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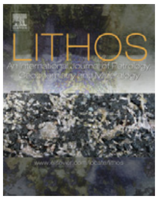

# Extra-terrestrial igneous granites and related rocks: A review of their occurrence and petrogenesis

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ABSTRACT

The telluric planets and the asteroid belt display the same internal structure with a metallic inner core and a silicate outer shell. Experimental data and petrological evidence in silicate systems show that granite can be produced by extreme igneous differentiation through various types of igneous processes.

On Moon, 4.4–3.9 Ga granite clasts display dry mineral assemblages. They correspond to at least 8 discrete intrusive events. Large K/Ca enrichment and low REE abundances in granite relative to KREEP are consistent with silicate liquid immiscibility, a process observed in melt inclusions within olivine of lunar basalts and in lunar meteorites. Steep-sided domes identified by remote sensing can represent intrusive or extrusive felsic formations.

On Mars, black-and-white rhythmic layers observed on the Tharsis rise along the flanks of the peripheral scarps of the Tharsis Montes giant volcanoes suggest the possible eruption of felsic pyroclastites. Though no true granites were found so far in the Martian SNC meteorites, felsic glasses and mesostases were identified and a component close to terrestrial continental (granitic) crust is inferred from trace element and isotope systematics.

Venus has suffered extensive volcanic resurfacing, whereas folded and faulted areas resemble terrestrial continents. Near large shield volcanoes, with dominant basaltic compositions, steep-sided domes have been interpreted as non-degassed silicic extrusions. The hypothesis of a granitic component is "tantalising".

Extra-terrestrial granite is frequently found as clasts and mesostases in asteroidal meteorites. Porphyritic textures, with alkali feldspar crystals up to several centimetres in size, were observed in silicate enclaves within iron meteorites. In the chondrite clan, polymict breccias can contain granitic clasts, whose provenance is debated. One clast from the Adzhi-Bogdo meteorite yields a 4.53 ± 0.03 Ga Pb–Pb age, making it the oldest known granite in the solar system.

The vast majority of granitic materials recognised so far in the extra-terrestrial record are characterised by ferroan A-type compositions, characterised by high to very high $K_2O$ and medium CaO contents, sodic varieties being exceedingly rare. Textural evidence of graphic quartz–alkali feldspar intergrowths within crystallised products suggests that they are igneous in origin and crystallised quickly from a liquid. In water-depleted to water-free environments, fluorine and chlorine can play significant roles, as their effects on liquidus temperatures and crystallising assemblages are nearly identical to those of water. The distribution of alkalis and alkaline earths cannot be related only to extensive crystal fractionation, but is likely induced by supplementary silicate liquid immiscibility. Medium-temperature silicate liquid immiscibility is well known as a mode of differentiation in experimental petrology studies at very low pressures on systems dominated by Fe, Ti, K, and P as major elements.

The ultimate question is, therefore, not whether granite (s.l.) occurs in any given planetary body, but if sufficient volumes of granitic materials could have been produced to constitute stable continental nuclei.

## 1. Introduction

Granite, a major component of the Earth's crust, can be generated in all geodynamic settings. Well exposed at the Earth's surface, it represents only 0.001% of the bulk planet (Clarke, 1996). Considering that it occurs dominantly within the upper part of the continental crust and, albeit in smaller amounts, within the lower continental crust and oceanic crust as well as within the upper mantle (Bonin and Bébien, 2005), the total mass of Earth's granitic rocks could amount to ~$10^{19}$ t, which corresponds (assuming an average density of 2.67) to a volume of ~$3.75*10^9$ $km^3$.

Granite low density favours continental accretion. Thus, the occurrence or absence of granite and associated silicic volcanism in the telluric planets is not a trivial question. Granite is generally thought to be produced through "wet" hydrous-bearing processes. The opposite lunar evidence shows that dry conditions may apply as well. Terrestrial planets, from Mercury to the asteroid belt, therefore provide an attractive challenge assessing the granite inventory within our solar system.

