Andesitic Magmatism on a Differentiated Asteroid

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Abstract

The Earth differs from other terrestrial planets in having a substantial silica-rich continental crust with a bulk andesitic composition[1]. The compositional dichotomy between oceanic and continental crust is likely related to water-rich subduction processes[2]. Over the past decade, the discovery of meteorites with andesitic bulk compositions have demonstrated that continental-crust like compositions can be attained through partial melting of chondritic protoliths[3,4,5]. Here we show that a newly identified achondrite meteorite, Erg Chech (EC) 002, is a high-Mg andesite but that, unlike previous andesitic achondrites has strongly fractionated and low abundances of the highly siderophile elements (HSE), reminiscent of Earth's upper continental crust[6]. The major and HSE composition of EC 002 can be explained if its asteroid parent body underwent metal-silicate equilibrium prior to silicate partial melting without losing significant volatile components. The chemistry of pyroxene grains in EC 002 suggests it approximates a parental melt composition, which cannot be produced by partial melting of pre-existing basaltic lithologies, but more likely requires a metal-free chondritic source. Erg Chech 002 likely formed by ~ 15% melting of the mantle of an alkali-undepleted differentiated asteroid. The discovery of EC 002 shows that extensive silicate differentiation after metal-silicate equilibration was already occurring in the first two million years of solar system history[7], and that andesitic crustal compositions do not always require water-rich subduction processes to be produced.

Introduction

Numerous properties of the Earth set it apart from the other rocky planets in the solar system, one of the most striking being the presence of Si-rich continental crust (CC). In contrast to Earth, the vast majority of achondritic meteorites range between chondritic and basaltic in bulk rock composition[8]. However, a small but growing number of achondrites with SiO_2 content up to ~61 wt.% have been identified over the past decade[3,4,9-11]. Most high-Si meteorites have been concluded to be the result of low-degree melting of alkali-undepleted chondritic lithologies[5]. This petrogenetic model differs from that for intermediate and felsic rocks on Earth, which are the result of either extensive fractional crystallization of a mafic magma or more often partial melting and assimilation of mafic or sedimentary lithologies, all facilitated by the lowering of solidus temperatures by hydration[1].

The first high-Si achondrites identified, Graves Nunatak (GRA) 06128 and 06129 show high concentrations of the highly siderophile elements (HSE; Os, Ir, Ru, Pt, Pd, Re) relative to terrestrial rocks[3]. The HSE partition extremely strongly into Fe-metal over silicate phases and are thus highly depleted in the silicate portions of differentiated planets, including Earth. The high concentrations of the HSE in GRA 06128/9 indicates that its parent body had not segregated a metallic core and was thus likely chondritic. The GRA 06128/9 meteorites have been linked to the brachinite parent body[3,12], and many primitive achondrites such as winonites, brachinites, ureilites and acapulcoites/lodranites, probably result from the extraction and removal of a high SiO_2 melt from a chondritic lithology[5,13,14]. Like GRA 06128/9, most other evolved achondrites formed by low-degree (~13%) melting of chondrites[3,4,9,11,12]. The only known evolved lithology in asteroidal meteorites that formed by melting of a mafic rock is a single dacitic clast in the howardite Dominion Range (DOM) 2010 that likely results from 10-20% melting of a rock similar in composition to the eucrite Juvinas[10]. This dacite lithology is probably minor in the Vestan crust, as the bulk of Vestan meteorites are mafic[10]. A new meteorite, Erg Chech 002 (~31.78 kg) was found in the Algerian Sahara in May 2020 and recognized as a new evolved achondrite[15]. Here we present new geochemical data for this meteorite to constrain its petrogenesis and to compare its composition to terrestrial continental crust.

Results

Erg Chech 002 has a plumose variolitic texture of 44.7 modal % 0.5-3 mm long, high aspect ratio (~2:1 long to short axis) pyroxene grains enclosed by a groundmass of 50 modal % plagioclase feldspar with 4.4 modal % Si-rich phase (**Figure 1**). Modal abundances were determined quantitatively using the *ImageJ* software. Accessory minerals include a total of ~0.7 modal% chromite, ilmenite, sulfide, and iron metal that occur interstitial to the silicate grains. The plagioclase grains in-fill the space between pyroxene crystals and long, thin silica patches are present in the center of the feldspar regions. Two textural types of pyroxene are evident, including pyroxenes with distinctly colored cores and rims that are both larger and typically rounder than the more common pyroxenes that have more elongate shapes (**Figure 1**).

