**Timing and Mechanisms of
Silicate Differentiation and
Basalt Magma Generation on
the
Howardite–Eucrite–Diogenite
Asteroid Parent Body**

by

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Abstract

Meteorites provide the only direct record of the chronology and nature of the processes that occurred in the early solar system. In this study, meteorites were examined in order to gain insight into the timing and nature of magmatism and silicate differentiation on asteroidal bodies in the first few million years of the solar system. These bodies are considered the precursors to terrestrial planets, and as such they provide information about conditions in the solar system at the time of planet formation.

This study focuses on eucrites, which are basaltic meteorites that are believed to represent the crust of the Howardite-Eucrite-Diogenite (HED) parent body. The processes of silicate differentiation and the relationship between eucrites and the diogenitic mafic cumulate of the HED parent body are poorly understood. The major and trace element chemistry of the minerals in the eucrite suite was measured. There is little variability in mineral major element concentrations in eucrites, however considerable variability was observed in mineral trace element concentrations, particularly with respect to incompatible elements in the mineral phases. Magnesium was separated from digested eucrite samples, and the Mg isotope composition of the eucrites was measured to high precision in order to date the samples using the short-lived ^{26}Al – ^{26}Mg chronometer and examine magmatic evolution on the HED parent body.

Correlations between incompatible elements in pyroxene and ^{26}Mg anomalies, produced by the decay of ^{26}Al , indicate that the eucrite suite was formed from a single, evolving magma body. Large trace element and Mg isotopic differences between eucrites and diogenites indicate that the two meteorite groups did not, as previously suggested, originate from the same magma body. Instead they may have formed from two large

magma bodies, which were spatially or temporally separated on the HED parent body. The application of the short-lived ^{26}Al – ^{26}Mg chronometer to this suite of eucrites constrains the onset of eucrite formation to ~ 3 Myr after the formation of the solar system's first solids, as a result of rapid accretion and melting of planetesimals due to heating from the decay of ^{26}Al .

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The asteroid Vesta photographed by the Dawn Spacecraft (*Image credit: NASA*).

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Chapter 1

Introduction

Astronomical observations and astrophysical models can provide important insights into the formation of the stars and their planetary systems. However, meteorites provide the only samples that directly record the chronology and processes of solar system formation. In this study, the petrographic, chemical and ^{26}Al – ^{26}Mg isotopic properties of a suite of differentiated and genetically related meteorites (eucrites) thought to originate from the solar system's third largest asteroid (Vesta) were examined (Drake, 1979). These data were acquired in order to gain insights into the timing and nature of magmatism and silicate differentiation on asteroidal bodies that is known to have occurred in the first few million years of the 4567 Myr history of our Solar System (Mittlefehldt, 2007; McKeegan and Davis, 2007). As these bodies are considered to be the precursors to terrestrial planets, they provide important insights into conditions in the early solar system and the nature of planet formation (e.g., Greenberg et al., 1978; Fernández and Ip, 1984).

The howardite–eucrite–diogenite (HED) group of meteorites provide an important record of magmatic evolution in the early solar system, with meteorites sampling both the mantle and crust of the HED parent body, which is thought to be the asteroid Vesta (Drake, 1979). This study focuses on eucrites, which are basaltic meteorites representing the crustal material of the HED parent body.

Constraining the timing of silicate differentiation on asteroids requires the application of an appropriate chronometer. In this thesis study, the short-lived ^{26}Al – ^{26}Mg chronometer was chosen as Al and Mg are fractionated by igneous processes making this chronometer ideal for dating silicate differentiation. Moreover, the short half-life of the chronometer (0.73 Myr; Walker et al., 1989) means it can provide very precise relative ages (± 0.1 Myr) of processes that occurred in the first few million years of the solar system.

1.1 Early solar system evolution and chronology

1.1.1 Formation of a central star and proto-planetary disk

It is generally accepted that the creation of stars occurs exclusively within molecular clouds, which form from the diffuse interstellar medium over relatively short lifetimes of 10–20 Myr (McKeegan and Davis, 2007). Initially, turbulent motion and gas pressure within the molecular cloud support the dense core, preventing gravitational collapse of the core. Eventually the turbulent motion diminishes, and magnetic fields support the cloud against its own gravity. However, over timescales of a few million years the magnetic field is no longer sufficient to support the dense cloud core, leading to the rapid collapse of the core and formation of low mass stars. It is likely that this process was responsible for the formation of the proto-sun and the solar nebula from which the solar system originated (Boss et al., 2008). After collapse of the molecular cloud, the sun was an embedded young solar object surrounded by gas and dust (proto-planetary disk) that was eventually distributed into an envelope from which an accretion disk evolved (McKeegan and Davis, 2007). The timescales of this process are poorly constrained. By summing the amount of rocky and icy material comprising the planets, as well as enough hydrogen and helium to produce a nebula with the same composition as the sun, Weidenschilling (1977) determined that this accretion disk contained a minimum of 1% of the mass of the sun.

1.1.2 Formation of the first solids

The components of chondrite meteorites are regarded as the solar system's earliest solids (Scott and Krot, 2007) and, as such, provide records of the conditions in the early solar system. Chondrules are a major component of almost all primitive meteorites, and comprise mostly crystalline silicate material with some glass. Chondrule textures suggest that they were almost heated to their melting point and then rapidly cooled. The short cooling times indicate that chondrules were heated in events that only affected a small area of the solar nebula (Desch and Connolly, 2002). This idea is supported by the fact that pre-solar grains have not experienced significant heating events (Mendybaev et al., 2002).

In addition to chondrules, many primitive chondritic meteorites contain small amounts of refractory inclusions, such as calcium–aluminium-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs). Refractory inclusions contain minerals that have been heated for longer than chondrules, and their refractory nature (i.e., Ca–Al–Ti-rich) suggests that they may have formed closer to the sun than chondrules (Alexander et al., 2008). Age dating of CAIs has shown they are the oldest solids in the solar system (e.g., Amelin et al., 2002) having formed as condensates from a cooling gas phase during the early stages of the proto-planetary disk (Ireland and Fegley, 2000; Wood, 2004). AOAs are found in carbonaceous chondrites and have similar textures, mineralogies and oxygen isotope compositions as accretionary rims on some CAIs, which indicates that AOAs formed in the CAI-forming region as aggregates of condensates from the solar nebula (Krot et al., 2004). Dating of refractory inclusions requires that they survived in the solar nebula for several million years before being incorporated into larger planetary bodies (Chambers, 2007).

1.1.3 Planetary accretion

After formation of the proto-sun, bipolar winds from the young sun efficiently expelled gas from the nebula, allowing the dust particles that had been supported in the gas to settle into the mid-plane of the neb-

ula over a timescale of 10^3 – 10^4 yr (Weidenschilling, 1980). Gravitational instability cannot account for the initial stages of planetesimal formation, as gravity is only important once bodies become kilometre-sized (Weidenschilling, 2000). The most likely process responsible for the initial coagulation of dust is “dust grain sticking”, which occurs due to low velocity collisions between dust grains. Laboratory studies and theoretical models have shown that surface forces make it possible for small grains to stick together when they collide at the velocities expected in the solar nebula (Weidenschilling, 2000). The process of “dust grain sticking” results in the formation of centimetre-sized dust aggregates. However, little is understood about the growth of these macroscopic aggregates into kilometre-sized bodies. Once bodies are kilometre-sized, gravitational interactions between them become significant and influence their velocities and orbital trajectories and the likelihood of collision and accretion of larger bodies (Chambers, 2007).

There are three stages of planetary accretion that followed the formation of planetesimals: runaway growth, oligarchic growth and late stage accretion and giant impacts. Initially runaway growth occurred when larger bodies with relatively slow velocities grew rapidly by colliding with and incorporating smaller, faster bodies. This resulted in the formation of planetary embryos up to 1000 times the size of the planetesimals from which they formed. During oligarchic growth, the planetary embryos were so large they gravitationally disturbed the area surrounding them, resulting in fewer collisions with smaller bodies, and slowed growth. Oligarchic growth produced Moon- to Mars-sized bodies in a process thought to take approximately 1 Myr at 1 AU (Weidenschilling, 2000). The final stage of accretion is the giant impact stage, which began when the planetesimals no longer had a significant gravitational effect on the much larger embryos. This resulted in sizable collisions between embryos, eventually forming the larger terrestrial planets (Chambers, 2007). This entire process of planetary accretion is considered to have taken approximately 100 Myr, with some planets experiencing several impacts in the final stages of their formation. While not every impact results in accre-

tion, some were energetic enough to cause extensive melting and possibly resulted in the formation of large-scale magma oceans.

1.1.4 Differentiation of planetesimals

In various meteoritic materials there is evidence for the former presence of at least 14 short-lived radionuclides with half-lives of ≤ 100 Myr (Table 1.1). Although these radionuclides are now extinct, their existence can be inferred from excesses in their decay or daughter products found in some meteorites. In addition to their use as chronometers, short-lived radionuclides are thought to have played an integral role in the differentiation of planetesimals. Early studies considered that planetesimal melting was the result of heating due to the radioactive decay of K, U and Th (Kuiper, 1954). However, as these are long-lived nuclides with half-lives of billions of years, the time required to produce sufficient heat to melt early formed planetesimals is too long. Urey (1955) suggested that the heat produced by the radioactive decay of short-lived ^{26}Al may have been responsible for the melting and, in turn, differentiation of planetesimals. Although several other heat sources have been proposed for the early melting and differentiation of planetesimals, such as impact energy and electromagnetic induction, the radioactive decay of short-lived nuclides remains the most widely accepted and plausible hypothesis. The decay of both ^{60}Fe and ^{26}Al were thus considered to be the most important heat sources for planetesimal melting (e.g., Shukolyukov and Lugmair, 1993). However the recent revision of the half-life of ^{60}Fe to a longer value (Rugel et al., 2009) suggests that it was not a significant source of heat, implying that ^{26}Al was the most important source of heat in the early solar system (Hevey and Sanders, 2006). This is supported by evidence of excesses of the daughter product of ^{26}Al (^{26}Mg) in many CAIs and meteorite groups, indicating that at least in a general sense it was widely distributed in the solar nebula (Baker et al., 2005; Bizzarro et al., 2005b; Wadhwa et al., 2009; Schiller et al., 2010, 2011).

Relative age differences between CAIs and achondritic meteorites can

provide constraints on the timing of planetesimal differentiation and, combined with thermal modelling, can be used to estimate the timing of planetesimal accretion. Application of ^{26}Al – ^{26}Mg chronometry to basaltic meteorites suggests that silicate melting and differentiation of planetesimals occurred within the first 3–4 Myr of solar system formation, which implies that accretion took place in the first 1 Myr of the solar system (Baker et al., 2005; Bizzarro et al., 2005b; Wadhwa et al., 2009; Schiller et al., 2010, 2011).

1.2 Early solar system chronometers

Application of various chronometers to meteorites and their constituent solids and minerals provides unique constraints on the timing and rates of processes in the early solar system. A variety of chronometers can be used to date meteorites. Pb–Pb dating is based on the long-lived decay chains of ^{235}U and ^{238}U and is the only absolute chronometer with sufficient precision to resolve time differences in the first few million years of the solar system. In addition, a number of short-lived or relative chronometers also allow relative ages of early solar system processes to be determined with high temporal resolution (Table 1.1).

The short-lived chronometers most widely used to study early solar system processes are the ^{182}Hf – ^{182}W , ^{53}Mn – ^{53}Cr and ^{26}Al – ^{26}Mg systems, which are briefly reviewed below.

Hf is a lithophile element (has a strong affinity to be in silicate reservoirs) whereas W is a siderophile element (has a strong affinity to be in metallic iron, e.g., metallic cores of differentiated bodies) and, as such, the ^{182}Hf – ^{182}W chronometer is ideally suited to dating metal–silicate differentiation (i.e., core formation) of planetesimals. Superchondritic Hf/W ratios in the silicate portion of planets results in ^{182}W excesses, and complementary deficits in the metal core, provided core formation occurred during the lifetime of ^{182}Hf ($t_{1/2} = 8.9$ Myr; Vockenhuber et al., 2004). The ^{53}Mn – ^{53}Cr short-lived chronometer is suitable for dating processes that occurred in the first ca. 20 Myr of the solar system ($t_{1/2} = 3.7$ Myr; Honda and

Table 1.1: Short-lived radionuclides that existed in the early solar system. Table from McKeegan and Davis (2007). Half-lives are taken from National Nuclear Data Centre. References: (1) Chaussidon et al. (2006); (2) Srinivasan et al. (1994); (3) Lin et al. (2005) and Hsu et al. (2006); (4) Bizzarro et al. (2005a), Bizzarro et al. (2005b) and McKeegan and Davis (2007); (5) Chaussidon et al. (2006) and McKeegan and Davis (2007); (6) Mostefaoui et al. (2005) and Tachibana et al. (2006); (7) Dauphas et al. (2005); (8) Chen and Wasserburg (1990); (9) Kleine et al. (2005); (10) Jeffery and Reynolds (1961); (11) Nielsen et al. (2006); (12) Schönbächler et al. (2002); (13) Hudson et al. (1988).

Parent nuclide	Half-life	Daughter nuclide	Estimated initial solar system abundance	References
^7Be	53.1 days	^7Li	$^7\text{Be}/^9\text{Be} = 1 \times 10^{-3}$	(1)
^{41}Ca	102 kyr	^{41}K	$^{41}\text{Ca}/^{40}\text{Ca} = 1 \times 10^{-8}$	(2)
^{36}Cl	301 kyr	$^{36}\text{S}, ^{36}\text{Ar}$	$^{36}\text{Cl}/^{35}\text{Cl} = \sim 4 \times 10^{-6}$	(3)
^{26}Al	717 kyr	^{26}Mg	$^{26}\text{Al}/^{27}\text{Al} = \sim 5\text{--}6 \times 10^{-5}$	(4)
^{60}Fe	1.5 Myr	^{60}Ni	$^{60}\text{Fe}/^{56}\text{Fe} = \sim 5\text{--}10 \times 10^{-7}$	(5)
^{10}Be	1.51 Myr	^{10}B	$^{10}\text{Be}/^9\text{Be} = \sim 1 \times 10^{-3}$	(6)
^{53}Mn	3.74 Myr	^{53}Cr	$^{53}\text{Mn}/^{55}\text{Mn} = 1 \times 10^{-5}$	(7)
^{107}Pd	6.5 Myr	^{107}Ag	$^{107}\text{Pd}/^{108}\text{Pd} = \sim 5 \times 10^{-5}$	(8)
^{182}Hf	8.90 Myr	^{182}W	$^{182}\text{Hf}/^{180}\text{Hf} = 1.07 \times 10^{-4}$	(9)
^{129}I	15.7 Myr	^{129}Xe	$^{129}\text{I}/^{127}\text{I} = 1 \times 10^{-4}$	(10)
^{205}Pb	17.3 Myr	^{205}Tl	$^{205}\text{Pb}/^{204}\text{Pb} = \sim 1\text{--}2 \times 10^{-4}$	(11)
^{92}Nb	34.7 Myr	^{92}Zr	$^{92}\text{Nb}/^{93}\text{Nb} = 1 \times 10^{-4}$	(12)
^{244}Pu	80.0 Myr	Fission Xe	$^{244}\text{Pu}/^{238}\text{U} = 7 \times 10^{-3}$	(13)
^{146}Sm	103 Myr	^{142}Nd	$^{146}\text{Sm}/^{147}\text{Sm} = 9 \times 10^{-4}$	(14)

Imamura, 1971). Mn and Cr undergo relative fractionation during evaporation/condensation and magmatic processes, making the chronometer suitable for investigating the time between accretion and differentiation of planetesimals (McKeegan and Davis, 2007). Short-lived chronometers only allow for relative dating between samples of two different ages, as the initial abundance of the parent nuclide is unknown. However, these relative ages can be anchored onto an absolute timescale by dating the same material with the Pb-Pb chronometer.

1.2.1 ^{26}Al – ^{26}Mg chronometer

There are three stable isotopes of magnesium (^{24}Mg , ^{25}Mg and ^{26}Mg) that are produced in stellar environments. ^{24}Mg is produced through hydrogen burning, whereas neon burning during the α process, carbon burning and explosive nucleosynthesis are responsible for the production of ^{25}Mg and ^{26}Mg (Burbidge et al., 1957). In addition, ^{26}Mg is produced by the decay of the short-lived radionuclide ^{26}Al , with a half-life of 0.73 Myr through positron emission/electron capture to ^{26}Mg (Lee et al., 1977).

The ^{26}Al – ^{26}Mg chronometer has been widely applied to obtain precise relative ages of silicate melting and crystallization in the early solar system (e.g., Srinivasan et al., 1999; Baker et al., 2005; Bizzarro et al., 2005b; Spivak-Birndorf et al., 2009; Wadhwa et al., 2009; Schiller et al., 2010, 2011) as Al and Mg are fractionated by partial melting and the formation of basaltic magmas as well as the crystallization of different mineral phases (McKeegan and Davis, 2007).

The validity of short-lived radionuclides as chronometers relies on an understanding of their distribution within the solar nebula, which also requires some knowledge of how and where the short-lived nuclide originated from. The origin of short-lived nuclides is a subject of controversy, with a number of models having been proposed to account for their existence, such as formation by energetic particle irradiation in the protomolecular cloud, or in the solar nebula by the early sun (Sahijpal et al., 1998). The most widely accepted model for the formation of most short-lived radionuclides is, however, by nucleosynthetic processes of a stellar origin (Sahijpal et al., 1998).

A homogeneous distribution of ^{26}Al in the solar system has been inferred from the agreement between ^{26}Al – ^{26}Mg and ^{206}Pb – ^{207}Pb ages of refractory inclusions and chondrules from primitive meteorites (Amelin, 2002) and Mg isotope measurements of these components (Villeneuve et al., 2009). However, high-precision Mg isotope measurements of solids from the inner solar system indicate that there is widespread heterogeneity in the abundance of ^{26}Mg , reflecting early heterogeneity in the distribu-

tion of ^{26}Al throughout the proto-planetary disk (Larsen et al., 2011). This means that rather than applying a solar system wide initial $^{26}\text{Al}/^{27}\text{Al}$ ratio (the canonical ratio based on measurements of CAIs), variations in initial ^{26}Al abundances need to be considered when applying the ^{26}Al - ^{26}Mg chronometer to material from different source regions.

The decay equation for the ^{26}Al - ^{26}Mg chronometer can be written as:

$$\left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_{\Delta t} = \left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_0 + \left(\frac{^{26}\text{Al}}{^{24}\text{Mg}}\right)_0 \times e^{-\lambda t} \quad (1.1)$$

where $(^{26}\text{Mg}/^{24}\text{Mg})_{\Delta t}$ is the Mg isotopic composition after an interval of time, and $(^{26}\text{Mg}/^{24}\text{Mg})_0$ is the Mg isotopic composition at $t = 0$, which is usually the time of solar system formation. $(^{26}\text{Al}/^{24}\text{Mg})_0$ is the initial abundance (i.e., $t = 0$) of ^{26}Al relative to ^{24}Mg , and λ is the decay constant of ^{26}Al . ^{26}Al is now extinct, so the initial abundance $(^{26}\text{Al}/^{24}\text{Mg})_0$ cannot be measured, however $(^{26}\text{Al}/^{24}\text{Mg})_0$ can be replaced in the equation by $[(^{26}\text{Al}/^{27}\text{Al})_0 \times (^{27}\text{Al}/^{24}\text{Mg})]$ where $(^{26}\text{Al}/^{27}\text{Al})_0$ is given by slope of the correlation line (isochron) on a plot of $^{26}\text{Mg}/^{24}\text{Mg}$ versus $^{27}\text{Al}/^{24}\text{Mg}$ (e.g., Fig. 1.1), and $^{27}\text{Al}/^{24}\text{Mg}$ is the measured Al/Mg ratio of the sample. With knowledge of the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio, based on this ratio in CAIs, an age relative to CAIs can be calculated using the equation:

$$\Delta t = \frac{-\left(\ln \left[\left(\frac{^{26}\text{Al}}{^{27}\text{Al}} \right)_{\Delta t} / \left(\frac{^{26}\text{Al}}{^{27}\text{Al}} \right)_0 \right] \right)}{\lambda} \quad (1.2)$$

Based on the assumption that CAIs are the solar system's first solids, a time calculated relative to CAIs can be interpreted as the time that has elapsed since the beginning of the solar system.

1.3 Classification of meteorites

Meteorites are divided into two general groups (chondrites and non-chondrites) on the basis of their bulk compositions and textures, with non-

Figure 1.1: Example of an ^{26}Al – ^{26}Mg isochron from Spivak-Birndorf et al. (2009).

chondrites further sub-divided into achondrites, irons and stony-irons (Table 1.2).

Chondrites are generally considered to be the most primitive meteorites, originating from parent bodies that did not melt and differentiate, unlike the parent bodies of non-chondrites that have experienced varying degrees of melting and differentiation. Some non-chondritic meteorites have characteristics of both chondrites and achondrites, and are referred to as primitive achondrites. With a greater metal and siderophile element content than most achondrites, primitive achondrites are thought to have come from parent bodies that underwent a lesser degree of melting, and thus did not fully differentiate into a mantle and core (Krot et al., 2003). The most evolved achondrites are considered to be products of silicate differentiation, and share some similar characteristics to terrestrial basalts. Iron meteorites are believed to represent core material of differentiated planetesimals that have metal-rich cores (Krot et al., 2003). Stony-iron meteorites comprise approximately equal amounts of silicate and metal, which suggests that they may originate from the core–mantle boundary of small, differentiated planetesimals (Krot et al., 2003).

1.3.1 Chondrites

Whole-rock elemental and oxygen isotope compositions provide the basis for categorizing chondrites into 14 groups. A chondrite group is defined where there are at least five unpaired chondrites with similar mineralogy, petrography, oxygen isotopic properties and bulk chemical compositions (Krot et al., 2003). There are also several chondrites with unique properties that are ungrouped. From these 14 chondrite groups, 13 of them comprise three major classes of chondrites i.e., carbonaceous (C), ordinary (O) and enstatite (E).

Carbonaceous chondrites

Carbonaceous chondrites are divided into eight groups: CI, CM, CR, CH, CB, CV, CK and CO. The second letter of these acronyms refers to the type meteorite of that class (e.g., the CV group takes its name from the Vigarano meteorite). Carbonaceous chondrites contain variable amounts of refractory material, including calcium–aluminium-rich inclusions (CAIs), which are thought to be the first solids that condensed from the cooling proto-planetary disk.

Ordinary chondrites

Ordinary chondrites are divided on the basis of their Fe content into three groups i.e., H (highest total iron but lower iron oxide), L (relatively lower total iron but higher iron oxide than H group) and LL chondrites (lowest total iron but the highest iron oxide content) (Krot et al., 2003). The oxygen isotope composition of chondrules from chondrites of all three groups define a common fractionation line, which suggests that all the ordinary chondrites originate from a common source (Wasson, 1972).

Enstatite chondrites

Enstatite chondrites are grouped based on Fe-content, mineralogy and bulk chemistry into EH (high enstatite) and EL (low enstatite) chondrites.

The oxygen isotope composition of enstatite chondrites is indistinguishable from the terrestrial fractionation line, suggesting a potential genetic relationship between enstatite chondrites, Earth and the Moon (Clayton et al., 1984).

1.3.2 Non-chondrites

Non-chondrites are considered to be derived from chondritic material that has melted and fractionated, the degree of which determines how much their bulk composition deviates from that of chondrites. Two major categories of non-chondrites are defined based on their degree of melting i.e., primitive and differentiated. Primitive non-chondrites have bulk compositions that are very similar to those of chondrites, but have igneous or metamorphic textures consistent with them representing either metamorphosed chondrites or residues from a small degree of partial melting (Krot et al., 2003). Differentiated non-chondrites originate from parent planetesimals that are thought to have undergone large-scale melting and differentiation.

Differentiated achondrites

The following summarizes the most common groups of achondrites. More detailed descriptions of the achondrite meteorite groups can be found in Krot et al. (2003) and references therein.

Howardite–Eucrite–Diogenite group

The howardite–eucrite–diogenite (HED) achondrites originated from a differentiated parent body that experienced extensive processing, producing mafic and ultramafic igneous rocks that, in some respects, closely resemble terrestrial igneous rocks. The oxygen isotope compositions of HED meteorites indicate that these meteorites originate from a single parent body (Clayton and Mayeda, 1996), which is believed to be the asteroid

Vesta (Drake, 1979). Howardites are regolith breccias of eucrite and diogenite material, representing lithified impact ejecta. Eucrites are basalts composed of orthopyroxene, pigeonite, Ca-rich clinopyroxene and plagioclase with minor amounts of chromite, ilmenite, troilite and Fe-Ni metal (Mittlefehldt, 2007) that likely originated from the crust of the HED parent body. Diogenites are primarily monomict orthopyroxenites containing lesser amounts of plagioclase and olivine, which are thought to have originated from relatively deeper levels than eucrites within the HED parent body (Mittlefehldt, 2007).

As the HED meteorites are the subject of this thesis research, a separate, detailed description of their characteristics follows in Section 1.4.

Angrites

Angrites are basaltic in composition, consisting of Ca–Al–Ti- rich pyroxene, anorthitic plagioclase and Ca-rich olivine. Based on experimental partial melting of chondrite meteorites, angrites are believed to have formed from partial melting of primitive material under oxidizing conditions (Jurewicz et al., 1993). Unlike the HED suite of meteorites, most angrites show no signs of thermal or shock metamorphism, suggesting that either the parent body was smaller, or that the parent body formed in an area of the solar system that was less affected by the late heavy bombardment associated with the shock metamorphism of eucrites (Mittlefehldt et al., 2002). Angrites can be precisely dated with the Pb–Pb chronometer owing to their extreme volatile depletion and very low $^{204}\text{Pb}/^{238}\text{U}$ of their parent body (Amelin, 2008). As such absolute and relative ages for angrites provide a useful time anchor for short-lived chronometers applied to other meteorite suites.

Aubrites

Aubrites are primarily composed of enstatite, with lesser amounts of olivine, iron–nickel metal and troilite, which indicates formation under extremely reducing conditions. Aubrites lack a basaltic component, and

the process by which they formed is enigmatic. However, aubrites are thought to be cumulate material from a magma ocean on what was an extremely reduced planetesimal (Mittlefehldt, 2007).

Ureilites

Ureilites are ultramafic rocks composed of olivine, pyroxene and carbon-rich interstitial material. Ureilites display a wide range of oxygen isotope compositions that plot along a mass-independent line with the same 1:1 slope as that of the carbonaceous chondrites anhydrous mineral line (Goodrich, 1992). The origin of ureilites is poorly understood as they exhibit some properties that suggest that they are primitive rocks, while other features indicate that they have a high-temperature origin, perhaps reflecting partial melting of a differentiated planetesimal that did not experience complete melting (Goodrich et al., 2004).

Brachinites

Brachinites are predominantly comprised of olivine and pyroxene, and have variable bulk chemistry. The origins of brachinites are uncertain, and they may be primitive rocks, partial melt residues or igneous cumulates (Krot et al., 2003). The petrological and geochemical variations between different brachinites suggests that they may have formed by a range of these processes.

Stony-irons

Mesosiderites

Mesosiderites are stony-iron meteorites consisting of silicate material and iron–nickel metal. The silicate material in mesosiderites is a polymict breccia of crustal rocks, similar to that of the HED meteorites, leading to speculation that mesosiderites originated from the HED parent body. However, differences in mineralogy and composition imply that mesosiderites

come from a separate parent body, possibly with a similar thermal history to the HED parent body (Mittlefehldt, 2007). The metal component of mesosiderites is presumed to be from the core of a planetesimal, which was mixed with silicate material due to an impact. However, there is debate as to whether the silicate and metal components originated from the same parent body.

Pallasites

Pallasites are stony-iron meteorites composed predominantly of olivine, iron–nickel metal and troilite. On the basis of their mineralogy and composition, pallasites are separated into three groups, possibly originating from three separate parent bodies. Pallasites are believed to originate from the core–mantle boundary of asteroids, despite some apparent difficulties of this model in explaining all the features of pallasites, such as mixing of olivine and metal (Krot et al., 2003)

Irons

Iron meteorites are classified into 13 groups based on chemistry, and are assumed to originate from the metal-rich cores of differentiated bodies (Krot et al., 2003).

1.4 Howardite–eucrite–diogenite meteorites

1.4.1 Petrology and geochemistry of HED meteorites

Howardites are regolith breccias predominantly comprising eucritic and diogenitic material, along with abundant melt clasts. Howardites also occasionally contain xenoliths of carbonaceous chondritic material that is thought to have been introduced by impactors (Metzler et al., 1995). The high noble gas content of howardites was likely introduced by solar winds, confirming their origin as surface material from the HED parent body (Suess et al., 1964).

Eucrites are basalts composed predominantly of high- and low-Ca pyroxene and plagioclase, with minor amounts of chromite, ilmenite, troilite and Fe–Ni metal. There are three sub-classes of eucrites: non-cumulate eucrites, cumulate eucrites and polymict eucrites. Polymict eucrites are breccias consisting of at least 90% eucritic material, and a variety of clasts of diagenetic material, pyroxene cumulates, feldspar cumulates and other minerals. The variety of lithologies that comprise the polymict eucrites suggests that they are the result of serial magmatism, which has produced a diverse crust on the HED parent body (Delaney et al., 1984). Non-cumulate eucrites are the most common group of eucrites, most of which belong to one of three sub-groups; main group eucrites and the Stannern and Nuevo Laredo trend eucrites. These sub-groups are defined on the basis of Mg# (whole rock molar $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$) and incompatible trace element concentrations (Basaltic Volcanism Study Project, 1981). Non-cumulate eucrites typically have relatively flat chondrite-normalized rare earth element (REE) patterns, in some cases characterized by a negative Eu anomaly (Hsu and Crozaz, 1996). Non-cumulate eucrites are thought to have formed as surface lava flows that cooled rapidly (Mittlefehldt, 2007).