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The fundamentals of the argumentation are based on the following two lines of evidence: (i) telluric planets, including the Earth and the asteroid belt, display an identical internal structure with a metallic inner core and a silicate outer shell, (ii) experimental petrology provides ample evidence that granite can melt at various pressures, even less than $10^5$ Pa and at temperatures of the order of 600–1000 °C, which are the lowest recorded in silicate systems. Thus, there is no reason why granite cannot occur in the silicate outer shell of any telluric planets. Since a preliminary review (Bonin et al., 2002), the data set of observed and/or inferred extra-terrestrial felsic igneous rocks has been considerably expanded.

The mineralogical, petrological, chemical and field aspects of intermediate and felsic silicate rocks from the Moon, Mars, Venus, and meteorites are reviewed and discussed in this paper. Evidence for granite occurrence in planets beyond the asteroid belt is not available for discussion. *Granite* is given here the wider sense of *granitoid*. In the simplified "field" classification of plutonic rocks, *granitoid* refers to "any plutonic rock consisting essentially of quartz, alkali feldspar and/or plagioclase … tentatively identified as granite, granodiorite or tonalite" (Le Maitre, 1989). Albite being alkali feldspar as well as plagioclase, alkali feldspar granite enters this group as well. Due to severe size limitations, modal data are rarely offered in the extra-terrestrial literature. The wide variety of rock types is illustrated by simple major-element chemical diagrams.

The TAS diagram is modified from the original one (Le Maitre, 1989) by the addition of the feldspathoid (nepheline)–alkali feldspar–silica boundary line. This line separates the fields for natural rocks from a "forbidden" zone, in which only peralkaline compositions can plot. The alkaline–subalkaline boundary line is from Miyashiro (1976).

Similarly, the MALI diagram is modified. The original diagram (Frost et al., 2001) was drawn for compositions ranging from 50 to 75 wt.% $SiO_2$ only. Like in the TAS diagram, the feldspathoid (nepheline)–alkali feldspar–silica boundary line separates the fields for natural rocks from a "forbidden" zone, in which only peralkaline compositions can plot. Many extra-terrestrial samples are highly silicic, so that the four fields determined by alkali-lime indices are extended up to 80 wt.% $SiO_2$ compositions, while taking into account dilution effects exerted on CaO, $Na_2O$ and $K_2O$ abundances by extremely high quartz ($SiO_2$) amounts.

## 2. Granite occurrences in the asteroid belt

The Earth accretes currently 15,000 – 50,000 t of extra-terrestrial matter per year, but most of it (~95 wt.%) is dust, within the 40–1500 μm particle grain-size range, forming micrometeorites. Pristine micrometeorites recovered in polar ice sheets are compositionally varied. Carbonaceous chondrites predominate (Engrand and Maurette, 1998; Kurat et al., 1994). Recently, non-chondritic matter was identified (Gounelle et al., 2009; Taylor et al., 2007).

### 2.1. Terrestrial and extra-terrestrial granites in the meteoritic record

Extra-terrestrial granites provide qualitative insights on the internal evolution of telluric planets. A preliminary discussion on whether and how terrestrial and extra-terrestrial granitoids can be discriminated is necessary here. Tektites are silicic ($SiO_2 > 65$ wt.%) glasses ejected from terrestrial impact craters over large distances. Their chemical and isotopic compositions show that they formed by melting of the Earth's upper crust. In their review of terrestrial impact formations, Dressler and Reimold (2001) reported no crystallised silicic materials, suggesting that either they did not survive impact and were completely melted during ejection, or they could not be distinguished from other granitic blocks or gravels in the sedimentary record.

