EARTHQUAKE

EARTH SCIENCE MUSEUM

e-Newsletter about what's movin' and shakin' at the Earth Science Museum

Earth Science Museum, 3215 W. Bethany Home Rd., Phoenix, AZ 85017
www.earthsciencemuseum.org, scote@earthsciencemuseum.org, 602-973-4291

Rhodochrosite
China
S. Coté photo

Special Bulletin - Earth Science Week
Monday, October 12, 2020, Minerals Day - Part 2

Smartphone Minerals
Text and photos by Harvey Jong

In 2015, the Earth Science Museum (ESM) created an exhibit on *Smartphone Minerals* for its booth at the Tucson Gem & Mineral Show™. The display, which was very popular with show attendees, featured a disassembled phone with the chemical elements and minerals used in making various components. This article revisits the exhibit with a detailed exploration of some key elements, their properties, and main mineral sources. (Note: mineral names will appear in a bold italic typeface.)

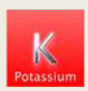
Modern life seems to be more and more dependent on technology, such as the ubiquitous smartphone. In 2019, global sales of the mobile device reached 1.37 billion units (Canalys Smartphone Analysis, Jan. 2020). The widespread ownership (estimated to be around 3.5 billion phones involving 45% of the world's population) is driven by the smartphone's multifunction capabilities which enable incredible ways of interacting with people and sharing data. Equally amazing are the number of different chemical elements involved in producing such a phone. There are 83 naturally-occurring, stable, nonradioactive elements, and up to 70 of these elements (84%) may be present in a smartphone (Rohrig, 2015).

Our journey of smartphone deconstruction begins with the touchscreen which has to be both durable and responsive to frequent tapping, swiping, pinching, and other gestures.

Some Elements Used in a Touchscreen
Aluminum, silicon, potassium, indium, tin

To provide scratch resistance, the touchscreen's aluminosilicate glass is chemically tempered where compressive stress is introduced by substituting smaller sodium ions (0.97 Å) with larger potassium ions (1.33 Å). The tempering is typically performed by immersing the glass in a bath of potassium nitrate.

Rob Lavinsky photo, iRocks.com – CC-BY-SA-3.0, via Wikimedia Commons



Sylvite
Carlsbad Potash District, Eddy and Lea Counties, New Mexico
5.5 x 4.5 x 3.5 cm

Potassium nitrate or saltpeter occurs as the mineral ***niter***, but it may also be derived from the mineral ***sylvite*** which is potassium chloride.

Potash is a mixture of potassium salts which is mainly used in the fertilizer industry. In 2019 the U.S. produced 510,000 tons where most of this potash was mined in southeastern New Mexico. Arizona's Holbrook Basin is estimated to contain about 0.7 to 2.5 billion tons.

To detect and track finger movements, a thin layer of indium tin oxide (ITO) is deposited on the glass. This material is both transparent and conductive which are the key properties that are needed to make touchscreens work. An electric current is passed through the screen using a set of charging wires. When your finger or some other conductive object makes contact with the screen, the current flow is interrupted, and the change is detected by a set of sensing wires. The transparency of the ITO layer allows you to see and interact with the objects appearing on the smartphone's display.

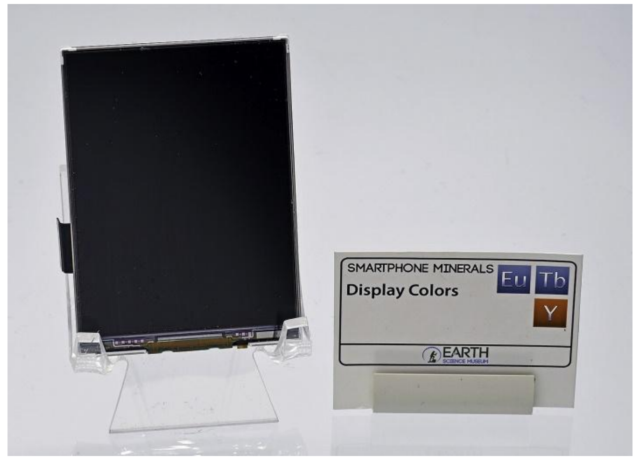
Sphalerite* with *Quartz
Iron Cap Mine, Aravaipa, Graham County, Arizona
3.5 x 3.5 x 5 cm

Indium is commonly extracted from the mineral ***sphalerite*** (zinc sulfide) where the element occurs in the range of 1 to 100 parts per million. The U.S. consumed about 110 tons of indium in 2019. With no domestic sources of production, it depends on imports from China, Canada, and the Republic of Korea.

