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Some Industrial Mineral Deposit Models: Descriptive Deposit Models

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INTRODUCTION

This compilation of industrial mineral deposit models is meant as an extension of U.S. Geological Survey Bulletin 1693, *Mineral Deposit Models*. Bulletin 1693 contains very few descriptive or grade-tonnage models for industrial minerals and yet industrial minerals comprise a large proportion, if not the majority, of mineral production in the United States and the rest of the world. This compilation is not exhaustive of the deposit types for industrial minerals and future publication of additional models is planned. To maintain compatibility with Bulletin 1693, the models in this compilation follow a similar format and have been given an alphanumeric model number that fits into the Cox-Singer litho-tectonic classification presented in that publication. Appendix B is a complete listing of that classification scheme with the addition of the industrial mineral models in this compilation (shown in bold-faced type) as well as others in the development stage.

Many industrial mineral deposits are similar to metal deposits in that certain geologic criteria are clearly identified as necessary for the presence of a deposit. However, many types of industrial mineral deposits have been studied in a geologic sense to a very limited extent, if at all, and this is reflected in the level of information present in the descriptive models. Many industrial minerals are known under a variety of trade names or names that reflect their usages and that do not correspond to a mineral name or deposit type in a geologic sense. The mineral kaolinite which occurs in a variety of deposit types may be referred to as kaolin, flint clay, ball clay, or china clay; each of these names indicates different uses and physical properties of a single mineral form.

The reader should know that model identity numbers followed by a "(T)" are working numbers and may be changed at a later time. Most often this results because of uncertainty in discriminating between some deposit types. For example, should lithium in playa brines be a separate model from boron in playa brines even though Li and B are commonly different components of the same brine? On the other side of the issue, the Li and B may not have originated from the same source or been concentrated by the same mechanism. Additional data and more complete models may help address these issues. The reader should also know that country(state) codes are listed in Appendix A.

Grade-tonnage and other models are not included in this compilation, but will be released in future Open-File Reports.

DESCRIPTIVE MODEL OF DIAMOND-BEARING KIMBERLITE[1] PIPES

By Thomas C. Michalski and Peter J. Modreski

BRIEF DESCRIPTION

Previous and (or) Alternate Version of Model: *"Descriptive model of diamond pipes"* (Cox, 1986.)

Deposit synonyms: Diatreme, blow, vent, explosion pipe, explosion breccia.

Principal commodities produced: Diamond.

By-products: Gem quality pyrope garnet, serpentine.

End uses: Gemstones, abrasives, semiconductors, scientific instruments, surgical instruments, machine tools, drill bits.

Descriptive/genetic synopsis: Diamond bearing kimberlite pipes have been recognized for over 100 years as the most important primary source of economic quantities of gem-quality diamonds on the earth's surface. Kimberlite is rare, hybrid, ultrabasic rock that forms in the earth's upper mantle and is rapidly emplaced into the earth's crust along deep seated fractures developed on or near ancient cratons. As the kimberlite magma approaches the earth's surface, contained volatiles exsolve from the magma and the fracture along which they are emplaced is enlarged leading to the formation of a pipe-like diatreme near the earth's surface. It is generally assumed that most kimberlite pipes erupted on the earth's surface (although surface features are only rarely preserved in most known kimberlite provinces).

Kimberlite diatremes form steeply dipping, downward tapering, conical shaped bodies of relatively small surface area. Surface exposures of diamond-bearing pipes generally range from small bodies less than 30 m in diameter up to pipes slightly larger than 1.5 km in diameter. Most diamond bearing kimberlite pipes occur in ancient cratonic areas as part of a kimberlite field or cluster. Pipes within a given field generally have a highly variable size, shape, and diamond content. Only about 5-17 percent of diamond-bearing pipes within a given field will prove to be economically viable. Generally the larger size pipes within a diamond-bearing kimberlite field tend to be the most diamondiferous (although the very largest pipe is not necessarily the most diamondiferous).

On a worldwide basis only about 10% of known kimberlites are diamond-bearing and only one or two percent of kimberlites contain economic quantities of diamond. The amount of diamond contained within diamond bearing pipes is extremely small, with commercially mineable concentrations ranging from .01 ppm to .20 ppm (.04 to 1.0 carats per ton). The clarity, size, shape, color, and volume of diamonds within a pipe need to be carefully determined before the true economic potential of a diamond-bearing pipe can be determined.

Until relatively recently most researchers believed that diamond crystallized within the kimberlite melt during its formation within the mantle or during its transport to the earth's surface. Recent research however indicates that most, if not all, diamond contained within kimberlites was originally crystallized in eclogite or peridotite layers within the upper mantle. Kimberlite (and lamproite) magma acts as the fluid medium that transport diamond-bearing eclogite or peridotite nodules to the earths surface. Because of the violent and abrasive nature of diatreme formation, most nodules become disaggregated during transport and their contained diamonds become incorporated into the groundmass of the kimberlite pipe.

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Lamproites are rare ultrapotassic alkaline rocks which can occasionally form diatremes which contain commercial quantities of diamond. Although genetically related to kimberlites, diamond-bearing lamproites tend to form in regions of higher tectonic activity.
The whole rock chemistry and mineral content of lamproites is also different and should be taken into account when designing exploration programs.

Whether or not a kimberlite is diamond-bearing, and the volume of diamond contained within a diamond-bearing pipe, is dependent on a variety of factors. The ideal situation for the formation of a high-grade, economic, diamond-bearing kimberlite pipe would include the following: 1) the presence of large quantities of high-quality diamonds within peridotite or eclogite layers in the upper mantle, 2) the development of a kimberlite magma at or below the diamond-bearing layer, 3) the development of deep-seated fractures which could act as a conduit from the mantle to the earth's surface, 4) the dislodging of relatively large quantities of the diamond-bearing layer and its incorporation into the kimberlite as it ascends rapidly, 5) the magma maintains low oxygen fugacity thus preventing the oxidation of diamonds, 6) a diatreme forms near and penetrates the earth's surface - thus quenching the kimberlite and preventing the resorption of diamonds, and 7) erosion has not been extensive, thus preserving the upper diatreme facies part of the pipe. The likelihood of all of these conditions occurring together is small and thus accounts for the rarity of economically mineable, diamond-bearing kimberlite pipes that have been discovered to date.

Ore grade in economic pipes generally decreases with depth. Average diamond-bearing ore has a grade of about .25 carats per ton. Most pipes consist of several pipe- or dike-like columns of kimberlite ore, each of which will have a different ore grade. The economic viability of a given pipe is often determined more by the ratio of gem-quality to industrial diamond, and the size, shape, clarity, and color of the gemstones, than by the absolute ore grade. The ratio of gem quality to industrial diamonds in most economic deposits is about 1 to 4.

The size, degree of brecciation, serpentinization, and diamond content of most pipes decreases with depth. Surface exposures generally consist of weathered kimberlite (yellow ground) that is enriched in diamond as a residual weathering product. Below this layer serpentinized, brecciated, diatreme facies kimberlite (blue ground) is often encountered. With depth the size of the diatreme decreases, and the degree of brecciation and serpentinization decreases. Eventually diatreme facies kimberlite grades into hard, relatively massive, hypabyssal facies kimberlite (hardbark) that shows little serpentinization, has a reduced cross-sectional area, and a reduced diamond grade. With depth the kimberlite body eventually grades into a dike-like body of hard, massive kimberlite.

Typical Deposits: African deposits
        (Clement and others, 1986)
                Western Australia deposits   (Atkinson and others, 1984)
                Wyoming-Colorado deposits   (Lincoln, 1983)

Relative importance of the deposit type: Major source of gem and industrial diamonds.

Associated/related deposit types: Kimberlite dikes, diamond placers, lamproites.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Ancient stable cratons, alkalic rock provinces, regions of crustal tension with deep-seated fractures, broad anteclises and syneclises with deep-seated fractures, regions of low geothermal gradient.

Regional depositional environment: Any rock type may host kimberlite intrusions.

Age range: 2.5 billion years to 30 million years.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Kimberlite breccia, tuff, hypabyssal kimberlite, lamproite.

Associated rock(s):   Kimberlite dikes, carbonatite, alkalic rocks.

Ore mineralogy: Diamond, bort (imperfectly crystallized), carbonado (polycrystalline generally dark colored), ballas (spherulitic polycrystalline).

Gangue mineralogy: Olivine, pyroxene, garnet, ilmenite, serpentine, chromite.

Alteration: Serpentinization of diatreme facies kimberlite is very common. Silicification of internal and contact zones occurs in some pipes. Fracture filling of secondary calcite, quartz, and zeolites has often been noted.   Metasomatism of country rock adjacent to pipe contacts is common. Hydrothermal alteration, zeolitization, silicification, calcification, and fenitization of country-rocks can occur near diatremes.

Structural setting: The trend of kimberlites often is parallel to prominent joints, dikes, or other linear trends within a district. On occasion diatreme emplacement is fault controlled and occurs near major faults or at the intersection of major and secondary faults. Contacts between pipes and country rock are generally sharp with little or no arching, doming, or radial fractures.

Ore control(s):   Ore grade is generally believed to decrease with depth and is attributed to the resorption of diamond in the less quenched, deep-seated hypabyssal kimberlite zone. Most pipes also consist of several separate and distinct columns of kimberlite, each of which has a different ore grade.

Typical ore dimensions: Economic pipes generally have an oval or irregular surface outline and vary in size from 4 to 146 hectares. Most deposits, however, have a surface exposure of less than 40 hectares and greater than 10 hectares.

Typical alteration/other halo dimensions: Alteration is extremely localized (a few cm from contact).

Effect of weathering: Negative relief and the development of yellow ground (weathered kimberlite consisting of chlorite, clays, and iron hydroxides) occurs in tropical areas. Effects of weathering are less pronounced in cooler, less humid areas. In arctic and subarctic areas yellow ground seldom develops and there is little or no difference in relief between kimberlites and country rock. Hypabyssal facies kimberlite tends to weather less readily than diatreme facies kimberlite and may on occasion form small areas of positive relief.

Effect of metamorphism: Metamorphism at low pressure, high temperature, and moderate to high oxygen fugacity can lead to resorption, graphitization and (or) oxidation of diamonds.

Maximum limitation of overburden: Most economic kimberlite pipes discovered to date have had little or no overburden. Weathering of diamond-bearing pipes often leaves a weathered surface layer enriched in diamonds. Economic evaluation of pipes not exposed at the earth's surface would depend on the size of the pipe, the value of gemstones contained within the pipe, and the amount of overburden above the pipe. Determination of the economic value of a deeply buried diamond-bearing pipe would be very difficult and likely involve an extensive core drilling program.

Geochemical signature(s):   Kimberlites are generally enriched in the following trace elements: Cr, Ni, Co, Re, Os, Nb, Sr, Rb, Ba, U, Th, and rare earth elements. Geochemical exploration for , and delineation of kimberlites using Ni, Cr, and Nb has proved successful in some areas. Stream sediment sampling for Mg-ilmenite, Cr-pyrope, and Cr-diopside is a commonly used technique for locating kimberlite pipes. The presence of high-Cr/low-Ca pyrope and chromite is indicative of diamond bearing kimberlite.

Geophysical signature(s):   Airborne magnetometer surveys have been used to locate high local magnetic anomalies over kimberlite pipes intruded into sedimentary rocks. Negative gravity anomalies can occur over highly brecciated pipes. High resistivity of weathered kimberlite has been used to delineate buried contacts between kimberlite and country rock.

Other exploration guide(s):   There is often a difference in soil type and vegetation that has developed on top of weathered kimberlite versus country rock. This difference has been attributed to higher soil moisture in weathered kimberlite and (or) toxic or fertilizer effects of certain elements contained within kimberlites. High levels of soil-hosted *Bacillus cereus* bacteria over pipes versus country rock has also been noted.

Most readily ascertainable regional attribute: Region of crustal tension on or near ancient cratons.; alkalic rock provinces with deep seated ultramafic nodules; micro or macro diamonds, Cr-pyrope, or Mg-ilmenite in stream sediments in the region.

Most readily ascertainable local attribute: A high level magnetic anomaly; a change in local vegetation; and micro/macro diamonds, Cr-diopside, high Cr/low-Ca pyrope, Mg-ilmenite, or deep seated ultramafic nodules in soil and/or stream sediments .

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Size, shape, clarity and color are of major importance for gemstones. Crystal type and trace element content are of major importance for electrical applications. Size, shape, and degree of crystallization dictate type of industrial use.

Compositional/mechanical processing restrictions: Serpentinized and weathered kimberlites are more friable, easy to process, and often have a higher diamond content than deep-seated, hypabyssal facies kimberlites.

Distance limitations to transportation, processing, end use: Processing plants are usually built adjacent to diamond-bearing pipes because large volumes of kimberlite must be processed in order to produce a very small volume of diamonds. Transportation is generally not a problem since the diamond-bearing rock has to only be transported a short distance from the mine to the processing plant. Since diamonds occupy a relatively small volume, transportation to end users is generally quite easy. The high value-to-volume ratio of diamonds, however, makes security during processing and transport a concern to most producers.

REFERENCE:

Atkinson and others, 1984   Gold, 1984.
Boyd and Meyer, 1979.   Kornprobst, 1984.
Clement and others, 1986   Lincoln, 1983.
Cox, 1978.   McCallum and Mabarak, 1976.
Cox, 1986   Meyer, 1976.
Dawson, 1980.   Milashev, 1988.
Glover and Harris, 1985.   Mitchell, 1986.

DESCRIPTIVE MODEL OF WOLLASTONITE SKARN

by G.J. Orris

BRIEF DESCRIPTION

Deposit synonyms: None.

Principal commodities produced: Wollastonite.

By-products: Rarely garnet, limestone, or marble.

End uses: The major end use is as a source of silica and alkalies in the production of ceramics such as semivitreous bodies, wall tiles, electrical insulators, and glazes. Wollastonite is also used for filler and extender due to its chemical inertness and a whiteness aspect ratio as much as 20:1.

Descriptive/genetic synopsis: Most economic wollastonite deposits are formed through contact metamorphism of siliceous limestone or other calcareous sedimentary rocks. In this process, the intrusion, commonly acidic, introduces silica, alumina, iron, and manganese into the altered calcareous rocks leading to the formation of skarn minerals including

wollastonite. This hornblende hornfels facies reaction occurs at temperatures of 400° to 600° C which are at least partly dependent on depth (Hyndman, 1972).

