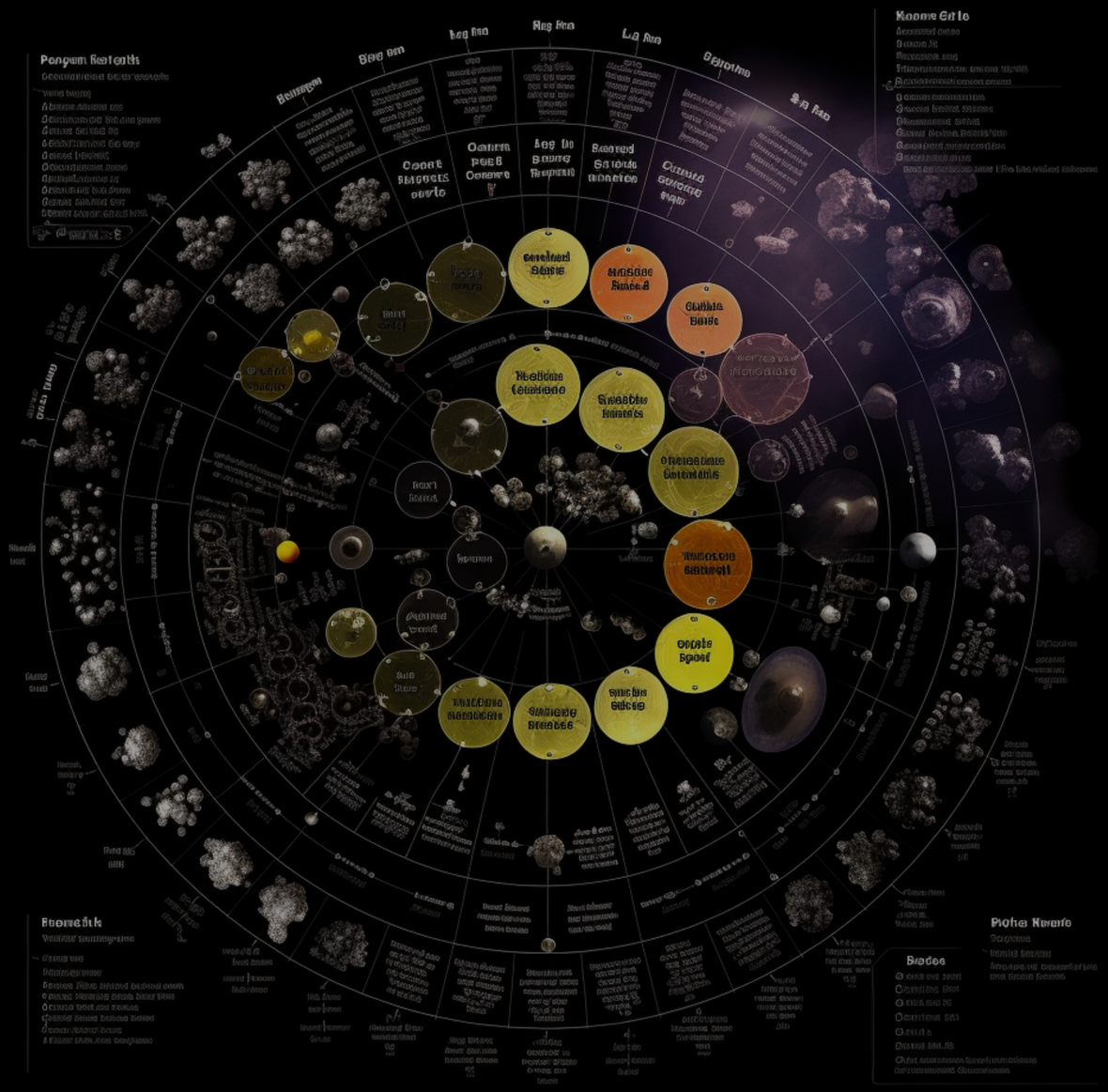


# ORE MINERALS, THE MINERALOGICAL BARRIER, AND THE ELEMENTOME IN SPACE

Kevin M. Cannon

COLORADO SCHOOL OF MINES

**Is there a source of *resource X* on *planetary body Y?***

# FUEL-MINERALS

Coal, uranium, oil, natural gas

# INDUSTRIAL MINERALS

Sand, gravel, gypsum, salt, diamond

# METALS

Iron, ferro-alloys, non-ferrous metals, precious metals

