Achondrite meteorites as snapshots of Earth's earliest history

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Overview

The formation and earliest evolution of Earth is key to our understanding of modern terrestrial system. From a spheroid of accreting dust and gas in the solar nebula, to a differentiated body, with metallic core and silicate mantle, early processes shaped the planet on which we live today. Knowledge of the chemical composition of the material that accreted to Earth whilst it was growing, and also that of Earth's core today would tell us much about the physiochemical conditions during its formation. Unfortunately, direct sampling of the core is impossible; however, planetary differentiation also left its fingerprint on the chemical composition of Earth's mantle [1]. In addition, other differentiated planet(oid)s in our Solar System also record the chemical effects of core formation in their mantles. The silicate portion of these bodies may closely resemble the type of material added to Earth's mantle towards the later stages of planetary growth due to the limited metal silicate equilibration [2].

Different elements have characteristic geochemical affinities whereby they prefer to partition into the silicate (lithophile), metal (siderophile) or sulphide (chalcophile) phase during equilibration [1]. By experimentally parametrising this partitioning behaviour over a range of physical conditions, the concentration of elements in the Earth's mantle can be used to infer pressure, temperature and oxygen fugacity during Earth's differentiation. Isotope compositions of an element also are affected by phase equilibration – if this fractionation is experimentally characterised, physical and compositional information can be more precisely constrained [3]. A complication arises because core formation on Earth did not occur

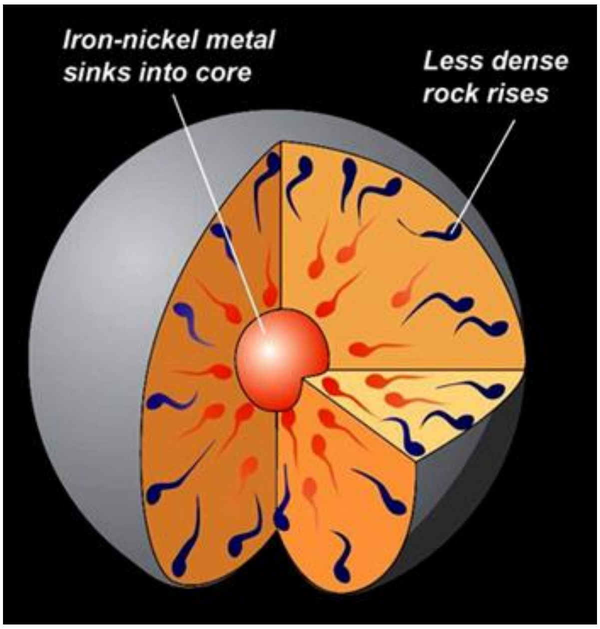

Figure 1. Cartoon showing idealised planetary differentiation (taken from www.nau.edu)

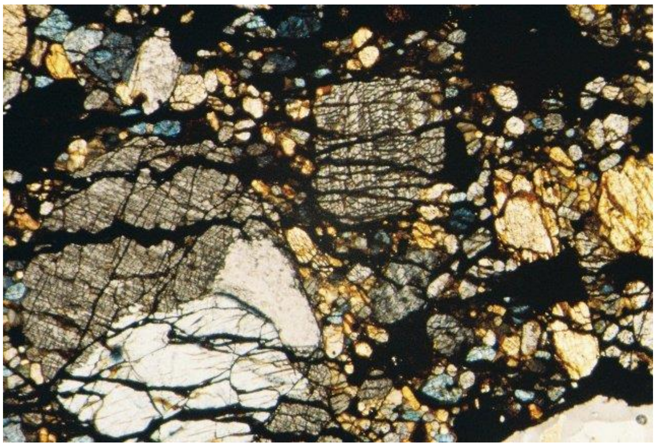

Figure 2. Thin-section of an aubrite (enstatite achondrite) showing the dominant pyroxene mineralogy, breccia textures and metal/sulphide opaque grains (from www.cefns.nau.edu)

as a single discrete event. A more likely scenario is that terrestrial differentiation occurred over a prolonged period and as the chemistry, pressure and temperature of Earth's mantle changed, so did phase equilibria. A further consideration is that at the later stages of Earth accretion, mass addition to Earth was probably in the form of a number of large scale planetary-sized collisions, where the mantles and cores of two potentially very chemically different bodies merged without significant equilibration between the metal and silicate portions [2]. It is most likely, therefore, that the chemical fingerprint of core formation on small asteroid-sized bodies dominates the composition of many elements in the modern terrestrial mantle.