Typical deposits: Fox Knoll, USNY   (Harben and Bates, 1984;
   1990)

                               Lappeenranta, FNLD   (Isokangas, 1978)
                               Khila (Belkapahar), INDA   (Smith, 1981; Andrews, 1970)

Relative importance of the deposit type: Skarn deposits are the dominant commercial source of wollastonite.

Associated/related deposit types: Other types of economic skarn deposits including Zn-Pb-, W-, and Au-bearing skarns; sediment-hosted Au-Ag; polymetallic and other replacement deposits; porphyry Cu, skarn-related deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Magmatism, generally felsic, associated with continental margin orogenesis and rifting; other magmatic settings.

Age range: Precambrian to Tertiary.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Limestone, calcareous sediments including sandstone.

Associated rock(s):   Commonly, acidic intrusive bodies.

Ore mineralogy: Wollastonite, (garnet).

Gangue mineralogy: Garnet, diopside, epidote, quartz, calcite.

Alteration: Contact metamorphism, metasomatism.

Structural setting: Epizonal level.

Ore control(s):   In carbonate or calcareous rocks near igneous contacts.

Typical ore dimensions: Highly variable-- some bodies are only a few meters in all dimensions, others are over 1000 m long.

Effect of metamorphism: N/A.

Maximum limitation of overburden: Unknown.

Geochemical signature(s):   None.

Other exploration guide(s):   Commonly, wollastonite mineralization is outboard of the garnet-diopside zone but closer to the intrusive contact than the calcite(marble)-quartz zone.

Most readily ascertainable regional attribute: Presence of calcareous sediments with acidic intrusions.

Most readily ascertainable local attribute: Evidence/presence of any skarn formation.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Chemically inert. For ceramic uses has good strength and firing characteristics. Relative whiteness of wollastonite has a reported GE value of 90 to 93 and a whiteness aspect ratio as much as 20:1. In glass/ceramic use, high iron contents may be a concern especially if the iron content is not lowered adequately through removal of garnet and diopside in processing.

OTHER
Industrial uses for wollastonite were not discovered until the 1950's; prior to that time wollastonite deposits were considered mineralogical curiosities and utilization was limited to local use of wollastonite blocks in oven construction and experimental production of mineral wool (1930's).

REFERENCE

Andrews, 1970.   Hyndman, 1972.
Elevatorski, 1975.   Smith, 1981.
Harben and Bates, 1984.

DESCRIPTIVE MODEL OF AMORPHOUS GRAPHITE

by David M. Sutphin

BRIEF DESCRIPTION

Deposit synonyms: Microcrystalline graphite.

Principal commodities produced: Amorphous graphite.

End uses: Amorphous graphite is used in brake linings, foundry applications, lubricants, pencils, refractories, and steelmaking.

Descriptive/genetic synopsis: Amorphous graphite deposits are formed by the contact metamorphism of coal beds or other highly carbonaceous sediments by nearby intrusions. Intrusives may be cross-cutting diabasic or granitic dikes or adjacent sills. Host rocks are usually quartzites, phyllites, metagraywackes, and conglomerates.

Typical deposits: Raton, USNM
Sonora, MXCO
Kaiserberg, ASTR
Kureika, USSR
deposits in South Korea.

Relative importance of the deposit type: These deposits are an important source of amorphous graphite. For most applications, synthetic graphite or other materials may be substituted for amorphous graphite but at increased cost or reduced performance.

Associated/related deposit types: Coal beds may be found associated with amorphous graphite deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Continental margin or intercratonic basinal sediments having coal seams or other highly carbonaceous sedimentary beds are metamorphosed by nearby igneous intrusions or by regional metamorphism.

Age range: Mississippian-Cretaceous, but may be younger.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Metamorphosed quartzite, phyllite, metagraywacke, and conglomerate.

Associated rock(s):   Diabasic to granitic intrusives.

Ore mineralogy: Amorphous graphite, anthracite, coke.

Gangue mineralogy: Quartz, pyrite.

Alteration: Coke may be formed where the intrusion comes into contact with the coal seam. Graphite may grade into coal with increasing distance from the heat source.

Structural setting: Areas where coal has been thermally metamorphosed. Location may be structurally simple, as at Raton, New Mexico, or highly faulted and folded, as in deposits at Sonora, Mexico.

Ore control(s): Size, grade, and mineral impurities of the graphite deposit depend on the characteristics of the original coal seams and sediments. Faulting and folding may control the amount of graphitization and are therefore important ore controls.

Typical ore dimensions: There may be several beds each a few meters thick. Deposits may be several miles in length and width.

Effect of weathering: Graphite does not chemically weather, but it does not form resistant outcrops. In Sonora, Mexico, deposits are located by observing blackened graphite-rich soil where the deposit approaches the surface.

Effect of metamorphism: Coal is graphitized producing a dull black, earthy amorphous graphite that may or may not be recognizable as having previously been coal.

Maximum limitation of overburden: Unknown.

Geochemical signature(s): Positive vanadium and nickel anomalies and negative boron anomalies.

Geophysical signature(s): Graphite deposits have been located using induced potential, resistivity, electromagnetism, spontaneous potential (SP), and audiomagnetotelluric mapping (AMT). Outcrops may have associated radioactivity because of trace amount of uranium.

Other exploration guide(s): Amorphous graphite deposits form only by thermal metamorphism of coal or other carbonaceous material. Areas to prospect are those in which such beds have been cut by intrusion(s) or subjected to regional metamorphism.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Major mines currently being mined commonly contain over 80 percent graphitic carbon.   The graphite may contain several percent of volatile material (South Korean low-grade amorphous graphite has such volatile content that it can be burned as fuel.)

Compositional/mechanical processing restrictions: Quantity and type of impurities are major concerns.

OTHER

REFERENCES

Cameron and Weis, 1960.   Weis, 1973.
Graffin, 1975.   Weis and Salas, 1978.
Krauss and others, 1988.

DESCRIPTIVE MODEL OF LITHIUM IN SMECTITES OF CLOSED BASINS

By Sigrid Asher-Bolinder

BRIEF DESCRIPTION

Deposit synonyms: High-lithium clays; hectorite; bentonite.

Principal commodities produced: Hectorite, potentially Li.

Other products: Uranium, mercury, boron, magnesium, fluorine, halite, strontium, zeolites, gypsum, sodium sulfate, sodium carbonate.

End uses: Cosmetics and skin preparations, drilling gels, building materials, ceramics and glass industry, primary aluminum production, manufacture of lubricants and greases.

Descriptive/genetic synopsis: Three forms of genesis are postulated: Alteration of volcanic glass to lithium-rich smectite; precipitation from lacustrine waters; and incorporation of lithium into existing smectites. In each case, depositional/diagenetic model is characterized by abundant Mg, silicic volcanics, and an arid environment.

Typical Deposits: Hector Mine, Hector, USCA
McDermitt caldera, USNV and USOR
Lyles Lithium Deposit, USAZ

Relative importance of the deposit type: At present only two hectorite and related clay deposits are developed; next most important after currently produced pegmatites and lithium-rich brines.

Associated/related deposit types: Associated with sedimentary borate, zeolite, gypsum, and montmorillonite deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Basin-and-Range or other rift settings characterized by bimodal volcanism, crustal extension, and high rates of sedimentation.

Regional depositional environment: Closed basins of tectonic or caldera origin in arid environments.

Age range: Tertiary to Holocene.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Volcanic ashes, pre-existing smectites, lacustrine beds rich in calcium and magnesium.

Associated rock(s):   Volcanic flows and detritus, alluvial-fan and-flat and lacustrine rocks, spring deposits.

Ore mineralogy: Hectorite, saponite, stevensite, montmorillonite.

Gangue mineralogy: Silica, calcium carbonate, zeolites, gypsum, soluble salts, iron oxides.

Alteration: Rocks could be altered to shales or slates; no reported occurrences.

Structural setting: Down-dropped closed valleys or unbreached caldera moats.

Ore control(s):   Extent of lacustrine beds; source of lithium.

Typical ore dimensions: Meter to several meters thick by a few kilometers of area.

Typical alteration/other halo dimensions: None.

Effect of weathering: Clays may expand with moisture, leading to "popcorn weathering"; lithium may be leached by rainwater if it is held as soluble salts; or lithium may be exchanged for other cations by groundwater if lithium is in exchangeable sites.

Effect of metamorphism: Unknown.

Maximum limitation of overburden: Unknown.

Geochemical signature(s): Li >300 ppm; +/-F, U, Be, B enrichment; high Mg.

Geophysical signature(s):   Unknown.

Other exploration guide(s):   Presence of white or light pastel swelling clays.

Most readily ascertainable regional attribute: Hydrologically closed basins and presence of silicic volcanic rocks.

Most readily ascertainable local attribute: Light-colored, ash-rich, lacustrine rocks containing swelling clays.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Presence of excess gangue minerals, especially iron oxides; presence of fluorine, which prevents its use in cosmetics and medications.

Compositional/mechanical processing restrictions: Silicification hampering disaggregation.

OTHER

At present, only hectorite in a pure white form is suitable as a colloidal clay suitable for use in cosmetics and medications.

REFERENCES

Ames and others, 1958.   Brenner-Tourtelot and Glanzman, 1978.
Asher-Bolinder, 1982.   Rytuba and Glanzman, 1979.

DESCRIPTIVE MODEL OF FUMAROLIC SULFUR

By Keith R. Long

BRIEF DESCRIPTION

Deposit synonyms: Volcanic sulfur.

Principal commodities produced: Sulfur.

By-products: None, but potential for recovery of As, Te, and (or) Se.

End uses: As sulfuric acid: production of phosphate fertilizers, leaching of metal ores, inorganic and organic chemicals, synthetic materials, pulp and paper products, agricultural chemicals, explosives.   As native sulfur: agricultural chemicals, petroleum/coal products, inorganic chemicals, pulp and paper products.

Descriptive/genetic synopsis: Surficial sublimates, open space fillings and replacements of native sulfur in the vent areas of volcanos. Rare precipitates in volcanic lakes fed by thermal waters, molten sulfur flows and alluvial deposits.

Typical deposits: Crater, USCA (Lynton, 1938)
                              Matsuo, JAPN (Vila, 1953)
                              Ollague, CILE and BLVA (Chidester, 1947)

Relative importance of the deposit type: Fumarolic sulfur accounts for only 2 percent of world supply, but is important locally.

Associated/related deposit types: Hot springs Hg, hot springs Mn. the ultimate source of heat and (or) mineralizing fluids may be intrusions with related epithermal Au-Ag, polymetallic, or porphyry Cu-Mo deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Active or recently active volcanic zones.

Regional depositional environment: Vent areas of stratovolcanoes.

Age range: Late Miocene to Recent. Older deposits almost certainly have been destroyed by erosion.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Porous volcanoclastic rocks and lava flows associated with felsic volcanic centers; less commonly in intruded sediments.

Associated rock(s):   Less porous, sealing volcanoclastic rocks and lavas.

Ore mineralogy: Native sulfur.

Gangue mineralogy: Iron sulfides and gypsum may be present in variable quantities. Gypsum only found in deposits overlying or within limestone. Cinnabar, stibnite, barite, melanterite and selenium/arsenic sulfates are sometimes found.

Alteration: In solfataric zones, rock replaced by quartz, sulfur and minor calcite. Intense alteration reduces host rock to alunite and clay.

ZONING: Sulfur grades gradually diminish with depth.

Structural setting: Faults, breccias and other conduits related to vents for lavas and thermal waters.

Ore control(s):   Open space at or near paleosurface or below paleosurface capped by a less porous, sealing lithology. Proximity to vents for thermal waters which are typically located along steeply-dipping faults or shear zones. Climate determines gangue composition: pyrite (wet climate) or gypsum (dry climate).

Typical ore dimensions: Range from tabular and chimney-like to highly irregular. Horizontal dimensions exceed vertical dimensions with diameters up to 1000 m and thickness rarely exceeds 150 m.

Typical alteration/other halo dimensions: Deposits typically found in zones of solfataric alteration that may be many tens of square kilometers in extent.

Effect of weathering: Deposits are not likely to survive weathering and would be lost with the erosion of the host volcano.

Effect of metamorphism: Any deposits that escape erosion will undergo remobilization when pressure-temperature conditions are such that the native sulfur will be melted. Contact with metal-bearing solutions may lead to precipitation of metal sulfides.

Maximum limitation of overburden: Thin cover of soil, alluvium, travertine, siliceous sinter, clay or lava.

Geochemical signature(s): $\pm$ As $\pm$ Se $\pm$ Te $\pm$ Bi $\pm$ Sb $\pm$ Hg.

Other exploration guide(s):   Altered zones appear bleached and are easily recognized by remote sensing.

Most readily ascertainable regional attribute: Broad zones of solfataric alteration in stratovolcanoes.

Most readily ascertainable local attribute: Areas of current or recent fumarolic activity.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Trace As, Se, and Te must be removed from crude sulfur before marketing.

Compositional/mechanical processing restrictions: marketable crude sulfur grades 99.5 percent S or better. Thus most fumarolic sulfur ores require considerable and expensive concentration.

Distance limitations to transportation, processing, end use: Most fumarolic sulfur deposits are distant from transportation infrastructure and potential markets and are rarely of sufficient size to justify development under these circumstances.

REFERENCE

Banfield, 1954.   Sillitoe, 1975.
Colony and Nordlie, 1973.

DESCRIPTIVE MODEL OF SEDIMENTARY ZEOLITES

Deposit subtype: Zeolites in tuffs of open hydrologic systems

By Richard A. Sheppard

BRIEF DESCRIPTION

Deposit synonyms: Open-system zeolites.

Principal commodities produced: Chabazite, clinoptilolite, mordenite, phillipsite.

Other products: Bentonite, pumicite.

End uses: Zeolites for use in ion-exchange and adsorption applications. for example, clinoptilolite to remove NH_4^+ in tertiary sewage treatment; phillipsite to remove Cs and Sr from radioactive materials.

Descriptive/genetic synopsis: Microcrystalline zeolites crystallized in relatively thick, generally nonmarine tephra sequences that commonly show a more or less vertical zonation of zeolites and associated silicate minerals and that reflects the chemical modification of meteoric water as it flowed through the vitric sequence. The zeolites crystallized in the post-depositional environment over periods ranging from thousands to millions of years.

