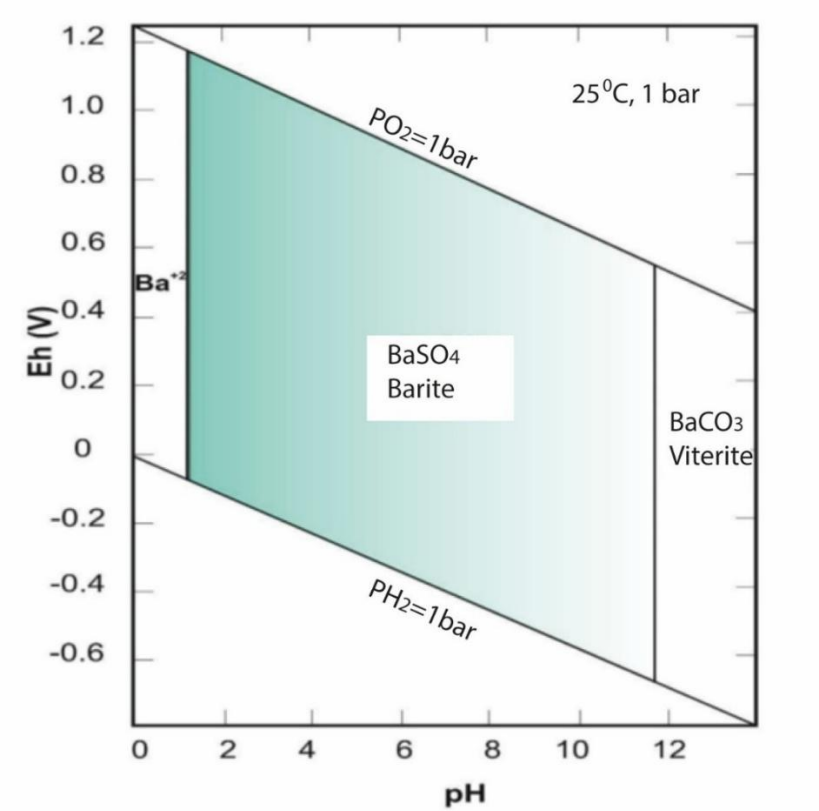
The solubility of barium in natural environments such as ocean water, alkaline soils, and groundwater is governed by multiple physicochemical parameters, most notably pH and the concentrations of various anions, including carbonate (CO_3^{2-}), chloride (Cl^-), sulfate (SO_4^{2-}), and organic ligands [Church & Kenneth, 1972]. Barium solubility increases significantly as the pH decreases from 11 to 7, and it remains relatively stable at pH values below 7. Conversely, at alkaline conditions (pH ≥ 8), the solubility of barium decreases due to enhanced precipitation with available

anions, leading to the formation of various barium-bearing minerals [Neubrand, 2000].

In sedimentary environments, barium commonly precipitates as barite ($BaSO_4$), which is considered the dominant and most stable phase under typical oxidizing and sulfate-rich conditions. Barite exhibits a broad stability field across the Eh–pH spectrum, and its solubility is extremely low across most natural water compositions. However, barite can become soluble under strongly acidic conditions, specifically when pH falls below ~1.2 (Figure 1). According to Bodek et al. [1988], the precipitation of barium sulfate effectively limits dissolved barium concentrations at pH 9.3 or lower. At pH values above 9.3, the availability of carbonate ions favors the formation of other barium minerals such as witherite ($BaCO_3$) [Singer, 1974; Bodek et al., 1988].

Under slightly acidic to near-neutral pH conditions (<9.3), the presence of chloride, nitrate, and carbonate ions has been shown to enhance the solubility of barium sulfate in soil, marine, and groundwater systems, potentially increasing barium mobility in these environments.

Figure 1. Diagram showing the stability field of barite on the Eh-ph diagram



[Brookins, 1987]

2.Formation of Barite Deposits

Barite exhibits a broad genetic and geological formation spectrum, particularly within late-stage magmatic environments (Figure 2). In addition to magmatic settings, barite is also commonly encountered in sedimentary and metamorphic formations, underscoring its widespread occurrence across diverse geological regimes. Several economically significant barite deposit types have been recognized and are summarized below.

The most important and voluminous form of barite accumulation is the bedded-sedimentary type, which consists of stratiform, massive ore bodies developed within marine sedimentary basins. These deposits typically occur within sequences containing organic-rich shale, mudstone, or chert, and can exhibit lateral continuity extending over several kilometers, with thicknesses exceeding 100 meters. In marine evaporite settings, bedded and replacement-type barite and witherite ($BaCO_3$) deposits are formed through the interaction of reduced, barium-rich brines with ambient marine sulfate or carbonate phases.