Cassiterite
Viloco Mine, Loayza Province, La Paz, Bolivia
3.5 x 1.5 x 3 cm

The main ore mineral of tin is ***cassiterite*** (tin oxide). Last year, the U.S. used about 82,000 tons of tin. It hasn't mined the metal since 1993 and relies on recycling and imports from Indonesia, Malaysia, Peru, and Bolivia.

One of the most attractive features of a smartphone is the bright, colorful display. While smartphones originally included liquid crystal displays (LCD), most current models use organic light emitting diode (OLED) technology.



Rare-Earth Elements Used to Produce OLED Display Colors
Europium, terbium, yttrium
Note an older smartphone was used in this deconstruction, so the above display is a LCD panel. OLED displays are much thinner, lighter, and brighter.

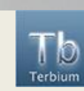
An OLED display is made of a series of thin films of organic compounds placed between two conductors. These compounds, such as tris(8-hydroxyquinolinato)aluminum, have semiconducting properties which produce light when an electric current is applied. To generate the primary red, green, and blue colors, chemical complexes containing rare-earth elements are added. These complexes act as luminescent centers which absorb light energy in one wavelength and emit light in a longer wavelength. Think of fluorescent minerals but on a nanometer scale.

The rare-earth elements are a set of 17 chemical elements which include 15 lanthanide elements (with atomic numbers 57-71) along with scandium (number 21) and yttrium (number 39). These elements exhibit similar chemical properties and tend to occur in the same ore deposits. Although their name implies scarcity, the rare-earth elements are relatively abundant in the Earth's crust. (Promethium, which is radioactive, is an exception.) They are, however, found in extremely low concentrations, so ore deposits that can be mined economically are not common. Some rare-earth elements used in OLED displays include europium, terbium, and yttrium.

Bastnäsite
Mountain Pass, San Bernardino County, California
9 x 4 x 5.5 cm

Europium is found in minor amounts in many minerals. One significant source includes ***bastnäsite*** which is a group of fluorocarbonate minerals. The specific mineral species is determined by the presence of the most abundant rare-earth element.

In 2018, the U.S. restarted rare-earth mining in Mountain Pass, California. Oddly, all the domestic production (26,000 tons) was exported, and the U.S. continues to rely on imports for rare-earth materials, mainly from China.

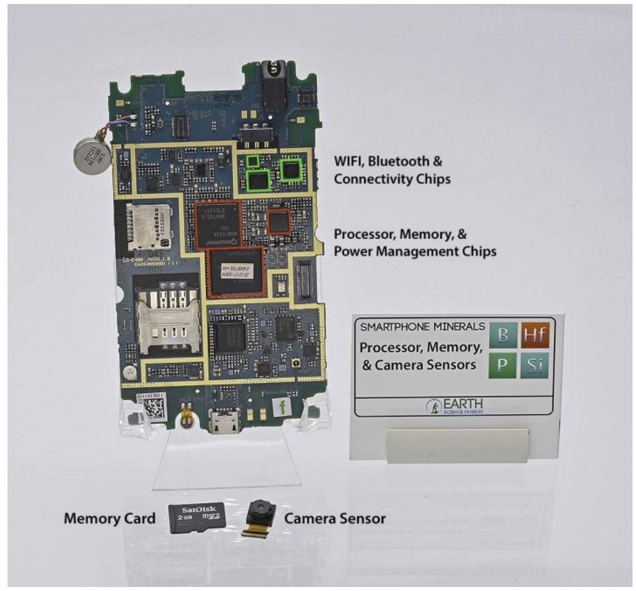


Euxenite-(Y)
Caterpillar Tractor Testing Grounds, Maricopa County, Arizona
5 x 4 x 2 cm

Euxenite–(Y) [(Y,Ca,Ce,U,Th)(Ti,Nb,Ta)$_2$O$_6$] may contain minable quantities of terbium (around 1% or more). The richest commercial terbium-bearing deposits are found in southern China; however, a 2018 discovery of rare-earth mud off the coast of Japan's Minamitorishima Island may yield enough terbium to meet demand for 420 years (Takaya et al., 2018). Production is difficult to estimate since terbium is not reported separately from other rare-earth elements.

