Nevada. About 52 percent of all kaolin sold was water-washed, followed by airfloat (16 percent); calcined (15 percent); delaminated (12 percent); and unprocessed (5 percent). Production data were estimated based on current and previous producer reports as well as employment hours published by the Mine Safety and Health Administration.

World production of kaolin was an estimated 42 Mt in 2019, unchanged 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 321 kt valued at $40.0 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
In December 2019, an outbreak of a novel coronavirus (COVID-19) was first identified in China. The World Health Organization declared that COVID-19 was a global pandemic on March 11, 2020. 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 are naturally occurring polymorphic minerals that have the same chemical composition, Al₂SiO₅, yet differ in their crystal structures and thermodynamic properties. These minerals, collectively referred to as the sillimanite minerals group, are valued for their high alumina content, about 62.9 percent Al₂O₃, and thermal and chemical stability in high-temperature industrial applications. The mineral mullite, Al₆Si₂O₁₃, is a closely related aluminum silicate with even higher alumina content, about 71.8 percent Al₂O₃, and physical properties that add flexural and compressive strength at very high temperatures in ceramics. Mullite occurs rarely in nature with no known commercial deposits, but synthetic formulations are produced when sillimanite minerals are calcined. Apart from industrial uses, exceptional natural specimens of kyanite, andalusite and sillimanite are highly valued in the gemstone jewelry industry and for their reported metaphysical properties.

Geology and economic deposits
Kyanite, andalusite and sillimanite occur as accessory minerals in metamorphic rocks derived from aluminous protoliths, typically making up a percent or two of the mineral composition of pelitic gneisses and schists. The predominance of one of the polymorphic minerals over another reflects the distinct stability fields 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. These include hornfels and other thermally altered pelitic rocks within contact metamorphic aureoles. In

www.miningengineeringmagazine.com
Industrial properties and uses

In metallurgical, glass manufacture and ceramics industries, the intrinsic refractory properties of kyanite, andalusite and sillimanite provide volumetric stability, resistance to thermal shock, low thermal conductivity, electrical insulation and resistance to chemical corrosion. The minerals convert to mullite and silica at decomposition temperatures ranging from about 1,250°C for kyanite, 1,450°C for andalusite, and 1,650°C for sillimanite. 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 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 6 percent and 4 percent, respectively. 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 consumes as much as 70 percent of the annual supply of sillimanite minerals produced by mining operations. The minerals are used in refractories for firebrick, insulating brick, furnace and ladle lining materials, castables, mortar and many other high-performance heat- and corrosion-resistant products. Industrial ceramics and glass manufacture consume most of the remaining 30 percent of the annual supply, for kiln furniture, investment casting, monolithics, porcelain and sanitaryware, among other refractory materials. Other important end products include refractory additives and fillers, electrical insulators, ceramic tiles, brake shoes and spark plugs.

Global production highlights

The global supply of sillimanite minerals has historically come from mining operations in France, India, Peru, South Africa and the United States. The U.S. Geological Survey (USGS) estimated global production in 2019 to be more than 430 kt including about 190 kt of andalusite from South Africa, 91 kt of kyanite and calcined kyanite from the United States, 110 kt of combined sillimanite and kyanite from India, and 40 kt of andalusite from Peru (Ghalayini, 2020). Although there are no official mining statistics available for operations in China, estimates based on known geologic resources and company marketing materials indicate annual production of less than 50-60 kt of combined sillimanite minerals annually.

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 operates surface mines and processing facilities at the Willis Mountain mining complex near Dillwyn, VA. Ores extracted at the Willis Mountain and East Ridge quarries consist of kyanite-quartzite rocks associated with a sequence of interlayered metamorphosed felsic and mafic volcanic strata of Ordovician age. These rocks are mapped as part of the Chopawamsic Formation in Virginia’s central Piedmont geological province. Ore-grade material contains 10 to 40 percent kyanite, averaging about 25 percent. The quarries, located about 1.25 miles apart east to west, are situated on opposing limbs of the Whispering Creek Anticline, where the kyanite-quartzite host rocks stand out as resistant topographic ridges. In 2019, the company reported annual production of about 91 kt of combined kyanite (80 percent) and calcined kyanite (20 percent). This represents an increase of about 2 percent over production in 2018. KMC states 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 (>55 percent Al₂O₃, <0.85 percent Fe₂O₃) products that are shipped mainly by truck to domestic customers and
port facilities for delivery to international customers. Exports currently account for about 50 percent of KMC’s sales.