Typical Deposits: Oligocene-Miocene John Day Formation, USOR (clinoptilolite)
Miocene Paintbrush Tuff, tuffaceous beds of Calico Hills,
     and Crater Flat tuff at Yucca Mountain, Nye County,
     USNV (clinoptilolite and mordenite)
Quaternary Campainian and Neapolitan yellow tuffs near Naples,
     ITLY (phillipsite and chabazite)
Death Valley Junction, USCA   (clinoptilolite)   (Sheppard, 1985)

Relative importance of the deposit type: Very widespread and thick zeolite deposits throughout the world; especially important sources of clinoptilolite and mordenite.

Associated/related deposit types: The zonation of the open-system type of zeolite deposit is similar to the upper zones of burial diagenesis (burial metamorphism) that affected thick sequences of silicic, vitric tuffs. Associated deposits include pumicite and bentonite.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Variety of nonmarine and shallow marine basins in volcanic terrains. Some thick tuffaceous deposits were air-laid onto the land surface and not into water.

Regional depositional environment: Most deposits are nonmarine (fluviatile and lacustrine), but some are shallow marine.

Age range: Mesozoic to Holocene, but most are Cenozoic.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Tuffs having a broad compositional range, including rhyolite to dacite, trachyte or phonolite, and basalt to basanite. The silicic tuffs commonly were deposited as nonwelded ash flows.

Associated rock(s):   Rhyolite to basalt flows; fluviatile mudstone, sandstone, and conglomerate; diatomite.

Ore mineralogy: Chabazite, clinoptilolite, mordenite, phillipsite.

Gangue mineralogy: Authigenic smectite, mixed layer illite/smectite, opal-(cristobalite/tridymite), quartz, and calcite; variety of pyrogenic crystal fragments; variety of volcanic rock fragments; unreacted vitric material.

Alteration: In silicic tuff sequences, the alkali-rich siliceous zeolites (clinoptilolite and mordenite) in the upper part of the deposit are replaced at depth by analcime, potassium feldspar, and (or) albite.

Structural setting: No apparent correlation with deposit type.

Ore control(s):   Grain size and permeability of host tuff; flow of meteoric water downward in an open hydrologic system; hydrolysis and solution of vitric material by the subsurface water in the upper part of the system raised the pH, activity of SiO_2, and content of dissolved solids to values where zeolites crystallized; resulted in a vertical or near-vertical zonation of zeolites and other authigenic minerals; composition of the vitric material may have dictated which zeolite species precipitated; clinoptilolite and mordenite are common in silicic tuffs, but chabazite and phillipsite are common in mafic or trachytic tuffs.

Typical ore dimensions: Thickness of the zeolitic tuffs commonly ranges from 100s to 1000s m. Areal extent is commonly 100s to 1000s km^2.

Typical alteration/other halo dimensions: N/A

Effect of weathering: Zeolitic tuffs resist weathering and are ledge formers. Local yellow to brown stains by hydrous iron oxides.

Effect of metamorphism: Conversion of zeolitic tuff to an assemblage of alkali feldspar+quartz.

Maximum limitation of overburden: Unknown, but probably tens of meters.

Geochemical signature(s):   None recognized.

Geophysical signature(s):   Possible use of color-composite imagery from airborne multispectral scanner data to distinguish zeolitic tuffs.

Other exploration guide(s):   Vertical zonation of zeolites and associated authigenic silicate minerals in thick (100s to 1000s m) tuffaceous sequences, especially siliceous tuffs of Neogene age that were air-laid on land. The vertical zonation commonly is (from top to bottom) unaltered vitric material±smectite to clinoptilolite±mordenite±opal-(cristobilite-tridymite) to analcime±potassium feldspar±quartz and then to albite±quartz. This zonation may cut across bedding.

Most readily ascertainable regional attribute: Regional depositional environment containing thick sequence of vitric tuffs of Cenozoic age.

Most readily ascertainable local attribute: Vertical zonation of authigenic silicate minerals.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: The Si/Al ratio and exchangeable cation ratios of the zeolites affect certain uses. Cation exchange capacity and adsorption capacity for various gases are important. Color (due to iron staining) and the abundance of non-zeolitic minerals may limit use.

Compositional/mechanical processing restrictions: Hardness and attrition resistance of zeolitic tuff (commonly affected by abundance of opal-CT or quartz) are important in processing and end use. Crystallite size of the zeolite is < 2 μm to 30 μm and can affect the adsorption of gases and the extent and rapidity of cation exchange.

Distance limitations to transportation, processing, end use: Unknown at present due to brief historical production.

REFERENCES

Broxton and others, 1987.   Hay and Sheppard, 1981.
Gottardi and Obradovic´, 1978.   Sersale, 1978.
Hay, 1963.   Sheppard, 1985.

DESCRIPTIVE MODEL OF SEDIMENTARY ZEOLITES

Deposit subtype: Zeolites in tuffs of saline, alkaline-lake deposits

By Richard A. Sheppard

BRIEF DESCRIPTION

Deposit synonyms: Closed-basin (closed-system) zeolites.

Principal commodities produced: Analcime, chabazite, clinoptilolite, erionite, mordenite, phillipsite.

By-products: Bentonite, fluorite, pumicite, potassium feldspar.

End uses: Zeolites for use in ion-exchange and adsorption applications. For example, chabazite to remove CO_2 and H_2S from sour natural gas; clinoptilolite to remove NH_4^+ in tertiary sewage treatment.

Descriptive/genetic synopsis: Microcrystalline zeolites that formed during early diagenesis in silicic, vitric tuffs of closed hydrographic basins. The zeolites crystallized in the post-depositional environment over periods ranging from thousands to hundreds-of-thousands of years by reaction of the vitric material with saline, alkaline pore water trapped during lacustrine sedimentation. Locally, zeolites also formed from detrital clays, feldspars, and feldspathoids and from chemically precipitated aluminosilicate gels in the same depositional environment. Unlike zeolites of open hydrologic systems, this subtype is characterized by a lateral zonation of zeolites and associated silicate minerals.

Typical Deposits: Late Cenozoic Lake Tecopa, Inyo County, USCA
Miocene-Pliocene Big Sandy Formation, Mohave County, USAZ
Bowie Deposit (Late Cenozoic Lake Graham), Graham and Cochise
         Counties, USAZ (Sheppard and others, 1987)
Quaternary Lake Magadi, KNYA

Relative importance of the deposit type: This deposit type contains the largest variety of zeolite species, and it is the type that accounts for most of the present zeolite production in the U.S. This deposit type is an especially important source for chabazite, erionite, and phillipsite in the United States.

Associated/related deposit types: Continental-basin bedded evaporites; finely crystalline, disseminated fluorite in lacustrine rocks.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Closed hydrographic basins in either block-faulted terrains (such as the Basin and Range province) or trough valleys associated with rifting (such as the Eastern Rift Valley of Kenya).

Regional depositional environment: Lacustrine basins that received silicic, vitric material either directly by airfall or by reworking. The saline lake water commonly was of the sodium

carbonate-bicarbonate variety and had a pH of 9 or greater. These lakes are common in arid and semi-arid regions where annual evaporation exceeds rainfall.

Age range: Late Paleozoic to Holocene, but most deposits are Cenozoic.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Rhyolitic to dacitic, vitric tuff.

Associated rock(s):   Bedded evaporites (trona, halite, borates), mudstone, diatomite, Magadi-type chert, oil shale.

Ore mineralogy: Analcime, chabazite, clinoptilolite, erionite, mordenite, phillipsite.

Gangue mineralogy: Authigenic smectite, mixed layer illite/smectite, opal-(cristobalite/tridymite), quartz, searlesite, potassium feldspar, and calcite; pyrogenic biotite, sanidine, sodic plagioclase, and hornblende; unreacted volcanic glass.

Alteration: In certain highly alkaline and saline lacustrine deposits, siliceous and alkalic zeolites have been replaced during late diagenesis by analcime or potassium feldspar in the central part of the basin.

Structural setting: Lakes are commonly in block-faulted terranes or rift valleys.

Ore control(s):   Grain size and permeability of the host silicic, alkali-rich, vitric tuff. Salinity, pH, and ratios of alkali and alkaline-earth ions in the pore water are important.

Typical ore dimensions: Thickness of the zeolitic tuffs commonly ranges from 10 cm to 10 m. Areal extent is commonly tens to hundreds of square kilometers.

Typical alteration/other halo dimensions: N/A

Effect of weathering: Zeolitic tuffs resist weathering and are ledge formers in the lacustrine sequence. Local yellow to brown stains by hydrous iron oxides.

Effect of metamorphism: Conversion of zeolitic tuff to an assemblage of alkali feldspar+quartz.

Maximum limitation of overburden: Unknown, but as much as about 30 m can be tolerated.

Geochemical signature(s):   Lacustrine environment of sodium carbonate-bicarbonate type, may be enriched in boron.

Geophysical signature(s):   Possible use of color-composite imagery from airborne multispectral scanner data to distinguish zeolitic alteration.

Other exploration guide(s):   Molds of saline minerals, chemical delta of calcite or aragonite, associated dolomitic mudstone, occurrence of bedded or nodular Magadi-type chert. Concentric zonation and lateral gradation in a basinward direction of unaltered volcanic glass to alkali-rich, silicic zeolites to analcime and then to potassium feldspar in the central part of the depositional basin.

Most readily ascertainable regional attribute: Regional depositional environment of silicic, vitric tuffs in an alkaline, saline-lake deposit.

Most readily ascertainable local attribute: Host rock of vitric tuff of rhyolitic or dacitic composition; lateral zonation of zeolites and associated silicate minerals.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: The Si/Al ratio and exchangeable cation ratios of the zeolites affect certain uses. Cation exchange capacity and adsorption capacity for various gases are important. Color (due to iron staining) and the abundance of non-zeolitic minerals may affect use.

Compositional/mechanical processing restrictions: Hardness and attrition resistance of zeolitic tuff (commonly affected by abundance of opal-CT or quartz) are important in processing and end use. Crystallite size of the zeolite is < 2 μm to 30 μm and can affect the adsorption of gases and the extent and rapidity of cation exchange.

Distance limitations to transportation, processing, end use: Unknown at present due to brief historical production.

REFERENCES

Sheppard and Gude, 1968.   Surdam and Eugster, 1976.
Sheppard and Gude, 1973.   Surdam and Sheppard, 1978.
Sheppard and others, 1987.

VEIN BARITE

by Sandra Clark and G. J. Orris

BRIEF DESCRIPTION

Deposit synonyms: Epigenetic vein barite, carbonatite-associated vein deposits.

Principal commodities produced: Barite.

By-products: $\pm$ fluorite $\pm$ rare earths $\pm$ base metals $\pm$ Au $\pm$ Ag

End uses: Weighting agent in drilling muds, fillers, chemicals, ceramics, pigments, rubber, plastics, radiation shields, friction materials.

Descriptive/genetic synopsis: Barite mineralization along faults, fractures, or shear zones. Barite is fine to coarse grained, crystalline or cataclastic and typically white or light gray.

Typical deposits:

Del Rio District, USTN	(Ferguson and Jewell, 1951)
Jebel Ighoud, MRCO	(Power, 1986)
Darreh, IRAN	(Roman'ko and others, 1985)
Sangilyn, AFGH	(Abdullah and others, 1977)
Oraparinna, AUSA	(Stevens, 1976)
Boguszów, PLND	(Paulo, 1982)

Relative importance of the deposit type: Probably the major source of world barite production; minor in the United States, but important locally.

Associated/related deposit types: Spatial associations known with the following deposit types: sediment-hosted Au-Ag deposits, polymetallic veins, sedimentary exhalative Zn-Pb, epithermal Au-Ag deposit types, fluorite veins, Kuroko massive sulfide, carbonatites;, southeast Missouri Pb-Zn, evaporites, Appalachian Zn,

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Highly varied.

Regional depositional environment: Highly varied.

Age range: Precambrian to Tertiary.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Any type.

Ore mineralogy: Barite $\pm$ fluorite $\pm$ galena $\pm$ sphalerite $\pm$ chalcopyrite $\pm$ rare earth minerals $\pm$ Au $\pm$ Ag.

Gangue mineralogy: Quartz, pyrite, celestite, rhodochrosite, calcite, siderite, chalcopyrite, galena, sphalerite, clay minerals, fluorite, dolomite, hematite, limonite, rare-earth minerals.

Structural setting: Areas of faults, fractures, shear zones.

Ore control(s):   Faults, fractures, shear zones.

Typical ore dimensions: Widths of a few centimeters to tens of meters, lengths from tens of meters to > 1 km.

Effect of weathering: Indistinct, barite is resistant to weathering.

Maximum limitation of overburden: Unknown, but not much.

Geochemical signature(s):   Ba $\pm$ F $\pm$ Zn $\pm$ Pb $\pm$ Au $\pm$ Ag $\pm$ Sr

Geophysical signature(s):   Relative linear gravity highs for larger deposits.

Other exploration guide(s):   Very heavy sedimentary-looking rock; commonly white to gray in color, but may also be green, orange, other colors.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Barite is resistant to weathering , inert, nonabrasive, dense, and absorbs radiation.   Siderite content may be a serious problem for drilling mud use. The presence of radioactive minerals may limit use

Compositional/mechanical processing restrictions: Gravity separation may be ineffective for some sulfide -rich ores and more expensive flotation techniques are needed when ore grade needs to be improved or sulfides removed for end use.

Distance limitations to transportation, processing, end use: High density of material contributes to relatively high ground transportation costs which may exceed the mined cost of the raw material.

OTHER

REFERENCES
Brobst, 1980.   Clark and Poole, 1990.
Brobst, 1984.   Harben and Bates, 1990.
Clark and others, 1990.

SEDIMENTARY EXHALATIVE BARITE

by Sandra Clark and G.J. Orris

BRIEF DESCRIPTION

Previous and (or) Alternate Version of Model: *"Descriptive model of bedded barite"*   (Orris, 1986.)

Deposit synonyms: Bedded barite; sediment-hosted, stratiform, syngenetic-diagenetic barite; syndepositional barite.

Principal commodities produced: Barite.

