

on current and previous producer reports as well as employment hours published by the U.S. Mine Safety and Health Administration.

World production of kaolin was an estimated 42 Mt in 2019, no change from 2018. The United States continued to lead the world in the production of refined kaolin, followed by Uzbekistan, Germany, India, Czechia, China, Ukraine and Brazil.

## Consumption

The major domestic markets for kaolin were, in descending order of tonnage, paper coating (31 percent of domestic sales); miscellaneous ceramics (16 percent); refractory products (15 percent); paint (8 percent); and catalysts, rubber and miscellaneous fillers, extenders and binders (about 6 percent each). Smaller but significant domestic markets were adhesives, chemical manufacture, floor and wall tile, heavy-clay products (brick and portland cement), paper filling, plastics and sanitaryware. The leading export markets for kaolin were paper coating and filling.

## Prices

The average unit value of kaolin in 2019 was estimated to be \$158/t, a slight increase from an estimated \$156/t in 2018. Unit values for individual kaolin types ranged from an estimated \$40/t for unprocessed kaolin to \$170/t for calcined kaolin. Estimated prices for kaolin from Georgia ranged from \$35 to \$900/t. The average free-alongside-ship value

of exported kaolin was \$242/t in 2019, a slight increase from \$238/t in 2018, and the average customs value of imported kaolin was \$125/t, up from \$120/t.

## Foreign trade

Kaolin exports declined by 5 percent in 2019 to 2.27 Mt valued at \$550 million from 2.38 Mt valued at \$567 million in 2018. China received 19 percent of the U.S. export tonnage, followed by Mexico (18 percent), Japan (13 percent), Finland (7 percent), Canada (6 percent) and Taiwan (5 percent). Imports of kaolin totaled to 321 kt valued at \$40 million, an increase of 8 percent from 297 kt valued at \$35.5 million during the prior year. Nearly all of the imported kaolin (92 percent) originated in Brazil. Based on entry and departure ports, refractory kaolin may have been exported under the category for fire clay, and some imports from Brazil were likely destined for paper plants in Canada.

## Outlook

Measures instituted to mitigate the spread of the COVID-19 pandemic, such as closures of nonessential businesses, are likely to cause disruptions in the mining industry across the United States and around the world. The duration and the outcome of the COVID-19 pandemic remains uncertain, but it is expected that the economies of the United States and the world as a whole will likely be negatively affected, which could influence the performance of the kaolin industry.

## KYANITE, ANDALUSITE AND SILLIMANITE

by William L. Lassetter, Geology and Mineral Resources Program, Virginia Department of Energy

Kyanite, andalusite and sillimanite are naturally occurring polymorphic minerals that have the same chemical composition,  $\text{Al}_2\text{SiO}_5$ , but differ in their crystal structures and thermodynamic properties. Collectively, they are often referred to as the sillimanite minerals group. The minerals are characterized by high alumina content, about 63 percent  $\text{Al}_2\text{O}_3$  in the pure mineral state, and are valued in high-temperature industrial applications that require refractory products to retain strength, and increase thermal and chemical stabilities. Treatment by calcination produces the mineral mullite,  $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ , which is a closely related aluminum silicate that occurs rarely in nature with no known commercial deposits. Pure mullite has higher alumina content, about 72 percent  $\text{Al}_2\text{O}_3$ , and physical properties that add flexural and compressive strength at very high temperatures in ceramics. Exceptional natural specimens of kyanite, andalusite and sillimanite are valued in the gemstone industry and for their purported metaphysical properties.

## Geology and economic deposits

Kyanite, andalusite and sillimanite typically occur as accessory minerals in metamorphic rocks derived

from aluminous protoliths, often making up several percent of the mineral composition of pelitic gneisses and schists. The occurrence and predominance of one of the polymorphic minerals over another reflects the stability field of each mineral, defined by the pressure and temperature conditions under which the metamorphic rock formed. Andalusite is stable in rocks formed under relatively low pressure and low to moderate temperature conditions. In regional metamorphic terrains formed under high temperature with low to moderate pressure conditions, sillimanite is often the predominant mineral form. Kyanite has the densest crystal structure of the polymorphs and is stable in rocks formed under relatively high pressure and low to high temperature conditions.

