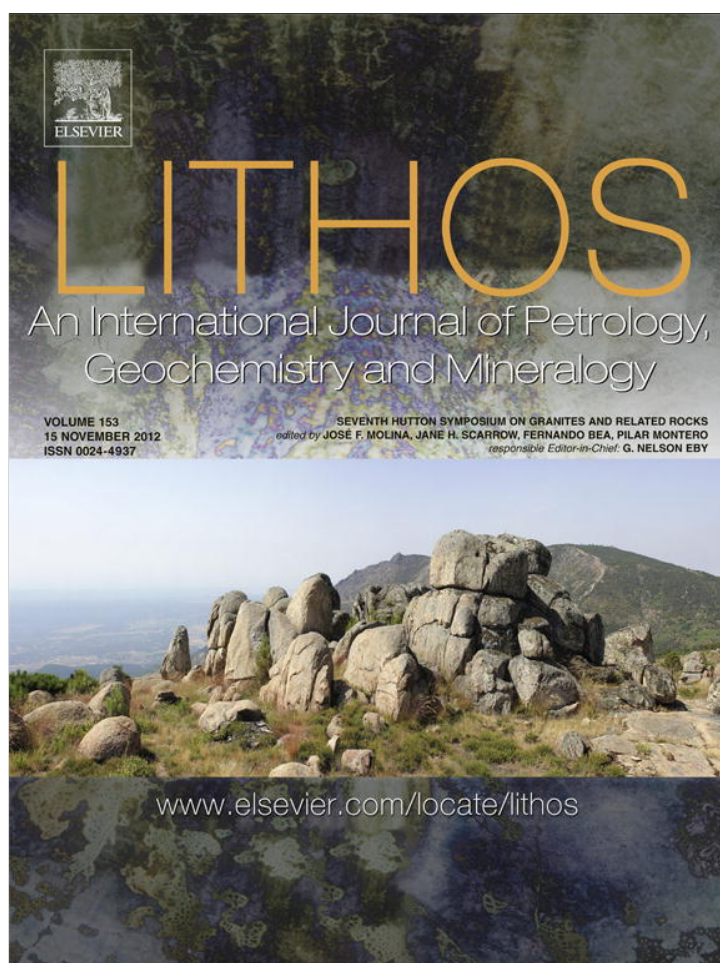




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Extra-terrestrial igneous granites and related rocks: A review of their occurrence and petrogenesis

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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.

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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 $\sim 10^{19}$ t, which corresponds (assuming an average density of 2.67) to a volume of $\sim 3.75 \times 10^9$ km³.

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 ($\text{SiO}_2 > 65$ 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 $1.402 \times 10^{-11} \text{ a}^{-1}$), and a BABI-like $^{87}\text{Sr}/^{86}\text{Sr}$ 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).

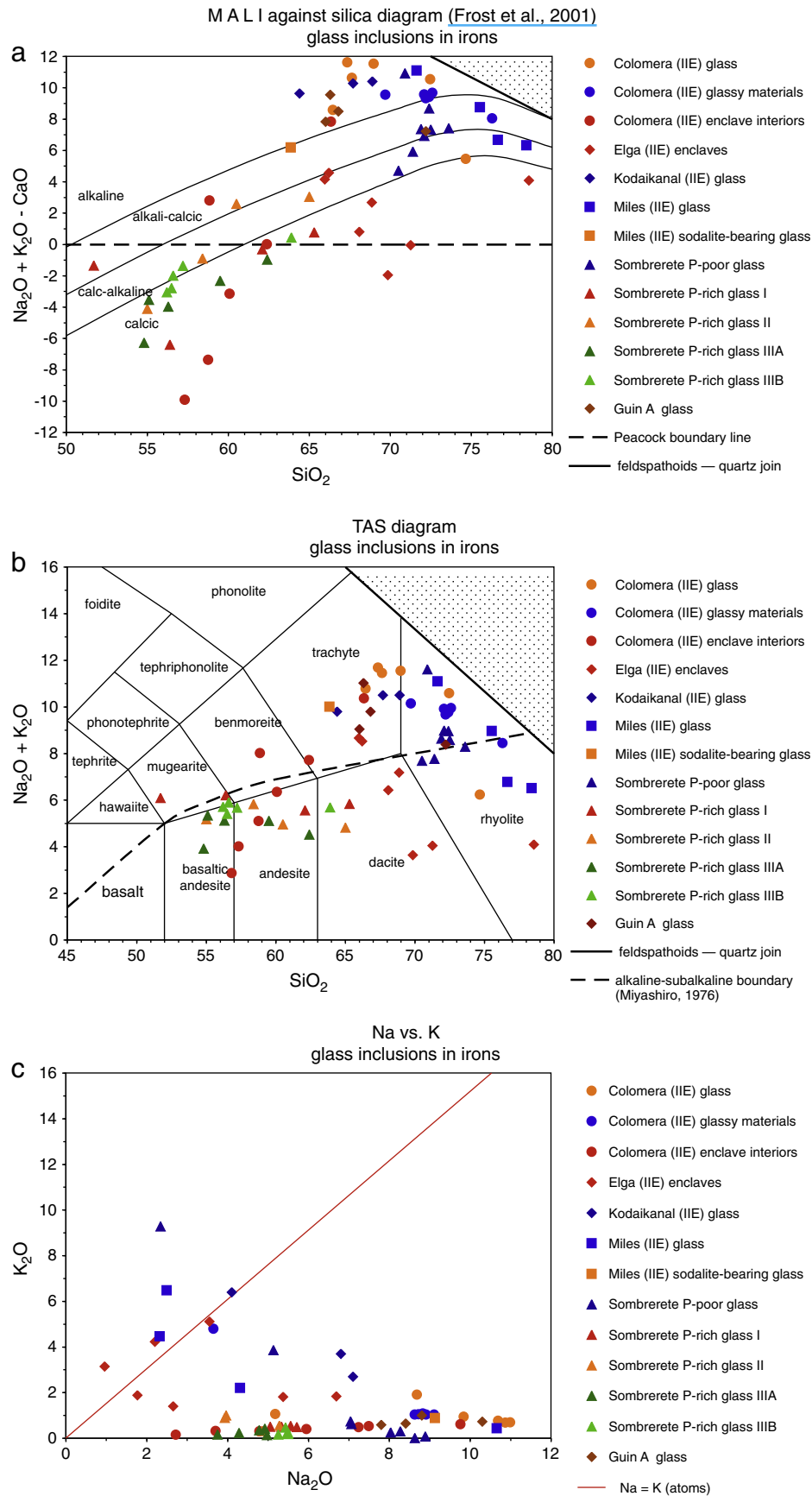


Fig. 1. Nomenclatural diagrams for glass inclusions in iron meteorites. a. MALI against silica diagram (modified from [Frost et al., 2001](#)). The feldspathoids–quartz join (thick line) and the Peacock line (dashed thick line) are indicated. b. TAS diagram (modified from [Le Maitre, 1989](#)). The feldspathoids–quartz join (thick line) is indicated. c. Na_2O vs. K_2O diagram. The straight line corresponds to $\text{Na} = \text{K}$ (in atoms) compositions.

The silicate enclaves of the Weekeroo Station iron meteorite, though lacking large alkali feldspar phenocrysts, yield Rb–Sr and K–Ar ages from 4.49 ± 0.10 to 4.33 ± 0.23 Ga, overlapping within analytical uncertainty and roughly similar to Colomera. Fairly high $^{87}\text{Sr}/^{86}\text{Sr}$ initial isotopic ratios range from 0.7013 to 0.703. CHUR-normalised Nd model ages of 700 Ma of two silicate enclaves are interpreted as implying a protracted history of processing of the silicate portion of the parent body (Snyder et al., 2001).

The current isotopic record evidences several stages of melting, mixing, and processing by impacts over a period of 3 Gy. Hf–W isotopic studies in metal and silicates offer little evidence that silicate enclaves were ever in equilibrium with the host Fe–Ni metal (Snyder et al., 2001). This opens a large room for doubt regarding the nature of parent bodies and their alleged relationship with H chondrites (see also Bogard et al., 2000).

2.3. Granites in achondrites

Achondrites, with dominantly basaltic compositions, are interpreted commonly as pieces of crust formed in planetary bodies in the asteroidal belt. They can represent products of early whole planetary body melting (e.g., lunar ferroan anorthosites), residuum of low degrees of melting and melt extraction (e.g., acapulcoites and lodranites), or products of episodic mantle partial melting (e.g., lunar and martian basalts). Many achondrites contain silicate glasses yielding intermediate to silicic, calcic to alkaline compositions, with dominantly sodic and scarce sodic–potassic varieties (Fig. 2). Silicate glasses are either magnesian, or ferroan, depending upon the achondrite group, in which they are found.

Aubrites display abundant (13–51 vol.%) rhyolitic compositions. They are issued from E, i.e. enstatite and chondrites (Fogel, 2005), so that rhyolitic enclaves and inclusions, even the more differentiated ones, retain magnesian characteristics. Igneous clasts are sodic (67–73 wt.% SiO_2 , 5.8–7.8 wt.% Na_2O), resembling tonalite–trondhjemite, while glass inclusions are highly evolved (74–80 wt.% SiO_2), less rich in Na_2O (1–4 wt.% Na_2O), and have Na–K (in atoms).

The Dar al Gani (DaG) 896 meteorite yields different features. It is a primitive achondrite sharing affinities with igneous enclaves in the H, i.e. high in iron, group of ordinary chondrites. It can represent a sample of a dyke complex intruding a cooler basement below a crater floor (Folco et al., 2000). The picritic host lithology is governed by olivine microcrysts set within a groundmass consisting mainly of interstitial glass and, to a lesser extent, by chondritic relicts. The silicic interstitial glass yields K-poor, Na-rich subalkaline rhyolite composition. The meteorite is veined and locally brecciated, indicating surface reworking due to moderate shock events. The first major shock event ~3.7 Ga ago may mark the early disruption of the initial H chondrite parent body. Ar–Ar ages of the later events are bracketed between 2.6 and 1.7 Ga ago.

Ureilite regolith breccias are mainly monomict, but contain in some cases a significant amount (~2 vol.%) of feldspathic components. The most abundant population is characterised by albitic plagioclase in association with pyroxenes, phosphates, ilmenite, a silica phase forming small blocky crystals, and incompatible element-enriched glass. Glasses range from ferroan Na-rich and K-poor benmoreite to rhyolite. From model calculations, intermediate to silicic glasses formed by extensive fractional crystallisation of primary magmas, from which the most magnesian ureilites crystallised. Such primary magmas were produced early and extracted rapidly from the ureilite parent body (Cohen et al., 2004).

A unique granite clast, $550 \times 850 \mu\text{m}$ in size (Downes et al., 2009), was observed in the EET 87720 polymict ureilite breccia, recovered in 1989 from Elephant Moraine, Antarctica. It is composed of granophyre-like intergrowths of quartz and An_{1-7} albite and of a euhedral normally zoned An_{17-9} oligoclase phenocryst, suggesting that the clast was part of a larger granite fragment. Due to its fragmental aspect, no reliable compositions could be obtained. Its presence in an achondritic regolith

indicates that granite was already present on differentiated planetary bodies involved in collisions early in the solar system history.

The howardite–eucrite–diogenite (HED) family of achondrites probably came from the asteroid 4Vesta (Barrat et al., 2000; and references therein). Meteorites of the HED family are characterised by low to very low alkalis and incompatible element abundances. Glass inclusions and mesostases are not granitic, but range from andesite to dacite. Five unpaired howardite breccias yield K-rich lithologies (Barrat et al., 2009). In the NWA 1664 howardite, one composite spherule, interpreted as impact melt, displays a complex immiscible association of two magnesian, one K-poor (0.06 wt.% K_2O) and the other K-rich (up to 1.4 wt.% K_2O), basaltic glasses coexisting with a K-rich ferroan dacite glass. They evidence that differentiated K-rich rocks occur at the surface of Vesta (Barrat et al., 2009). Similarly, in EET 90020 eucrite, a hot crust (~870 °C) underwent a short reheating event up to 1060 °C, causing partial melting and rapid cooling, 4.51 ± 0.04 Ga ago. A [pyroxene + plagioclase + K-bearing tridymite ± apatite ± merrillite] assemblage crystallised from a silica-oversaturated liquid of unknown composition (Yamaguchi et al., 2001). However, the occurrence of silica phases, diagnostic of granitoid, should not always be used as evidence for silicic liquids. In the Tatahouine diogenite, inclusions within orthopyroxene of α -cristobalite are locally in symplectic association with chromite, or associated with metal. The [SiO_2 + chromite + metallic iron + pyroxene] assemblage is explained by breakdown reaction under reducing conditions without incongruent melting (Benzerara et al., 2002).

Last, two paired achondrites, discovered in the 2006 meteorite field season on the Graves Nunataks Ice Field, Antarctica, and known as GRA 06128/06129 (Day et al., 2009; Shearer et al., 2008), attracted considerable interest from the meteorite scientific community, due to intermediate composition distinct from any other known achondrites. Mineral paragenesis is dominated by a high abundance (~81 vol.%) of sodic plagioclase (oligoclase An_{16-13}), two pyroxenes (~9 vol.%), and Fe-rich olivine Fo_{41-40} (~8 vol.%). Fe–Ni alloy (64–68 wt.% Ni), troilite, and pentlandite are included in olivine grains. Pyroxene exsolution lamellae suggest that the meteorites formed close to the surface of their parent body. Apatite (Cl~5.0 wt.%, F~0.7 wt.%) overgrowths on halogen-poor merrillite occur in individual phosphate clusters up to 600 μm in size (~1 vol.%). Ilmenite and spinel are commonly intergrown in trace abundances. Iron-rich mafic silicates and sodic plagioclase imply that GRA 06128/06129 is highly evolved. Accordingly, they yield intermediate mugearite to trachyte alkaline compositions. The cooling age of 4.52 ± 0.06 Ga (Pb–Pb isotope data on chlorapatite, corresponding to ~500 °C closure temperature) argues against an origin in major planetary bodies, including Venus and Mercury, and demonstrates that they formed early in the solar system history. The enigmatic origin is emphasised by oxygen isotopic compositions that differ from most known differentiated bodies, including the Earth, the Moon, and Mars.