## FUEL-MINERALS

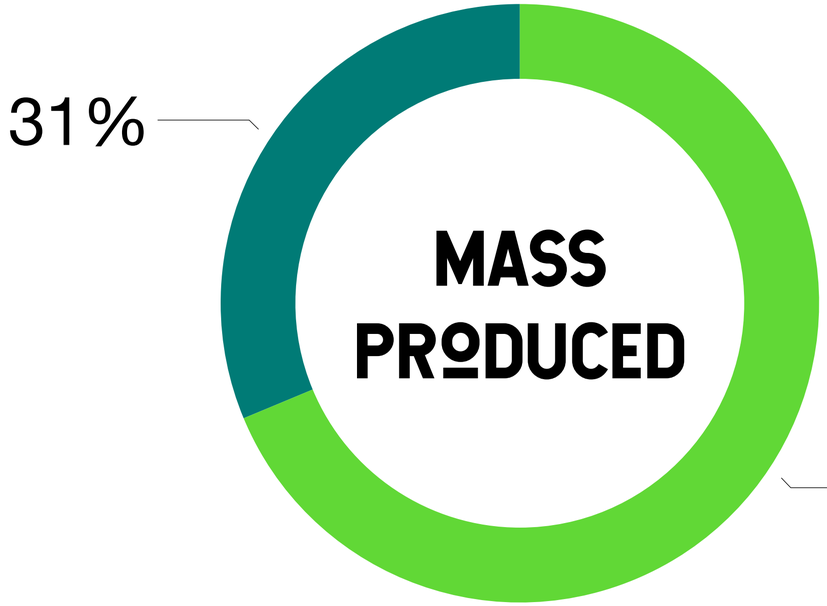
Coal, uranium, oil, natural gas

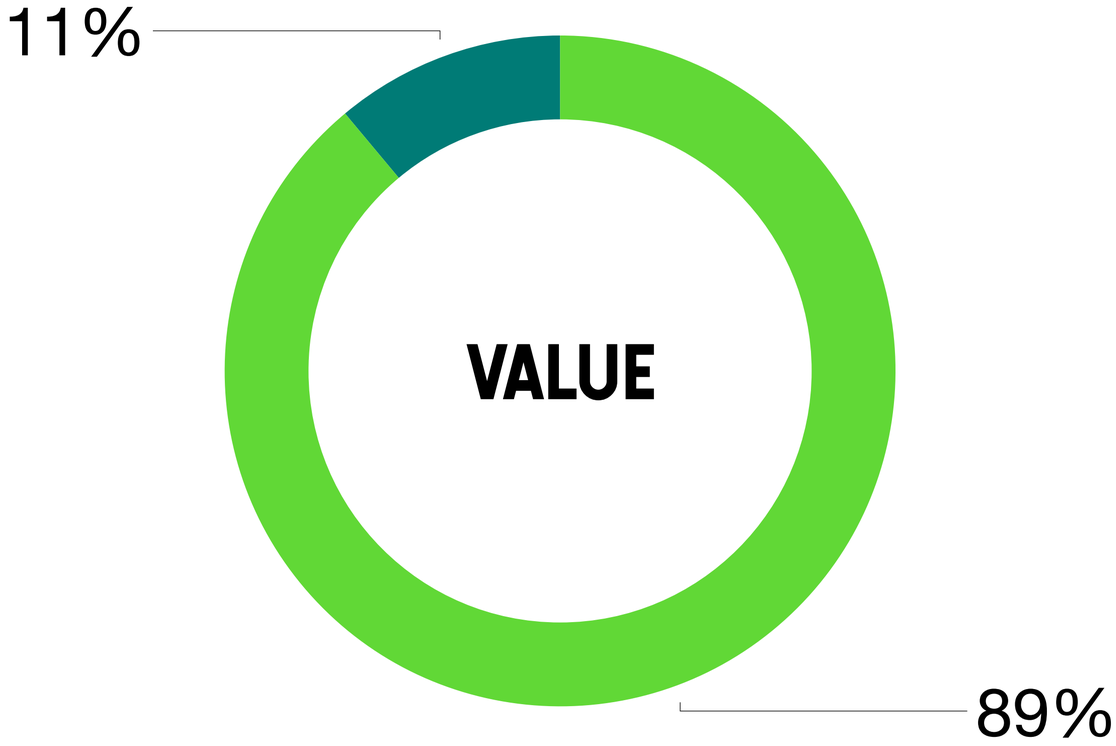
## INDUSTRIAL MINERALS

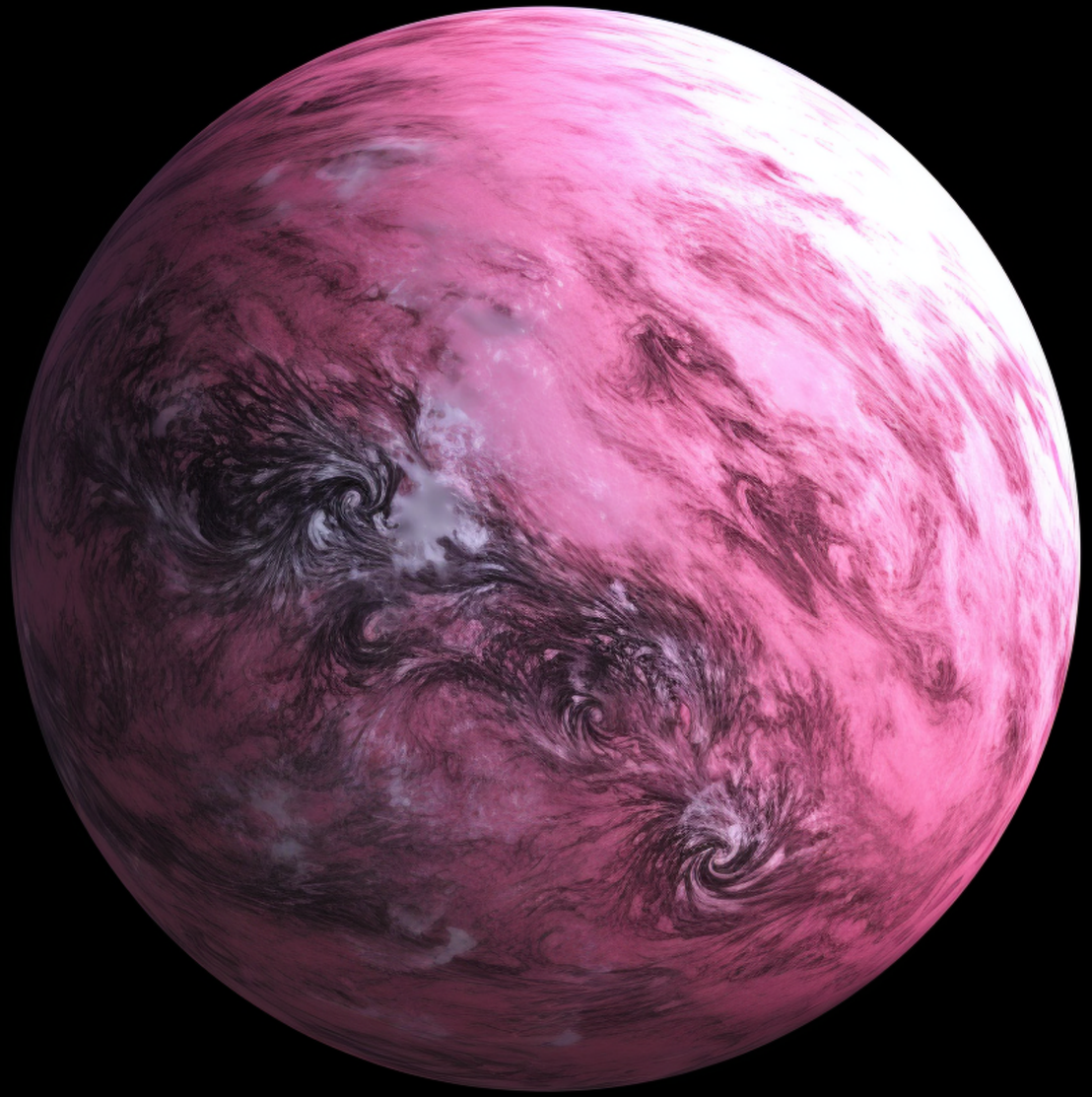
Sand, gravel, gypsum, salt, diamond

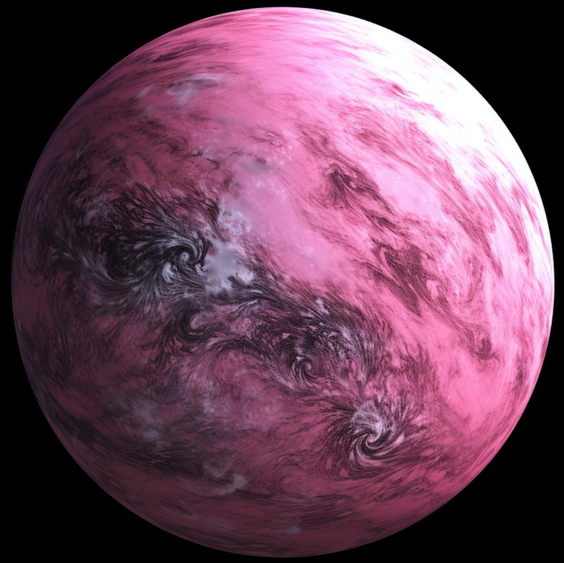
## METALS

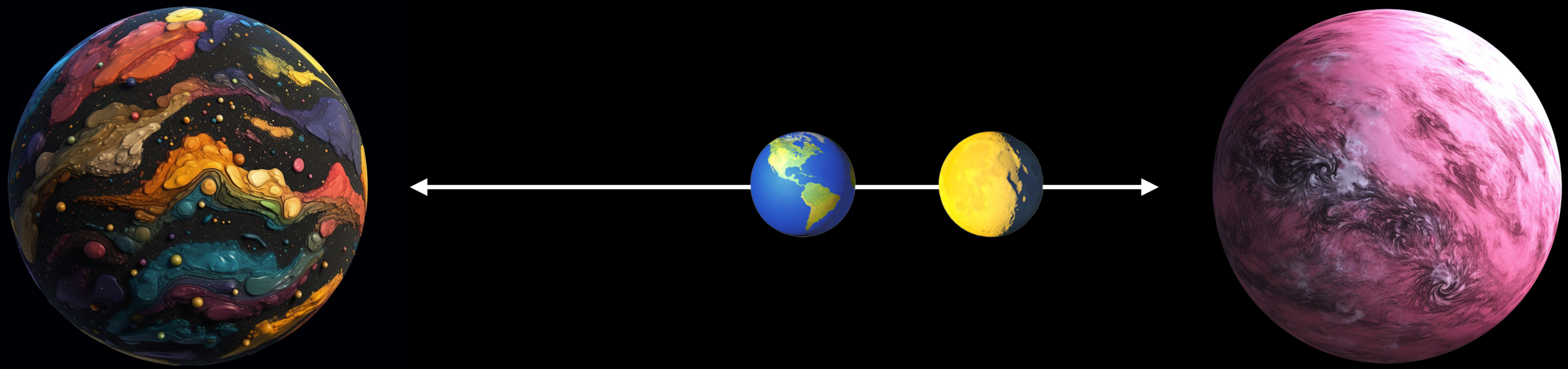
Iron, ferro-alloys, non-ferrous metals, precious metals









| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H Hydrogen 1.008 | | | | | | | | | | | | | | | | | 2 He Helium 4.003 |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.012 | | | | | | | | | | | 5 B Boron 10.511 | 6 C Carbon 12.011 | 7 N Nitrogen 14.007 | 8 O Oxygen 15.999 | 9 F Flourine 18.958 | 10 Ne Neon 20.180 |
| 11 Na Sodium 22.990 | 12 Mg Magnesium 24.305 | | | | | | | | | | | 13 Al Aluminum 25.982 | 14 Si Silicon 28.086 | 15 P Phosphorus 30.974 | 16 S Sulfur 32.056 | 17 Cl Chlorine 35.453 | 18 Ar Argon 39.948 |
| 19 K Potasium 39.098 | 20 Ca Calcium 40.078 | 21 Sc Scandium 44.956 | 22 Ti Titanium 47.857 | 23 V Vanadium 50.942 | 24 Cr Chromium 51.996 | 25 Mn Manganese 54.938 | 26 Fe Iron 55.845 | 27 Co Cobalt 58.933 | 28 Ni Nickel 58.593 | 29 Cu Copper 63.546 | 30 Zn Zinc 65.38 | 31 Ga Gallium 69.723 | 32 Ge Germanium 72.631 | 33 As Arsenic 74.922 | 34 Se Selenium 78.971 | 35 Br Bromine 79.904 | 36 Kr Krypton 84.796 |
| 37 Rb Rubidium 84.468 | 38 Sr Strontium 87.62 | 39 Y Yttrium 88.906 | 40 Zr Zirconium 91.224 | 41 Nb Niobium 92.906 | 42 Mo Molybdenum 95.95 | 43 Tc Technetium 98.907 | 44 Ru Ruthenium 101.07 | 45 Rh Rhodium 102.906 | 46 Pd Palladium 106.42 | 47 Ag Silver 107.868 | 48 Cd Cadmium 112.411 | 49 In Indium 114.818 | 50 Sn Tin | 51 Sb Antimony 11.760 | 52 Te Tellurium 127.6 | 53 I Iodine 126.904 | 54 Xe Xenon 131.293 |
| 55 Cs Caesium 132.905 | 56 Ba Barium 132.327 | | 72 Hf Hafnium 178.49 | 73 Ta Tantalum 180.948 | 74 W Tungsten 183.84 | 75 Re Rhenium 186.207 | 76 Os Osmium 190.23 | 77 Ir Iridium 192.217 | 78 Pt Platinum 195.084 | 79 Au Gold 196.967 | 80 Hg Mercury 200.59 | 81 Tl Thallium 204.3833 | 82 Pb Lead 207.2 | 83 Bi Bismuth 208.98040 | 84 Po Polonium (208.982) | 85 At Astantine (209.987) | 86 Rn Radon (222.018) |
| 87 Fr Francium (223) | 88 Ra Radium (226) | | 104 Rf Rutherfordium (261) | 105 Db Dubnium (262) | 106 Sg Seaborgium (266) | 107 Bh Bohrium (264) | 108 Hs Hassium (277) | 109 Mt Meitnerium (268) | 110 Ds Darmstadtium (271) | 111 Rg Roentgenium (272) | 112 Cn Copernium (277) | 113 Uut Ununtrium | 114 Fl Flerovium (289) | 115 Uup Ununpentium | 116 Lv Livermorium (298) | 117 Uus Ununseptium | 118 Uuo Ununoctium |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 La Lanthanum 138.905 | 58 Ce Cerium 140.116 | 59 Pr Praseodymium 140.90765 | 60 Nd Neodymium 144.908 | 61 Pm Promethium (145) | 62 Sm Samarium 150.36 | 63 Eu Europium 151.964 | 64 Gd Gadolinium 157.25 | 65 Tb Terbium 158.925 | 66 Dy Dysprosium 162.5 | 67 Ho Holmium 164.93 | 68 Er Erbium 167.259 | 69 Tm Thulium 148.934 | 70 Yb Ytterbium 173.054 | 71 Lu Lutetium 174.967 |
| 89 Ac Actinium (227) | 90 Th Thorium 232.038 | 91 Pa Protactinium 231.036 | 92 U Uranium 238.029 | 93 Np Neptunium (237) | 94 Pu Plutonium (244) | 95 Am Americium (243) | 96 Cm Curium (247) | 97 Bk Berkelium (247) | 98 Cf Californium (251) | 99 Es Einsteinium 252 | 100 Fm Fermium (257) | 101 Md Mendelevium (258) | 102 No Nobelium (259) | 103 Lr Lawrencium (262) |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| 87 Fr Francium (223) | 88 Ra Radium (226) | | 104 Rf Rutherfordium (261) | 105 Db Dubnium (262) | 106 Sg Seaborgium (266) | 107 Bh Bohrium (264) | 108 Hs Hassium (277) | 109 Mt Meitnerium (268) | 110 Ds Darmstadtium (271) | 111 Rg Roentgenium (272) | 112 Cn Copernium (277) | 113 Uut Ununtrium | 114 Fl Flerovium (289) | 115 Uup Ununpentium | 116 Lv Livermorium (298) | 117 Uus Ununseptium | 118 Uuo Ununoctium |

| | | | | | | | | | | | | | | |
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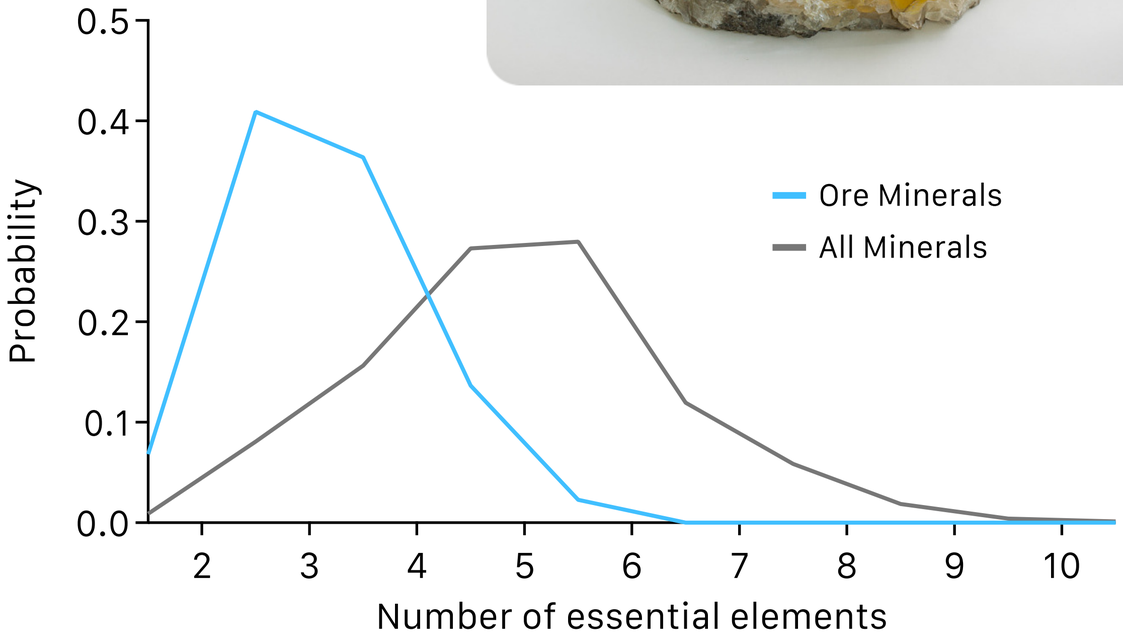
# Aldridgeite

