

Mineral Resources Program

Compilation of Gallium Resource Data for Bauxite Deposits

Open-File Report 2013–1272

U.S. Department of the Interior
U.S. Geological Survey

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By Ruth F. Schulte and Nora K. Foley

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[Tables are available for downloading at <http://pubs.usgs.gov/of/2013/1272/>]

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Table 2. Ranges and averages of gallium concentrations and calculated tonnages in the major bauxite provinces worldwide, plus average alumina and average total tonnages for deposits within the bauxite provinces.

Table 3. Ranges and averages of gallium concentrations and calculated tonnages for the major bauxite districts worldwide, plus average alumina and average total tonnages for deposits within the bauxite districts.

Conversion Factors

Multiply	By	To obtain
Length		
kilometer (km)	0.6214	mile (mi)
Area		
square kilometer (km ²)	247.1	acre
square kilometer (km ²)	0.3861	square mile (mi ²)
Mass		
metric ton (t)	1.102	ton, short (2,000 lb)

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Abstract

Gallium (Ga) concentrations for bauxite deposits worldwide have been compiled from the literature to provide a basis for research regarding the occurrence and distribution of Ga worldwide, as well as between types of bauxite deposits. In addition, this report is an attempt to bring together reported Ga concentration data into one database to supplement ongoing U.S. Geological Survey studies of critical mineral resources.

The compilation of Ga data consists of location, deposit size, bauxite type and host rock, development status, major oxide data, trace element (Ga) data and analytical method(s) used to derive the data, and tonnage values for deposits within bauxite provinces and districts worldwide. The range in Ga concentrations for bauxite deposits worldwide is <10 to 812 parts per million (ppm), with an average of 57 ppm. Gallium concentrations in lateritic bauxites range from below detection (< 8 ppm) to 146 ppm; the average concentration is 57 ppm Ga. The average Ga concentration for karst bauxite deposits is 58 ppm with a range between <10 to 180 ppm Ga. As a result, there are no substantial differences in gallium concentrations between karst- and laterite-type bauxites. We calculate the range in geologically available Ga in bauxite deposits worldwide between 30 and 82,720 metric tons (t), with an average of 14,909 t.

Introduction

A global compilation of gallium (Ga) concentrations for bauxite deposits worldwide has not been attempted in the literature, in part because of the limited number of scientific investigations reporting Ga as a trace element in bauxite. This report is, therefore, an attempt to bring together reported Ga concentration data into one database to supplement the study of Foley and others (in press) and to also be used as a basis for further research on the distribution and occurrence of Ga in bauxite.

Bauxite deposits are traditionally regarded as economic sources of aluminum (Al). However, bauxite deposits are also important sources of Ga as a byproduct commodity because the close geochemical affinity of Ga to Al enables Ga to substitute easily in rock-forming aluminosilicates such as feldspar (Burton and others, 1959). Gallium also shows an affinity with iron (Fe) and zinc (Zn), which enable it to substitute for these elements in common rock-forming minerals. Gallium can also be found in geochemical association with germanium (Ge), silicon (Si), indium (In), cadmium (Cd), and tin (Sn) (Burton and Culkin, 1978).

The majority of the world supply of Ga metal comes from the mining of bauxite and sediment-hosted lead-zinc (Pb-Zn) resources, the latter of which is not discussed in this manuscript (fig. 1). World primary Ga production in 2012 was estimated by the U.S. Geological Survey (USGS) at 273 metric tons (t), with China, Germany, Kazakhstan, and Ukraine as the leading producers (Jaksula, 2013). This

number is down 7 percent from 292 tons in 2011, owing to a combination of delayed manufacturing processes and a decrease in Ga prices. In the United States, primary recovery of gallium in 2012 was nonexistent. However, the U.S.-based Molycorp Inc. recovered and refined Ga from scrap and impure gallium metal (Molycorp Inc., 2013). Only Ga recovered from bauxite deposits will be covered in this report.