Copper and nickel are both multi-isotope elements that have the potential to reveal important aspects of planetary differentiation. This is because both are siderophile and chalcophile to varying degrees (around 2/3 of Earth's Cu, and 95% of Earth's Ni is thought to be in the core) so, chemically, both are significantly affected by core formation. Isotopically, there is good experimental evidence that both of these systems have measurable isotopic fractionations induced by metal-silicate-sulphide equilibria [4, 5], i.e., core formation should impart not only an elemental fractionation on Earth's mantle, there may also be measurable isotopic differences between Earth's mantle, and 'primitive solar system' compositions.

We have relatively good estimates of both the Cu and Ni isotope compositions of Earth's mantle as well as the so-called primitive meteorites [4, 5]. We also have the expectation that both Cu and Ni should be fractionated by planetary differentiation – and in the case of Cu isotopes, this seems to be the case – but for Ni the situation is more equivocal. There are still open questions as to how the Earth's mantle came to have its current Cu and Ni isotope compositions.

The starting composition for the evolution of terrestrial reservoirs can be estimated from the compositions of the primitive meteorites. The end point is clearly constrained by the composition of Earth's mantle. However, up to now we have inferred via models and experimental work the evolution between these two crucial compositions. Knowledge of this evolution is vital for both estimating the composition of the core and the bulk compositions of the Earth in addition to constraining terrestrial differentiation processes. Achondrites (i.e. meteorites from differentiated bodies) give us the opportunity to study snapshots of the differentiation process from an elemental and isotopic standpoint. Importantly, because equilibration between metal and silicate was likely limited during late stage accretion, small achondrite parent bodies may represent very closely the intermediate stages of Earth's isotopic and chemical evolution. This project would aim to study the behaviour of both Cu and Ni isotopes during planetary differentiation using our current inventory of achondrite meteorites, which display a range of different bulk compositions, but also a range of differentiation 'degrees' from nascent partial melting to complete core-mantle separation.

Methodology

The main aim of this project is to investigate the Cu and Ni isotopic fractionation behaviour between metal, silicate and sulphide phases in a suite of achondrite meteorites. By selecting samples that underwent different relative degrees of planetary-scale differentiation we can, potentially, investigate snapshots of Earth's mantle during its early evolution. The ultimate goal is to place robust constraints on the evolution of the Cu and Ni isotope compositions of the terrestrial mantle which have significant implications for Earth's formation and differentiation. This will be accomplished by coupling analysis of natural samples with numerical modelling of planetary accretion.

Sample characterisation will be made at the microprobe and mass spectrometer facilities at St Andrews and Durham Universities. Isotope measurements will be made using high resolution multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS).

The two suites of achondrites that are envisioned as starting points for this project are the aubrites (enstatite achondrites, see Fig 2) and the acapulcoite-lodranites. The aubrites are differentiated achondrites, predominantly of enstatite with varying amounts of metal and sulphide, whose parent body formed a core by removal of c. 25% metal and 5% of sulphide from that body's mantle [6]. The acapulcoite-lodranites clan are primitive achondrites from a common parent body but with a range of melt depletions, from <1% to >10%, resulting in the removal of varying amounts of both metal and sulphides [7]. Students will have the opportunity to visit and utilise the meteorite collections at both the Hunterian Museum in Glasgow, and the Natural History Museum in London – where some components of the sample characterisation (e.g. probe mapping) can take place.

It is envisioned that each meteorite sample will be characterised via SEM and image maps created with microprobe to assess the major hosts of Cu and Ni. Further to this, high precision Cu and Ni isotope analyses will be performed on both bulk meteorite and phase separate samples. The new range of achondrite Cu and Ni compositions will be included into models of continuous core formation on Earth, to predict core composition and the physiochemical conditions present during this event.

Timeline

Year 1: Literature review and compilation of existing Cu isotope data for mantle and meteorite samples; training in meteorite handling and characterisation; preparation of meteorite samples; training in and start of Cu and Ni isotope analysis; write and defend Year 1 Research Proposal.

Year 2: Further analysis and preparation of meteorite samples; continued Cu and Ni stable isotope analysis of all samples; begin stable isotope modelling of data. Further sample collection, as needed. Prepare research for presentation/publication; attend international geochemistry / cosmochemistry conference.

Year 3-3.5: Completion of isotope work and interpretation and modelling of data, writing up. Presentation of results at national/international conferences; complete thesis.

Training & Skills

- Training in meteoritics.
- Training in clean laboratory techniques
- Training in the measurement of Cu and Ni stable isotopes using high precision MC-ICP-MS at St Andrews and Durham, as well as routine sample characterisation and imaging.
- Interpretation and modelling of isotope and elemental data to place new constraints on the core composition and planetary differentiation.
- Presentation of research at both national and international geochemistry conferences.

References & Further Reading

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Further Information

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