$(Cd,Ca)(Cu,Zn)_4(SO_4)_2(OH)_6 \cdot 3H_2O$

# Greenockite

$CdS$

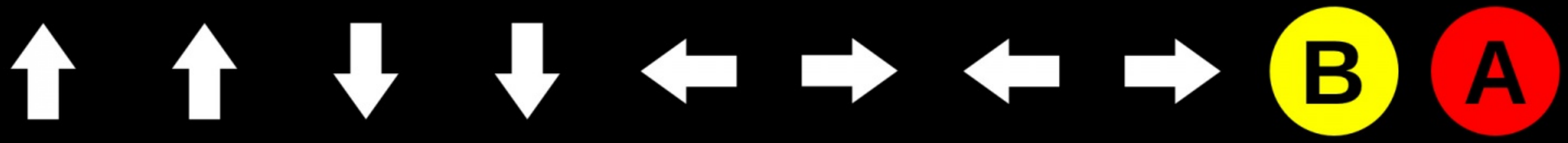


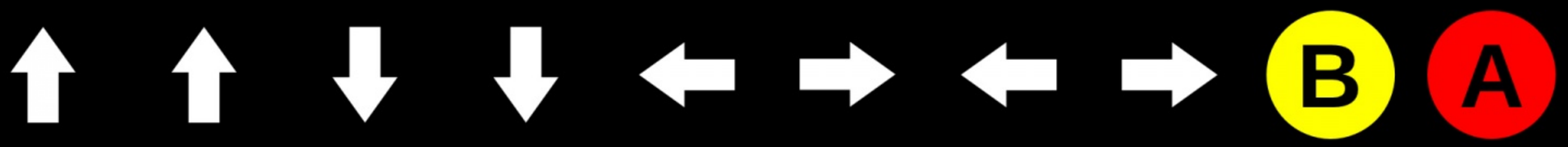
| | | | |
|---|---|---|---|
| **Mg** | Magnesite, Dolomite, Brucite, Bischofite, Carnallite, Olivine | **Sr** | Celestine, Strontianite |
| **Ti** | Ilmenite, Rutile, Anatase, Brookite, Perovskite, Geikielite, Titanite, Leucoxene, Arizonite | **Co** | Cobaltite, Carrollite, Cattierite, Linnaeite, Skutterudite, Erythrite, Smaltite |
| **Fe** | Hematite, Magnetite, Siderite, Goethite, Limonite | **Sc** | Thortveitite, Bazzite, Kolbeckite |
| **Cr** | Chromite | **Sn** | Cassiterite |
| **Si** | Quartz | **Cd** | Greenockite |
| **P** | Apatite, Francolite, Dahllite, Collophane | **Au** | Native gold, Electrum |
| **Ca** | Calcite, Aragonite, Dolomite | **Bi** | Bismuthinite, Bismite, Native bismuth |
| **Zr** | Zircon, Baddelyite, Eudialyte | **Sb** | Stibnite, Jamesonite |
| **Ni** | Garnierite, Pentlandite, Millerite, Violarite, Polydymite, Nickeliferous limonite, Genthite, Hengleinite | **B** | Colemanite, Kernite, Tincal, Ulexite |
| **C** | Graphite | **W** | Scheelite, Wolframite |
| **Cu** | Chalcopyrite, Chalcocite, Covellite, Bornite, Tetrahedrite, Digenite, Malachite, Azurite, Cuprite, Chrysocolla, Tennantite, Dioptase, Enargite | **U** | Uraninite, Coffinite |
| **Zn** | Sphalerite | **I** | Lautarite, Dietzeite |
| **REEs** | Bastnäsite, Monazite, Xenotime | **Ta** | Columbotantalite, Wodginite, Microlite |
| **Hg** | Cinnabar, Native mercury | **Al** | Gibbsite, Böhmite, Diaspore) |
| **Na** | Halite | **S** | Native sulfur |
| **Mo** | Molybdenite, Wulfenite, Molybdite, Powellite | **Th** | Thorite, Thorianite |
| **Ba** | Barite, Witherite | **Cs** | Pollucite |
| **Pb** | Galena, Cerussite, Anglesite | **Nb** | Columbite-(Fe), Pyrochlore group |
| **Mn** | Pyrolusite, Cryptomelane, Romanechite, Braunite, Hausmannite, Rhodochrosite, Manganite | **Ag** | Acanthite, Native silver, Pyrargyrite, Electrum, Argentite |
| **As** | Realgar, Orpiment, Arsenopyrite | **V** | Vanadinite, Roscoelite, Carnotite, Descloizite, Mottramite |
| **K** | Sylvite, Carnallite, Langbeinite, Kainite, Picromerite, Schoenite | **Li** | Spodumene, Petalite, Lepidolite, Amblygonite, Eucryptite, Zinnwaldite |
| **Be** | Bertrandite, Beryl | | |