Currently, electronic components with Ga arsenide (GaAs) wafers and (or) Ga nitride (GaN) represent 99 percent of domestic Ga consumption (Jaskula, 2013). Approximately 71 percent of this use is in integrated circuits, whereas optoelectronic devices (including laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells) comprise the remaining 29 percent of Ga consumption (Jaskula, 2013). Gallium is also an important commodity because of its expanding use in applications for thin film photovoltaics, such as copper-In-Ga selenide (CIGS) semiconductors (Foley and others, in press).

Bauxite Deposits

Bauxite is a type of rock that consists of one or more aluminum hydroxide minerals, most notably gibbsite ($\text{Al}(\text{OH})_3$), boehmite ($\gamma\text{-AlO}(\text{OH})$) and diaspore ($\alpha\text{-AlO}(\text{OH})$) (Bárdossy and Aleva, 1990). Diaspore has the same general chemical composition as boehmite but is denser and harder. A typical bauxite rock also contains a mixture of goethite ($\text{FeO}(\text{OH})$), hematite (Fe_2O_3), the clay mineral kaolinite, and a minor amount of anatase (TiO_2).

The formation of bauxites requires intense weathering in tropical or subtropical climates (Bárdossy, 1994). Bauxites typically occur within the thick profiles of laterites, which are formed by the intense subaerial weathering and leaching of aluminosilicate rocks (Bárdossy and Aleva, 1990; Ferenczi, 2001; Retallack, 2010). These bauxites are referred to as lateritic bauxites. The lateritic bauxite horizon can be homogeneous or heterogeneous throughout, with different structures (such as massive or columnar), textures (such as massive or heterolithic), or compositions. The color of the bauxite can vary from almost white to pink, yellow, orange, tan, reddish brown, and brown (Bárdossy and Aleva, 1990). An example of a lateritic bauxite deposit is Weipa in Queensland, Australia (fig. 1, point 1; Anand and others, 1991). Alternately, bauxites may occur in paleokarst depressions as accumulations of clayey material within carbonate (that is, limestone) sequences; these are referred to as karst bauxites (Bárdossy, 1982; Pajović, 2009). Karst bauxites tend to be black to gray in color with admixed organic matter and, occasionally, chemically reduced minerals such as pyrite (Retallack, 2010). The Doğankuzu deposit in Seydişehir, Turkey, is an example of a karst bauxite deposit (fig. 1, point 2; Öztürk and others, 2002). Roughly 88 percent of global bauxite deposits are lateritic bauxites, whereas the remaining 12 percent belong to the karst bauxite group (Bárdossy and Aleva, 1990).

Major world bauxite resources occur in Africa, Australia, South America, and the Caribbean (fig. 1). Guinea hosts the world's largest bauxite reserves at an estimated 15.3 billion metric tons (Mosier, 1986b). The Adoom mine in the Weipa bauxite deposit of Queensland, Australia, reports an estimated 3.2 billion tons of total ore (table 1¹; Taylor and others, 2008). The Darling Range bauxite deposits in Western Australia contain an estimated 900 to 1,000 million metric tons total ore (fig. 1, point 3; Anand and others, 1991; Mosier, 1986b). Important bauxite deposits in South America include Pitinga, Tucuruí, Paragominos, Porto Trombetas, Cataguases, and Poço de Caldas (fig. 1, points 4–9; Bárdossy and Aleva, 1990; Boulangé and Carvalho, 1997; Valetton and others, 1997). Jamaica is the dominant Caribbean bauxite resource, with deposits in Saint Ann, Saint Catherine, Saint Elizabeth, and Manchester Provinces (fig. 1, points 10–13; Bárdossy and Aleva, 1990).

¹ Tables are available for downloading at <http://pubs.usgs.gov/of/2013/1272/>.