Almost all eucrites have experienced some degree of metamorphism resulting in mineral re-equilibration and recrystallization, with the majority of eucrites being metamorphosed at temperatures between 700°C and 1000°C (Takeda and Graham, 1991; Yamaguchi et al., 1996). It has been proposed that the crust of the HED parent body formed from a series of stacked lava flows, resulting in thermal metamorphism where earlier erupted eucrites were buried and heated by subsequent flows (Yamaguchi et al., 1996). However, a study by Metzler et al. (1995) contends that thermal metamorphism resulted from the intrusion of dykes and hot melt sheets created by impacts. Multiple impacts have resulted in considerable reworking of the crust of the HED parent body, as evidenced by significant brecciation of howardites and many eucrites, recrystallization of minerals and melt inclusions of impact origin (Yamaguchi et al., 2009). These impact events occurred before, during and after thermal metamorphism and, therefore, many eucrites show evidence of both shock and thermal meta-

morphism (Metzler et al., 1995; Yamaguchi et al., 2009).

Cumulate eucrites are gabbros with plutonic textures. They are distinct from non-cumulate eucrites not only in terms of their texture, but also chemistry. The Mg# of high-Ca pyroxene is usually higher in cumulate eucrites than non-cumulate eucrites. Similarly, REE abundances in cumulate eucrites are lower than non-cumulate eucrites. The cumulate eucrites also exhibit positive Eu anomalies (Consolmagno and Drake, 1977).

Diogenites are coarse-grained cumulates from the HED parent body. These cumulates are predominantly comprised of orthopyroxene, with minor amounts of olivine, plagioclase and clinopyroxene. There is also evidence of dunite meteorites that are linked to diogenites that may originate from the HED parent body (Mittlefehldt, 2007; Beck et al., 2011).

1.4.2 Origins of HED meteorites

Oxygen isotope variations in differentiated planetesimals such as the HED parent body are mass-dependent, with fractionation lines that have a slope of ~ 0.52 in three oxygen isotope space (Clayton, 2003) (Fig. 1.2). Although different bodies have parallel trends, their $\Delta^{17}\text{O}$ ($\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52\delta^{18}\text{O}$) values differ, reflecting the unique oxygen isotope composition of their parent body (Fig: 1.2). Extensive melting of differentiated bodies resulted in isotopic homogenization to varying degrees, and allows genetic relationships between different meteorites to be established. The HED meteorites were determined to have originated from the same parent body based on a uniform $\Delta^{17}\text{O}$ of -0.25‰ for howardites, eucrites and diogenites (Clayton and Mayeda, 1996). This finding is consistent with a number of early petrological and chemical studies that identified the HED meteorites as originating from a common parent body (e.g., Duke and Silver, 1967; Bunch, 1975; Fukuoka et al., 1977). Similarities in the Fe/Mn ratios of pyroxenes from eucrites, diogenites and howardites also provides further evidence that these meteorites originate from a common parent body (Papike, 1998), as does the existence of rocks containing pyroxene and plagioclase with compositions intermediate to those found in diogenites and

Figure 1.2: Oxygen isotope composition of the HED meteorites, martian meteorites and lunar meteorites. The terrestrial fractionation line (TF) represents the oxygen isotope composition on Earth. Figure taken from Clayton (2003).

cumulate eucrites (Takeda and Mori, 1985).

A high precision study of oxygen isotopes in the HED meteorites revealed some subtle oxygen isotope heterogeneity (Wiechert et al., 2004). In general, HED meteorites have consistent $\Delta^{17}\text{O}$. However, howardites generally have a slight enrichment in ^{16}O , whilst some eucrites display slight depletions in ^{16}O . This suggests that there may have been incomplete mixing and isotopic equilibration on the HED parent body, resulting in some primary oxygen isotope heterogeneity (Wiechert et al., 2004). This could reflect formation of eucrites from localized partial melts (Stolper, 1977), or partial melting of the mantle with near surface layers experiencing much lower temperatures and undergoing little or no melting (Ghosh and McSween, 1998), and thus preserving some of this initial primary oxygen isotope heterogeneity.

1.4.3 Differentiation of the HED parent body

The relationships between cumulate eucrites, non-cumulate eucrites and diogenites is poorly understood, and is the subject of a long-standing debate. There are two distinct models that have been proposed in order to explain the formation of eucrites and diogenites and the differentiation of

the HED parent body.

An early study of eucrites by Stolper (1977) utilizing low pressure melting experiments suggested that eucrites formed from increasing degrees of partial melting of primitive, undifferentiated material. In this model, cumulate eucrites are the products of liquids resulting from fractionation of partial melts, and diogenites formed from melting of a source region that had undergone earlier melting to form eucrites, and were thus depleted in basaltic components (Fig. 1.3 A). Since the work of Stolper (1977), a number of other studies of HED meteorites have proposed variations on the partial melting model (e.g., Consolmagno and Drake, 1977; Jones, 1984; Mittlefehldt and Lindstrom, 2003). If eucrites and diogenites were indeed formed by partial melting, there is still uncertainty as to whether or not they are cogenetic, with some studies suggesting that diogenites and eucrites formed as part of the same crystallization sequence, with diogenites crystallizing first and eucrites forming from residual liquids (Fig. 1.3 A). Conversely, it is possible that eucrites and diogenites are not cogenetic and that they crystallized from different parental magmas, with the difference between the two reflecting compositionally distinct magma sources, resulting from heterogeneities on the parent body (Jurewicz et al., 1995) or differing degrees of partial melting (Shearer et al., 1997) (Fig. 1.3 B). Both variations on the partial melting model require relatively low to moderate temperatures, which are inconsistent with the amount of heat required for the metal–silicate differentiation that took place during core formation on the HED parent body (Newsom and Drake, 1983). Another difficulty with the partial melting model is that there is no evidence for unmelted primitive material on the HED parent body (other than small amounts in howardites thought to originate from impactors), which would likely comprise a reasonably large proportion of a body that was not entirely melted. A common argument against the partial melting model on the HED parent body is that the oxygen isotope homogeneity of the HED meteorites could only be achieved with (near-) complete melting of the parent body, even though a high precision study of oxygen isotopes in the HED meteorites did reveal some subtle oxygen isotope heterogeneity (Wiechert et al.,

Figure 1.3: End-member models for the differentiation of the HED parent body. Figure adapted from Shearer et al. (1997). Models A and B require relatively small degrees of partial melting, while model C requires near complete melting of the HED parent body. In models A and C eucrites and diogenites are part of the same crystallization continuum, whereas in model B the eucrites and diogenites crystallize independently from separate magma sources.

2004).

As an alternative to the partial melting models, it was proposed that eucrites and diogenites are the products of extensive fractional crystallization of an asteroidal magma ocean resulting from large scale melting that existed on the HED parent body (Ikeda and Takeda, 1985). Diogenites and cumulate eucrites would have formed as the magma ocean crystallized, with non-cumulate eucrites forming from residual magmas (Fig. 1.3 C). A number of studies have favoured this model (Righter and Drake, 1997; Wiechert et al., 2004; Greenwood et al., 2005; Schiller et al., 2010, 2011), as it explains the absence of unmelted, primitive material on the HED parent body and is also consistent with core segregation. However, the extreme trace element variability in HED meteorites (e.g., Fowler et al., 1995) is dif-

difficult to reconcile with eucrites and diogenites forming from continuous crystallization of the same magma body.

Barrat et al. (2000) suggested that the HED parent body differentiated as a result of *in situ* crystallization, which is a concept originally proposed by Langmuir (1989) to explain geochemical variations in terrestrial magmas. Without this crystallization model, the decoupling of major and trace elements in non-cumulate eucrites is difficult to reconcile with fractional crystallization of a magma ocean (Barrat et al., 2000). The *in situ* crystallization model still invokes the presence of a global magma ocean, but cumulate eucrites are envisaged to have crystallized in solidification zones at the margins of magma bodies where heat was being lost. Residual melts were trapped in the solidification zone and extruded as non-cumulate eucrites, with Nuevo Laredo and Stannern trend eucrites resulting from heterogeneities brought about by the *in situ* crystallization regime within the magma ocean (Barrat et al., 2000).

1.4.4 Relationship to the asteroid Vesta

The HED meteorites are unusual amongst meteorites found on Earth, in that their parent body has potentially been identified. Similarities between the mineralogy of the HED meteorites and the surface mineralogy of the asteroid Vesta, as determined by spectral reflectance measurements (McCord et al., 1970), suggest that the HED meteorites may have originated from Vesta (Drake, 1979). Vesta is the second most massive object in the asteroid belt and has a diameter of 525 km. It is dynamically linked to a group of smaller asteroids called the Vestoids that originated from a large impact on Vesta that may have produced the HED meteorites (Drake, 2001). Images captured by NASA's Dawn spacecraft show evidence of giant impacts and the youngest impact basin (Rheasilvia) is a ~500 km wide and ~19 km deep feature (Schenk et al., 2012). These large impacts excavated a substantial volume of material, sufficient to have created the Vestoids and the HED meteorites (Schenk et al., 2012).

1.4.5 Outstanding research questions

The HED meteorites have been studied extensively. However, there are many research questions that remain unanswered, and in particular, two important questions relating to the origin of these meteorites:

1. There is still uncertainty as to the timing and nature of silicate differentiation on the HED parent body and, as such, the relationship between the eucrites and diogenites remains unclear. It is possible that the eucrites and diogenites crystallized from separate partial melts, or that they are part of the same crystallization sequence either resulting from fractional crystallization of partial melts or a large-scale magma ocean. This research question is the main focus of this study.

2. The asteroid Vesta has similar surface mineralogy to the HED meteorites, suggesting that it may be the HED parent body. However there are a number of unexplored basaltic planetesimals in the asteroid belt that are also potential parent bodies. NASA has recently sent a space probe to the asteroid Vesta as part of the Dawn mission, which should provide important information about Vesta making it possible to confirm if it is the HED parent body (Russell et al., 2007).

1.5 Structure of this thesis

This thesis is structured into seven chapters:

1. An introduction that provides the background information for this study.
2. A chapter that presents the methods used in order to determine the major element, trace element and Mg isotopic compositions of the eucrite meteorites analysed in this study.
3. A description of the suite of samples, including the petrographic features and the major element composition of each sample.
4. The trace element chemistry of each sample.
5. Mg isotope data and model ages of the studied eucrites.
6. A discussion chapter where the major element, trace element and

Mg isotopic compositions are used to constrain the timing and nature of processes occurring on the HED parent body in the early solar system.

7. A brief conclusion that summarizes the main findings of this study and provides suggestions for future work.

Chapter 2

Methods

Twenty-three eucrite meteorites were used in this study, the majority of which were obtained on request from NASA's Antarctic meteorite collection.

2.1 Major and trace element measurements

2.1.1 Sample preparation

Fragments of each meteorite sample weighing 100–200 mg were mounted in blocks of epoxy resin and polished. Prior to major element analysis by electron probe microanalysis (EPMA), sample mounts were coated with a thin (25 nm) film of carbon (Reed, 2005). Following major element analysis, the carbon coatings were removed using methanol, and mounts were then cut in half for analysis by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

2.1.2 Major element measurements

Major element compositions of pyroxene and plagioclase were determined by EPMA using a JEOL JXA-8230 Superprobe. Analyses were performed using an accelerating voltage of 15 kV, a beam current of 12 nA and a focused beam (spot size <0.5 μm).

Measured X-ray intensities in pyroxene analyses were calibrated against elemental concentrations by analysis of the standards Natural Bridge diopside (NMNH 117733) (Ca, Mg, Si), Johnstown hypersthene (USNM 746) (Al, Fe), Kakanui augite (NMNH 122142) (Ti, Na) and pure synthetic oxides (Cr, Mn). Johnstown hypersthene and Natural Bridge diopside were also used as secondary standards and measured repeatedly throughout the analytical sessions (Table 2.1).

Elemental concentrations in plagioclase were calibrated by analysis of Plagioclase (Labradorite) Lake County, OR (NMNH 115900) (Na, Si, Al, Ca), Orthoclase Or-1a (K), and pure synthetic oxides (Ti, Mg, Fe, Mn). The plagioclase standard was also analysed throughout the session as a secondary standard (Table 2.1). Measurements of secondary standards are within error of the reference values for most elements, particularly the high concentration elements for which more robust measurements can be made (Table 2.1).

2.1.3 Trace element measurements

Trace elements measurements were performed using an Agilent 7500cs ICP-MS coupled to a New Wave deep UV laser that operates at a wavelength of 193 nm. Pyroxene and plagioclase were each analysed 10–15 times per sample, as close as possible to EPMA analytical sites. Each analysis comprised 90 s of background measurement followed by 60 s of sample ablation. For pyroxene analyses, the BCR-2G glass standard (GeoRem, 2010) was used as a bracketing standard and measured before and after every five sample analyses. Analyses of the BHVO-2G glass standard were used as a secondary standard (Table 2.2). Plagioclase analyses were bracketed with measurements of the NIST612 glass standard (GeoRem, 2010) before and after every five sample measurements, and the ATHO-G glass standard (GeoRem, 2010) was used as a secondary standard (Table 2.2).

Trace element data reduction was carried out with the software *iolite* using the “trace element IS” data reduction scheme (Paton et al., 2011). Any laser ablation or instrumentally induced trace element fractionation

Table 2.1: Major element compositions measured in the secondary standards: Plagioclase (Labradorite) Lake County, OR; Natural Bridge diopside and Johnstown hypersthene, and reference values for these standards. Reference values taken from Jarosewich et al. (1980).

Plagioclase (Labradorite) Lake County, OR (n = 22)				
	average (wt %)	2 s.d.	ref. values (wt %)	difference %
SiO ₂	50.79	1.93	51.25	-0.9
TiO ₂	0.05	0.05	0.05	3.1
Al ₂ O ₃	30.56	1.36	30.91	-1.1
FeO	0.45	0.05	0.46	-0.7
MnO	0.01	0.02	0.01	-1.2
MgO	0.15	0.04	0.14	3.7
CaO	13.62	0.16	13.64	-0.2
Na ₂ O	3.42	0.17	3.45	-0.8
K ₂ O	0.19	0.05	0.18	4.7
Total	99.24	3.34	100.09	-0.8

Natural Bridge diopside (n = 39)				
	average (wt %)	2 s.d.	ref. values (wt %)	difference %
SiO ₂	54.76	0.85	54.87	-0.2
TiO ₂	0.01	0.02		
Al ₂ O ₃	0.24	0.20	0.11	121.0
Cr ₂ O ₃	0.00	0.02		
FeO	0.23	0.08	0.24	-4.6
MnO	0.03	0.03	0.04	-32.4
MgO	18.58	0.33	18.30	1.5
Na ₂ O	0.19	0.03	0.34	-45.6
CaO	25.52	0.33	25.63	-0.4
Total	99.56	1.21	99.29	0.3

Johnstown hypersthene (n = 23)				
	average (wt %)	2 s.d.	ref. values (wt %)	difference %
SiO ₂	53.76	0.60	54.09	-0.6
TiO ₂	0.06	0.02	0.16	-59.9
Al ₂ O ₃	0.89	0.92	1.23	-27.4
Cr ₂ O ₃	0.72	0.05	0.75	-4.6
FeO	14.89	0.27	15.22	-2.2
MnO	0.49	0.04	0.49	0.3
MgO	27.25	0.60	26.79	1.7
Na ₂ O	0.02	0.02	<0.05	0.0
CaO	1.28	0.05	1.52	-15.6
Total	99.36	0.87	100.25	-0.9

was corrected using the bracketed standard measurements of the respective glass standards (BCR-2G and NIST612). Bracketed standards were interpolated with the 'spline smooth auto' function, and a two standard deviation outlier rejection was used for all baselines and integrations. Background-corrected data were converted to absolute element concentrations using internal corrections based on mean Si concentrations for each sample and mineral phase previously measured by EPMA. Measurements of secondary standards are within error or close to the reference values for most of the measured elements (Table 2.2).

2.2 Mg isotopes

2.2.1 Sample preparation for Mg isotope measurements

All sample preparation, including digestion and ion exchange chromatography, was carried out in a class 10 laminar flow hood in a class 100 clean laboratory. Ultrapure Optima acids and $>18.2\text{ M}\Omega$ water were used for cleaning, acid dilutions and sample digestions. Savillex Teflon beakers were used throughout the laboratory work.

Beakers were cleaned by fluxing in 6M HCl for 24 h, followed by fluxing in 7M HNO₃ for 24 h, before being rinsed three times with ultrapure water. Following this, 1 mL of a concentrated HF–HNO₃ solution was fluxed in each beaker for 24 h, after which each beaker was rinsed three times with ultrapure water. Then, 2 mL of 6M HCl was fluxed in each beaker for 24 h, before being rinsed three times with ultrapure water, and dried ready for use.

Any obviously altered surfaces were removed from meteorite samples using an agate mortar and pestle, in order to ensure that the digested samples were unaltered. A 100–200 mg piece of each meteorite was then selected for digestion. Given that the maximum grain size in the samples is 2000 μm , chips of this size are likely to be broadly representative of each sample. The sample chips were rinsed in ethanol and placed in 10 mL of 0.05M HNO₃ in an ultrasonic bath for 5 min for cleaning prior to digestion.

Table 2.2: Trace element compositions of secondary standards BHVO-2G and ATHO-G measured in this study, and reference values for the same standards. Reference values taken from GeoRem (2010).

	BHVO-2G (n = 15)					ATHO-G (n = 15)			
	average (ppm)	2 s.d.	ref. values (ppm)	difference %		average (ppm)	2 s.d.	ref. values (ppm)	difference %
Li	4.38	0.32	4.40	-0.4	Li	36.16	1.29	28.60	-20.9
Na	16718	482	17805	-6.1	Na	38003	1296	27820	-26.8
Mg	38818	876	42996	-9.7	Mg	798.8	22.6	621.1	-22.2
Al	64128	674	71978	-10.9	Al	82442	2875	64569	-21.7
Sc	27.56	0.96	33.00	-16.5	Ti	1893.8	49.7	1021.7	-46.1
Ti	15571	246	11178	39.3	Mn	887.1	40.0	820.9	-7.5
V	316.2	4.81	308.0	2.7	Rb	72.46	2.89	65.30	-9.9
Cr	307.9	13.26	293.0	5.1	Sr	96.89	3.89	94.10	-2.9
Mn	1282	26	1317	-2.7	Ba	580.0	28.43	547.0	-5.7
Co	44.3	1.93	44.0	0.6	La	57.91	2.76	55.60	-4.0
Ni	121.8	9.77	116.0	5.0	Ce	133.8	5.75	121.0	-9.5
Cu	158.1	31.57	127.0	24.5	Pr	14.95	0.74	14.60	-2.3
Zn	93.4	2.43	102.0	-8.5	Nd	65.33	2.94	60.90	-6.8
Rb	8.95	0.47	9.20	-2.8	Sm	15.45	0.75	14.20	-8.1
Sr	369.9	7.93	396.0	-6.6	Eu	2.79	0.18	2.76	-1.0
Zr	143.1	4.19	170.0	-15.8	Gd	15.73	1.32	15.30	-2.8
Ba	125.2	1.92	131.0	-4.4					
La	13.55	0.36	15.20	-10.9					
Ce	36.35	1.22	37.60	-3.3					
Pr	4.83	0.20	5.35	-9.6					
Nd	22.0	0.90	24.5	-10.3					
Sm	5.52	0.55	6.10	-9.6					
Eu	1.88	0.21	2.07	-9.4					
Gd	5.53	0.51	6.16	-10.3					
Tb	0.76	0.07	0.92	-17.4					
Dy	4.51	0.35	5.28	-14.6					
Ho	0.82	0.11	0.98	-16.8					
Er	2.13	0.23	2.56	-16.8					
Tm	0.26	0.05	0.34	-22.4					
Yb	1.78	0.16	2.01	-11.4					
Lu	0.23	0.03	0.28	-19.3					
Hf	3.57	0.42	4.32	-17.3					
W	0.21	0.10	0.23	-10.7					

The samples were digested, along with two USGS basaltic rock standards (BHVO-2 and BCR-2) in concentrated HF–HNO₃ (3:1) at a temperature of 120°C. Following this, samples were refluxed repeatedly in concentrated HNO₃ and HCl acids, before a final reflux in aqua regia, in order to ensure that the samples were completely dissolved. All samples were visually inspected during these latter digestion steps to ensure that no material remained undigested. Two procedural blanks also went through the digestion process and the subsequent Mg separation process.

2.2.2 Chemical separation of Mg

The procedures for chemical separation of Mg from eucrites samples were carried out using a modified version of the method reported by Bizzarro et al. (2011) as described below. Mg was separated from elements that may result in isobaric interferences during isotope measurements, such as ⁴⁸Ca, ⁴⁸Ti, ⁵⁰Ti, ⁵⁰V, ⁵⁰Cr and ⁵²Cr, and elements such as Al, Fe, Na, Ni and Ca, which may affect instrumental mass bias (Bizzarro et al., 2011). Following digestion, an aliquot of each of the digested samples was evaporated to dryness and redissolved in 6M HCl. A volume of this solution equivalent to 2.5–5.0 mg of digested sample was sequentially loaded onto several ion exchange or extraction chromatographic columns for Mg separation as listed below.

Step 1: Removal of Fe

The sample was passed through a 1.25 mL pipette tip column loaded with 0.5 mL of AG1–X8 100–200 mesh anion exchange resin that had been cleaned with dilute HCl and pre-conditioned with 2 mL of 6M HCl. The sample matrix, including Mg, was eluted from the column with 2 mL of 6M HCl, while Fe was retained on the column.

Step 2: Removal of Cr, Na, Al and Ti

After drying down the Mg cut from step 1, this was dissolved in 100 µL of 6M HCl and refluxed over night. Immediately prior to adding the sample to the columns, 1.9 mL of refrigerated ultrapure water was added to the Mg cut, diluting it to 2 mL of 0.5M HCl. The solution was then

passed through a 10 mL Biorad cation exchange column loaded with 1 mL of Biorad AG50W-X8 200–400 mesh resin, that had been cleaned with alternating volumes of 6M HCl and ultrapure water and conditioned with 4 mL of 0.5M HCl. Na and Cr were eluted with 3 mL of 0.5M HCl, followed by 4 mL of 1M HNO₃. Following this, 1 mL of ultrapure water was passed through the column, and Al and Ti were eluted with 2 mL of 1M HF. Finally, Mg was eluted and collected in 10 mL of 6M HCl.

Step 3: Removal of Ca

After drying down the Mg cut from step 2, this was converted from chloride to nitrate form, and then dissolved in 1 mL of 3M HNO₃. This solution was passed through a 10 mL Biorad cation exchange column loaded with 1 mL of diglycolamide resin, which was cleaned with dilute HCl and conditioned with 4 mL of 3M HNO₃. After the Mg cut was loaded onto the columns a further 4 mL of 3M HNO₃ was used to elute Mg, with Ca retained on the resin.

Step 4: Removal of Ni

Columns loaded with 1 mL of Eichrom Ni-spec resin were cleaned with three column volumes of ultrapure water and conditioned with 4 mL of 0.2M NH₄ + 0.1M HCl. The Mg cuts from the previous step were dissolved in 0.5 mL of 0.1M HCl, and 1.25 mL of ultrapure water and 0.25 mL of 1M NH₄ were added to the solution, resulting in a solution with a pH of 9–10. This solution was loaded onto the columns, with Mg eluted in 4 mL of 0.2M NH₄ + 0.1M HCl. A small amount of 6M HCl was added to the Mg cuts before they were dried down. Once dried down, the Mg cuts were fluxed in 1 mL of aqua regia for at least 12 h before being evaporated again.

Step 5: Removal of Mn

The evaporated Mg cut from step 4 was converted to chloride form and dissolved in 2 mL of 0.5M HCl–95% acetone. This solution was passed through a column containing 1 mL of Biorad AG50W-X8 200–400 mesh resin, which had been pre-cleaned with alternate volumes of 6M HCl and ultrapure water and conditioned with 4 mL of 0.5M HCl–95% acetone. Mn was eluted with 4 mL of 0.5M HCl–95% acetone and Mg was collected in

10 mL of 6M HCl.

Step 6: A repeat of step 2

Finally, step 2 was repeated on the Mg cuts to ensure complete Al removal, as well as removal of any Na that may have been introduced as blank during the previous steps. After this final separation step, the Mg cuts were converted to nitrate form in preparation for analysis.

This chemical separation process ensures 99.9% recovery of Mg of a high a degree of purity. The full procedural blanks were <15 ng, which is negligible compared to the amount of Mg processed and recovered (>200 µg). The ratios of Fe/Mg, Na/Mg, Ti/Mg, Cr/Mg, V/Mg and Al/Mg observed in the separated Mg cuts were typically <0.0001 and therefore do not affect the quality of the obtained Mg isotope data.

2.2.3 Measurement of Mg isotopes by MC-ICP-MS

High precision Mg isotope measurements were made using a ThermoFisher Neptune multiple-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, using a modified version of the method outlined in Bizzarro et al. (2011). In preparation for measurement, the chemically separated Mg cuts were dissolved in 2% HNO₃, before being introduced into the plasma source with an Apex IR desolvating nebulizer combined with an ACM unit for additional membrane desolvation. Measurements were made in medium resolution mode, allowing for the resolution of molecular interferences on the high mass side of Mg. The low-3, axial and high-3 Faraday collectors were used to measure ²⁶Mg, ²⁵Mg and ²⁴Mg, respectively, with the Mg isotope data acquired in static mode. A 10¹⁰ Ω resistor was used on the low-3 collector, while the axial and high-3 collectors were both equipped with 10¹¹ Ω resistors.

Samples and standards were all analysed at a signal intensity of at least 100 V on mass ²⁴Mg. Each analysis comprised a total of 630 s of baseline measurements, followed by 1667 s of data acquisition (100 scans integrated

Table 2.3: Mg isotope compositions (in ‰) of the secondary standard BHVO-2 as measured in this study and by Schiller et al. (2010) and Bizzarro et al. (2011).

BHVO-2	$\delta^{25}\text{Mg}$	2 s.e.	$\delta^{26}\text{Mg}$	2 s.e.	$\delta^{26}\text{Mg}^*$	2 s.e.
This study	-0.133	0.020	-0.252	0.038	-0.0015	0.0010
Bizzarro et al. (2011)	-0.101	0.009	-0.189	0.023	-0.0004	0.0012
Schiller et al. (2010)	-0.153	0.049	-0.300	0.095	-0.0017	0.0044

over 16.67 s. An 8 min rinse was carried out between all analyses. Sample analyses were bracketed with analyses of the DTS-2 standard to monitor instrumental mass fractionation, and each sample was analyzed 10 times, resulting in the consumption of 10–20 μg of Mg per sample. Mg separated from the BHVO-2 standard was measured and compared to measurements made by Schiller et al. (2010) and Bizzarro et al. (2011), to verify the quality of the Mg isotope analyses (Table 2.3). The measurements of BHVO-2 are within error of those made by Schiller et al. (2010) and Bizzarro et al. (2011) (Table 2.3). Mg isotope ratios are expressed as the per mil (‰) deviations from the mean Mg isotopic composition measured on the bracketing standards (DTS-2 standard):

$$\delta^x \text{Mg} = \left[\frac{\left(\frac{x \text{Mg}}{^{24}\text{Mg}} \right)_{\text{sample}}}{\left(\frac{x \text{Mg}}{^{24}\text{Mg}} \right)_{\text{standard}}} - 1 \right] \times 10^3 \quad (2.1)$$

2.2.4 Measurement of $^{27}\text{Al}/^{24}\text{Mg}$ ratios

$^{27}\text{Al}/^{24}\text{Mg}$ ratios were measured using a Thermo X-series 2 ICP-MS at the Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen. Aliquots of digested samples were diluted in 2% HNO_3 to a Mg concentration of approximately 250 ppb for analysis. A gravimetrically prepared solution with an $^{27}\text{Al}/^{24}\text{Mg}$ ratio of 1.0 was prepared from Aristar single element ICP-MS solutions and used as the bracketing standard. This standard solution was measured before and after every five sample analyses. $^{27}\text{Al}/^{24}\text{Mg}$ ratios in BHVO-2 and BCR-2 were also measured, and were within estimated uncertainties of

Table 2.4: $^{27}\text{Al}/^{24}\text{Mg}$ ratios measured in the secondary standards BCR-2 and BHVO-2 and reference values for these standards. Reference values taken from GeoRem (2010).

	measured $^{27}\text{Al}/^{24}\text{Mg}$	2 s.e.	reference $^{27}\text{Al}/^{24}\text{Mg}$	difference %
BCR-2	3.82	0.009	3.76	1.65
BHVO-2	1.78	0.004	1.87	-4.96

reference values for these standards (Table 2.4).

Chapter 3

Petrology and mineral chemistry

In order to investigate the evolution of the crust of the HED parent body, it is important that the eucrites chosen for this study encompassed a range of geochemical compositions that reflect varying degrees of magmatic evolution. To this end, a range of samples were selected for this study on the basis of their pyroxene ferrosilite (Fs) content, which ranges from 12–65% (the least and most evolved compositions, respectively). Weathering grades of A, B and C are assigned to Antarctic meteorites by the Meteorite Working group at the Johnson Space Centre to denote the degree of terrestrial alteration of each meteorite, with the official definitions being as follows:

A: Minor rustiness = rust haloes on metal particles and rust stains along fractures are minor.

B: Moderate rustiness = large rust haloes occur on metal particles and rust stains on internal fractures are extensive.

C: Severe rustiness = metal particles have been mostly stained by rust throughout.

e: Evaporite minerals visible to the naked eye (added to the above grades).

3.1 Sample petrology

Twenty-three eucrites were selected for study. Nineteen of these were requested from the NASA Antarctic meteorite collection and the other four samples are well characterised and widely available eucrites (Dhofar 007, Camel Donga, Juvinas and Millbillillie). With the exception of Dhofar 007, all of the studied eucrites are non-cumulates, and the majority are brecciated. The key characteristics of each studied eucrite are outlined in Table 3.1, and backscattered electron images of each sample are shown in Fig. 3.1.

Polymict eucrites

EET 83227 is the only eucrite that is classified as being polymict, meaning that it contains some diagenetic material (<10 vol.%). This sample has a weathering grade of A, and is relatively fine grained with a maximum grain size of 200 μm . EET 83227 has a heavily brecciated texture with larger pyroxene and plagioclase clasts set in a comminuted matrix of the same material. The pyroxene in this sample exhibits simple zoning and exsolution lamellae that are <10 μm in width.

Mg-rich eucrites

There are two Mg-rich eucrites in the sample suite (EET 87548 and LEW 87002), which have weathering grades of B/C and A, respectively. EET 87548 contains pyroxene with exsolution lamellae that have a maximum width of 50 μm , whilst LEW 87002 shows no pyroxene exsolution. LEW87002 has a high proportion of pyroxene to plagioclase (5:1) and a maximum grain size of 1800 μm . EET 87548 contains approximately twice as much pyroxene as plagioclase, and has a maximum grain size of 1500 μm .