Economic mineral concentrations occur in several main deposit types. Massive and semimassive aggregates are found in thermally altered rocks such as hornfels within contact metamorphic aureoles adjacent to intrusive stocks. Stratiform replacement deposits occur in silica-rich metasedimentary and metavolcanic strata that in some cases were primed by hydrothermal alteration, resulting in alumina enrichment. Sillimanite minerals may also occur in pegmatites and mineralized quartz veins. The specific

gravity of the mineral group ranges from about 3.2 to 3.7 (compared to about 2.65 for quartz sand), so these minerals may be concentrated in heavy mineral placer deposits found in beach sands and other unconsolidated sediments.

In the United States, economic and subeconomic concentrations of kyanite, andalusite and sillimanite occur in the Appalachian regions of Alabama, Georgia, North Carolina, South Carolina and Virginia. Other known geologic occurrences are in Alaska, California, Florida, Idaho, Nevada and New Mexico. Outside of the United States, economic deposits occur in Australia, Brazil, Cameroon, Canada, China, Finland, France, India, Ireland, Kenya, Madagascar, Nigeria, Norway, Peru, Russia, South Africa, Spain, Ukraine and Zimbabwe.

## Industrial properties and uses

The sillimanite group minerals are used primarily in refractory products that are essential in metallurgical, glass manufacture and ceramics industries. Refractories provide volumetric stability, resistance to thermal shock, low thermal conductivity, electrical insulation, and resistance to chemical corrosion. Kyanite, andalusite and sillimanite convert to mullite and silica glass at decomposition temperatures ranging from about 1,250 to 1,650 °C. The percent volume expansion during the conversion is both predictable and irreversible. Calcined kyanite will expand in volume by an amount that is dependent on the initial particle size. Very fine particles (325 mesh, 0.044 mm) increase volumetrically by about 3 percent, while coarser particle fractions (35 mesh, 0.5 mm) can potentially expand by about 25 percent. Calcined andalusite and sillimanite expand in volume by about 5 to 7 percent. Below temperatures of decomposition, the minerals have relatively low coefficients of thermal expansion. Synthetic mullite has an even higher thermal resistance (melting point about 1,840 °C), and crystallizes in interlocking forms with a high aspect ratio that enhances the mechanical strength of ceramic products.

The global iron and steel manufacturing industry requires refractories that consume as much as 70 percent of the annual supply of sillimanite minerals produced by mining operations. Refractory products include firebrick, insulating brick, furnace and ladle lining materials, castables and mortar, among other high-performance heat- and corrosion-resistant materials. Industrial ceramics and glass manufacture consume most of the remaining annual supply of refractory minerals for kiln furniture, investment casting, monolithics, porcelain and sanitaryware. Other important end-use products include additives and fillers, electrical insulators, ceramic tiles, brake shoes and spark plugs.

## Mineral production

The global supply of sillimanite group minerals comes mainly from mining operations located in France, India, Peru, South Africa and the United

States. Refractory minerals are also mined in Australia, China, Madagascar and Nepal, but little information is readily available regarding annual tonnages, mine capacities, mineral

grades, and domestic versus export markets. Annual world production estimates reported by the U.S. Geological Survey (USGS) over the five years from 2016 to 2020 average about 382 kt. During 2021, global production was roughly estimated to be 473 kt, an increase of about 24 percent over the previous five-year average. This total includes 190 kt of andalusite from South Africa, 105 kt of kyanite and calcined kyanite from the United States, 65 kt of andalusite from France, 40 kt of andalusite from Peru and 73 kt of combined sillimanite and kyanite from India (including reclassified beach sand mineral deposits).