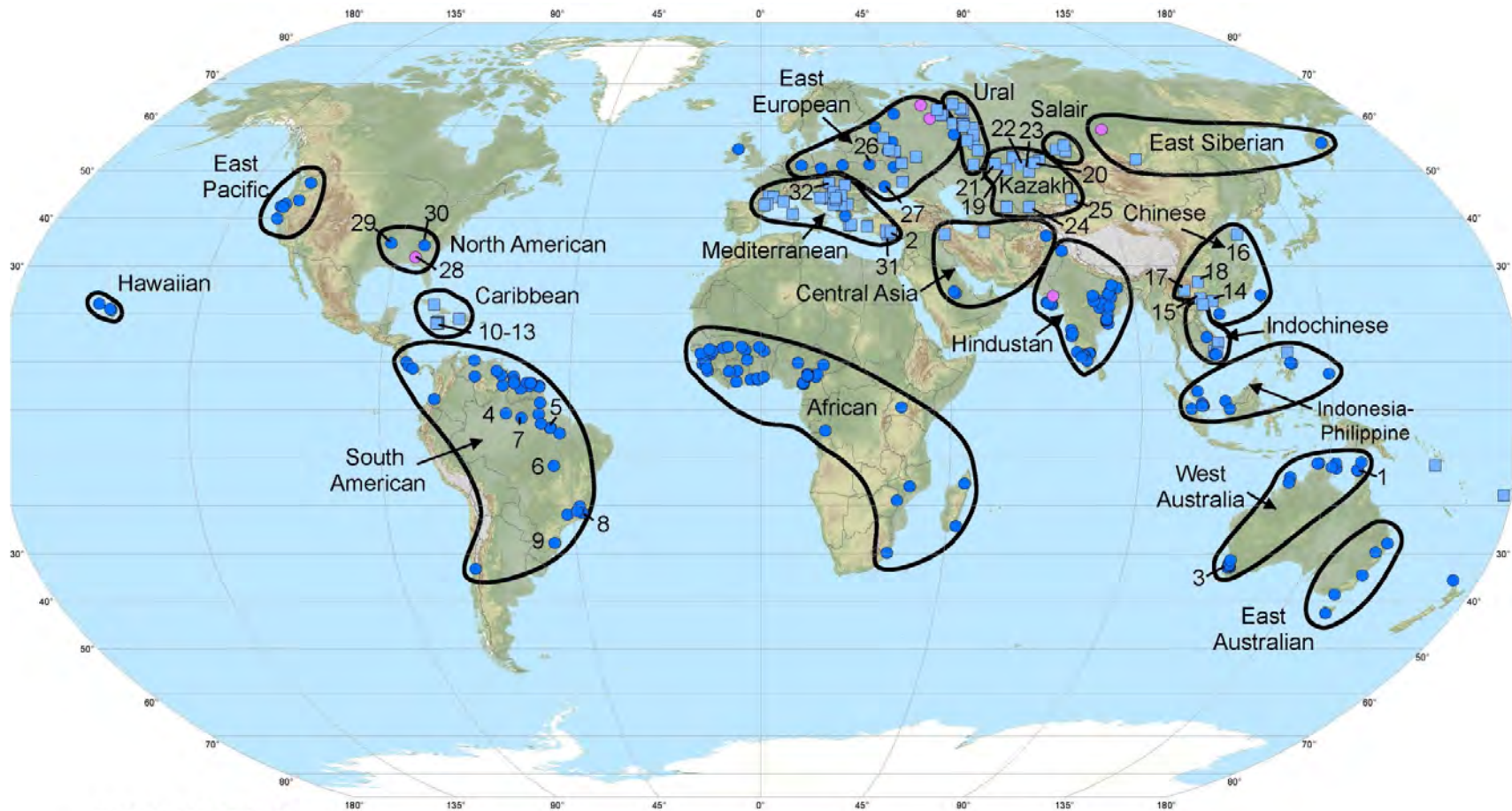
Significant deposits are present in Asia and Europe. In fact, China, Germany, Kazakhstan, and Ukraine were the leading Ga producers in 2012 (Jaksula, 2013). Chinese karst bauxite deposits include Dajia and Xinxu in the Western Guangxi Province (table 1; fig. 1, points 14–15; Wang and others, 2011), as well as lesser deposits at Nanting, Kunmin, and Queyang (fig. 1, points 16–18). Kazakhstan hosts the Arqalyk and Ekisbastoz-Pavlodar bauxite deposits (fig. 1, points 19–20; Bogatyrev and Zhukov, 2009). Other deposits in Kazakhstan include Naurzum, Astana, Aqtas, Shimkent, and Ili (fig. 1, points 21–25). The Pripyat and Vysokopl'ye deposits are the main bauxite resources in Ukraine (fig. 1, points 26–27; Bogatyrev and Zhukov, 2009).