Xenotime-(Y)
Novo Horizonte, Bahia, Brazil
4.0 x 2.2 x 10.0 mm

Yttrium is associated with most rare-earth minerals, including ***xenotime-(Y)*** (yttrium phosphate). No U.S. yttrium production has been reported, but yttrium is estimated to represent about 0.12% of the rare-earth elements in the ***bastnäsite*** ore mined in Mountain Pass, California. In 2019, 26,000 tons of this ore were produced which implies around 31 tons of yttrium. To meet demand, the U.S. imported about 570 tons of yttrium compounds from China, Estonia, and the Republic of Korea.



Some Elements Used for Processor, Memory, and Camera Sensors
Boron, hafnium, phosphorus, silicon
The processor, memory, and power management chips are indicated by red outlines, while the WIFI, Bluetooth, and connectivity chips appear in green.

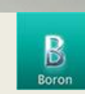
The “smart” part of a smartphone involves the processor chip which performs an astounding number of computations. For example, Apple’s A13 Bionic chip, which is part of the iPhone 11, is capable of up to one trillion 8-bit operations per second. Such high performance is made possible by the chip’s 8.5 billion transistors which are organized into 18 processing cores.

The processor is implemented using silicon-based semiconductor technology. To build transistors, elements, such as boron and phosphorus, are introduced into the silicon to modify semiconducting properties and create charge carriers. Additionally, a thin layer of hafnium oxide is deposited to form transistor gate structures and improve carrier conductance when a voltage is applied. Finally, copper wiring is added to connect the transistors.

The memory chip and camera sensors are also fabricated with silicon technology.

Quartz
Diamond Point, Payson, Gila County, Arizona
2.7 x 2.7 x 5.0 cm

Silicon is the second most abundant element in the Earth's crust, and more than 90% of the crust is made of silicate minerals. The main sources of silicon include quartzite and ***quartz*** (silicon dioxide) sand which are reduced with coke to produce 96-99% pure silicon. In 2019, the U.S. produced 320,000 tons of silicon, but it still had to import an additional 270,000 tons from Russia, Brazil, and Canada.



Ulexite
Boron, Kern County, California
5.5 x 4.0 x 6.5 cm

The main sources for boron include ***kernite*** (sodium borate hydroxide) and borates in brines, while ***ulexite*** (sodium calcium borate hydroxide) may also be used. The U.S. and Turkey are largest producers of boron products. About a quarter of global production comes from the U.S. Borax Boron Mine in California. The glass and ceramic industries are the leading users of boron in the U.S.

Fluorapatite
Norcross-Madagascar Apatite quarry, Madagascar
Middle specimen: 4.0 x 2.0 x 2.5 cm

Phosphate rock, which is partially made of minerals from the ***apatite*** [$Ca_5(PO_4)_3(Cl/F/OH)$] group, is the main commercial source of phosphorus. In 2019, the U.S. produced 23 million tons of phosphates through 10 mines in four states. More than 95% of this output was used to manufacture acids and fertilizers.

Zircon
Mud Tank, Harts Range, Northern Territory, Australia
2.4 x 1.7 x 2.8 cm

Hafnium is found with zirconium minerals, such as ***zircon*** (zirconium silicate) where it occurs in a ratio of about 1 to 36. Hafnium production data is not available; however, in 2019 the U.S. produced 100,000 metric tons of zirconium ore and imported over 26,000 tons. Superalloys represent the leading use of hafnium.

Chalcopyrite
Huanzala Mine, Huanuco Department, Peru
6.4 x 3.0 x 5.2 cm

Most copper is mined from copper sulfide minerals, such as ***chalcopyrite*** (copper iron sulfide). In 2019, U.S. copper production was around 1.3 million tons, and Arizona was the leading producer accounting for about 68% of domestic output.