Table 3.1: Petrographic descriptions of eucrite samples

Sample	NASA classification	Weathering grade	Grain size (μm)	Plagioclase: pyroxene	Mineral properties	Description
EET 83227	polymict	B	<10–200	2:3	Pyroxene shows zoning, and fine (<10 μm) exsolution lamellae	Heavily brecciated anhedral pyroxene and plagioclase clasts in a comminuted matrix.
EET 87548	Mg-rich	B/C	30–1800	1:2	Pyroxene exsolution lamellae up to 50 μm	Large brecciated pyroxene and plagioclase clasts, with some finer grained areas.
EET 92003	brecciated	A/Be	10–200	1:2	No exsolution or zoning	Fine grained aggregate of pyroxene and plagioclase, with few larger brecciated clasts.
EET 92023	unbrecciated	A	1000–2000	2:3	Fine (<10 μm) pyroxene exsolution	Subhedral intergrowth of pyroxene and plagioclase.
GRA 98006	brecciated	A/B	10–1000	3:1	Pyroxene exsolution lamellae ~10 μm	Coarse plagioclase clasts set in brecciated pyroxene.
GRA 98033	brecciated	A/B	>1000	1:2	Pyroxene exsolution lamellae up to 100 μm	Coarse, heavily brecciated pyroxene and plagioclase clasts.
GRA 98043	brecciated	C	50–500	1:1	Pyroxene exsolution lamellae ~30 μm	Ophitic intergrowth of elongate euhedral plagioclase clasts and anhedral pyroxene, with some areas of comminuted pyroxene and plagioclase.
GRA 98055	brecciated	B	100–500	1:1	Pyroxene exsolution lamellae 10 μm - 50 μm	Equigranular intergrowth of euhedral plagioclase and pyroxene.
GRA 98114	brecciated	B	<10–500	1:1	Pyroxene exsolution lamellae 10 μm - 50 μm	Granular aggregate of pyroxene and plagioclase, with few large pyroxene clasts.

Table 3.1: Euclite sample descriptions (continued).

Sample	NASA classification	Weathering grade	Grain size (μm)	Plagioclase: pyroxene	Mineral properties	Description
GRO 95533	brecciated	A/B	500	2:3	Pyroxene exsolution lamellae $\sim 10 \mu\text{m}$	Coarse-grained brecciated anhedral plagioclase and pyroxene.
LAP 031062	brecciated	A/B	100–1000	1:10	Pyroxene exsolution lamellae $< 10 \mu\text{m}$	Heavily brecciated subhedral pyroxene clasts with occasional euhedral plagioclase clasts.
LAR 06875	brecciated	B/C	50–100	2:3	Pyroxene exsolution lamellae $< 10 \mu\text{m}$	Fine grained, cataclastic texture of relatively rounded plagioclase and pyroxene.
LEW 85305	unbrecciated	A	500–1000	1:1	Pyroxene exsolution lamellae $< 10 \mu\text{m}$	Subhedral intergrowth of plagioclase and pyroxene, and some areas of granulated pyroxene.
LEW 87002	Mg-rich	Ae	100–1500	1:5	No exsolution or zoning	Coarse grained euhedral pyroxene clasts, with areas of ophitic pyroxene–plagioclase intergrowth.
PCA 91193	brecciated	A/Be	50–500	2:3	Pyroxene exsolution lamellae $10\text{--}50 \mu\text{m}$	Brecciated subhedral clasts of pyroxene and plagioclase in a comminuted matrix.
QUE 97014	unbrecciated	A	100–300	1:1	Pyroxene exsolution lamellae $< 50 \mu\text{m}$	Anhedral clasts of plagioclase and pyroxene and some areas of granulated pyroxene.
QUE 99005	brecciated	B	< 1000	1:1	No exsolution	Ophitic texture, with large plagioclase and pyroxene grains in a comminuted matrix.
RKPA 80204	brecciated	A	< 200	1:1	Pyroxene shows zoning and exsolution lamellae $< 10 \mu\text{m}$	Fine grained ophitic texture with larger plagioclase and pyroxene grains in a cryptocrystalline matrix of these minerals.

Table 3.1: Eucrite sample descriptions (continued).

Sample	NASA classification	Weathering grade	Grain size (μm)	Plagioclase: pyroxene	Mineral properties	Description
SCO 06041	brecciated	A	10–2000	2:3	Pyroxene exsolution lamellae <10 μm	Large basaltic clasts in a comminuted pyroxene and plagioclase groundmass.
Milbillillie	brecciated	N/A	10–500	1:1	Pyroxene exsolution lamellae <10 μm	Ophitic texture, with large plagioclase and pyroxene grains in a comminuted matrix.
Juvinas	brecciated	N/A	500–1000	1:2	Pyroxene exsolution lamellae <10 μm	Granoblastic texture, with euhedral plagioclase grains, with numerous oxide inclusions along grain boundaries.
Camel Donga	brecciated	N/A	10–500	2:3	Pyroxene exsolution lamellae <10 μm	Range of rounded and angular grains of pyroxene and plagioclase in a comminuted groundmass of these minerals.
Dhofar 007	cumulate	N/A	50–1000	2:3	Pyroxene exsolution lamellae <10 μm	Brecciated with a coarse-grained gabbroic texture of euhedral plagioclase and pyroxene.

Brecciated eucrites

Brecciated eucrites comprise the majority of the sample suite, with weathering grades ranging from A–C. The maximum grain size of samples in this group ranges from 100 μm (LAR 06875) through to 2000 μm (SCO 06041), although most of the samples have a maximum grain size of 500–1000 μm . Apart from two samples (EET 92003 and QUE 99005), the brecciated eucrites exhibit pyroxene exsolution lamellae, which range in maximum width from 10–100 μm . The degree of brecciation and textural nature is variable amongst this group of eucrites. Most of the brecciated eucrites have equal or sub-equal proportions of pyroxene and plagioclase, with the exception of LAP 031062, which is almost exclusively comprised of pyroxene.

Unbrecciated eucrites

There are three unbrecciated eucrites in the sample suite, which all have a weathering grade of A. All the unbrecciated eucrites exhibit pyroxene exsolution lamellae, with maximum widths ranging from 10–50 μm . EET 92023 has the largest grain size of all the eucrite samples, and QUE 97014 is relatively fine grained, with a maximum grain size of 300 μm . LEW 85305 and EET 92023 have very similar textures comprising subhedral intergrowths of pyroxene and plagioclase crystals, whereas QUE97014 does not show this distinctive intergrown texture and contains some individual brecciated clasts.

Cumulate eucrites

Dhofar 007 is the only cumulate eucrite in the eucrite suite. Like most cumulate eucrites, Dhofar 007 has a coarse-grained gabbroic texture, with a maximum grain size of 1000 μm , and slightly more modal pyroxene than plagioclase (3:2). Pyroxene exsolution lamellae are all <10 μm in width.

Figure 3.1: Back-scattered electron images of the studied eucrite samples

Figure 3.1: Back-scattered electron images of the studied eucrite samples (continued).

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Figure 3.1: Back-scattered electron images of the studied eucrite samples (continued).

Figure 3.1: Back-scattered electron images of the studied eucrite samples (continued).

Figure 3.1: Back-scattered electron images of the studied eucrite samples (continued).

Figure 3.2: Ternary diagrams showing (A) plagioclase and (B) pyroxene mineral compositions in the studied eucrite samples.

3.2 Mineral chemistry

This chapter presents summarized major element data, the full data set can be found in Appendix A. The eucrite samples predominantly comprise plagioclase and high- and low-Ca pyroxene (>90 vol.%), with lesser amounts of chromite, ilmenite, troilite and Fe-Ni metal. As such, this study focused on the mineral chemistry of plagioclase and both types of pyroxene. However, samples EET 92003, EET 92023, LEW 87002, Dhofar 007 and Juvinas only contain a low-Ca pyroxene phase. The major element composition of plagioclase in the eucrites is summarised in Table 3.2, and the major element chemistry of low- and high-Ca pyroxene are given in Tables 3.3 and 3.4, respectively. The plagioclase is anorthite (An) rich (>86%) (Fig. 3.3A) with a negligible orthoclase component ($\leq 0.5\%$) (Fig. 3.2A). Low-Ca pyroxene falls into two groups on the basis of ferrosilite (Fs) contents (Fig. 3.2B, Fig. 3.3E). One group has Fs of 50–62%, and the other group is more enstatite (En)-rich with Fs of 31–50%. The average Wo content of the low-Ca pyroxene phase ranges from 2–15% (Fig. 3.2B and 3.3D). The high-Ca pyroxene phases are relatively wollastonite (Wo)-rich, with a range in average Wo contents of 30–45% (Fig. 3.2B and 3.3B). The Fs content of the high-Ca pyroxene is variable, with average Fs contents ranging from 17–39% (Fig. 3.2B and 3.3C).

Figure 3.3: Major element mineral compositions of the eucrite groups. (A) Anorthite content of plagioclase. (B) Wollastonite content of high-Ca pyroxene. (C) Ferrosillite content of high-Ca pyroxene. (D) Wollastonite content of low-Ca pyroxene. (E) Ferrosillite content of low-Ca pyroxene.

Table 3.2: Plagioclase major element concentrations in wt%.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
EET 83227	average	46.70	0.03	34.91	0.53	0.05	17.73	1.14	0.11	101.21	88.36	11.21	0.43
	2 s.d.	2.92	0.05	1.96	0.54	0.10	1.80	0.93	0.10	0.63	9.52	9.13	0.41
	min	44.91	0.00	33.52	0.20	0.00	16.25	0.50	0.04		81.07	4.94	0.18
	max	48.88	0.08	36.25	0.97	0.15	18.91	1.83	0.21		94.80	18.09	0.83
EET 87458	average	45.56	0.01	35.98	0.17	0.00	18.60	0.82	0.05	101.20	91.73	8.06	0.21
	2 s.d.	0.33	0.03	0.31	0.07	0.01	0.35	0.10	0.02	0.53	1.06	1.05	0.06
	min	45.27	0.00	35.73	0.12	0.00	18.39	0.74	0.04		90.85	7.16	0.16
	max	45.82	0.05	36.19	0.25	0.01	18.95	0.91	0.06		92.63	8.89	0.25
EET 92003	average	47.19	0.03	34.81	0.48	0.03	17.54	1.37	0.14	101.59	86.12	13.33	0.55
	2 s.d.	1.94	0.05	1.19	0.39	0.04	1.20	0.62	0.11	0.73	6.31	5.94	0.41
	min	46.13	0.00	33.57	0.26	0.01	16.37	1.06	0.08		79.68	10.33	0.34
	max	49.21	0.07	35.36	0.77	0.07	18.14	2.01	0.24		89.31	19.38	0.94
EET 92023	average	47.11	0.05	35.30	0.34	0.03	17.69	1.22	0.12	101.87	87.53	11.98	0.49
	2 s.d.	1.77	0.05	1.12	0.29	0.02	1.14	0.47	0.10	1.54	5.10	4.72	0.39
	min	46.17	0.00	34.18	0.17	0.00	16.12	1.09	0.08		80.47	10.68	0.31
	max	49.37	0.08	36.08	0.56	0.05	18.03	1.87	0.25		88.91	18.52	1.01
GRA 98006	average	45.33	0.01	35.07	0.32	0.01	17.92	1.02	0.11	99.79	89.46	10.11	0.43
	2 s.d.	1.79	0.02	1.13	0.25	0.04	0.65	0.28	0.08	2.42	2.93	2.78	0.31
	min	44.20	0.00	34.25	0.09	0.00	17.36	0.85	0.06		87.24	8.35	0.23
	max	47.23	0.03	36.05	0.50	0.06	18.36	1.23	0.18		91.19	12.18	0.70
GRA 98033	average	46.24	0.00	35.59	0.14	0.01	17.92	1.21	0.12	101.24	87.79	11.73	0.49
	2 s.d.	0.27	0.01	0.30	0.08	0.01	0.18	0.04	0.03	0.58	0.48	0.43	0.10
	min	46.07	0.00	35.37	0.06	0.00	17.80	1.19	0.11		87.25	11.52	0.42
	max	46.50	0.02	35.83	0.22	0.02	18.06	1.26	0.15		88.06	12.17	0.58
GRA 98043	average	46.44	0.00	35.42	0.55	0.01	17.44	1.15	0.11	101.15	87.95	11.60	0.45
	2 s.d.	1.61	0.01	0.73	0.44	0.01	0.59	0.11	0.02	2.20	0.95	0.94	0.08
	min	44.90	0.00	34.82	0.27	0.00	17.06	1.07	0.10		87.43	10.90	0.39
	max	47.26	0.02	35.86	0.87	0.02	17.85	1.23	0.12		88.65	12.15	0.51
GRA 98055	average	46.54	0.01	35.33	0.35	0.00	17.76	1.23	0.12	101.35	87.51	12.02	0.47
	2 s.d.	0.25	0.02	0.25	0.26	0.01	0.27	0.11	0.03	0.45	1.10	1.09	0.10
	min	46.27	0.00	35.17	0.19	0.00	17.50	1.11	0.10		86.68	10.89	0.41
	max	46.71	0.03	35.54	0.59	0.01	17.95	1.30	0.15		88.63	12.81	0.58
GRA 98114	average	45.96	0.02	35.35	0.25	0.01	17.70	1.16	0.11	100.57	87.98	11.58	0.44
	2 s.d.	0.51	0.08	0.40	0.22	0.01	0.96	0.16	0.02	1.68	0.84	0.82	0.07
	min	45.46	0.00	35.10	0.08	0.00	16.35	0.98	0.10		87.60	10.87	0.39
	max	46.32	0.13	35.73	0.45	0.01	17.95	1.22	0.12		88.72	11.93	0.50

Table 3.2: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
LAP 031062	average	47.88	0.03	34.56	0.46	0.01	0.06	17.12	1.47	101.88	85.05	14.53	0.42
	2 s.d.	3.64	0.04	2.43	0.36	0.01	0.03	2.28	0.98	1.41	10.11	9.78	0.34
	min	45.67	0.00	32.96	0.14	0.00	0.04	15.89	0.84		79.22	8.21	0.23
	max	50.30	0.06	36.10	0.85	0.02	0.08	18.63	2.04		91.56	20.15	0.69
LAR 06875	average	46.73	0.02	35.29	0.87	0.03	0.05	17.89	1.07	102.03	89.15	10.53	0.32
	2 s.d.	1.29	0.05	1.04	0.51	0.03	0.08	0.34	0.17	0.87	1.55	1.52	0.14
	min	45.80	0.00	34.33	0.33	0.01	0.00	17.58	0.96		87.82	9.70	0.20
	max	48.17	0.07	35.98	1.19	0.06	0.13	18.08	1.20		89.92	11.82	0.39
LEW 85305	average	46.52	0.01	35.13	0.16	0.00	0.02	17.62	1.32	100.88	86.70	12.85	0.45
	2 s.d.	0.50	0.03	0.32	0.06	0.01	0.01	0.30	0.14	0.86	1.30	1.34	0.15
	min	46.27	0.00	34.79	0.11	0.00	0.00	17.43	1.23		85.93	12.04	0.30
	max	46.96	0.04	35.29	0.21	0.02	0.03	17.81	1.41		87.54	13.67	0.60
LEW 87002	average	45.59	0.01	35.48	0.30	0.01	0.08	18.40	0.93	100.88	90.55	9.09	0.37
	2 s.d.	1.26	0.02	0.67	0.25	0.02	0.17	0.61	0.25	1.75	2.57	2.46	0.15
	min	44.38	0.00	34.96	0.15	0.00	0.02	18.00	0.70		88.79	6.82	0.25
	max	46.39	0.03	36.05	0.56	0.04	0.29	18.85	1.10		92.92	10.81	0.45
PCA 91193	average	46.32	0.02	35.47	0.33	0.01	0.04	17.90	1.11	101.31	88.65	10.93	0.42
	2 s.d.	1.12	0.02	1.05	0.19	0.01	0.05	0.41	0.09	2.41	0.86	0.81	0.09
	min	45.36	0.01	34.71	0.24	0.00	0.02	17.58	1.05		88.07	10.33	0.37
	max	46.79	0.03	36.17	0.48	0.02	0.07	18.09	1.17		89.26	11.45	0.49
QUE 97014	average	45.99	0.01	35.41	0.39	0.02	0.02	17.84	1.21	101.00	87.78	11.78	0.44
	2 s.d.	0.35	0.03	0.92	0.57	0.03	0.10	0.17	0.10	0.72	0.92	0.88	0.12
	min	45.76	0.00	34.22	0.17	0.00	0.00	17.72	1.13		87.00	11.16	0.34
	max	46.37	0.04	35.86	1.15	0.04	0.16	18.00	1.29		88.45	12.55	0.56
QUE 99055	average	46.11	0.00	35.27	0.47	0.02	0.04	17.85	1.13	100.99	88.73	10.86	0.41
	2 s.d.	1.16	0.00	0.38	0.62	0.04	0.11	0.64	0.41	1.59	4.05	3.87	0.20
	min	45.28	0.00	34.98	0.12	0.00	0.00	17.35	0.75		85.47	7.50	0.23
	max	47.08	0.00	35.48	1.07	0.06	0.16	18.37	1.43		92.28	13.97	0.57
RKPA 80204	average	47.86	0.01	34.39	0.59	0.01	0.03	17.04	1.26	101.31	86.49	13.00	0.50
	2 s.d.	5.47	0.03	4.27	0.39	0.03	0.07	1.84	0.46	1.40	3.72	3.56	0.19
	min	46.19	0.00	30.14	0.29	0.00	0.00	15.23	0.94		83.49	11.34	0.37
	max	53.37	0.03	35.99	0.85	0.04	0.10	17.73	1.63		88.29	15.89	0.61
SCO 06041	average	44.31	0.01	35.66	0.13	0.01	0.01	18.72	0.89	99.79	91.75	7.92	0.32
	2 s.d.	1.31	0.02	0.76	0.09	0.02	0.01	0.39	0.14	1.89	1.25	1.20	0.08
	min	43.15	0.00	34.87	0.08	0.00	0.00	18.50	0.82		90.26	7.49	0.25
	max	45.29	0.04	36.19	0.23	0.02	0.02	19.00	1.06		92.44	9.36	0.37

Table 3.2: Plagioclase major element concentrations in wt% (continued).

Sample		SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
GRO 95533	average	44.65	0.00	35.36	0.09	0.01	0.01	18.25	1.08	0.07	99.52	89.96	9.64	0.40
	2 s.d.	1.91	0.01	0.45	0.07	0.01	0.02	0.56	0.22	0.02	2.22	2.11	2.01	0.13
	min	43.38	0.00	35.08	0.05	0.00	0.00	17.96	0.92	0.05		88.49	8.17	0.32
	max	46.07	0.01	35.79	0.14	0.02	0.03	18.65	1.24	0.09		91.52	11.04	0.51
Millbillillie	average	46.01	0.00	34.85	0.56	0.02	0.11	17.94	1.25	0.08	100.82	88.38	11.12	0.50
	2 s.d.	1.91	0.01	1.32	0.94	0.04	0.35	1.36	0.75	0.07	0.95	6.98	6.61	0.40
	min	45.08	0.00	33.88	0.22	0.00	0.00	16.59	0.92	0.06		81.43	8.17	0.35
	max	47.95	0.02	35.60	1.70	0.07	0.42	18.71	1.99	0.16		91.39	17.64	0.93
Juvinas	average	44.86	0.00	35.62	0.42	0.01	0.12	18.83	0.79	0.06	100.71	92.66	6.99	0.35
	2 s.d.	1.25	0.00	0.88	0.54	0.03	0.20	0.76	0.40	0.04	1.14	3.73	3.52	0.24
	min	43.88	0.00	34.68	0.13	0.00	0.00	17.78	0.60	0.03		87.21	5.39	0.19
	max	46.56	0.00	36.30	1.01	0.05	0.32	19.37	1.37	0.12		94.28	12.11	0.67
Camel Donga	average	45.17	0.00	35.17	0.19	0.01	0.01	18.40	1.09	0.08	100.12	89.88	9.68	0.44
	2 s.d.	2.09	0.01	1.20	0.18	0.01	0.02	1.33	0.64	0.07	1.45	5.95	5.66	0.42
	min	43.11	0.00	33.87	0.08	0.00	0.00	17.29	0.73	0.04		84.20	6.98	0.24
	max	46.69	0.01	35.82	0.35	0.02	0.03	19.19	1.71	0.15		93.38	15.09	0.85
Dhofar 007	average	45.29	0.01	35.28	0.24	0.01	0.08	18.28	1.05	0.08	100.31	90.16	9.39	0.45
	2 s.d.	0.83	0.01	0.39	0.09	0.02	0.13	0.37	0.15	0.06	1.11	1.45	1.31	0.34
	min	44.74	0.01	35.02	0.19	0.00	0.01	17.99	0.96	0.06		89.21	8.60	0.34
	max	45.74	0.02	35.60	0.31	0.02	0.21	18.56	1.17	0.14		91.02	10.39	0.84

Table 3.3: Low-Ca pyroxene major element concentrations in wt%.

Sample		SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
EET 83227	average	49.20	0.92	2.96	0.67	14.05	0.48	11.93	19.19	0.05	99.45	40.97	35.55	23.47
	2 s.d.	0.89	0.34	1.59	0.45	2.03	0.10	1.06	1.99	0.05	1.09	4.09	2.62	3.62
	min	48.19	0.56	1.67	0.23	12.63	0.39	10.91	16.33	0.02		35.64	33.47	20.86
	max	50.06	1.22	4.89	1.15	16.05	0.58	12.76	20.44	0.14		43.91	37.60	27.33
EET 87548	average	51.74	0.22	1.00	0.21	10.37	0.41	13.40	21.90	0.06	99.31	45.02	38.33	16.65
	2 s.d.	0.86	0.04	0.96	0.07	1.05	0.04	0.47	0.97	0.03	0.83	1.15	0.79	1.87
	min	50.73	0.19	0.60	0.17	10.06	0.38	12.91	20.98	0.04		43.64	37.38	16.04
	max	52.23	0.26	2.10	0.27	11.69	0.43	13.60	22.48	0.09		45.59	38.59	18.98
GRA 98006	average	50.24	0.29	1.01	0.24	17.50	0.52	10.18	19.72	0.06	99.77	41.49	29.79	28.72
	2 s.d.	0.67	0.08	1.20	0.09	4.40	0.13	0.47	3.73	0.04	1.41	7.89	0.99	7.04
	min	49.93	0.21	0.65	0.14	15.90	0.46	9.79	14.57	0.03		30.55	29.28	26.49
	max	51.05	0.34	2.70	0.30	23.52	0.70	10.60	20.93	0.10		43.76	30.94	38.51
GRA 98033	average	49.89	0.26	0.78	0.20	17.05	0.50	9.97	20.57	0.08	99.30	43.07	29.05	27.87
	2 s.d.	0.71	0.12	0.37	0.08	1.19	0.06	0.38	0.97	0.04	1.46	1.90	0.60	1.85
	min	49.21	0.17	0.58	0.12	16.44	0.47	9.65	19.41	0.04		40.80	28.60	27.00
	max	50.35	0.35	1.13	0.26	18.39	0.55	10.29	21.06	0.12		44.34	29.42	30.17
GRA 98043	average	50.17	0.28	0.78	0.23	18.93	0.56	9.67	19.44	0.07	100.13	40.77	28.23	31.00
	2 s.d.	0.81	0.14	0.31	0.05	3.95	0.10	0.22	3.24	0.04	1.04	6.59	0.44	6.61
	min	49.65	0.17	0.63	0.20	17.07	0.51	9.52	15.39	0.04		43.49	27.92	27.92
	max	50.83	0.42	1.05	0.29	24.05	0.68	9.84	20.75	0.10		32.34	28.59	39.45
GRA 98055	average	49.70	0.39	0.86	0.24	18.50	0.54	10.09	19.16	0.07	99.55	40.21	29.47	30.32
	2 s.d.	0.95	0.08	0.40	0.07	5.01	0.12	0.36	4.46	0.03	1.48	9.21	0.94	8.33
	min	48.83	0.32	0.66	0.20	16.80	0.49	9.86	14.74	0.06		30.79	29.08	27.44
	max	50.22	0.47	1.31	0.33	23.75	0.69	10.49	20.76	0.10		43.44	30.49	38.71
GRA 98114	average	49.56	0.36	0.89	0.23	18.59	0.55	9.88	19.33	0.07	99.46	40.63	28.87	30.50
	2 s.d.	0.78	0.08	0.31	0.07	3.75	0.11	0.71	3.45	0.03	1.22	7.16	1.85	6.20
	min	48.96	0.28	0.71	0.18	17.07	0.50	9.37	15.94	0.05		33.92	27.68	27.61
	max	50.22	0.41	1.18	0.28	22.32	0.65	10.27	20.79	0.10		43.49	30.27	35.81
GRO95533	average	50.35	0.31	0.12	0.22	16.62	0.51	10.23	19.68	0.08	98.69	42.17	30.14	27.70
	2 s.d.	1.79	0.10	0.06	0.12	2.51	0.08	0.52	2.77	0.05	1.83	4.45	1.07	4.73
	min	49.61	0.27	0.08	0.15	15.54	0.46	10.03	17.81	0.05		38.19	29.59	25.54
	max	52.22	0.38	0.16	0.30	18.94	0.58	10.72	20.99	0.11		44.22	31.09	31.70

Table 3.3: Low-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
LAP 031062	average	50.43	1.37	1.53	0.56	12.92	0.45	15.08	17.59	100.03	36.12	43.13	20.75
	2 s.d.	1.78	3.03	0.75	0.29	5.38	0.12	2.66	8.36	1.71	16.84	8.12	8.89
	min	49.25	0.34	1.18	0.40	10.31	0.40	13.69	11.43		23.87	39.58	16.46
	max	51.74	4.40	2.19	0.76	17.24	0.56	17.01	21.16		43.27	49.40	26.61
LAR 06875	average	49.87	0.42	0.97	0.20	17.24	0.51	10.12	19.96	99.37	42.01	29.63	28.36
	2 s.d.	2.33	0.80	0.93	0.11	1.88	0.07	0.99	2.00	1.74	3.51	2.03	3.90
	min	46.63	0.20	0.57	0.14	16.02	0.48	8.88	17.89		39.57	27.31	26.21
	max	50.64	1.53	2.21	0.30	19.18	0.58	10.82	21.11		44.27	31.26	33.12
LEW 85305	average	49.12	0.64	1.18	0.33	21.23	0.65	9.34	16.41	99.00	35.69	28.26	36.05
	2 s.d.	0.89	0.07	0.18	0.07	3.09	0.12	0.29	2.77	1.10	5.74	0.73	5.50
	min	48.57	0.60	0.99	0.30	18.74	0.57	9.24	14.78		32.60	27.79	31.63
	max	49.73	0.70	1.25	0.40	22.69	0.73	9.61	18.76		40.57	28.84	39.06
PCA 91193	average	50.67	0.51	1.15	0.39	12.42	0.48	12.79	20.07	98.59	42.19	37.42	20.39
	2 s.d.	0.26	0.10	0.13	0.07	1.99	0.06	0.29	1.78	0.79	3.50	0.80	3.36
	min	50.52	0.42	1.05	0.34	11.54	0.45	12.62	18.46		38.92	36.88	19.11
	max	50.88	0.58	1.24	0.44	14.37	0.53	13.02	21.04		44.20	38.00	23.64
QUE 97014	average	50.24	0.25	0.67	0.21	16.41	0.54	10.09	20.33	98.81	43.08	29.76	27.15
	2 s.d.	0.51	0.07	0.12	0.05	3.03	0.13	0.17	2.92	0.80	5.86	0.72	5.27
	min	49.82	0.21	0.58	0.19	15.33	0.47	9.98	17.36		37.15	29.47	25.48
	max	50.59	0.29	0.72	0.25	19.45	0.66	10.20	21.09		44.94	30.37	32.48
QUE 99005	average	49.63	0.92	0.56	0.22	22.71	0.69	10.05	13.82	98.64	30.36	30.71	38.93
	2 s.d.	4.92	3.57	0.21	0.34	2.31	0.09	0.96	1.84	1.15	4.32	2.76	3.38
	min	45.51	0.08	0.43	0.06	20.87	0.63	9.23	12.92		28.21	28.26	36.41
	max	51.70	4.12	0.67	0.47	23.88	0.74	10.46	15.06		33.14	31.58	40.65
RKP80204	average	50.54	0.17	0.53	0.15	18.00	0.57	10.65	18.61	99.28	39.21	31.21	29.58
	2 s.d.	0.79	0.07	0.30	0.09	6.86	0.22	0.68	6.13	1.99	12.98	1.89	11.15
	min	49.88	0.12	0.31	0.06	15.37	0.46	10.30	13.37		27.94	30.30	25.28
	max	51.00	0.22	0.76	0.24	24.20	0.78	11.20	20.94		44.13	32.65	39.48
SCO 06041	average	51.86	0.33	0.15	0.23	10.33	0.38	13.66	21.65	98.63	44.45	39.01	16.54
	2 s.d.	0.14	0.19	0.03	0.13	1.78	0.02	0.73	2.04	0.28	4.50	1.79	2.72
	min	51.81	0.23	0.13	0.16	9.78	0.37	13.40	20.48		41.85	38.45	15.66
	max	51.94	0.42	0.16	0.29	11.35	0.39	14.08	22.31		45.80	40.04	18.11

Table 3.3: Low-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %	
Camel Donga	average	50.40	0.29	0.13	0.25	15.26	0.61	11.10	19.90	0.06	98.52	42.22	32.63	25.14
	2 s.d.	0.87	0.12	0.04	0.08	1.47	0.05	0.67	1.81	0.03	0.81	3.25	1.34	2.70
	min	49.99	0.25	0.11	0.22	14.76	0.59	10.69	18.77	0.05		39.39	31.58	24.06
	max	51.16	0.39	0.15	0.33	16.64	0.65	11.43	20.73	0.08		43.38	33.35	27.26
Millbillillee	average	49.31	0.85	0.09	0.16	18.72	0.57	10.43	16.72	0.04	98.81	37.17	30.98	31.84
	2 s.d.	3.76	3.65	0.07	0.08	8.57	0.29	1.14	9.36	0.04	1.18	17.94	3.44	15.00
	min	46.32	0.11	0.06	0.10	15.19	0.45	9.86	10.80	0.02		23.34	29.28	24.93
	max	50.75	5.36	0.16	0.20	26.13	0.87	11.56	21.57	0.07		45.34	33.94	44.06

Table 3.4: High-Ca pyroxene major element concentrations in wt%.