2.4. Unexpected occurrences of granite in chondrites

Because they are not differentiated, chondrites were not supposed to include granitic melts. Accordingly, scarce non-altered glasses observed in carbonaceous chondrites have been observed. They range from basaltic andesite to phonolite in the TAS diagram (Fig. 3). No granite compositions were identified.

Non-carbonaceous chondrites are quite different in that respect. The Bovedy L3 chondrite contains a large ($4.5 \times 7 \times 4 \text{ mm}$) igneous-textured clast of silica-rich orthopyroxenite, which consists of normally zoned orthopyroxene, tridymite, an intergrowth of feldspar and sodic glass, pigeonite, and small amounts of glass, together with chromite, augite and Fe–Ni metal. The moderately silicic glass, of andesitic composition (Fig. 3), is rather similar in composition to the mean of the interior of enclaves in the Colomera IIE iron meteorite (Fig. 1). The clast is not regarded as a chondritic component. Rather it is interpreted as an igneous differentiate from a siliceous liquid that probably cooled in the near-surface region of another parent object, which was an asteroid or

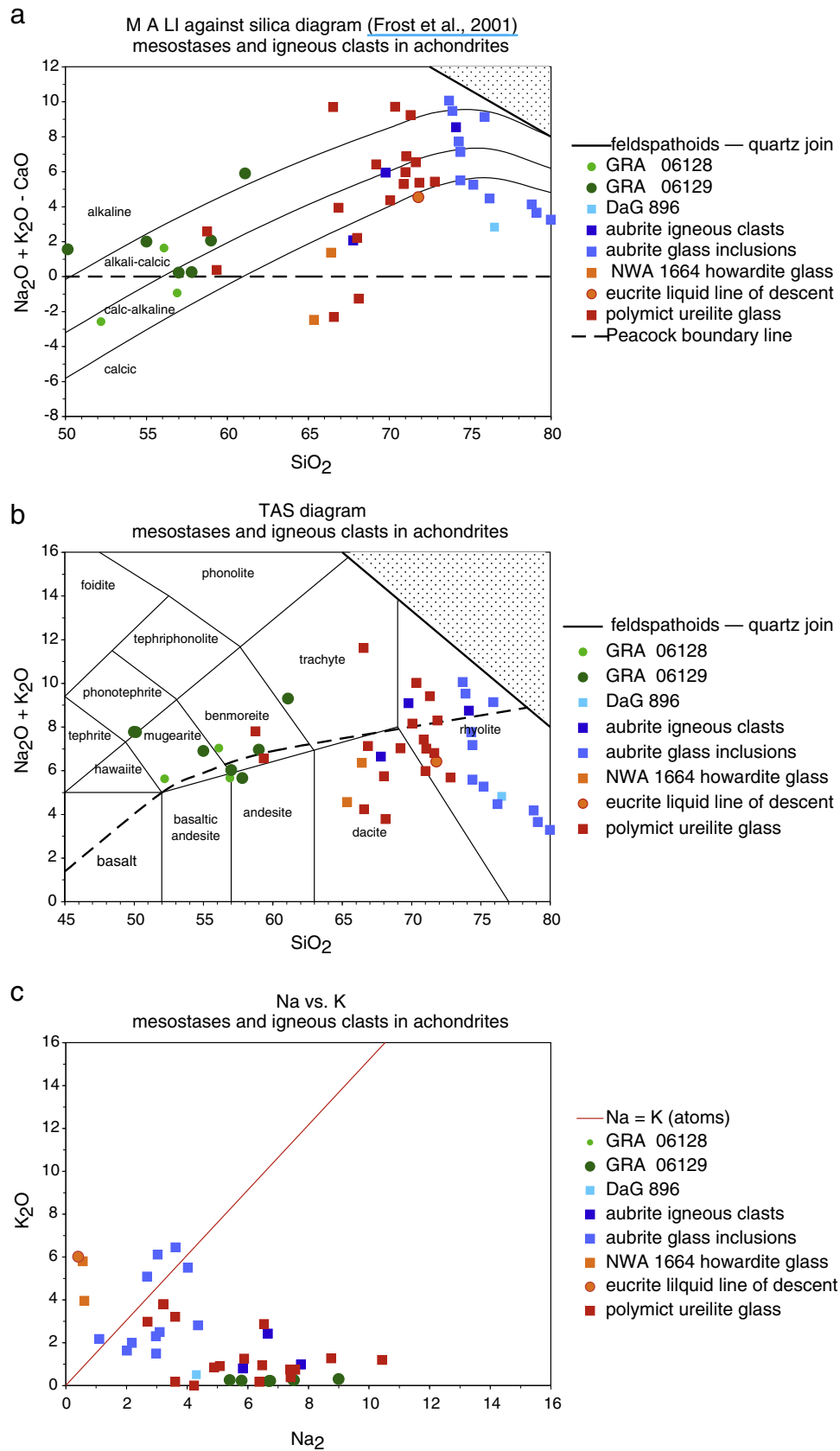


Fig. 2. Nomenclatural diagrams for mesostases and igneous clasts in achondrites. Same diagrams as in Fig. 1.

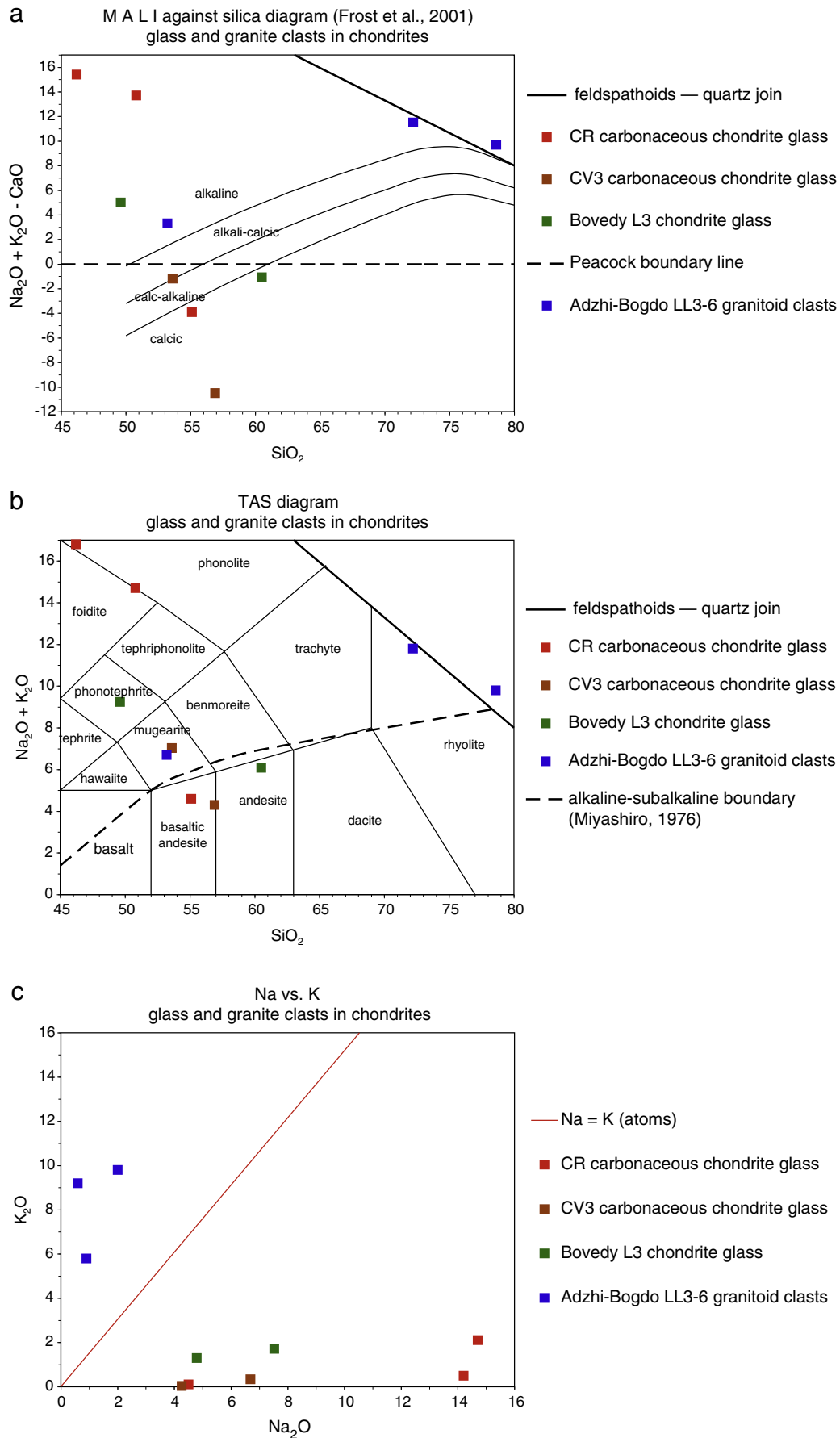


Fig. 3. Nomenclatural diagrams for glasses and granite clasts in chondrites. Same diagrams as in Fig. 1.

a planetesimal formed in the vicinity of the ordinary chondrite parent bodies. Though the age of the clast has not yet been determined, it is likely to have been produced very early, within 100 My after solar nebula formation, as small planetesimals cooled extremely fast (Ruzicka et al., 1995).

The Adzhi-Bogdo meteorite is a breccia, belonging to the LL, i.e. very low in iron, group of ordinary chondrites. The breccia contains various types of clasts, including impact glasses, some of which are K-rich, associated with alkali feldspar granite fragments. Coarse-grained alkali feldspar granite clasts (Fig. 4) consist chiefly of K-feldspar (35 vol.%), quartz and/or tridymite (26 vol.%), ilmenite (21 vol.%), and aenigmatite (9 vol.%), a mineral typical of peralkaline granites. Accessory mineralogy includes albite, chlorapatite, whitlockite, zircon, and Ca-poor Fe-rich pyroxene (Bischoff et al., 1993). Bulk rock compositions are Si, K-rich (72–79 wt.% SiO₂, 5–10 wt.% K₂O) and Na-poor (≤2 wt.% Na₂O). Oxygen isotope compositions fall in the range of ordinary chondrites, implying that granites were derived from an ordinary chondrite precursor, or formed on a parent body in the same oxygen isotopic region of the solar nebula. Since no ²⁶Mg was detected, granites must have been formed at least 4.8 My after the 4567-Ma Ca-Al-rich inclusions of carbonaceous chondrites. A single zircon U–Pb age of 4.6 ± 0.2 Ga was reported and, later on, confirmed by SIMS Pb–Pb isochron age of 4.47 ± 0.12 Ga on rock-forming minerals (aenigmatite, ilmenite, pyroxene, whitlockite, and apatite) of one clast (Fig. 4). A minimum formation age of 4.53 ± 0.03 Ga was calculated as the weighted mean of each model ages, making the dated granitic clast in Adzhi-Bogdo the oldest known granitoid in the solar system (Takeda and Bischoff, 2009) and adding fuel to the suggestion (Bonin, 2007; Bonin et al., 2002) that A-type granite magmatism may have been a universal process on early-formed planetary crusts.

So far K-rich clasts are known in 14 LL chondritic breccias, but only Vishnupur and Adzhi-Bogdo yield alkali feldspar granite and associated pyroxenite clasts (Jäckel and Bischoff, 1997). Two types of K-rich clasts are identified: (i) “coarse-grained” (~100 µm grain size) granitic clasts (up to 700 µm in length) may result from slow cooling of a chondritic parent magma differentiating ultimately into alkali feldspar granite residual liquid and pyroxenite cumulates, and (ii) fine-grained (~1 µm grain size) clasts (several mm in length), composed of euhedral olivine and skeletal pyroxene set in a K-rich groundmass, are likely to have crystallised from impact melts composed of various mixtures of the already crystallised granite and the LL chondritic parent-body.

Chondrules, diagnostic of chondrites, display interstitial glassy materials (Fig. 5). As their structure is highly sensitive to alkali loss, especially Na, analytical results do not represent pristine glass compositions. Two groups were discriminated (Grossman and Brearley,

2005). The K-poor (<0.5 wt.% K₂O) group yields a wide range of mafic to trachytic compositions, corresponding to various [plagioclase + pyroxene] normative mixtures. The K-bearing (0.9–2.1 wt.% K₂O) felsic group corresponds to a compositionally more restricted [sodic plagioclase + orthoclase + pyroxene] normative assemblage.

Replacement of glassy groundmass by nepheline ± sodalite was documented in almost all types of carbonaceous and ordinary chondrites, as well as in some achondrite clasts (Bridges et al., 1995). Alkali–calcic exchanges were promoted by alkali- and halogen-rich gas, according to the reaction: plagioclase + (Na, Cl) gas → nepheline + sodalite + calcic silicate phases (Ikeda and Kimura, 1997). As calcic silicate phases are less abundant than predicted by the reaction, anhydrous metasomatism should have taken place in open systems.

2.5. Concluding remarks

The growing meteorite record provides ample evidence that granite was formed early in the history of the solar system and that it was generated by extreme differentiation of planetary bodies. Granitic clasts in undifferentiated chondrites were not expected. Their occurrence is best explained by the collision of two contrasting planetary bodies, one still undifferentiated (the chondrite parent), the second already differentiated (the granite parent). All reported occurrences provide convincing evidence that a silicic crust similar, yet not identical, to parts of the current Earth's continental crust could have formed in some planetary bodies. The earliest known silicic crust in the asteroidal belt was generated no more than 5–30 My after the very beginning of the inner solar system.