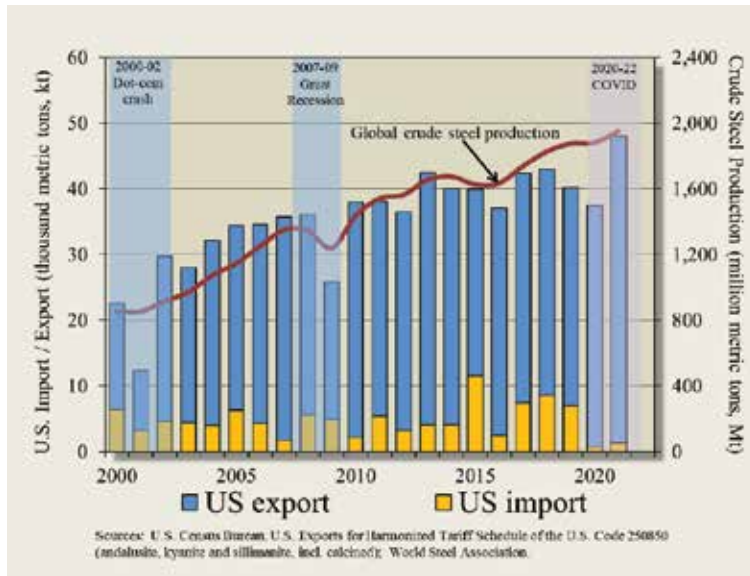
In the United States, Kyanite Mining Corp. (KMC) is the world's largest producer of industrial-grade kyanite and calcined kyanite marketed under the trademark names Virginia Kyanite and Virginia Mullite, respectively. The company has been in continuous operation since 1945, producing kyanite products from surface mines and processing facilities in central Virginia. KMC reported production of about 105 kt of combined kyanite and calcined kyanite during 2021, up significantly from about 67 kt (revised) reported in 2020. Ores extracted at the Willis Mountain and East Ridge Mines, near Dillwyn, consist of kyanite quartzite rocks associated with a sequence of interlayered metamorphosed felsic and mafic volcanic strata of Ordovician age. The two mine areas are located on opposing limbs of the Whispering Creek Anticline where the kyanite quartzite host rocks stand out as resistant topographic ridges. Ore-grade material contains 10 to 40 percent kyanite, averaging about 25 percent. The annual production capacity at the Virginia operations is about 130 kt for commercial-grade kyanite concentrates. The company markets a range of milled kyanite and calcined kyanite (more than 55 percent  $Al_2O_3$ , less than 0.85 percent  $Fe_2O_3$ ) products that are shipped mainly by truck to domestic customers and port facilities for delivery to international customers.

In Hillsborough, NC, Resco Products Inc. (Piedmont Minerals Division) produces refractory mineral products from deposits of pyrophyllite ( $AlSi_2O_5(OH)$ ) ore containing 15 to 20 percent

**Figure 1**  
Kyanite quartzite from the Baker Mountain deposit, Prince Edward Co., VA. (Photo by J. Wyman)



**Figure 2**  
Sillimanite minerals foreign trade and global steel production.



disseminated andalusite. The company has been in continuous operation since 1958. The mineralized zones formed in structurally controlled, hydrothermally altered andesitic to dacitic metavolcanic rocks that are part of the Proterozoic-age Carolina terrane. The company produces high-purity alumina and silica mixes used in castable refractory formulations, high-alumina brick and specialty mineral products serving the foundry and ceramic industries.