Co-products: $\pm$ Pb $\pm$ Zn $\pm$ Cu $\pm$ Ag $\pm$ Au (when intimately associated with exhalative Zn-Pb deposits).

End uses: Mainly as a weighting agent in drilling muds. Other uses of high-purity barite are in fillers, ceramics, pigments, rubber, plastics, radiation shields, friction materials, and chemicals.

Descriptive/genetic synopsis: Fine-grained and finely laminated bedded to massive barite in siliceous, sedimentary basinal sequences and (or) barite clasts incorporated in turbidites and debris flows. Mineralization results from the migration of deep-circulating heated and reduced fluids along faults or rifts in oceanic crust to sites of precipitation on or just below the seafloor. The brines may migrate into seafloor depressions some distance from the discharge sites. Barite in peripheral parts of deposits may form rosettes. Detritus derived from reworking bedded barite may be transported as debris flows and turbidites. Because of organic content, color is often dark gray.

Typical deposits: Meggen, Federal
Republic of Germany   (Krebs, 1981)
                                                Rammelsberg, Federal Republic of Germany   (Hannak, 1981)
                                                Barita de Cobachi, Mexico   (Salas, 1982)
                                                Nevada barite belt deposits, USA   (Papke, 1984)

Relative importance of the deposit type: A major source of world barite production.

Associated/related deposit types: Sedimentary exhalative Zn-Pb deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Epicratonic or continental margin marine basins associated with oceanic faults or rifts.

Regional depositional environment: Marine basins.

Age range: Commonly Paleozoic, also Proterozoic.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Siliceous , commonly carbonaceous, sedimentary sequences containing chert , argillite, mudstone, and shale. Locally occurs with limestone, dolostone, siltstone, sandstone, quartzite, greenstone, tuff.

Ore mineralogy: Barite, $\pm$ minor witherite.

Gangue mineralogy: Minor pyrite, limonite, sphalerite, galena; up to several percent organic matter plus some H_2S in fluid inclusions.

Alteration: Secondary barite veining; weak to moderate sericitization reported in or near some deposits in Nevada.

Structural setting: Marine basins adjacent to rifts or deep-seated faults in oceanic crust.

Effect of weathering: Indistinct, barite is resistant to weathering.   Weathered-out nodules or rosettes can be found.

Effect of metamorphism: Loss of carbonaceous content.

Geochemical signature(s):   Ba $\pm$ Zn $\pm$ Pb $\pm$ Cu $\pm$ Mn $\pm$ Sr $\pm$ organic C

Geophysical signature(s):   May be associated with relative gravity highs. When associated with base-metal sulfides may have relative magnetic high.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Barite is resistant to weathering , inert, nonabrasive, dense, and absorbs radiation. Density and purity affect end use.

Compositional/mechanical processing restrictions:

Distance limitations to transportation, processing, end use: High density of material contributes to relatively high ground transportation costs which may exceed the mined cost of the raw material.

OTHER

REFERENCES
Brobst, 1980.   Harben and Bates, 1990.
Brobst, 1984.   Papke, 1984.
Clark and others, 1990.

LACUSTRINE DIATOMITE

by Jonathan D. Shenk*

BRIEF DESCRIPTION

Deposit synonyms: Diatomaceous earth, kieselguhr, bog deposits.

Principal commodities produced: Diatomaceous earth.

By-products: Possibly sand and gravel or clays.

End uses: Filter aid, functional filler, insulation material, absorbent, silica source.

Descriptive/genetic synopsis: Lacustrine diatomite deposits form in fresh to brackish water, are invariably associated with volcanism, and are found worldwide both in paleosediments and in recent lake sediments. It is widely held that the large quantity of silica necessary for thick accumulations of diatoms is derived from the weathering and decomposition of silica rich volcanic rocks. The released silica is subsequently transported to the lake through runoff, groundwater, and hot or cold springs.

Relative importance of the deposit type: Lacustrine diatomite deposits, while more numerous, are of secondary importance to the fewer, but larger, marine diatomite deposits.

Associated/related deposit types: Trona, gypsum.

Representative deposits: Juntura and Otis basins, USOR (Brittain, 1986)
Kariandus, KNYA (Barnard, 1950)
Lake Myvatn, ICLD (Kadey, 1983)
Riom-les-Montagnes, FRNC (Clarke, 1980)
Luneburger-Heide, GRMY (Luttig, 1980)

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Typically found in volcanic terrain. Often associated with crustal extension (ex: the Basin and Range Province of the western United States, the East African Rift system, and the Icelandic portion of the mid-Atlantic Rift).

Regional depositional environment: Depositional conditions necessary for thick diatom accumulations include: 1) extensive, shallow basins for photosynthesis; 2) an abundant supply of soluble silica and nutrients; 3) an absence of toxic or growth-inhibiting constituents; 4) sustained high rates of diatom reproduction; 5) minimal clastic, chemical, and organic contamination, and 6) a low energy environment for preservation of the delicate diatom structure.

Age range: Miocene to Recent. Occurrences noted as early as Late Eocene.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Diatomaceous lake sediments are typically hosted in: 1) volcanic rocks (craters, maars) -- example: Riom-les-Montagnes; 2) volcanic and sedimentary rocks (interbedded volcanic flows or tuffs

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* *Consultant, Tucson, Arizona*

and fluvial or alluvial sediments) -- example: Juntura and Otis basins; or 3) sedimentary rocks (fluvial or alluvial sediments) -- example: Luneburger-Heide.

Associated rock(s):   Diatomite is typically interbedded with: 1) siliciclastic sediments (sandstone, siltstone, mudstone, volcanic ash); 2) chemical sediments (limestone, marl), and 3) organic sediments (lignite, peat).

Ore mineralogy: Diatomaceous silica, opal-cristobalite.

Gangue mineralogy: Contaminants consist of siliciclastics (various clays, quartz and feldspar grains, and volcanic glass), calcite, organic matter, $\pm$ Fe- and Mn-oxides, $\pm$ gypsum, $\pm$ halite.

Alteration: N/A.

Structural setting: Flat lying to gently dipping, some minor folding and faulting.

Ore control(s):   The formation and localization of ore is controlled by the physical and chemical boundaries of the regional depositional environment.

Typical ore dimensions: Deposits commonly extend over areas of 1 to 25 square miles and attain thicknesses of 10 to >200 ft. Deposits covering <1 mi^2 and < 10 ft thick are generally uneconomic.

Typical alteration/other halo dimensions: N/A.

Effect of weathering: Positive-- the oxidation and removal of organic contaminants. Negative-- Fe-oxide staining and soil formation.

Effect of metamorphism: During diagenesis, dissolution of diatomaceous silica will destroy the diatom structure. Silica is then available to be redeposited as porcelainite, chert, or silica cement.

Maximum limitation of overburden: Ratios up to 10:1, but typically <5:1.

Geochemical signature(s):   N/A.

Geophysical signature(s):   Apparent resistivity and refraction seismic surveys have been utilized as exploration tools.

Other exploration guide(s):   Varying thermal characteristics of diatomaceous sediments have been noted using narrow pass-band infrared imagery.

Most readily ascertainable regional attribute: Tectonostratigraphic setting.

Most readily ascertainable local attribute: Basinal sediments.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Physical properties include: 1) high surface area, 2) high absorptive capacity, 3) high surface area, 4) low bulk density, 5) high porosity, 6) relative chemical inertness, 7) relative low abrasion, and 8) diatom structure. Chemical analyses have the following ranges: SiO_2 - 80.0 to 95.0 percent, Al_2O_3 - 1.0 to 6.0

percent, Fe_2O_3 - 0.4 to 2.2 percent, CaO - 0.2 to 3.5 percent, and minor to trace amounts of TiO_2, MgO, Na_2O, K_2O, and P_2O_5.

Compositional/mechanical processing restrictions: Processing is kept to a minimum to preserve the diatom structure. Well lithified diatomite generally requires excessive milling.

Distance limitations to transportation, processing, end use: Distances of 70 to 100 miles have been reported for transporting crude to the processing plant; higher percentages of contained water reduces this distance. While local sources compete for low end use markets, high end use products are shipped worldwide.

OTHER
The International Agency for Research on Cancer (IARC) has classified crystalline silica as a probable carcinogen. The effect of this classification as it relates to diatomite is still being debated. The International Diatomite Producers Association (IDPA) is currently sponsoring research into the health and safety issues.

REFERENCES:

Barnard, 1950.   Durham, 1973.
Breese, 1989.   Industrial Minerals, 1987.
Brittain, 1986.   Kadey, 1983.
Clarke, 1980.   Luttig, 1980.
Coombs, 1990.   Williamson, 1966.

POTASH-BEARING BEDDED SALT

by Sherilyn Williams-Stroud
11-89

BRIEF DESCRIPTION

Deposit synonyms: Marine evaporites, altered marine and rift-valley evaporites.

Principal commodities produced: Potash.

By-products: None.

End uses: Fertilizer is 95 percent of U.S. consumption, other uses include soaps and detergents, glass and ceramics, chemical dyes and drugs, liquid fertilizer, synthetic rubber.

Descriptive/genetic synopsis: Widespread thick accumulations of chloride evaporite deposits found in basins where evaporation exceeds inflow rate of waters. Some deposits formed in marine basins which were restricted as a result of sea level fluctuations. Other basins are altered marine rift-valley grabens with associated hydrothermal inflow.

Relative importance of the deposit type: These deposits yield high grade, large tonnage ore bodies, many of which are amenable to low cost mining and beneficiation.

Associated/related deposit types: Bedded evaporite deposits containing limestone, dolomite, gypsum, anhydrite, and halite.

Representative deposits: Devonian Elk Point group in Saskatchewan, Manitoba, and Alberta in Canada, Pennsylvanian Hermosa Formation in Colorado and Utah, Permian Castile, Salado, and Rustler Formations in SE New Mexico and west Texas, Permian Zechstein Formation in East and West Germany, Netherlands, Denmark, Poland and England, Miocene Tortorian Formation in Sicily.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Marginal marine basins that underwent subsidence during deposition of the evaporites. Pre-existing deep basins into which seawater inflow became restricted (for $MgSO_4$-rich potash evaporites). For $MgSO_4$-poor potash deposits, rift-valley grabens forming incipient seas.

Regional depositional environment: Arid climate where evaporation exceeds inflow and (or) hydrologic closure of the depositional basin so the outflow is less than inflow, such as local rain shadow deserts formed by rift or strike-slip basins. The supply of sand and mud into the basin must be less than the supply of solutes.

Age range: $MgSO_4$-poor potash deposits are found throughout the Phanerozoic. $MgSO_4$-rich potash deposits are found mostly in the Permian, Miocene, and Quaternary.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Primarily halite, some anhydrite.

Associated rock(s):   Halite, anhydrite, carnallite.

Ore mineralogy: Sylvite interbedded with halite, bedded sylvinite (halite + sylvite), lower grade ores include carnallite, kainite, langbeinite.

Gangue mineralogy: Halite, dolomite, anhydrite, bischofite, kieserite, polyhalite, epsomite, tachyhydrite, leonite, bloedite, hexahydrite, vanthoffite, loeweite, glasserite, schonite.

Alteration: Groundwater dissolution can destroy potash deposits because of the high solubility of the ore minerals, or, since sylvite is often considered to be secondary after carnallite, incongruent dissolution by groundwater can actually result in conversion of low-grade carnallite to high-grade sylvite.

Structural setting: Bedded evaporite deposits. Deformation after burial of salt can lead to intense folding in the very plastic salt.

Ore control(s):   Basin brines of the appropriate composition with salinities high enough to precipitate potash minerals.

Typical ore dimensions: Thickness of potash beds ranges from a few to several tens of meters. Volume of a single deposit can be thousands of cubic kilometers, though many high-grade deposits are much smaller, on the order of a few to a few tens of cubic kilometers.

Typical alteration/other halo dimensions: N/A

Effect of weathering: Surface weathering causes dissolution of potash and deposits do not form outcrops.

Effect of metamorphism: Plastic flow of salt and other saline minerals is greatly enhanced. Salt deposits are eventually destroyed by regional metamorphism.

Maximum limitation of overburden: Potash is mined by conventional underground mining techniques, or, in cases where beds are highly deformed, by solution mining. Solution mining techniques are also used if the ore depth is below 1100 m, where halite creep becomes a problem.

Geochemical signature(s):   K, Na, Ca, Mg, Br, Cl_2, SO_4, and H_2O.

Geophysical signature(s):   High gamma radiation from natural isotope K^{40} provides measure of potassium content of salt in drill hole logs. Relative gravity lows.

Other exploration guide(s):   Potash may be concentrated in areas of deposit containing thickest halite, and is associated with zones of highest insolubles (clay) content of salt deposit.

Most readily ascertainable local attribute: Saline well or spring water, thick gypsum or anhydrite outcrops, domal or collapse structures, low gravity geophysical anomalies.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Muriate of potash (KCl), which is the highest potassium content product, and potassium sulfate (K_2SO_4) are purer than potassium-magnesium sulfate and are preferred for chemical industry applications. The low chlorine

content and lower solubility of potassium sulfate makes it more desirable for certain crops and soil conditions. All the fertilizer products are sold on the basis of chemical composition and particle size, with higher potash grades and coarser particles generally more desirable.

Compositional/mechanical processing restrictions: Potash products are concentrated by flotation, selective dissolution ("washing"), or precipitation of the potash mineral from a hot brine. Insolubles, such as clays and quartz must be removed. The amounts of insolubles present in the ore and their reactivity increase processing costs.

Distance limitations to transportation, processing, end use: Transportation represents a major portion of the delivered price of potash products so costs of mining, processing and transportation must be balanced to achieve a saleable product.

OTHER

REFERENCES

Adams and Hite, 1983.   Hardie, in press.
Borchert and Muir, 1964.   Searles, 1985.

DESCRIPTIVE MODEL OF BEDDED SALT

Deposit subtype: Marine Evaporite Salt

By Omer B. Raup

BRIEF DESCRIPTION

Deposit synonyms: N/A

Principal commodities produced: Sodium chloride (salt).

By-products: None.

End uses: Chemical and food industry, snow and ice removal, domestic consumption.

Descriptive/genetic synopsis: Bedded salt deposits of marine origin occur in marginal marine basins of many sizes. These basins had periodic inflow of sea water which was the major source of the sodium chloride. Bedded marine salt deposits are frequently of large areal extent and of considerable thickness.