Sample		SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
EET 83227	average	49.20	0.92	2.96	0.67	14.05	0.48	11.93	19.19	0.05	99.45	40.97	35.55	23.47
	2 s.d.	0.89	0.34	1.59	0.45	2.03	0.10	1.06	1.99	0.05	1.09	4.09	2.62	3.62
	min	48.19	0.56	1.67	0.23	12.63	0.39	10.91	16.33	0.02		35.64	33.47	20.86
EET 87548	max	50.06	1.22	4.89	1.15	16.05	0.58	12.76	20.44	0.14		43.91	37.60	27.33
	average	51.74	0.22	1.00	0.21	10.37	0.41	13.40	21.90	0.06	99.31	45.02	38.33	16.65
	2 s.d.	0.86	0.04	0.96	0.07	1.05	0.04	0.47	0.97	0.03	0.83	1.15	0.79	1.87
GRA 98006	min	50.73	0.19	0.60	0.17	10.06	0.38	12.91	20.98	0.04		43.64	37.38	16.04
	max	52.23	0.26	2.10	0.27	11.69	0.43	13.60	22.48	0.09		45.59	38.59	18.98
	average	50.24	0.29	1.01	0.24	17.50	0.52	10.18	19.72	0.06	99.77	41.49	29.79	28.72
GRA 98033	2 s.d.	0.67	0.08	1.20	0.09	4.40	0.13	0.47	3.73	0.04	1.41	7.89	0.99	7.04
	min	49.93	0.21	0.65	0.14	15.90	0.46	9.79	14.57	0.03		30.55	29.28	26.49
	max	51.05	0.34	2.70	0.30	23.52	0.70	10.60	20.93	0.10		43.76	30.94	38.51
GRA 98043	average	49.89	0.26	0.78	0.20	17.05	0.50	9.97	20.57	0.08	99.30	43.07	29.05	27.87
	2 s.d.	0.71	0.12	0.37	0.08	1.19	0.06	0.38	0.97	0.04	1.46	1.90	0.60	1.85
	min	49.21	0.17	0.58	0.12	16.44	0.47	9.65	19.41	0.04		40.80	28.60	27.00
GRA 98055	max	50.35	0.35	1.13	0.26	18.39	0.55	10.29	21.06	0.12		44.34	29.42	30.17
	average	50.17	0.28	0.78	0.23	18.93	0.56	9.67	19.44	0.07	100.13	40.77	28.23	31.00
	2 s.d.	0.81	0.14	0.31	0.05	3.95	0.10	0.22	3.24	0.04	1.04	6.59	0.44	6.61
GRA 98114	min	49.65	0.17	0.63	0.20	17.07	0.51	9.52	15.39	0.04		43.49	27.92	27.92
	max	50.83	0.42	1.05	0.29	24.05	0.68	9.84	20.75	0.10		32.34	28.59	39.45
	average	49.70	0.39	0.86	0.24	18.50	0.54	10.09	19.16	0.07	99.55	40.21	29.47	30.32
GRA 98114	2 s.d.	0.95	0.08	0.40	0.07	5.01	0.12	0.36	4.46	0.03	1.48	9.21	0.94	8.33
	min	48.83	0.32	0.66	0.20	16.80	0.49	9.86	14.74	0.06		30.79	29.08	27.44
	max	50.22	0.47	1.31	0.33	23.75	0.69	10.49	20.76	0.10		43.44	30.49	38.71
GRO95533	average	49.56	0.36	0.89	0.23	18.59	0.55	9.88	19.33	0.07	99.46	40.63	28.87	30.50
	2 s.d.	0.78	0.08	0.31	0.07	3.75	0.11	0.71	3.45	0.03	1.22	7.16	1.85	6.20
	min	48.96	0.28	0.71	0.18	17.07	0.50	9.37	15.94	0.05		33.92	27.68	27.61
GRO95533	max	50.22	0.41	1.18	0.28	22.32	0.65	10.27	20.79	0.10		43.49	30.27	35.81
	average	50.35	0.31	0.12	0.22	16.62	0.51	10.23	19.68	0.08	98.69	42.17	30.14	27.70
	2 s.d.	1.79	0.10	0.06	0.12	2.51	0.08	0.52	2.77	0.05	1.83	4.45	1.07	4.73
GRO95533	min	49.61	0.27	0.08	0.15	15.54	0.46	10.03	17.81	0.05		38.19	29.59	25.54
	max	52.22	0.38	0.16	0.30	18.94	0.58	10.72	20.99	0.11		44.22	31.09	31.70

Table 3.4: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
LAP 031062	average	50.43	1.37	1.53	0.56	12.92	0.45	15.08	17.59	100.03	36.12	43.13	20.75
	2 s.d.	1.78	3.03	0.75	0.29	5.38	0.12	2.66	8.36	1.71	16.84	8.12	8.89
	min	49.25	0.34	1.18	0.40	10.31	0.40	13.69	11.43		23.87	39.58	16.46
	max	51.74	4.40	2.19	0.76	17.24	0.56	17.01	21.16		43.27	49.40	26.61
LAR 06875	average	49.87	0.42	0.97	0.20	17.24	0.51	10.12	19.96	99.37	42.01	29.63	28.36
	2 s.d.	2.33	0.80	0.93	0.11	1.88	0.07	0.99	2.00	1.74	3.51	2.03	3.90
	min	46.63	0.20	0.57	0.14	16.02	0.48	8.88	17.89		39.57	27.31	26.21
	max	50.64	1.53	2.21	0.30	19.18	0.58	10.82	21.11		44.27	31.26	33.12
LEW 85305	average	49.12	0.64	1.18	0.33	21.23	0.65	9.34	16.41	99.00	35.69	28.26	36.05
	2 s.d.	0.89	0.07	0.18	0.07	3.09	0.12	0.29	2.77	1.10	5.74	0.73	5.50
	min	48.57	0.60	0.99	0.30	18.74	0.57	9.24	14.78		32.60	27.79	31.63
	max	49.73	0.70	1.25	0.40	22.69	0.73	9.61	18.76		40.57	28.84	39.06
PCA 91193	average	50.67	0.51	1.15	0.39	12.42	0.48	12.79	20.07	98.59	42.19	37.42	20.39
	2 s.d.	0.26	0.10	0.13	0.07	1.99	0.06	0.29	1.78	0.79	3.50	0.80	3.36
	min	50.52	0.42	1.05	0.34	11.54	0.45	12.62	18.46		38.92	36.88	19.11
	max	50.88	0.58	1.24	0.44	14.37	0.53	13.02	21.04		44.20	38.00	23.64
QUE 97014	average	50.24	0.25	0.67	0.21	16.41	0.54	10.09	20.33	98.81	43.08	29.76	27.15
	2 s.d.	0.51	0.07	0.12	0.05	3.03	0.13	0.17	2.92	0.80	5.86	0.72	5.27
	min	49.82	0.21	0.58	0.19	15.33	0.47	9.98	17.36		37.15	29.47	25.48
	max	50.59	0.29	0.72	0.25	19.45	0.66	10.20	21.09		44.94	30.37	32.48
QUE 99005	average	49.63	0.92	0.56	0.22	22.71	0.69	10.05	13.82	98.64	30.36	30.71	38.93
	2 s.d.	4.92	3.57	0.21	0.34	2.31	0.09	0.96	1.84	1.15	4.32	2.76	3.38
	min	45.51	0.08	0.43	0.06	20.87	0.63	9.23	12.92		28.21	28.26	36.41
	max	51.70	4.12	0.67	0.47	23.88	0.74	10.46	15.06		33.14	31.58	40.65
RKPA80204	average	50.54	0.17	0.53	0.15	18.00	0.57	10.65	18.61	99.28	39.21	31.21	29.58
	2 s.d.	0.79	0.07	0.30	0.09	6.86	0.22	0.68	6.13	1.99	12.98	1.89	11.15
	min	49.88	0.12	0.31	0.06	15.37	0.46	10.30	13.37		27.94	30.30	25.28
	max	51.00	0.22	0.76	0.24	24.20	0.78	11.20	20.94		44.13	32.65	39.48
SCO 06041	average	51.86	0.33	0.15	0.23	10.33	0.38	13.66	21.65	98.63	44.45	39.01	16.54
	2 s.d.	0.14	0.19	0.03	0.13	1.78	0.02	0.73	2.04	0.28	4.50	1.79	2.72
	min	51.81	0.23	0.13	0.16	9.78	0.37	13.40	20.48		41.85	38.45	15.66
	max	51.94	0.42	0.16	0.29	11.35	0.39	14.08	22.31		45.80	40.04	18.11

Table 3.4: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
Camel Donga	average	50.40	0.29	0.13	0.25	15.26	0.61	11.10	19.90	98.52	42.22	32.63	25.14
	2 s.d.	0.87	0.12	0.04	0.08	1.47	0.05	0.67	1.81	0.81	3.25	1.34	2.70
	min	49.99	0.25	0.11	0.22	14.76	0.59	10.69	18.77	0.05	39.39	31.58	24.06
	max	51.16	0.39	0.15	0.33	16.64	0.65	11.43	20.73	0.08	43.38	33.35	27.26
Miltbillille	average	49.31	0.85	0.09	0.16	18.72	0.57	10.43	16.72	98.81	37.17	30.98	31.84
	2 s.d.	3.76	3.65	0.07	0.08	8.57	0.29	1.14	9.36	1.18	17.94	3.44	15.00
	min	46.32	0.11	0.06	0.10	15.19	0.45	9.86	10.80	0.02	23.34	29.28	24.93
	max	50.75	5.36	0.16	0.20	26.13	0.87	11.56	21.57	0.07	45.34	33.94	44.06

Polymict eucrites

Low-Ca pyroxene

EET 83227 is the only polymict eucrite in the sample suite, and there is a large range in the major element composition of the low-Ca pyroxene in this sample. The Wo content ranges from 1.4–15.0% (average = 5.3%) and the Fs content is also variable ranging from 30.0–51.6% (average = 37.6%) (Table 3.3).

High-Ca pyroxene

The major element chemistry of high-Ca pyroxene in EET 83227 is similar to the brecciated and unbrecciated eucrites, and is less variable than the major element chemistry of the low-Ca pyroxene in this sample. The Wo content ranges from 35.6–43.9% (average = 40.1%) and the Fs content ranges from 20.9–27.3% (average = 23.5%) (Table 3.4).

Plagioclase

The major element chemistry of plagioclase in EET 83227 is similar to the majority of the other eucrites. However, there is considerable variation in plagioclase chemistry within this sample. The An content ranges from 81.1–94.8% (average = 88.4%) (Table 3.2).

Mg-rich eucrites

Low-Ca pyroxene

Low-Ca pyroxene in the two Mg-rich eucrites (EET 87548 and LEW 87002) have average Wo contents of 3.0% and 2.3%, respectively, and average Fs contents of 44.4% and 31.3%, respectively. EET 87458 has a much greater range in Wo contents of 1.7–8.5%, as compared with a range of 1.5–3.2% for LEW 87002 (Table 3.3).

High-Ca pyroxene

EET 87458 is the only Mg-rich eucrite to contain a high-Ca pyroxene phase. This pyroxene has a Wo content of 45.0%. Compared with other eucrites in the sample suite, high-Ca pyroxene in EET 87458 also has a relatively low average Fs content of 16.7% (Table 3.4).

Plagioclase

Plagioclase compositions of the two Mg-rich eucrites are similar, with average An contents of 91.7% and 90.6%, respectively (Table 3.2).

Brecciated eucrites**Low-Ca pyroxene**

Low-Ca pyroxene in the brecciated eucrites has an average Wo content of <6%. However, low-Ca pyroxene in EET 92003 has an average Wo content of 14.7%. The majority of the brecciated samples contain low-Ca pyroxene with an average Fs content of 49.1–53.5%. However, some of the brecciated eucrites contain less ferroan low-Ca pyroxene (e.g., LAP 031062 (average Fs = 38.4%), PCA 91193 (average Fs = 45.2%) and SCO 06041 (average Fs = 42.6%)) (Table 3.3).

High-Ca pyroxene

The high-Ca pyroxene in the brecciated eucrites has a range in average Wo content from 36.1–44.6%. However, high-Ca pyroxene in QUE 99005 has a considerably lower average Wo content of 30.4%. The average Fs content ranges from 25.1–31.8%, with the exception of three samples with lower average Fs content (LAP 031062 (average Fs = 20.8%), PCA 91193 (average Fs = 20.4%) and SCO 06041 (average Fs = 16.5%). QUE 99005 has the highest average Fs content (38.9%) of high-Ca pyroxene in any of the samples (Table 3.4).

Plagioclase

Plagioclase in the brecciated eucrites has a range in average An contents of 85.1–89.9%. However, SCO 06041 and Juvinas contain plagioclase with higher average An contents of 91.8% and 92.7%, respectively. Most of the brecciated eucrites exhibit little variability in plagioclase composition within a sample. However, EET 92003, LAP 031062, Millbillillie and Camel Donga all have intra-sample variations in An contents of 9–12.5% (Table 3.2).

Unbrecciated eucrites**Low-Ca pyroxene**

Low-Ca pyroxene from two of the unbrecciated eucrites (QUE 97014 and LEW 85305) has similar major element compositions with average Wo contents of 2.6% and 4.0% and average Fs of 61.7% and 61.6%, respectively. Low-Ca pyroxene in EET 92023 is different to the aforementioned unbrecciated eucrites and is higher in Wo (average = 13.7%) and more magnesian (average Fs = 42.2%) (Table 3.3).

High-Ca pyroxene

EET 92023 and QUE 97014 both have average Wo contents of 43.1%, and similar average Fs contents of 27.9% and 27.2%, respectively. LEW 85305 has a considerably lower Wo content (average = 35.7%) and a higher average Fs content of 36.1% (Table 3.4).

Plagioclase

There is little difference in the average major element composition of plagioclase in the three unbrecciated eucrites. EET 92023, LEW 85305 and QUE 97014 have average An contents of 87.6%, 86.7% and 87.8%, respectively. However, EET 92023 has a considerably larger variation in An content within the sample, with An content varying >7%, as compared with

the <2% variation observed in the other two samples (Table 3.2).

Cumulate eucrites

Low-Ca pyroxene

Low-Ca pyroxene in Dhofar 007 is relatively magnesian, with a low average Fs content of 44.1% as compared with an average of Fs content of 53.0% for the non-cumulate eucrites. The average Wo content is 3.9%, which is similar to the majority of the non-cumulate eucrites (Table 3.3).

Plagioclase

Plagioclase in Dhofar 007 is compositionally similar to that in the non-cumulate eucrites. Dhofar 007 has an average An content of 90.2% and exhibits little variability within the sample (Table 3.2).

Chapter 4

Trace element data

Trace element data is summarized in this chapter, the full data set can be found in Appendix B.

4.1 Chondrite-normalized REE plots

4.1.1 Intra-sample variability

The low concentration of heavy rare earth elements (REE) in plagioclase meant that only light and medium REE concentrations were measured in plagioclase. While pyroxene is relatively depleted in light REE, these were in measurable concentrations in the pyroxene analysed in this study.

The intra-sample variability of REE concentrations in plagioclase and pyroxene was examined to determine if an average REE pattern for each sample would be representative of the entire sample. Chondrite-normalized REE plots for a selection of samples from all the eucrite groups are discussed below (Fig. 4.1).

Plagioclase

Chondrite-normalized REE data for plagioclase have flat to light REE enriched patterns across the suite of samples, with all samples exhibiting marked positive Eu anomalies. Samples such as GRA 98033 and QUE

Figure 4.1: CI-chondrite normalized REE plots showing individual analyses for selected eucrites. CI-chondrite values from Anders and Grevesse (1989).

Figure 4.1: CI-chondrite normalized REE plots showing individual analyses for selected eucrites (continued).

Figure 4.1: CI-chondrite normalized REE plots showing individual analyses for selected eucrites (continued).

97014 show very limited REE variability that is comparable to the estimated analytical uncertainty (Fig. 4.1 A and L), whereas analyses of plagioclase in some other samples (e.g., EET 92023) have REE concentrations that may vary by up to a factor of three (Fig. 4.1 J). Eu in all samples shows little intra-sample variability and, as such, Eu anomalies (Eu/Eu^*) generally become smaller (i.e., less positive) with increasing plagioclase REE contents. The polymict eucrite EET 83227 has more variation between REE analyses of plagioclase than most other samples, with one analysis in particular having considerably higher REE concentrations (Fig. 4.1 T). The majority of the plagioclase REE analyses of GRA 98043 have a negative Ce anomaly (Ce/Ce^*) (Fig. 4.1 G), whereas the other samples do not exhibit Ce anomalies in plagioclase.

Low-Ca pyroxene

Chondrite-normalized REE patterns for low-Ca pyroxene in the eucrite samples are more variable than those for plagioclase. Low-Ca pyroxene in all samples is LREE depleted and HREE enriched, and all analyses have marked negative Eu anomalies. Some low-Ca pyroxene analyses exhibit positive Ce anomalies (e.g., Fig. 4.1 B), whereas others have negative Ce anomalies (e.g., Fig. 4.1 M and P) or no Ce anomaly. In general, there is limited variation in REE analyses of low-Ca pyroxene within most samples, particularly with respect to Eu anomalies. However, there is some intra-sample variability in Ce anomalies for low-Ca pyroxene. For example, both positive and negative Ce anomalies are evident in analyses of GRA 98043 (Fig. 4.1 H).

High-Ca pyroxene

High-Ca pyroxene in all samples is LREE depleted and HREE enriched, and all the samples have negative Eu anomalies. Like the low-Ca pyroxene phase there is variability in the Ce anomalies of high-Ca pyroxene within individual samples. The heavy REE patterns of the high-Ca pyroxene generally have flatter chondrite-normalized REE profiles than low-Ca

pyroxene for the same samples, but have very similar Yb and Lu concentrations. However, chondrite-normalized REE patterns for high-Ca pyroxene in some samples are almost identical to those of low-Ca pyroxene in the same samples, such as SCO 06041 and LEW 87002 (Fig. 4.1 F and Q respectively). This may be because the two-pyroxene phases in these samples are more compositionally similar to each other than for other samples. There is limited intra-sample REE variability in high-Ca pyroxene in some samples and REE analyses are within analytical error of each other in the majority of samples. However, REE analyses of some samples such as GRA 98033 have larger variations (Fig. 4.1 C), although the overall shape of the chondrite-normalized REE patterns are similar for all analyses in samples such as this example.

Single-phase pyroxene

In samples with only a single pyroxene phase, chondrite-normalized REE patterns of pyroxene show LREE depletion and HREE enrichment, and marked negative Eu anomalies. REE analyses of pyroxene in Dhofar 007 are all within analytical error of each other (Fig. 4.1 S), whereas those of EET 92023 are more variable, but still have consistent chondrite-normalized REE profiles (Fig. 4.1 K). These samples both have relatively flat HREE profiles, which are similar to the high-Ca pyroxene phase of some other samples. There is a very large amount of variability between individual REE analyses of pyroxene in the polymict sample EET 83227 (Fig. 4.1 U). With the exception of Ce and Eu the REE concentration data in the polymict sample vary by about an order of magnitude. Some analyses exhibit positive Ce anomalies (up to 4.12), whereas other analyses have no Ce anomaly. Eu anomalies are almost absent in the most REE-depleted analyses and become increasingly negative (as low as 0.04) with increasing REE concentrations.

4.1.2 Inter-sample variability

The trace element abundances in the eucrites analysed in this study show considerable variability as illustrated by the CI-chondrite normalized REE patterns in plagioclase and pyroxene (Fig. 4.2). The general REE patterns of plagioclase and pyroxene are as expected, with plagioclase exhibiting a relative enrichment in the light REE and a positive Eu anomaly, while pyroxene has negative Eu anomalies, and is enriched in heavy REE.

The intra-sample mineral variations in REE concentrations of the polymict eucrite EET 83227 were so large that calculating an average value for this sample was not undertaken as it is clearly heterolithic. The average CI-chondrite normalized REE patterns for the other samples are discussed below.

Plagioclase

REE abundances in plagioclase (Fig. 4.2 A; Table 4.1) are less variable between samples than pyroxene (Fig. 4.2 B, C and D). However, there is still approximately an order of magnitude range in light REE abundances in plagioclase. Eu anomalies in plagioclase are positive and exhibit a large range from 5.9 in LAR 06875 to 57.3 in Juvinas. In addition to its relatively low Eu anomaly, LAR 06875 has considerably higher abundances of both heavy and light REE compared with the rest of the samples, and a generally much flatter REE profile (Fig. 4.2 A).

Low-Ca Pyroxene

There is considerable variation in the abundance of REE in low-Ca pyroxene between the eucrite samples, particularly light REE abundances (Fig. 4.2 B; Table 4.2), which exhibit more than an order of magnitude variability. Eu anomalies in low-Ca pyroxene are negative, and range from 0.02 in Camel Donga (which has a distinctly lower Eu abundance than other samples) to 0.45 in the Mg-rich eucrite EET 87458. The samples also exhibit a wide range of Ce anomalies ranging from the most positive anomaly of

Figure 4.2: Average CI-chondrite normalized REE plots for plagioclase and pyroxene phases from each sample. CI-chondrite values from Anders and Grevesse (1989).

Table 4.1: Average CI-chondrite normalized REE concentrations in plagioclase in eucrite samples. CI-chondrite values from Anders and Grevesse (1989).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Ce/Ce*	Eu/Eu*
EET 83227	2.60	2.32	1.95	1.69	1.36	25.6	0.86	1.03	23.7
EET 87548	1.23	0.90	0.59	0.44	0.44	16.4	0.23	1.06	50.8
EET92003	2.77	2.72	2.26	2.05	1.63	25.5	1.12	1.09	18.9
EET 92023	2.81	2.35	1.96	1.64	1.06	24.1	0.73	1.00	27.4
GRA 98006	1.88	1.39	1.01	0.82	0.60	22.1	0.36	1.01	47.6
GRA 98033	2.90	2.09	1.53	1.31	0.92	27.2	0.68	0.99	34.4
GRA 98043	2.86	1.72	2.05	2.54	1.78	26.9	1.54	0.71	16.2
GRA 98114	3.00	2.52	1.69	1.32	1.19	24.6	1.05	1.12	22.0
LAP 031062	2.68	2.25	2.36	1.97	1.91	35.4	1.07	0.89	24.8
LAR 06875	8.14	7.81	6.95	6.31	5.78	31.3	4.82	1.04	5.9
LEW 85305	6.49	4.71	3.64	2.84	1.84	34.0	1.15	0.97	23.4
LEW 87002	1.91	1.50	1.09	1.01	0.96	27.4	0.73	1.04	32.8
PCA 91193	4.27	3.22	2.24	1.66	1.18	24.6	0.62	1.04	28.7
QUE 97014	2.37	1.86	1.46	1.27	1.02	27.5	0.88	1.00	28.9
QUE 99005	1.50	0.86	1.21	1.08	1.13	29.1	0.79	0.64	30.8
SCO 06041	1.98	1.46	1.05	0.82	0.59	20.6	0.44	1.01	40.4
GRO 95533	5.04	4.18	3.15	2.50	1.73	25.4	0.96	1.05	19.7
Millbillillie	2.07	1.60	1.22	1.09	0.85	24.9	0.71	1.00	31.9
Juvinas	0.72	0.74	0.55	0.50	0.45	19.5	0.26	1.18	57.3
Dhofar 007	4.27	3.60	2.77	2.35	1.18	22.3	0.87	1.05	22.1
Camel Donga	4.63	3.42	2.64	1.87	1.21	28.0	0.71	0.98	30.0

37.8 measured in GRA 98114, to an anomaly of 0.39 in QUE 99005 (Table 4.2). As was the case for REE abundances in plagioclase in LAR 06875, the low-Ca pyroxene in this sample has a much flatter REE pattern than other samples, and higher abundances of the middle and light REE (Fig. 4.2 B). The two Mg-rich eucrites EET 87548 and LEW 87002 have the lowest REE abundances in low-Ca pyroxene. LEW 85305 has the highest heavy REE abundance, and has a flatter heavy REE profile as compared with the other samples.

High-Ca Pyroxene

Like plagioclase and low-Ca pyroxene, high-Ca pyroxene REE abundances show considerable variability between samples, as evidenced by CI-chondrite normalized REE plots (Fig. 4.2 C; Table 4.3). In general, the

Table 4.2: Average CI-chondrite normalized REE concentrations in low-Ca pyroxene in the eucrite samples. CI-chondrite values from Anders and Grevesse (1989).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ce/Ce*	Eu/Eu*
EET 87548	0.25	0.22	0.34	0.34	0.78	0.41	1.07	1.42	1.09	1.75	2.22	3.01	3.53	4.05	0.77	0.45
EET 92003	0.40	0.61	1.02	1.81	3.30	0.66	4.91	5.41	5.60	6.59	8.15	6.45	8.03	9.28	0.95	0.16
GRA 98006	0.68	3.40	1.16	1.11	2.19	0.53	2.64	3.74	4.93	5.90	7.64	9.04	11.9	13.12	3.82	0.22
GRA 98033	0.39	1.92	0.68	0.97	1.80	0.28	2.96	3.92	5.38	6.84	9.14	11.1	12.9	16.57	3.73	0.12
GRA 98043	1.80	2.35	2.13	2.30	3.66	0.43	4.50	6.20	7.64	8.36	11.1	12.6	14.8	18.59	1.20	0.11
GRA 98055	0.31	0.93	0.55	0.73	1.59	0.32	2.75	3.53	5.07	6.12	8.04	10.2	12.6	16.62	2.26	0.15
GRA 98114	0.17	9.83	0.40	0.53	1.13	0.26	2.45	3.29	4.19	5.85	7.79	10.8	10.8	13.42	37.8	0.16
LAR 06875	4.02	4.07	4.06	3.99	4.67	1.40	5.11	6.00	6.41	7.95	8.64	10.8	12.0	12.76	1.01	0.29
LEW 85305	0.54	1.03	1.98	3.00	6.19	0.49	9.48	11.86	14.3	15.0	16.8	18.6	18.0	20.07	1.00	0.06
LEW 87002	0.11	0.07	0.22	0.40	0.99	0.56	1.80	2.08	2.47	2.90	3.99	4.23	4.17	4.73	0.44	0.42
PCA 91193	0.65	0.69	1.06	1.48	2.76	0.66	3.67	4.35	5.50	5.93	7.06	8.29	7.81	8.92	0.83	0.21
QUE 97014	0.55	0.49	0.96	1.15	2.31	0.46	3.57	5.18	6.12	7.11	10.3	12.7	13.0	18.68	0.68	0.16
QUE 99005	1.17	0.51	1.42	1.35	1.67	0.16	1.97	2.53	2.69	3.29	4.38	5.01	7.73	7.65	0.39	0.09
RKPA 80204	2.10	5.33	2.22	2.47	2.86	0.26	3.49	4.40	5.45	5.44	6.82	8.95	10.5	12.80	2.47	0.08
SCO 06041	0.40	0.56	0.72	1.16	2.14	0.64	3.16	3.71	4.11	4.30	5.78	6.34	6.33	7.96	1.05	0.25
GRO 95533	0.31	0.39	0.62	0.72	1.96	0.55	2.99	4.33	5.66	6.81	9.11	9.86	11.6	13.51	0.90	0.23
Camel Donga	0.28	0.36	0.55	0.87	1.90	0.04	3.43	5.20	7.27	8.04	10.4	12.4	13.1	14.72	0.93	0.02

heavy REE profile of high-Ca pyroxene is much flatter than that of low-Ca pyroxene. As in low-Ca pyroxene, Camel Donga has the largest negative Eu anomaly of 0.04, while LEW 87002, an Mg-rich eucrite, has the smallest negative Eu anomaly of 0.38 (Table 4.3). Ce anomalies range from 0.43 in QUE 99005 to 7.8 in GRA 98114, which are also the samples with the smallest and largest respective Ce anomalies in low-Ca pyroxene. The Mg-rich eucrites LEW 87002 and EET 87458 have the lowest abundances of the heavy REE, and LEW 87002 also has the lowest light REE abundance. LAR 06875 exhibits the same flat REE pattern as in plagioclase and low-Ca pyroxene.

Single-phase pyroxene

There are five samples with only one discernible pyroxene phase, and with the exception of Millbillillie, the CI-chondrite normalized REE patterns of these samples are similar to those of high-Ca pyroxene in that they have relatively flat heavy REE profiles (Fig. 4.2 D). There is less variability in REE abundances in these samples (Table 4.4). However, there are only five samples in this group. Juvinas and Dhofar 007 have the most negative Eu anomalies of 0.03, while LAP 031062 has smallest negative anomaly of 0.15, Ce anomalies range from 0.26–1.16.

