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Scandium

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Element Data
Atomic symbol: ***Sc***
Atomic number: ***21***
Atomic weight: 44.95591
Isotopes and abundances: ^{45}Sc *100 %*
1 Atm melting point: 1541 °C
1 Atm boiling point: 2836 °C
Common valences: 3+
Ionic radii: 6-fold, 74.5 pm, 8-fold, 87 pm
Pauling electronegativity: 1.36
First ionization energy: 633.1 kJ/mol
Chondritic (CI) abundance: 5.81 ppm
Silicate Earth abundance: 16.4 ppm
Crustal abundance: 21.9
Seawater abundance: 2–20 pmol/L
Core abundance: ∼0

Properties

Scandium is the lightest group 3 (IIIB) element and is the lightest of the transition metals. Its atomic number (proton number) is 21, has only one long-lived isotope, and has an atomic mass of 44.95591 u. Scandium's electronic configuration is [Ar]$4s^2 3d^1$ and only occurs in the trivalent state (Sc^{3+}) in nature. Thus, unlike most other period 4 transition metals, the geochemical behavior of scandium is not affected by redox conditions and shows lithophile behavior. The effective ionic radii in six- and eightfold coordination are 74.5 and 87 pm, respectively (Shannon, 1976), and its Pauling electronegativity is 1.36. Pure scandium metal has a melting point of 1541 °C at 1 atm. The International Union of Pure and Applied Chemistry considers Sc to be a rare earth element (REE) (Damhus et al., 2005); however, the ionic radius and electronic configuration of Sc are sufficiently different from yttrium and the lanthanides that it is generally excluded from discussions of the REE.

History and Use

Scandium was "discovered" by Lars Fredrik Nilson in 1879 by separation from rare earth mixtures from euxenite and gadolinite and is named for Scandinavia.

Global production of Sc is small (∼10 tonnes per year) as a by-product from mining of ores of titanium, rare earths, apatite, and uranium. Bauxites are another potential source of Sc, as it gets concentrated, along with other elements, in the "red mud" residue that results from Al processing (Deady et al., 2016). The principal uses of Sc are in Sc-Al alloys and in solid oxide fuel cells. Minor amounts of Sc are also used in a variety of other applications including electronics, lasers, and lighting.

Natural Abundances

The abundance of Sc in the solar system, as estimated from chondritic meteorites, is ca. 5.81 ppm (McDonough and Sun, 1995). The refractory behavior of this element in the solar nebula as well as its lithophile behavior led to the relative concentration of this element in the silicate Earth, with an estimated abundance of about 16 ppm, which is also the

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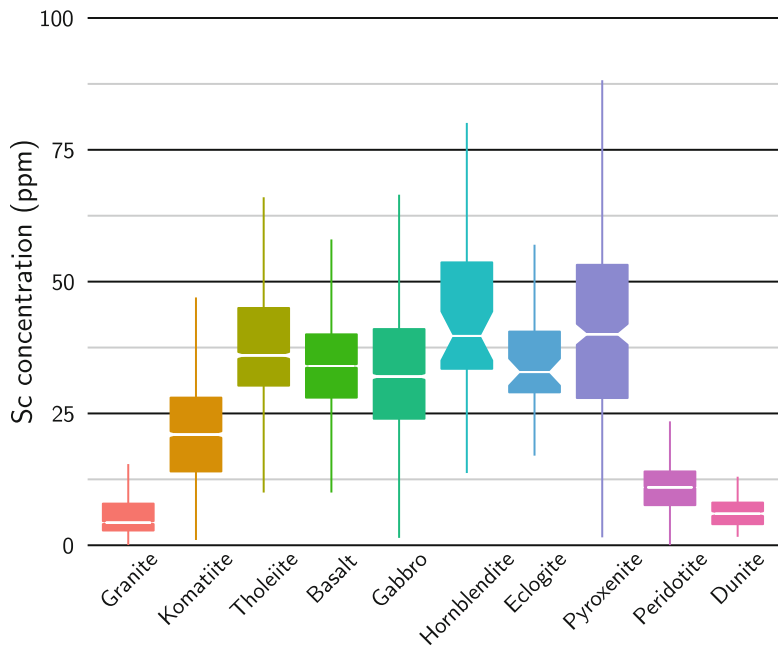