Typical Deposits: Silurian Salina Formation in the Michigan and Appalachian basins with deposits in northern Ohio, Michigan, and western New York; Permian Hutchinson salt of central Kansas; Mississippian Charles Formation in the Williston basin, North Dakota; Permian Zechstein evaporites of Germany and Poland.

Relative importance of the deposit type: This deposit type contains the thickest and most areally extensive deposits of salt and it accounts for the major production of salt of all of the deposit types.

Associated/related deposit types: Marine evaporites that contain gypsum and potash; sulfur.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Marginal marine basins that were subsiding at a rapid rate during deposition of the evaporites. Influx of sea water maintained water levels in the basin that were being lost by evaporation. Some evaporites in this type of setting have some contribution from inflow from the continent. For most, however this contribution is salt.

Regional depositional environment: Same as the tectonostratigraphic setting.

Age range: Late Proterozoic to Miocene.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Primarily anhydrite, with some limestone and dolomite.

Associated rock(s):   Anhydrite, gypsum, potash.

Ore mineralogy: Halite with thinly interlaminated anhydrite.

Gangue mineralogy: Anhydrite.

Alteration: Groundwater dissolution can modify the layering, grain size, or porosity, or it can even destroy a deposit.

Structural setting: Marine evaporites occur in basins near continental margins in ares of rapid subsidence.

Ore control(s):   Basin brines with salinity high enough to precipitate sodium chloride.

Typical ore dimensions: Thickness of mineable bedded salt deposits range from 10 to 100 m. Areal extent of some deposits covers many square kilometers.

Effect of weathering: Surface weathering causes total dissolution of salt in most climatic areas. Salt can be preserved at the surface, however, in areas of extreme aridity.

Effect of metamorphism: Regional metamorphism destroys salt deposits and can cause albitization of the surrounding rocks by sodium metasomatism.

Maximum limitation of overburden: Specific limit is unknown but bedded salt is mined by conventional methods at depths over 100 m. Much bedded salt is solution-mined at depths exceeding 500 m.

Geochemical signature(s):   Bedded salt from marine evaporites contains bromine in solid solution in the range of 60 to 200 ppm. Salt that has been recrystallized or is from a continental source often contains bromine of lower values.

Geophysical signature(s):   Bedded salt gives a very low response on a gamma-ray well logs.

Other exploration guide(s):   Occurrence of basin-edge sediments that contain gypsum or anhydrite which may indicate sediments that are the products of higher salinity (i.e., salt) in the basin center. High-salinity brines in wells.

Most readily ascertainable regional attribute: High-salinity and high bromine content in well water; low response on gamma-ray well logs; salt springs.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Impurities must be low.

Compositional/mechanical processing restrictions: Material must be pure enough so that minimal physical beneficiation is necessary for the intended product.

Distance limitations to transportation, processing, end use: Transportation is a major cost of the finished product. Therefore, costs of mining, processing, and transportation must be balanced to achieve a saleable product.

REFERENCES

Borchert and Muir, 1964.   Morse, 1985.
Braitsch, 1971.   Raup and Bodine, in press.
Kostick, 1985.   Smith and others, 1973.

DESCRIPTIVE MODEL OF SALT DOMES

Deposit subtype: Diapiric Salt Structures

By Omer B. Raup

BRIEF DESCRIPTION

Deposit synonyms: N/A

Principal commodities produced: Sodium chloride (salt).

By-products: None.

End uses: Chemical and food industry, snow and ice removal, domestic consumption. Mining produces cavities for petroleum storage.

Descriptive/genetic synopsis: Salt dome deposits occur in marginal marine basins that originally contained thick bedded salt deposits. These basins had periodic inflow of sea water which was the major source of the sodium chloride. Differential loading by thick overlying sediments initiated and drove the upward movement of the lower density salt into domes and ridges, some of which have risen to the present-day land surface.

Typical Deposits: Jurassic (?) Louann Salt , USTX and USLA
                      Permian Zechstein evaporites , WGER and PLND

Relative importance of the deposit type: Salt domes contain large volumes of relatively pure salt, some at depths quite close to the surface. In the United States the Gulf Coast salt domes are close to the coast which affords inexpensive shipping.

Associated/related deposit types: Some salt domes contain potash deposits, notably in Germany and Poland; associated gypsum and sulfur deposits. Various types of Cu, Fe, Pb, Zn, and Ba deposits in the surrounding strata.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Salt domes occur in marginal marine basins that had received thick accumulations of bedded salt. Subsequent clastic sedimentation in the basin initiated and drove the less dense salt into domes and ridges, some of which rose close to the present land surface. Salt domes occur in basins near continental margins in areas of rapid subsidence and sedimentation.

Regional depositional environment: Same as the tectonostratigraphic setting.

Age range: The age range of the salt in the salt domes is the same as that for bedded salt which is Late Proterozoic to Miocene, but most are Paleozoic and Mesozoic. The formation of the domes was, of course, later than the deposition of the salt.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   The host rocks of the salt domes are any of the sedimentary units that the dome penetrated during its rise. this could be any of the normal marine sedimentary rocks.

Associated rock(s):   Anhydrite, gypsum, potash.

Ore mineralogy: Halite with thinly interlaminated anhydrite.

Gangue mineralogy: Anhydrite.

Alteration: Groundwater dissolution can modify the original rock textures, or porosity, or it can even destroy a deposit.

Structural setting: Some salt intrusions form as a result of tectonic deformation and follow faults and anticlinal axes.

Ore control(s):   Basin brines with salinity high enough to precipitate sodium chloride plus the tectonic setting to form the domes.

Typical ore dimensions: Salt domes can range from one to several square kilometers in areal extent, and thousands of meters in depth.

Typical alteration/other halo dimensions: N/A

Effect of weathering: Surface weathering causes total dissolution of salt in most climatic areas. Salt can be preserved at the surface, however, in areas of extreme aridity. Dissolution of salt by groundwater at the top of a salt dome can cause the accumulation of anhydrite that was disseminated in the salt. This anhydrite usually hydrates to gypsum. Gypsum deposits of this type can be extensive, thick, and very pure.

Effect of metamorphism: N/A

Maximum limitation of overburden: Specific limit is unknown but salt domes are mined by conventional methods at depths over 100 m. Much salt dome salt is is solution-mined at depths exceeding 500 m.

Geochemical signature(s):   N/A

Geophysical signature(s):   Salt gives a very low response on a gamma-ray well logs and salt domes are indicated by ares of low gravity.

Other exploration guide(s):   Salt domes sometimes show up as circular features on areal photographs or detailed topography. Salt springs are another indicator.

Most readily ascertainable regional attribute: Large marginal marine basins containing thick sediments, with basin-edge sediments of higher-tan-normal salinity.

Most readily ascertainable local attribute: High-salinity and high bromine content in well water; low response on gamma-ray well logs; salt springs, local topographic features indicating uplift of domes, circular gravity lows.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Impurities must be low; crystal size optimum for intended use.

Compositional/mechanical processing restrictions: Material must be pure enough so that minimal physical beneficiation is necessary for the intended product.

Distance limitations to transportation, processing, end use: Transportation is a major cost of the finished product. Therefore, costs of mining, processing, and transportation must be balanced to achieve a saleable product.

REFERENCES

Borchert and Muir, 1964.
Kostick, 1985.
Lefond, 1969.
Symposium on Salt, 1963 through 1985.

Morse, 1985.
Raup and Bodine, in press.
Smith, and others, 1973.

DESCRIPTIVE MODEL OF BEDDED GYPSUM

Deposit subtype: Marine evaporite gypsum

By Omer B. Raup

BRIEF DESCRIPTION

Deposit synonyms: N/A

Principal commodities produced: Gypsum.

By-products: None.

End uses: Wallboard, plaster products, Portland cement, agriculture, fillers.

Descriptive/genetic synopsis: Gypsum deposits of marine origin occur in marginal marine basins of many sizes. These basins had periodic inflow of sea water which was the major source of the calcium sulfate. Gypsum deposits are frequently of large areal extent and of considerable thickness.

Typical Deposits: Silurian Salina Formation in the Michigan and Appalachian basins with deposits in New York, Pennsylvania, West Virginia, Ohio, and Michigan; Permian Blaine Formation in Kansas, Oklahoma, and Texas; Tertiary deposits of the Paris basin, France.

Relative importance of the deposit type: This deposit type contains the thickest and most areally extensive deposits of gypsum and it accounts for the major production of gypsum of all of the deposit types.

Associated/related deposit types: Marine evaporites that contain limestone and dolomite; bedded celestite.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Marginal marine basins that were subsiding at a moderate rate during deposition of the evaporites. Influx of sea water maintained water levels in the basins that were being lost by evaporation. Some evaporites in this type of setting have some contribution from inflow from the continent. For most, however, this contribution is small.

Regional depositional environment: Same as the tectonostratigraphic setting.

Age range: Late Proterozoic to Miocene, but most are Paleozoic and Mesozoic.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Primarily dolomite, with some limestone and halite.

Associated rock(s):   Anhydrite, dolomite and halite.

Ore mineralogy: Gypsum with thinly interlaminated layers of calcite of dolomite.

Gangue mineralogy: Calcite and dolomite.

Alteration: Many gypsum deposits are formed by the hydration of anhydrite. Purity and usefulness of the gypsum is dependent of the completeness of the alteration. Groundwater dissolution can modify the layering, grain size, or porosity of gypsum deposits or it can even destroy a deposit.

Structural setting: Marine evaporites occur in basins near continental margins in areas of moderate subsidence.

Ore control(s):   Basin brines with salinity high enough to precipitate calcium sulfate.

Typical ore dimensions: Thickness of mineable bedded gypsum deposits range from 10 to 50 m. Areal extent of some deposits covers many square kilometers.

Effect of weathering: Surface weathering causes dissolution of gypsum in most climatic areas. Gypsum is preserved at the surface, however, in areas of aridity.

Effect of metamorphism: Metamorphism of rocks containing bedded gypsum can cause alteration of the surrounding rocks by calcium and sulfur metasomatism. Skarn minerals and pyrite are some of the products.

Maximum limitation of overburden: Most gypsum is mined by strip mining but bedded gypsum is also mined by conventional methods at depths over 50 m.

Geochemical signature(s):   There is no particular geochemical signature for gypsum.

Geophysical signature(s):   Bedded gypsum gives a high response on a neutron log because of the large amount of water of crystallization.

Other exploration guide(s):   Occurrence of basin-edge sediments that contain thin beds of gypsum or anhydrite which may indicate thicker deposits toward the basin center. High-sulfate brines in wells.

Most readily ascertainable regional attribute: Large basin containing marine sediments, with basin-edge sediments of higher-than-normal salinity.

Most readily ascertainable local attribute: High-sulfate content in well water; high response on neutron well logs; saline springs.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Impurities must be low.

Compositional/mechanical processing restrictions: Material must be pure enough so that minimal physical beneficiation is necessary for the intended product.

Distance limitations to transportation, processing, end use: Transportation is a major cost of the finished product. Therefore, costs of mining, processing, and transportation must be balanced to achieve a saleable product.

REFERENCES

Davis, 1986.

Pressler, 1985.

Raup and Bodine, in press.

Smith and others, 1973.

DESCRIPTIVE MODEL OF NATURALLY OCCURRING IODINE BRINES

by Sherilyn Williams-Stroud

BRIEF DESCRIPTION

Deposit synonyms: N/A

Principal commodities produced: Iodine.

Co-products: Bromine, salt, magnesium, calcium salts.

End uses: Catalysts, animal feed additives, pharmaceuticals, photography, sanitary uses. Minor uses include cloud seeding, herbicides, Geiger counters, airport luggage scanners, and quartz-iodine lights for automobiles, sports stadiums, and television studios.

Descriptive/genetic synopsis: Brines with high iodine concentrations are theorized to be of marine origin. Iodine is fixed in the marine environment by plants and other organisms. Organic material derived from seaweeds and planktonic organisms are deposited in muddy sediments and iodine liberated by anaerobic decomposition of the organic matter in sediments is transferred to the brine.

Typical deposits: Devonian Sylvanian Formation in Michigan; Miocene Monterey Formation and Pliocene Repetto Formation in California; Pennsylvanian Morrowan Formation in Oklahoma; Pliocene Kazusa Group in Japan; Pliocene Kalibeng Formation in Indonesia; Permian Inder Salt Dome of Western Kazakhstan in the U.S.S. R.

Relative importance of the deposit type: Economic amounts of iodine occur in brines. Brines represent one of two distinct iodine deposit types.

Associated/related deposit types: Bedded salt, salt domes, potassium, magnesium, nitrates, borates, hydrocarbons, bromine.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Iodine occurs with hydrocarbons and (or) with salts and bromine in subsurface brines.

Regional depositional environment: Deposition and accumulation of marine life produces hydrocarbons as an organic residue and iodine is contained in associated brines.

Age range: Devonian to Pliocene for associated brine-bearing host rocks.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Salt, sandstone, diatomaceous marl, limestone.

Ore mineralogy: N/A.

Gangue mineralogy: Evaporite minerals such as halite, potash, gypsum, etc.

Structural setting: Permeable rock reservoirs.

Ore control(s):   Permeable reservoirs in sediments.

Typical ore dimensions: Resources of iodine-containing brines have not been precisely measured.

Typical alteration/other halo dimensions:

Maximum limitation of overburden: Unknown, but in Japan, it has been noted that the iodine:chlorine ratio decreases markedly with age. This may be a function of diagenesis.

Most readily ascertainable local attribute: Saline well or spring water.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Bromine and chlorine can be substituted for iodine in some germicidal and antiseptic applications, but for most of its uses, iodine has no substitute. Iodine is highly toxic and corrosive and must not be allowed to escape into the atmosphere.

Compositional/mechanical processing restrictions: After iodine is removed from brine, the spent brine is neutralized and reinjected into the formation of origin, thereby maintaining hydraulic balance and minimizing pressure losses which could cause surface subsidence.

Distance limitations to transportation, processing, end use: The United States imports the majority of its iodine from Japan and Chile. In times of high iodine prices recycling iodine wastes to produce crude iodine is especially cost effective.

OTHER

REFERENCES

Collins and others, 1971.   Lyday, 1985a.
Fukata and Fujii, 1982.   Motojima and Hirukawa, 1979.