4.2 Other trace element variations

4.2.1 Trace element plots

Plagioclase

Trace element concentrations in plagioclase are presented in 4.5, with selected elements plotted in 4.3. There is considerable overlap in the concentrations of trace elements in plagioclase amongst samples from all the different groups of eucrites in the sample suite and, as such, they are all considered together here, rather than in separate groups. Plagioclase has a range of La concentrations from 0.17–1.91 ppm, which correlates pos-

Table 4.3: Average CI-chondrite normalized REE concentrations in high-Ca pyroxene in the eucrite samples. CI-chondrite values from Anders and Grevesse (1989).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ce/Ce*	Eu/Eu*
EET 92003	0.50	0.86	1.47	2.08	3.80	0.76	5.51	7.12	8.02	9.11	10.0	10.9	10.7	11.3	1.01	0.17
GRA 98006	1.37	2.23	3.50	4.18	7.00	1.05	10.9	13.0	15.4	15.1	14.9	14.3	15.8	18.1	1.01	0.12
GRA 98033	1.06	4.27	3.48	4.75	8.96	0.85	12.4	15.0	18.1	17.5	18.8	18.3	18.7	20.2	2.23	0.08
GRA 98043	2.41	4.92	5.85	7.70	13.3	1.57	14.2	17.6	20.3	19.9	19.4	19.3	19.8	22.0	1.31	0.11
GRA 98055	3.07	6.56	8.87	13.07	20.6	1.10	22.8	26.2	29.8	27.4	28.2	26.5	26.7	27.6	1.26	0.05
GRA 98114	0.85	10.9	2.33	3.07	4.92	0.49	7.97	9.64	11.00	11.7	13.30	13.9	14.0	15.3	7.77	0.08
LAR 06875	8.35	8.84	8.94	9.06	8.52	2.64	8.60	8.86	9.06	9.98	9.96	10.4	10.6	9.79	1.02	0.31
LEW 85305	5.78	9.90	15.4	19.0	26.6	1.89	27.7	31.2	29.0	26.3	29.7	23.5	24.9	24.6	1.05	0.07
LEW 87002	0.17	0.12	0.31	0.37	1.04	0.51	1.79	2.37	3.22	3.66	4.43	5.04	5.02	6.16	0.54	0.38
PCA 91193	2.71	5.32	9.11	13.7	22.0	1.53	25.6	24.6	25.0	21.9	20.7	17.1	14.7	14.1	1.07	0.06
QUE 97014	1.01	1.42	2.90	4.08	7.83	1.13	11.6	13.5	15.4	15.9	18.1	19.4	16.8	20.6	0.83	0.12
QUE 99005	1.72	0.77	1.86	1.96	1.83	0.62	2.92	4.34	5.36	4.98	6.48	7.50	9.60	8.93	0.43	0.27
RKPA 80204	0.77	3.58	1.47	1.79	2.99	0.88	3.99	5.52	6.74	7.35	8.62	9.50	10.6	13.9	3.37	0.25
SCO 06041	0.42	0.59	0.90	1.40	2.60	0.67	3.78	4.28	5.97	5.17	6.83	6.33	7.17	7.16	0.97	0.21
GRO 95533	0.30	0.57	0.88	1.19	1.96	0.32	4.43	5.44	6.81	6.91	9.50	10.5	10.4	13.3	1.13	0.11
Camel Donga	0.87	1.59	2.80	3.37	6.75	0.30	7.63	11.3	12.9	12.4	13.9	14.3	14.5	15.5	1.02	0.04

Table 4.4: Average CI-chondrite normalized REE concentrations in pyroxene from eucrite samples with a single pyroxene phase. CI-chondrite values from Anders and Grevesse (1989).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ce/Ce*	Eu/Eu*
EET 83227	1.16	2.31	3.15	4.45	7.17	0.66	8.41	8.76	10.4	9.40	10.8	10.0	9.46	9.27	1.20	0.09
EET 92023	0.49	0.85	1.58	2.44	4.70	0.60	6.77	7.47	8.52	8.94	10.2	9.88	9.77	11.2	0.96	0.11
LAP 031062	0.19	0.41	0.68	1.10	2.43	0.47	4.09	4.77	5.04	5.55	6.38	6.25	6.43	7.53	1.13	0.15
Millbillilie	1.10	1.19	1.67	1.89	3.19	0.31	4.41	5.44	7.57	7.93	11.1	12.3	14.1	17.6	0.88	0.08
Juvinas	0.11	0.19	0.29	0.52	1.39	0.06	2.25	3.46	4.64	5.62	7.85	9.24	10.6	12.2	1.04	0.03
Dhofar 007	0.26	0.52	0.96	1.47	2.95	0.10	4.65	4.89	5.74	6.27	6.84	7.23	6.98	7.95	1.05	0.03

itively with Sr concentrations (4.3). However, Li and Ba concentrations do not correlate with La concentrations in plagioclase. No correlations exist between the concentrations of Sr, Li, Ba and La and Ce anomalies. Eu anomalies in plagioclase range from 5.9–57.3 across the sample suite and correlate negatively with Sr concentration (4.6), and positively with La concentration. Although increasing La is correlated with increasingly smaller positive Eu anomalies, no obvious correlations exists between the concentrations of Li and Ba, and Eu anomalies. The CI-chondrite normalized La/Sm ratio in plagioclase ranges from 1.3–3.8 across the sample suite, which does not correlate with Li, Sr and Ba concentrations, but does correlate with light and middle REE concentrations.

Low-Ca Pyroxene

As is the case for plagioclase there is overlap in the concentrations of trace elements in low-Ca pyroxene amongst samples from all the different groups of eucrites in the sample suite, so they are not considered here in individual groups (Table 4.7, Fig. 4.4). However, the Mg-rich samples do exhibit systematic differences from the other samples, particularly in terms of Yb concentrations, Eu anomalies and Ce anomalies (Fig. 4.4). There is a strong positive correlation in low-Ca pyroxene across the entire suite of samples between most of the HREE (Fig. 4.8). Pr, Nd and Sm also correlate well across the entire sample suite, as do Sm, Gd and Tb (Table 4.8). There is a negative correlation between the concentrations of Sc and Yb and Eu anomalies in low-Ca pyroxene (Fig. 4.4 E, H and P). Sc positively correlates with Yb, whereas V and Yb exhibit a general negative correlation (Fig. 4.4 R). Al and Eu appear to exhibit a subtle positive correlation (Fig. 4.4 U), as do Ti and Hf (Fig. 4.4 T), and Hf and Zr (Fig. 4.4 V). La concentrations do not correlate with the concentrations of Li, Sc, V and Yb in low-Ca pyroxene. There is no correlation between Yb concentrations and Li concentrations, or between Ce anomalies and concentrations of Li, Sc, Yb and La (Fig. 4.4). The concentrations of Li and La do not

Table 4.5: Trace element concentrations in plagioclase from eucrite samples. All concentrations in ppm.

Sample		Li	Na	Mg	Al	Ca	Ti	Mn	Rb	Sr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd
EET 83227	average	9.4	5902	448	204917	130167	98	39.7	0.09	190	50.6	0.61	1.40	0.17	0.76	0.20	1.43	0.17
	2 s.d.	2.4	1186	239	18795	5912	120	29.2	0.10	9	6.1	0.95	2.05	0.23	1.02	0.19	0.16	0.15
EET 87548	average	5.5	6122	96	196083	124968	42	15.9	0.08	149	13.3	0.29	0.55	0.05	0.20	0.07	0.92	0.05
	2 s.d.	0.8	731	17	10522	3256	11	4.1	0.04	11	1.6	0.06	0.11	0.01	0.10	0.07	0.07	0.06
EET 92003	average	9.9	7898	1102	196870	123670	282	110.5	0.11	199	62.7	0.65	1.64	0.20	0.93	0.24	1.43	0.22
	2 s.d.	2.4	2079	1686	17319	5800	453	154.5	0.10	21	20.8	0.57	1.48	0.19	1.03	0.26	0.20	0.33
EET 92023	average	5.7	8612	539	204727	121536	185	28.8	0.29	193	53.0	0.66	1.42	0.17	0.74	0.16	1.35	0.14
	2 s.d.	1.3	3622	348	17238	11389	108	27.1	0.24	10	36.8	0.61	1.21	0.15	0.61	0.07	0.13	0.13
GRA 98006	average	20.5	6874	35	199129	117200	29	9.7	0.59	177	84.9	0.44	0.84	0.09	0.37	0.09	1.24	0.07
	2 s.d.	16.3	996	4	6330	5070	17	1.4	1.28	13	98.7	0.12	0.26	0.03	0.17	0.07	0.10	0.10
GRA 98033	average	12.1	8052	2271	200711	120511	104	220.5	0.07	195	63.8	0.68	1.26	0.14	0.59	0.13	1.52	0.13
	2 s.d.	1.5	572	1609	12226	5408	48	134.5	0.03	14	5.6	0.17	0.29	0.03	0.12	0.04	0.09	0.04
GRA 98043	average	12.3	8123	1836	196925	118163	83	189.5	0.39	192	49.8	0.67	1.04	0.18	1.15	0.26	1.50	0.30
	2 s.d.	1.3	1220	3342	16082	6118	82	325.5	1.01	18	55.9	0.22	0.28	0.09	1.74	0.19	0.15	0.22
GRA 98114	average	12.2	7909	1000	192457	118957	170	128.3	0.33	185	66.9	0.71	1.52	0.15	0.60	0.18	1.38	0.21
	2 s.d.	2.3	776	3044	24256	4413	278	337.6	0.44	14	19.5	0.35	0.52	0.10	0.50	0.15	0.16	0.22
LAP 031062	average	4.0	7160	476	231875	145350	117	19.0	0.03	252	36.2	0.63	1.35	0.21	0.89	0.28	1.99	0.21
	2 s.d.	0.2	172	72	25425	14205	35	4.0	0.04	21	8.7	0.57	0.93	0.25	1.13	0.35	0.36	0.26
LAR 06875	average	14.1	8243	1989	209275	128295	299	227.2	0.10	219	61.7	1.70	4.22	0.55	2.57	0.77	1.73	0.87
	2 s.d.	4.4	950	2914	32701	18909	73	282.4	0.13	23	18.4	1.80	4.60	0.70	2.89	1.06	0.14	0.87
LEW 85305	average	3.8	10070	176	223250	137700	102	44.4	0.18	239	104.3	1.52	2.84	0.32	1.28	0.27	1.90	0.23
	2 s.d.	0.5	917	23	7598	4824	40	6.8	0.24	10	12.6	0.60	1.03	0.13	0.59	0.14	0.12	0.11
LEW 87002	average	7.4	6442	3530	198075	130423	130	91.1	0.11	209	87.9	0.45	0.90	0.10	0.46	0.14	1.53	0.14
	2 s.d.	2.0	1624	3607	19157	7706	132	91.1	0.09	17	8.6	0.29	0.63	0.06	0.25	0.07	0.16	0.09
PCA 91193	average	8.3	8314	365	199971	127024	100	24.1	0.16	197	42.9	1.00	1.94	0.20	0.75	0.17	1.38	0.12
	2 s.d.	0.7	508	60	14271	7431	46	25.2	0.15	21	19.1	0.59	1.08	0.10	0.43	0.06	0.21	0.09
QUE 97014	average	14.5	9058	1108	194400	123833	53	105.3	0.11	200	38.3	0.56	1.12	0.13	0.57	0.15	1.54	0.17
	2 s.d.	1.6	430	2980	18649	10347	33	229.1	0.12	13	18.2	0.43	1.15	0.13	0.73	0.18	0.21	0.26

Table 4.5: Trace element concentrations in plagioclase from eucrite samples (continued). All concentrations in ppm.

Sample		Li	Na	Mg	Al	Ca	Ti	Mn	Rb	Sr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd
QUE 99005	average	17.6	9450	1983	197683	123983	96	174.9	0.63	212	87.4	0.35	0.52	0.11	0.49	0.17	1.63	0.16
	2 s.d.	6.6	4294	1231	25676	19093	101	71.2	1.41	9	66.9	0.25	0.38	0.10	0.51	0.11	0.10	0.21
SCO 06041	average	10.4	6451	107	207330	132510	92	12.0	0.08	173	40.7	0.47	0.88	0.09	0.37	0.09	1.15	0.09
	2 s.d.	1.9	1070	28	7726	6242	76	2.7	0.09	10	3.8	0.26	0.62	0.07	0.23	0.11	0.11	0.07
GRO 95533	average	11.4	7711	90	205413	130188	57	21.4	0.14	190	70.5	1.18	2.52	0.28	1.13	0.25	1.42	0.19
	2 s.d.	2.4	1330	114	12721	7393	14	10.0	0.18	17	15.4	1.62	4.79	0.62	2.56	0.61	0.25	0.41
Millbillillie	average	18.2	10356	3244	183786	114514	188	315.3	0.58	179	80.1	0.49	0.96	0.11	0.49	0.13	1.39	0.14
	2 s.d.	4.8	2678	2439	14109	8090	237	244.7	1.59	19	78.0	0.21	0.47	0.05	0.16	0.08	0.27	0.06
Juvinas	average	9.0	5841	1697	203940	134028	50	177.4	0.12	159	47.6	0.17	0.45	0.05	0.22	0.07	1.09	0.05
	2 s.d.	1.4	971	610	7710	5259	15	61.8	0.06	21	24.7	0.13	0.39	0.04	0.18	0.11	0.24	0.09
Camel Donga	average	10.2	8632	172	220760	134480	59	26.7	0.05	223	84.9	1.09	2.06	0.23	0.85	0.18	1.57	0.14
	2 s.d.	2.7	2089	111	20280	13552	25	16.4	0.19	40	14.4	0.71	1.29	0.13	0.50	0.13	0.27	0.12
Dhofar 007	average	5.9	7886	571	216929	136586	165	43.0	0.30	194	42.3	1.00	2.17	0.25	1.06	0.17	1.25	0.17
	2 s.d.	1.2	1469	147	7768	13751	114	13.7	0.20	21	17.5	1.00	1.91	0.19	0.83	0.13	0.11	0.16

Figure 4.3: Plots of trace element variations in plagioclase in the eucrite samples.

Figure 4.3: Plots of trace element variation in plagioclase in the eucrite samples (continued).

Table 4.6: Correlation matrix for trace elements in plagioclase. The numbers represent r^2 values, and are coloured according to what range of r^2 values they fall into: r^2 values between 0.8–1.0 are red, 0.60–0.79 are blue, 0.40–0.59 are orange, and values <0.40 are green. The highest r^2 values denote the best correlations.

	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	Sr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Ce/Ce*	Eu/Eu*
Li		0.07	0.11	0.30	0.41	0.00	0.26	0.41	0.05	0.12	0.02	0.02	0.01	0.00	0.00	0.01	0.02	0.06	0.00
Na	0.07		0.04	0.00	0.06	0.07	0.15	0.18	0.19	0.23	0.16	0.09	0.09	0.08	0.04	0.24	0.04	0.15	0.19
Mg	0.11	0.04		0.19	0.10	0.12	0.68	0.06	0.00	0.09	0.03	0.02	0.01	0.00	0.01	0.03	0.05	0.02	0.00
Al	0.30	0.00	0.19		0.77	0.00	0.19	0.21	0.45	0.00	0.29	0.27	0.29	0.22	0.16	0.27	0.08	0.00	0.07
Ca	0.41	0.06	0.10	0.77		0.00	0.18	0.36	0.28	0.01	0.14	0.14	0.15	0.09	0.08	0.14	0.03	0.01	0.01
Ti	0.00	0.07	0.12	0.00	0.00		0.15	0.00	0.07	0.01	0.17	0.28	0.31	0.35	0.38	0.07	0.41	0.02	0.38
Mn	0.26	0.15	0.68	0.19	0.18	0.15		0.11	0.00	0.05	0.00	0.00	0.01	0.04	0.07	0.02	0.13	0.03	0.02
Rb	0.41	0.18	0.06	0.21	0.36	0.00	0.11		0.03	0.16	0.06	0.08	0.06	0.04	0.04	0.01	0.02	0.21	0.00
Sr	0.05	0.19	0.00	0.45	0.28	0.07	0.00	0.03		0.16	0.33	0.27	0.34	0.29	0.27	0.91	0.19	0.14	0.37
Ba	0.12	0.23	0.09	0.00	0.01	0.01	0.05	0.16	0.16		0.09	0.05	0.04	0.03	0.02	0.20	0.01	0.03	0.04
La	0.02	0.16	0.03	0.29	0.14	0.17	0.00	0.06	0.33	0.09		0.95	0.89	0.79	0.62	0.28	0.53	0.00	0.50
Ce	0.02	0.09	0.02	0.27	0.14	0.28	0.00	0.08	0.27	0.05	0.95		0.95	0.86	0.74	0.22	0.65	0.03	0.51
Pr	0.01	0.09	0.01	0.29	0.15	0.31	0.01	0.06	0.34	0.04	0.89	0.95		0.96	0.88	0.31	0.79	0.00	0.58
Nd	0.00	0.08	0.00	0.22	0.09	0.35	0.04	0.04	0.29	0.03	0.79	0.86	0.96		0.93	0.29	0.88	0.00	0.62
Sm	0.00	0.04	0.01	0.16	0.08	0.38	0.07	0.04	0.27	0.02	0.62	0.74	0.88	0.93		0.30	0.97	0.00	0.52
Eu	0.01	0.24	0.03	0.27	0.14	0.07	0.02	0.01	0.91	0.20	0.28	0.22	0.31	0.29	0.30		0.23	0.19	0.40
Gd	0.02	0.04	0.05	0.08	0.03	0.41	0.13	0.02	0.19	0.01	0.53	0.65	0.79	0.88	0.97	0.23		0.01	0.48
Ce/Ce*	0.06	0.15	0.02	0.00	0.01	0.02	0.03	0.21	0.14	0.03	0.00	0.03	0.00	0.00	0.00	0.19	0.01		0.06
Eu/Eu*	0.00	0.19	0.00	0.07	0.01	0.38	0.02	0.00	0.37	0.04	0.50	0.51	0.58	0.62	0.52	0.40	0.48	0.06	

correlate with Eu anomalies. Chondrite normalized La/Sm ratios range from 0.1–0.9 and correlate with La concentration (Fig. 4.4 J) but not with concentrations of Li, Sc or Yb.

High-Ca Pyroxene

Like the other mineral phases, trace element concentrations in high-Ca pyroxene amongst samples from the different groups of eucrites in the sample suite overlap, and so they are considered together here (Fig. 4.5; Table 4.9). There is a strong positive correlation in high-Ca pyroxene across the entire suite of samples between the different heavy REE (Table 4.10). Light REE also correlate positively with each other, and Sm is correlated with most heavy REE across the entire sample suite (Table 4.10). There are positive trace element correlations amongst the entire group of samples, including Mg-rich samples, between La and Eu (Fig. 4.5 W), Sc and Eu (Fig. 4.5 E), Sc and La (Fig. 4.5 O), Na and Nd, Na and Pr (Table 4.10), Pr and Nd, and Zr and Hf in the high-Ca pyroxene phase (Table 4.10). However, there are also a number of other trace element correlations for the brecciated and, possibly, unbrecciated eucrites, which the Mg-rich eucrites are not part of, largely due to their distinct middle to heavy REE concentrations (Table 4.9). As is the case for low-Ca pyroxene, the high-Ca pyroxene phases in the Mg-rich samples have distinct Eu anomalies compared to the other samples (Fig. 4.5 B–K). Trace element analyses of the high-Ca pyroxene exhibit general positive correlations between Yb and La (Fig. 4.5 S), V and La (Fig. 4.5 Q), Sc and La (Fig. 4.5 O) and, possibly, Li and La concentrations in the brecciated eucrites (Fig. 4.5 M). Li, Sc and V concentrations appear to positively correlate with Yb concentrations (Fig. 4.5 N, P and R). However, there is no clear correlation between Sc and V. Eu concentrations correlate with concentrations of both Sc and Yb (Fig. 4.5 E and H), and Sc concentration also correlates positively with middle and heavy REE concentrations (Table 4.10). Na correlates positively with concentrations of some light REE (e.g., Pr, Table 4.10) and geochemically similar Zr and Hf are also positively correlated (Table 4.10). Ce anomalies

and CI-chondrite normalized La/Sm ratios do not correlate with Li, Sc or Yb concentrations (Fig. 4.5 A, D and J), although there is a correlation between La/Sm ratios and La concentrations (Fig. 4.5 J).

Single-phase pyroxene

Five samples only contain one pyroxene phase on the basis of trace element chemistry. The trace element concentrations are detailed in Table 4.11, however with relatively few samples it is difficult to identify meaningful trace element correlations. However, there does appear to be a negative correlation between the concentrations of Sc and Yb and Ce anomalies (Fig. 4.6 F and I). There also appears to be positive correlations between the concentration of both V and Sc and the Yb concentration (Fig. 4.5 R and P).

4.2.2 Correlations between plagioclase and pyroxene trace element data

There is no correlation between concentrations of La, Li, Sr and Eu and Ce anomalies in plagioclase and pyroxene (Fig. 4.7 A, B, C). There is a general positive correlation between Yb in pyroxene and La in plagioclase (Fig. 4.5 E), with Yb concentrations in pyroxene increasing from 0.6–4.0 ppm across the entire eucrite suite, and La concentration in plagioclase increasing from 0.2–1.5 ppm (excluding one sample). In addition, Eu concentrations in plagioclase positively correlate with Yb concentrations in pyroxene (Fig. 4.5 F).

Table 4.7: Trace element concentrations in low-Ca pyroxene from eucrite samples. All concentrations are in ppm.

sample		Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb	Sr	Zr	Ba	La
EET 87548	average	3.21	17.7	99588	1983	6563	36.0	945	61.9	858	6400	4.05	0.56	1.93	0.03	0.88	1.33	0.04	0.06
	2 s.d.	0.85	9.7	3801	656	3293	3.1	170	9.5	182	115	2.51	0.44	1.43	0.03	2.60	0.74	0.05	0.04
EET 92003	average	8.88	180.1	71700	2809	33650	41.8	2581	98.9	2616	6445	14.38	11.28	5.71	0.02	2.20	17.69	0.13	0.09
	2 s.d.	1.19	19.2	849	16	424	3.0	3	24.2	1317	14	3.10	8.27	1.10	0.02	0.28	12.47	0.16	0.12
GRA 98006	average	0.69	125.8	72414	1774	14174	38.8	970	68.2	1696	7910	10.76	0.90	3.09	0.14	0.34	3.02	0.20	0.16
	2 s.d.	0.46	37.4	13300	728	7851	7.5	1010	119.7	5265	1909	3.52	1.07	2.17	0.08	1.73	4.77	0.16	0.08
GRA 98033	average	5.39	49.5	61825	821	14305	38.0	622	42.1	462	7453	7.25	0.18	2.23	0.02	0.15	2.48	0.05	0.09
	2 s.d.	1.33	97.1	3711	424	12754	11.6	265	16.8	174	469	1.01	0.56	0.74	0.03	1.89	2.51	0.02	0.11
GRA 98043	average	4.04	86.3	57303	1470	22033	44.7	909	38.8	475	7689	4.62	0.47	3.25	0.09	1.42	2.45	0.16	0.42
	2 s.d.	2.43	42.4	2092	746	15629	8.7	506	13.5	151	709	8.89	0.69	2.08	0.07	1.87	2.42	0.25	0.81
GRA 98055	average	4.23	62.3	60664	1477	17984	43.9	1024	44.0	513	7332	7.80	0.21	2.76	-	-	1.68	0.11	0.07
	2 s.d.	3.10	27.3	1567	1148	7342	10.7	404	19.8	208	380	1.35	0.32	0.92	-	-	0.96	0.40	0.08
GRA 98114	average	4.89	77.1	57820	1980	13930	37.0	1044	36.7	463	7328	5.47	-	2.87	0.06	-	1.61	0.06	0.04
	2 s.d.	3.30	67.5	3863	1079	5902	5.9	166	5.3	112	526	2.87	-	0.99	0.10	-	0.67	0.04	0.06
LAR 06875	average	3.81	414.7	58900	7057	19097	31.6	1061	55.7	1829	6757	5.32	0.59	2.33	0.11	-	6.17	3.98	0.94
	2 s.d.	2.20	394.5	2571	7688	10628	3.6	795	34.1	2296	460	1.05	0.53	1.02	0.14	-	12.80	4.03	1.17
LEW 85305	average	3.35	235.8	59341	2679	33691	45.6	2465	59.2	1509	6729	7.92	0.54	2.89	0.04	0.50	41.77	0.04	0.13
	2 s.d.	0.47	118.3	1503	1114	12804	12.3	868	23.7	470	447	1.44	0.94	0.81	0.06	0.53	33.70	0.05	0.13
LEW 87002	average	4.39	29.2	123240	2848	6218	15.1	1026	60.8	2787	3748	14.05	7.77	2.00	0.00	0.86	7.40	0.04	0.03
	2 s.d.	1.08	15.7	2115	444	1894	1.8	286	18.4	2632	204	0.86	1.06	0.36	0.07	3.62	0.89	0.01	0.02
PCA 91193	average	4.02	90.0	94570	2078	17207	36.3	1647	66.0	1284	5727	7.43	-	2.95	0.07	0.38	9.87	0.14	0.15
	2 s.d.	0.86	33.2	3268	1066	7879	8.9	538	17.4	384	309	3.79	-	1.97	0.09	4.81	10.16	0.06	0.15
QUE 97014	average	5.83	75.6	64144	1026	26892	46.2	1172	53.3	1310	7268	1.02	0.14	2.68	0.05	1.12	3.39	0.15	0.13
	2 s.d.	2.62	48.4	1180	352	14552	6.6	1128	28.3	2109	658	0.53	0.37	1.11	0.05	5.44	2.41	0.14	0.13
QUE 98005	average	2.62	27.4	66176	1370	5043	36.7	880	109.7	3769	7558	7.94	2.34	3.71	0.03	-	5.25	0.41	0.27
	2 s.d.	0.35	14.7	5048	221	391	2.8	271	29.9	2466	339	0.62	0.27	0.39	0.07	-	1.73	0.30	0.34
RKPA 80204	average	4.43	65.3	65100	1217	13828	35.9	921	61.0	2076	7095	7.05	0.58	2.41	0.01	-	1.04	0.24	0.49
	2 s.d.	1.74	67.9	2574	1276	6169	2.6	875	49.7	3188	416	1.30	0.29	1.05	0.08	-	0.61	0.52	1.54
SCO 06041	average	3.35	62.5	100867	2874	16272	29.9	1390	107.6	3718	5656	11.17	4.22	4.82	0.04	1.02	6.55	0.40	0.09
	2 s.d.	1.06	45.0	2712	612	4420	6.5	782	40.1	3943	463	1.98	0.93	2.88	0.07	3.21	6.53	0.48	0.05
GRO 95533	average	4.71	37.4	63838	778	15580	34.9	1289	48.3	1009	7547	3.13	-	3.00	0.03	0.62	2.46	0.09	0.07
	2 s.d.	1.76	19.1	1993	221	6897	5.5	1397	39.5	1864	370	1.06	-	1.63	0.09	3.76	1.93	0.11	0.06
Camel Donga	average	6.09	94.6	73360	1163	21900	40.2	1125	61.6	982	9315	0.25	0.49	1.66	0.02	0.88	3.92	0.23	0.06
	2 s.d.	2.43	32.8	4731	351	3984	1.9	347	11.0	285	437	0.48	0.19	0.65	0.09	2.38	2.22	0.20	0.04

Figure 4.4: Plots of trace element variations in low-Ca pyroxene in the eucrite samples.

Figure 4.4: Trace element concentrations in low-Ca pyroxene from eucrite samples (continued). All concentrations are in ppm.

Table 4.8: Correlation matrix for trace elements in low-Ca pyroxene. The numbers represent r^2 values, and are coloured according to what range of r^2 values they fall into; r^2 values between 0.8–1.0 are red, 0.60–0.79 are blue, 0.40–0.59 are orange, and values <0.40 are green. The highest r^2 values denote the best correlations.