The typical pyroxene grains in EC 002 are augite with $En_{39}Wo_{32}Fs_{29}$, whereas the cores of the two analyzed zoned grains are enstatite with variable, Mg-rich and Ca-poor compositions ($En_{49-75}Wo_{4-38}Fs_{18-45}$) (**Figure 1**). The pyroxenes have low La/Yb_{CI} (0.44) negative Eu anomalies ($Eu/Eu^* = Eu_N/(Sm_N{*}Gd_N)^{0.5} = 0.06$) and rare earth element abundances of ~3-10 × CI chondrite. Plagioclase is oligoclase at $Ab_{\sim77}An_{\sim19}Or{\sim}_4$ (**Figure 1**) and has relatively high Ti (370 ±70ppm), low Ba (33 ±11 ppm) contents and high Rb/Sr (0.14). The silica-rich phase has >94 wt.% SiO_2 with ~2.3 wt.% Al_2O_3, ~1.1 wt.% Na_2O, 1350 ±640 ppm Ti and Rb/Sr = ~6. Erg Chech 002 contains spinel with high Cr# ($100{*}Cr/(Cr+Al+Fe^{+3})$) of ~94 and low Mg# ($100{*}Mg/(Fe^{+2}+Mg)$) of ~5, plotting at the extreme end of spinel compositions for diogenites, acapulcoites and brachinites (*Supplementary Information*). Compositions of sulfide are pyrrhotite and the Fe-metal contains very low Co (0.26 wt.%) and Ni (0.02 wt.%) abundances.

The bulk rock composition of EC 002 is equivalent in composition to a terrestrial high-Mg andesite, with a SiO_2 content of 59.5 wt.% and Na_2O and K_2O contents of 4.2 and 0.4 wt.% respectively. The bulk composition is compared to other achondrites in **Figure 2a** in a total alkali silica (TAS) diagram, and in **Figure 3** in a FeO/MnO versus $D^{17}O$ diagram. The bulk composition of EC 002 is depleted in incompatible trace elements (ITE) relative to basaltic achondrites, such as eucrites and angrites. The rare earth element (REE) pattern is flat at approximately five times chondritic with a small positive Eu anomaly of 1.24 (**Figure 2b**). This pattern is analogous to those of other high-Si achondrites GRA 06128/9 and NWA 11119, although EC 002 has a smaller Eu anomaly[3,4]. The EC 002 pattern differs from that of basaltic eucrites and angrites, which have Eu anomalies of 0.61-1.06 and higher REE abundances of 10 to 40 times CI chondrite[16,17].

Highly siderophile element abundances as well as ^{187}Re-^{187}Os isotopic systematics of EC 002 show that it has a fractionated HSE pattern and much lower HSE compared to the achondrite andesites GRA 068128/9, with highly fractionated $(Re/Os)_N$ and $(Pd/Ir)_N$ of 120 and 30 (GRA 068128/9 = 1.3 and 2.9-3.1; Day et al., 2009; **Figure 4**). Total HSE abundances in EC 002 are low at 2 ppb, compared to between 750 and 960 ppb in GRA 068128 and GRA 068129. The CI-chondrite normalized HSE pattern of EC 002 overlaps with the range of differentiated achondrites diogenites[18] and angrites[17] and plots close to upper CC[6] (**Figure 4**). The $^{187}Os/^{188}Os$ ratio of EC 002 is 0.1502; more radiogenic than the present-day chondritic reference value[19] with a g^{187}Os value of +15.9, suggesting a moderately suprachondritic Re/Os ratio since ~4.5 Ga. Although EC 002 has a high measured $^{187}Re/^{188}Os$ ratio of ~40, this feature is the result of recent terrestrial alteration which happens readily in meteorites[20]. While terrestrial alteration can explain the high Re content in EC 002, this process is not effective at redistributing the platinum group elements (Pd, Pt, Ir, Ru, Os), which instead require parent body processes to account for their distribution in EC 002.