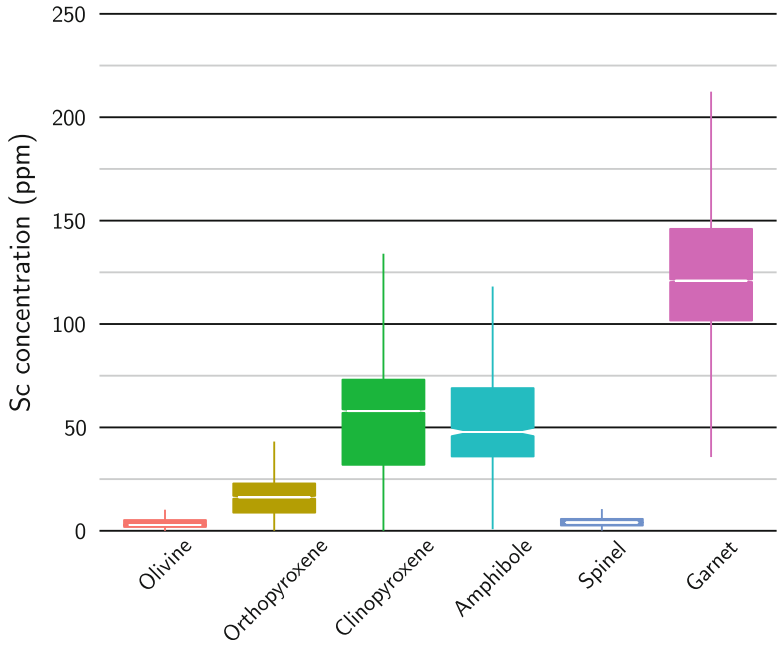
Scandium, Figure 1 Box-and-whisker plot of Sc concentrations in some common lithologies. (Data from the GEOROC database, Sarbas and Nohl (2008); 11,846 analyses.) "Tholeiite" stands for tholeiitic basalt, whereas "basalt" includes a wide range of other basalt types. The boxes represent the first and third quartiles of the data distribution. The horizontal line represents the median, and the width of the adjacent notches provides the 95 % confidence interval about the median. The "whiskers" represent the last value before 1.5 × midrange (arithmetic mean of maximum and minimum values) beyond the first or third quartile.

estimated abundance of the primitive mantle (Palme and O'Neill, 2014). The abundance of Sc in the Earth's continental crust is higher, with average values of 31, 19, and 14 ppm for the lower, middle, and upper crust, respectively, and an average continental crust value of 21.9 ppm (Rudnick and Gao, 2014). It occurs in higher concentrations in oceanic crust as reflected in values in MORB of between 34 and 48 ppm (Klein, 2003). Thus, as with the rare earth elements, scandium is not particularly rare, and is found in similar concentrations in the crust to Pb, and is orders of magnitude more abundant than most of the precious metals in the Earth's crust.

The relatively large ionic radius to charge ratio (ionic potential) of Sc^{3+} means that it is incompatible in the structures of many of the common rock-forming minerals, such that it is generally present in low concentrations, ranging from a few ppm to a few tens of ppm. The concentration of Sc in different rock types is shown in Figure 1. Scandium is generally incompatible in mantle rocks (Davis et al., 2013), which explains the lower Sc concentration in komatiites compared to basalts and the low Sc content of peridotites and dunites. The latter reflects low concentrations and mineral/melt partition coefficients for olivine and spinel compared to garnet, clinopyroxene, and amphibole (Davis et al., 2013; Bédard, 2014; Figure 2). The very similar ionic radii (74.5 and 72 pm in sixfold coordination) and electronegativities (1.36 and 1.31) of Sc and Mg, respectively, explain the substitution of Sc for Mg in the M1 octahedral site of clinopyroxene and M octahedral sites of amphibole. Scandium also substitutes for Mg due to similar ionic radii in the cubic X site of pyrope garnets (Oberti et al., 2006). Felsic rocks, such as granites, are depleted in Sc, as quartz and feldspars cannot accommodate significant amounts of Sc. Because vanadium (V) has comparable behavior to Sc, but also variable valence, V/Sc ratios are sensitive to fO_2 and have been used to provide information on the redox conditions in the mantle (Li and Lee, 2004).

Scandium is residually concentrated in soils and typically reaches concentrations between about 1 and 10 ppm (e.g., Jeske and Gworek, 2013). Coal can contain significant Sc. Average Sc concentrations in a wide variety of coals from Asia range from 0.85 to 16.0 ppm, with an overall average of 4.3 ppm and a maximum value of 230 ppm (Arbuzov et al., 2014). Consequently, coal fly ash can also contain significant Sc, generally several tens of ppm (e.g., Bettinelli et al, 1987; Franus et al., 2015).

Although Sc generally occurs in low concentrations in common minerals and rocks, it can achieve higher concentrations in restricted environments, most notably alkaline igneous rocks, including carbonatites, in granitic pegmatites, in hydrothermal veins, and in some meteorites. It is in these environments that Sc-rich minerals occur.



Scandium, Figure 2 Box-and-whisker plot of Sc concentrations in various mantle-related minerals. (Data from the GEOROC database, Sarbas and Nohl (2008); 21,475 analyses.) The minerals mostly come from xenoliths of various mafic and ultramafic lithologies.