Sulfide mineralization, particularly of the zinc-lead type, is commonly associated with extensive hydrothermal fluid-flow systems that are responsible for the genesis of Mississippi Valley-type (MVT) and Sedimentary Exhalative (SEDEX) deposits. These hydrothermal systems are often spatially and genetically related to the formation of bedded barite accumulations.

In submarine volcanic environments, bedded-volcanic barite deposits are often spatially linked to volcanogenic massive sulfide (VMS) systems. These deposits form at or near seafloor volcanic centers, where hydrothermal fluids release barium that precipitates as barite in association with volcaniclastic sedimentation.

Another major deposit type includes vein and cavity-fill barite, which typically forms along structural conduits such as faults, breccia zones, and other permeable lithologies. These features serve as pathways for barium-bearing fluids, which precipitate barite upon interaction with the host rock or due to changes in temperature, pressure, or fluid chemistry.

In addition to these primary deposit types, residual barite deposits may develop as a result of the weathering and supergene alteration of pre-existing barite-bearing formations. These secondary

accumulations represent the remobilization and concentration of barium under surface weathering conditions [USGS, 2019].

Figure 2. a) Barite from Kings Creek, South Carolina, b) Barite from Mercur, Utah, c)This "barite rose" is a cluster of bladed barite crystals that have grown in sand, incorporating many of the sand grains within each crystal, d) Barite from Madoc, Ontario, Canada

[URL1]

2.1.Exhalative-Sedimentary Barite Deposits (Volcano-Sedimentary Barite Deposits)

Exhalative–sedimentary barite deposits, also referred to as volcano–sedimentary barite deposits, form in association with submarine volcanic activity. These deposits result from barite precipitation concurrent with volcaniclastic sedimentation, as barium-bearing fluids and volcanic emissions interact with the depositional environment. The primary source of barium in these

systems is volcanic gases and hydrothermal solutions, whereas sulfur may be derived either from seawater or volcanic volatiles.

These deposits typically occur within volcano-sedimentary successions, where volcanic rocks are interbedded with sedimentary layers. Barite is deposited in stratiform layers, often displaying typical sedimentary structures such as laminations and bedding. These deposits may be enriched in base metal sulfides (e.g., Zn, Pb), and iron and manganese oxide bands are frequently concentrated within certain horizons. They exhibit a layered morphology, commonly aligned with specific stratigraphic levels, and may grade into vein-type barite mineralization at deeper structural levels.

Exhalative–sedimentary barite deposits are considered hypogene–syngenetic in nature, having formed contemporaneously with the host sediments. Notable examples include the Meggen deposit in Germany, which is genetically linked to syngenetic sulfide mineralization [Amstutz, 1963; Zimmermann, 1970].

2.2.Hydrothermal- Sedimentary Barite Deposits

Hydrothermal–sedimentary barite deposits share several structural, textural, and genetic similarities with exhalative–sedimentary types; however, they lack associated volcanic host rocks. Instead, their formation is driven by the input of hydrothermal fluids into the sedimentary basin, often emanating from plutonic intrusions or deeply circulated groundwater that has been heated at depth.

These hydrothermal fluids ascend through fractures, faults, and porous zones within the host rock during active sedimentation. Precipitation of barite is triggered by factors such as increasing barium concentration, cooling, neutralization, and the availability of sulfate ions, either from the hydrothermal fluids themselves or from the surrounding environment. The barium may originate directly

from plutonic rocks, or it may be mobilized during interaction with acidic, high-temperature fluids.

The principal transport mechanism for barium in hydrothermal solutions is through complexation with chlorine-bearing species, facilitating its mobility and subsequent precipitation [Temur, 2001]. Base metal sulfides such as pyrite, sphalerite, and galena are frequently associated with these deposits, especially when formed in proximity to intrusive bodies.

2.3.Hydrothermal Barite Deposits

Hydrothermal barite vein-type deposits form as a result of deeply circulated groundwaters, which are heated by plutonic activity or magmatic intrusions, and are subsequently enriched in dissolved elements under the influence of lithostatic pressure and magmatic gases. These hydrothermal fluids migrate through pore spaces, fractures, and voids within the surrounding rocks, acquiring significant concentrations of highly soluble ions.

Upon interaction with carbonate rocks, which enhance dissolution, porosity development, and pH buffering, these fluids induce the precipitation of barite and associated minerals. Barite typically forms in the medium- to low-temperature hydrothermal regime, and is often the terminal phase in the paragenetic sequence. These epigenetic, vein-type deposits are accompanied by a suite of minerals including fluorite, pyrite, sphalerite, galena, chalcopyrite, bornite, quartz, dolomite, calcite, and siderite, and exhibit high $BaSO_4$ grades [Temur, 2001].