DESCRIPTIVE MODEL OF NATURALLY OCCURRING BROMINE BRINES

Subtypes: Subsurface brines

by Sherilyn Williams-Stroud

BRIEF DESCRIPTION

Deposit synonyms:

Principal commodities produced: Bromine.

By-products: Iodine.

End uses: Ethyline dibromide (EDB) is the chief compound of bromine. It is used in leaded gasoline as an antiknock compound. EDB is also used as a reagent in the synthesis of dyes and pharmaceutical intermediates and as an anesthetic, sedative, and antispasmodic agent. Other uses of EDB and methyl bromide include gauge fluids, solvents, catalysts, and fire extinguishers. Elemental bromine is used as a bleaching and disinfecting agent and in high-intensity light bulbs. Metal compounds of bromine are used in photography, in drilling fluids, for sink-float separation, and in pharmaceutical preparations.

Descriptive/genetic synopsis: Bromine is found in the earth's oceans at a concentration of 65 ppm. Underground brines associated with evaporite deposits have bromine concentrations ranging from 1000 ppm to 5000 ppm.

Typical deposits: Jurassic Smackover Limestone, USAR
Devonian Sylvania Sandstone Formation, Michigan Basin

Relative importance of the deposit type: The underground brines have the highest concentrations of bromine, although the largest potential resource for bromine is the oceans. Bromine was primarily produced from seawater until discovery of the high-concentration underground brines.

Associated/related deposit types: Oilfield brines in sandstone or limestone aquifers; bedded salt, salt domes, bedded gypsum (?).

REGIONAL GEOLOGIC ATTRIBUTES

Age range: Devonian to Cenozoic.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Limestone, sandstone, evaporites.

Ore mineralogy: Brine.

Gangue mineralogy: Evaporite minerals such as gypsum and halite.

Alteration: N/A

Structural setting: Underground brines occur in permeable rock reservoirs .

Ore control(s):   Permeable sediments.

Typical ore dimensions: Reserves of bromine presently under production in natural well brines in Arkansas and Michigan are vast and have not shown significant depletion since bromine was first produced.

Typical alteration/other halo dimensions: N/A

Geochemical signature(s):   Br + Cl $\pm$ I .

Most readily ascertainable local attribute: Saline well or spring water.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Bromine is highly corrosive and toxic in elemental form and cannot be allowed to escape into the atmosphere. The Environmental Protection Agency has suspended the use of EDB in pesticides and cancelled its use as a fumigant for fruit and other produce. The EPA regulations to reduce lead in gasoline have reduced consumption of EDB as a gasoline additive.

Compositional/mechanical processing restrictions: Chlorine in used to oxidize the bromide in brines to bromine and represents approximately 30% of the cost of manufacturing bromine.

Distance limitations to transportation, processing, end use: Special handling and transportation is required for bromine by the Interstate Commerce Commission. Compounds of bromine are usually safer to handle than liquid bromine. Most elemental bromine is converted into bromine compounds in the integrated plants at the brine extraction site.

OTHER

REFERENCES

Carpenter and Trout, 1978.   Lyday, 1985b.
Collins and others, 1967.   Sorensen and Segall, 1974.

DESCRIPTIVE MODEL OF SODIUM CARBONATE IN BEDDED LACUSTRINE EVAPORITES

Deposit subtype: Green River

By John R. Dyni

BRIEF DESCRIPTION

Deposit synonyms: Trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), nahcolite ($NaHCO_3$).

Associated Minerals: Dawsonite, shortite. Dawsonite [$NaA1(OH)_2CO_3$] has potential economic value for alumina and soda ash--most likely would be recovered as a byproduct of oil shale. Shortite [$Na_2CO_3 \cdot 2CaCO_3$] has potential economic value for its sodium carbonate content. The most likely method of recovery of soda ash from shortite would be incidental to solution mining of trona beds whereby adjacent shortite-bearing oil shales and marlstones would be fractured and exposed to mining solutions.

Other Sources of Soda Ash: Playa lake brines, i.e., Searles Lake, CA. In past years, the major source of soda ash was its manufacture from salt and limestone by the Solvay process. The deposits of sodium carbonate minerals in Wyoming and the sodium carbonate brines at Searles Lake, Calif. have gradually become the principal sources of domestic soda ash. No Solvay plant operates today in the U.S.

Principal commodities produced: Light and dense soda ash (Na_2CO_3).

By-products: None. However, large amounts of carbon dioxide are produced during the manufacture of soda ash. Possibly, this gas could be economically recovered and sold as a byproduct and, at the same time, reduce a significant local source of atmospheric pollution.

End uses: Soda ash, an important industrial chemical, is used in the manufacture of glass, chemicals, soaps and detergents, pulp and paper, water treatment, flue gas desulfurization, and a wide variety of other products (Kostick, 1989; 1990).

Descriptive/genetic synopsis: Two major deposits of sodium carbonate minerals are found in fine-grained lacustrine rocks of the Eocene Green River Formation in Wyoming and Colorado. One deposit consists of bedded trona and disseminated shortite and locally abundant halite in the Wilkins Peak Member of the Green River Formation in the Green River Basin, southwest Wyoming. Twenty-five of the thickest trona beds contain an estimated 82 billion short tons of trona and an additional 53 billion tons of mixed trona and halite.

   In the Green River Basin, the Wilkins Peak Member consists of oil shale, marlstone, mudstone, sandstone, and as many as 42 beds of trona ranging from a few centimeters to 11 meters in thickness. The 25 thickest beds occupy areas in the basin ranging from 105 to 870 square miles. Halite is locally abundant, especially in the older deeper beds. Because of its greater solubility, halite (mixed with nahcolite) occurs as a depocenter facies that grades laterally away from the lake-basin deeps into trona. Nahcolite is locally abundant in some beds, but its distribution with respect to trona is not yet well known. Trona is mined by conventional room-and-pillar methods, and in recent years, by solution mining as well. Scattered crystals of shortite are abundantly distributed through the oil shale and marlstone

beds. Although shortite is a large potential source of sodium carbonate, it would be difficult to mine by conventional methods because of its occurrence as disseminated crystals.

A large resource of nahcolite is found in the Parachute Creek Member of the Green River Formation in the Piceance Creek Basin, northwest Colorado. Nahcolite occurs in beds as thick as 1.4 meters, in laterally persistent zones of disseminated crystals mixed with oil shale, and in scattered nodules as large as 1 meter across in medium-to high-grade oil shale. Halite is locally abundant in some of the nahcolite beds as a basin-center evaporite facies similar to its occurrence in Wyoming. The nahcolite resource is estimated at 32 billion short tons of which about 60 percent is of the nodular type.

The sodium carbonate/chloride salts were deposited in several large alkaline lakes that occupied parts of Wyoming, Colorado, and Utah during middle Eocene time. The salts were derived from weathering and dissolution of soluble components of early Tertiary, Cretaceous, and older sedimentary rocks which were exposed in the hydrographic basin of the lakes. Intermittent volcanism throughout middle Eocene time contributed significant amounts of dacitic ash to the Green River lakes. Most of the ash was completely altered and contributed dissolved ions to the lake and sediment waters.

Major ions in solution in the inflowing stream waters were probably Ca, Mg, Na, HCO3, SO4, and C1, similar to the composition of present-day streams in the region. In addition to normal chemical processes of evaporation and precipitation of the salts, biogenic processes are believed to have strongly influenced the chemistry and composition of the lake waters from which the salts were precipitated.

A restricted, but prolific, biotic community of cyanobacteria ("blue-green" algae, sulfate-reducing bacteria, and other associated microorganisms) were important constituents of the alkaline lake waters. This biocoenose controlled, in part, the makeup of the dissolved mineral constituents of the lake and sediment waters as illustrated by the following schematic (unbalanced) reactions:

1. $SO4^{--} + CH_2O \longrightarrow (H_2S, HS^-) + (CO_2, HCO_3^-, CO3^{--})$,
   (organic matter)

2. $HCO3^- + (Ca^{++}, Mg^{++}, Fe^{++}) \longrightarrow Ca(MgFe)(CO_3)_2$,

3. $Fe^{++} + HS^- \longrightarrow FeS_2$,

4. $HCO_3^- + Na^+ \longrightarrow (Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O, NaHCO_3)$.

5. $Na^+ + Cl^- \longrightarrow NaCl$

Reaction 1, mediated by sulfate-reducing bacteria which utilized metabolizable organic compounds from decaying algae, resulted in formation of abundant carbonate species $(CO_2, HCO_3^-,$ and $CO3^{--})$ which reacted with available calcium, magnesium, and ferrous iron to precipitate as insoluble ferroan dolomite or ankerite (reaction 2). The remaining soluble sodium, carbonate species, and chloride were concentrated in the lake and sediment waters driving up pH and lowering Eh. Ferrous iron, stable at low Eh, reacted with reduced sulfur species (reaction 3) to precipitate as iron sulfide minerals (typically pyrite, marcasite, pyrrhotite), thereby lowering the concentration of H_2S to tolerable life-sustaining levels for the sulfate-reducing bacteria. During evaporative phases of the lake---depending on the water temperature, partial pressure of CO_2, and concentrations of dissolved species---trona, nahcolite, and halite were precipitated (reactions 4 and 5). Depending on local conditions, other evaporite minerals were precipitated in abundance as disseminated crystals in the host sediments. Such minerals include shortite $(Na_2CO_3 \cdot CaCO_3)$ and dawsonite $[NaA1(OH)_2CO_3]$.

Because organic matter was abundant in the Green River lakes, all of the sulfate was reduced and effectively removed from the system. (Syngenetic sulfate minerals are essentially absent in the Green River Formation). Because of its higher solubility, NaCl remained in solution and

migrated toward the lake-basin deeps where it ultimately crystallized with trona during continued evaporation of the lake waters.

The Green River type of sodium carbonate deposit may be considered an end-member of lacustrine sodium carbonate-sulfate-chloride deposits whereby the sulfate ion is completely lost by bacterial reduction. If insufficient quantities of metabolizable organic matter are present, not all of the sulfate may be reduced. Also, sulfate reduction may cease if the amount of ferrous iron is insufficient to maintain the concentration of H_2S at levels that the bacteria can tolerate. Thus, sulfate minerals could be present with sodium carbonate/chloride minerals in other lacustrine deposits.

Relative importance of the deposit type: The Wyoming trona deposit is the largest resource of sodium carbonate minerals known in the world. The Colorado nahcolite deposit is the second largest known resource of sodium carbonate minerals.

Typical Deposits: Possibly several in Turkey that are associated with oil shale deposits; also possibly one in Chad, and others in China(?)
> Green River Basin, USWY   (Bradley and Eugster, 1969)
> Ankara-Beypazari, TRKY   (Harben and Bates, 1990)

Associated/related deposit types: Valuable resources of oil shale.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting:

Regional depositional environment: The Green River lake system consisted of two large hydrographic basins lying to the north and to the south of the Uinta Mountains-Axial Basin Uplift in a mild temperate climate marked by periods of aridity. A variety of sedimentary rocks of marine and continental origin ranging from early Tertiary to Precambrian in age were exposed in these hydrographic basins which contributed sediments and solutes to local streams feeding the lakes. Episodic volcanism through Eocene time contributed substantial amounts of ash of dacitic composition to the Green River sediments. The ash, now mostly altered to quartz, analcime, and feldspar, contributed dissolved ions to the lakes and sediment waters.

The Green River lakes were closed for considerable periods of time. This permitted the concentration of ions in the lake waters to increase to the point of precipitation of sodium carbonate salts and halite. Major quantities of evaporites were deposited at about the same time in the Green River Basin (Wilkins Peak Member of the Green River Formation) and in the Piceance Creek Basin (Parachute Creek Member of the Green River Formation). Geochemical and sedimentological evidence suggest that both lakes were probably permanent bodies of water, rather than ephemeral, even during low stages of the lake when the bedded evaporites were being deposited.

Although the Wyoming and Colorado deposits share some common regional attributes such as paleoclimate and source rock types, the physical and chemical conditions of evaporite deposition were different in each basin. In the Piceance Creek Basin, large quantities of medium- to high-grade oil shale were deposited with bedded nahcolite and locally halite and with nodules and disseminated crystals of nahcolite and finely disseminated dawsonite. In the Green River Basin, trona was the major sodium carbonate mineral to be deposited. In many trona beds, especially the older beds in the southern part of the Green river basin, halite is a major constituent, comprising from a few percent to 100 percent of a bed. The halite is areally confined by lake-bottom topography to deeper parts of the lake basin during the time of evaporite deposition.   Abundant quantities of shortite were deposited as euhedral scattered crystals in the marlstones and oil shales interbedded with the trona probably during early diagenesis when the sediments were still soft and plastic.

Age range: Middle Eocene, deposited approximately 46 to 50 ma ago.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Fine-grained lacustrine rocks, commonly oil shale, dolomitic marlstone, mudstone and shale. In outcrop, saliniferous features may include solution breccias, zones of crystal cavities and vugs, and calcite pseudomorphs after saline minerals.

Associated rock(s):   Volcanic rocks. Hydrolysis of glassy alkalic rocks can supply substantial sodium to solutes of lacustrine waters of closed basins.

Ore mineralogy: Wyoming trona: The beds, relatively pure where mined, includes some thin interbeds of marlstone, shale and oil shale. The combined chloride and sulfate content of mined trona is commonly less than 0.1 percent. Vertical seams of mudstone cut trona beds in some of the mines.   Typical analyses show the trona to range from 85 to 94 percent of a mined bed.
       Colorado nahcolite: One type of bedded nahcolite is white and coarsely crystalline. Such beds are relatively pure, except for some interbedded marlstone or oil shale, and are as thick as 10 meters. Another variety of bedded nahcolite is microcrystalline, dense, and occurs in beds ranging from a few centimeters to 3.4 meters in thickness.   Zones of disseminated nahcolite consist of mixtures of oil shale and nahcolite; these may be as much as 7 meters thick and contain from about 40 to 65 percent nahcolite by weight. Much of the nahcolite occurs in nonbedded coarsely crystalline aggregates, a few millimeters to 1.7 meters across, which are scattered through oil shale. About two-thirds of the aggregates are a few millimeters to 8 cm in diameter; about 10 percent of the aggregates are larger than 10 cm. Selected zones of oil shale and nahcolite aggregates contain as much as 35 percent nahcolite by weight.