The global supply of industrial-grade andalusite for the refractories industries comes mainly from deposits located in France, South Africa and Peru. Imerys Group, headquartered in Paris, is the world's leading producing company. Imerys' Kerphalite Mine, located just south of Glomel in northwestern France, has been in operation since the mid-1960s producing andalusite from deeply weathered Ordovician-age schists proximal to granitic rocks of the Armorican Massif. Imerys Group markets sieved and milled andalusite products ranging in minimum alumina content from 53.6 to 60.8 percent  $Al_2O_3$  under the trademarked name Kerphalite. Kerphalite KF is a premium-grade product with low  $Fe_2O_3$  content (less than 0.45 percent) for use as specialty foundry sand in moulding processes, in ceramics, and other refractory applications.

In South Africa, Imerys' active andalusite production operations include the Annesley Mine in the Lydenburg District, Mpumalanga Province, and the Rhino Mine near Thabazimbi in western Limpopo Province. These deposits occur in highly weathered pelitic rocks of the Pretoria Group within the contact metamorphic aureole of the Bushveld Igneous Complex. Imerys markets a range of size-classified products under the trademarked names Durandal, Randalusite and Purusite. Annual production tonnages and capacities for the individual Imerys mine sites are not readily available.

In northern Peru, Andalucita S.A. recovers andalusite from alluvial sediments in surface mining operations located about 14 km south of the port of Paita. The company markets products ranging from fine (0 to 1 mm) premium-grade andalusite (58.5 percent  $Al_2O_3$ , less than 0.75 percent  $Fe_2O_3$ ) to coarse (3 to 6 mm) premium-grade (58 percent  $Al_2O_3$ , less than 1 percent  $Fe_2O_3$ ) in 25-kg bags up to bulk quantities. The company reports annual production capacity at about 60 kt, with mineral reserves that will extend for decades.

Andalusite Resources (Pty) Ltd. began mining operations in 2001 at the Maroeloesfontein Mine near Thabazimbi in Limpopo Province, South Africa. The deposit is located about 13 km southwest of Imerys' Rhino Mine. The company reports annual production capacity in excess of 70 kt, with reserves amounting to about 100 years of mining at that annual rate. Following a period of intermittent operations in 2019–2020 due to financial distress, the company developed a business rescue plan in accordance with procedures of the S.A. Companies and Intellectual Property Commission. As of November 2021, the company remained in Section 11 Suspensive Condition under the business rescue plan.

With vast resources of sillimanite, India is the primary source in the global supply chain for this refractory mineral. The Indian Bureau of Mines has estimated total resources of over 70.2 Mt of sillimanite, which includes about 6.5 Mt in the reserves category. About 73 percent of the total resource is classified as high-grade granular material that occurs in heavy mineral beach sand deposits also containing ilmenite, rutile, zircon, garnet and monazite resources. Official production statistics for 2021 are not presently available. One of the largest producers in the state of Andhra Pradesh is Trimex Sands Private Ltd., which has capacity to recover about 50 kt of sillimanite per year at the Srikurmam Mineral Sands Project.

Other sillimanite mining operations are located in Odisha, Kerala and Maharashtra. The Indian Bureau of Mines also estimated about 105 Mt of kyanite resources in the country, of which less than 2 percent are classified as medium to high grade. During 2019–2020, total production of about 4 kt of kyanite (more than 40 percent  $Al_2O_3$ ) was reported by three principal producers located in Maharashtra and Karnataka. Estimated andalusite resources, classified in the "reconnaissance" category, stand at about 28.2 Mt. There has been no reported production of andalusite since 1988.

## Foreign trade and prices

Sales prices for imported and exported minerals vary depending upon many factors, including quantity, grade and purity, particle (mesh) size, packaging, monetary exchange rates, source and destination.

During 2021, the U.S. Census Bureau reported exports of about 48 kt of combined andalusite, kyanite and sillimanite refractory minerals, a record level (Fig. 2). The average value of these exports was about \$368/t, essentially unchanged from the previous year. The United States also exported about 27 kt of mullite, which includes calcined kyanite, with an average value of about \$430/t. Imports of sillimanite minerals to the United States during 2021 were less than 1.4 kt, and were valued at about \$492/t. Fastmarkets assessed the price range of andalusite, 57 percent  $Al_2O_3$  minimum, on a cost, insurance and freight (CIF) Europe basis, at about \$413 to 519/t. The average export price of sillimanite produced in India reported in 2019–2020, 56 to 60 percent  $Al_2O_3$ , on a free-on-board (FOB) basis, was about \$189/t.