Refined gallium has been processed from an impure form and includes low-grade (99.9 percent pure) gallium (Foley and others, in press; Jaksula, 2013) as well as electronic-grade and high purity gallium (also known as semiconductor grade) that ranges from greater than 99.9 to 99.99999 percent Ga (Bautista, 2003). In 2012, China, Japan, the United Kingdom, and the United States were the primary producers of refined gallium (Jaksula, 2013). Past production of bauxite in the United States occurred at the Eufaula deposit in Alabama (fig. 1, point 28; Clarke, 1966), the Pulaski and Saline deposits in Arkansas (fig. 1, point 29; Gordon and Murata, 1952), and the Hall and Veneer deposits in Georgia (fig. 1, point 30; Ayorinde, 2011). Potential sources of bauxite in the United States have also been identified in Oregon (Hotz, 1964), Washington, and Hawaii (Bogatyrev and Zhukov, 2009).

Gallium Abundance in Bauxite

According to Mordberg and others (2001), the reported concentration of Ga in bauxite ranges from <10 to 160 parts per million (ppm). However, we report a range for bauxite deposits of <10 to 812 ppm, with an average Ga concentration of 57 ppm (table 1). Lateritic bauxites have Ga concentrations that range from below detection (< 8 ppm) to 146 ppm, with an average of 57 ppm. Karst-type bauxite deposits have Ga concentrations that range from 6.3 to 812 ppm, though the upper value is associated with only one deposit; the Maşatdağı deposit in Antalya, Turkey, ranges from 22 to 812 ppm, with an average Ga concentration of 106 ppm (fig. 1, point 31). Therefore, the more realistic typical range for karst bauxite deposits is <10 to 180 ppm, with an average of 58 ppm Ga. This comparison shows that there is no substantial difference in gallium concentrations between karst- and laterite-type bauxites.

In addition, we calculate the average geologically available quantity of Ga in global bauxites to be 14,909 t, with a range from 30 to 82,720 t (table 1). The averages for the bauxite provinces and districts are provided in tables 2 and 3, both of which have been compiled from data reported in table 1.



EXPLANATION

- Both karstic and lateritic
- Karstic bauxite
- Lateritic bauxite

Figure 1. World map showing distribution of bauxite deposits. Major bauxite provinces are identified. Selected deposits are indicated with numbers: 1–Weipa, Australia; 2–Doğankuzu, Turkey; 3–Darling Range, Australia; 4–Pitinga, Brazil; 5–Tucuruí, Brazil; 6–Paragominos, Brazil; 7–Porto Trombetas, Brazil; 8–Cataguases, Brazil; 9–Poço de Caldas, Brazil; 10–Saint Ann, Jamaica; 11–Saint Catherine, Jamaica; 12–Saint Elizabeth, Jamaica; 13–Manchester, Jamaica; 14–Dajia, China; 15–Xinxu, China; 16–Nanting, China; 17–Kunmin, China; 18–Queyang, China; 19–Arqalyk, Kazakhstan; 20–Ekisbatov-Pavlodar, Kazakhstan; 21–Naurzum, Kazakhstan; 22–Astana, Kazakhstan; 23–Aqtas, Kazakhstan; 24–Shimkent, Kazakhstan; 25–Ili, Kazakhstan; 26–Pripyat, Ukraine; 27–Vysokopl'ye, Ukraine; 28–Eufaula, United States; 29–Pulaski-Saline, United States; 30–Hall-Veneer, United States; 31–Maşatdağı, Turkey; 32–Ishkaszentgyörgy, Hungary.