Some Elements Used for Communication Chips
Gallium, arsenic, beryllium, silicon
The chips are indicated by the orange outlines.

Communication chips in a smartphone include radio frequency transceivers, duplexers, filters, and power amplifiers. Because of higher operating frequencies, these components use the compound semiconductor, gallium arsenide. To build transistors in this material, elements, such as silicon or beryllium, are incorporated to make localized changes in the electrical characteristics.

Bauxite
Bauxite Mines, Saline County, Arkansas
Larger specimen:3.3 x 2.0 x 4.0 cm

Gallium occurs in very small concentrations in metallic ores. The most common gallium source involves a byproduct associated with the processing of ***bauxite*** (a mixture of iron and aluminum hydroxides/oxides, the primary ore of aluminum). The average gallium content is about 50 parts per million. The U.S. does not produce gallium and imports the element from China, Japan, and the Republic of Korea.

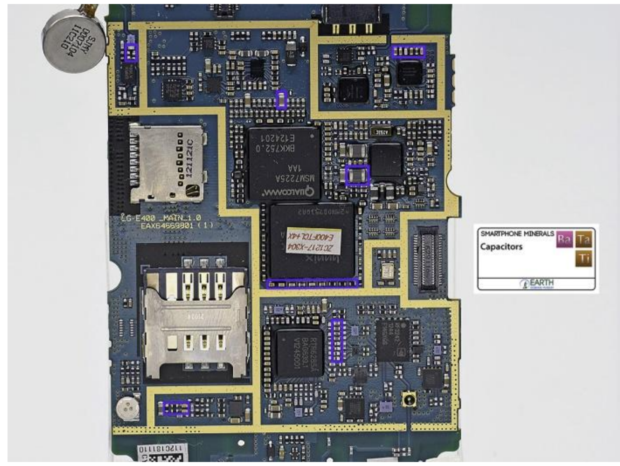
Arsenopyrite
Yaogangxian Mine, Hunan Province, China
4.4 x 2.9 x 4.0 cm

Arsenic is the 53rd most abundant element in the Earth's crust. A main mineral source includes ***arsenopyrite*** (iron arsenic sulfide). The U.S. hasn't produced arsenic since 1985 and imports over 90% from China. Aside from semiconductors, arsenic may be used in batteries, antifriction additives, and hardening lead shot.

Beryl var. Aquamarine
Pingwu Beryl Mine, Mt. Xuebaoding,
Sichuan, China
5.5 x 2.5 x 6.0 cm

Be
Beryllium

Beryllium may be extracted from ***beryl*** (beryllium aluminosilicate) or ***bertrandite*** (beryllium silicate hydroxide). The U.S. has very little beryl that can be mined economically, while Utah has ***bertrandite*** reserves estimated to contain around 20,000 tons of beryllium. U.S. production in 2019 was 170 tons, but only 1% was used for semiconductor components.



Elements Used for Capacitors
Barium, titanium, tantalum
The numerous tiny squares and rectangles in the above photo are the smartphone's - capacitors, and a few different sizes and groups are outlined in blue.

Capacitors are found throughout the subsystems of a smartphone and used for frequency tuning, filtering, and impedance matching. These energy storage components are made of different dielectric materials including ceramic, tantalum, and barium titanate. The electrodes of a capacitor may be comprised of palladium or silver.

Baryte "Rose"
Norman, Cleveland County, Oklahoma
6.0 x 6.0 x 5.0 cm

Baryte (barium sulfate) is the main commercial source of barium. Although the U.S. produced around 2.9 million tons of ***baryte*** in 2019, it still had to import an additional 2.6 million tons. It is the world's leading consumer where more than 90% is used as "drilling mud" for oil and natural gas wells.

Rutile
Graves Mountain, Lincoln County, Georgia
1.4 x 1.5 x 3.2 cm

Titanium is the ninth-most abundant element in the Earth's crust. The element frequently occurs as oxide minerals in igneous rocks. ***Rutile*** (titanium oxide) is one commercial source. The U.S. has some limited production (output data unavailable due to proprietary reasons), but must import or recycle. In 2019, 27,000 tons were imported, and the aerospace industry accounted for around 80% of the titanium consumption.