If it is not so easy to recognise terrestrial granites in the meteoritic record, it is likely that extra-terrestrial granites are even more difficult to detect. The probability to observe extra-terrestrial granites in the dust collection and to distinguish them from terrestrial particles is exceedingly low. In the meteoritic record, rare individual fragments have been recognised through mineralogical oddities and/or isotopic anomalies. The bulk of silicic occurrences is made up of crystalline and glassy enclaves and groundmasses in the majority of meteorite types, supplemented by clasts within polymict breccias. As they can be easily fragmented into barely recognisable particles, their apparent paucity could be meaningless in terms of absolute abundances in the solar system. Despite their scarcity and small sizes, the granitic material observed in contrasting meteorite types sheds light on the feasibility of highly evolved liquids of granite composition in the asteroidal belt.

### 2.2. Granites in iron meteorites

Iron meteorites consist overwhelmingly of iron–nickel alloys. As they are easy to detect and despite their rarity, they constituted one of the earliest sources of usable iron available to humans, as evidenced by artefacts from the 5th millennium BC in Iran. Most irons are related to M-type, *i.e.* metal-rich, asteroids and interpreted as fragments of the cores of about 50 larger ancient bodies that have been shattered by impacts. Silicate enclaves, though not uncommon, display high-Mg silicate mineralogy and no silicic glasses.

The exceptional IIE class of irons is interpreted as originating from the crust of the S-type, *i.e.* silicate-rich, asteroid 6Hebe. They show a large diversity, among which Colomera, Kodaikanal and Weekeroo Station form a distinctive group. Fairly abundant high-alkalicate enclaves define a compositionally expanded calcic to alkaline andesite–trachyte–rhyolite trend, with sodic and scarce sodic–potassic varieties (Fig. 1). They were the first meteoritic constituents to give reliable Rb–Sr and K–Ar ages. Dates determined in the 1960s were consistent with the "rhyolitic plums in the pudding" model. Silicates (plums) crystallised from strongly differentiated silicate liquids, which were trapped in the cooling metal (pudding) at a relatively shallow depth in the parent body after a shock event.

The Colomera IIE iron meteorite is outstanding, because silicate enclaves containing alkali feldspar megacrysts up to several centimetres in length are reported at its surface. Two types of silicate enclaves, K-rich at the surface and K-poor in the interior, illustrate the entire range of compositions (Fig. 1). In the K-rich surface of the enclave, K-feldspar (sanidine) phenocrysts, orthopyroxene and relict olivine coexist with silica and sub-rounded Cr-diopside. Textural relationships suggest that a K-rich silicate liquid segregated as a fluid phase that leached K from surrounding materials. The interior of silicate enclaves is chiefly composed of Cr-diopside and albite, coexisting with chromite, chlorapatite, whitlockite and a silica-oversaturated albitic glass containing minor mafic components. The absence of large enclaves in the core of the meteorite suggests that Colomera formed as a small-mass molten iron segregation contained in a silicate matrix. The drop-like silicate enclaves are considered as globules of molten silicate, which were trapped into the freezing Fe–Ni liquid (Takeda et al., 2003). Albite, sanidine, diopside, whitlockite, and a clear pink glass define an isochron Rb–Sr age of 4.59 ± 0.13 Ga (recalculated with the decay constant of $1.402 * 10^{-11}\ a^{-1}$), and a BABI-like $^{87}Sr/^{86}Sr$ initial isotopic ratio of 0.6994. Despite the large scatter of data (MSWD = 66.5), an upper limit of 47 ± 7 My can be set for the time interval between dispersion of silicate liquid in the metal phase and final Sr isotopic equilibration (Sanz et al., 1970).

The Kodaikanal iron meteorite is characterised by abundant up to 2 cm-large silicate enclaves containing diopside, orthopyroxene, two species of alkali feldspar, and an alkali feldspar glass (Fig. 1). Though the host Fe–Ni metal retains a Re–Os age of 4.62 ± 0.02 Ga, silicate enclaves yield Rb–Sr, U–Pb, and Ar–Ar ages clustered at 3.75–3.68 Ga. The two contrasting groups of ages suggest resetting by a large impact event inducing melting and differentiation of metal and silicates (Bogard et al., 2000).