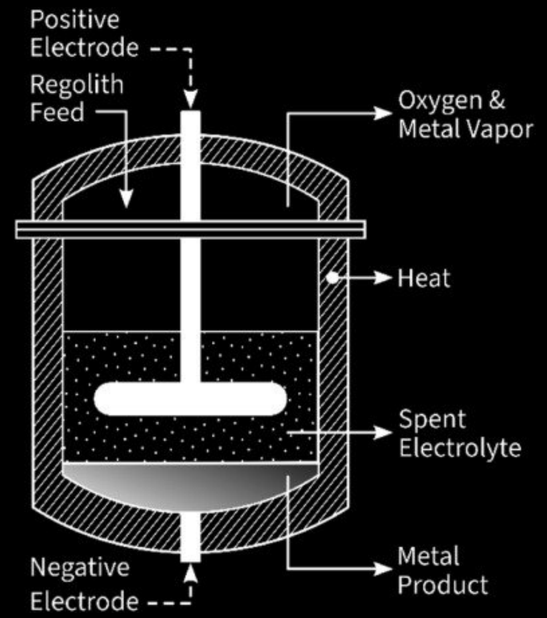
| Element | Moon | Asteroids | Mars | Alternatives | Score (with alternatives) | Score (without) | # of Modes | First Stage | Mode Occurrences |
|---|---|---|---|---|---|---|---|---|---|
| Mg | Olivine (Ma) | Olivine (Ma) | Magnesite (Ma) | None | 9 | 9 | 30 | 0.0 | 69.0 |
| Ti | Ilmenite (Ma) | Ilmenite (Ac) | Ilmenite (Mi) | None | 6 | 6 | 27 | 0.0 | 67.0 |
| Fe | Magnetite (Ac) | Magnetite (Mi) | Hematite (Ma) | Native iron-nickel (Moon; Mi) | 7 | 6 | 36 | 0.0 | 64.0 |
| Cr | Chromite (Mi) | Chromite (Mi) | Chromite (Mi) | None | 6 | 6 | 11 | 0.0 | 41.0 |
| Si | Quartz (Ma) | Quartz (Ac) | Quartz (Mi) | Hydrated silica (Mars; Ma) | 7 | 6 | 14 | 1.0 | 34.0 |
| P | Apatite (Mi) | Apatite (Mi) | Apatite (Mi) | None | 6 | 6 | 19 | 2.0 | 28.0 |
| Ca | NR | Dolomite (Mi) | Calcite (Ac) | Gypsum (Mars; Ma) | 5 | 3 | 23 | 2.0 | 37.0 |
| Zr | Zircon (Ac) | Zircon (Ac) | Zircon (Ac) | None | 3 | 3 | 13 | 1.0 | 37.0 |
| Ni | Pentlandite (Ac) | Pentlandite (Ac) | Pentlandite (Ac) | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 3 | 15 | 1.0 | 36.0 |
| C | Graphite (Ac) | Graphite (Mi) | NR | Atmosphere (Mars; Ab), Sequestered Ices (Moon; | 8 | 3 | 13 | 0.0 | 35.0 |
| Cu | Chalcopyrite (Ac) | Chalcopyrite (Ac) | Chalcopyrite (Ac) | Native copper (Asteroids; Mi) | 4 | 3 | 22 | 2.0 | 29.0 |
| Zn | Sphalerite (Ac) | Sphalerite (Ac) | Sphalerite (Ac) | None | 3 | 3 | 15 | 1.0 | 27.0 |
| REEs | Monazite (Ac) | Monazite (Ac) | Monazite (Ac) | None | 3 | 3 | 10 | 3.0 | 13.0 |
| Hg | Cinnabar (Ac) | Cinnabar (Ac) | NR | Polar ices (Moon; Mi) | 3 | 2 | 6 | 2.0 | 13.0 |
| Na | NR | Halite (Ac) | NR | Sodium carbonate (Asteroids; Ma) | 3 | 1 | 8 | 2.0 | 10.0 |
| Cl | NR | Halite (Ac) | NR | Apatite (all; Mi) | 6 | 1 | 8 | 2.0 | 10.0 |
| Mo | NR | NR | NR | None | 0 | 0 | 15 | 2.0 | 22.0 |
| Ba | NR | NR | NR | None | 0 | 0 | 18 | 2.0 | 20.0 |
| Pb | NR | NR | NR | None | 0 | 0 | 20 | 3.0 | 15.0 |
| Mn | NR | NR | NR** | None | 0 | 0 | 14 | 2.0 | 14.0 |
| As | NR | NR | NR | None | 0 | 0 | 13 | 3.0 | 12.0 |
| K | NR | NR | NR | None | 0 | 0 | 12 | 2.0 | 10.0 |
| Be | NR | NR | NR | None | 0 | 0 | 6 | 4.0 | 10.0 |
| Sr | NR | NR | NR | None | 0 | 0 | 9 | 3.5 | 9.0 |
| F | NR | NR | NR | Apatite (all; Mi) | 6 | 0 | 12 | 4.0 | 9.0 |
| Co | NR | NR | NR | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 0 | 9 | 4.0 | 8.0 |
| Sc | NR | NR | NR | None | 0 | 0 | 5 | 1.0 | 8.0 |
| Sn | NR | NR | NR | None | 0 | 0 | 6 | 4.0 | 7.0 |
| Cd | NR | NR | NR | None | 0 | 0 | 6 | 3.0 | 6.0 |
| Au | NR | NR | NR | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 0 | 6 | 3.5 | 5.0 |
| Bi | NR | NR | NR | None | 0 | 0 | 7 | 3.0 | 5.0 |
| Sb | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 5.0 |
| B | NR | NR | NR | None | 0 | 0 | 2 | 4.0 | 4.0 |
| W | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 4.0 |
| U | NR | NR | NR | None | 0 | 0 | 8 | 4.0 | 4.0 |
| I | NR | NR | NR | None | 0 | 0 | 1 | 4.0 | 3.0 |
| Ta | NR | NR | NR | None | 0 | 0 | 3 | 4.0 | 3.0 |
| Al | NR | NR | NR | Anorthite (Moon; Ab), Spinel (Asteroids; Mi), | 9 | 0 | 2 | 4.0 | 2.0 |
| S | NR | NR | NR | Polar ices (Moon; Mi), Sulfates (Mars; Ma) | 6 | 0 | 6 | 4.0 | 2.0 |
| Th | NR | NR | NR | Monazite (All; Ac) | 3 | 0 | 3 | 4.0 | 2.0 |
| Cs | NR | NR | NR | None | 0 | 0 | 2 | 4.0 | 2.0 |
| Nb | NR | NR | NR | None | 0 | 0 | 3 | 4.0 | 2.0 |
| Ag | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 1.0 |
| V | NR | NR | NR | None | 0 | 0 | 7 | 4.0 | 1.0 |
| Li | NR | NR | NR | None | 0 | 0 | 3 | 4.5 | 0.0 |