Rob Lavinsky photo, iRocks.com – CC-BY-SA-3.0, via Wikimedia Commons

Tantalite-(Mn)

Shigar Vallley, Skardu District, Ballistan, Northern Areas, Pakistan

1.4 x 1.4 x 1.3 cm

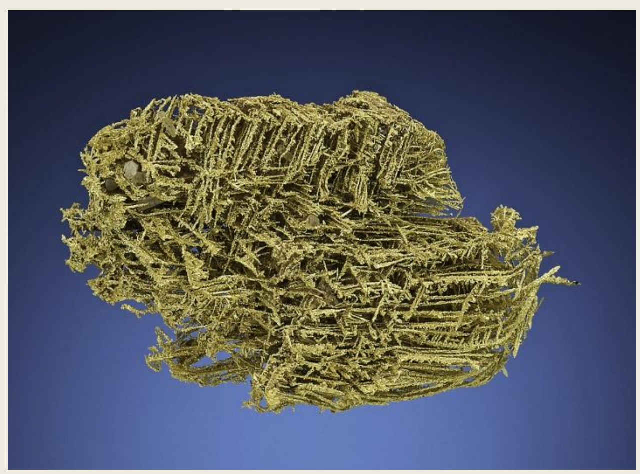
Ta Tantalum

Tantalum occurs in the ***tantalite*** [(Mn,Fe)(Ta,Nb)$_2$O$_6$] mineral series where the specific species is determined by the amount of iron or manganese present. No U.S mine production has been reported since 1959, and in 2019 around 1300 tons were imported from countries such as Rwanda, Brazil, Australia, and Congo.

Elements Used for Connectors and Wiring

Gold and copper

Copper is extensively used to connect smartphone components where multiple wiring layers separated by a woven glass and epoxy substrate are combined on the motherboard. Gold plating provides a corrosion-resistant conductive layer for top level traces, component leads, and electrical connectors.



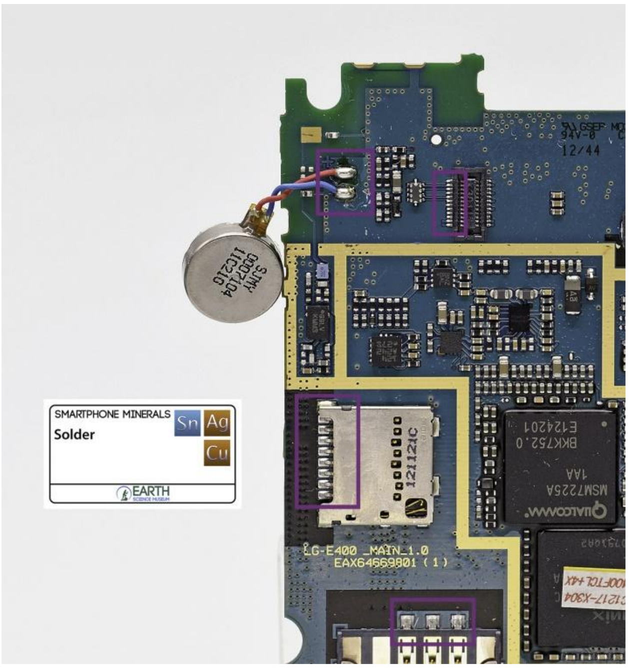
Jeff Scovil photo

Native Gold

Yuba Mine, Greaterville, Pima County, Arizona

Au Gold

Gold occurs most often in native form. The U.S. produced 200 tons in 2019. About 37% of domestic gold consumption (excluding bullion) involved electrical and electronic applications.



Elements Used in Solder
Tin, silver, copper
Close-up view of a motherboard shows numerous solder connections, and some examples are highlighted with purple outlines.

For many years, lead-tin alloys have been used in soldering electronic components to circuit boards. In 2006, however, a European Union manufacturing directive removed lead from the soldering process, so smartphones are now assembled with a tin-silver-copper solder. Typical alloys contain 3-4% silver, 0.5-0.7% copper, and 95%+ tin.