3. The lunar record

The Moon is the only telluric planet to have been visited by man, with carefully selected samples ultimately analysed by sophisticated methods. It was speculated before the Surveyor programme that granitic rocks could predominate in the lunar crust, but sample recovery has failed to provide large samples of pristine granitic rocks. In the lunar vocabulary, a pristine rock is “compositionally endogenous (igneous or thermally metamorphosed igneous) and unadulterated by other materials” (Neal and Taylor, 1989). In order to be considered as free of foreign contamination, igneous clasts should fulfil the following criteria (Warren and Wasson, 1977): (i) glassy, shock-melted areas have compositions appropriate for mixtures of crystals from the remainder of the clasts, and (ii) siderophile elements, Ir and Au, are well below the concentrations recommended as a cut-off for distinguishing pristine from non-pristine lunar rocks. Many lunar samples are non-pristine polymict products of impact-induced mixing of lunar plus minor meteoritic materials. The pristine clasts and felsites recovered from Apollo 12 and 14 to 17 missions and from Luna 24 yield a large range of intermediate to silicic (SiO₂ from 52 up to 80 wt.%), subalkaline and alkaline compositions (Fig. 6), identifying igneous suites from gabbro (basaltic andesite) to monzonite (dacite) to granite (rhyolite).

3.1. Lunar granites

Lunar granites occur either as components in polymict breccias, or as small isolated clasts, or as felsites. “Felsite” is a descriptive term for pale brown K-Si-rich glasses that are found in many regolith breccias, and soil samples. Felsites contain a few quenched phases and rare relict mafic phases, and almost certainly represent total impact melts from a granite precursor (Shervais and McGee, 1999).

Granite clasts are fairly common at the Apollo 14 site. Based on the abundance of felsite in Apollo 14 soils and regolith breccias, the volumetric proportion of granites was estimated to constitute locally 0.5–2.0 vol.% of the crust (Shervais and Taylor, 1983). Actually, the largest sample (14321,1027) consists of a 16 × 7 mm outcrop on breccia 14321. The original clast mass is estimated to be 1.8 g, while the breccia

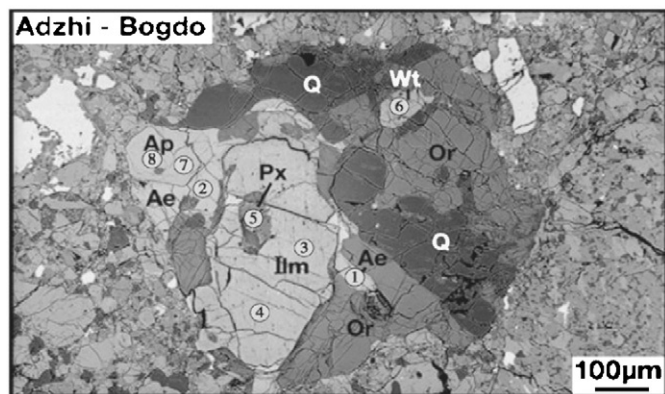


Fig. 4. Backscattered electron image of the granitic clast in the Adzhi-Bogdo chondrite regolith breccia (courtesy Takeda and Bischoff). Apatite (Ap), aenigmatite (Ae), ilmenite (Ilm), K-feldspar (Or), pyroxene (Px), quartz (Q), and whitlockite (Wt) constitute the paragenesis of the granite fragment. Spot for Pb–Pb isotopic dating (Takeda and Bischoff, 2009) are shown.

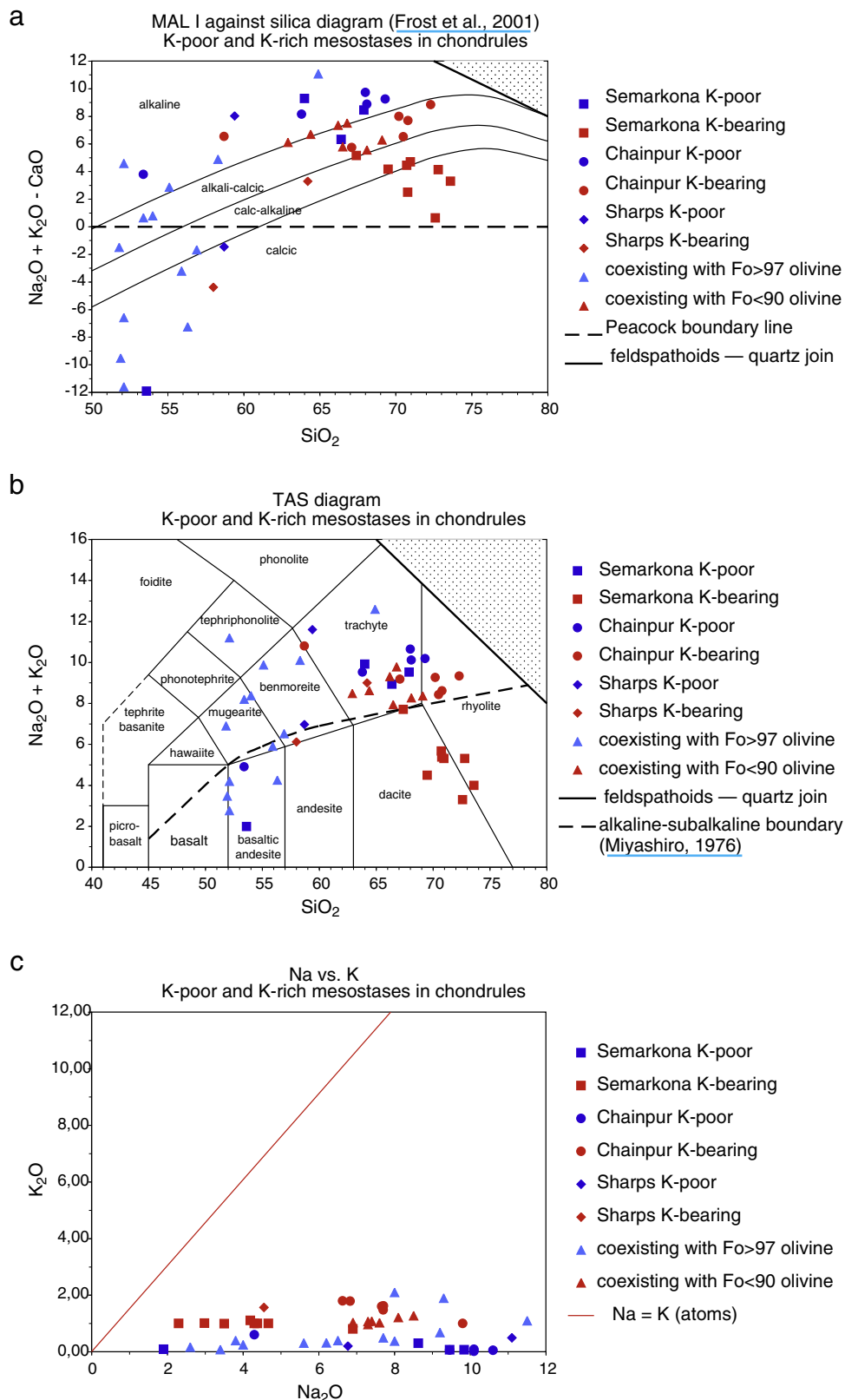


Fig. 5. Nomenclatural diagrams for K-poor and K-rich mesostases in chondrules. Same diagrams as in Fig. 1.

has a total mass of 9 kg. A smaller clast (14303,204) forms an 11×6 mm outcrop on breccia 14303, with an original mass of 0.17 g (Warren et al., 1983). In the IUGS classification, 14321,1027 is an alkali feldspar granite, with 40 vol.% quartz and ~60 vol.% K-feldspar, while 14303,204 is a monzogranite, with 23 vol.% quartz, 32 vol.% K-feldspar and 33 vol.%

plagioclase. Where not brecciated or impact-melted (30–50 vol.%), the undamaged igneous texture is dominantly granophyric, with feldspar and quartz occurring as 0.05-mm up to 2-mm intergrown crystals. As these rock samples are devoid of volatile-rich phases, volatiles cannot constitute a prerequisite for the formation of graphic intergrowths.

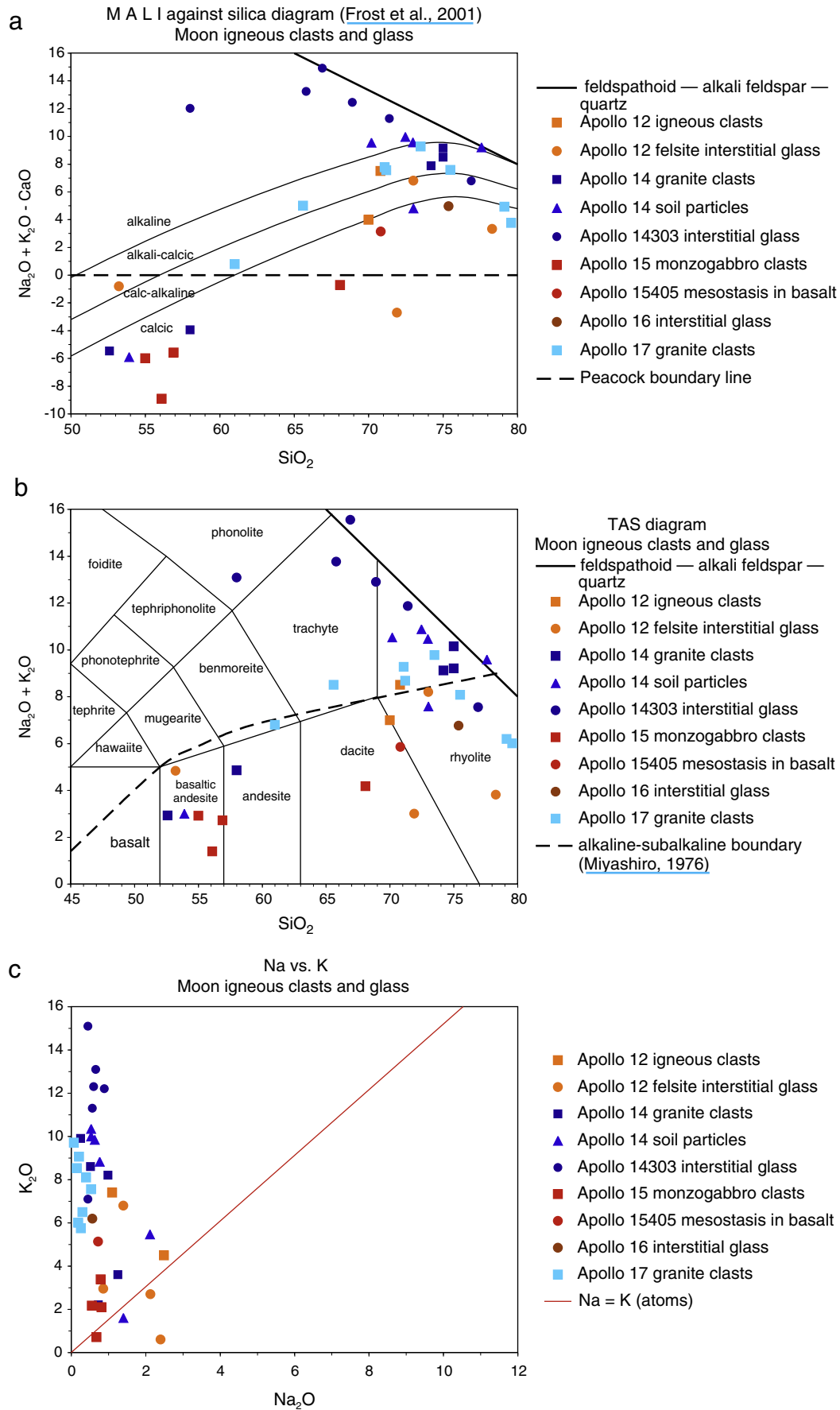


Fig. 6. Nomenclatural diagrams for granitic igneous clasts and glasses sampled on the Moon. Same diagrams as in Fig. 1.

Felsic mineralogy is quite uncommon: alkali feldspar lies in the Or₈₀–Or₉₇ range, while coexisting plagioclase is highly calcic. Alkali feldspar granite contains no albite, and only Ba-poor K-feldspar with compositions bracketed between Or₈₈ and Or₉₁. In monzogranite, barian (1.5–4.8 wt.% BaO) Or_{90–95} alkali feldspar and normally zoned An_{86–59} bytownite–labradorite plagioclase constitute the main feldspar assemblage. Moreover, rare ternary feldspar intergrown with quartz has average compositions (Or₄₅Ab₂₅An₃₀, ~1.5 wt.% BaO) plotting in the “forbidden zone” of the feldspar triangle (Shervais and Taylor, 1983). The association of almost pure K-feldspar with calcic plagioclase is unknown in terrestrial granites.

Anhydrous mafic and accessory minerals include olivine, clinopyroxene (pigeonite, augite, hedenbergite), ilmenite, Fe–Ni metal, occasionally zircon, Y-bearing fluorapatite, whitlockite, and troilite. The alkali feldspar granite yields extremely Fe-rich olivine and clinopyroxene, compared with monzogranite, i.e. Fo₂ (fayalite) vs. Fo₄₁, and hedenbergite vs. zoned En_{37–20} augite, respectively. As they are poorer in Ni (less than 0.2 wt.% to 2.8 wt.%) than meteoritic metals that should contain more than 4 wt.% Ni, Warren et al. (1983) considered that

metallic iron grains are lunar products, suggesting crystallisation at fO₂ controlled by iron–wüstite (IW) buffer. Variations in rock-forming mineral assemblages and compositions (e.g. BaO in alkali feldspar, Mg/Fe ratios in mafic phases) can imply the involvement of at least four distinct parent magmas (Shervais and McGee, 1999).