	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb	Sr	Zr	Ba	La	Ce	Pr	Nd	Sm
Li	0.00	0.00	0.01	0.01	0.26	0.03	0.15	0.00	0.02	0.00	0.00	0.20	0.06	0.21	0.02	0.01	0.01	0.03	0.01	0.03	0.00	0.00
Na	0.00	0.00	0.12	0.70	0.27	0.01	0.15	0.00	0.00	0.00	0.00	0.00	0.01	0.24	0.68	0.20	0.65	0.47	0.04	0.63	0.69	0.60
Mg	0.01	0.12	0.00	0.01	0.19	0.54	0.00	0.13	0.18	0.56	0.19	0.21	0.00	0.08	0.01	0.00	0.04	0.12	0.18	0.19	0.18	0.17
Al	0.01	0.70	0.01	0.01	0.12	0.12	0.05	0.02	0.08	0.14	0.06	0.05	0.01	0.12	0.77	0.06	0.75	0.42	0.02	0.42	0.39	0.21
Ca	0.26	0.27	0.19	0.01	0.39	0.39	0.55	0.00	0.03	0.05	0.00	0.02	0.13	0.02	0.06	0.39	0.00	0.00	0.01	0.07	0.22	0.51
Sc	0.03	0.01	0.54	0.12	0.39	0.06	0.06	0.04	0.22	0.48	0.19	0.15	0.02	0.04	0.03	0.04	0.04	0.00	0.00	0.02	0.04	0.14
Ti	0.15	0.15	0.00	0.05	0.55	0.06	0.12	0.05	0.80	0.05	0.25	0.34	0.45	0.02	0.01	0.69	0.01	0.03	0.06	0.00	0.10	0.34
V	0.00	0.00	0.13	0.02	0.00	0.04	0.12	0.05	0.80	0.05	0.25	0.34	0.45	0.02	0.00	0.04	0.00	0.00	0.14	0.00	0.00	0.00
Cr	0.02	0.00	0.18	0.08	0.03	0.22	0.05	0.34	0.38	0.19	0.34	0.38	0.28	0.02	0.00	0.03	0.02	0.01	0.07	0.01	0.02	0.00
Mn	0.00	0.00	0.56	0.14	0.05	0.48	0.05	0.05	0.19	0.41	0.41	0.30	0.02	0.05	0.01	0.05	0.00	0.01	0.04	0.01	0.00	0.00
Co	0.00	0.00	0.19	0.06	0.00	0.19	0.12	0.25	0.34	0.41	0.58	0.58	0.30	0.01	0.00	0.09	0.01	0.02	0.01	0.01	0.00	0.00
Ni	0.20	0.00	0.21	0.05	0.02	0.15	0.23	0.34	0.38	0.30	0.58	0.37	0.37	0.10	0.02	0.06	0.01	0.03	0.09	0.03	0.00	0.00
Zn	0.06	0.01	0.00	0.01	0.13	0.02	0.32	0.45	0.28	0.05	0.30	0.10	0.00	0.00	0.00	0.07	0.01	0.01	0.01	0.00	0.01	0.03
Rb	0.21	0.24	0.08	0.12	0.02	0.04	0.01	0.02	0.02	0.02	0.02	0.10	0.00	0.17	0.17	0.00	0.18	0.53	0.12	0.24	0.16	0.13
Sr	0.02	0.68	0.01	0.77	0.06	0.03	0.01	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.82	0.53	0.01	0.47	0.39	0.19
Zr	0.01	0.20	0.00	0.06	0.39	0.04	0.69	0.04	0.03	0.05	0.09	0.06	0.07	0.00	0.00	0.00	0.00	0.53	0.01	0.04	0.20	0.54
Ba	0.01	0.65	0.04	0.75	0.00	0.04	0.01	0.00	0.02	0.01	0.01	0.01	0.01	0.18	0.82	0.00	0.00	0.72	0.04	0.62	0.45	0.16
La	0.03	0.47	0.12	0.42	0.00	0.00	0.03	0.00	0.01	0.01	0.02	0.03	0.01	0.21	0.53	0.01	0.72	0.09	0.09	0.90	0.69	0.27
Ce	0.01	0.04	0.18	0.02	0.01	0.00	0.06	0.14	0.07	0.04	0.01	0.09	0.01	0.12	0.01	0.05	0.04	0.09	0.06	0.06	0.03	0.00
Pr	0.03	0.63	0.19	0.42	0.07	0.02	0.00	0.00	0.01	0.01	0.01	0.03	0.00	0.24	0.47	0.04	0.62	0.90	0.06	0.91	0.91	0.57
Nd	0.00	0.69	0.18	0.39	0.22	0.04	0.10	0.00	0.02	0.00	0.00	0.00	0.01	0.16	0.39	0.20	0.45	0.69	0.03	0.57	0.80	0.80
Sm	0.00	0.60	0.17	0.21	0.51	0.14	0.34	0.00	0.00	0.00	0.00	0.00	0.03	0.13	0.19	0.54	0.16	0.27	0.00	0.37	0.34	0.22
Eu	0.00	0.57	0.01	0.76	0.04	0.08	0.06	0.00	0.04	0.18	0.05	0.04	0.03	0.22	0.73	0.03	0.61	0.36	0.00	0.29	0.55	0.90
Gd	0.02	0.45	0.16	0.10	0.66	0.18	0.49	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.07	0.73	0.04	0.07	0.00	0.25	0.47	0.85
Tb	0.01	0.37	0.22	0.04	0.66	0.25	0.39	0.02	0.02	0.04	0.01	0.01	0.01	0.05	0.05	0.64	0.02	0.05	0.00	0.18	0.36	0.73
Dy	0.01	0.27	0.25	0.01	0.62	0.28	0.30	0.06	0.06	0.08	0.03	0.05	0.00	0.04	0.01	0.55	0.00	0.02	0.00	0.18	0.36	0.69
Ho	0.01	0.32	0.33	0.01	0.63	0.31	0.27	0.09	0.10	0.11	0.04	0.06	0.00	0.06	0.03	0.50	0.01	0.03	0.00	0.18	0.34	0.56
Er	0.03	0.20	0.39	0.00	0.64	0.38	0.20	0.13	0.14	0.16	0.08	0.08	0.00	0.06	0.01	0.36	0.00	0.01	0.00	0.11	0.23	0.56
Tm	0.01	0.18	0.45	0.00	0.46	0.37	0.06	0.26	0.24	0.23	0.18	0.23	0.04	0.08	0.00	0.21	0.00	0.02	0.04	0.12	0.20	0.43
Yb	0.00	0.15	0.65	0.01	0.38	0.46	0.02	0.24	0.24	0.38	0.17	0.24	0.02	0.12	0.00	0.11	0.01	0.04	0.04	0.15	0.21	0.38
Lu	0.01	0.07	0.62	0.04	0.38	0.51	0.00	0.32	0.31	0.34	0.20	0.25	0.02	0.08	0.00	0.05	0.00	0.02	0.04	0.08	0.12	0.25
Hf	0.08	0.20	0.02	0.04	0.59	0.11	0.83	0.06	0.02	0.02	0.11	0.15	0.19	0.00	0.00	0.91	0.01	0.02	0.06	0.02	0.17	0.51
W	0.00	0.03	0.10	0.00	0.04	0.05	0.02	0.10	0.07	0.13	0.39	0.20	0.19	0.00	0.00	0.08	0.00	0.00	0.01	0.02	0.03	0.08
Ce/Ce*	0.00	0.00	0.06	0.00	0.01	0.00	0.02	0.11	0.10	0.02	0.01	0.04	0.00	0.02	0.01	0.03	0.01	0.03	0.70	0.04	0.06	0.07
Eu/Eu*	0.05	0.00	0.50	0.15	0.23	0.44	0.02	0.00	0.02	0.47	0.08	0.07	0.02	0.00	0.08	0.04	0.03	0.00	0.03	0.03	0.08	0.13

Table 4.8: Correlation matrix for trace elements in low-Ca pyroxene (continued).

	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Ce/Ce*	Eu/Eu*
Li	0.00	0.02	0.01	0.01	0.01	0.03	0.01	0.00	0.01	0.08	0.00	0.00	0.05
Na	0.57	0.45	0.37	0.27	0.32	0.20	0.18	0.15	0.07	0.20	0.03	0.00	0.00
Mg	0.01	0.16	0.22	0.25	0.33	0.39	0.45	0.65	0.62	0.02	0.10	0.06	0.50
Al	0.76	0.10	0.04	0.01	0.01	0.00	0.00	0.01	0.04	0.04	0.00	0.00	0.15
Ca	0.04	0.66	0.66	0.62	0.63	0.64	0.46	0.38	0.38	0.59	0.04	0.01	0.23
Sc	0.08	0.18	0.25	0.28	0.31	0.38	0.37	0.46	0.51	0.11	0.05	0.00	0.44
Ti	0.06	0.49	0.39	0.30	0.27	0.20	0.06	0.02	0.00	0.83	0.02	0.02	0.02
V	0.00	0.00	0.02	0.06	0.09	0.13	0.26	0.24	0.32	0.06	0.10	0.11	0.00
Cr	0.04	0.00	0.02	0.06	0.10	0.14	0.24	0.24	0.31	0.02	0.07	0.10	0.02
Mn	0.18	0.00	0.04	0.08	0.11	0.16	0.23	0.38	0.34	0.02	0.13	0.02	0.47
Co	0.05	0.00	0.01	0.03	0.04	0.08	0.18	0.17	0.20	0.11	0.39	0.01	0.08
Ni	0.04	0.00	0.01	0.05	0.06	0.08	0.23	0.24	0.25	0.15	0.20	0.04	0.07
Zn	0.03	0.03	0.01	0.00	0.00	0.00	0.04	0.02	0.02	0.19	0.19	0.00	0.02
Rb	0.22	0.04	0.05	0.04	0.06	0.06	0.08	0.12	0.08	0.00	0.00	0.02	0.00
Sr	0.73	0.07	0.05	0.01	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.08
Zr	0.03	0.73	0.64	0.55	0.50	0.36	0.21	0.11	0.05	0.91	0.08	0.03	0.04
Ba	0.61	0.04	0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.03
La	0.36	0.07	0.05	0.02	0.03	0.01	0.02	0.04	0.02	0.02	0.00	0.03	0.00
Ce	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.06	0.01	0.70	0.03
Pr	0.37	0.29	0.25	0.18	0.18	0.11	0.12	0.15	0.08	0.02	0.02	0.04	0.03
Nd	0.34	0.55	0.47	0.36	0.34	0.23	0.20	0.21	0.12	0.17	0.03	0.06	0.08
Sm	0.22	0.90	0.85	0.73	0.69	0.56	0.43	0.38	0.25	0.51	0.08	0.07	0.13
Eu	0.09	0.09	0.04	0.01	0.01	0.00	0.00	0.01	0.02	0.03	0.02	0.04	0.22
Gd	0.09	0.97	0.97	0.89	0.85	0.73	0.57	0.45	0.33	0.71	0.13	0.03	0.19
Tb	0.04	0.97	0.96	0.96	0.93	0.85	0.71	0.59	0.46	0.62	0.21	0.02	0.26
Dy	0.01	0.89	0.96	0.98	0.98	0.92	0.82	0.70	0.57	0.52	0.23	0.01	0.35
Ho	0.01	0.85	0.93	0.98	0.96	0.96	0.87	0.77	0.63	0.49	0.23	0.00	0.34
Er	0.00	0.73	0.85	0.92	0.96	0.93	0.83	0.85	0.77	0.39	0.21	0.00	0.41
Tm	0.00	0.57	0.71	0.82	0.87	0.93	0.91	0.91	0.86	0.19	0.27	0.01	0.42
Yb	0.01	0.45	0.59	0.70	0.77	0.85	0.91	0.94	0.94	0.12	0.18	0.00	0.51
Lu	0.02	0.33	0.46	0.57	0.63	0.77	0.86	0.94	0.07	0.07	0.12	0.01	0.47
Hf	0.03	0.71	0.62	0.52	0.49	0.39	0.19	0.12	0.07	0.02	0.02	0.02	0.07
W	0.02	0.13	0.21	0.23	0.23	0.21	0.27	0.18	0.12	0.02	0.01	0.01	0.05
Ce/Ce*	0.04	0.03	0.02	0.01	0.00	0.00	0.01	0.00	0.01	0.02	0.01	0.01	0.01
Eu/Eu*	0.22	0.19	0.26	0.35	0.34	0.41	0.42	0.51	0.47	0.07	0.05	0.01	

Table 4.9: Trace element concentrations in high-Ca pyroxene from eucrite samples. All concentrations are in ppm.

sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb	Sr	Zr	Ba	La
EET 87548	average	3.52	160.5	92833	2894	51267	48.0	1071	85.7	1131	5350	8.43	1.38	1.33	1.80	5.41	0.05	0.18
	2 s.d.	0.27	118.0	3972	1844	23266	6.5	159	10.2	275	572	10.92	1.17	0.76	3.34	1.71	0.06	0.17
EET 92003	average	11.77	309.6	66903	5203	48301	54.7	3122	115.7	3344	6453	8.34	4.18	4.08	2.07	5.59	0.08	0.12
	2 s.d.	6.19	113.1	13146	413	9435	7.3	1819	24.8	1202	536	7.23	4.41	2.77	2.42	4.13	0.19	0.11
GRA 98006	average	1.50	336.8	68100	2458	66150	65.6	2070	134.3	3250	6025	9.22	0.56	2.70	3.73	17.05	0.27	0.32
	2 s.d.	0.97	151.2	13857	381	28902	23.3	1574	91.7	3554	1552	1.24	0.45	1.61	1.75	17.04	0.35	0.21
GRA 98033	average	9.50	326.1	59888	1922	80375	78.8	1154	101.1	1300	5493	6.20	0.62	1.64	3.01	15.66	0.12	0.25
	2 s.d.	4.08	267.2	4385	1158	58705	39.4	808	59.3	1352	2223	1.94	0.60	1.27	2.88	12.60	0.28	0.22
GRA 98043	average	13.30	526.2	52188	3622	122375	117.1	2171	122.1	1602	4188	2.40	-	2.80	5.98	24.76	0.10	0.56
	2 s.d.	5.88	289.9	2669	2403	31766	36.3	767	47.2	816	1728	1.57	-	1.16	4.29	15.67	0.07	0.55
GRA 98055	average	14.89	572.7	53448	4120	125300	117.6	2712	144.5	1906	3609	5.63	0.31	1.33	5.15	33.19	0.04	0.72
	2 s.d.	2.65	39.9	3513	1083	3973	14.0	476	24.8	401	132	0.41	0.66	0.46	2.39	12.65	0.03	0.25
GRA 98114	average	7.53	226.6	58933	2801	51763	56.5	1822	97.6	2280	5947	7.69	-	3.39	5.70	12.74	0.09	0.20
	2 s.d.	2.60	206.9	3443	980	25220	17.0	1632	102.1	4768	1240	1.29	-	1.72	12.82	8.96	0.05	0.01
LAR 06875	average	3.52	746.7	35733	12633	29533	25.5	1370	35.2	655	3743	3.01	0.76	1.32	15.90	10.33	6.90	1.96
	2 s.d.	0.35	622.3	8768	15981	32810	26.9	638	26.7	645	14	1.60	0.93	1.05	22.49	4.23	1.84	0.96
LEW 85305	average	4.31	797.0	52850	4430	106250	91.1	3537	130.7	2538	4473	6.50	0.92	1.90	5.40	102.95	0.14	1.36
	2 s.d.	0.83	59.4	990	677	3253	1.8	112	9.8	249	7	0.33	0.42	0.00	3.68	55.30	0.19	0.53
LEW 87002	average	3.34	21.2	122340	3038	11124	19.9	1651	61.3	1985	3924	14.74	-	1.77	-	10.72	0.08	0.04
	2 s.d.	0.54	16.6	2492	663	3862	5.0	312	14.1	634	85	6.01	-	0.24	-	6.36	0.09	0.06
PCA 91193	average	8.00	677.3	75760	6900	110367	75.7	2976	159.7	2470	3803	7.26	0.22	1.71	7.53	64.20	0.79	0.64
	2 s.d.	2.43	404.3	8086	8528	31431	23.7	1606	87.6	1086	733	1.66	0.36	0.45	10.63	36.41	1.90	0.25
QUE 97014	average	11.54	341.5	59480	2181	87825	79.4	1162	91.7	1396	5197	1.29	0.05	2.01	2.48	11.80	0.25	0.24
	2 s.d.	3.02	227.8	2726	2167	17693	9.1	454	24.7	916	751	0.67	0.57	0.63	4.11	3.73	0.50	0.14
QUE 98005	average	2.82	87.3	61550	4375	16465	33.7	1263	129.3	6095	7360	7.74	2.22	4.07	2.55	5.57	1.08	0.40
	2 s.d.	1.63	51.5	3818	4709	410	7.3	222	3.0	1937	424	0.37	0.58	0.96	11.74	2.64	1.21	0.19
RKPA 80204	average	6.82	260.9	62300	3780	45605	48.6	1038	81.2	2355	6185	6.36	0.55	2.08	4.95	2.85	0.60	0.18
	2 s.d.	1.64	39.2	4808	1612	12997	3.0	188	20.8	523	240	0.98	0.45	0.33	4.10	0.30	0.42	0.22
SCO 06041	average	3.60	66.7	101475	2893	23593	33.7	1749	106.9	2973	5384	11.35	3.85	3.74	0.06	15.68	0.22	0.10
	2 s.d.	0.34	48.2	5832	999	5837	6.6	834	28.5	1321	500	1.87	0.98	2.31	-	22.73	0.41	0.04
GRO 95533	average	5.33	67.2	63770	856	25943	39.7	926	42.4	551	7403	2.88	0.09	1.93	0.30	2.82	0.04	0.07
	2 s.d.	0.85	17.4	635	90	1167	2.0	58	12.3	234	50	1.00	0.56	1.20	-	4.51	1.19	0.04
Camel Donga	average	8.07	280.6	70660	3783	62833	56.2	1649	104.3	2546	7533	0.33	0.89	1.50	3.13	12.17	1.32	0.20
	2 s.d.	4.28	165.3	2604	5639	25843	9.3	902	27.5	2339	1295	0.23	0.28	1.03	5.95	10.58	2.32	0.13

sample	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	
EET 87548	average	0.54	0.13	0.77	0.32	0.05	0.63	0.13	0.88	0.19	0.71	0.11	0.54	0.11	0.25	0.05
	2 s.d.	0.28	0.09	0.35	0.07	0.02	0.16	0.04	0.31	0.11	0.09	0.02	0.28	0.02	0.18	0.07
EET 92003	average	0.52	0.13	0.94	0.56	0.04	1.08	0.26	1.95	0.51	1.59	0.26	1.74	0.27	0.25	0.06
	2 s.d.	0.48	0.10	0.60	0.33	0.03	0.66	0.13	1.14	0.27	0.94	0.17	0.74	0.14	0.19	0.03
GRA 98006	average	1.34	0.31	1.89	1.03	0.06	2.15	0.47	3.73	0.84	2.37	0.35	2.57	0.44	0.77	0.09
	2 s.d.	0.59	0.30	1.74	0.79	0.05	1.48	0.34	1.34	0.45	0.75	0.17	1.37	0.17	0.53	0.08
GRA 98033	average	2.57	0.31	2.15	1.32	0.05	2.44	0.54	4.39	0.98	2.99	0.44	3.05	0.49	1.20	0.05
	2 s.d.	2.77	0.30	2.06	1.23	0.04	1.93	0.42	3.37	0.55	1.49	0.18	1.07	0.12	0.97	0.05
GRA 98043	average	2.97	0.52	3.48	1.96	0.09	2.79	0.64	4.93	1.11	3.08	0.47	3.22	0.53	1.83	0.07
	2 s.d.	3.08	0.40	2.16	1.22	0.05	1.43	0.40	1.89	0.48	1.05	0.21	1.26	0.18	0.77	0.03
GRA 98055	average	3.96	0.79	5.91	3.04	0.06	4.48	0.95	7.24	1.53	4.48	0.64	4.34	0.67	2.43	0.03
	2 s.d.	2.11	0.36	2.51	1.49	0.06	1.27	0.35	3.12	0.71	2.02	0.27	2.01	0.24	0.63	0.04
GRA 98114	average	6.58	0.21	1.39	0.72	0.03	1.57	0.35	2.67	0.65	2.11	0.34	2.28	0.37	0.83	0.05
	2 s.d.	6.23	0.11	0.87	0.45	0.02	1.29	0.19	0.97	0.29	1.06	0.12	0.90	0.16	0.57	0.06
LAR 06875	average	5.33	0.80	4.10	1.25	0.15	1.69	0.32	2.20	0.55	1.58	0.25	1.73	0.24	0.39	0.08
	2 s.d.	1.70	0.21	0.93	0.00	0.09	0.52	0.17	1.36	0.19	0.66	0.08	0.85	0.06	0.16	0.06
LEW 85305	average	5.97	1.38	8.58	3.92	0.11	5.46	1.13	7.05	1.46	4.73	0.57	4.04	0.60	3.63	-
	2 s.d.	2.23	0.52	3.61	1.54	0.03	0.95	0.03	0.27	0.20	0.78	0.26	0.06	0.02	1.48	-
LEW 87002	average	0.07	0.03	0.17	0.15	0.03	0.35	0.09	0.78	0.20	0.70	0.12	0.82	0.15	0.41	0.07
	2 s.d.	0.16	0.03	0.18	0.08	0.03	0.11	0.03	0.31	0.08	0.17	0.02	0.18	0.04	0.25	0.04
PCA 91193	average	3.21	0.81	6.20	3.24	0.09	5.03	0.89	6.06	1.22	3.29	0.41	2.39	0.34	1.90	0.06
	2 s.d.	1.22	0.20	2.38	0.59	0.08	1.09	0.20	0.99	0.17	0.92	0.12	0.65	0.03	0.62	0.01
QUE 97014	average	0.86	0.26	1.85	1.15	0.06	2.28	0.49	3.73	0.88	2.88	0.47	2.72	0.50	0.98	0.02
	2 s.d.	0.24	0.11	0.44	0.37	0.01	0.72	0.07	0.79	0.19	0.46	0.02	0.68	0.10	0.37	0.05
QUE 99005	average	0.47	0.17	0.89	0.27	0.03	0.58	0.16	1.30	0.28	1.03	0.18	1.56	0.22	0.30	0.06
	2 s.d.	0.26	0.05	0.35	0.29	0.00	0.35	0.06	0.65	0.10	0.40	0.08	0.11	0.02	0.27	0.17

Figure 4.5: Plots of trace element variations in high-Ca pyroxene from eucrite samples.

Figure 4.5: Plots of trace element variations in high-Ca pyroxene from eucrite samples (continued).

Table 4.10: Correlation matrix for trace elements in high-Ca pyroxene. The numbers represent r^2 values, and are coloured according to what range of r^2 values they fall into; r^2 values between 0.8–1.0 are red, 0.60–0.79 are blue, 0.40–0.59 are orange, and values <0.40 are green. The highest r^2 values denote the best correlations.

	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb	Sr	Zr	Ba	La	Ce	Pr	Nd	Sm
Li																						
Na	0.09				0.44	0.53	0.08	0.10	0.05	0.04	0.21	0.07	0.00	0.04	0.00	0.00	0.07	0.01	0.02	0.02	0.06	0.13
Mg	0.13	0.39			0.49	0.33	0.37	0.11	0.05	0.37	0.15	0.16	0.14	0.08	0.60	0.50	0.17	0.69	0.52	0.86	0.83	0.75
Al	0.01	0.39	0.14		0.18	0.20	0.01	0.01	0.01	0.00	0.52	0.54	0.00	0.09	0.44	0.03	0.17	0.35	0.36	0.26	0.21	0.17
Ca	0.44	0.49	0.18	0.00		0.03	0.05	0.01	0.00	0.19	0.02	0.01	0.03	0.10	0.74	0.03	0.77	0.65	0.19	0.24	0.17	0.07
Sc	0.53	0.33	0.20	0.03	0.93		0.31	0.41	0.04	0.22	0.16	0.19	0.10	0.03	0.06	0.39	0.06	0.07	0.20	0.43	0.55	0.71
Ti	0.08	0.37	0.01	0.05	0.31	0.25		0.45	0.05	0.16	0.02	0.00	0.02	0.01	0.03	0.26	0.13	0.02	0.15	0.30	0.40	0.55
V	0.10	0.11	0.01	0.01	0.41	0.40	0.45		0.31	0.02	0.01	0.08	0.07	0.11	0.00	0.29	0.19	0.00	0.02	0.14	0.23	0.35
Cr	0.05	0.05	0.01	0.00	0.04	0.02	0.05	0.31		0.15	0.12	0.00	0.49	0.08	0.06	0.00	0.03	0.03	0.05	0.01	0.01	0.01
Mn	0.04	0.37	0.00	0.19	0.22	0.13	0.16	0.02	0.15		0.03	0.06	0.17	0.00	0.22	0.23	0.05	0.29	0.21	0.35	0.37	0.34
Co	0.21	0.15	0.52	0.02	0.16	0.15	0.02	0.01	0.12	0.03		0.43	0.00	0.04	0.14	0.00	0.09	0.08	0.04	0.06	0.05	0.06
Ni	0.07	0.16	0.54	0.01	0.19	0.19	0.00	0.08	0.00	0.06	0.43		0.00	0.15	0.13	0.02	0.01	0.06	0.12	0.09	0.09	0.10
Zn	0.00	0.14	0.00	0.03	0.10	0.03	0.02	0.07	0.49	0.17	0.10	0.00		0.00	0.09	0.05	0.06	0.11	0.04	0.13	0.13	0.13
Rb	0.04	0.08	0.09	0.10	0.03	0.01	0.01	0.11	0.08	0.00	0.04	0.15	0.00		0.21	0.00	0.14	0.08	0.01	0.02	0.02	0.01
Sr	0.00	0.60	0.44	0.74	0.06	0.02	0.03	0.00	0.06	0.22	0.14	0.13	0.09	0.21		0.06	0.65	0.74	0.52	0.38	0.30	0.18
Zr	0.00	0.50	0.03	0.03	0.39	0.26	0.57	0.29	0.00	0.23	0.00	0.02	0.05	0.00	0.06		0.01	0.25	0.30	0.76	0.80	0.81
Ba	0.07	0.17	0.17	0.77	0.06	0.13	0.03	0.19	0.03	0.05	0.09	0.01	0.06	0.14	0.65	0.01		0.56	0.10	0.08	0.03	0.00
La	0.01	0.69	0.35	0.65	0.07	0.02	0.10	0.00	0.03	0.29	0.08	0.06	0.11	0.08	0.74	0.25	0.56	0.46	0.53	0.53	0.48	0.39
Ce	0.02	0.52	0.36	0.19	0.20	0.15	0.16	0.02	0.05	0.21	0.04	0.12	0.04	0.01	0.52	0.30	0.10	0.46	0.46	0.68	0.54	0.34
Pr	0.02	0.86	0.26	0.24	0.43	0.30	0.43	0.14	0.01	0.35	0.06	0.09	0.13	0.02	0.38	0.76	0.08	0.68	0.53	0.53	0.48	0.39
Nd	0.06	0.83	0.21	0.17	0.55	0.40	0.50	0.23	0.01	0.37	0.05	0.09	0.13	0.02	0.30	0.80	0.03	0.54	0.48	0.97	0.95	0.95
Sm	0.13	0.75	0.17	0.07	0.71	0.55	0.54	0.35	0.01	0.34	0.06	0.10	0.13	0.01	0.18	0.81	0.00	0.34	0.39	0.87	0.95	0.95
Eu	0.00	0.75	0.26	0.57	0.16	0.08	0.11	0.00	0.07	0.47	0.06	0.06	0.10	0.13	0.09	0.24	0.40	0.83	0.34	0.60	0.50	0.36
Gd	0.14	0.70	0.17	0.04	0.75	0.59	0.51	0.39	0.01	0.31	0.06	0.12	0.11	0.02	0.15	0.77	0.00	0.27	0.37	0.79	0.90	0.98
Tb	0.18	0.67	0.20	0.02	0.79	0.67	0.50	0.40	0.01	0.25	0.08	0.13	0.11	0.02	0.12	0.74	0.01	0.24	0.36	0.77	0.87	0.96
Dy	0.26	0.61	0.21	0.01	0.85	0.76	0.44	0.42	0.01	0.24	0.10	0.14	0.10	0.02	0.10	0.61	0.02	0.18	0.32	0.67	0.78	0.90
Ho	0.30	0.63	0.26	0.01	0.86	0.79	0.42	0.38	0.02	0.23	0.13	0.15	0.10	0.02	0.12	0.55	0.01	0.19	0.35	0.64	0.75	0.87
Er	0.28	0.57	0.27	0.00	0.81	0.76	0.40	0.34	0.02	0.18	0.14	0.16	0.09	0.00	0.08	0.58	0.02	0.17	0.35	0.64	0.73	0.85
Tm	0.41	0.49	0.35	0.00	0.80	0.80	0.28	0.27	0.03	0.13	0.22	0.19	0.08	0.01	0.08	0.38	0.02	0.13	0.30	0.49	0.58	0.70
Yb	0.38	0.46	0.38	0.00	0.71	0.77	0.29	0.29	0.01	0.09	0.19	0.18	0.04	0.01	0.08	0.37	0.02	0.14	0.32	0.50	0.56	0.66
Lu	0.33	0.34	0.36	0.02	0.70	0.79	0.18	0.21	0.02	0.06	0.23	0.19	0.05	0.01	0.04	0.26	0.05	0.06	0.24	0.35	0.41	0.52
Hf	0.11	0.53	0.10	0.00	0.67	0.60	0.51	0.35	0.00	0.29	0.02	0.05	0.07	0.00	0.05	0.83	0.04	0.22	0.36	0.75	0.83	0.90
W	0.08	0.01	0.05	0.07	0.07	0.07	0.00	0.00	0.02	0.03	0.14	0.09	0.08	0.16	0.03	0.09	0.07	0.00	0.02	0.05	0.06	0.08
Ce/Ce*	0.01	0.01	0.04	0.02	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.05	0.04	0.00	0.02	0.01	0.01	0.02	0.31	0.02	0.01	0.01
Eu/Eu*	0.29	0.15	0.22	0.06	0.47	0.49	0.19	0.28	0.00	0.01	0.24	0.32	0.00	0.01	0.00	0.19	0.10	0.00	0.13	0.15	0.22	0.34

Table 4.10: Correlation matrix for trace elements in high-Ca pyroxene (continued).