EC 002 is an Extraterrestrial Lava

The bulk composition of EC 002 is close to terrestrial CC[1], although the bulk CC is enriched in Al and K and depleted Fe and Ca relative to EC 002. The question naturally arises whether EC 002 is indeed a meteorite or a misidentified terrestrial rock. Preliminary oxygen isotopic data[15] for EC 002 show D^{17}O of –0.103 to –0.142, distinct from terrestrial values. The FeO/MnO ratio is also useful for distinguishing achondrite parent bodies, and the bulk EC 002 shows a FeO/MnO of 26, distinct from the CC at 67, as well as other evolved achondrites (**Figure 3**). Erg Chech 002 overlaps in D^{17}O with the ungrouped achondrite Bunburra Rockhole[21] and despite strongly differing bulk rock chemistry, they could potentially share a parent body. The large augite grains in EC 002 are close to equilibrium with the bulk composition with respect to Na and Ti, whose partitioning into pyroxene is relatively unaffected by temperature and pressure[22]. The Mg-rich grain is likely a xenocryst due to its strongly differing composition and the fact that it is rimmed by the predominant augite composition. Therefore, despite the presence of xenocrysts of enstatite, bulk EC 002 is likely close to its parental melt composition. This is consistent with the textures showing large pyroxenes with interstitial oligoclase containing pockets of evolved melts (**Figure 1a**), and no clear cumulate texture.

Two-Stage Petrogenesis of EC 002

Erg Chech 002 is distinct from the andesitic achondrite GRA 06128/9 in having low and fractionated HSE concentrations (**Figure 4**). The HSE pattern shows chondrite-normalized $(Os/Ir)_N$ ~1 and elevated $(Re/Ir)_N$, $(Pd/Ir)_N$, $(Pt/Ir)_N$ and $(Ru/Ir)_N$, similar to the upper terrestrial CC. These fractionations are likely the result of silicate melting during which Re, Pd, Pt and Ru are more incompatible than Os and Ir. Low HSE concentrations in rocks reflect metal removal from source regions, where metal-silicate equilibrium leads to near-quantitative removal of highly siderophile elements. This scenario is supported by the low Ni concentration of bulk EC 002 (13.1 ppm) as well as the lack of low Ni (0.02 wt.%) in the metal grains, which are almost pure Fe. Graves Nunataks 06128/9 formed by melting of a chondritic parent body that never segregated a core[3]. The HED parent body (likely 4-Vesta) and the angrite parent bodies both segregated cores[17,18], and EC 002 shows an HSE pattern overlapping both of these groups (**Figure 4**). Therefore, EC 002 is the first identified evolved achondrite from a differentiated asteroidal parent body.

Four possible scenarios for the petrogenesis of EC 002 are considered: 1) formation in a subduction zone like terrestrial CC, 2) impact melting or metamorphic heating and anatexis of a mafic achondrite, 3) melting of a chondritic body leading to simultaneous metal and silicate segregation, and 4) silicate melting on a differentiated asteroid. The first scenario can be readily discounted due to the early formation of EC 002[7], and the lack of any evidence for subduction zone-like processes on non-Earth bodies It is possible that EC 002 is the result of melting of a mafic precursor through impact or metamorphic heating. Melting experiments of basaltic eucrites[23,24] show that eucrite melts differ strongly in major-element composition from EC 002 (**Figure 2**). Additionally, eucrites and angrites show higher concentrations of the incompatible REE than EC 002 (**Figure 2**), making them unlikely protoliths. The DOM 2010 dacite clast formed by impact-related eucrite partial melting and differs strongly from EC 002 with very low Na content[10]. Erg Chech 002 therefore is unlikely to represent a partial melt of a basaltic precursor. Petrogenetic modeling of the evolution of eucrite melts also does not yield compositions consistent with EC 002[10]. Finally, it is unlikely that impact melts would have such low HSE contents as contamination with chondritic material would be predicted to add large quantities of the HSE, as observed in lunar impact rocks[25].