Chondrite-normalised REE patterns (Fig. 7a) are characterised by high abundances (125–8500 ppm Σ REE), weak to no fractionation, (La_N/Yb_N) ranging from 3.2 down to 0.9, and increasingly pronounced Eu negative anomalies (Eu/Eu* ranging from 0.8 down to 0.1), with the exception of the cumulative 73255c clast having Eu/Eu* = 2.14. Chondrite CI-normalised multi-element diagrams (Fig. 7b) yield pronounced Sr, P and Ti negative anomalies, due to extensive [apatite + ilmenite] crystal-liquid fractionation. Both LILE and HFSE yield high abundances, e.g., 1000–16,000 ppm (Zr + Σ REE) and 12–150 ppm (Yb + Ta) (Fig. 7c), all diagnostic features of A-type granites (Bonin, 2007). Despite their evolved nature, depicted by high silica and K₂O contents, very low Mg/Fe ratios, etc., lunar granites have REE contents and patterns similar to, and K/REE ratios higher than, urKREEP. urKREEP, a Na-poor ferrobasalt composition, would correspond to the residual liquid left by the lunar magma ocean after ~99% crystallisation (Warren and Wasson, 1979). Never found in pristine lunar samples, urKREEP is a chemical signature marked by high K (1.29 wt.% K₂O), REE (1200–1700 ppm), and P (2.80 wt.% P₂O₅) contents (Neal and Taylor, 1989).

3.2. Lunar granite-bearing igneous suites

A monzogabbro–granite igneous suite (Fig. 6) occurs as discrete [quartz + feldspar] clasts, as well as interstitial glasses within basaltic clasts. All chemical compositions are markedly Na-poor and K-rich, while CaO contents decrease with increasing silica. Very low MgO contents coupled with high, yet varying, iron abundances expressed as total FeO imply that lunar granitoids plot on top of the ferroan field defined by Frost et al. (2001). Because of exceedingly low Na₂O contents, almost all samples are calc-alkaline or calcic in the MALI diagram.

Two examples of such igneous suites have been studied. The association of coeval igneous rocks was observed first in the sample 15405 collected from a boulder at Station 6a on the Apennine Front (Ryder, 1976). The sample is a black fine-grained rock containing small fragments. Thin sections indicate that sample 15405 contains a varied lithic fragment population: (i) a coarse-grained granite, (ii) a KREEP-rich monzogabbro (described as “quartz–monzodiorite”), and (iii) Apollo 15-type KREEP basalt. A supplementary clast of unusual KREEPy olivine vitrophyre is also present. Soil (2–10 mm) particles collected at the same place display the same compositional range (Marvin et al., 1991; Ryder and Martinez, 1991). “Quartz–monzodiorite” was defined as a leucocratic to mesocratic intermediate rock, irrespective of An content of plagioclase. This definition is inconsistent with the recommendations of the IUGS Subcommittee of Systematics on Igneous Rocks (Le Maitre, 1989). From modal mineralogy and bulk-rock chemical compositions, “monzogabbro” is more appropriate.

Granite fragments are somewhat crushed, but still retain coarse (>1 mm) grain size and the original mineralogical assemblage. They contain An_{88–61} plagioclase, [cristobalite + K-feldspar + silica-rich glass] μ m-size intergrowths, two distinct ferroaugites, minor ilmenite, whitlockite, rare chromite, and blebs of low-Ni metallic iron and troilite. Monzogabbro fragments (up to 1 cm in diameter) form uncrushed black and white clasts, with the same mineralogy as in granite, but contain more ilmenite and whitlockite, and less silica. Silica–K-feldspar intergrowths occur, but single grains of K-feldspar are rare. Plagioclase grains have An_{82–50} compositions, hence the definition as a quartz monzogabbro. Though it is possible that granite and quartz monzogabbro clasts do not represent fragments of the same igneous association, the abundance of whitlockite and ilmenite, the occurrence of zircon, and identical pyroxene compositions suggest that they are genetically related. However, they cannot represent immiscible counterparts, since both are felsic. On the other hand, as KREEP basalt fragments contain a

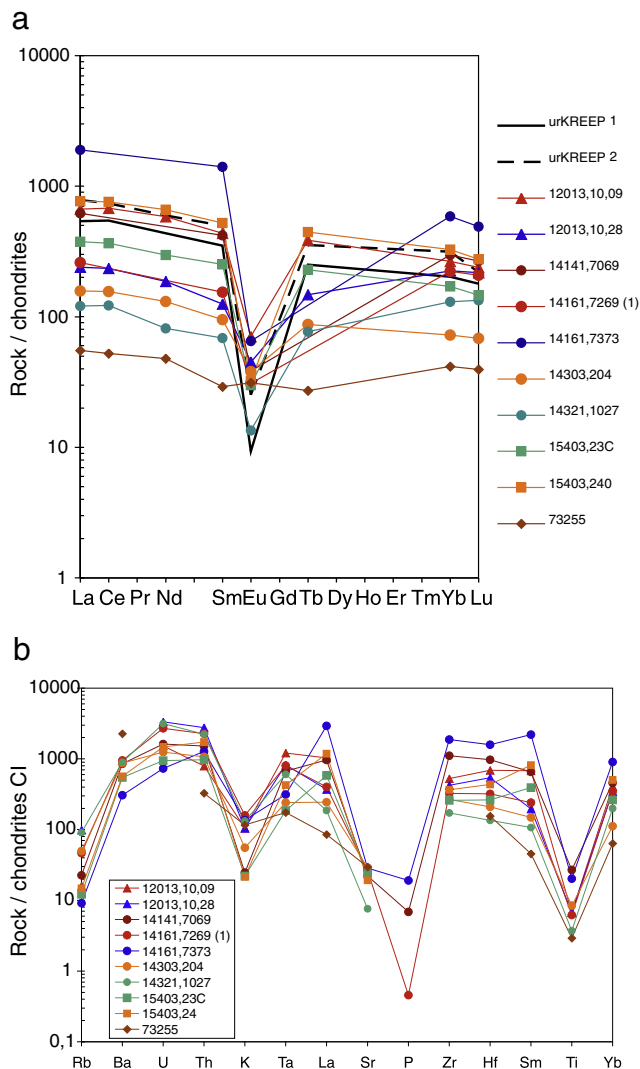


Fig. 7. Trace element compositions of granitic igneous clasts sampled on the Moon. a. REE patterns. Chondritic values from McDonough and Sun (1995). b. Chondrite CI-normalised patterns. Chondritic values from McDonough and Sun (1995). c. (Yb + Ta) vs. (Zr + Nb + Ce + Y) plot of granitic igneous clasts sampled on the Moon and in lunar meteorite NWA4472. The 6-ppm limit for (Yb + Ta) corresponds roughly to the boundary between within-plate and volcanic arc granites and the 350-ppm limit for (Zr + Nb + Ce + Y) corresponds roughly to the boundary between A-type granites and the group of I- and S-type granites (see Bonin, 2007).

more evolved silicic mesostasis, granite clasts are likely to have evolved under slower cooling conditions than at the surface level.

The petrogenesis of the monzogabbro–granite association remains a controversial issue. [Ryder \(1976\)](#) interpreted the association of various clasts within sample 15405 as a mixture of KREEP basalt flows and a shallow “KREEP pluton” containing monzogabbro and granitic rocks, which crystallised before the ultimate granitic residual liquid reached the immiscibility field. Phase relations in monzogabbro ([Rutherford et al., 1976](#)) indicate a high liquidus temperature (1220 °C) compared to the solidus of most basalts. Alternatively, monzogabbro was regarded instead as a mixture of granitic liquid and cumulates of co-genetic plagioclase and pyroxene. In fact, sample 15405 showed to be a polymict regolith with fragments of contrasting ages. The monzogabbro–granite hypabyssal suite crystallised ~4.3 Ga ago, while the KREEP basaltic lava yields a markedly younger ~3.9 Ga age, both pre-dating the Imbrium crisis. Later, a 1.29 ± 0.04 Ga impact event ([Bernatowicz et al., 1978](#)) could have ejected the upper levels of the gabbro–granite intrusion and the overlying KREEP basalt flows, with some of the ejecta spraying the Apennine Front ([Ryder and Martinez, 1991](#)).

Monzogabbro is not limited to the Apollo 15 site but also occurs as particles within Apollo 14 soils ([Jolliff et al., 1999](#)). A survey of 2–4 mm soil particles from Apollo 14 identified varied rock types: (i) whitlockite-rich gabbro (containing 44.9 wt.% SiO₂, only 1.3 wt.% (Na₂O + K₂O), 12.9 wt.% CaO, up to 5.0 wt.% P₂O₅), (ii) monzogabbro, and (iii) felsite. The coarse-grained whitlockite-rich gabbroic particles are regarded as pyroxene–phosphate cumulates and yield the highest REE contents (>4700 ppm) of any lunar rocks reported so far. The three rock types are co-genetic and derived from KREEP basalt parent magmas. Whitlockite and zircon joined pyroxene and plagioclase in the crystallising assemblage of whitlockite-rich quartz gabbro to give rise to residual melts with trace element characteristics of lunar granites. Semi-quantitative modelling involving removal of cumulative whitlockite-rich gabbro followed by separation of two immiscible liquids reproduced successfully most features displayed by the gabbro–monzogabbro–granite trend. Primary pyroxene exsolution into lamella–host pairs of ferroaugite and ferropigeonite suggests unmixing at depths of no more than 700–800 m. Such shallow depths support the interpretation that lunar monzogabbro and granite are late-stage differentiates of high-level intrusions unrelated to differentiation in deep crustal KREEP reservoirs.

The interstitial glasses of Apollo 14303 ([Neal et al., 1988](#)) are exceptional by their high K₂O (up to 15 wt.%) and low Na₂O and CaO contents (less than 1 wt.% for each oxide). Accordingly, they plot near the feldspathoid–alkali feldspar–quartz join in both TAS and MALI diagrams. Their compositions range from phonolite to trachyte to rhyolite. Such interstitial glasses, associated with Ba-rich K-feldspar grains, occur in the specific 3.83 Ga basalts that define the Very High Potassium (VHK) group by yielding much higher K contents and higher K₂O/Na₂O ratios than mare basalts. High Rb and Ba abundances, relative to Sr and La, are also characteristic. VHK basalts can be modelled by AFC processes involving a KREEP component and/or lunar granite. Because granite, or both granite and KREEP signatures are involved in their genesis, VHK basalts emphasise how significant granite can be in the lunar crust, at least locally.

3.3. Lunar melt inclusions

In lunar igneous samples and just as in most terrestrial igneous rocks, irregularities in the crystal growth process resulted in the trapping of small portions of surrounding fluid and silicate liquid. Unlike terrestrial rocks, almost all inclusions in lunar samples are primary and can readily provide information on the igneous environment, i.e. temperature and pressure of trapping, liquid compositions. A systematic survey of inclusions within crystals of all lunar samples was undertaken and the results are reported in the numerous papers presented at the continuing series of Lunar Science Conferences, since

the first dedicated to Apollo 11 samples (e.g., [Roedder and Weiblen, 1970, 1978](#)). Melt inclusions were observed systematically within olivine, plagioclase, pyroxene, spinel, ilmenite, cristobalite, and as interstitial inclusions at grain boundaries. The major result is that the parent magma evolved during cooling to late-stage residual liquids that separated ultimately into two immiscible high-iron and high-silica liquids.

High-silica (~75 wt.% SiO₂ in average) melt inclusions are chemically identical to granite clasts ([Fig. 7](#)). They yield dominantly rhyolitic compositions, with rare dacitic compositions in Luna 24 samples ([Fig. 8](#)). Low Na₂O and high K₂O contents, coupled with variable CaO contents, result into dominantly calcic, calc-alkaline and alkali-calcic compositions. The coexisting high-iron (range 23–47% FeO) melt inclusions correspond to high-Ti low-silica (<43 wt.%) ferro-pyroxenite.

The close association of high-silica and high-iron glasses within one single inclusion reproduces immiscible high-silica and high-iron liquids obtained experimentally by low-pressure (≤ 0.1 MPa) fractionation of a basaltic magma under anhydrous conditions near the iron–wüstite buffer ([Dixon and Rutherford, 1979](#); [Dixon Spulber and Rutherford, 1983](#)). The liquid line of descent indicates that 88 to 95% of a [olivine + plagioclase + pyroxene + ilmenite] mineral assemblage should crystallise before the onset of silicate liquid immiscibility. There are still enough fluids, making feasible the physical separation of the two immiscible liquid phases. In the lunar samples, two additional melts, with compositions of metallic Fe and iron sulphide, provide evidence of four simultaneously immiscible liquids ([Roedder and Weiblen, 1972](#)).

3.4. Lunar meteorites

After the end of Apollo and Luna missions in 1976, there were no more follow-on, return-samples missions to the Moon. Since 1979, the discovery in the Antarctic and in hot desert regions of meteorites that were blasted off the Moon by large impacts has provided new types of “returned” lunar samples. As they are likely to come randomly from various locations on the Moon, they open up a new source of information. About 134 lunar meteorites have been discovered and published as of February, 2012, representing perhaps more than 50 separate meteorite falls, i.e. many of the stones are “paired” fragments from the same meteoroid. The total mass is higher than 46 kg. Lunar meteorites are predominantly made up of highland-derived feldspathic regolith breccias. Breccias consisting of basaltic clasts coming from mare formations are comparatively rare and non-brecciated mare basaltic meteorites are very rare. Importantly, granite compositions were found within lunar meteorites younger than the lunar granitic samples.

Very few lunar meteorites display fine-grained zones corresponding to residual liquids. The breccia EET 96008, found during the 1995–1996 field season in the vicinity of Elephant Moraine, in Antarctica, contains distinctive small pockets (~400 × 500 μm) of mesostasis consisting of coarse (~20 μm) intergrowths of ferroaugite, fayalite and Si-rich glass. Ilmenite, armalcolite, apatite, and whitlockite form laths distributed within these areas ([Anand et al., 2003](#)). Major-element analyses of the glasses from two clasts yield different compositions: the glass within clast G is almost pure silica (98.7 wt.% SiO₂), while glass compositions within clast A are compositionally subalkaline granite (69.7–74.7 wt.% SiO₂), plotting in the dacite to rhyolite fields in the TAS diagram ([Fig. 9](#)). Though Ca-poor, these glasses are calc-alkaline and Na-rich (K₂O/Na₂O ratios ranging from 0.29 to 0.89). In this respect, they differ sharply from K-rich Na-poor glasses analysed in lunar samples and other lunar meteorites.