Elsewhere in the United States, Resco Products Inc. (Piedmont Minerals Division), acquired by Wellspring Capital Management LLC in 2011, operates a surface mine located in Hillsborough, NC that extracts pyrophyllite (AlSi$_2$O$_5$(OH)) containing 15 percent to 20 percent disseminated andalusite. The mineralized zones were formed in structurally controlled, hydrothermally altered andesitic to dacitic metavolcanic rocks that are part of the late Precambrian Carolina terrane. The company produces high-purity aluminia and silica mixes used in a range of castable refractory formulations, high-alumina brick, and specialty mineral products serving the foundry and ceramic industries.

Imerys, based in France, is the world’s leading producer of industrial andalusite products for refractories, with major markets located in Western Europe, North America and emerging-market countries. In 2019, Imerys’s Refractory Minerals business sector reported production of andalusite from mines in France and South Africa.

The Kerphalite Mine located just southwest of Glomel, France has been in operation since the 1960s and recovers andalusite from deeply weathered Ordovician-age schists proximal to granitic rocks of the Armorican Massif. Imerys markets andalusite products under the trademarked name Kerphalite KF for use as specialty foundry sand in moulding processes, in ceramics, and other refractory applications. In South Africa, surface mining operations in Mpumalanga Province include the Annesley Mine, north of Burgersfort, and the Rhino Mine at Thabazimbi in Limpopo Province.

In 2019, the former Krugerspost Mine, located about 19 km north of Lydenburg in Mpumalanga Province, remained in final closure and reclamation. These deposits occur in 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 Pursosite. Annual tonnages and capacities for the individual Imerys mine sites are not readily available but, based on the historic trend and apparent market conditions in 2019, production may have been somewhat lower compared to 2018. In its annual financial report for 2019, Imerys reported total mineral reserves for minerals for refractories (proven and probable at worldwide operations) of about 11,803 kt. Estimated total mineral resources (measured, indicated, inferred) for the same product were reported to be about 24,261 kt. These estimates include refractory mineral sources other than andalusite, such as bauxite and refractory clays.

Also in South Africa, Andalusite Resources (Pty) Limited produces milled and run-of-mine andalusite products from surface mine operations at the Maroeoloesfontein Mine located near Thabazimbi in Limpopo Province. The mineral deposit is on strike to the southwest of Imerys’s Rhino Mine. Financial liquidity difficulties caused a month-long suspension of operations starting in June 2019 resulting in the loss of as much as 10 kt of mine output for the year. In 2017, the South African Competition Tribunal rejected a proposed acquisition of the company by Imerys. Andalusite Resources reports annual production capacity in excess of 70 kt, with reserves amounting to about 100 years of mining at that annual rate. The company globally markets a range of fine- and medium-grade products under the trade name Marlusite with average alumina content stated to be >57 percent Al$_2$O$_3$.

In northern Peru, Andalicita S.A. extracts andalusite from alluvial sediments in surface mining operations near the port of Paita. The company markets products ranging from fine (0-1 mm) premium-grade andalusite (58.5 percent Al$_2$O$_3$, <0.75 percent Fe$_2$O$_3$) to coarse (3-6 mm) premium grade (58 percent Al$_2$O$_3$, <1 percent Fe$_2$O$_3$) in 25-kg bags up to bulk quantities. The company reports annual production capacity at about 60 kt, with 100 years of mineral reserves.

With vast resources of sillimanite, India is the primary source in the global supply chain for this refractory mineral. Although production statistics for 2019 are not presently available, the Indian Bureau of Mines has estimated 70.2 kt of sillimanite geologic resources. About 73 percent of this resource is classified as granular high-grade material in heavy mineral-enriched beach sand deposits that also contain ilmenite, rutile, zircon, garnet and monazite resources. During 2017-18, more than 81 kt of sillimanite were produced mainly at four operations located in Andhra Pradesh, Odisha, Kerala and Maharashtra. About 20 percent of the total mineral produced was exported to China, Nepal and Germany, while the remainder served domestic refractory consumers. The Indian Bureau of Mines also estimated about 105 kt of kyanite resources in the country, of which less than 2 percent is classified as medium- to high-grade. During 2017-18, total production of about 8 kt of kyanite (>40 percent Al$_2$O$_3$) was reported by two operations located in Maharashtra. About 2 percent of this was exported, mainly to Greece. Estimated andalusite resources, classified in the reconnaissance category, stand at about 28.2 kt. There has been no reported production of the mineral since 1988.