Hydrothermal barite deposits occur across various tectonic settings, particularly around the Pacific Ocean, including block-faulted transform margins, volcanic arcs, fracture zones, and spreading centers (both mid-ocean and back-arc). Prominent examples include:

The Blanco Fracture Zone, a transform fault linking the Gorda and Juan de Fuca spreading centers in the northeastern Pacific, The Guaymas Basin in the Gulf of California, Several sites along the California Continental Borderland, and The Escanaba Trough, the southernmost segment of the Gorda Ridge. These hydrothermal systems are closely associated with magma emplacement, volcanic activity, and hydrothermal fluid circulation, and commonly host barite-dominant mineralization (see Figure 3).

Figure 3. (a, b) Oxidized barite–lead ores of the Ushkatyn-III deposit

[Brusnitsyn et al., 2023]

2.4.Residual Barite Deposits

Residual barite deposits form as a result of the chemical stability of barite under surface weathering conditions. In tropical to subtropical climates characterized by high temperatures and intense rainfall, rocks containing disseminated barite, particularly limestones or primary barite-bearing beds, undergo chemical weathering and decomposition. While most rock-forming minerals are leached or altered during this process, barite remains chemically resistant, and either accumulates in situ or becomes concentrated through short-distance transport.

Barite frequently accumulates in karstified zones, where it is retained in solution cavities, sinkholes, and karstic depressions. Consequently, these deposits are commonly referred to as karst-type barite beds [Bonel, 2005; Zuffardi, 2012]. Although barite grades in such residual accumulations can reach 50–60 wt.% $BaSO_4$, they are generally not economically viable for large-scale exploitation due to their irregular distribution, limited thickness, and manual recovery requirements.

One of the most notable examples of karst-related residual barite is found in Washington State (USA) [Zuffardi, 2012]. During the 20th century, small-scale manual mining was undertaken in Missouri, primarily targeting these types of shallow, residual barite concentrations. However, no active production from such deposits remains today [Bonel, 2005].

In Türkiye, Cengiz & Kuşçu [1993] documented residual barite occurrences in the Çarıksaraylar region, located within the Şarkikaraağaç district of Isparta, where barite enrichment is similarly associated with weathered carbonate formations and karst topography.

2.5. Sedimentary Barite Deposits

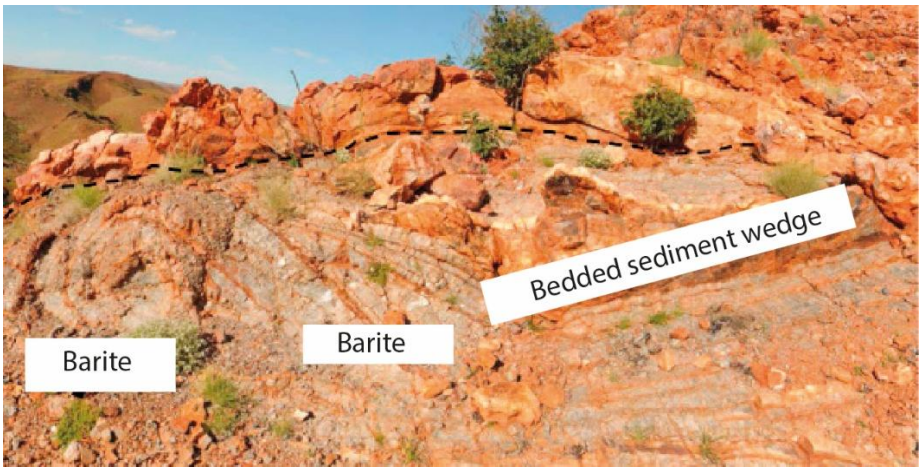
In terrestrial environments, barium is released into aqueous solutions through the chemical weathering of barium-bearing rocks, a process that is often enhanced by the action of organic acids. During weathering, barium ions are mobilized and transported to sedimentary basins, frequently adsorbed onto clay minerals. Within the sedimentation environment, these barium ions react with organic-derived or juvenile sulfate ions, leading to the precipitation of barite ($BaSO_4$).

Sedimentary barite deposits typically exhibit bedded or layered morphologies and display classical sedimentary features, such as laminations and bedding planes. These deposits are commonly found intercalated with carbonate rocks, or they may occur as lenses and nodules embedded within shale sequences. Importantly, these deposits lack any evidence of hydrothermal alteration at their contacts with host rocks, distinguishing them from hydrothermal-related barite systems (Figure 4).