It is possible that EC 002 was the product of melting on a chondritic body in which silicate and metallic melts equilibrated with each other and segregated in a single event. The high concentration of moderately volatile elements, such as Na, in EC 002 indicates that its protolith did not reach high enough temperatures to volatilize these elements, which is unlikely if a single high temperature event led to its formation but we cannot rule out this scenario with the available evidence. The final petrogenetic mechanism involves melting of the silicate portion of a differentiated parent body that had already formed a core, which can readily explain the low fractionated HSE signature of EC 002. Melting experiments of chondrites yield a number of liquids with composition close to bulk EC 002 with both H and LL chondrites melted at 1202°C and oxygen fugacity (fO_2) of Iron-Wüstite –1.38, producing plausible parental magmas[5]. The low fO_2 of these experiments is consistent with the presence of metal in EC 002. Disequilibrium melting of R chondrites can also yield high Na and Si liquids similar to EC 002[26].

Our favored mechanism of formation of EC 002 first involves an ordinary-chondrite like parent body segregating a core without reaching high enough temperatures to lose Na (i.e. <1040°C). This initial melting event is followed by ~15% melting leaving residual pyroxene ~$En_{77}Fs_{19}Wo_4$[14], a small portion of which was incorporated into the melt as xenocrysts, indicating rapid melt ascent in order to entrain solid grains. The segregated melt cools quickly and forms augite crystals, some of which rim enstatite xenocrysts, and then crystallizes plagioclase An_{15-25} and finally a residual 5% of Si-rich melt is quenched as thin veins. The modal quartz abundance and plagioclase An content are consistent with those predicted for the experimental melts[5]. Preliminary Mg isotopic data[7] show that EC 002 was formed with the first 2 million years of solar system history, when ^{26}Al was still present. This short-time scale indicates that the EC 002 parent body experienced two separate heating events to segregate a core and then melt to form EC 002 shortly after accretion. Short-lived nuclides like ^{26}Al are significant sources of heat and could have provided sufficient heat for differentiation of the EC 002 parent body. The new data show that differentiated asteroids were present within the first 2 Ma of solar system formation, indicating that some early-formed parent bodies may be underrepresented in the meteorite record. These results emphasize that the continental crust composition of Earth may not be unique to a plate tectonic process, that planetary scale differentiation to metal cores, and andesitic crusts could have taken place on relatively small planetesimals to large planets without complete melting and that discovery of exoplanets with andesitic crusts may not mean plate tectonics acts upon them.