Argentiferous Galena
Wickenburg area, Yavapai County, Arizona
Larger specimen: 4.5 x 2.8 x 2.8 cm

While silver may occur as sulfide minerals, it is primarily obtained as a byproduct of polymetallic ore deposits. ***Argentiferous galena*** (lead sulfide) is an example of a secondary silver association with lead ore. The U.S. produced 980 tons of silver in 2019, while 4700 tons were imported. About 30% of this supply was used by the electrical and electronics industry.

Elements Used for the Speaker, Microphone, Vibration Unit, and Camera Focus Unit
Neodymium, iron, boron

Up to 14 tiny magnets may be present in a smartphone. They are used in the speaker (2-5 magnets), microphone (2 magnets), vibration unit (1 magnet), and camera auto-focus mechanism (2-4 magnets per camera).

To provide strong magnetic fields in the very compact space of a smartphone, a neodymium iron boron alloy is utilized. The alloy has a tetragonal, mirror symmetrical crystal lattice structure where neodymium and iron ions are in parallel alignment. Neodymium is strongly paramagnetic (unpaired electrons form dipoles that can be temporarily aligned and attract a magnetic field), while iron is ferromagnetic (unpaired electrons form domains which can be aligned and create a permanent magnet). This combination leads to dense magnetic fields and represents the strongest permanent magnetic material yet discovered.

One way of rating the strength of magnets involves the maximum energy product which measures the density and strength of a magnetic field per volume. Neodymium magnets have a maximum energy product of around 40 MegaGuass Oersted (MGOe). In comparison, ceramic magnets (often used in refrigerators) have a maximum energy product of only 3.5 MGOe.

Rob Lavinsky photo, iRocks.com – CA-BY-SA-3.0, via Wikimedia Commons

Monazite

João Torres Mine, Muqui, Espinto Santo, Southest Region, Brazil

4.7 x 4.4 x 1.4 cm

Nd Neodymium

Neodynium may occur in the mineral groups ***monazite*** (monoclinic phosphates and arsenates) and ***bastnäsite*** (fluorocarbonates). These minerals may include a variety of different rare-earth elements, and neodymium typically makes up 10-18% of the rare-earth content of commercial deposits. Most of the current production comes from China.

Hematite
BCC Mine, La Paz County, Arizona
5.5 x 3.7 x 5.0 cm

Iron is the world's most commonly used metal. ***Hematite*** (iron oxide) is one of the main ore minerals. In 2019, the U.S. produced around 23 million tons of pig iron which was used primarily for steelmaking.

Elements Used in the Battery
Lithium, cobalt, carbon

Most smartphones are powered by lithium ion batteries. The positive electrode may be comprised of lithium cobalt oxide, while the negative electrode may be made of carbon.

"Lepidolite"
Londonderry Feldspar quarry, Western Australia, Australia
5.8 x 5.2 x 4.0 cm

Spodumene
Tin Mountain Mine, Black Hills, South Dakota
9.2 x 4.7 x 1.8 cm

Lithium is mainly extracted from brines since mining ore minerals, such as ***"lepidolite"*** and ***spodumene,*** is more expensive and less competitive. (Note that the International Mineralogical Association discredited ***"lepidolite"*** as a valid mineral name in 1989. It is now part of a mica series with ***polylithionite*** and ***trilithionite*** as end members.) In 2019, U.S. lithium production was limited to a brine operation in Nevada, and 2.5 million tons had to be imported from Argentina and Chile. Batteries accounted for 65% of global lithium consumption.

Cobaltite
Tres Hermanas, Luna County, New Mexico
Larger specimen: 4.4 x 3.2 x 2.8 cm

There are approximately 30 main cobalt-bearing minerals, and ***cobaltite*** (cobalt arsenic sulfide) has been found in economic deposits. The U.S. produced 3.2 million tons of cobalt and imported 13.6 million tons. Most of this cobalt (about 46%) was used in making superalloys for aircraft gas turbine engines.

Graphite
USA
3.2 x 1.4 x 2.8 cm

Natural Graphite is a crystalline form of carbon. In 2019, the U.S. did not mine any ***graphite*** and had to import about 58,000 tons from China, Mexico, Canada, and India. It is used in a variety of applications including batteries, brake linings, lubricants, refractories, and steelmaking. Usage for battery anodes is estimated to be around 25%.