	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	Ce/Ce*	Eu/Eu*
Li	0.00	0.14	0.18	0.26	0.30	0.28	0.41	0.33	0.38	0.11	0.08	0.01	0.29
Na	0.75	0.70	0.67	0.61	0.63	0.57	0.49	0.46	0.34	0.53	0.01	0.01	0.15
Mg	0.26	0.17	0.20	0.21	0.26	0.27	0.35	0.38	0.36	0.10	0.05	0.04	0.22
Al	0.57	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.07	0.02	0.06
Ca	0.16	0.75	0.79	0.85	0.86	0.81	0.80	0.71	0.70	0.67	0.07	0.00	0.47
Sc	0.08	0.59	0.67	0.76	0.79	0.76	0.80	0.77	0.79	0.60	0.07	0.00	0.49
Ti	0.11	0.51	0.50	0.44	0.42	0.40	0.28	0.29	0.18	0.51	0.00	0.01	0.19
V	0.00	0.39	0.40	0.42	0.38	0.34	0.27	0.29	0.21	0.35	0.00	0.00	0.28
Cr	0.07	0.01	0.01	0.01	0.02	0.02	0.03	0.01	0.02	0.00	0.02	0.01	0.00
Mn	0.47	0.31	0.25	0.24	0.23	0.18	0.13	0.09	0.06	0.29	0.03	0.01	0.01
Co	0.06	0.06	0.08	0.10	0.13	0.14	0.22	0.19	0.23	0.02	0.14	0.00	0.24
Ni	0.06	0.12	0.13	0.14	0.15	0.16	0.19	0.18	0.19	0.05	0.09	0.05	0.32
Zn	0.10	0.11	0.11	0.10	0.10	0.09	0.08	0.04	0.05	0.07	0.08	0.04	0.00
Rb	0.13	0.02	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.00	0.16	0.00	0.01
Sr	0.69	0.15	0.12	0.10	0.12	0.08	0.08	0.08	0.04	0.05	0.03	0.02	0.00
Zr	0.24	0.77	0.74	0.61	0.55	0.58	0.38	0.37	0.26	0.83	0.09	0.01	0.19
Ba	0.40	0.00	0.01	0.02	0.01	0.02	0.02	0.02	0.05	0.04	0.07	0.01	0.10
La	0.83	0.27	0.24	0.18	0.19	0.17	0.13	0.14	0.06	0.22	0.00	0.02	0.00
Ce	0.34	0.37	0.36	0.32	0.35	0.35	0.30	0.32	0.24	0.36	0.02	0.31	0.13
Pr	0.60	0.79	0.77	0.67	0.64	0.64	0.49	0.50	0.35	0.75	0.05	0.02	0.15
Nd	0.50	0.90	0.87	0.78	0.75	0.73	0.58	0.56	0.41	0.83	0.06	0.01	0.22
Sm	0.36	0.98	0.96	0.90	0.87	0.85	0.70	0.66	0.52	0.90	0.08	0.01	0.34
Eu	0.30	0.30	0.25	0.20	0.22	0.18	0.13	0.12	0.07	0.21	0.01	0.04	0.00
Gd	0.30	0.98	0.98	0.94	0.91	0.88	0.75	0.69	0.57	0.87	0.08	0.00	0.42
Tb	0.25	0.98	0.98	0.98	0.96	0.95	0.83	0.80	0.68	0.91	0.10	0.00	0.49
Dy	0.20	0.94	0.98	0.99	0.99	0.97	0.90	0.86	0.76	0.85	0.08	0.00	0.55
Ho	0.22	0.91	0.96	0.99	0.98	0.98	0.94	0.90	0.82	0.82	0.08	0.00	0.56
Er	0.18	0.88	0.95	0.97	0.98	0.98	0.96	0.93	0.85	0.85	0.15	0.00	0.59
Tm	0.13	0.75	0.83	0.90	0.94	0.96	0.96	0.96	0.94	0.70	0.15	0.00	0.64
Yb	0.12	0.69	0.80	0.86	0.90	0.93	0.96	0.95	0.95	0.71	0.13	0.01	0.61
Lu	0.07	0.57	0.68	0.76	0.82	0.85	0.94	0.95	0.59	0.59	0.18	0.01	0.61
Hf	0.21	0.87	0.91	0.85	0.82	0.85	0.70	0.71	0.59	0.12	0.00	0.01	0.34
W	0.01	0.08	0.10	0.08	0.08	0.15	0.15	0.13	0.18	0.12	0.00	0.01	0.12
Ce/Ce*	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.05	0.05
Eu/Eu*	0.00	0.42	0.49	0.55	0.56	0.59	0.64	0.61	0.61	0.34	0.12	0.05	0.05

Table 4.11: Trace element concentrations in pyroxene from eucrites with a single pyroxene phase. All concentrations are in ppm.

sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb	Sr	Zr	Ba
EET 83227	6.48	133.2	89965	5771	34290	46.1	2051	132.4	3942	5723	8.78	5.40	2.91	0.05	0.72	24.35	0.10
	2 s.d.	2.69	54.1	31581	21349	19.4	2750	57.9	2026	1391	4.25	1.42	2.68	0.09	1.21	51.92	0.18
EET 92023	6.70	398.6	81825	4742	37705	43.2	3001	107.3	3403	5358	33.36	-	8.73	0.09	0.63	16.09	0.08
	2 s.d.	1.40	124.0	4411	377	3.4	884	11.7	559	294	31.46	-	1.52	0.20	0.26	20.21	0.10
LAP 031062	4.02	182.8	106727	3986	22360	32.6	1984	120.7	3358	5104	9.22	-	1.59	-	-	9.30	0.02
	2 s.d.	4.09	81.9	8258	3541	4.3	631	20.5	1297	375	3.40	-	0.47	-	-	13.47	0.04
Millbillillie	4.65	89.9	74923	2896	29441	51.2	2404	104.6	3702	8146	9.04	0.76	2.47	0.01	2.91	6.25	0.76
	2 s.d.	0.90	149.5	9063	4628	11.403	10.0	42.3	2012	1135	1.01	0.54	0.61	0.11	3.48	5.12	1.46
Juvinas	3.04	38.8	83123	1924	18673	42.0	1206	137.6	5276	8692	5.33	0.28	2.50	0.01	-	4.49	0.04
	2 s.d.	0.84	15.0	3048	3348	7.0	414	35.1	2748	194	1.18	0.53	0.83	0.06	-	0.80	0.06
Dhofar 007	4.85	213.5	96567	3412	26147	34.8	2192	110.8	3878	5820	30.20	-	7.49	0.02	5.36	17.59	1.08
	2 s.d.	2.67	42.9	2135	5485	2.7	798	12.8	443	267	11.90	-	1.35	0.07	8.15	13.84	1.61
sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W	
EET 83227	0.27	1.39	0.28	2.01	1.05	0.04	1.65	0.32	2.52	0.52	1.72	0.24	1.54	0.23	0.76	0.07	
	2 s.d.	0.52	2.33	0.58	4.10	0.03	3.31	0.63	5.20	0.99	3.31	0.43	2.77	0.38	1.50	0.08	
EET 92023	0.12	0.51	0.14	1.11	0.69	0.03	1.33	0.27	2.07	0.50	1.63	0.24	1.59	0.27	0.44	0.08	
	2 s.d.	0.10	0.38	0.08	0.71	0.35	0.54	0.10	0.61	0.13	0.48	0.06	0.67	0.08	0.49	0.07	
LAP 031062	0.05	0.25	0.06	0.50	0.36	0.03	0.80	0.17	1.22	0.31	1.01	0.15	1.05	0.18	0.38	0.04	
	2 s.d.	0.05	0.30	0.09	0.60	0.37	0.76	0.16	1.05	0.26	0.56	0.08	0.46	0.10	0.55	0.05	
Millbillillie	0.26	0.72	0.15	0.86	0.47	0.03	0.87	0.20	1.84	0.44	1.76	0.30	2.30	0.43	0.41	0.01	
	2 s.d.	0.25	0.64	0.13	0.65	0.26	0.47	0.09	0.63	0.14	0.42	0.07	0.46	0.15	0.25	0.10	
Juvinas	0.03	0.11	0.03	0.23	0.20	0.01	0.44	0.13	1.13	0.31	1.25	0.22	1.73	0.30	0.16	0.03	
	2 s.d.	0.04	0.09	0.02	0.17	0.12	0.23	0.05	0.19	0.09	0.27	0.09	0.48	0.11	0.09	0.09	
Dhofar 007	0.06	0.32	0.09	0.67	0.43	0.01	0.91	0.18	1.39	0.35	1.09	0.17	1.13	0.19	0.46	0.00	
	2 s.d.	0.04	0.11	0.05	0.30	0.15	0.28	0.04	0.24	0.10	0.27	0.04	0.29	0.07	0.44	0.08

Figure 4.6: Plots of trace element variations in pyroxene from eucrites with a single pyroxene phase.

Figure 4.6: Plots of trace element variations in pyroxene from eucrites with a single pyroxene phase (continued).

Figure 4.7: Variation in trace elements in plagioclase and pyroxene from eucrites.

Chapter 5

²⁶Al–²⁶Mg isotope data

²⁶Al–²⁶Mg isotope data were collected for all of the eucrites in the samples suite, with the exception of Dhofar 007 (Table 5.1). This chapter briefly discusses this data in four sections: ²⁷Al/²⁴Mg ratios, ²⁶Mg isotope anomalies ($\delta^{26}\text{Mg}^*$), stable $\delta^{25}\text{Mg}$ isotope data, and model initial ²⁶Al/²⁷Al values and ages. Standard–sample bracketing was used to conduct the isotopic measurements presented in this chapter. Mg separated from the dunite standard DTS was used as the bracketing standard. Mg isotope ratios are expressed as the per mil (‰) deviations from the mean Mg isotopic composition measured on the bracketing standards:

$$\delta^x \text{Mg} = \left[\frac{\left(\frac{x \text{Mg}}{^{24}\text{Mg}} \right)_{\text{sample}}}{\left(\frac{x \text{Mg}}{^{24}\text{Mg}} \right)_{\text{standard}}} - 1 \right] \times 10^3 \quad (5.1)$$

where ^xMg is either ²⁵Mg or ²⁶Mg. To calculate the mass-independent ²⁶Mg anomalies ($\delta^{26}\text{Mg}^*$) after correction for instrumental mass bias, the measured ²⁶Mg/²⁴Mg ratios were normalized to a ²⁵Mg/²⁴Mg ratio of 0.12663 (Catanzaro et al., 1966) using the exponential fractionation law (where $\beta = 0.511$). $\delta^{25}\text{Mg}$ and $\delta^{26}\text{Mg}$ values were also recalculated relative to the Mg standard DSM-3 using the $\delta^{25}\text{Mg}$ and $\delta^{26}\text{Mg}$ values reported for DTS-2 by Bizzarro et al. (2011), in order to compare the stable isotope data to previously published data. A model initial ²⁶Al/²⁷Al (²⁶Al/²⁷Al₀) value was calculated for each sample from the slope of a line (isochron) on a plot of

$\delta^{26}\text{Mg}^*$ versus $^{27}\text{Al}/^{24}\text{Mg}$. The model isochrons are based on the assumption that the precursor material of each sample initially had a chondritic $^{27}\text{Al}/^{24}\text{Mg}$ ratio of 0.1. ^{26}Al – ^{26}Mg model ages were then calculated relative to CAIs, assuming a canonical $^{26}\text{Al}/^{27}\text{Al}$ value of $5.23 \pm 0.13 \times 10^{-5}$ in CAIs (Jacobsen et al., 2008) using the equation below:

$$\Delta T = - \frac{\left(\ln \left[\frac{(^{26}\text{Al}/^{27}\text{Al})}{(^{26}\text{Al}/^{27}\text{Al})_0} \right] \right)}{\lambda} \quad (5.2)$$

5.1 $^{27}\text{Al}/^{24}\text{Mg}$ ratios

The majority of the eucrites have $^{27}\text{Al}/^{24}\text{Mg}$ ratios in the range 1.00–2.25, with the exception of three samples (EET 87458, LAP 031062 and LEW 87002) that all have ratios <1 (Table 5.1). LEW 87002 is a Mg-rich sample that has a particularly low Al/Mg ratio of 0.19, although this ratio is still considerably higher than Al/Mg ratios measured in diogenites (0.008–0.091) by Schiller et al. (2011).

5.2 $\delta^{26}\text{Mg}^*$ anomalies

There is a relatively large range in $\delta^{26}\text{Mg}^*$ values across the sample suite, ranging from +0.0038 to +0.0402 (Fig. 5.1, Table 5.1) with the exception of LEW 87002 which has a $\delta^{26}\text{Mg}^*$ value of -0.0005, which is considerably lower than all the other samples and not resolvable with respect to the terrestrial standard. The $\delta^{26}\text{Mg}^*$ values of Juvinas, Camel Donga and Millbillillie from this study are within error of $\delta^{26}\text{Mg}^*$ values from the same samples determined by Bizzarro et al. (2005b) and Schiller et al. (2010). There is a general positive correlation between $^{27}\text{Al}/^{24}\text{Mg}$ ratios and $\delta^{26}\text{Mg}^*$ (Fig. 5.3 A).

Table 5.1: Al/Mg ratios, Mg isotope data, model $^{26}\text{Al}/^{27}\text{Al}_0$ and model ages relative to CAIs of the studied eucrites

Eucrite sample	Eucrite type	$\delta^{25}\text{Mg}$ vs. <i>DTS-2</i>	$\delta^{25}\text{Mg}$ vs. <i>DSM-3</i>	± 2 se	$\delta^{26}\text{Mg}$ vs. <i>DTS-2</i>	$\delta^{26}\text{Mg}$ vs. <i>DSM-3</i>	± 2 se	$\delta^{26}\text{Mg}^*$ vs. <i>DTS-2</i>	± 2 se
EET 83227	polymict	0.0168	-0.1052	0.0056	0.0497	-0.1803	0.0096	0.0201	0.0022
EET 87548	Mg-rich	0.0180	-0.1040	0.0250	0.0380	-0.1920	0.0470	0.0043	0.0010
EET 92003	brecciated	0.0810	-0.0410	0.0120	0.1780	-0.0520	0.0240	0.0191	0.0023
EET 92023	unbrecciated	0.0263	-0.0957	0.0049	0.0740	-0.1560	0.0110	0.0252	0.0025
GRA 98006	brecciated	0.0552	-0.0668	0.0099	0.1420	-0.0880	0.0180	0.0365	0.0033
GRA 98033	brecciated	0.0390	-0.0830	0.0130	0.1060	-0.1240	0.0250	0.0286	0.0025
GRA 98043	brecciated	0.0590	-0.0630	0.0140	0.1410	-0.0890	0.0270	0.0257	0.0024
GRA 98055	brecciated	0.0520	-0.0700	0.0250	0.1410	-0.0890	0.0490	0.0375	0.0024
GRA 98114	brecciated	0.0390	-0.0830	0.0180	0.1190	-0.1110	0.0360	0.0402	0.0025
LAP 031062	brecciated	0.0620	-0.0600	0.0120	0.1340	-0.0960	0.0240	0.0117	0.0013
LAR 06875	brecciated	0.0880	-0.0340	0.0170	0.2040	-0.0260	0.0320	0.0340	0.0014
LEW 85035	unbrecciated	0.0570	-0.0650	0.0170	0.1390	-0.0910	0.0330	0.0291	0.0012
LEW 87002	Mg-rich	0.0850	-0.0370	0.0140	0.1650	-0.0650	0.0300	-0.0005	0.0023
PCA 91193	brecciated	0.0560	-0.0660	0.0180	0.1210	-0.1090	0.0350	0.0082	0.0015
QUE 97014	unbrecciated	0.0670	-0.0550	0.0140	0.1560	-0.0740	0.0280	0.0270	0.0010
QUE 99005	brecciated	0.0600	-0.0620	0.0110	0.1490	-0.0810	0.0210	0.0297	0.0010
RKPA 80204	brecciated	0.0565	-0.0655	0.0089	0.1370	-0.0930	0.0170	0.0300	0.0024
SCO 06041	brecciated	0.1010	-0.0210	0.0110	0.2010	-0.0290	0.0200	0.0038	0.0018
GRO 95533	brecciated	0.0680	-0.0540	0.0130	0.1690	-0.0610	0.0250	0.0359	0.0014
Millbillillie	brecciated	0.0620	-0.0600	0.0280	0.1540	-0.0760	0.0650	0.0259	0.0027
Juvinas	brecciated	0.0158	-0.1062	0.0041	0.0559	-0.1741	0.0071	0.0227	0.0016
Camel Donga	brecciated	0.1550	0.0330	0.0210	0.3410	0.1110	0.0430	0.0354	0.0019

Eucrite sample	$^{27}\text{Al}/^{24}\text{Mg}$	Model $^{26}\text{Al}/^{27}\text{Al}_0$ ($\times 10^{-6}$)	± 2 se	ΔT after CAIs (Myr)	+ 2 se (Myr)	- 2 se (Myr)	n
EET 83227	1.20	2.54	0.28	3.18	0.11	0.12	10
EET 87548	0.66	1.08	0.25	4.08	0.22	0.28	10
EET 92003	1.48	1.93	0.23	3.47	0.12	0.14	10
EET 92023	1.13	3.42	0.34	2.87	0.10	0.11	10
GRA 98006	1.75	3.09	0.28	2.97	0.09	0.10	10
GRA 98033	2.14	1.95	0.17	3.46	0.09	0.10	10
GRA 98043	2.01	1.88	0.18	3.50	0.09	0.10	10
GRA 98055	1.72	3.23	0.21	2.93	0.07	0.07	10
GRA 98114	2.09	2.82	0.18	3.07	0.06	0.07	10
LAP 031062	0.25						10
LAR 06875	1.99	2.51	0.10	3.19	0.04	0.04	10
LEW 85035	1.23	3.60	0.15	2.82	0.04	0.04	10
LEW 87002	0.19						10
PCA 91193	1.26	0.98	0.18	4.18	0.18	0.21	10
QUE 97014	2.25	1.76	0.06	3.57	0.04	0.04	10
QUE 99005	1.86	2.36	0.08	3.26	0.03	0.04	10
RKPA 80204	2.01	2.19	0.18	3.34	0.08	0.09	10
SCO 06041	1.04	0.56	0.27	4.77	0.41	0.68	10
GRO 95533	1.94	2.72	0.11	3.11	0.04	0.04	10
Millbillillie	1.87	2.04	0.21	3.41	0.10	0.12	10
Juvinas	1.86	1.79	0.13	3.55	0.07	0.08	10
Camel Donga	1.96	2.66	0.14	3.13	0.06	0.06	10

Figure 5.1: Histogram of $\delta^{26}\text{Mg}^*$ values in eucrite samples and diogenite samples (Schiller et al., 2011), with superimposed probability curve.

5.3 Stable $\delta^{25}\text{Mg}$ isotope data

The eucrite samples have $\delta^{25}\text{Mg}_{\text{DSM-3}}$ values in the range -0.1062 to -0.0210 , with the exception of Camel Donga, which has a considerably higher value of 0.0330 (Table 5.1, Fig. 5.2 A). Terrestrial basalts have very similar $\delta^{25}\text{Mg}_{\text{DSM-3}}$ values to terrestrial mantle olivines, while most of the eucrites have slightly heavier $\delta^{25}\text{Mg}_{\text{DSM-3}}$ values (Fig. 5.2).

The $\delta^{25}\text{Mg}_{\text{DSM-3}}$ values measured in eucrites in this study are also heavier than $\delta^{25}\text{Mg}$ values measured in the diogenites studied by Schiller et al. (2011), which range from -0.0496 to -0.1621 . The $\delta^{25}\text{Mg}$ value for Camel Donga reported by Bizzarro et al. (2005b) is -0.087 , which is considerably less than the value measured in this study. The $\delta^{25}\text{Mg}$ value of Juvinas measured in this study is within error of the $\delta^{25}\text{Mg}$ value measured in the same sample by Bizzarro et al. (2005b) and Schiller et al. (2010). The $\delta^{25}\text{Mg}$ value of Millbillillie determined in this study is also within error of the $\delta^{25}\text{Mg}$ value for this sample measured by Schiller et al. (2010), however, the Millbillillie $\delta^{25}\text{Mg}$ value (-0.131 ± 0.025) determined by Bizzarro et al. (2005b) is not within error of this study.

5.4 Model initial $^{26}\text{Al}/^{27}\text{Al}$ values and model ages

Model $^{26}\text{Al}/^{27}\text{Al}_0$ values range from 0.56×10^{-6} to 3.42×10^{-7} , with the exception of two samples. LAP 031062 has a higher model $^{26}\text{Al}/^{27}\text{Al}_0$ value of 1.06×10^{-5} and LEW 87002 has an implausible value of -7.50×10^{-7} . Both of these samples have very low $^{27}\text{Al}/^{24}\text{Mg}$ ratios for eucritic meteorites (0.25 and 0.19) and $\delta^{26}\text{Mg}^*$ values within uncertainty of the terrestrial standard, which means that calculations of model $^{26}\text{Al}/^{27}\text{Al}_0$ values are not meaningful. The model $^{26}\text{Al}/^{27}\text{Al}_0$ values correspond to a range in single-stage model ages of 2.82–4.77 Myr after the formation of CAIs. The ages of Millbillillie, Juvinas and Camel Donga obtained in this study are within error of those determined for the same samples by Bizzarro et al.

(2005b) and Schiller et al. (2010).

Figure 5.2: Histogram of $\delta^{25}\text{Mg}$ values in eucrite samples, with superimposed probability (A). Histograms of $\delta^{25}\text{Mg}$ values in terrestrial basalt from Teng et al. (2010) (B) and mantle olivine from Handler et al. (2009) (C), with super imposed probabilities.

Figure 5.3: A- ^{26}Al – ^{26}Mg isochron diagram, with eucrite data from this study, and reference isochrons. B- Histogram of model $^{26}\text{Al}/^{27}\text{Al}_0$ values of eucrite samples with superimposed probability curve. C- Histogram of model ages of eucrites relative to CAIs with superimposed probability curve.

Chapter 6

Discussion

This chapter begins with a discussion of previously proposed models for the genesis of eucrites and diogenites. The majority of eucrites analysed in this study are from the NASA Antarctic meteorite collection and may have been affected by weathering. As such, the effect of weathering on the samples from this study is evaluated.

Major and trace element and Mg isotope data for the eucrites presented in the previous three chapters are integrated in this chapter. The data from this study are also compared to data from other studies on eucrites and diogenites. Based on correlations in eucrite and diogenite data, four models for the genesis of the eucrites and diogenites are proposed and evaluated. Age data for eucrites obtained in this study with the Al-Mg chronometer are compared to ages from other studies of eucrites and diogenites. The relationship between the eucrites and the asteroid Vesta is also considered.

6.1 Existing models for eucrite and diogenite genesis

Non-cumulate eucrites can be divided into three groups based on their whole-rock major and trace element compositions: main group eucrites, Stannern trend eucrites and Nuevo Laredo trend eucrites. The main group

Figure 6.1: Plot of whole-rock TiO_2 versus $\text{Mg\#}$ in eucrites showing the classification of eucrites into Stannern trend, Nuevo Laredo trend, main group and cumulate eucrites. Nuevo Laredo trend eucrites plot within the left trending arrow, Stannern trend eucrites plot within the right, downward trending arrow, and main group eucrites plot in the cluster of samples between both arrows. Cumulate eucrites plot in the lower right corner of the diagram at higher $\text{Mg\#}$. Figure taken from Basaltic Volcanism Study Project (1981).

eucrites are the most common and cluster on a plot of TiO_2 versus $\text{Mg\#}$ ($\text{Mg}/(\text{Mg} + \text{Fe})$). The Stannern trend eucrites are characterized by a significant decrease in TiO_2 contents with only a slight decrease in $\text{Mg\#}$, whereas the Nuevo Laredo trend eucrites exhibit increasing TiO_2 contents and a marked decrease in $\text{Mg\#}$ (Basaltic Volcanism Study Project, 1981) (Fig. 6.1). Cumulate eucrites have high $\text{Mg\#}$ numbers and low TiO_2 contents as compared with non-cumulate eucrites. Some eucrites do not fit into any of these geochemical groupings and are referred to as being anomalous.

Any model for the silicate differentiation of the HED parent body must account for these variations observed amongst the suite of eucrite meteorites. In addition, the formation of diogenites and their relationship to eucrites also needs to be explained. Understanding the formation of diogenites is complicated by the fact that they exhibit a large range in incompatible element concentrations (e.g., Yb varies by a factor of 16 across the diogenite suite) over a relatively small range in $\text{Mg\#}$ (Fowler et al., 1995).

There are three general processes which could be responsible for the compositional variation observed amongst the eucrites: (i) different degrees of partial melting of a single homogeneous source material possibly combined with: (ii) fractional crystallization (or equilibrium or *in situ* crystallization) of a relatively homogeneous source magma (e.g., a magma ocean) or; (iii) partial melting of heterogeneous sources to produce different magma batches (Basaltic Volcanism Study Project, 1981).

In an early study of eucrites, Stolper (1977) argued that main group and Stannern trend eucrites resulted from different degrees of partial melting of primitive chondritic material. Following partial melting, fractional crystallization of these melts produced the main group and Stannern trend eucrites, and the Nuevo Laredo trend eucrites formed from residual liquid (Stolper, 1977). However, the primary criticism of this model is that it does not account for the large range of incompatible element concentrations in diogenites (Righter and Drake, 1997). Modelling performed by Consolmagno and Drake (1977) determined that the REE compositions of main group eucrites are consistent with 10–15% partial melting of a chondritic source, with the Stannern trend eucrites resulting from small degrees (~4%) of partial melting of the same source. However, this model does not account for the formation of diogenites, which are more primitive than the eucrites. In addition, melting experiments have shown it is implausible for eucrites and diogenites to both be derived from primary melts of the same source material (Jurewicz et al., 1995).

Others studies have suggested that diogenites crystallized as cumulates from primary magmas produced by partial melting, followed by the fractional crystallization of eucrites from the residual magma (e.g., Warren and Jerde, 1987), rather than the eucrites being primary magmas. This model implies that eucrites and diogenites are related to each other, and represent a crystallization continuum of partial melts. However, it is again difficult to relate all the diogenites with this model, as it requires very high levels of crystallization of a single magma source to produce the large range in incompatible trace element concentrations in the diogenite suite (Fowler et al., 1995). The limitations of these two partial melting models

might be overcome if eucrites and diogenites are both the products of crystallization of primary melts, but formed from two heterogeneous magma batches.

There are several drawbacks to these partial melting models, which are all based on 15–20% partial melting of the HED parent body. For example, there is no evidence of primitive, unmelted material from the HED parent body in the meteorite suite, which would be expected if the parent body had only undergone partial melting (Shearer et al., 1997). The partial melting model is also difficult to reconcile with mechanisms for core formation and metal–silicate differentiation, which would require a minimum of 50% silicate melting (Taylor, 1992). Similarly, in order to achieve oxygen isotope homogeneity as observed in the HED meteorites on the parent body, a minimum of 50% melting has been suggested as being required (Greenwood et al., 2005).

An alternative to partial melting models is the magma ocean hypothesis, which requires near complete melting of the HED parent body. (Righter and Drake, 1997). This model suggests that eucrites formed progressively as residual liquids of magma ocean crystallization that were extruded from the magma ocean onto or close to the surface of the HED parent body, whereas diogenites are cumulates from the same magma body (Righter and Drake, 1997). This model can account for some of the limitations of the partial melting models, as it is consistent with conditions required for core formation and consequently the very low concentrations of siderophile elements in the HED meteorites (Righter and Drake, 1997), as well as the three-oxygen isotope homogeneity of the HED meteorite suite. In this model eucrites and diogenites form as part of the same crystallization sequence. However, it would require extraordinarily high amounts of crystallization in order to produce the compositional trace element range exhibited by the diogenites and eucrites (Fowler et al., 1995).

To explain this extreme trace element heterogeneity, Barrat et al. (2000) proposed that *in situ* crystallization of a magma ocean could generate the observed trace element characteristics of eucrites i.e., decoupling of major and trace elements. Diogenites would form as cumulates in this magma

ocean. However, it is still not clear how this model can account for the large range in incompatible element concentrations in diogenites.

Thus, it does not appear that a single, simple model like those outlined above can explain the formation of eucrites and diogenites and silicate differentiation of the HED parent body. This has prompted the proposal of more complex models in order to account for all the compositional features of the HED meteorites. For example, Shearer et al. (1997) argued that it is possible to produce diogenites and eucrites by fractional melting of a source that was originally homogeneous (thus explaining the homogeneity in three-oxygen isotope compositions), but was subsequently disturbed by varying degrees of partial melting and melt extraction. Remelting of this material could produce batches of magmas from which eucrites and diogenites with realistic compositions formed if there was substantial changes to the orthopyroxene/melt distribution coefficients during melting or crystallization (Shearer et al., 1997). However, this model offers no explanation as to the cause of the two melting episodes, as it is widely believed that there was only a single, early, melting episode resulting from the heat produced by the decay of ^{26}Al (Hevey and Sanders, 2006). It is also not clear how the required changes in distribution coefficients were brought about. Shearer et al. (1997) also proposed a “serial-magmatism” model to explain the genesis of eucrites and diogenites. In this model, there are varying degrees of partial melting, and the magmas from which diogenites form transfer heat to the outer portions of the HED parent body, resulting in melting that generates eucritic magmas. This is consistent with models that suggest that the eucrites are primary melts, with compositional differences resulting from varying degrees of partial melting (e.g., Stolper, 1977). However, this model requires high degrees of melting in the production of diogenites (possibly facilitating core formation), which is, yet again, not consistent with the range of incompatible trace element contents (Shearer et al., 1997).

6.2 Effect of weathering on Antarctic meteorites

Weathering of meteorites found in Antarctica has the potential to alter the original chemical composition of these meteorites (Mittlefehldt and Lindstrom, 1991; Floss and Crozaz, 1991; Crozaz et al., 2003). A weathering classification for Antarctic meteorites was introduced (Antarctic Meteorite Newsletter, vol. 1, no. 3, Nov 1978) due to the potential problems that may arise from weathering of Antarctic meteorites. This weathering classification scheme was outlined in Chapter 3. Based on this scheme, samples in this study were selected with weathering grades of B or better wherever possible. However, Crozaz et al. (2003) noted that these weathering grades are not well suited to eucrites, as rust is used as the primary indicator of the weathering degree, and eucrites are poor in metal and sulfide, thus making them less likely to show large amounts of rust even after high degrees of weathering.

A number of studies (e.g., Mittlefehldt and Lindstrom, 1991; Floss and Crozaz, 1991; Crozaz et al., 2003) have documented evidence of unusual REE compositions in some Antarctic eucrites, most likely as a result of REE mobilization caused by weathering on the Antarctic ice. REE mobilization may be due to interaction with weakly acidic melt water (Mittlefehldt and Lindstrom, 1991) infiltrating the meteorite through shock-induced fractures (Floss and Crozaz, 1991). Ca-phosphates are most susceptible to dissolution and, as such, are most likely to be the first mineral altered, although other minerals can also be potentially altered. Due to density differences, pyroxene is more likely than plagioclase to have extensive micro-fracturing, making it more susceptible than plagioclase to leaching and redistribution of REE (Floss and Crozaz, 1991).

Mittlefehldt and Lindstrom (1991) found that samples taken from the exterior of meteorite samples had REE concentrations that exhibited greater variability than interior samples. In this study, only small pieces of each meteorite were used, and the external surfaces were removed from all the samples to minimize the affects of alteration on the measured compositions of these samples.

The presence of either negative or positive Ce anomalies is considered an indicator of weathering in Antarctic meteorites (Mittlefehldt and Lindstrom, 1991; Floss and Crozaz, 1991), as mineral–melt partition coefficients mean it is difficult to explain Ce anomalies as representing magmatic processes on the HED parent body. Ce is particularly affected by weathering because oxidation partially converts Ce^{3+} to Ce^{4+} , and Ce^{4+} is less soluble than trivalent REE, resulting in some Ce being separated from other REE due to the difference in solubility of Ce^{3+} and Ce^{4+} (Mittlefehldt and Lindstrom, 1991; Floss and Crozaz, 1991). Both negative and positive Ce anomalies characterise pyroxene from some samples in this study, which is most likely the result of weathering.

In addition to the presence of Ce anomalies, Mittlefehldt and Lindstrom (1991) noted that the whole rock REE patterns of altered eucrites are also generally characterized by positive Eu anomalies, as opposed to the negative Eu anomalies observed in most unaltered eucrites. Pyroxene and plagioclase from samples in this study have Eu anomalies consistent with what would be expected from unaltered eucrites i.e., plagioclase would be expected to exhibit positive Eu anomalies, whereas pyroxene should have negative Eu anomalies. For this reason, it does not appear that Eu anomalies in pyroxene and plagioclase in samples in this study have been affected by weathering. Mittlefehldt and Lindstrom (1991) also noted that the whole rock REE compositions of altered eucrites are relatively low. The Antarctic samples in this study have REE abundances in both plagioclase and pyroxene that are consistent with the REE abundances in the four non-Antarctic samples, which is an indication that, apart from Ce, the REE concentrations have not been significantly affected by weathering. In addition, the REE chemistry of both low- and high-Ca pyroxene in samples from this study is consistent with the REE compositions of both whole rock and pyroxene from non-Antarctic eucrites published in other studies (Fig. 6.2).

The Antarctic samples from this study do not appear to have the low REE abundances relative to non-Antarctic eucrites that characterize altered eucrites. Floss and Crozaz (1991) found that pyroxene in altered

Figure 6.2: Concentrations of Lu and Yb in low- and high-Ca pyroxene in eucrites from this study, pyroxene from non-Antarctic eucrites from Hsu and Crozaz (1996), and whole-rock non-Antarctic eucrites from Barrat et al. (2000).

Antarctic eucrites may display a negative correlation between Nd concentration and Ce anomalies. However, no correlation between Nd concentration and Ce anomalies was observed in this study either within a single sample, or amongst the mean compositions for each eucrite (Fig. 6.3).

