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Fluorine in the Earth and the solar system, where does it come from and can it be found?

Le fluor dans la Terre et le système solaire, d'où vient-il et où peut-on le trouver ?

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ABSTRACT

This review (1) presents a summary of the distribution of fluorine in different fluid (surficial, subterranean, metamorphic, and magmatic–hydrothermal–geothermal) and solid (oceanic and continental crust, mantle, and core) domains of the Earth, and various extraterrestrial materials and bodies (meteorites, planets and moons, and the Sun); (2) it provides an estimate of the total fluorine abundance for the Earth and in its dominant reservoirs contributing to the Earth's fluorine endowment; and (3) it discusses key observations that could further improve our understanding of fluorine abundances and geochemical systematics.

RÉSUMÉ

Cet article constitue une synthèse qui présente (i) un résumé de la distribution du fluor dans différents fluides (superficiels, souterrains, métamorphiques, magmatiques, hydrothermauxet géothermaux) et dans les domaines solides de la Terre (croûte continentale, manteau et noyau) comme dans une variété de matériaux et de corps extra-terrestres (météorites, planètes et lunes, ainsi que le Soleil), qui donne (ii) une estimation de l'abondance totale du fluor sur Terre et de sa proportion dans chacun des principaux réservoirs terrestres, et qui fournit (iii) une discussion des observations clés qui pourraient accroître encore notre compréhension des abondances du fluor et de sa systématique géochimique.

Mots clefs:
Fluor
Terre
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Géochimie

1. Introduction

Since Goldschmidt [1] presented his pioneering vision to study element distribution in various natural materials, geochemists have produced a large body of data describing the abundance of elements and isotopes in natural objects. Such data have lead to Earth Scientists to identify the geologic processes operating on the planet today. An Earth scientist was asked to give a summary about F in the Earth at *Colloque Français de Chimie du Fluor* 2017, Murol (CFCF 2017). Luckily, we have just completed a review article

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discussing the significance of F and other halogens in the nature [2]. This article aims to introduce the discussion given in that article to the community of CFCF 2017 and beyond geochemical perspectives about F found in water and rocks.

Fluorine plays an important role in geochemical and biogeochemical systems despite its relatively low overall abundance on the Earth and in the Cosmos. For example, F can exert a significant control on the behavior and composition of magmas [3], the composition of hydrothermal fluids, and the transportation of ore metals in the crust [4]. Fluorapatite is a well-known mineral constituting teeth of many animals. Furthermore, it has been reported that a geologic input of F in nature affects the environment and human health [5]. Knowledge of the key F reservoirs can be used to address many ongoing areas of research for geochemists. For example, these include tracing the evolution and source of hydrothermal fluids and how they play a role in ore deposit formation, metamorphism and subsolidus alteration, tracking mantle to crust mass transfer associated with subduction, and the modeling marine-land biogeochemical cycling. In this review, we present descriptions of the distribution of F in various terrestrial and extraterrestrial rocks, fluids, and reservoirs. Some representative data sets from these media are presented, and a short discussion is also presented on the Earth's F mass balance.

2. Origin of fluorine in the solar system

Fluorine was produced via nucleosynthetic processes in stars, which predate the solar system [6]. Specifically, fluorine, with a single mass $^{19}_{9}F$ was produced through neutrino spallation of ^{20}Ne and cascade reactions of hydrogen–helium burning involving ^{14}N, ^{18}F, ^{18}O, and ^{15}N [7]. During the formation of the solar system, gaseous nebula of elements (including F) was condensed to form dust and grains, which were accreted to form planetesimals and planets. During this condensation, F behaves as a moderately volatile element with a 50% condensation temperature of 734 K for fluorapatite [8].

The abundance of F in the solar system has been assessed by several methods, including spectrometry of the Sun's photosphere and corona, and measurements of particles derived from the Sun (such as solar wind) and meteorites that are rich in volatile element (such as CI chondrite). However, data of high-energy particles from the Sun (known as solar energetic particles) provide a strong constraint on its composition, they are also biased to lower abundances for the atoms with high first ionization potential [9] (note first ionization potential of F is 17.4228 eV; CRC Handbook). Absorption signals from sunspots have also been used for photosphere abundances of F, but the data have significant uncertainty [10]. Recommended solar abundance values for F are therefore tied to assessments of CI chondrite composition. This is because the abundance of volatile elements (including F) decreases from CI to CV (Fig. 1), indicating CI as the best representation of an early condensed object. Despite the challenges faced by different methods, the abundance data agree within the data uncertainties, which are 10% (Table 1).

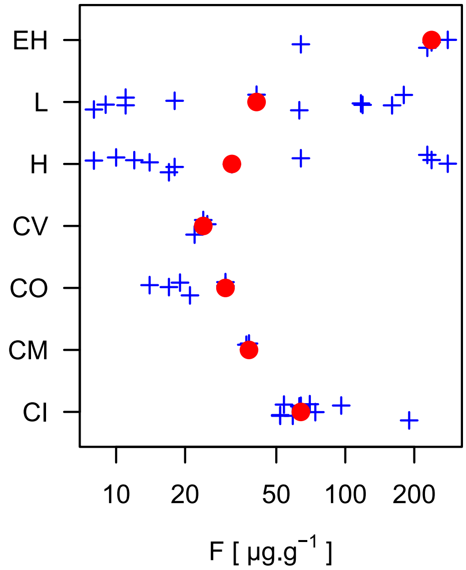

Fig. 1. Abundance of fluorine found in different classes of meteorites. The meteorites classifications are indicated as CI, CM, CO, CV, H, L, and EH. They are all chondritic meteorites of which CI is rich in volatile element and considered as the closest representation of the solar system. Note the concentration axis (horizontal) is on the log scale. The filled red circles are published compilation values [58]. Blue crosses are individual values.

There are several assessments of F abundances in CI chondrites, and reported values differ by some degrees (Table 2). These variations reflect an increased number and improved quality of measurements in recent years. In addition to these changes, the variation in the solar F abundance is also due to the choices of the average Si content for CI chondrites and the statistical weight of Longueuil meteorite (France), which is the largest CI chondrite meteorite with an observed fall. In consequence, there are more studies of Orgueil than other CI chondrites. Nevertheless, the variations in the reported average F abundance of CI chondrites are comparable to other relatively well-characterized elements. We conclude that F abundance in the solar system is 59 ± 5 μg g^{-1} as a weighted average of the values in Table 2.

Table 1
Solar system abundance of fluorine ($Si = 10^6$).

Solar photosphere	CI [9,43]	CI [44]	CI [8]
812 (617)	843 (126)	806 (121)	804 (121)

Normalized to $Si = 10^6$. Data of solar photosphere is from Ross and Aller [42], and the values are converted by $10^{(\log A - 1.65)}$, where "log A" is reported in the article. Numbers inside parentheses indicate one standard deviation of least significant digits, for example, 25(10) should read as 25 ± 10 and 0.51(9) as 0.51 ± 0.09.

Table 2
Abundance of fluorine in CI chondrite (ppm = μg g^{-1}).

Orgueil [43]	CI [9]	CI [44]	CI [8]
58.2 (8.7)	60.7 (9.1)	58.2 (8.7)	58.2 (8.7)

Concentration is reported as ppm (i.e., μg g^{-1}). Values in the parenthesis are one σ standard deviation.

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