## Trends and outlook

The global production statistics of the steel manufacturing industry, as the predominant consumer of refractory mineral products, are a reliable indicator of market demand and the final destination of sillimanite minerals. According to the World Steel

Association (WSA), global steel production in 2021 increased by about 3.8 percent over the output reported in 2020. Total produced crude steel was about 1,952 Mt. (Fig. 2). By far the largest producing country in 2021 was China, reporting about 1,033 Mt, or about 53 percent of global output. The United States ranked fourth in crude steel production with 85.8 Mt, up about 18 percent from 2020. Steel production in the EU countries totaled 152.5 Mt, up 15 percent for the region compared to 2020.

The recovery of the steel industry in 2021 following production impacts from the global pandemic may be tempered in the upcoming years by new uncertainties around inflation risks, increased energy costs, enormous increases in ocean freight rates, and the war in Ukraine.

The WSA short-term outlook projects muted growth rates of 0.4 percent in 2022 and 2.2 percent in 2023. From a regional perspective, positive demand for mineral refractories is likely to continue in Africa, Asia and North America, but markets in the European Union remain quite uncertain with the war being a big factor. *Source citations available from the author.*

## LIME

by L.E. Apodaca, National Minerals Information Center, U.S. Geological Survey

In 2021, all commercially produced lime in the United States was manufactured from limestone or dolomite, but lime also can be produced from a variety of similar carbonate materials, such as aragonite, chalk, coral, marble and seashells, if they are of high chemical purity. The term lime in this report refers to high-calcium and dolomitic quicklime, their hydroxide (hydrated) forms and dead-burned dolomite.

In the United States, most lime (about 83 percent) is produced as quicklime. Hydrated lime, also called slaked lime, is a dry calcium hydroxide powder made from reacting quicklime with a controlled amount of water in a hydrator. Slaked lime is widely used in aqueous systems as a low-cost alkali to neutralize or balance acidity. Dead-burned dolomite is the primary form of lime used in refractories.

## Production and consumption

In 2021, an estimated 17 Mt of quicklime and hydrate was produced (excluding independent commercial hydrators), an increase of about 8 percent from that of 2020. At the end of the year, 28 companies were producing lime, including 18 companies with commercial sales and 10 companies that produced lime strictly for internal use (for example, sugar companies). These companies had 73 primary lime plants (plants operating quicklime kilns) in 28 states and Puerto Rico. Five of these 28 companies operated only hydrating plants in nine states. In 2021, the five

leading U.S. lime companies produced quicklime or hydrate in 22 states and accounted for about 78 percent of total U.S. lime production. Principal producing states were, in alphabetical order, Alabama, Kentucky, Missouri, Ohio and Texas. The United States was the world's second-ranked lime producer in the world after China.

Apparent consumption at 17 Mt was estimated to have increased by 7 percent from that of 2020. Major markets for lime were, in descending order of consumption, steelmaking chemical and industrial applications (such as the manufacture of fertilizer, glass, paper and pulp, and precipitated calcium carbonate and in sugar refining), flue-gas treatment, construction, water treatment and nonferrous-metal mining.

## Foreign trade

Imports of lime increased by 5 percent to 323 kt in 2021 from 308 kt in 2020. Canada (88 percent) and Mexico (7 percent) were the leading sources of U.S. lime imports. U.S. lime exports increased by 26 percent to 335 kt in 2021 from 266 kt in 2020. Lime exports were primarily shipped to Canada (96 percent).

## Prices

The U.S. Geological Survey calculates unit values of lime products from the quantity and value data reported for lime sold or used by the lime producers