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Figures

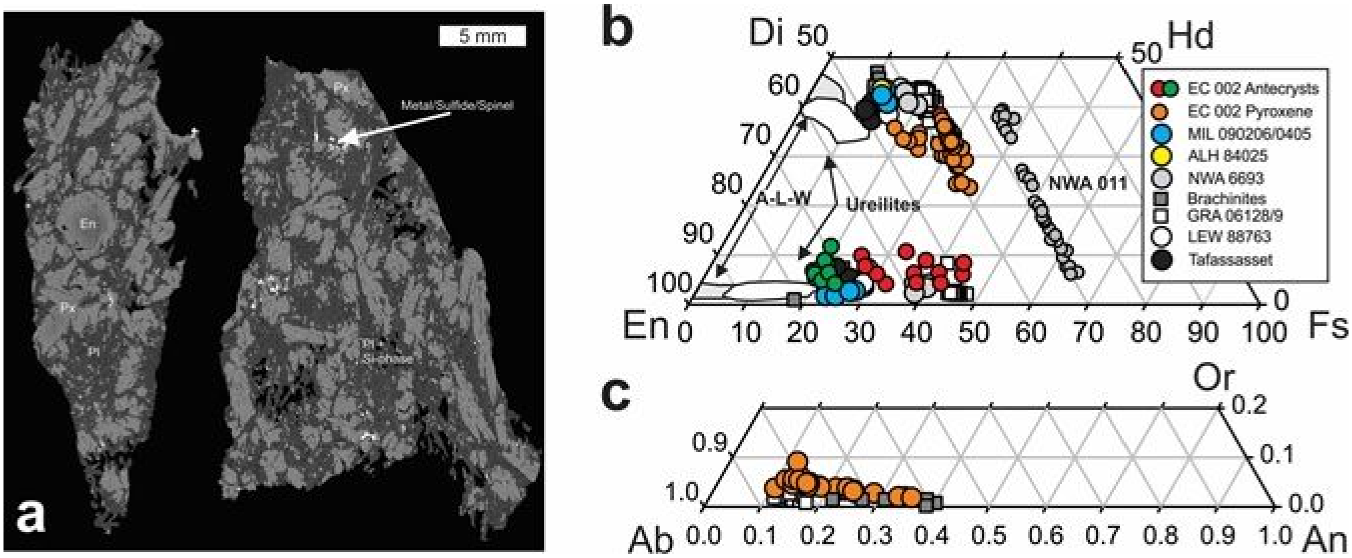

Figure 1

1a. Back-scattered electron (BSE) of the studied EC 002 thin section. Large crystals of augite are shown set in a fine-grained ground mass of oligoclase and a SiO2-rich phase. A xenocrystic enstatite rimmed by augite is visible in the section. 1b. Ternary diagram of EC 002 pyroxenes compared to brachinites and evolved achondrites3,12,27-29. 1c. Ternary diagram of EC 002 feldspars compared to brachinites and evolved achondrites. Data are from same sources as Figure 1b.