Several mining operations in China produce sillimanite group minerals mainly for the domestic market. Nanyang Kaiyuan Cyanite Mining Company Ltd., mines kyanite in Nanyang City, south of China's capital city, Beijing. The company also produces sillimanite, andalusite and ilmenite from its Resco Products Inc. (Piedmont Minerals Division), acquired by Wellspring Capital Management LLC in 2011, operates a surface mine located in Hillsborough, NC that extracts pyrophyllite (AlSi$_2$O$_5$(OH)) containing 15 percent to 20 percent disseminated andalusite. The mineralized zones were formed in structurally controlled, hydrothermally altered andesitic to dacitic metavolcanic rocks that are part of the late Precambrian Carolina terrane. The company produces high-purity aluminia and silica mixes used in a range of castable refractory formulations, high-alumina brick, and specialty mineral products serving the foundry and ceramic industries.

Imerys, based in France, is the world’s leading producer of industrial andalusite products for refractories, with major markets located in Western Europe, North America and emerging-market countries. In 2019, Imerys’s Refractory Minerals business sector reported production of andalusite from mines in France and South Africa.

The Kerphalite Mine located just southwest of Glomel, France has been in operation since the 1960s and recovers andalusite from deeply weathered Ordovician-age schists proximal to granitic rocks of the Armorican Massif. Imerys markets andalusite products under the trademarked name Kerphalite KF for use as specialty foundry sand in moulding processes, in ceramics, and other refractory applications. In South Africa, surface mining operations in Mpumalanga Province include the Annesley Mine, north of Burgersfort, and the Rhino Mine at Thabazimbi in Limpopo Province.

In 2019, the former Krugerspost Mine, located about 19 km north of Lydenburg in Mpumalanga Province, remained in final closure and reclamation. These deposits occur in 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 Pursosite. Annual tonnages and capacities for the individual Imerys mine sites are not readily available but, based on the historic trend and apparent market conditions in 2019, production may have been somewhat lower compared to 2018. In its annual financial report for 2019, Imerys reported total mineral reserves for minerals for refractories (proven and probable at worldwide operations) of about 11,803 kt. Estimated total mineral resources (measured, indicated, inferred) for the same product were reported to be about 24,261 kt. These estimates include refractory mineral sources other than andalusite, such as bauxite and refractory clays.

Also in South Africa, Andalusite Resources (Pty) Limited produces milled and run-of-mine andalusite products from surface mine operations at the Maroeoloesfontein Mine located near Thabazimbi in Limpopo Province. The mineral deposit is on strike to the southwest of Imerys’s Rhino Mine. Financial liquidity difficulties caused a month-long suspension of operations starting in June 2019 resulting in the loss of as much as 10 kt of mine output for the year. In 2017, the South African Competition Tribunal rejected a proposed acquisition of the company by Imerys. Andalusite Resources reports annual production capacity in excess of 70 kt, with reserves amounting to about 100 years of mining at that annual rate. The company globally markets a range of fine- and medium-grade products under the trade name Marlusite with average alumina content stated to be >57 percent Al$_2$O$_3$.

In northern Peru, Andalicita S.A. extracts andalusite from alluvial sediments in surface mining operations near the port of Paita. The company markets products ranging from fine (0-1 mm) premium-grade andalusite (58.5 percent Al$_2$O$_3$, <0.75 percent Fe$_2$O$_3$) to coarse (3-6 mm) premium grade (58 percent Al$_2$O$_3$, <1 percent Fe$_2$O$_3$) in 25-kg bags up to bulk quantities. The company reports annual production capacity at about 60 kt, with 100 years of mineral reserves.