| Paragenetic mode[a] | Age (Ga) | Moon | Asteroid | Mars |
|---|---|---|---|---|
| 1. Stellar atmosphere condensates | | 2 | 2 | 2 |
| 2. Interstellar condensates[e] | | 2 | 2 | 2 |
| 3. Solar nebular condensates (CAIs, AOAs, URIs) | >4.565 | 2 | 2 | 2 |
| 4. Primary chondrule phases | 4.566–4.561 | 2 | 2 | 2 |
| 5. Primary asteroid phases | 4.566–4.560 | 2 | 2 | 2 |
| 6. Secondary asteroid phases | 4.565–4.550 | 2 | 2 | 2 |
| 7. Ultramafic igneous rocks | | 2 | 2 | 2 |
| 8. Mafic igneous rocks | | 2 | 2 | 2 |
| 9. Lava/xenolith minerals (hornfels, sanidinite facies) | | 1 | 1 | 2 |
| 10. Basalt-hosted zeolite minerals | | 0 | 0 | 1 |
| 11. Volcanic fumarole minerals; reduced phases (see also #45) | | 1 | 0 | 1 |
| 12. Hadean hydrothermal subsurface sulfide deposits (see also #33) | | 0 | 1 | 1 |
| 13. Hadean serpentinization | | 0 | 1 | 2 |
| 14. Hot springs, geysers, and other subaerial geothermal minerals | | 0 | 0 | 2 |
| 15. Black/white smoker minerals and other seafloor hydrothermal minerals | | 0 | 0 | 1 |
| 16. Low-*T* aqueous alteration of Hadean subaerial lithologies (see also #23) | | 0 | 1 | 2 |
| 17. Marine authigenic Hadean minerals (see also #24) | | 0 | 0 | 1 |
| 18. Minerals formed by freezing | | 0 | 1 | 2 |
| 19. Granitic intrusive rocks | | 1 | 0 | 1 |
| 20. Acidic volcanic rocks | | 2 | 1 | 2 |
| 21. Chemically precipitated carbonate, phosphate, iron formations | | 0 | 0 | 1 |
| 22. Hydration and low-*T* subsurface aqueous alteration (see also #23) | | 0 | 0 | 2 |
| 23. Subaerial aqueous alteration by non-redox-sensitive fluids (see also #47) | | 0 | 0 | 1 |
| 24. Authigenic minerals in terrestrial sediments (see also #17) | | 0 | 0 | 1 |
| 25. Evaporites (prebiotic) | | 0 | 1 | 2 |
| 26. Hadean detrital minerals | | 0 | 0 | 2 |
| 27. Radioactive decay; auto-oxidation | | 0 | 0 | 1 |
| 28. Photo-alteration, pre-biotic | | 1 | 1 | 1 |
| 29. Lightning-generated minerals | | 0 | 0 | 1 |
| 30. Terrestrial impact minerals | | 2 | 2 | 2 |
| 31. Thermally altered carbonate, phosphate, and iron formations | | 0 | 1 | 1 |
| 32. Ba/Mn/Pb/Zn deposits, including metamorphic deposits | | 0 | 0 | 1 |
| 33. Minerals deposited by hydrothermal metal-rich fluids (see also [#12]) | | 0 | 0 | 1 |
| 34. Complex granite pegmatites | | 0 | 0 | 0 |
| 35. Ultra-alkali and agpaitic igneous rocks | | 0 | 0 | 1 |
| 36. Carbonatites, kimberlites, and related igneous rocks | | 0 | 0 | 0 |
| 37. Layered igneous intrusions and related PGE minerals | | 1 | 1 | 1 |
| 38. Ophiolites | | 0 | 0 | 0 |
| 39. High-*P* metamorphism (blueschist, eclogite, ultrahigh *P* facies) | | 0 | 0 | 0 |
| 40. Regional metamorphism (greenschist, amphibolite, granulite facies) | | 0 | 0 | 1 |
| 41. Mantle metasomatism | | 1 | 0 | 1 |
| 42. Sea-floor Mn nodules | | 0 | 0 | 1 |
| 43. Shear-induced minerals (including mylonite/slickensides) | | 1 | 0 | 1 |
| 44. Anoxic microbially mediated minerals (see also #44) | | 0 | 0 | 1 |
| a. [Sulfates, arsenates, selenates, antimonates] | | 0 | 0 | 0 |
| b. [Other oxidized fumarolic minerals] | | 0 | 0 | 0 |
| 46. Near-surface hydrothermal alteration of minerals (see also #22) | | 0 | 0 | 0 |
| a. [Near-surface hydration of prior minerals] | | 0 | 0 | 0 |
| b. [Sulfates and sulfites] | | 0 | 0 | 0 |
| c. [Carbonates, phosphates, borates, nitrates] | | 0 | 0 | 0 |
| d. [Arsenates, antimonates, selenates, bismuthinates] | | 0 | 0 | 0 |
| e. [Vanadates, chromates, manganates] | | 0 | 0 | 0 |
| f. [Uranyl ($U^{6+}$) minerals] | | 0 | 0 | 0 |
| g. [Halogen-bearing surface weathering minerals] | | 0 | 0 | 0 |
| h. [Near-surface oxidized, dehydrated minerals] | | 0 | 0 | 0 |
| i. [Terrestrial weathering of meteorites] | | 0 | 0 | 0 |
| 48. Soil leaching zone minerals | <0.6 | 0 | 0 | 0 |
| 49. Oxic cellular biomineralization (see also #44) | <0.54 | 0 | 0 | 0 |
| 50. Coal and/or oil shale minerals | <0.36 | 0 | 0 | 0 |
| 51. Pyrometamorphic minerals (see also #54 and #56) | <0.36 | 0 | 0 | 0 |
| 52. Guano- and urine-derived minerals | <0.4 | 0 | 0 | 0 |
| 53. Other minerals with taphonomic origins | <0.4 | 0 | 0 | 0 |
| 54. Coal and other mine fire minerals (see also #51 and #56) | | 0 | 0 | 0 |
| 55. Anthropogenic mine minerals | | 0 | 0 | 0 |
| 56. Slag and smelter minerals (see also #51 and #55) | | 0 | 0 | 0 |
| 57. Other minerals formed by human processes | | 0 | 0 | 0 |

| Element | Moon | Asteroids | Mars | Alternatives | Score (with alternatives) | Score (without) | # of Modes | First Stage | Mode Occurrences |
|---|---|---|---|---|---|---|---|---|---|
| Mg | Olivine (Ma) | Olivine (Ma) | Magnesite (Ma) | None | 9 | 9 | 30 | 0.0 | 69.0 |
| Ti | Ilmenite (Ma) | Ilmenite (Ac) | Ilmenite (Mi) | None | 6 | 6 | 27 | 0.0 | 67.0 |
| Fe | Magnetite (Ac) | Magnetite (Mi) | Hematite (Ma) | Native iron-nickel (Moon; Mi) | 7 | 6 | 36 | 0.0 | 64.0 |
| Cr | Chromite (Mi) | Chromite (Mi) | Chromite (Mi) | None | 6 | 6 | 11 | 0.0 | 41.0 |
| Si | Quartz (Ma) | Quartz (Ac) | Quartz (Mi) | Hydrated silica (Mars; Ma) | 7 | 6 | 14 | 1.0 | 34.0 |
| P | Apatite (Mi) | Apatite (Mi) | Apatite (Mi) | None | 6 | 6 | 19 | 2.0 | 28.0 |
| Ca | NR | Dolomite (Mi) | Calcite (Ac) | Gypsum (Mars; Ma) | 5 | 3 | 23 | 2.0 | 37.0 |
| Zr | Zircon (Ac) | Zircon (Ac) | Zircon (Ac) | None | 3 | 3 | 13 | 1.0 | 37.0 |
| Ni | Pentlandite (Ac) | Pentlandite (Ac) | Pentlandite (Ac) | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 3 | 15 | 1.0 | 36.0 |
| C | Graphite (Ac) | Graphite (Mi) | NR | Atmosphere (Mars; Ab), Sequestered Ices (Moon; | 8 | 3 | 13 | 0.0 | 35.0 |
| Cu | Chalcopyrite (Ac) | Chalcopyrite (Ac) | Chalcopyrite (Ac) | Native copper (Asteroids; Mi) | 4 | 3 | 22 | 2.0 | 29.0 |
| Zn | Sphalerite (Ac) | Sphalerite (Ac) | Sphalerite (Ac) | None | 3 | 3 | 15 | 1.0 | 27.0 |
| REEs | Monazite (Ac) | Monazite (Ac) | Monazite (Ac) | None | 3 | 3 | 10 | 3.0 | 13.0 |
| Hg | Cinnabar (Ac) | Cinnabar (Ac) | NR | Polar ices (Moon; Mi) | 3 | 2 | 6 | 2.0 | 13.0 |
| Na | NR | Halite (Ac) | NR | Sodium carbonate (Asteroids; Ma) | 3 | 1 | 8 | 2.0 | 10.0 |
| Cl | NR | Halite (Ac) | NR | Apatite (all; Mi) | 6 | 1 | 8 | 2.0 | 10.0 |
| Mo | NR | NR | NR | None | 0 | 0 | 15 | 2.0 | 22.0 |
| Ba | NR | NR | NR | None | 0 | 0 | 18 | 2.0 | 20.0 |
| Pb | NR | NR | NR | None | 0 | 0 | 20 | 3.0 | 15.0 |
| Mn | NR | NR | NR** | None | 0 | 0 | 14 | 2.0 | 14.0 |
| As | NR | NR | NR | None | 0 | 0 | 13 | 3.0 | 12.0 |
| K | NR | NR | NR | None | 0 | 0 | 12 | 2.0 | 10.0 |
| Be | NR | NR | NR | None | 0 | 0 | 6 | 4.0 | 10.0 |
| Sr | NR | NR | NR | None | 0 | 0 | 9 | 3.5 | 9.0 |
| F | NR | NR | NR | Apatite (all; Mi) | 6 | 0 | 12 | 4.0 | 9.0 |
| Co | NR | NR | NR | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 0 | 9 | 4.0 | 8.0 |
| Sc | NR | NR | NR | None | 0 | 0 | 5 | 1.0 | 8.0 |
| Sn | NR | NR | NR | None | 0 | 0 | 6 | 4.0 | 7.0 |
| Cd | NR | NR | NR | None | 0 | 0 | 6 | 3.0 | 6.0 |
| Au | NR | NR | NR | Native iron-nickel (Moon; Mi), Native iron-nickel | 7 | 0 | 6 | 3.5 | 5.0 |
| Bi | NR | NR | NR | None | 0 | 0 | 7 | 3.0 | 5.0 |
| Sb | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 5.0 |
| B | NR | NR | NR | None | 0 | 0 | 2 | 4.0 | 4.0 |
| W | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 4.0 |
| U | NR | NR | NR | None | 0 | 0 | 8 | 4.0 | 4.0 |
| I | NR | NR | NR | None | 0 | 0 | 1 | 4.0 | 3.0 |
| Ta | NR | NR | NR | None | 0 | 0 | 3 | 4.0 | 3.0 |
| Al | NR | NR | NR | Anorthite (Moon; Ab), Spinel (Asteroids; Mi), | 9 | 0 | 2 | 4.0 | 2.0 |
| S | NR | NR | NR | Polar ices (Moon; Mi), Sulfates (Mars; Ma) | 6 | 0 | 6 | 4.0 | 2.0 |
| Th | NR | NR | NR | Monazite (All; Ac) | 3 | 0 | 3 | 4.0 | 2.0 |
| Cs | NR | NR | NR | None | 0 | 0 | 2 | 4.0 | 2.0 |
| Nb | NR | NR | NR | None | 0 | 0 | 3 | 4.0 | 2.0 |
| Ag | NR | NR | NR | None | 0 | 0 | 5 | 4.0 | 1.0 |
| V | NR | NR | NR | None | 0 | 0 | 7 | 4.0 | 1.0 |
| Li | NR | NR | NR | None | 0 | 0 | 3 | 4.5 | 0.0 |