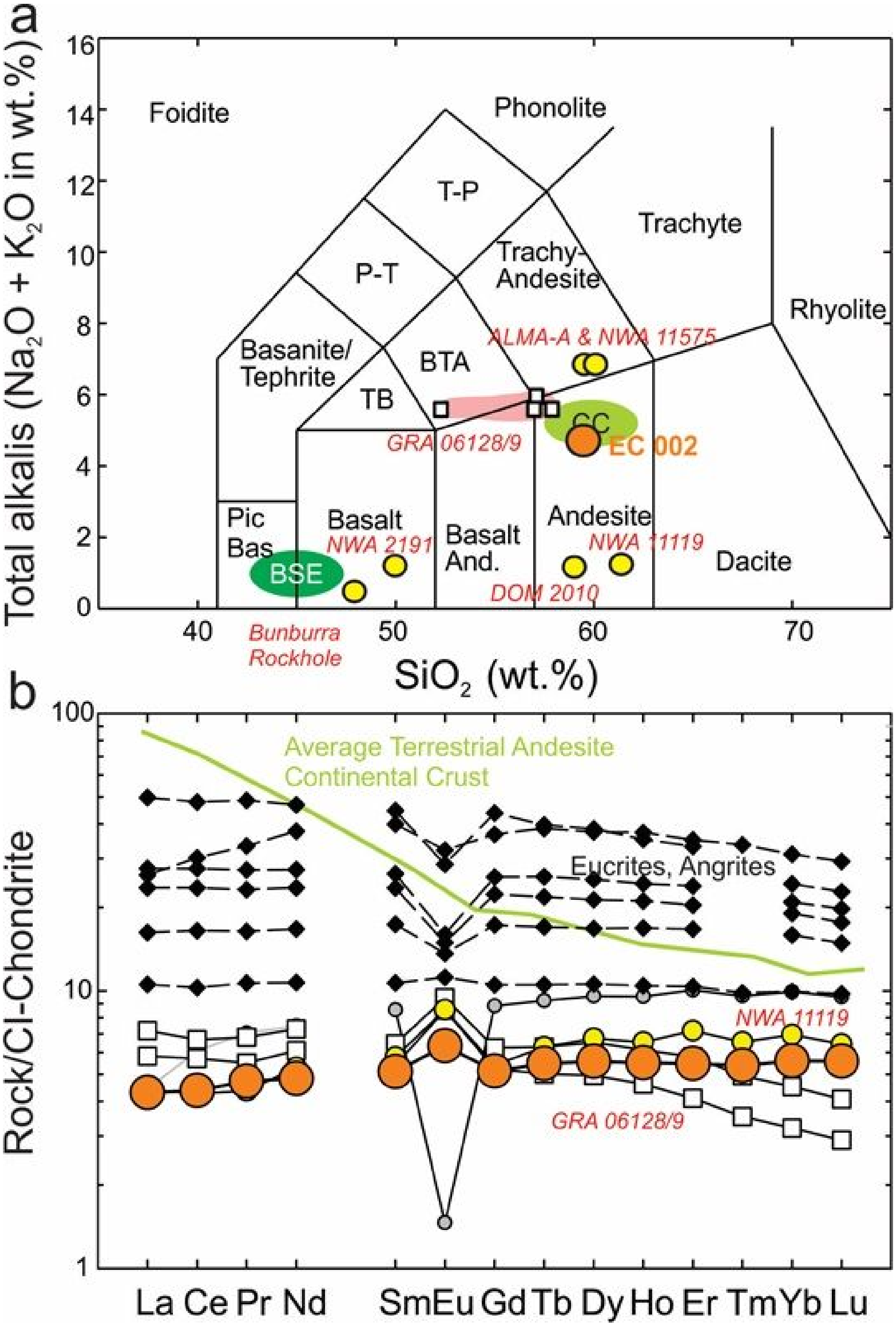

Figure 2

2a. Total Alkali (Na2O + K2O) Silica (SiO2) diagram for EC 002, evolved achondrites, the upper terrestrial CC, and bulk silicate Earth (BSE). Domain boundaries from [32]. 2b. CI-Chondrite-normalized REE patterns for the same samples. Data are from: GRA 06128/93, NWA 111194, Bunburra Rockhole21, dacite clast from Dominion Range (DOM) 201010, the high Si Almahata Sitta clast ALM-A9, high Si achondrites NWA 1157511 and NWA 219130, terrestrial upper CC1, BSE31.

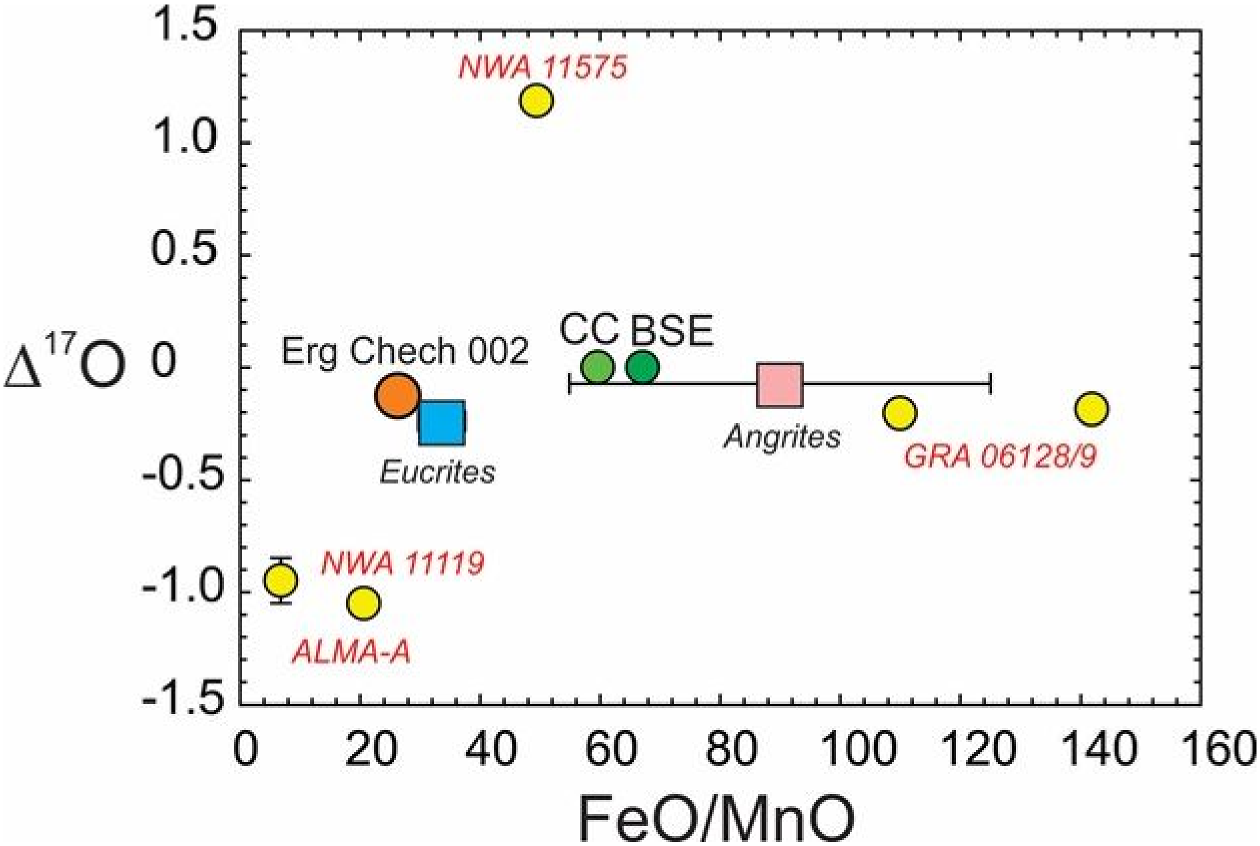

Figure 3

Bulk rock FeO/MnO ratios and 17O values for EC 002 and other evolved achondrites3,4,9,11, eucrites33,35, angrites33,34 and the terrestrial CC1 and BSE31.