Five paired lunar mare basalt meteorites, found during the 2002–2003 field season in the LaPaz Icefield, in Antarctica, weigh a total mass of 1.88 kg. Evidence for silica liquid immiscibility and incompatible element enrichment in the mesostases is witnessed by high-silica (74–75 wt.% SiO₂), very K-rich (7–8 wt.% K₂O) and Na-poor (<0.12 wt.% Na₂O) compositions ([Anand et al., 2006](#); [Day et al., 2006](#)), resembling lunar granite samples.

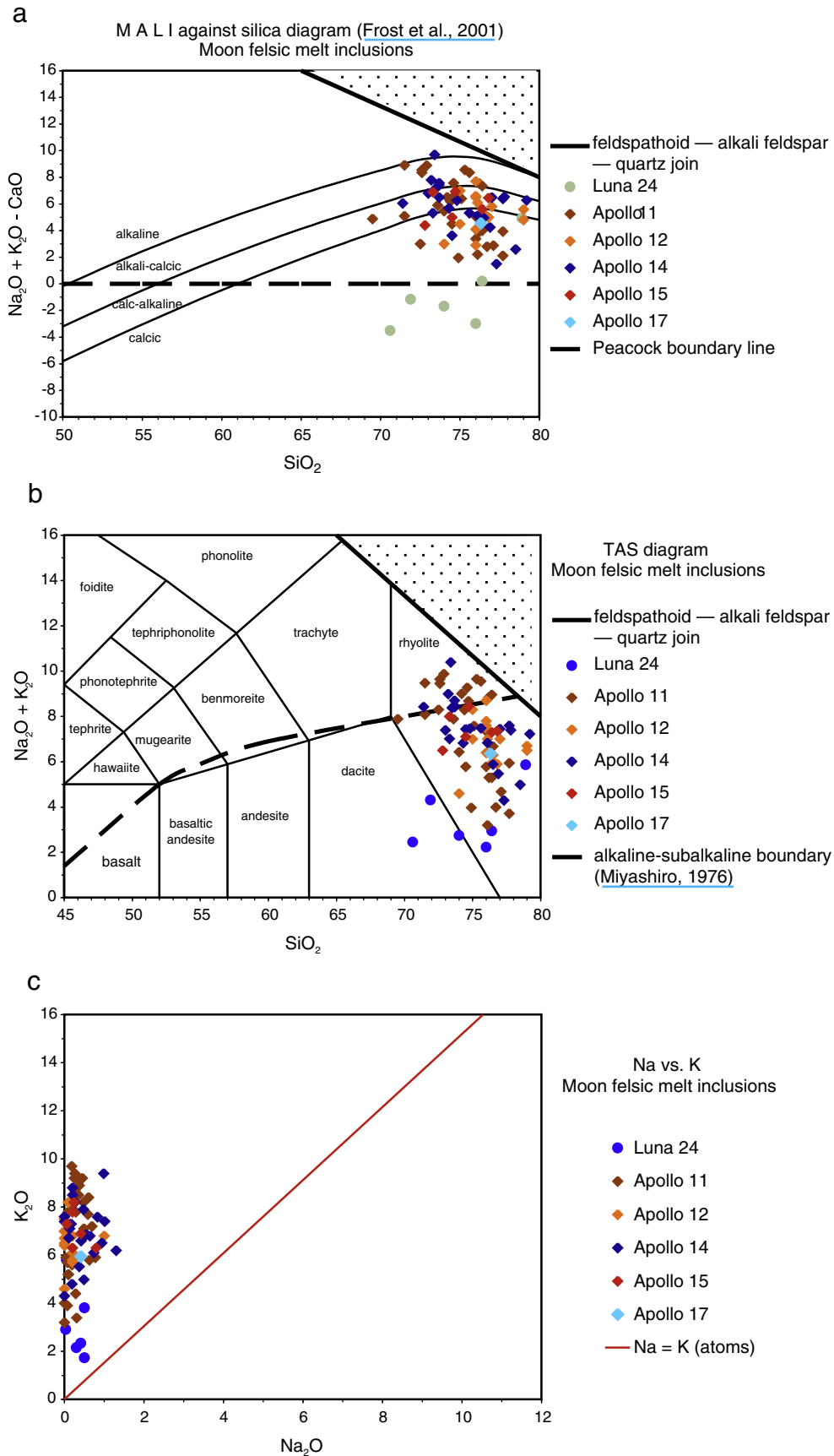


Fig. 8. Nomenclatural diagrams for lunar felsic melt inclusions. Same diagrams as in Fig. 1.

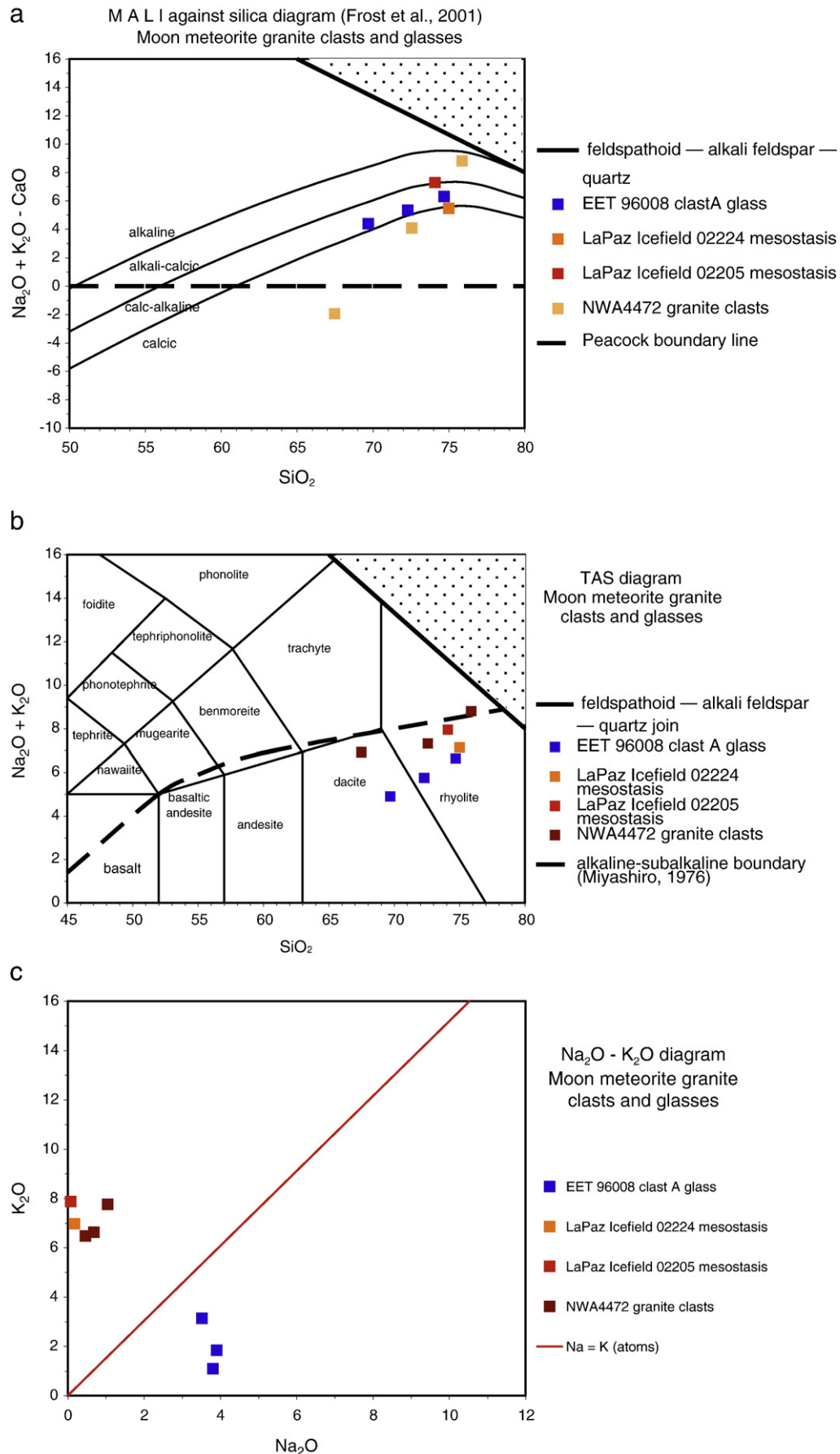


Fig. 9. Nomenclatural diagrams for lunar meteorite granite clasts and glasses. a. to c. Same diagrams as in Fig. 1. d. REE patterns of granite igneous clasts in NWA4472. Chondritic values from McDonough and Sun (1995).

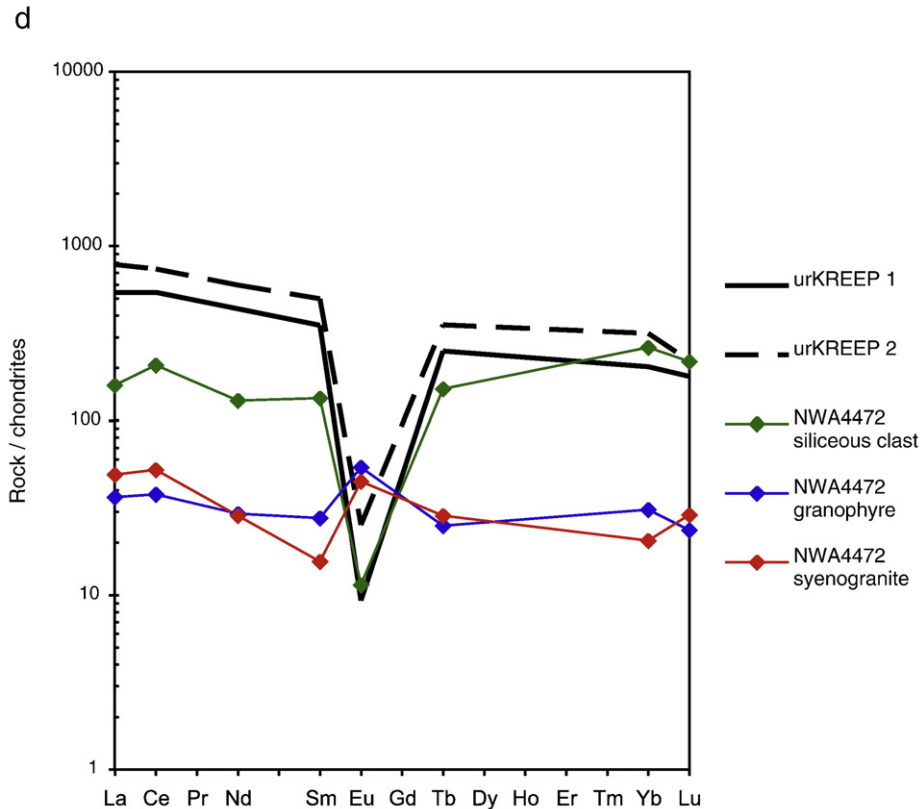


Fig. 9 (continued).

Outside Antarctica, two lunar meteorites found in Algeria in summer 2006 are referred to as paired meteorites NWA 4472/NWA 4485. They consist of a polymict breccia that probably sampled regolith of a mixed highland-mare region surrounding the Imbrium impact basin (Joy et al., 2011). Granite and monzogabbro clasts display chemical compositions similar to the monzogabbro–granite suite described in Apollo 14 and 15 sites. Three granite clasts are classified as “granophyre, syenogranite, and siliceous clast”. All plot in the rhyolite field and are potassic (Fig. 9), but yield contrasting incompatible element patterns: the siliceous clast composition is similar to the majority of granitic clasts sampled on the Moon, while granophyre and syenogranite are distinctly lower in incompatible elements, with feldspar cumulative aspects recalling 73255 sample collected in Apollo landing site (Figs. 7 and 9).

3.5. Lunar granite ages

Two major events marked the Moon's geological history (Ogg et al., 2008; Stöffler et al., 2006): (i) the lunar magma ocean, resulting in the formation of the first anorthositic crust 4.51–4.33 Ga ago in the Pre-Nectarian period, and (ii) the terminal cataclysm, ending ~3.88 Ga ago, due to the late heavy bombardment producing most of the observable lunar basins at the very end of the Nectarian period. Mare volcanism took place after, with ages of flooding ranging from “middle-aged” 3.90–3.60 Ga (Late Nectarian to Late Imbrian) to “young” 3.40–3.25 Ga (Late Imbrian). Thus, the complete lunar age range determined from samples collected on the Moon substantiates at least a ~1.3 Gy-long igneous history. Younger rocks are missing, but sample recovery in small areas has biased the isotopic record. Lunar meteorites evidence ~3.0 Ga (Eratosthenian) episode.

Lunar granites have been dated by a large range of isotopic methods including K–Ar or ^{40}Ar – ^{39}Ar , K–Ca, Rb–Sr, Sm–Nd, U–Pb and Pb–Pb systems. Because the ^{40}K – ^{40}Ca system is considered as more resistant to

impact reheating than Rb–Sr and K–Ar systems, three lunar granites have been analysed by this method (Shih et al., 1993). Sample 14303,206, a subsample of the 14303,204 granitic clast, has an average K–Ca model age of 4.25 ± 0.12 Ga (Pre-Nectarian), in agreement with U–Pb model age of 4.314 ± 0.008 Ga determined on zircon. Sample 14321,1062 yields a K–Ca isochron age of 4.06 ± 0.07 Ga, in agreement with 4.09 ± 0.03 Ga (Rb–Sr) and 4.11 ± 0.20 Ga (Sm–Nd) ages. The available set of isotopic ages indicates that granite crystallised from a magma ~4.1 Ga ago (Nectarian) and underwent brecciation 3.88 ± 0.03 Ga ago (Late Nectarian), as recorded by the ^{40}Ar – ^{39}Ar system. The third sample 12013,141, corresponding to the felsite portion of the 12013 breccia (Warren et al., 1983), yields an imprecise K–Ca model age of 3.91 Ga, which agrees with Rb–Sr isochron ages of 3.99 ± 0.05 Ga and 4.01 ± 0.09 Ga (Nectarian) determined on other felsite fragments in the same 12013 breccia.