B
A

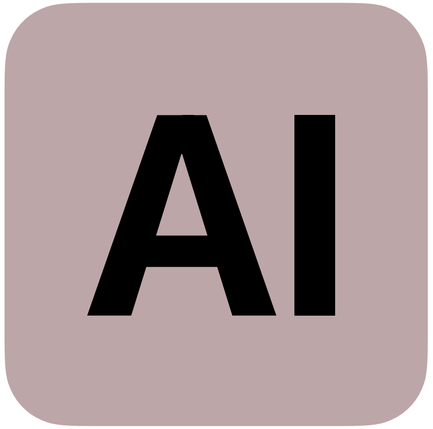

B
A


Positive Electrode
Regolith Feed
Oxygen & Metal Vapor
Heat
Spent Electrolyte
Metal Product
Negative Electrode

Fe Si Al

## 🌎 HALL-HEROUT PROCESS

13–15 kWh for 1 kg Al (bauxite ore)

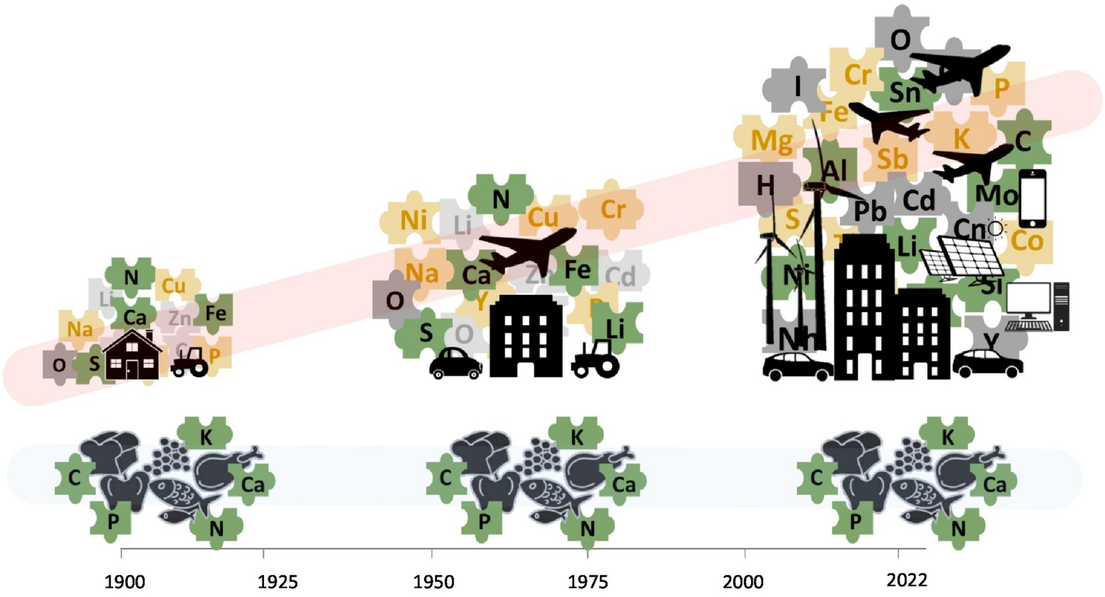



## 🌔 MOLTEN REGOLITH ELECTROLYSIS

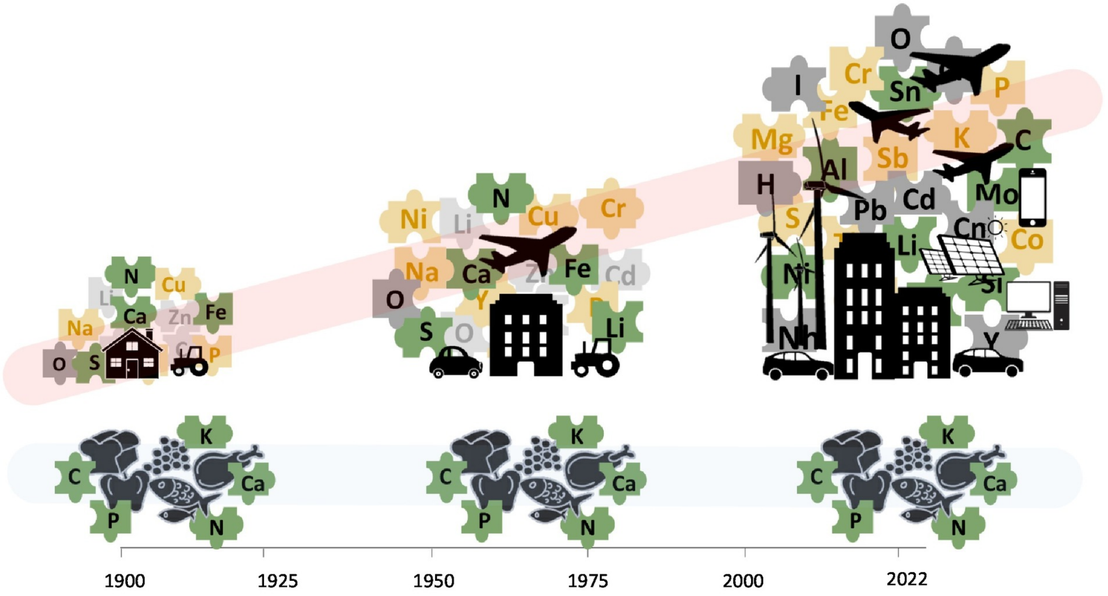
~80 kWh for 1 kg Al

## ⚛️ MASS SPEC/CALUTRON

Up to 250,000 kWh for 1 kg Al (crude estimate based on calutrons)