Genetically, these deposits are classified as supergene–syngenetic, meaning they formed contemporaneously with sedimentation and under near-surface conditions [Amstutz, 1963]. The color of barite in these deposits typically ranges from grey to black, often due to high organic matter (bitumen) content. The crystal habit of barite in such environments is generally elongated and subhedral.

In the Toguima Range, as well as in Arkansas and Nevada (USA), barite deposits commonly contain chert, phosphate minerals, and detrital rock fragments within their matrix, indicating a complex interplay between chemical precipitation and mechanical deposition in their formation [Kuzvart, 1984].

Figure 4. Large barite mass outcrop view

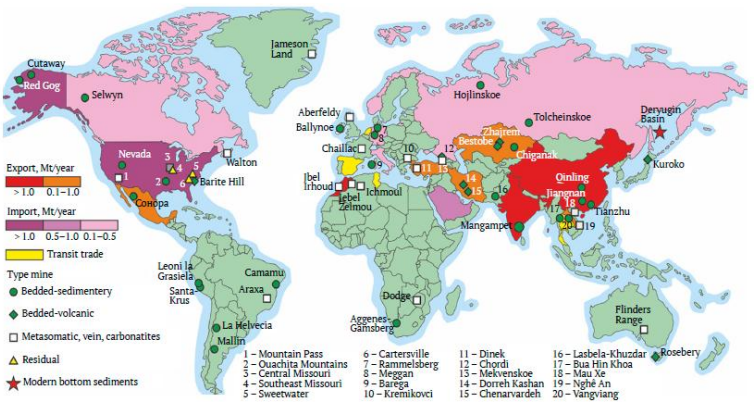


[from Djokic et al. 2017]

3.Resources of Barite

Globally, barite resources are widely dispersed (Figure 5). All continents except Antarctica are used for production. Kazakhstan, China, India, the United States, Morocco, Russia, and Algeria own the majority of the world's barite reserves.

Figure 5. Map of the world with the localization of barite deposits and lead to a Global map showing the locations of barite reserves and the top exporting, importing, and transiting nations in the global commerce of barite raw materials



[Boyarko & Bolsunovskaya, 2023]

Barite ($BaSO_4$) is the primary and only commercially significant barium mineral utilized for the production of barium sulfate at varying degrees of purity. While most industrial-grade barite is derived from primary barite deposits—where barite is the dominant gangue or ore mineral—increasing attention is being paid to barite-bearing ores where barite occurs as a secondary phase or gangue mineral in polymetallic systems.

In deposits where barite is the principal mineral, it commonly occurs in coarsely crystalline form, exhibiting well-developed crystal morphologies. In contrast, when barite coexists with other ore minerals, it may appear intergrown or inclusively disseminated, reducing its liberation efficiency during beneficiation. Structurally, barite belongs to the rhombic holohedral crystal system, with a characteristic mineralogical framework. The microstructure of $BaSO_4$ comprises nearly regular tetrahedra, where the sulfur atom occupies the central position, and the oxygen atoms define the vertices, resulting in a highly symmetrical crystal lattice.

Barite is extracted globally from a diverse array of geological environments. In the United States and Eastern Europe, economically significant deposits are found in limestones and argillites, often with barite replacement textures. A typical example includes bedded dark grey chert intercalated with fossiliferous, carbonaceous limestone lenses, indicative of diagenetic replacement in a low-energy depositional environment.

3.1.Vein-Type Deposits

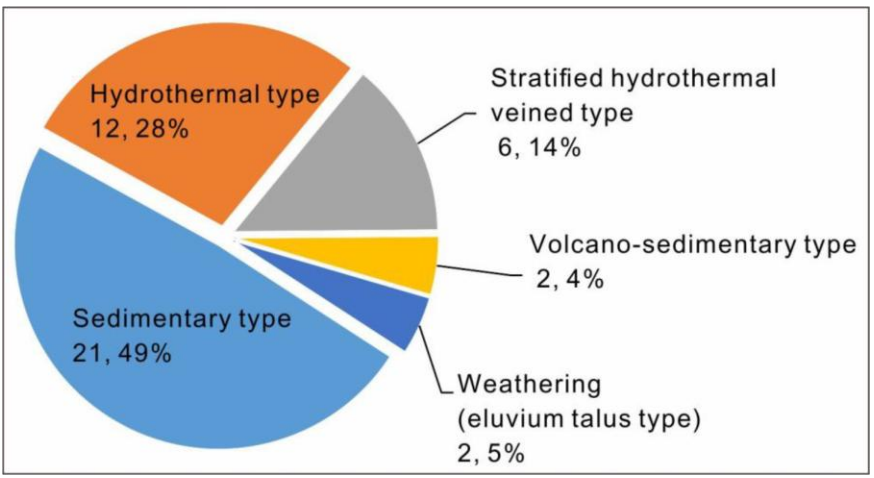
Vein barite deposits are often associated with replacement textures in vein-hosted settings. These systems may include minerals such as fluorite and calcite, in which barite can be intergrown, encapsulated, or disseminated. Minor accessory minerals include iron oxides, quartz, and celestite. These deposits frequently exhibit impurities, with common contaminants including alumina,