Lunar granite samples yield a range of isotopic dates from 4.32 ± 0.01 Ga (Pre-Nectarian) to 3.88 ± 0.05 Ga (Nectarian), indicating a ~490 My-long episode of granitic activity. In a detailed analysis of the more retentive Rb–Sr, K–Ca, and U–Pb ages, Shih et al. (1993) recognised from the age distribution curve at least eight peaks, which they consider as defining discrete igneous events. From a dataset of 4374 ± 5 Ma to 3883 ± 3 Ma zircon grains, Meyer et al. (1996) defined an old group of granophyres with KREEP-like REE patterns that are older than 4.2 Ga and a young group of granites with bow-shaped REE patterns that can be as young as 3.9 Ga. The youngest 3.88 Ga date corresponds to the terminal cataclysm marked by giant impacts having induced the formation of Imbrium and Orientale basins. No lunar granites postdating this event have been recognised.

Markedly younger silicic mesostases in lunar meteorites indicate that they were scavenged from different parts of the Moon. The Elephant Moraine meteorite EET 96008 yields a U–Pb age of 3.57 ± 0.10 Ga, determined on apatite and whitlockite, consistent with

derivation from a pristine Late Imbrian low-Ti mare basaltic precursor (Anand et al., 2003). The LaPaz Icefield meteorites give even younger dates averaging 2.99 Ga (Eratosthenian), while leachable REE-rich phosphate phases define an older Sm–Nd age of 3.25 ± 0.25 Ga, indicating contamination, or open-system behaviour, of the phosphates. The Eratosthenian crystallisation age defined by four different, Rb–Sr, Sm–Nd, U–Pb, and Ar–Ar, isotopic systems makes this meteorite one of the youngest lunar samples known to-date and provides further evidence for extended igneous activity on the Moon (Rankenburg et al., 2007).

To sum up, the currently available age dataset implies that (i) the majority of lunar granites did not crystallise from the primordial magma ocean, except perhaps the old group of granophyres, (ii) either granites were no longer produced after the terminal cataclysm ~3.9 ago, or they were missed. Lunar meteorites define episodes of igneous activity as young as 2.99 Ga (Eratosthenian), but, though silicic pockets do occur in young meteorites, they constitute negligible volumes.

3.6. Concluding remarks

Lunar pristine granite fragments were found systematically in all landing sites at the Moon's surface, though erosion rates, even at the Gy scale, are likely to be low. Common quartz + feldspar intergrowths evidence low-pressure quench textures. Granite ± monzogabbro plutonic massifs were emplaced at shallow levels, making unroofing easier by repeated impact excavations. Rhyolitic domes at the surface level could occur as well. The current isotopic age dataset suggests tentatively that granitic magmas did not produce significant volumes after the ~3.9 Ga terminal cataclysm.

4. The ambiguous Martian record

Like the Moon, Mars underwent early differentiation through crystallisation of a magma ocean. The spacecrafts that fly over Mars, or landed on it, provided information on Martian landscapes governed by meteoritic cratering in a soft medium, with valleys suggesting the presence of a fluid capable of flowage, and abundant, gigantic volcanic activity (Greeley and Spudis, 1981). The data collected from natural samples suggest that intermediate and silicic magmatism may have taken place on Mars (Rutherford and Hess, 1981).

4.1. No granitic rocks analysed so far on Mars's surface

Few natural samples have been analysed *in situ* on Mars. The first source of information is the incomplete XRF analyses of basaltic materials by the two Viking Landers. The second source comes from the more accurate APXS analyses performed on board the rover of the Mars Pathfinder mission in 1997. Multi-spectral imaging has resolved four classes of objects variously coated by fine ferric aeolian dust and other minerals, probably maghemite or ferrihydrite. Refined chemical analyses of the same samples indicate intermediate (53.2 ± 1.0 wt.% SiO_2) iron-rich compositions, with aqueous volatiles containing about 2 wt.% SO_3 and 0.5 wt.% Cl (Foley et al., 2001). Recalculated on a volatile-free basis, these compositions yield ~56–58 wt.% SiO_2 . The inferred andesite composition is akin to terrestrial icelandites formed by fractionation of a tholeiitic basaltic magma, except for lower TiO_2 content. Terrestrial tholeiitic suites include andesitic to rhyolitic residual liquids. This yet only andesite occurrence opens the probability of more silicic occurrences on Mars.

The third, and last, source comes from APXS analyses performed on board the Spirit Rover that landed on January 4, 2004, in Gusev Crater, logged about 10 km of driving up to 2009, and was still communicating with Earth on March 22, 2010. Though soils are abundant, scattered rocks of obvious volcanic origin grade in colour from dark grey to light-toned (coated with dust). The softness of rocks analysed by abrasion and the anomalously high concentrations of sulphur, chlorine and bromine provide evidence for interaction between

water and igneous rocks. The Spirit Rover traversed various ejecta blankets. Four classes of fine-grained or fragmental, relatively unaltered rocks were identified using the full Athena instrument payload (McSweeney et al., 2006a, 2006b): olivine-rich picritic basalt (Adirondack), mildly alkaline basalt (Irvine), trachybasalt (Backstay), and tephrite (Wishstone). Textural evidence shows that the Wishstone class has a pyroclastic origin, but the other classes are composed of lava flows and possibly dykes. Rock compositions plot on, or near liquid lines of descent from Adirondack picritic basalt at pressures varying from 0.1 to 1.0 GPa. No trachytic differentiates were encountered so far. The alkaline Gusev province differs from the subalkaline provinces thought from meteoritic evidence to dominate most of Mars's surface.

4.2. Martian meteorites

SNC (shergottite–nakhilite–chassignite) and ALH84001 meteorites are interpreted as samples of igneous Martian rocks, based on their crystallisation ages and a close match between the composition of gases implanted in them during shock metamorphism and the atmosphere of Mars. Petrological and geochemical studies of Martian meteorites provide additional clues to the origin and evolution of Mars. Lithologies include: basalt–lherzolite–harzburgite (shergottites), clinopyroxenite–wehrlite (nakhilites), dunite (chassignites), and orthopyroxenite (ALH84001). Andesite resembling Mars Pathfinder rocks was not recognised so far in the Martian meteorites.

Isotopic data for shergottites define model ages of about 4.5 Ga, interpreted as the time of planetary differentiation. Martian global differentiation, including core formation, was likely to be contemporaneous with the completion of accretion, probably less than 4 My after the onset of the solar system. Associated thermal models necessitate a radioactive element-enriched component. ALH84001 is the oldest meteorite, with a concordant ~4.1 Ga age, while nakhilites and chassignites yield 1.3 Ga isotopic ages (Bouvier et al., 2009). Crystallisation ages of shergottites remain a controversial issue. The available dates using Rb–Sr, Sm–Nd, Lu–Hf, and U–Pb chronometers range from 1.3 to 0.9 Ga down to 150 Ma and are assumed to represent either crystallisation ages, or shock metamorphic events. By contrast, the Pb–Pb isotope chronometer suggests a 4.05 Ga age (Bouvier et al., 2005). Based on trace element and radiogenic isotope data, the youngest Shergotty and Zagami shergottites are interpreted as unrelated to older Antarctic shergottites, suggesting that separate reservoirs of differing compositions were individualised early, with involvement of highly evolved residual liquids resulting from differentiation of the parent body of Mars (Shih et al., 1982). This “contaminant” may resemble terrestrial continental (granitic) crust (McSweeney, 1994). Shock metamorphism ages are definitively younger, ranging from 150 Ma to less than 15 Ma.

4.3. The Martian crust conundrum

The nature of the crust is a critical, yet unresolved problem. The older crust is supposedly similar to basaltic shergottite, except for higher K and P, and lower Ca abundances (McSweeney, 1994). The abundance and nature of volatiles constitute also a key issue in Martian petrology. Using analysed H_2O contents of kaersutite occurring as inclusions within all SNC types, water abundances in the parent magmas were calculated to be in the 100–1000 ppm range, implying a rather dry (1–35 ppm H_2O) mantle (Mysen et al., 1998). However, trace element distributions within shergottite pyroxene and crystallisation paths compared with hydrous and anhydrous experimental results imply that pre-eruptive magmas at 1120 °C and 55 MPa, *i.e.* at a depth of 5 km, should have contained up to 1.8 wt.% water, with most water ultimately lost during magma ascent to the surface (McSweeney et al., 2001). Such a quantity of water is inconsistent with the conventional Martian dry mantle model.

A survey on Martian meteorites of volatile contents in apatite, with average Cl:F:OH ionic ratios of ~5:3:2 and rare fluorapatite, and in kaersutite, with average Cl:F atomic ratios of 1:10 and low H₂O contents of 0.1–0.7 wt.%, show that magmas may have contained abundant chlorine and fluorine, but little water (Filiberto and Treiman, 2010). An appraisal of volatiles trapped in rock-forming minerals and inclusions in nakhlites and chassignites confirmed the occurrence of Cl-rich fluids, as evidenced by chlorapatite and potassic chlorohastingsite (McCubbin and Elardo, 2011).

Experimentally determined phases relations on an Adirondack-class rock composition with 0.7 wt.% Cl and 0.1 wt.% H₂O indicate that the liquidus is depressed by ~50 °C compared with the liquidus of nearly anhydrous (0.1 wt.% H₂O) composition, but coincides with the liquidus of hydrous (0.8 wt.% H₂O) composition. Mineral textures and compositions interpreted previously as indicating water enrichment could equally be explained by chlorine enrichment (Filiberto and Treiman, 2010).

4.4. Silicic glasses in Martian meteorites

Silicate glasses are fairly abundant in shergottites and nakhlites. They define a compositionally expanded alkali-calcic to alkaline igneous suite from mugearite to trachyte to rhyolite (Fig. 10). Calcic exceptional glasses occur in shergottites, perhaps due to alkali loss during EMP analysis. Sodic and potassic varieties coexist. Textural evidence and chemical compositions are consistent with protracted crystal fractionation followed by silicate liquid immiscibility (e.g., Folco et al., 2000; McCoy et al., 1999).

Silicate glasses in chassignites were extensively studied. They follow a well-defined felsic trend from alkaline trachyte to alkali-calcic rhyolite (Fig. 10). Atomic K/(Na + K) ratios range between 0.33 and 1.0, with rare sodic varieties. Diffusive equilibration of Fe–Mg in olivine and exsolution textures in pigeonite imply glass entrapment under cooling rates of 28–30 °C per year, consistent with emplacement at shallow depths as a thick lava flow, or as a dyke (Beck et al., 2006). From a comprehensive study of inclusions in the Chassigny meteorite, three bubble-free types within olivine grains were identified (Varela et al., 2000): pure glass, glass + one single grain, and glass + a variety of minerals, including kaersutite and jarosite, a hydrated potassium iron sulphate detected in Meridiani Planum sediments (Klingelhöfer et al., 2004). All glasses contain appreciable amounts of Cl and high, yet variable, N contents.

The occurrence of silicate glasses in chassignites was interpreted in two contrasting ways. The classical SNC model involves [olivine + spinel] accumulation from differentiating basaltic magmas (Beck et al., 2006, and references therein). A non-conventional model (Varela et al., 2000) states that inclusions correspond to precipitates from a primitive, Cl chondrite-like (HCl + SO₂) gas phase that was heterogeneously trapped at subsolidus temperatures and that olivine grains could be non-igneous as well.

4.5. Concluding remarks

The evidence in the rock record for granites on Mars is tenuous at best. Because of the mass of the planet, intermediate between the Moon and the Earth, granite occurrence cannot be ruled out. Silicic residual liquids trapped as interstitial fine-grained mesostases and/or glasses in Martian meteorites, experimentally produced crystallisation paths in liquids derived from Martian lithologies, and geochemical modelling on Martian meteorites show that granitic liquids could form a significant component of the Martian crust that remains yet to be observed.

5. Planetary granite geology

Planetary crusts display landscapes mainly controlled by external and internal processes. Internal processes include crystallisation of the

cooling primordial magma ocean in the first times of the planetary history and, later on, emplacement at various depths of variously differentiated residual liquids issued from mantle-derived primary magmas. External processes include impact cratering in decreasingly intense rates and interaction of lithosphere with atmospheric fluids and, possibly, liquid–solid water. These processes create heterogeneous landforms and newly formed scarps or excavations can unveil deep-seated formations, such as plutonic intrusions. The orbiters that fly, or have flight, over the Moon, Mars, Venus, Mercury and, more recently, some asteroids provide an abundant imagery that can provide insights into the shallowest parts of the terrestrial planets.

5.1. Lunar granite generation and volumes

Lunar granites have been sampled within the regolith at the Moon's surface. The regolith is composed of tiny particles that either form loose soils or are set within polymict breccias, and consists mostly of the lunar crust pulverised during a protracted meteoritic impact history. As such, it is representative of the lunar crust at the vicinity of the impacts. It is probably no coincidence that the largest pristine lunar granite clasts are from Apollo 14. Gamma ray spectrometry shows that, on the Moon's nearside surface, high K, Th, and U abundances are concentrated in the longitude range 0–50°W, which corresponds to the Western Highland Province, where Apollo 14 landed. After a first crude estimation of 4% granitic glass in Apollo 14 soils (Warren et al., 1983), later modelling reduced it to no more than 0.5–2.0% (Shervais and McGee, 1999).