**Increasing divergence between total and biological human elementomes**




**Increasing divergence between total and biological human elementomes**

innovation

The Spectrum of Clean Energy Innovation

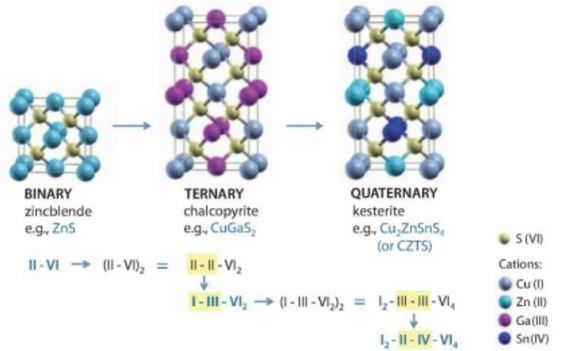
Fundamental Science
Market-Relevant Research
Systems Integration
Testing and Validation
Commercialization
Deployment

# NREL Explores Earth-Abundant Materials for Future Solar Cells

Researchers at the National Renewable Energy Laboratory (NREL) are using a theory-driven technique—sequential cation mutation—to understand the nature and limitations of promising solar cell materials that can replace today's technologies. Finding new materials that use Earth-abundant elements and are easily manufactured is important for large-scale solar electricity deployment.

The goal of the U.S. Department of Energy SunShot Initiative is to reduce the installed cost of solar energy systems by about 75% by the end of the decade. Obtaining that goal calls for photovoltaic (PV) technologies to improve in three main areas: solar-cell efficiencies, material processing costs, and scalability to the terawatt (TW), or $10^{12}$ watt, level. A promising route to simultaneously address all three SunShot challenges may be in discovering and evaluating novel, potentially efficient, and less costly Earth-abundant thin-film PV materials.

Sequential cation mutation is a systematic and theory-driven approach used to narrow a set of candidate materials that may be ideal for use in solar cells. By focusing on altering the composition one element at a time, researchers can examine changes in the optical, electrical, and structural properties of the material and determine which technologies can be further developed by experimentation to meet the SunShot Initiative's performance, cost, and scalability goals.




*The evolution of crystal structures of binary, ternary, and quaternary compounds. To address concerns regarding indium and gallium scarcity, it has been proposed that CIGS can be replaced by $Cu_2ZnSn(S,Se)_4$ in the kesterite structure, in which every two group III (In or Ga) atoms in chalcopyrite structure are replaced by a Zn (group II) and Sn atom (group IV), a substitution that honors fundamental principles of chemistry.*

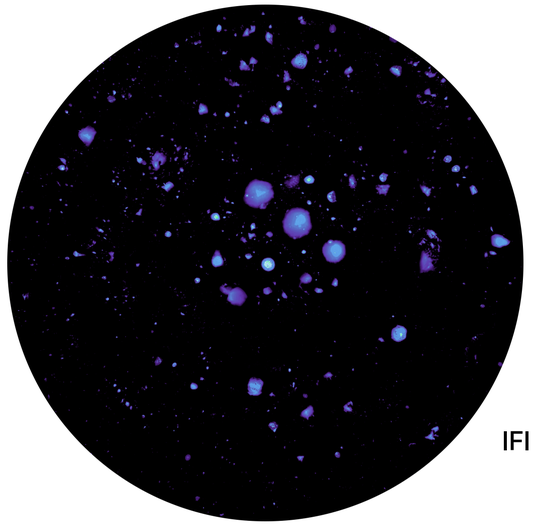
*Through deep technical expertise and an unmatched breadth of capabilities, NREL leads an integrated approach across the spectrum of renewable energy innovation. From scientific discovery to accelerating market deployment, NREL works in partnership with private industry to drive the transformation of our nation's energy systems.*

*This case study illustrates NREL's innovations in Fundamental Science through Market-Relevant Research.*

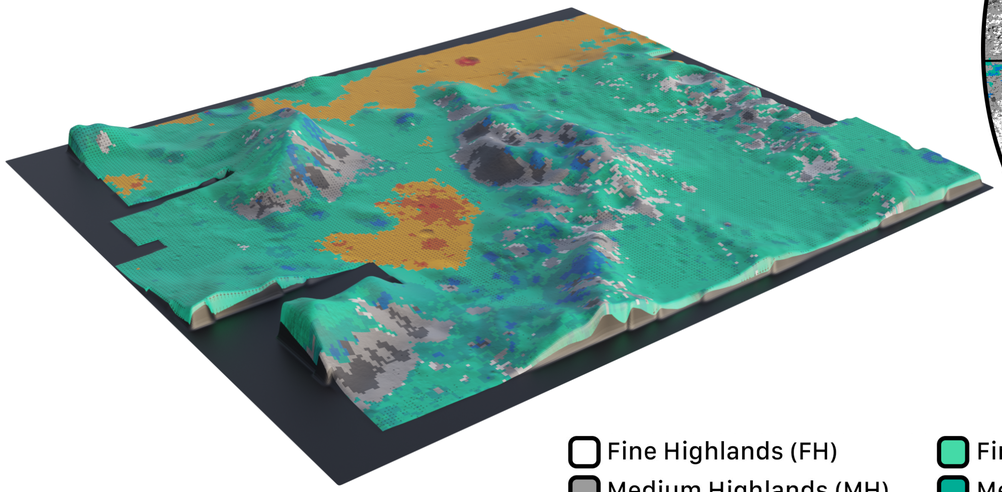
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

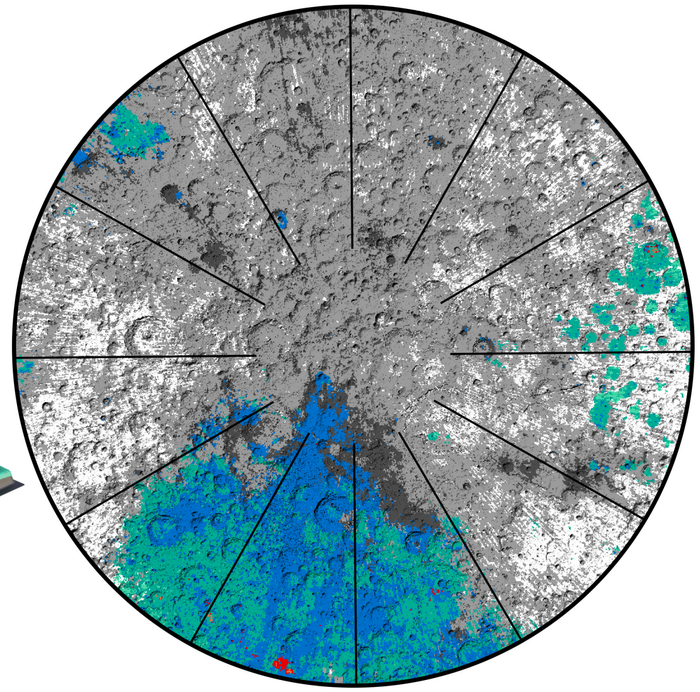
**NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.**

H O Fe Si Al Ti



IFI v2





- Fine Highlands (FH)
- Medium Highlands (MH)
- Coarse Highlands (CH)
- Fine Intermediate (FI)
- Medium Intermediate (MI)
- Coarse Intermediate (CI)
- Fine Mare (FM)
- Medium Mare (MM)
- Coarse Mare (CM)

MOON

H O C Fe N Si

Zn Cr Cu S Ni Mn

MARS