Scandium Mineralogy

Minerals that contain Sc at concentrations greater than a few tens of ppm include Sc-rich varieties of minerals such as columbite, rutile, perrierite, euxenite, ixiolite, and pyrochlore (e.g., Åmli, 1977; Bergstøl and Juve, 1988; Wise et al., 1998), as well as minerals in which Sc is an essential element. There are relatively few minerals known that contain Sc as an essential element, and only seventeen IMA-approved minerals exist, comprising silicates, phosphates, and oxides. Silicates belong to the inosilicate (e.g., cascandite [$Ca(Sc,Fe^{2+})Si_3O_8(OH)$]), cyclosilicate (e.g., bazzite [$Be_3(Sc,Al)_2Si_6O_{18}$]), sorosilicate (e.g., thortveitite [$(Sc,Y)_2Si_2O_7$]), and orthosilicate (eringaite [$Ca_3Sc_2(SiO_4)_3$]) subclasses. Phosphates include anhydrous and hydrous species, such as pretulite [$ScPO_4$] and kolbeckite [$ScPO_4 \cdot 2H_2O$]. A number of scandium-bearing oxides have been recognized, and most of these occur in meteorites, such as allendeite [$Sc_4Zr_3O_{12}$], named for its type locality, the Allende meteorite. These minerals are rare, and, as described above, most scandium on Earth occurs as a trace component of other minerals.

Aqueous Geochemistry

Scandium concentrations in surface waters are invariably very low, generally in the parts per trillion (ppt) range. The limited data available on Sc concentrations in seawater indicate an average concentration of around 13 pmol L^{-1} (~0.6 ppt) (Horovitz, 1999). This is consistent with a profile through the Pacific Ocean that shows a gradual increase from 2 pmol L^{-1} (0.09 ppt) at the surface to 20 pmol L^{-1} (2 ppt) at the ocean floor, which is considered to be a nutrient-like profile (Amakawa et al., 2007). Concentrations in river water are also very low, in the range of 1–16 ppt (Silker, 1964; Tanizaki et al., 1992; Cerutti et al., 2003); however, concentrations can be higher (ppb levels) in acid mine drainage (e.g., Jerez et al., 2014).

The relatively small radius of Sc^{3+} and its trivalent nature make it a "hard" acid in the sense of Pearson (1963) and, in aqueous solutions, will preferentially bond to hard bases, including OH^- and F^-, and certain organic ligands, such as acetate. This is confirmed by available thermodynamic and experimental data which indicate that in most low-temperature environments (pH ~ 4–10), the aqueous complexes $Sc(OH)^{2+}$, $Sc(OH)_2^+$, and $Sc(OH)_3^0$ will predominate. At low pH, Sc^{3+} will predominate. With increasing temperature, the hydroxy complexes with higher ligand numbers are predicted to become increasingly important. Scandium fluoride complexes are relatively stable and could be important in fluorine-rich environments, particularly at low pH. There are few data on the aqueous solubility of the Sc minerals described above. Calculated solubilities for the phase ScOOH at 25 °C indicate low solubilities (~9 ppb) and a solubility minimum between pH ~ 6 and 10, but that under acidic conditions, solubilities can reach several hundred ppm (Wood and Samson, 2006). In low-temperature phosphate-rich environments, the phase $ScPO_4$ is calculated to have even lower solubilities and would severely limit the mobility of Sc (Wood and Samson, 2006), for example, in some soil environments where REE phosphates are known to occur (Aide and Aide, 2012).

Biological Utilization and Toxicity

Scandium does not bioaccumulate readily in plants (Alloway, 2013) and, given the concentrations found in biomaterials, is generally not considered a toxic element, except at higher than normal doses, but can have some beneficial effects on organisms (Bordean et al., 2013). Scandium chloride ($ScCl_3$) is, however, more toxic (Horovitz, 2000).

Summary

Scandium, a lithophile element, is the lightest of the transition elements and has crustal abundances that generally range between 15 and 50 ppm. Scandium can occur in higher concentrations, generally in alkaline rocks, where it can form Sc minerals, but is mostly present as a trace component in a wide range of rock-forming minerals, most easily substituting for Mg. It occurs in very low concentrations in natural waters and does not easily bioaccumulate.

Cross-References

- ▶ Earth's Mantle Geochemistry
- ▶ Earth's Oceanic Crust
- ▶ Electronegativity
- ▶ Elements: Lanthanide Series, Rare Earths
- ▶ Fugacity
- ▶ Geochemical Classification of the Elements
- ▶ Incompatible Elements
- ▶ Ionic Radii
- ▶ Lanthanide Rare Earths
- ▶ Lithophile Elements
- ▶ Low-Temperature Geochemistry
- ▶ Magnesium
- ▶ Marine Geochemistry
- ▶ Meteorites
- ▶ Mid-ocean Ridge Basalt
- ▶ Mineralogy
- ▶ Ore Deposits
- ▶ Oxide Minerals
- ▶ Partitioning and Partition Coefficients
- ▶ Silicate Minerals
- ▶ Soil
- ▶ Solubility
- ▶ Surface Geochemistry
- ▶ Trace Elements
- ▶ Transition Elements

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