From the relationship between heat producing element abundances, i.e. Th, U, Sm and K, the average lunar mantle was computed to contain 0.15 ppm Th, 0.34 ppm Sm, 0.039 ppm U, and 212 ppm K (Hagerty et al., 2006). The urKREEP component, and lunar granitoids as well, yield more than 100 times these mantle abundances. Compared with the Earth's protracted ~4.5 Gy-long igneous history, the volume of granites produced within the Moon was generally considered as insignificant. However, trace element modelling has substantiated the role played by lunar granites in the petrogenesis of various basaltic lineages (e.g., Neal et al., 1988).

Remote sensing characterization of mineralogy through thermal emission spectroscopy has been considerably developed since the end of the 20th century. Infrared emission spectroscopy is sensitive to bulk compositions and is able to readily identify major rock-forming mafic minerals, such as pyroxene and olivine. High-resolution lunar mapping was limited, first, to visible and near-infrared spectroscopy multi-spectral imaging. It was unable to detect nominally iron-free minerals, such as quartz and feldspar, and, therefore, to identify important rock types, such as anorthosite. Since 2009, multi-spectral thermal emission data using mid-infrared (about 8 µm) wavelengths, which are sensitive to iron-free minerals, such as silica phases and alkali feldspars, were acquired with a high spatial resolution, near-global coverage (Greenhagen et al., 2010).

Using data obtained from the Diviner Lunar Radiometer Experiment, four regions within the Procellarum KREEP Terrane (PKT), previously described as “red spots” characterised by relatively high albedo and strong absorption in the UV, exhibit mid-infrared (8-µm channels) spectra that are best explained by quartz, silica-rich glass, and/or alkali feldspar (Glotch et al., 2010). The distribution of high-Si compositions is spatially correlated with high-Th anomalies and low Fe abundances, suggesting that rocks derived from evolved magmas. The detected lithologies are consistent with the lunar granites sampled in the Apollo missions. The spectral character of “red spots” is distinct from surrounding highlands and mare materials and from regions composed of pure plagioclase. In the lunar nearside, “red spots” with high-Th and low-FeO abundances are Hansteen Alpha, Gruithuisen Domes, Lassell Massif, and Aristarchus Crater.

The variety of landforms associated with silicic spectral features suggests that both extrusive and plutonic silicic magmatism may occur on the Moon. Hansteen Alpha is an arrowhead-shaped highlands feature

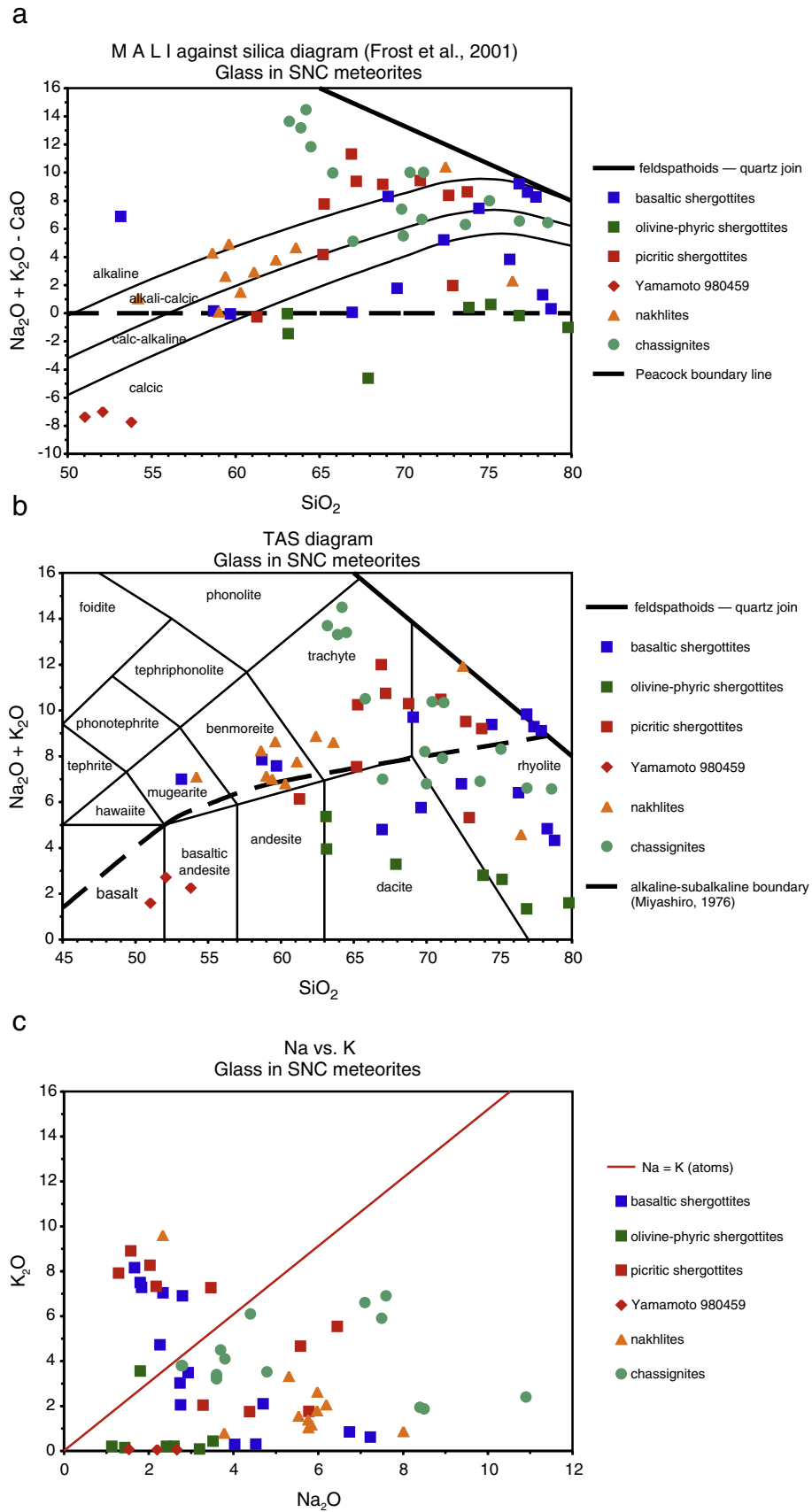


Fig. 10. Nomenclatural diagrams for glasses in Martian SNC meteorites. Same diagrams as in Fig. 1.

located at the southern margin of Oceanus Procellarum. The feature is a triangular mound that is ~25 km on a side. Its morphology and surface texture is strongly reminiscent of many terrestrial features of dacitic and rhyolitic composition formed by extrusions of relatively viscous lavas. High viscosity implies high-Si and Al, low-Fe and Ti magmas. The values are not so high (~6.1 ppm in average), ruling out that Hansteen Alpha is related to the 4.32–3.88 Ga silicic samples of the Apollo collection that contain much more Th (36–40 ppm in monzogabbro and granite). Thus, Hansteen Alpha could be composed of a yet non-sampled rock type. Accordingly, field evidence indicates that it was emplaced during a highlands volcanic episode that occurred after 3.8 Ga, probably before the onset of mare volcanism (Hawke et al., 2003).

The Gruithuisen Domes, located in the northern vicinity of Oceanus Procellarum, yield the same spectral features. A circular 20 km flat dome (height of about 1200 m), a rectangular 33 × 15 km flat dome (height up to 1600 m), and a cone-shaped 8 km structure (height of ~1100 m) are distinguished. Dome summits are speckled with small impact craters. The three domes form a belt affected by volcanic eruptions of highly viscous lavas, with possible explosive eruptions (Wagner et al., 2002). Cratering model ages of 3.85–3.70 Ga evidence a geologically short timescale in the Imbrian period.

The two other “red spots” appear to sample silicic lithologies emplaced at depth. Silicic materials in the Lassell Massif are detected in within a ~50 × 20 km area of probably Imbrian highlands excavated by small impact craters. The association of silicic signature with impact craters suggests that either plutonic material, or a thick sequence of buried extrusive lavas were sampled at depth and exposed by impact phenomena. Similarly, silicic materials exposed in the ~175 Ma (Copernician) Aristarchus Crater are confined to the southern rim and ejecta. Ti-poor pyroclastic materials covering much of the surrounding Aristarchus Plateau have a different spectral signature, suggesting that the crater unroofed an intrusive body of unknown age, but definitively older than the pyroclastic formations.

In the lunar farside, only the isolated Compton–Belkovich Th-anomaly appears so far to contain silicic rocks (Jolliff et al., 2011). Gamma ray spectrometry indicates that source materials could have Th contents as high as 40–55 ppm, reminiscent of pristine granite fragments in Apollo 12 regolith. The mid-infrared spectral signature is consistent with silica and/or alkali feldspar, thus indicating alkali feldspar rhyolite compositions. High reflectance characterises a 25 × 35 km central feature, reaching up to 1800 m in elevation, and composed of a series of domes with diameters ranging from less than 1 km to more than 6 km. Like in the lunar nearside, domes are interpreted as volcanic features formed from viscous lavas. Field data are consistent with a near-surface volcanic complex, including possible collapsed caldera and/or a series of vents. The remarkable preservation of dome features and field relationships with surrounding formations reveal that the Compton–Belkovich structure postdates ejecta deposits of the nearby Nectarian and Lower Imbrian craters. Low crater densities suggest a Copernician age that is yet to be confirmed.

Remote sensing imagery has revealed a limited number of silicic igneous formations. Further studies using the Diviner Lunar Radiometer Experiment, which was launched very recently will confirm, or not, the occurrence of silicic magmatism outside the Procellarum KREEP terrane. Similarly, ages of emplacement of these structures should be re-assessed.

5.2. Evidence for quartzo-feldspathic materials on Mars

The combination of lower gravity and lower atmospheric pressure resulted in volcanic features differing from what is currently observed on Earth: lava flows with a typical length of 200–350 km, giant volcanoes of the order of 500–700 km in diameter, probably more common plinian fall deposits and pyroclastic flows, and possibly ignimbrites (Scott and Tanaka, 1982). The conditions prevailing on Mars have two major consequences: (i) the production of large-scale plinian deposits may not signal the presence of silicic compositions, but rather

be linked to enhanced fragmentation of magmas of any compositions, from basaltic to silicic, (ii) however, lava flows associated with steep-sided domes, described in the Arcadia Planitia region of Mars, have been cited as evidence for viscous, more silicic magma (Fink, 1980). Moreover, the widespread occurrence of late, presumably basaltic to andesitic lava flows (Cipa, 1994) capping the giant volcanoes cannot rule out the eruption of earlier, more silicic formations, as observed in terrestrial volcanoes.

High-albedo surfaces, coated by heterogeneous, fine-grained bright dust, cannot be used as evidence for silicic compositions. More interesting is the occurrence of “black-and-white” layered formations on slopes of canyons and gullies. Such banded formations are exposed on the flanks of Olympus Mons, the largest volcano of the Solar System (Cipa, 1994; Tanaka, 1985). On the basal scarp, materials underlying the late lava flows have been uncovered by large landslides, and display a spur-and-gullied pattern. Sub-horizontal bright-dark bands are clearly identified. Simple piles of lava flows cannot plausibly explain their regular banding as well as their low mechanical resistance witnessed by intense channelling and gravitational instabilities. Calculated shear stresses in the 5–10 MPa range are consistent with low cohesive strength and low internal friction materials, with a high initial porosity filled with ground ice or other easily decayed minerals, such as hydrous calcium sulphates. Such materials may correspond to thick, more or less consolidated pyroclastic deposits of silicic composition (hence, their bright albedo) with intercalated dark-coloured lava flows (Cipa et al., 1995).

Thermal emission spectrometer (TES) data from the Mars Global Surveyor (MGS) were used to determine compositions and distributions of relatively dust-free low-albedo surfaces. Two surface spectral signatures were identified and interpreted as: (i) a basaltic component (surface type 1) dominated by plagioclase and clinopyroxene, and (ii) an “andesitic” component (surface type 2) dominated by plagioclase and volcanic glass. The basaltic component is confined to older, heavily cratered, surfaces, and the “andesitic” component is concentrated in the younger northern plains (Bandfield et al., 2000). The “andesitic” component is a matter of disagreement, because it was argued that weathered basalt can yield the same spectral signature (Wyatt and McSweeney, 2002). Because of the ongoing debate about its composition, TES data on surface type 2 have been reassessed (Michalski et al., 2005). The basis of the controversy lies in the interpretation of a “spectrally amorphous” material that constitutes a significant component of the surface type 2. This amorphous component is similar to high-silica (felsic) glass, i.e. a silica-rich (Si/O ratios between 0.4 and 0.5), highly polymerised material with limited long-range structural ordering. Such material could represent a mixture of opaline silica, silica-rich allophane mineraloids, and/or an aluminosilicate phase, including clay minerals or clay-precursors. TES patterns of amorphous materials are best explained by global scale weathering processes, but a volcanic origin cannot be ruled out.

The 1300-km diameter Syrtis Major volcanic assembly of Hesperian (2–3 Ga) age is composed of a wide diversity of igneous rocks. In the northern area, a unique spectral component is displayed near and on the central peaks of two 30-km diameter craters, compared to the surrounding basaltic plains (Bandfield et al., 2004). After having tested several hundred mineral and rock spectra, results suggest that the surface can be modelled by a single felsic lithology, added to plains and intra-crater low-albedo spectral signature (high-Si glass and/or phyllosilicate, pyroxene, possibly carbonates and sulphates). The felsic lithology (quartz, alkali feldspar, and plagioclase) corresponds roughly to granodiorite or trondhjemite. Because central peak rocks were uplifted during cratering, granodiorite and/or trondhjemite were excavated from depth. Their occurrence in two craters separated by a distance of 100 km can imply a differentiated pluton of considerable extent. Later on, granodiorite and/or trondhjemite surfaces have been extended to a region of about 230 × 125 km (Bandfield, 2006). Granitoids could be part of the ancient Noachian crust and predate Syrtis Major eruptions.