Gangue mineralogy: Wyoming trona: Gangue materials in the mined trona beds include oil shale, marlstone, shale, shortite, authigenic minerals in small amounts including dolomite, bradleyite, quartz, loughlinite, calcite, pyrite and searlesite; and some organic matter.
       Colorado nahcolite: Gangue in bedded nahcolite includes stringers and thin beds of oil shale and marlstone. Gangue minerals are quartz, iron sulfide minerals, and traces of other authigenic minerals including searlesite and northupite. The microcrystalline bedded nahcolite also contains some interbedded marlstone and oil shale stringers, and small amounts of microcrystalline quartz in irregular patches.

Alteration: The upper part of the nahcolite deposit in the Piceance Creek Basin has been dissolved and removed by groundwater. The upper boundary of the deposit is marked today by a distinct dissolution surface.

Structural setting: The Green River Basin in southwestern Wyoming and the Piceance Creek Basin in northwestern Colorado are asymmetric sedimentary-structural basins that formed during Laramide time and are separated by the Uinta Mountain-Axial Basin (UM-AB) Uplift. The deeper parts of the basins lie closer to the UM-AB Uplift and may be bounded by high-angle faults at depth. Depositional gradients are highest adjacent to the uplift and are quite shallow in those portions of the basins farthest from the uplift.
    Basin asymmetry strongly influenced the distribution and type of sediments within the basins. Evaporites were deposited in the topographically deeper parts of the lakes, then tended to shift away from these areas as they became filled with sediments and as downwarping of the basins diminished.

Typical alteration/other halo dimensions:

Maximum limitation of overburden: Trona mining is presently restricted to the northern part of the Green River Basin where the beds are at mineable depths. Five beds of trona are presently mined by room-and-pillar and long-wall methods at depths ranging from 800 to 1700 feet below the surface. The oldest trona beds in the southern part of the basin are at depths of as much as 3,000 or more feet. Some of these deeper beds are amenable to solution mining. One solution mining operation extracts sodium carbonate liquor from several beds of trona as deep as 585-615 m.

Geophysical signature(s):   Seismic and gravity geophysical surveys may provide information on the tectonic configuration of a basin and were to look for basin deeps that might contain evaporites.

Other exploration guide(s):   Target basins might include those containing deposits of oil shale similar to those of the Green River Formation. Analysis of spring waters and well waters may provide clues to the occurrence of sodium carbonate deposits at depth. Study of outcropping sections of lacustrine rocks may reveal evaporative sequences containing crystal cavities, vugs, and solution breccias from leaching of water-soluble minerals. Careful study of these features, and the mineralogy of the host rocks might provide clues to the possible presence of evaporite facies containing sodium carbonate minerals.

ECONOMIC LIMITATIONS

Distance limitations to transportation, processing, end use: There are large waste ponds for spent leachate waters from processing Wyoming trona. Although little is known about them, waters in these ponds probably have high pH and may contain some toxic components (fluoride?, organic components?). In recent years, liquors from some trona waste ponds are being reclaimed for their soda ash content. Carbon dioxide is a major effluent in processing trona but it might be a recoverable byproduct for use in secondary recovery of oil in oil fields in the Rocky Mountain region. Soda ash is shipped dry in bulk carload lots and bags and as sodium carbonate liquor. Although the Wyoming trona district lies hundreds of miles from seaports, foreign sales of soda ash from Wyoming are important.

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DESCRIPTIVE MODEL OF IODINE-BEARING NITRATE

by Sherilyn Williams-Stroud

BRIEF DESCRIPTION

Principal commodities produced: Nitrogen, iodine.

End uses: Catalysts, animal feed additives, pharmaceuticals, photography, sanitary uses. Minor uses include cloud seeding, herbicides, Geiger counters, airport luggage scanners, and quartz-iodine lights for automobiles, sports stadiums, and television studios.

Descriptive/genetic synopsis: Natural nitrate deposits formed by accumulation of saline minerals from the atmosphere in a nearly rainless environment. Saline components are transported and deposited from the atmosphere as dry fallout and as fog-condensate solutions.

Typical deposits: Atacama Desert deposits of Northern Chile; Antarctica.

Relative importance of the deposit type: Chile was the major producer of iodine as a byproduct of nitrate production until Japan began producing three times the Chilean production from brines in 1966.

Associated/related deposit types: Other evaporite deposits, especially halite or sulfate mineral crusts.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Nitrate fields occur in areas of low relief with rounded hills and ridges and broad shallow valleys. Deposits occur as veins and impregnations in host rocks and in unconsolidated sediments.

Regional depositional environment: The Atacama Desert lies between the Andes Mountains and the low, narrow Coastal Range in Chile. Annual precipitation is approximately 50 mm. The highest grade deposits occur in the Central Valley.

Age range: Miocene (?) to present.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Nitrate ore occurs as veins and impregnations in granitic intrusions, andesite and rhyolite flows and tuff layers, limestone, sandstone, and shale. Most widespread deposits are cements in unconsolidated regolith (caliche).

Associated rock(s):   Anhydrite, chalcedony.

Ore mineralogy: Caliche contains sodium nitrate ($NaNO_3$), dietzeite ($2CaO \cdot I_2O_5 \cdot CrO_3$), lautarite ($Ca(IO_3)_2$), iodates.

Gangue mineralogy: Evaporite minerals such as gypsum and halite; chromates, borates.

Typical ore dimensions: The Chilean deposit is 15 to 75 km wide and 720 km long. Ore layers are 1 to 3 m thick.

Typical alteration/other halo dimensions: N/A

Effect of weathering: Very little chemical weathering occurs in the nitrate deposits due to extremely low precipitation. Heavy rainfalls could completely destroy the deposit.

Maximum limitation of overburden: Caliche crusts are found at or near the surface.

Geochemical signature(s):   Nitrates + I + B + Cr + Br. Only known naturally occurring perchlorate ion has been identified in Chilean deposits.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Bromine and chloride can be substituted for iodine in some germicidal and antiseptic applications, but for most of its uses, iodine has no substitute. Iodine is highly toxic and corrosive and must not be allowed to escape into the atmosphere.

Distance limitations to transportation, processing, end use: The United States imports the majority of its iodine from Japan and Chile. In times of high iodine prices recycling iodine wastes to produce crude iodine is especially cost effective.

OTHER

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Ericksen, 1981.   Mueller, 1968.
Harben and Bates, 1990.

DESCRIPTIVE MODEL OF LITHIUM-RICH PLAYA BRINE

By Sigrid Asher-Bolinder

BRIEF DESCRIPTION

Deposit synonyms: Lithium brine in salars or salt lakes.

Principal commodities produced: Potassium chloride and sulfate; magnesium oxide and carbonate; boric acid; lithium carbonate and sulfate; and sodium sulfate, nitrate, carbonate, and chloride.

By-products: Sodium chloride.

End uses: Ceramics and glass industry, primary aluminum production, manufacture of lubricants and greases.

Descriptive/genetic synopsis: Deposits found in chloride brines in salt pans (salars, playas) of closed basins in arid environments. Precipitation and spring waters entering the basins typically have flowed over and though acid- to intermediate-composition volcanic rocks and(or) saline continental sedimentary rocks, leaching their soluble lithium, either by hydrothermal or ground-water processes. High rates of natural near-surface solar evaporative concentration and precipitation of Na, K, and Mg compounds further concentrate the brine and raise its relative lithium content.

Typical Deposits: Salar de Atacama, CILE (Evans, 1986)
Salar de Uyuni, BLVA (Ballivian and Risacher, 1981)
Silver Peak, USNV (Papke, 1976)

Relative importance of the deposit type: Major in market-economy countries.

Associated/related deposit types: Boron-, magnesium-, and potassium-rich brines from continental evaporites.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Horst-and-graben or other structural basin development in volcanoclastic terrane.

Regional depositional environment: Closed basin in arid climate.

Age range: Tertiary to Recent.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   Porous detritus or evaporites, lacustrine sediments.

Associated rock(s):   Volcanic ash; lacustrine mudstones, sandstones, and siltstones; bedded evaporites.

Ore mineralogy: Brine, most deposits will have evaporite minerals appropriate to the major brine constituents that form surface crusts and deposits at the periphery of the playa.

Gangue mineralogy: Lacustrine evaporite mineral suite including gypsum, halite, others.

Ore control(s):   Closed basin in arid climate; lithium source.

Typical ore dimensions: Known deposits show > 0.03% Li over areas of several tens of square kilometers in aquifers ranging from near surface to >200 m below the surface.

Typical alteration/other halo dimensions:

Effect of weathering: Weathering may dilute or concentrate brine.

Effect of metamorphism: Unknown.

Maximum limitation of overburden: Unknown, depends on the grade and chemistry of the brine, total reserves, and host permeability.

Geochemical signature(s):   Li (commonly interested in concentrations containing >0.03 weight percent Li); low Mg/Li ratio (1.3-133); high Li/Na (>1:100) ratios in spring waters; anions primarily chloride.

Geophysical signature(s):   Lithologic logging of brine resistivity in boreholes may be of some use.

Other exploration guide(s):   Presence of salar /playa at surface.Shallow drilling of salars surrounded by silicic volcanic rocks and (or) continental evaporites.

Most readily ascertainable regional attribute: Horst-and-graben or other structural basins in silicic volcanic-rock terranes in arid environments.

Most readily ascertainable local attribute: Presence of saline mineral-rich playa; high Li/Na (>1:100) ratios in spring waters.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: None.

Compositional/mechanical processing restrictions:
       1) Mg/Li ratios as low as 1.3 to 133;
      2) high present-day evaporation-to-precipitation ratios for further solar
         concentration of brines;
      3) Li content >0.03 weight percent.

Distance limitations to transportation, processing, end use: Distance that concentrated brine or lithium compounds can be transported economically.

REFERENCES

Evans, 1986.
Harben and Bates, 1984.

DESCRIPTIVE MODEL OF DISSEMINATED FLAKE GRAPHITE

by David M. Sutphin

BRIEF DESCRIPTION

Deposit synonyms: Deposits of disseminated graphite flakes in katazonal metamorphosed siliceous rocks and marbles.

Principal commodities produced: Flake graphite.

By-products: Amorphous graphite.

End uses: Flake graphite's use in crucibles and related ware is an important application of its use in refractories. Other applications include batteries, brake linings, foundries, lubricants, and pencils.

Descriptive/genetic synopsis: Disseminated flake graphite deposits develop syngenetically from carbonaceous material in sedimentary rocks that have been subjected to garnet grade or higher regional metamorphism. Concurrent large-scale folding of the metasedimentary sequences is common and fold limbs often host deposits. Deposits are usually stratabound and consist of individual beds or lenses in gneisses, schists, and marbles that are richer in graphite than associated beds. Flakes may range from 1 to 250 mm in diameter.

Typical Deposits: Burnet-Llano, USTX
Clay, Coosa, and Chilton Counties, USAL
Kigluaik Mountains, USAK
Pollon Lake (Reindeer Lake), CNSK
Kropfmuehl, WGER
deposits in CINA and MDGS

Relative importance of the deposit type: Disseminated flake graphite deposits are the only source of flake graphite which, because of its use in crucibles, is part of the national defense stockpile.

Associated/related deposit types: Rarely, graphite veins may be associated with disseminated flake graphite deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Deposits occur in metamorphosed continental margin or intercratonic basinal sediments.

Regional depositional environment: Regional metamorphism to garnet grade or higher and large-scale deformation of carbon-rich sedimentary sequences.

Age range: Deposits may be any age, but are commonly Archean to late Proterozoic in age.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s): Metasediments-- quartz-mica schist, gneiss, micaceous quartzite, micaceous-feldspathic quartzite, marble. Deposits most commonly occur in rocks that have been metamorphosed to at least garnet grade.

Associated rock(s): Pegmatite, aplite, and granite intrusives.

Ore mineralogy: Flake graphite.

Gangue mineralogy: Quartz, calcite, biotite, muscovite, feldspars, garnet, and sometimes amphibole, pyrrhotite, pyrite, and magnetite. Biotite or muscovite intergrown with graphite is difficult to separate and lowers the deposit value.

Alteration: Graphite adjacent to pegmatites may be coarser than the remainder of the deposit.

Structural setting: Normally intense large-scale folding is concurrent with regional metamorphism. Graphite deposits commonly occur on limbs of such folds.

Ore control(s): Size, form, persistence, and grade of the deposits depend in large part on the dimensions and carbon content of the original sedimentary rocks and on the amount of deformation.

Typical ore dimensions: Beds and lenses may range from 30 cm to 30 m thick with lengths to two km or longer.

Typical alteration/other halo dimensions:

Effect of weathering: Graphite is impervious to chemical weathering. Weathering of host rocks removes degradable gangue minerals such as micas and sulfides and weakens the rock making it less costly to mine. Unweathered sulfides are generally undesirable. Madagascar's important flake deposits consist of laterite clays which contain graphite and other resistant minerals that were liberated by the kaolinization of feldspars in the host rocks. Those deposits can be hand mined.

Effect of metamorphism: Disseminated flake deposits occur only in metamorphic rocks of at least garnet grade.

Maximum limitation of overburden: Unknown.

Geochemical signature(s): Positive vanadium and nickel anomalies and negative boron anomalies are possible deposit signatures, as is the presence of sulfides. Flake graphite may be found in geochemical stream sediment samples.

Geophysical signature(s): Graphite deposits have been located using induced potential, resistivity, electromagnetism, spontaneous potential (SP), and audiomagnetotelluric mapping (AMT). SP can locate deposits within 50 m of the surface. Other techniques are used for deeper deposits. Some deposits have associated radioactivity because of trace amounts of uranium.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Flake size and purity are important. Abrasive gangue minerals that are difficult to remove will limit the utility of flake graphite.

Compositional/mechanical processing restrictions: Graphite is easy to concentrate and difficult to refine. Because graphite is graded by flake size and purity, grinding must be done carefully to remove impurities like quartz without excessively reducing flake size.

Distance limitations to transportation, processing, end use: The best flake graphite, such as that from Madagascar, is traded on the world market and has no economical substitute, so transportation may be of less concern with flake graphite than with some industrial minerals or other forms of graphite.