Limitations of the Gallium Data Compilation

Criteria used to identify bauxite deposits worldwide were based on the classifications assigned to the deposits in the literature. Owing to the limited number of publications reporting Ga concentrations, only those deposits with publicly accessible Ga concentration information were included in table 1. Some deposits are not presented in the Ga compilation despite their prominence as producers of Al ore (for example, Iszkaszentgyörgy, Hungary (fig. 1, point 32); Saint Ann, Jamaica; and Vysokopl'ye, Ukraine) because published Ga concentration data are not available for those deposits. Some of the published reports cited in table 1 are from the previous century and have not been recently updated; however, the data in table 1 are thought to be representative of Ga concentrations in bauxite.

In addition, some deposits with published Ga concentrations that are reported in table 1 may not be currently mined. These deposits may be in the exploration phase or have ceased operations altogether. Therefore, where possible, indication as to the production status for each deposit is also listed in table 1. Past producers are deposits that are no longer actively mined for bauxite ore. Reasons for the cessation of mining activity include depletion of resources, political instability, and issues with infrastructure (Bárdossy and Aleva, 1990). Deposits identified as prospects are those that are incompletely explored or lack complete mineral inventories. Those deposits listed as producers are currently being mined for bauxite, whereas those listed as occurrences are those that have been identified but not evaluated for their economic potential.

Data Fields

The attributes within the tables are defined in the following subsections.

Country

The most commonly used names and spellings for countries are provided in table 1. Where more than one country contains the extent of the bauxite deposit, the names of all countries are listed and separated by a comma.

Bauxite Province and District

Bauxite provinces are large territories (from a few hundred to a few million square kilometers) with relationships to large tectonic units. Ancient and young platforms, continental shields, island arcs and foldbelts, and active continental margins are the major criteria used to define bauxite provinces in which several bauxite districts and deposits locally occur (Bárdossy and Aleva, 1990). Bauxite deposits may differ in age and origin within one province (Bogatyrev and Zhukov, 2009).

Bogatyrev and Zhukov (2009) defined the following bauxite provinces, listed from west to east and south to north: (I) East Pacific, (II) North American, (III), Caribbean, (IV) South American, (V) African, (VI) Mediterranean, (VII) East European, (VIII) Ural, (IX) Kazakh, (X) Central Asian, (XI) Salair, (XII) East Siberian, (XIII) Hindustan, (XIV) Chinese, (XV) Indochinese, (XVI) Indonesian-Philippine, (XVII) West Australian, (XVIII) East Australian, and (XIX) Hawaiian. Bárdossy and Aleva (1990) also included Southeast Asia as a lateritic bauxite province. The identification of metallogenic provinces provides an opportunity to study the localization of bauxite ore deposits, which may assist in forecasting and prospecting presently unidentified resources.

Whereas a province consists of closely spaced bauxite districts and deposits that occur in the same tectonic regime and are of similar age (Bárdossy and Aleva, 1990), bauxite districts are smaller than provinces and range from 100–200 kilometers in length and 10–20 kilometers in width (Bogatyrev and Zhukov, 2009). In addition, bauxite districts may consist of one or more orebodies that have similar geological characteristics (Bárdossy and Aleva, 1990). The orebodies may have a simple morphology, such as sheetlike, mantlelike, lenticular, or funnel shaped; or, the orebodies may be split and convoluted. Neighboring bauxite deposits with different geological features are regarded as separate bauxite districts. Isolated districts are identified by the name of the bauxite deposit according to the classification system of Bárdossy and Aleva (1990).

Deposit

The names of the deposits within the bauxite provinces and districts are given in table 1. A bauxite deposit is continuous in space and fundamentally composed of bauxite and genetically related rocks, such as siliceous bauxite, ferriferous bauxite, or bauxitic laterite. A bauxite deposit may consist of one or more orebodies.

Mine

The names of the individual orebodies from which the bauxite ore is mined are provided when the literature specifies the exact location of the samples used to determine concentration data.