carbonate minerals, iron oxides, and silica, which must be removed during beneficiation processes.

3.2.Base Metal-Associated Deposits

Barite is also a common constituent of sulfide-rich base metal deposits, where it is associated with minerals such as copper, lead, zinc, and pyrite. These deposits typically contain barite in concentrations ranging from 20% to 45% $BaSO_4$. In such systems, sulfide tailings from mining operations are often processed to recover barite as a by-product. Documented occurrences of this type have been reported in South America, the United States, the former Soviet Union, Eastern Europe, and Canada (notably in Newfoundland and British Columbia) [Bulatovic, 2015].

Figure 6. World resources of barite in deposits prepared for exploitation (Mt)



[Li et al., 2023]

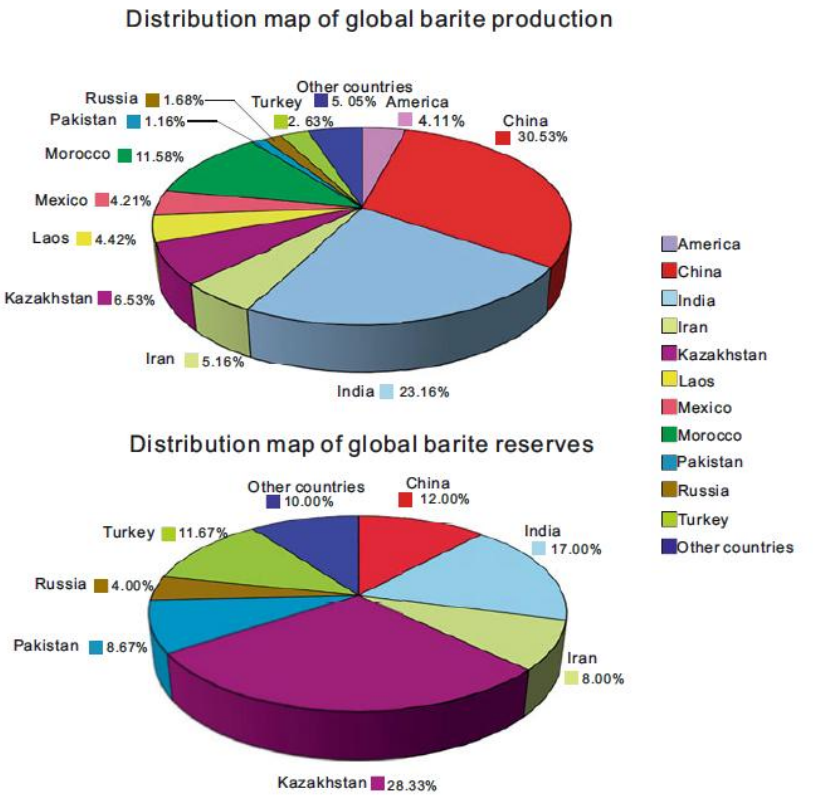
According to estimates by the United States Geological Survey (USGS), total global barite resources amount to approximately 2 billion metric tons, although only 740 million tons have been classified as proven reserves. As of 2022, the world's

economically recoverable barite reserves exceeded 390 million tons. Notably, Pakistan has significantly increased its reported reserves from 14 million tons to 40 million tons, while China has slightly revised its estimate downward, from 37 million tons to 36 million tons [Zhang & Lu, 2017].

More than 80% of the world's barite reserves are concentrated in just a few countries—China, India, Pakistan, Kazakhstan, and Iran—indicating a high degree of geopolitical and geographic concentration of barite resources (Figure 6). Among these, China holds approximately 12.0% of the global reserves, followed by India and Iran, with 17.0% and 8.0%, respectively. In terms of production, China alone accounts for one-third (30.53%) of total global output, making it the world's leading producer of barite.