OTHER

Deposits with grades as low as two percent graphite have been worked. Grades may range to a maximum of about 50 with a median around 9 percent. Flake graphite deposits containing up to about 150 million tonnes of material have been identified, but the median size is only about 240,000 tonnes.

REFERENCES

Cameron and Weis, 1960.   Krauss and others, 1988.
Harben and Bates, 1984.   Weis, 1973.

DESCRIPTIVE MODEL OF GRAPHITE VEINS

by David M. Sutphin

BRIEF DESCRIPTION

Deposit synonyms: Epigenetic graphite deposits.

Principal commodities produced: Vein (lump or chip) graphite.

End uses: Electric motor brushes, refractory applications, pencils, and lubricants. Sri Lankan vein graphite enjoys premium prices because of its high purity and excellent physical properties.

Descriptive/genetic synopsis: The origin of vein graphite deposits is still not certain. In regionally metamorphosed (granulitic, charnockitic) rocks, graphite is thought to form epigenetically from carbon-rich hydrothermal or pneumatolytic solutions as interlocking aggregates of coarse graphite crystals in veins containing 75-100 percent carbon.

Typical Deposits: Crystal Graphite Mine, USMT
Ticonderoga area, USNY
Bogala Mine , SRIL
Kahatagaha-Kolongaha Mines, SRIL
Botogol'sk, USSR.

Relative importance of the deposit type: Graphite veins are rare, but they are an important source of lump or chip ore.

Associated/related deposit types: Disseminated flake graphite deposits.

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting: Fracture systems; large- and small-scale folding.

Regional depositional environment: Regional metamorphism and folding.

Age range: Archean to Mesozoic; commonly Precambrian.

LOCAL GEOLOGIC ATTRIBUTES

Host rock(s):   High-grade metasediments (gneiss, schist, quartzite, and marble); Indian and Sri Lankan deposits are of granulite and charnockite facies.

Associated rock(s):   Granitic intrusions and pegmatites.

Ore mineralogy: Graphite which may occur as masses of parallel fibers or as needles to coarse platy or foliated structures.

Gangue mineralogy: Quartz, feldspar, calcite, garnet, sillimanite, pyroxene, apatite, and sulfides.

Alteration: Little or no wallrock alteration is seen in some veins. In Sri Lanka, rare wallrock alteration produces large crystals of sillimanite and others minerals. Veins in New Hampshire have graphite-tourmaline or graphite-sillimanite replacing schist wallrocks.

Structural setting: Area of intense metamorphism, such as a subduction zone, where organic matter in sandstones, limestones, and shales can be mobilized by magmatic fluids.

Ore control(s):   Fracture patterns, tensional jointing, geologic structures, and possibly solution chemistry control where the ore is deposited. Folding may cause the graphite to migrate. Veins often crosscut antiform structures.

Typical ore dimensions: Deposits may be lenses, pods, dikes, vugs, or veins. Veining may cover large areas as in Sri Lanka or New Hampshire. Individual veins may range from thin films to massive bodies greater than 3 m thick. Some veins extend along strike for several hundred meters and may be mined to a depth of 500 m.

Typical alteration/other halo dimensions:

Effect of weathering: Weathering may weaken host rocks allowing for easier removal of the graphite.

Effect of metamorphism: High-grade metamorphism of carbon-rich source rocks may provide carbon-laden solutions that precipitate vein graphite.

Maximum limitation of overburden:

Geophysical signature(s):   Induced potential, resistivity, electromagnetism, and spontaneous potential can be used to locate vein graphite deposits.

Most readily ascertainable regional attribute: High-grade regional metamorphism.

ECONOMIC LIMITATIONS

Physical/chemical properties affecting end use: Presence of gangue minerals, especially sulfides and abrasive silicates are detrimental.

Compositional/mechanical processing restrictions: Lump and chip ores are hand sorted, washed, and screened prior to sale.

Distance limitations to transportation, processing, end use: Sri Lankan vein graphite is exported throughout the industrial world.

OTHER

A major problem yet to be solved concerns the origin of vein graphite in deposits such as at the Crystal Graphite mine, Montana, and the Sri Lankan deposits and is the topic of much debate as described in Weis and others (1981). Theories put forth to explain the origin of vein graphite have included the following hypotheses: 1) magmatic (primary) origin where magmatic CO and CO_2 in hydrothermal or pneumatolytic solutions are reduced to deposit graphite as fracture fillings; 2) origin from carbonate rocks that have decomposed during metamorphism to form CO and CO_2 which again deposits graphite as fracture fillings; 3) origin from sedimentary organic matter that has become graphitized by high-grade

metamorphism;   and 4) solid-phase transportation of slippery graphite grains along grain boundaries down a pressure gradient. Recently Rumble and others (1986) proposed a combination of hypotheses 2 and 3 such that hydrothermal solutions containing CO_2 and methane(CH_4) from biogenic material and from the decomposition of carbonaceous sediments precipitate vein graphite upon mixing with fluids having different CO_2 /CH_4 ratios.

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Rumble and others, 1986.

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APPENDIX A:

COUNTRY CODES

Code	Name
AFGH	Afghanistan
AUSA	Australia, South Australia
ASTR	Austria
BLVA	Bolivia
CNSK	Canada, Saskatchewan
CILE	Chile
CINA	China
FNLD	Finland
FRNC	France
GRMY	Germany
ICLD	Iceland
INDA	India
IRAN	Iran
ITLY	Italy
JAPN	Japan
KNYA	Kenya
MDGS	Madagascar
MXCO	Mexico
MRCO	Morocco
PLND	Poland
SRIL	Sri Lanka
USSR	United Soviet Socialist Republics
USAL	United States, Alabama
USAK	United States, Alaska
USAZ	United States, Arizona
USAR	United States, Arkansas
USCA	United States, California
USLA	United States, Louisiana
USMT	United States, Montana
USNV	United States, Nevada
USNM	United States, New Mexico
USNY	United States, New York
USOR	United States, Oregon
USTN	United States, Tennessee
USTX	United States, Texas
WGER	West Germany

APPENDIX B:

COX-SINGER CLASSIFICATION OF DEPOSIT MODELS

CLASSIFICATION OF DEPOSIT MODELS

I. MAFIC AND ULTRAMAFIC INTRUSIONS

A. *TECTONICALLY STABLE AREA; STRATIFORM COMPLEXES*

STRATIFORM DEPOSITS

Basal Zone

Stillwater Ni-Cu	1

Intermediate Zone

Bushveld chromitite	2a
Merensky Reef PGE	2b

Upper Zone

Bushveld Fe-Ti-V	3

PIPE-LIKE DEPOSITS

Cu-Ni pipes	4a*
PGE pipes	4b*

B. *TECTONICALLY UNSTABLE AREA*

INTRUSIONS SAME AGE AS VOLCANIC ROCKS

Rift Environment

Duluth Cu-Ni-PGE	5a
Noril'sk Cu-Ni-PGE	5b

Greenstone Belt In Which Lowermost Rocks Of
Sequence Contain Ultramafic Rocks

Komatiitic Ni-Cu	6a
Dunitic Ni-Cu	6b

INTRUSIONS EMPLACED DURING OROGENESIS

Synorogenic In Volcanic Terrane

Synorogenic-synvolcanic Ni-Cu	7a

Synorogenic Intrusions In Non-Volcanic Terrane

Anorthosite-Ti	7b

Ophiolites

Podiform chromite	8a
Major podiform chromite	8b
(Lateritic Ni)	(38a)
(Placer Au-PGE)	(39a)

Serpentinite

Limassol Forest Co-Ni	8c
Serpentine-hosted asbestos	IM8d
Serpentinite-hosted magnesite	IM8e
Serpentinite-hosted talc-magnesite	IM8f
Verde antique	IM8j

E. *PORPHYROAPHANITIC INTRUSIONS PRESENT*

HIGH-SILICA GRANITES AND RHYOLITES

Climax Mo	1

OTHER FELSIC AND MAFIC ROCKS INCLUDING ALKALIC

Porphyry Cu	17

Wallrocks Are Calcareous

Deposits near contact

Porphyry Cu, skarn-related	18a
Cu skarn	18b
Zn-Pb skarn	18c
Fe skarn	18d
Au-bearing skarn	18f*
Wollastonite skarn	**18g**
Fluorite skarn	IM18h
Carbonate-hosted magnesite-talc	IM8i
Carbonate-hosted asbestos	IM18j
Amorphous graphite	**18k**

Deposits far from contact

Polymetallic replacement	19a
Replacement Mn	19b
Distal disseminated Ag-Au	19c
Manto fluorite	(IM32m)
(Carbonate-hosted Au)	(26a)

Wallrocks Are Coeval Volcanic Rocks

In granitic rocks in felsic volcanics

Porphyry Sn	20a
Sn-polymetallic veins	20b

In calcalkalic or alkalic rocks

Porphyry Cu-Au	20c
(Epithermal Mn)	(25g)

Wallrocks Are Older Igneous And Sedimentary Rocks

Deposits within intrusion

Porphyry Cu-Mo	21a
Porphyry Mo, low-F	21b
Porphyry W	21c*

Deposits within wallrocks

Volcanic hosted Cu-As-Sb	22a
Au-Ag-Te veins	22b
Polymetallic veins	22c
(Epithermal quartz-alunite Au)	(25e)
(Low-sulfide Au-quartz veins)	(36a)

III. EXTRUSIVE ROCKS

F. MAFIC EXTRUSIVE ROCKS
CONTINENTAL OR RIFTED CRATON

Basaltic Cu	23
(Sediment-hosted Cu)	(30b)

MARINE, INCLUDING OPHIOLITE-RELATED

Cyprus massive sulfide	24a
Besshi massive sulfide	24b
Volcanogenic Mn	24c
Franciscan-type volcanogenic Mn	24c-1
Cuban-type volcanogenic Mn	24c-2
Olympic Peninsula-type volcanogenic Mn	24c-3
Cyprus-type volcanogenic Mn	24c-4
Blackbird Co-Cu	24d
(Komatiitic Ni-Cu)	(6a)

G. FELSIC-MAFIC EXTRUSIVE ROCKS
SUBAERIAL-AERIAL
Deposits Mainly Within Volcanic Rocks

Hot-spring Au-Ag	25a
Creede epithermal vein	25b
Comstock epithermal vein	25c
Sado epithermal vein	25d
Epithermal quartz-alunite Au	25e
Volcanogenic U	25f
Epithermal Mn	25g
Rhyolite-hosted Sn	25h
Volcanic-hosted magnetite	25i
Lahir Island Au	25j
Perlite	IM25ka
Pumice scoria-volcanic cinders	IM25kb
Scoria-volcanic cinders	IM25kc
Hydrothermal bentonite	IM25la
Hydrothermal kaolin	IM25lb
Lithium in smectites of closed basins	**25lc**
Fumarolic sulfur	**25m**
Epithermal bertrandite replacement	IM25n
Sedimentary zeolites: Zeolites in tuffs of open hydrologic systesm	**25oa**
Sedimentary zeolites: Zeolites in tuffs of saline, alkaline-lake deposits	**25ob**
(Sn polymetallic veins)	(20b)

Deposits In Older Calcareous Rocks
    Carbonate-hosted Au-Ag   26a
    Fluorite veins   IM26b
    Barite-fluorite veins   IM26c

Deposits In Older Clastic Sedimentary Rocks
    Hot-spring Hg   27a
    Almaden Hg   27b
    Silica-carbonate Hg   27c
    Simple Sb   27d
    Vein Barite   **27e**

MARINE
    Kuroko massive sulfide   28a
    Algoma Fe   28b
    Sedimentary bentonite   IM28e
    (Volcanogenic Mn)   (24c)
    (Volcanogenic U)   (25f)
    (Low-sulfide Au-quartz veins)   (36a)
    (Homestake Au)   (36b)
    (Volcanogenic U)   (25f)

IV. SEDIMENTARY ROCKS

H. *CLASTIC SEDIMENTARY ROCKS*

CONGLOMERATE AND SEDIMENTARY BRECCIA
    Quartz pebble conglomerate Au-U   29a
    Olympic Dam Cu-U-Au   29b
    (Sandstone U)   (30c)
    (Basaltic Cu)   (23)

SANDSTONE
    Sandstone-hosted Pb-Zn   30a
    Sediment-hosted Cu   30b
    Sandstone U   30c
    Dimension stone - sandstone   IM30d
    Silica sandstone   IM30e
    (Basaltic Cu)   (23)
    (Kipushi Cu-Pb-Zn)   (32c)
    (Unconformity U-Au)   (37a)

SHALE-SILTSTONE
    Sedimentary exhalative Zn-Pb   31a
    Sedimentary exhalative barite   **31b**
    Emerald veins   IM31c
    (Basaltic Cu)   (23)
    (Carbonate-hosted Au-Ag)   (26a)

Marine Evaporites
    Evaporite   35a*
    Bedded Celestite   IM35aa
    Potash-bearing bedded salt   **35ab(T)**
    Bedded salt: Marine evaporite salt   **35ac**
    Salt domes: Diapiric salt structures   **35ad**
    Bedded gypsum: marine evaporite gypsum   **35ae**
    Salt-dome gypsum   IM35af
    Salt-dome sulfur   IM35ag
    Brines
      Naturally occurring iodine brines   **35am**
      Naturally occurring bromine brines   **35an**
Playa Evaporites
    Evaporite   35b*
    Sodium carbonate in bedded lacustrine evaporites: Green River   **35ba**
    Iodine-bearing nitrate deposits   **35bl**
    Brines
      Lithium-rich playa brines   **35bm(T)**
    (Saline alkaline lake zeolites)   (25ob)
Other
    Spring apron Bo   IM35c
    Travertine   IM35d

V. REGIONALLY METAMORPHOSED ROCKS

K. DERIVED MAINLY FROM EUGEOSYNCLINAL ROCKS
    Low-sulfide Au-quartz veins   36a
    Chugach-type low-sulfide Au-quartz veins   36a-1
    Homestake Au   36b
    (Serpentine-hosted asbestos)   (8d)
    (Gold on flat faults)   (37b)

L. DERIVED MAINLY FROM PELITIC AND OTHER SEDIMENTARY ROCKS
    Unconformity U-Au   37a
    Gold on flat faults   37b
    Gneiss-hosted kyanite Au   37c
    Gneiss-hosted epithermal Au   37d
    Disseminated flake graphite   **37f**