The 50-km diameter Nilis Patera volcano is part of a caldera complex 400 by 200 km at the summit of the Syrtis Major volcanic assembly (Christensen et al., 2005). Compositional mapping using infrared data (THEMIS) has revealed a large variety of igneous rocks, from low-silica olivine basalt to high-silica dacite, substantiating magma evolution through fractional crystallisation. Gravity anomalies reach a maximum amplitude over the 2 km-deep caldera complex and require the presence of a buried, high-density load, representing the magma chamber solidified and filled with dense cumulates (Kiefer, 2004). The inferred magma chamber would be approximately 300×600 km across, roughly twice as large as the topographic caldera, and thickness would range from 2.8 km (olivine-dominated cumulates) to 3.9 km (pyroxene-dominated cumulates). Such a system would be similar in size and thickness to the Bushveld Complex.

Granitoids detected below the Syrtis Major volcanic complex are definitively older than the complex itself and production of felsic materials would have occurred during discrete episodes during the Noachian and the Hesperian periods. In any case, the regional evidence for silicic igneous formations in the Syrtis Major volcano invalidates its alleged global-scale absence on Mars (Francis and Wood, 1982).

5.3. Granites on Mercury and Venus? Facts and speculations

Compared with the Moon and Mars, relatively little information on Mercury and Venus is available. Mercury is currently known only by imagery (Mariner 10 and MESSENGER). Due to its proximity to the Sun, Mercury is thought to have a relatively thin mantle layer and a thick iron core. Three tectonic stages are identified, like the Moon, though they differ in intensity (Thomas et al., 1982). Microwave and mid-infrared observations revealed that Mercury's surface contains less $\text{FeO} + \text{TiO}_2$ and at least as much feldspar on the lunar highlands. The results are compatible with the high albedo (brightness) of Mercury's surface at visible wavelengths, suggesting rock and soil compositions that are devoid of basalt (Solomon, 2003). Volcanic activity was longer-lasting than previously thought, with the last eruptions occurring possibly 1 Ga ago (Massironi et al., 2009). As lunar granites exist, occurrence of granite on Mercury cannot be ruled out.

Despite similar size (Venus has a diameter of 0.94 times the Earth), mass, density and global composition, Venus and the Earth are geologically different. The Venusian surface is governed by the following factors: (i) the atmospheric pressure is 9.8 MPa (only 0.1 MPa on Earth), (ii) the outer shell of the planet is considered as constituting a single lithospheric plate, (iii) low cratering densities imply that a large resurfacing (catastrophic?) event occurred 500 Ma ago or so (Namiki and Solomon, 1994), (iv) altimetric data, acquired by radar imagery since 1978 (Pioneer Venus) to 1990 (Magellan), suggest an unimodal population with a mean elevation of 0.0 ± 0.5 km. Two highland areas (Ishtar and Aphrodite Terra), with elevations not exceeding 7 km, are analogous in topographic style to terrestrial continents and yield evidence for both compressional and extensional tectonic regimes (Ansan, 1993; Vorder Bruegge and Head, 1989). By analogy with terrestrial continents, Ishtar and Aphrodite Terra could contain felsic rocks resembling Archean nuclei (Turcotte, 1996).

The volcanic evidence is more ambiguous. Besides large caldera-bearing shield volcanoes resembling those on the Earth and on Mars, small volcanic edifices were emplaced in the plains, the origin of which is not fully understood. The Venusian literature refers to typical steep-sided domes, with a mean diameter of 24 km and heights of several hm to km, known as “pancake” domes. Terrestrial analogues of basaltic composition could be, e.g., the subglacial volcanoes of Iceland and the flat-topped volcanic cones in the Pacific and Atlantic Oceans (Clague et al., 2000), which were emplaced under a hydrostatic pressure of the same order of magnitude as the Venusian atmosphere. Alternatively, pancake domes might be made up from multiple pulses (Fink et al., 1993) of silicic ($> 60\text{--}65$ wt.% SiO_2) magma, with viscosities ranging between 10^{14} and 10^{17} Pa s (McKenzie et al., 1992). A statistical study of

shapes and size distributions (Smith, 1996) shows that the pancake domes on Venus differ significantly from the terrestrial flat-topped submarine volcanoes by their height-to-diameter ratios and flatness, so that one or more of the variables governing their formation, such as magma composition, crystallinity, volume, effusion rate, cooling rate, pre-existing topography, may differ. The association of pancake domes, coronae, and dyke swarms lends support to the notion that batholithic-size granite bodies could exist on and beneath the surface of Venus (Petford, 2001).

Some Venusian rocks have been partly analysed *in situ* by XRF installed on the Venera and Vega stations that have landed successively since 1972 to 1985. Most landing sites (Venera 9 and 10 in 1975, Venera 14 in 1982, Vega 1 and 2 in 1985) are located in areas characterised by plains with wrinkle ridges that prevail on the surface of Venus. The crust appears to be dominated by subalkaline basalts, akin to tholeiitic MORB-like compositions (Abdrakhimov and Basilevsky, 2002). However, two sites revealed very high-K compositions (Kargel et al., 1993). A major-element analysis made in 1982 at the Venera 13 landing site, again located on a plain with wrinkle ridges, identifies a basanite containing 4.1 ± 0.63 wt.% K_2O . The Venera 8 spacecraft landed in an area where shield plains are associated with pancake domes. An incomplete analysis made in 1972 gave U (2.2 ± 0.7 ppm) and Th (6.5 ± 0.2 ppm) abundances 4 times higher than in the other landing sites, and 4.8 ± 1.4 wt.% K_2O . No other elements have been analysed, leaving a large room for speculation about the actual bulk-rock composition. These partial chemical data could indicate the occurrence of silicic (dacitic to rhyolitic) compositions (Abdrakhimov and Basilevsky, 2002). According to the Venusian “stratigraphy”, shield plains with pancake domes are slightly older than the plains with wrinkle ridges and their age is estimated at 1.11 ± 0.09 T, T being the mean surface age of the planet. T is not well constrained at ~ 750 Ma, with any age from ~ 1 Ga to ~ 300 Ma being possible (Basilevsky and Head, 2002). Thus, pancake domes could have been emplaced between 1.11 ± 0.09 Ga and 333 ± 27 Ma ago, with a mean age of 833 ± 68 Ma.

Partial (about 20%) fluid-absent melting of altered rocks, like the tholeiitic basalts analysed by Venera landers, can leave a garnet-bearing pyroxenite residue and produce high-Na and Al silicic (> 70 wt.% SiO_2) liquids, resembling Archean trondhjemites and more recent adakites (Petford, 2001). Repeated partial melting episodes generating silicic magmas in the garnet stability field would result over time in a bulk increase of crustal density, with important long-term consequences for topographic and isostatic evolution of the lithosphere. The combination of these lines of evidence aids speculations about the nature and evolution of a granitic crustal component on Venus.

5.4. Concluding remarks

Due to more and more improved accuracy, remote sensing techniques enable now to “see” granitic materials occurring at the planetary surfaces. The number of identified areas that are likely to display granitic, or rhyolitic formations is increasing, so that the occurrence of continental nuclei in terrestrial planets is worth considering and discussing. However, the resolution is not yet high enough to detect anomalies corresponding to granite-related ore deposits. A-type granites on the Earth are known to host mineralisations in elements like Nb–Ta, REE, U–Th, etc. Only U and Th positive anomalies could be detected by gamma ray spectrometry.

6. Discussion

Though not volumetrically abundant, extra-terrestrial granites sampled or inferred so far are likely to be representative of a variety of felsic igneous products produced in different parent bodies, including fairly large terrestrial planets. How the current collection is significant should be examined first. In a further step, elements for a simple

granite classification will be suggested in order to unravel how, from which and when extra-terrestrial granites formed.

6.1. Possible sampling biases

Petrographic samples are always very small, mainly in the cm to mm scales. They occur in two distinct ways: (i) clasts isolated or set within polymict breccias, and (ii) glassy to finely crystallised mesostases set within mafic to ultramafic host rocks. The meteoritic literature is full of glassy to finely crystallised occurrences and displays less numerous descriptions of medium- to coarse-grained clasts. By contrast, the lunar literature offers a number of granite occurrences recognised in all Apollo missions, due to careful and selective sampling.

In shock events, coarse-grained granites are easily disrupted into isolated grains of silica and feldspar, so that the former rocks are difficult to reconstruct. On the contrary, if they are not entirely shattered, mafic to ultramafic host rocks protect their silicic mesostases. Thus, it is likely that well-crystallised granites are more abundant in extra-terrestrial environments than implied by the current literature on the meteoritic record.

6.2. Elements for a genetic classification

As on Earth, there are two contrasting types of granites in extra-terrestrial environments. The first, yet apparently poorly represented group comprise the crystallised products of primary magmas issued from the partial melting of parent bodies. The second and more abundant group is composed on rocks formed after extensive fractional crystallisation of mafic magmas. Among the various occurrences offered in the literature, markedly sodic and fairly magnesian granitoids, not granites, seem characteristic of the first group. Though occurring also in the first group, potassic ferroan granites dominate largely the second group.

The first group reproduces somewhat terrestrial anatexis processes. Primary magmas need input of latent heat that can be supplied either by extinct radionuclides, implying they formed very early in non to poorly differentiated parent bodies, and/or by impact-induced shocks on crusts of already differentiated parent bodies. The paired meteorites GRA06128/06129 constitute a possible example of primary intermediate magmas issued from poorly differentiated parent bodies. Chemical modelling shows that moderate partial melting of primitive chondritic sources can produce felsic melts with GRA06128/06129 compositions and residues similar to brachinites (Day et al., 2012). The melting process halted well before extensive differentiation, due to exhaustion of the short-lived radionuclide ^{26}Al probably by felsic melt segregation. Other primitive achondrites are equally explained by cessation of run-away melting in asteroids. Alternatively, GRA06128/06129 could represent a near-surface breccia of floatation plagioclase cumulate material (Zeigler et al., 2009).

Granites issued from shock-induced melting constitute the most abundant population of felsic glasses in the meteoritic record. They are preserved as quenched glasses occurring either as interstitial mesostases, or as discrete spherules in which they are associated intimately with mafic glasses. They reflect their protoliths, hence their non-ferroan K-poor compositions. Exceptions exist, however, e.g., K=Na glass inclusions contrasting with K-poor igneous clasts in aubrites, and the unique K-rich felsic glasses in rare howardites. In the latter case, Barrat et al. (2009) made a strong case for the occurrence of K-rich terranes in the HED parent body, possibly due to earlier extensive differentiation of eucrite magmas (Powell et al., 1980).

Fully crystallised extra-terrestrial granites yield dominantly ferroan characteristics, with ferrous iron coexisting or not with metallic iron, suggesting reducing conditions ranging from IW buffer, e.g., in lunar granites, to FMQ buffer. Potassic felsic compositions coexist with K-poor iron-rich mafic compositions. Though silicate liquid immiscibility was not formally identified in crystallised rocks, this process was observed systematically in melt inclusions, suggesting similar processes

at the origin of felsic rocks. The currently preferred explanation is that ferroan potassic granites were produced through extreme differentiation of primary mafic magmas, including magma oceans, by crystal fractionation followed by low-pressure silicate liquid immiscibility.

Extra-terrestrial granites share strong affinities with Earth's A-type granites. Bonin (2007, page 22) quoted: "two conflicting facts should be emphasised: (i) A-type granites form a comparatively small, yet distinctive, group in the Earth's granite realm, (ii) they are the best represented, if not the only, group of granites generated in the other terrestrial planets and in the asteroid belt". This observation is of prime importance to unravel early planetary crustal evolution.

Supplementary evidence is provided by radiometric ages of granitic clasts in meteorites. From Adzhi-Bogdo data, it appears that planetary differentiation to A-type silicic crust could last no more than 30 My after the beginning of the solar system. The earliest lunar granites yield ages similar to the oldest terrestrial zircon grains (Wilde et al., 2001). However, their anhydrous and hot characteristics contrast with hydrous and cool terrestrial evidence (Valley et al., 2002).

6.3. Non-magmatic felsic compositions

Metamorphic reactions in open systems can induce growth of silica phases or feldspathoids. Increasing metamorphic imprints are recorded by K-enrichment in residual glasses, migration of sulphides, crystallisation of Ca-rich silicate phases, and new olivine zoning patterns, implying anhydrous alteration and open-system behaviour (Kimura and Ikeda, 1997). Silica can be produced through pyroxene breakdown reaction under reducing conditions to give a $[\text{SiO}_2 + \text{chromite} + \text{metallic iron} + \text{new aluminous pyroxene}]$ assemblage (e.g., Benzerara et al., 2002). In these cases, no silicic liquid is needed for cristobalite crystallisation.

Likewise, feldspathoids are not produced from a silica-undersaturated liquid (Bridges et al., 1995), which makes a major difference with terrestrial equivalents. They evidence metasomatic processes operating in the early history of the solar system. Varela et al. (1998) pushed the metasomatic theory to its limits: precipitation of silicate-loaded fluids or vapours is contended to mimic partial melting and to better explain silicic glass occurrences.

7. Summary and concluding remarks

Extra-terrestrial granites are dominated by ferroan compositions. Alkali-lime indices range from calcic to alkaline. However, small-size samples may be not representative of actual liquid compositions. Trace element data, where available, demonstrate A-type affinities. Radiometric age data support granite formation as early as 30 My, and even less, after the beginning of the solar system. Crystal fractionation from mafic parent magmas, followed or not by silicate-liquid immiscibility, can explain petrological features of almost all extra-terrestrial granites. Thus:

- (i) contrary to the conventional wisdom, water is not a prerequisite for granite formation,
- (ii) contrary to the conventional wisdom, an older pre-existing crust is not a prerequisite for granite formation.

The ultimate question is no longer whether granite can occur in a silicate planetary body, but rather whether enough volumes of granitic materials have constituted stable continental nuclei. Is the Earth an exception? The discovery of an increasing number of "Super-Earths" outside the solar system (see: <http://exoplanet.eu/catalog-RV.php>) makes this question increasingly topical.

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