Bauxite Type and Host Rock

Depending on the type of host rock, bauxites are classified as either laterite or karst. Laterite bauxites result from the intense subaerial weathering of aluminosilicate rocks (Bárdossy and Aleva, 1990; Ferenczi, 2001; Retallack, 2010), such as granite, gneiss, basalt, syenite, and shale. Karst bauxites form in paleokarst depressions within carbonate sequences, such as limestone or dolomite (Bárdossy, 1982; Pajović, 2009). Detailed petrologic descriptions are provided for the host rock where descriptions are available in the literature.

Development Status

Categories are those listed at the end of the preceding section “Limitations of the Gallium Data Compilation.”

Location

The geographic location (latitude-longitude) of each deposit is listed. The latitude and longitude coordinates are in decimal format, which were calculated from degrees, minutes, and seconds based on published location data cited in table 1 and (or) identification using Google Earth Pro, an advanced commercial 3D interactive virtual globe, map, and geographical information program (Google, 2013). Google Earth Pro maps the Earth by superimposing images obtained from satellites, aerial photography and geographic information system (GIS) 3D globe; this enables users to pinpoint the latitude and longitude of a specific location, such as a building within a city, a mountain peak, or an open pit mine. Images used by Google Earth Pro 2013 include those provided by TerraMetrics, Digital Globe, Map Link, USGS, and Cnes/Spot Image. Data sources for Google Earth Pro 2013 include the U.S. Department of State, Scripps Institution of Oceanography (SIO), National Oceanic and Atmospheric Administration (NOAA), U.S. Navy, National Geospatial Agency (NGA), and General Bathymetric Chart of the Oceans (GEBCO). Southern latitudes and western longitudes are given as negative values.

Size

Where possible, the estimated size of the bauxite deposit or province is given. Estimates regarding the size of bauxite deposits are difficult to obtain because of their extensive distribution across several orebodies, only some of which may be mined.

Major Oxide Compositions

Major oxide concentrations of ore for Al_2O_3 , Fe_2O_3 , CaO , Na_2O , and K_2O are provided in table 1. Compositional data are reported in weight percent (wt%). Where data are available, the range and average concentrations for each major oxide are listed. The abbreviation “n” represents the number of data points used to determine the range and average values. Error is provided in percent when reported.

Trace Elements

Although more complete trace element concentrations have been reported for bauxite deposits (for example, see Patterson and others, 1986), Ga is the only trace element reported here. Gallium compositional data are expressed in parts per million (ppm); the abbreviation “n” represents the number of data points used to determine the range and average values.

Tonnage

The tonnage for the total ore in a listed bauxite deposit is reported where data are available. These values are estimates provided in the literature and reflect the estimated tonnage associated with the lowest cutoff grades (Cox and Singer, 1986). Using the total tonnage and average Ga concentrations, the amount of Ga available in the deposits has been calculated and is reported in metric tons. The same calculation has been done with the average alumina (Al_2O_3) concentration, although the average alumina tonnage is reported in million metric tons.

Analytical Method

Various analytical techniques have been used to determine the concentration of gallium in bauxite. Early work involved techniques such as Hilger quartz spectrography (for example, Wolfenden, 1965) and rhodamine B fluorometry (for example, Chowdhury and others, 1965). Hilger quartz spectrography is a spectrophotometric technique using quartz prisms and lenses that enables the whole spectrum to be photographed; rhodamine B fluorometry is a spectrophotometric technique that uses the chemical compound rhodamine B as a tracer dye (Potts, 2003). Rhodamine S and crystal violet also have been used as colorimetric reagents for gallium (Thakur and Sant, 1972).

Atomic absorption spectrometry (AAS) has been known as an analytical technique since the first quarter of the 19th century (Potts, 2003). However, practical instrumentation was not successfully developed until the 1960s after the pioneering work of Walsh (1955) and Alkemade and Milatz (1955). Pattan and Appangoudar (1988) is one example of a bauxite study that reports major and trace element concentration data (including gallium) obtained by using AAS (table 1).