With vast resources of sillimanite, India is the primary source in the global supply chain for this refractory mineral. Although production statistics for 2019 are not presently available, the Indian Bureau of Mines has estimated 70.2 kt of sillimanite geologic resources. About 73 percent of this resource is classified as granular high-grade material in heavy mineral-enriched beach sand deposits that also contain ilmenite, rutile, zircon, garnet and monazite resources. During 2017-18, more than 81 kt of sillimanite were produced mainly at four operations located in Andhra Pradesh, Odisha, Kerala and Maharashtra. About 20 percent of the total mineral produced was exported to China, Nepal and Germany, while the remainder served domestic refractory consumers. The Indian Bureau of Mines also estimated about 105 kt of kyanite resources in the country, of which less than 2 percent is classified as medium- to high-grade. During 2017-18, total production of about 8 kt of kyanite (>40 percent Al$_2$O$_3$) was reported by two operations located in Maharashtra. About 2 percent of this was exported, mainly to Greece. Estimated andalusite resources, classified in the reconnaissance category, stand at about 28.2 kt. There has been no reported production of the mineral since 1988.

Several mining operations in China produce sillimanite group minerals mainly for the domestic market. Nanyang Kaiyuan Cyanite Mining Company Ltd., mines kyanite in Nanyang City, south of China's capital city, Beijing.
Industrial Minerals

Henan Province. The company reports proven reserves of 34 Mt of ore averaging 28.38 percent Al₂O₃, ranging up to 60 percent, with <0.5 percent Fe₂O₃. The annual production capacity is stated to be about 50 kt of raw kyanite concentrate and 30 kt calcined kyanite. Shijiazhuang Mining Import & Export Trade Company Ltd., established in 2008, reports andalusite reserves in Xinjiang Province to be about 213 Mt. Xinjiang Xinrong Yilong Andalusite Company Ltd., reports production capacity of 40 kt/a. The company was initially founded in 2003 and briefly operated as a subsidiary of Imerys until 2018.

Prices
Sales prices for imported and exported minerals vary depending upon many factors including quantity, grade and purity, particle (mesh) size, packaging, monetary exchange rate, source and destination. The price of andalusite delivered from Europe was assessed in a range of $357 to $480/t; andalusite for delivery from South Africa was assessed at $302 to $381/t (Fastmarkets, 2019). The U.S. Census Bureau reports the average sales price for kyanite and calcined kyanite exported from the United States to be about $358/t. The export price has remained relatively stable over the past five years, averaging about $351/t. The average export price of sillimanite (56-60 percent Al₂O₃) f.o.b. from India in 2017-2018 was about $140/t.

Trends and outlook
The strength of the global steel industry as measured by steel output has been a reliable indicator of the demand for refractories and the raw minerals used in their manufacture. Annual crude steel production statistics and annual exports of sillimanite minerals from the United States since 2000 show a close positive correlation (Fig. 1). The World Steel Association reported global steel production in 2019 reached 1,869.9 Mt, an increase of about 3.4 percent compared to 2018, setting a new record level. Increases in production were reported mainly in Asia and the Middle East, with China’s output reaching 996.3 Mt, about 55.3 percent of the total. Countries within the EU reported 159.4 Mt of crude steel, about 4.9 percent less production than in 2018. In North America, overall production was also somewhat lower, with only the United States reporting a 1.5 percent increase in steel output from 86.6 Mt in 2018 to 87.9 Mt in 2019.

Exports of sillimanite minerals from the United States in 2019 were about 40.2 kt, with primary destinations in Europe, followed by Asia and the NAFTA region. U.S. exports were 6.6 percent lower than in 2018, possibly a reflection of softer market conditions for refractory minerals in Europe. About 7 kt of sillimanite minerals were imported into the United States in 2019, about the same as in recent years. Most of this material is andalusite that originated from South Africa with lesser amounts imported from France and Peru.

Producers of kyanite, andalusite and sillimanite benefited from the strong economic conditions that characterized most of 2019. The COVID-19 outbreak that began spreading globally in early 2020 has the potential to negatively affect industrial output, including the manufacturing and construction sectors that rely upon refractory products. The outlook for the steel industry is cautiously positive, with pre-coronavirus forecasts estimating global steel output to increase by about 1.7 percent in 2020. This outcome clearly depends on the duration and extent of the imposed lockdown restrictions to prevent the spread of the coronavirus. The longer the restrictions remain in place, the deeper the disruptions will be to industrial operations, suspended construction activities, investor and consumer confidence. As part of the critical supply chain, the production of sillimanite minerals is closely balanced with demand to maintain low price volatility and minimize conditions of oversupply. As the health emergency begins to subside and economic conditions improve, there will likely be market growth opportunities in the emerging and developing economies in Brazil, India and Russia in particular.

(References available from the author.)