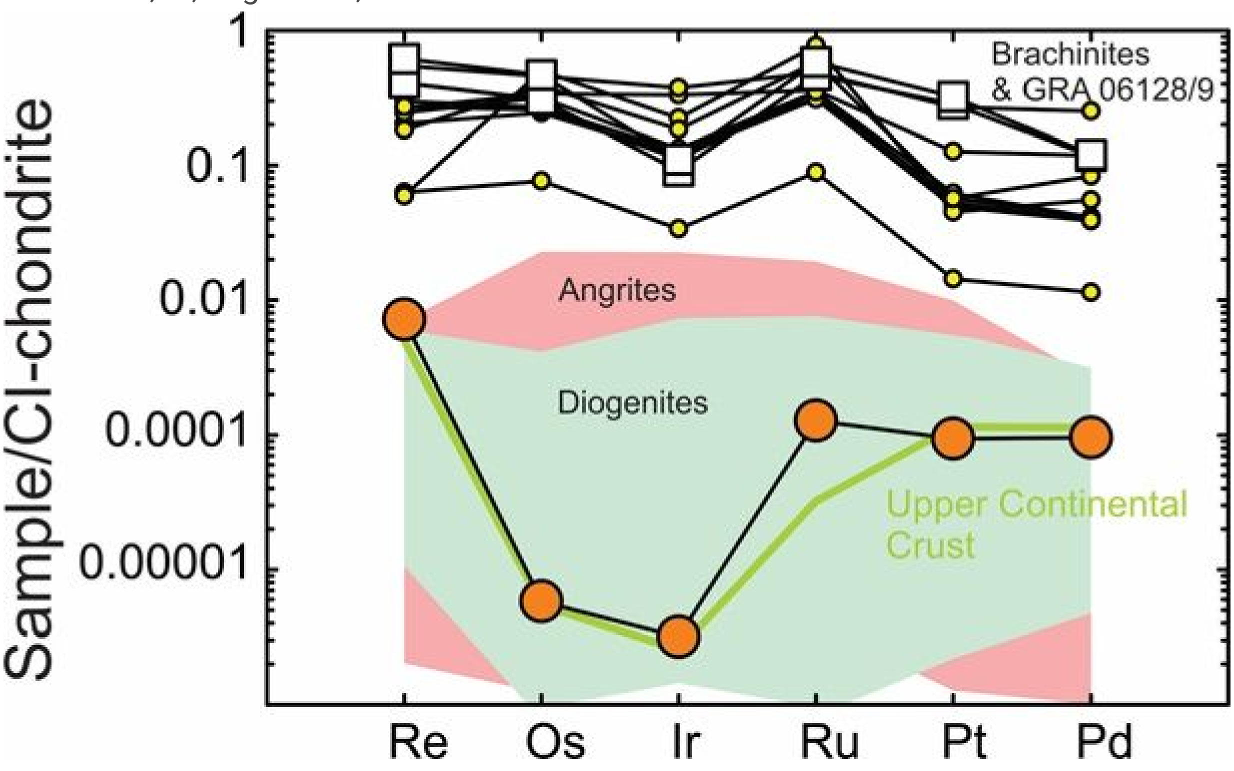

Figure 4

CI-Chondrite-normalized highly siderophile element abundances of achondrite meteorites and the terrestrial upper continental crust (UCC). Note the low and fractionated HSE pattern of Erg Chech 002 relative to Brachina, GRA 06128/9. Sources of data are: GRA 06128/9 and brachinites[3,12,27,28], diogenites[18], angrites[17] and UCC[6].

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FullEPMAData.xlsx
- FullLAData.xlsx
- EC002Maps.pdf
- ErgChechSupplement.docx