Neutron activation analysis (NAA) has also been applied to the geochemical analysis of bauxites (for example, see Chen and Tsai, 1983). NAA involves “activation” of the samples by irradiation with neutrons in a nuclear reactor, after which samples are removed and allowed to decay or “cool” (Potts, 2003). This procedure enables unwanted short-lived radioactivity to dissipate. After cooling, the measurement of gamma-ray spectra is made by using solid-state germanium gamma-ray detectors.

Accuracy of determining ^{68}Ga has been shown to improve with an increase in the cooling period (Tustanovskii and others, 1968). The limit of determination is reported to be ± 6 percent (Tustanovskii and others, 1968).

X-ray fluorescence (XRF) became a standard instrumental technique for trace element geochemistry in the 1950s and 1960s with the advent of commercial instrumentation (Potts, 2003). Unlike AAS, XRF has the benefit of analyzing multiple elements at the same time, and this increases the speed at which samples can be analyzed. The XRF technique uses X-ray radiation to excite electrons in pressed powdered pellets or fused glass discs and then measures them in an X-ray spectrometer; the detection limit of Ga for pellets is 6 ppm (Potts, 2003). The work by Valeton and others (1991) in the Cataguases bauxite deposit, Brazil, is an example of trace element geochemical data obtained by XRF (table 1).

Inductively coupled plasma atomic emission spectrometry (ICP-AES), also known as inductively coupled optical emission spectrometry (ICP-OES), is an optical emission spectrometry analytical technique that employs argon gas as an emission source for spectrographic measurements (Potts, 2003). The advantage of ICP-AES over AAS is the ability to measure multiple elements simultaneously. However, all samples must be reproducibly dissolved in order to analyze them by using ICP-AES (unlike XRF, which only requires powdered pellets for analysis). Hieronymus and others (2001) analyzed bauxites from the Bamiléké Plateau, Cameroon, and the Pará state of Brazil using both AAS and ICP-AES (table 1).

Electron microprobe analysis (EPMA) differs from other analytical techniques in that areas of a sample can be examined that are as small as a few micrometers in diameter, which requires that specimens be prepared as polished thin sections mounted on a glass slide or within a resin block (Potts, 2003). As a result, the composition of individual minerals or compositional variations within a single mineral grain can be obtained. For example, Valeton and others (1987) analyzed karst bauxites and associated lithologies from the Parnass Khiona region deposit in Greece by using EPMA, which enabled them to evaluate the degree of contamination by weathered debris, the paleogeography of the region, the transport of the detrital source material and depositional environment, and the amount of chemical alteration during diagenesis and epigenesis.

Inductively coupled plasma-mass spectrometry (ICP-MS) is a type of mass spectrometry in which the sample is taken up into solution and subsequently atomized and ionized in an argon plasma. The detection limits of trace element concentrations by using ICP-MS can reach as low as one part in 10^{12} (parts per trillion) (Potts, 2003). Compared to AAS, ICP-MS has the ability to simultaneously measure multiple elements, which increases the speed at which analyses can be done. Horbe and Anand (2011), for instance, used ICP-MS to measure the major and trace element data of bauxites from the Boddington deposit of the Darling Range in Western Australia and the Pitinga deposit in the Amazon District of Brazil (table 1).

In this report, the analytical method used to determine the Ga concentration of the bauxites is listed where information is available. However, not all research articles report their analytical methods. In those cases, the column cell is left blank.

Summary

Although bauxite deposits are traditionally mined for their Al content, they are also important sources of Ga as a byproduct commodity. Bauxite deposits occur worldwide due to intense weathering in tropical or subtropical climates. Depending on the type of host rock, such as aluminosilicate or carbonate, bauxites are classified as either laterite or karst, respectively. However, based on our extensive dataset, there is no substantial difference in Ga concentrations between laterite and karst bauxite deposits. As a result, either type of bauxite could be a potential source of Ga for subsequent refinement and use in modern technological applications.

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