According to USGS data, global barite production rose from 73.22 million tons in 2016 to 90.86 million tons in 2018, reflecting growing industrial demand. However, the COVID-19 pandemic caused a sharp decline in output, with global production falling to 66.62 million tons in 2020. Recovery efforts suggest a rebound, with production levels projected to increase to approximately 72.2 million tons in 2021. As of 2020, China remained the dominant global producer of barite. India, with an annual output of approximately 16 million tons, ranked as the second-largest producer, contributing 24.02% of global mine production [USGS, 2021] (Figure 7).

Figure 7. Histogram of fluorite production and reserves percentage of the World



[Zou et al., 2022]

4.Uses of Barite

Barite ($BaSO_4$) is a solid, high-density mineral with a broad range of economic and industrial applications, owing primarily to its high specific gravity, chemical inertness, and radiopacity.

The oil and gas industry is the largest consumer of barite, utilizing the mineral as a weighting agent in drilling muds. During drilling operations, high formation pressures are encountered, necessitating the use of heavy drilling fluids to stabilize the borehole, control subsurface pressures, and prevent blowouts. Drilling fluids

are typically prepared by mixing finely ground barite with a clay-water base, producing a dense suspension. In addition to providing weight, barite's softness acts as a lubricant, thereby reducing wear on drilling tools and equipment. Among its physical properties, specific gravity (typically 4.2–4.5 g/cm³) is the most critical parameter influencing its suitability in drilling fluid formulations.

Barite is also the primary industrial source of barium, and its derivatives play a vital role in medical and nuclear shielding applications. Due to its opacity to X-rays and gamma radiation, barite is widely used in radiation shielding for nuclear facilities, medical imaging rooms, power plants, and laboratory environments. In diagnostic radiology, barite compounds are employed as contrast agents in gastrointestinal tract imaging, enhancing visibility during X-ray and CT examinations [Ebunu et al., 2021].

Beyond the energy and healthcare sectors, barite has additional applications in various manufacturing industries. It is used as a pigment extender in paints, and as a weighted filler in paper, textiles, and rubber products, including "anti-sail" mudflaps for vehicles. Its high density and radiation absorption capability also make it an ideal aggregate for heavy-weight concrete, particularly in nuclear infrastructure and radiation shielding construction projects [Bonel, 2005].

Other industrial applications include its use in the production of plastics, industrial chemicals, traffic cones, clutch pads, brake linings, sound-deadening materials, and mould-release agents in metal casting processes (Figure 8).

Figure 8. Barite powder

5.Beneficiation of Barite

Over the past three decades, extensive research has been conducted on the beneficiation of barite ores using a variety of mineral processing techniques, including flotation, gravity preconcentration, and magnetic separation [Browning et al., 1964; Peck & Wadsworth, 1964; Drawafer, 1984; Bulatovic, 1987]. These methods have been refined and optimized to suit the mineralogical characteristics and complexity of the ore, particularly in cases where barite occurs with a diverse suite of gangue minerals.

In modern industrial operations, flotation is widely regarded as the most effective method for recovering barite from complex ores, especially when the liberation size of the barite is extremely

fine. The success of flotation depends heavily on the textural properties of the ore, the association of barite with other gangue minerals, and the mineralogical composition of the deposit

Two principal flotation approaches are used in barite processing: direct flotation and reverse flotation. In reverse flotation, sulfide minerals such as pyrite or other base metal sulfides are first removed from the pulp, with barite being concentrated in the tailings stream, which is subsequently subjected to flotation for recovery. In direct flotation, barite is floated selectively from ores containing silicates, fluorspar, or rare earth oxides (REOs)—a category commonly referred to as complex barite ores [Bulatovic, 2015].

Each beneficiation method must be tailored to the physical and chemical properties of the ore, including particle size, specific gravity, and surface chemistry. The choice of collectors, depressants, and pH regulators during flotation is also critical in enhancing selectivity and optimizing recovery rates.

5.1.Beneficiation of barite ores using the physical concentration method

When silicates, calcite, and iron-bearing minerals represent the dominant gangue phases in barite ores, physical concentration techniques are commonly employed for barite recovery. These include gravity separation and magnetic methods, which exploit differences in specific gravity and magnetic susceptibility between barite and associated impurities.