Our exploration into the make-up of a smartphone concludes with its case.

Elements Used in Case
Magnesium and nickel
A case with shielding plate.

Smartphones come in many distinctive styles where cases may be constructed of metal, plastic, or a combination of these materials. For metal cases, magnesium may be used due to weight and heat dissipation considerations. Magnesium forms the basis for some of the lightest metal alloys and is approximately 30% lighter than aluminum. The alkaline earth element is also less thermally conductive which may help make phones more comfortable to handle.

With billions of transistors switching on and off while you video chat with a friend, a smartphone can generate a lot of electrical noise. This noise can potentially interfere with other electronic systems, such as those on an airplane. Nickel plated sheets may enclose some smartphone subsystems to shield this electromagnetic interference.

Dolomite
Tri-State District, Jasper County, Missouri
6.7 x 2.0 x 6.0 cm
Mg
Magnesium

Magnesium and magnesium compound production may include seawater, natural brines, or ore minerals, such as ***dolomite*** (calcium magnesium carbonate) and ***magnesite*** (magnesium carbonate)***.*** In 2019, the U.S. output was 410,000 tons where seawater and brines accounted for about 73%. Approximately 72% of domestic consumption involved agricultural, chemical, construction, deicing, environmental, and industrial applications.

Pentlandite
Sudbury, Ontario, Canada
7.6 x 7.0 x 5.4 cm

Nickel mining may involve either laterite or magmatic sulfide deposits. ***Nickeliferous limonite*** (iron nickel oxide hydroxide) is the principal ore mineral associated with laterites, while ***pentlandite*** (nickel iron sulfide) is the main ore mineral found in sulfide deposits. The U.S. produced 14,000 tons of nickel in 2019 and imported an additional 158,000 tons. Stainless and alloy steels are the main uses of nickel accounting for about 77% of total consumption.

Summary

Smartphones represent not only technological marvels that connect everyone and their data, but they also provide a fairly comprehensive collection of the periodic table of the elements. The varied and unique properties of these elements are essential to make smartphones work. The sources of the elements involve many common and not-so common minerals. Some of these minerals are found in Arizona, but the mineral supply chain extends across the globe.

The content of some elements in a smartphone exceeds the concentration of many rich ore deposits. For example, one ton of iPhone 5S's has been estimated to yield about 9.72 oz. of gold, while a ton of ore from Peru's Yanacocha Complex (world's fourth largest gold mine) may produce around 0.03 oz. (NEO Mammalian Studios infographic, presented at https://www.911metallurgist.com/mining-iphones/). So, if a cost effective way of separating this gold along with other elements can be developed, "smartphone mining" might prove to be the next big thing.

References

Information on mineral commodities and associated production and consumption is from:

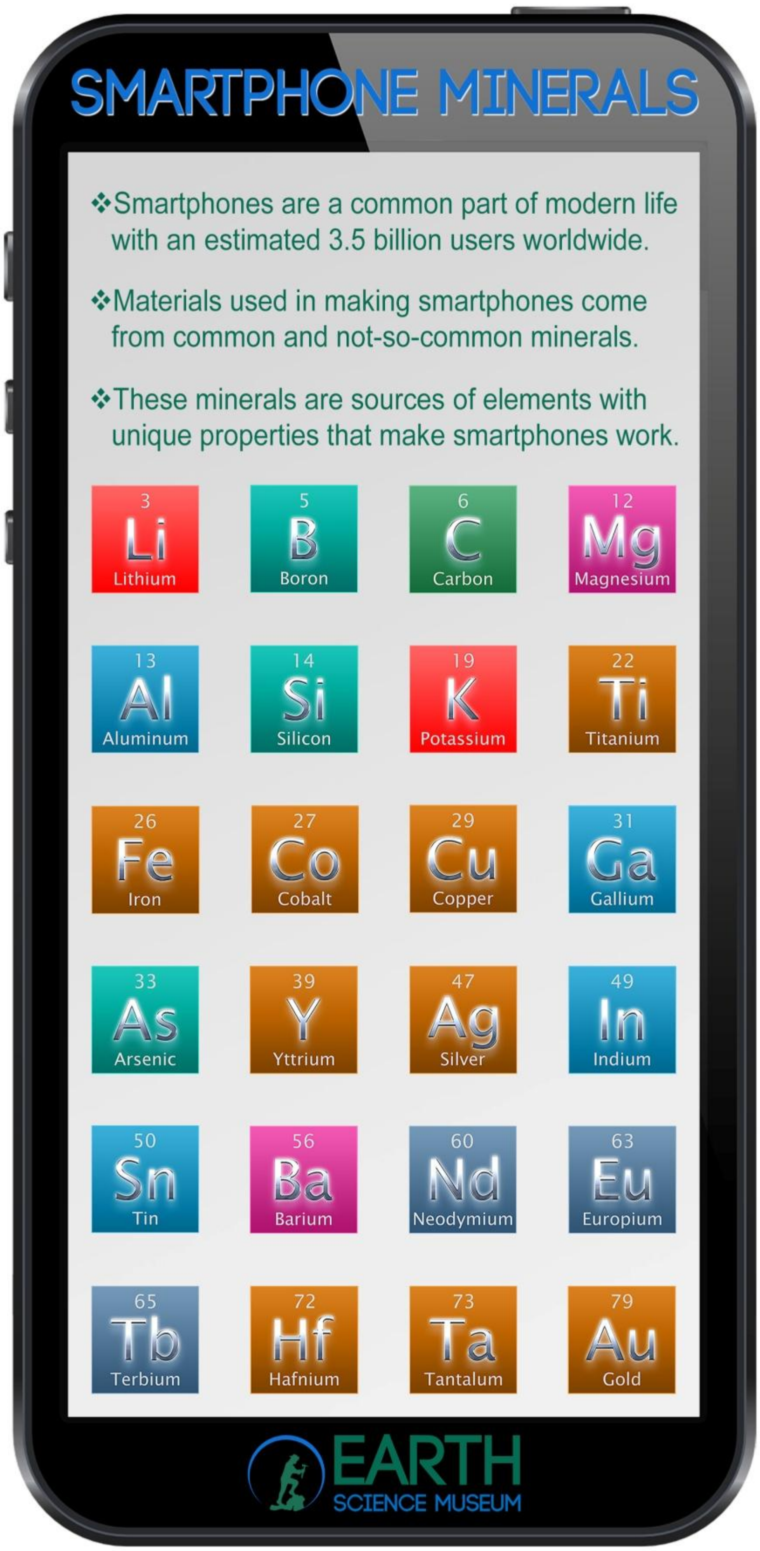
Mineral Commodity Summaries 2020. *USGS National Minerals Information Center* 200 p.

Other references include:

Rohrig, B. (2015) Smartphones smart chemistry. *ChemMatters April/May*: 10-12.

Takaya, Y., K. Yasukawa, T. Kawasaki, K. Fujinaga, J. Ohta, et al. (2018) The tremendous potential of deep-sea mud as a source of rare-earth elements. *Nature Scientific Reports* 8: 1-8.

See graphic next page



Alkali metals · Alkaline earth metals · Transition metals · Post-transition metals

Metalloids · Nonmetals · Lanthanoids

KEY ELEMENTS USED IN SMARTPHONE PARTS AND THEIR MINERAL SOURCES

Touchscreen
- In Sphalerite
- Sn Cassiterite

Display glass
- Al Bauxite
- K Sylvite
- Si Quartz

Display colors
- Eu Bastnasite, monazite
- Tb Euxenite, monazite
- Y Xenotime, zircon

Microprocessor & camera chips
- As Arsenopyrite
- B Kernite, ulexite
- Hf Zircon
- Si Quartz

Communication chips
- As Arsenopyrite
- Ga Bauxite
- Mg Dolomite
- Si Quartz

Capacitors
- Ba Barite
- Ta Tantalite
- Ti Rutile

Connectors & wires
- Au Native gold
- Cu Chalcopyrite

Solder
- Ag Acanthite, argentite
- Sn Cassiterite

Speaker & microphone
- B Kernite, ulexite
- Fe Hematite
- Nd Bastnasite, monazite

Battery
- C Graphite
- Co Cobaltite
- Li Lepidolite, spodumene

Graphic by Harvey Jong