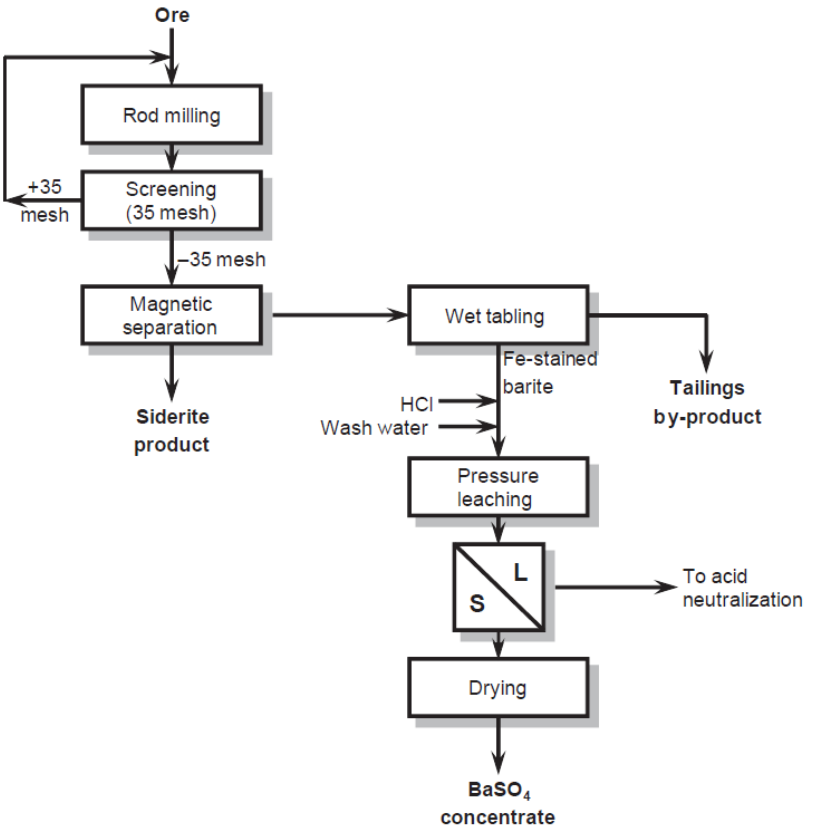
A generalized flow sheet for this beneficiation route is presented in Figure 9. Utilizing this method, a concentrate containing 97.5% $BaSO_4$, 0.0011% heavy metals, and 0.0001% Al_2O_3 was produced, meeting the stringent purity requirements for pharmaceutical-grade barium sulfate. The initial gravity concentrate, however, exhibited iron staining, necessitating an additional acid

leaching step. Iron was effectively removed through leaching with muriatic acid (hydrochloric acid), resulting in a highly purified final product.

An alternative and more comprehensive flow sheet, depicted in Figure 10, demonstrates a hybrid approach that integrates gravity separation with flotation. This combined process is particularly effective for producing barite concentrates suitable for both chemical and drilling mud applications. In the flotation stage, a fatty acid collector is employed under slightly alkaline conditions, typically at a pH range of 8.5 to 9.0, to selectively float barite while depressing unwanted gangue minerals.

These integrated beneficiation strategies are essential for processing complex barite ores, especially those with fine-grained textures or containing multiple gangue components, enabling the production of high-purity barite for a variety of industrial uses.

Figure 9. Generalized flow sheet for beneficiation of barite ores using magnetic separation gravity method



[Bulatovic, 2015]

5.2.Beneficiation of barite ore that contains fluorspar and silica gangue minerals

Information on the flotation behavior of barite from fluorspar-bearing ores remains relatively limited in the scientific literature. These complex ore types often contain a variable suite of accessory minerals, including rare earth oxides (REOs), which further complicate the beneficiation process. Notable occurrences of such deposits have been identified in Canada and Vietnam, where

both barite and fluorspar coexist within the same mineralogical assemblage.

To address the recovery of barite from these ores, two sequential flotation strategies have been investigated:

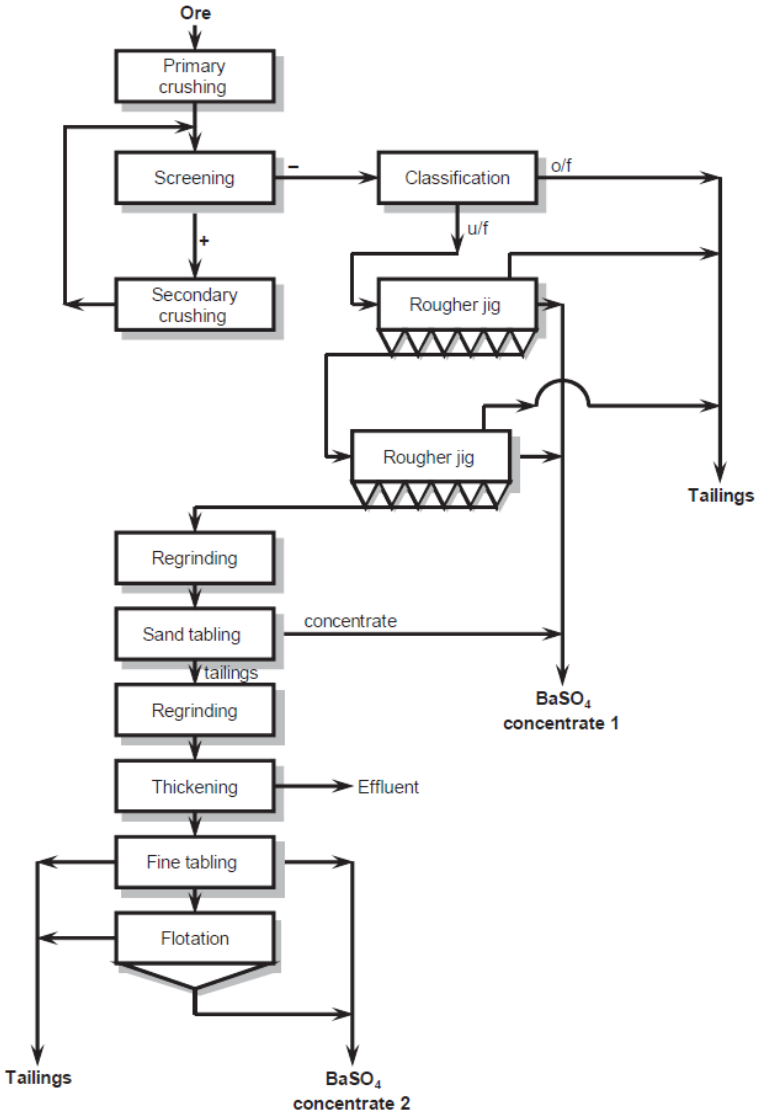
(1) Fluorspar flotation followed by barite flotation, and

(2) Barite flotation followed by fluorspar flotation.

In the first approach, known as fluorspar–barite flotation in sequence, fluorspar is selectively floated in the initial stage. During this process, barite is effectively depressed using reagents such as dextrin and quebracho, which inhibit barite flotation while allowing fluorspar to be recovered. Once fluorspar is removed, barite is subsequently floated under optimized conditions to maximize recovery and purity

These strategies are designed to exploit subtle differences in surface chemistry and collector affinity between barite and fluorspar, ensuring selective separation. Such sequential flotation schemes are essential when dealing with multi-mineral ore bodies, especially those enriched in fluorspar, REOs, or other high-value industrial minerals.

Figure 10. Flow sheet for beneficiation of barite using combinations of gravity and flotation



[Bulatovic, 2015]

6.Barium Behavior in the Environment

Barium (Ba) is a chemically reactive alkaline earth metal that occurs naturally only in combined forms, primarily as sulfate ($BaSO_4$) and carbonate ($BaCO_3$) minerals. Its presence in the environment arises from both anthropogenic and natural sources. Major anthropogenic contributors include industrial activities such as mining, beneficiation, and chemical processing of barium-bearing ores and compounds. Additional emissions stem from the combustion of fossil fuels, particularly coal, and the atmospheric entrainment of soil and rock dust particles.

Coal ash, in particular, is recognized as a significant source of airborne barium, exhibiting widely variable concentrations depending on coal composition. In the atmosphere, barium is most likely present as particulate matter, rather than in dissolved or gaseous forms. The removal of barium from the atmosphere primarily occurs via wet and dry deposition, although chemical transformations in the air may influence its speciation and environmental reactivity.

In aquatic environments, barium readily precipitates as insoluble salts, such as barite ($BaSO_4$) and witherite ($BaCO_3$), under suitable geochemical conditions. Barium can also adsorb onto suspended particulates, further facilitating its removal from the water column. When riverine waters—often containing dissolved barium—enter marine systems, the high sulfate concentrations in seawater promote the precipitation of barium sulfate, contributing to barite accumulation in marine sediments. Consequently, barite constitutes the dominant form of barium in most marine and lacustrine sediments.

Under alkaline conditions ($pH > 9.3$) and in the presence of carbonate ions, barium carbonate becomes the thermodynamically favored species. It exhibits extremely low solubility and rapid

precipitation kinetics, thereby significantly restricting the mobility of dissolved barium in such environments. In addition, barium can form low-solubility compounds through reactions with phosphate, fluoride, oxalate, arsenate, and chromate ions. In contrast, under more neutral to acidic aqueous conditions, soluble barium species such as barium hydroxide [$Ba(OH)_2$], barium nitrate [$Ba(NO_3)_2$], and barium chloride [$BaCl_2$] are commonly encountered [Gad, 2014].

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