If significant mobilization of elements were taking place within a sample, Ce anomalies would be expected to correlate with elements that are also easily mobilized. Floss and Crozaz (1991) observed this phenomenon in pyroxene from an altered Antarctic eucrite, where Na, Ba, Sr and P all correlate negatively with Ce anomaly. These correlations are not observed in samples from this study, indicating that there may not have been significant mobilization of elements in these samples (Fig. 6.4). Based on comparisons between non-Antarctic and Antarctic eucrites, major elements do not appear to be effected by weathering in Antarctic eucrites (Mittlefehldt and Lindstrom, 2003). This is consistent with major element concentra-

Figure 6.3: Plot of Nd concentration versus Ce anomaly for individual analyses of pyroxene in QUE 97014 and EET 92023.

tions in eucrites in this study, which are in the same range as major element mineral concentrations in non-Antarctic eucrites measured by Hsu and Crozaz (1996). In summary, while there is evidence for weathering induced Ce anomalies in pyroxene and to a lesser extent plagioclase in the Antarctic samples in this study, weathering does not appear to have had a noticeable effect on the other REE concentrations. Major element concentrations and, therefore, Mg isotopes are also unlikely to have been affected by weathering.

6.3 Compositional variations in eucrites

6.3.1 $\delta^{26}\text{Mg}^*$ variability in eucrite samples

The variations in $\delta^{26}\text{Mg}^*$ in eucrite samples do not correlate with the stable Mg isotope compositions of the same samples and, therefore, are not the result of an erroneous instrumental mass bias correction (Bizzarro et al., 2011; Schiller et al., 2011). While there are no cosmic ray exposure ages

Figure 6.4: Average Ce anomalies in pyroxene from Antarctic eucrites plotted versus concentrations of Na, Ba and Sr in the same samples.

for the Antarctic eucrites analysed in this study, Schiller et al. (2011) determined that there was no correlation between the $\delta^{26}\text{Mg}^*$ variation in diogenites and cosmic ray exposure ages of the same diogenites, so it is unlikely that $\delta^{26}\text{Mg}^*$ variations in the HED meteorites are the result of cosmogenic processes. Ruling out these processes that may result in variation in $\delta^{26}\text{Mg}^*$ between samples suggests that $\delta^{26}\text{Mg}^*$ in eucrites does reflect silicate differentiation and magmatic evolution on the HED parent body.

6.3.2 Major and trace element and Mg isotope variations in eucrites

The whole rock major and trace element characteristics of non-cumulate eucrites have been described extensively by a number of studies (e.g., Duke and Silver, 1967; Stolper, 1977; Warren and Jerde, 1987; Barrat et al., 2000; Mittlefehldt and Lindstrom, 2003). However, relatively few studies of eucrites have conducted *in situ* major and trace element measurements of mineral phases in eucrites. Some major elements such as Si, Al and Mg in pyroxene and Si, Al and Ca in plagioclase show little variation between the eucrite samples. However, other major elements such as Ca, Fe and Ti in pyroxene and K in plagioclase show a larger range in concentrations.

As described previously, eucrites can be grouped according to concentrations of bulk rock TiO_2 and Mg# (Basaltic Volcanism Study Project, 1981). Hsu and Crozaz (1996) used concentrations of TiO_2 plotted versus Mg# measured in pyroxene rather than bulk rock samples to classify their samples into eucrite groups. The TiO_2 versus Mg# differences between Stannern trend, Nuevo Laredo trend and main group samples are the same as they are for whole rocks (Hsu and Crozaz, 1996). Juvinas is considered to be a typical main group eucrite (Basaltic Volcanism Study Project, 1981), and the majority of eucrites in this study cluster around Juvinas on a plot of TiO_2 versus Mg# for low-Ca pyroxene and pyroxene (from samples with one phase), which indicates these samples belong to the main group (Fig. 6.5). There are three samples (EET 92003, Millbillillie and LEW 85305) from this study that appear to be part of the Stannern trend, based on their significantly higher TiO_2 concentrations, which decrease with only a slight decrease in Mg#. None of the eucrites from this study appear to fall in the Nuevo Laredo trend grouping, and there are some samples that do not fall in the main group or Stannern trend groupings. The Mg-rich eucrites have high Mg# and low TiO_2 , and are similar in composition to cumulate eucrites (Fig. 6.5), although they do not have a cumulate texture. There is a subtle positive correlation between the concentrations of Ca and Yb in low-Ca pyroxene. However the concentration

Figure 6.5: TiO_2 versus Mg# in pyroxene in eucrites from this study.

of Ca and other major elements do not appear to correlate with $\delta^{26}\text{Mg}^*$ or model $^{26}\text{Al}/^{27}\text{Al}_0$ values.

Trace element concentrations, particularly REE, in plagioclase and pyroxene vary by up to an order of magnitude or more in the suite of studied eucrites. These variations are consistent with REE concentrations measured in eucritic pyroxene and plagioclase by ion microprobe analysis by Hsu and Crozaz (1996) and whole rock REE concentrations presented by Barrat et al. (2000).

In general terms and based on the REE mineral–melt partition coefficients in pyroxene (Beattie et al., 1991), approximately 80–90% fractional crystallization would be required to produce the range of REE in melts as represented by the pyroxene observed in this study. A similar level of crystallization would also be required if equilibrium crystallization was the dominant process. These qualitative constraints are unlikely to be er-

aneous due to changing mineral–melt coefficients during crystallization, given the limited range of pyroxene major element compositions.

Heavy REE are moderately incompatible in pyroxene and, therefore, increasing concentrations of these elements in pyroxene should track increasing degrees of magmatic evolution and Yb concentration in the melt that the low-Ca pyroxene crystallized from. Relatively high concentrations of Yb in low-Ca pyroxene compared to other REE, also allows robust measurement of this heavy REE in this mineral phase. The concentrations of Yb are similar in the low- and high-Ca pyroxene, which suggests it is a suitable element to examine variations in all pyroxene phases in the eucrite samples. Yb concentrations in low-Ca pyroxene also provide a useful means to compare eucrites and diogenites. Given that there is little variability between the Yb concentration in both high-Ca and low-Ca pyroxene, Yb in pyroxene from samples with only a single phase should also be similar, and as such Yb concentrations in this phase are considered where necessary. For these reasons, the variation in concentration of Yb in low-Ca pyroxene with Mg isotope data is now considered.

A positive correlation exists between the concentration of Yb and other heavy REE in low-Ca pyroxene and the $\delta^{26}\text{Mg}^*$ anomaly in the eucrite samples (Fig. 6.6 D). However, three samples (Millbillillie, LEW 85305 and GRA 984043) have anomalously high Yb concentrations. As mentioned above Millbillillie and LEW 85305 both have high pyroxene TiO_2 , indicating they may belong to the Stannern trend eucrite group, which may account for their high Yb concentrations. However, GRA 984043 appears to be a main group eucrite, but still has a higher Yb concentration in pyroxene than the other main group eucrites. The Mg-rich eucrites have very small $\delta^{26}\text{Mg}^*$ anomalies and low Yb concentrations, which indicates that they are the least evolved samples in this eucrite suite. Positive correlations exist between the pyroxene Yb concentration and the bulk $^{27}\text{Al}/^{24}\text{Mg}$ ratios of eucrite samples, which is consistent with the $^{27}\text{Al}/^{24}\text{Mg}$ ratio increasing with increasing degrees of magmatic evolution (Fig. 6.6 E). However, there is no clear correlation between model $^{26}\text{Al}/^{27}\text{Al}_0$ values and Yb concentrations in pyroxene (Fig. 6.6 F). In addition, there appears to be two

parallel negative correlations between Eu anomaly (Eu/Eu^*) in pyroxene and $\delta^{26}\text{Mg}^*$ and model $^{26}\text{Al}/^{27}\text{Al}_0$ values (Fig. 6.6 A and C). Excluding the Mg-rich eucrites, concentrations of Ba in plagioclase correlate positively with both $\delta^{26}\text{Mg}^*$ and model $^{26}\text{Al}/^{27}\text{Al}_0$ values, but do not clearly correlate with $^{27}\text{Al}/^{24}\text{Mg}$ ratios of the bulk eucrite samples (Fig. 6.6 G, H and I). The correlation between elements such as Ba in plagioclase and Yb in pyroxene and $\delta^{26}\text{Mg}^*$ in eucrites suggests that eucrites represent varying degrees of evolution of a single magma body.

6.3.3 Comparison with diogenites

A study similar to the one presented in this thesis was undertaken on diogenites by Schiller et al. (2010, 2011), which allows for a comparison between the *in situ* trace element and Mg isotope data for eucrites and diogenites. Diogenites are predominantly composed of low-Ca pyroxene ($\pm$ olivine), and so for the purposes of comparison, only the trace element and Mg isotopic data for low-Ca pyroxene in both diogenites and eucrites are examined. REE concentrations in low-Ca pyroxene in diogenites vary by an order of magnitude (e.g., Yb concentrations range from 0.02–0.31 ppm), which would require a high degree of fractional crystallization of the parent melt(s) of diogenites. There is a coherent increase in REE and other elements (e.g., Ti), which is consistent across all the diogenite samples, implying that diogenites shared a common, but variably fractionated parental magma (Schiller et al., 2011). Notably, REE concentrations measured in low-Ca pyroxene from the eucrites (this study) are considerably higher than diogenites. For example, the Yb concentration in low-Ca pyroxene in the most evolved eucrite (2.92 ppm), is two orders of magnitude higher than the Yb concentration in the low-Ca pyroxene phase of the least evolved diogenite. In addition, excluding the Mg-rich eucrites there is a large gap in REE concentrations between the most evolved diogenite, and the least evolved eucrite (Fig. 6.7 A). The Mg-rich eucrites appear to have an intermediate REE composition between diogenites and eucrites.

As is the case for eucrites, there is a positive correlation between

Figure 6.6: Europium anomalies (Eu/Eu^*) and Yb concentration in low-Ca and single phase pyroxene (A–F) and Ba concentration in plagioclase (G–I) versus whole-rock $\delta^{26}\text{Mg}^*$, $^{27}\text{Al}/^{24}\text{Mg}$ and model $^{26}\text{Al}/^{27}\text{Al}_0$ values.

Yb concentration in low-Ca pyroxene and $\delta^{26}\text{Mg}^*$ values in diogenites (Schiller et al., 2011). Despite the large difference in REE concentrations between eucrites and diogenites, there is a slight overlap in $\delta^{26}\text{Mg}^*$ values between the two meteorite types, although most diogenites do have lower $\delta^{26}\text{Mg}^*$ values ($\leq 0.000\%$) than eucrites (Fig. 6.7 B). Comparison of the Mg isotopic and elemental compositions of the eucrites and diogenites potentially places important constraints on models of silicate differentiation on the HED parent body. The large variation in incompatible elements, such as Yb in low-Ca pyroxene across the diogenites and eucrites (Fig. 6.7 A) precludes the possibility that diogenites and eucrites represent a fractional crystallization continuum of a single magma body. The stable Mg isotope composition of diogenites is approximately the same as terrestrial basalts (Teng et al., 2010) and terrestrial mantle olivines (Handler et al., 2009). However $\delta^{25}\text{Mg}$ values of the eucrites are $\sim 0.05\%$ heavier than that of diogenites and the terrestrial samples (Fig. 6.8). In light of the observations described above, detailed below are four possible models for the formation of eucrites and diogenites.

6.4 Models for the genesis of eucrites and diogenites

Model A - Partial melting of a chondritic mantle

A possible model for explaining the difference in REE concentrations of pyroxene between eucrites and diogenites, involves partial melting of a “chondritic mantle” on the HED parent body. Eucrites crystallize from the partial melt that underwent variable degrees of fractionation, whereas the diogenites represent the residual HED parent body mantle after extraction of the eucritic magma (Fig. 6.9 A). This is consistent with modelling of volcanic activity on Vesta, which indicates that silicate melts were removed from the mantle, by networks of veins and dykes, possibly having been transported from melts up to 10 km deep by dykes, and then ex-

Figure 6.7: Yb concentration in eucrites and diogenites (Schiller et al., 2011) plotted versus Lu concentration (A) and $\delta^{26}\text{Mg}^*$ (‰) (B).

Figure 6.8: $\delta^{25}\text{Mg}$ compositions of eucrites (this study; Wiechert and Halliday, 2007), diogenites (Schiller et al., 2011), terrestrial mantle olivine (Handler et al., 2009) and terrestrial basalts (Teng et al., 2010). Terrestrial basalt and mantle olivine data are averages of sample groups. Vertical line is the average terrestrial $\delta^{25}\text{Mg}$ composition.

truded onto or near the surface as eucritic lava flows (Wilson and Keil, 1996, 2012). This model could possibly account for the large depletion in incompatible elements in diogenites as compared with the eucrites.

It is possible to evaluate the veracity of this model as it requires that some combination of mean diogenitic and eucritic compositions in appropriate proportions (i.e., the average degree of partial melting) should have a chondritic composition once the effect of core segregation on the elements being considered has been taken into account. In order to do this a simple mixing equation was used to determine if the whole rock eucrite and diogenite chemical compositions could be mixed in some proportion to produce a composition equal to chondrites. In order to account for the process of core formation on the HED parent body, only elements that are not sequestered into the Fe-Ni metal core were considered. Given that core formation results in an approximately two-fold enrichment in elements that are not sequestered into the core in the silicate portion of differentiated bodies, the mixing model was undertaken to solve for 2 × chondritic element concentrations (Mittlefehldt, 2007). In general, the concentrations of most elements in chondrites can be adequately modelled from a eucrite–diogenite mixture that requires ~80–95% diogenitic material (Table 6.1). However, Mg and Sc concentrations in chondrites cannot be modelled by mixing between eucrites and diogenites in any proportions, as chondrites have higher Mg than both diogenites and eucrites, and a lower Sc concentration than both diogenites and eucrites. Adding in 10–20% olivine to the eucrite–diogenite mix would, however, result in Mg and Sc concentrations consistent with chondrites.

This model would allow the diogenite mantle residues to have negative $\delta^{26}\text{Mg}^*$ values if melting took place very early. However, some diogenites have positive $\delta^{26}\text{Mg}^*$ values (Schiller et al., 2011). While it is possible that the positive $\delta^{26}\text{Mg}^*$ in some diogenites could be the result of (late) contamination by eucritic material, the amount of contamination required by adding relatively low-Mg eucrite material to high-Mg diogenites makes this an unlikely scenario and is inconsistent with the systematics of other elements (Schiller et al., 2011).

Figure 6.9: Proposed models for the genesis of eucrites and diogenites. Model A involves partial melting of a chondritic mantle, with eucrites crystallizing from the melt, and diogenites representing the residual mantle after removal of the eucritic magma. **Model B** involves variable degree partial melts which produce eucrites and diogenites separately. **Model C** involves two large melt bodies separated by depth or geography, from which eucrites and diogenites crystallized.

Another difficulty with this model is the apparent difference in model ages between eucrites and diogenites, with the formation of diogenites pre-dating eucrites by ~1.5 Myr (Schiller et al., 2011). If the eucrites and diogenites were produced during the same melting event as mantle residues and partial melts, then both meteorite groups should have the same model ages. In light of the observations described above it is unlikely that the diogenites and eucrites can be related as described by this model.

Table 6.1: The mixture of diogenite and eucrite compositions required to obtain concentrations equal to twice that of chondrites. Whole-rock diogenite concentrations from Barrat et al. (2008); whole-rock eucrite concentrations from Barrat et al. (2000); whole-rock CI-chondrite concentrations from Barrat et al. (2012).

Element	Diogenite concentration (ppm)	Eucrite concentration (ppm)	Chondrite concentration (ppm)	% Diogenite	% Eucrite
Ti	0.06	0.41	0.04	93.0	7.0
Al	0.46	6.51	0.78	81.7	18.3
Cr	0.59	0.24	0.26	81.3	18.7
Mg	16.36	4.93	9.44	122.0	-22.0
Sc	14.50	27.30	5.88	121.5	-21.5
Sr	1.40	73.65	7.91	80.0	20.0
Y	0.99	18.25	1.60	87.2	12.8
Zr	0.94	48.48	3.41	87.6	12.4
Nb	0.10	3.55	0.30	85.4	14.6
Ba	0.61	31.45	2.59	85.2	14.8
La	0.04	2.84	0.25	83.8	16.2
Ce	0.10	7.56	0.63	84.5	15.5
Nd	0.09	5.64	0.49	84.0	16.0
Sm	0.04	1.81	0.16	84.1	15.9
Ho	0.04	0.66	0.06	86.9	13.1
Yb	0.15	1.79	0.17	88.3	11.7
Lu	0.02	0.27	0.02	90.1	9.9
Th	0.01	0.36	0.03	85.2	14.8
U	0.00	0.10	0.01	86.2	13.8

Model B - Variable degrees of partial melting of the HED parent body

This model postulates that eucrites and diogenites formed from a number of different magma bodies produced by variable degrees of partial melting, with the diogenites representing crystal cumulates from large degree partial melts (Fig. 6.9 B). This model could account for the large range in incompatible elements exhibited by both the eucrite and diogenite suites. However, this model is not readily reconcilable with the positive correlations between incompatible elements, such as Yb, and $\delta^{26}\text{Mg}^*$ in pyroxene in eucrites. In such a model the oldest eucrites clearly should have the most positive $\delta^{26}\text{Mg}^*$ and also should originate from the largest degree partial melts due to the higher levels of ^{26}Al present. However large degrees of partial melting result in lower concentrations of incompatible elements and, therefore, the eucrites with the highest $\delta^{26}\text{Mg}^*$ should have the lowest incompatible element concentrations, which is the opposite of what is observed in the dataset.

Model C - Extensive melting of the HED parent body

Another possible model for the genesis of eucrites and diogenites, again, proposes that the eucrites and diogenites did not form from a common parental magma and therefore are not genetically related (Fig. 6.9 C). This model requires extensive melting (>50%) of the HED parent body, with two large magma bodies forming, which are either separated geographically or by depth in the parent body. Diogenites are cumulates that crystallized from a melt body produced by large degrees of partial melting, whereas eucrites are crystallized melt residues produced by crystallization of a second, separate magma body produced by smaller degrees of partial melting. Given that diogenites are older than eucrites, they likely formed from a larger magma body produced by larger degrees of melting than eucrites, as more ^{26}Al would have been present early in the HED parent body. Therefore, this model can account for the higher incompatible element concentration in eucrites, as lower degrees of melting are associated with higher concentrations of incompatible elements. This model also explains the positive correlation between $\delta^{26}\text{Mg}^*$ and incompatible elements in eucrite pyroxene, and the negative correlation between Eu anomaly and $\delta^{26}\text{Mg}^*$, because eucrites would represent varying degrees of magmatic evolution from a common parent magma, with the most evolved samples crystallizing with the highest incompatible element concentrations, the most “negative” Eu anomalies and the highest $\delta^{26}\text{Mg}^*$ values. The temporal and spatial separation of the two large magma bodies may be the result of non-instantaneous accretion of the HED parent body, which is believed to have taken 1-2 Myr (Mittlefehldt, 2007). Later accreted material would have relatively less ^{26}Al , and therefore would undergo less melting, and crystallization products of the melt, the eucrites, would be younger than diogenites which may have crystallized from melting of earlier accreted material.

This model overcomes the difficulty of the previous model in explaining the compositional coherency within the eucrite and diogenite suites, as both suites come from single magma bodies. This model is also consistent

with the range of $\delta^{26}\text{Mg}^*$ recorded by eucrites and diogenites, which requires their $\delta^{26}\text{Mg}^*$ values to be inherited from the evolving magma body from which they crystallized (Schiller et al., 2011).

This offset in stable Mg isotope ($\delta^{25}\text{Mg}$) composition between eucrites and diogenites and terrestrial samples (Fig. 6.8) may also indicate that the eucritic basalts did not form from small to medium degrees of partial melting as, for example, terrestrial basalts form on Earth. Instead, the slightly heavier stable Mg isotopic composition of basaltic eucrites might reflect their generation by extensive crystallization of a magma body on the HED parent body, which is consistent with this model. However, the difficulty with this model, is that it still remains problematic to reconcile the large range in REE concentrations across the diogenite suite with their formation from a single magma body. Schiller et al. (2011) determined that fractional crystallization of 50–75% would be required to produce the range in incompatible elements found in the diogenites, which is plausible.

Model D - Formation of eucrites and diogenites on separate parent bodies

A fourth possible model for the eucrites and diogenites could be that the two meteorite groups formed on different bodies. It is possible that two separate parent bodies may have accreted relatively close to each other, and thus have the same oxygen isotope compositions. To account for the age difference between eucrites and diogenites the diogenite parent body would have accreted earlier than the eucrite parent body. This model can explain the variability in incompatible elements between eucrites and diogenites, and the differences in $\delta^{25}\text{Mg}$ between the two meteorite groups. However, if the eucrites and diogenites are from separate parent bodies, the diogenite parent body is missing evidence for a relatively incompatible element enriched reservoir, such as the eucrites. This is also difficult to reconcile with the petrography of howardites, which contain both diogenitic and eucritic material (Mittlefehldt, 2007), although it is possible that howardites could originate from the diogenite parent body, and con-

tain evidence of the “missing” incompatible element enriched reservoir. If this were the case, it would have implications for the classification of meteorites based on oxygen isotope composition.

In summary, Model C appears to best explain all aspects of the eucrite data from this study, and can account for the compositional differences of eucrites and diogenites without requiring that they originate from separate parent bodies.

6.4.1 Timing of silicate differentiation on the HED parent body

^{26}Al - ^{26}Mg model ages of eucrites from this study relative to CAIs range from 2.8–4.7 Myr, with an average age of 3.4 Myr. This is consistent with a number of other studies that have applied various chronometers to eucrites (such as; the Al-Mg chronometer (Bizzarro et al., 2005b), the Mn-Cr chronometer (Lugmair and Shukolyukov, 1997, 2001; Trinquier et al., 2007), the Sm-Nd chronometer (Wadhwa and Lugmair, 1996; Kumar et al., 1999), the Hf-W chronometer (Kleine et al., 2004) and the Pb-Pb chronometer (Wadhwa et al., 2009)) that have determined that eucrites date to within ~3 Myr of solar system formation (Wadhwa et al., 2006). Schiller et al. (2011) determined that diogenite formation began in the first 0.6 Myr of the solar system and continued until to 2.5 Myr after the formation of CAIs. The ages of the eucrites from this and the several other aforementioned studies are considerably younger than the predicted age of 6.6 Myr for crustal formation on the asteroid Vesta as determined by thermal modeling (Ghosh and McSween, 1998).

6.5 Relationship to the asteroid Vesta

Similarities between the mineralogy of the HED meteorites and the surface mineralogy of the asteroid Vesta, as determined by spectral reflectance

measurements (McCord et al., 1970), suggest that the HED meteorites originated from Vesta (Drake, 1979). Observations made of Vesta from NASA's Dawn spacecraft provide further evidence for its identification as the HED parent body, as Vesta's mass, volume and gravitational field are consistent with it being a differentiated body and the mineralogy of the surface reflects that of the HED meteorites (Russell et al., 2012). There is considerable variation across Vesta, with a higher diogenitic component at the south pole, while eucritic material is concentrated at the equator (De Sanctis et al., 2012). This supports the possibility that the parent magmas for eucrites and diogenites were spatially separated as suggested in Model C. There is evidence on Vesta for stratigraphic layering, which is consistent with large scale melting (De Sanctis et al., 2012). It is clear from observations made of Vesta by the Dawn spacecraft that Vesta has undergone a complex magmatic evolution, which is supported by the complexity seen in the HED meteorite suite.

Chapter 7

Conclusions and suggestions for further work

This thesis has presented *in situ* major and trace element and high-precision whole rock Mg isotope analyses of a suite of eucrite meteorites. The objectives of this study were to discern the nature and timing of basalt magma generation and silicate differentiation on the HED parent body.

7.1 Conclusions

1. There is little variation in the major element compositions of pyroxene and plagioclase in the eucrite meteorites. However, trace element concentrations in these minerals exhibit large variations, particularly for REE which vary by more than an order of magnitude across the suite of eucrites.
2. Mg anomalies ($\delta^{26}\text{Mg}^*$) and model $^{26}\text{Al}/^{27}\text{Al}_0$ values also vary considerably among eucrites. This is reflected by a large range in model ages, which range from 2.8–4.7 Myr after CAIs.
3. There are positive correlations between the concentrations of incompatible elements in pyroxene and $\delta^{26}\text{Mg}^*$, and such correlations are also observed in pyroxene from diogenites (Schiller et al., 2011).

However, the incompatible element concentrations in eucrite pyroxene are considerably higher than diogenite pyroxene.

4. The range in incompatible element concentrations in pyroxene across the eucrite and diogenite suites cannot realistically be generated by crystallization of a single magma body. This suggests that eucrites and diogenites originate from separate magma bodies, and are therefore not genetically related.
5. The $\delta^{25}\text{Mg}$ composition of diogenites is approximately the same as the $\delta^{25}\text{Mg}$ composition of terrestrial basalts and terrestrial mantle olivines. However the $\delta^{25}\text{Mg}$ composition of the eucrites is $\sim 0.05\%$ heavier than that of diogenites and the terrestrial samples. This implies that basalt generation on the HED parent body was unlikely to be the result of small to medium degrees (up to 20–30%) of partial melting as it is on Earth.
6. The model for eucrite and diogenite genesis that best fits the data presented, suggests that eucrites and diogenites formed from two large, separate magma bodies on the HED parent body. The magma bodies, generated by large scale melting, may be separated temporally and spatially. In this model the $\delta^{26}\text{Mg}^*$ values in eucrites and diogenites are inherited from their parent magma bodies, and thus represent increasing degrees of magmatic evolution.

7.2 Suggestions for further work

Based on the findings of this thesis there is research that could further constrain the timing and processes of silicate differentiation on the HED parent body.

1. Internal ^{26}Al - ^{26}Mg mineral isochrons of eucrites

Internal ^{26}Al - ^{26}Mg isochrons of primary igneous minerals can be used to determine more precise ages than whole-rock model isochrons. Mineral

isochrons also provide information about the precursor material of the rock, and may record processes occurring in the melt. However, due to the relatively short distance required for isotopic exchange and re-equilibration in minerals, mineral isochrons may record the ages of post-magmatic processes such as metamorphism. Most mineral grains in eucrites appear to have been re-equilibrated by metamorphism, so internal isochrons of these minerals will provide re-setting rather than crystallization ages. However, it is possible that there are mineral grains in some eucrites that have not re-equilibrated, and Mg isotope analysis of these could be used to reconstruct precise ages for these eucrites.

2. Investigate the offset in $\delta^{25}\text{Mg}$ between eucrites and terrestrial rocks.

The $\delta^{25}\text{Mg}$ measured in eucrites in this and other studies is heavier than $\delta^{25}\text{Mg}$ in terrestrial basalts, terrestrial mantle olivines and diogenites. This has the important implication that the formation of the basaltic eucrites is not analogous to the formation of terrestrial basalts, which occurs through partial melting. However, there is the possibility that this offset in $\delta^{25}\text{Mg}$ is an analytical artifact, resulting from the measurement of samples in different laboratories. In order to test this, 10 terrestrial basalts, 10 eucrites and 10 diogenites could be analysed for $\delta^{25}\text{Mg}$ in the same laboratory.

3. Trace and major element and high-precision Mg-isotope analyses of cumulate eucrites.

There are a number of chemical and petrologic differences between cumulate and non-cumulate eucrites, for example most cumulate eucrites are unbrecciated, while the majority of non-cumulate eucrites are brecciated (Hsu and Crozaz, 1997). Cumulate eucrites also have higher Mg# and lower concentrations of REE than non-cumulates (Hsu and Crozaz, 1997). Sm-Nd and Pb-Pb dating has shown that the isotopic closure of cumulate eucrites occurred up to ~150 Myr after non-cumulate eucrites (Jacobsen and Wasserburg, 1984; Lugmair and Shukolyukov, 1997; Tera et al., 1997). Analyses of major element, trace element and Mg isotopic

composition of cumulate eucrites will help to constrain the poorly understood relationship between the cumulate and non-cumulate eucrites and diogenites. High-precision Mg isotope analyses of cumulate eucrites will also allow for more reliable age determination. A better understanding of the processes involved with the formation of cumulate eucrites will help to constrain models for silicate differentiation on the HED parent body.

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Appendices

Appendix A

Major element data

The following are tables of all of the major element data acquired for eucrite samples and geostandards in this study.

Table A1: Low-Ca pyroxene major element concentrations in wt%

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
EET 83227	52.1	0.10	1.39	0.71	20.6	0.69	21.3	2.95	0.00	99.9	6.05	60.94	33.01
	51.6	0.14	1.32	0.62	20.2	0.70	21.9	2.94	0.00	99.4	5.99	61.89	32.13
	52.0	0.10	1.30	0.81	22.3	0.68	20.9	1.63	0.02	99.7	3.40	60.49	36.11
	52.7	0.11	1.52	0.33	22.2	0.63	21.5	1.45	0.01	101	2.98	61.45	35.58
	52.5	0.12	1.22	0.36	19.1	0.64	23.1	1.72	0.04	98.7	3.54	65.89	30.57
	51.7	0.00	1.56	0.63	20.6	0.84	21.6	2.73	0.01	99.6	5.60	61.46	32.94
	51.2	0.00	2.99	0.50	19.7	0.78	20.3	2.97	0.00	98.4	6.39	60.58	33.03
	52.7	0.12	1.16	0.38	19.0	0.66	23.7	1.69	0.00	99.4	3.41	66.64	29.96
	50.9	0.02	1.00	0.51	27.2	0.97	17.2	2.38	0.00	100	4.99	50.34	44.67
	50.9	0.08	0.77	0.23	29.4	0.89	16.8	0.66	0.00	99.7	1.39	49.79	48.81
	49.1	0.21	4.96	0.43	28.6	0.91	13.5	2.17	0.04	99.9	5.02	43.40	51.58
average	49.6	0.28	2.69	0.34	25.0	0.83	13.6	6.77	0.02	99.2	14.97	41.93	43.10
2 s.d.	51.4	0.11	1.82	0.49	22.8	0.77	19.6	2.50	0.01	99.6	5.31	57.07	37.62
	2.3	0.16	2.37	0.35	7.5	0.23	7.0	3.05	0.03	1.2	6.79	16.89	14.88
EET 87458	51.0	0.13	0.36	0.18	27.4	0.93	18.1	2.46	0.02	101	5.01	51.41	43.59
	51.4	0.14	0.34	0.17	28.4	0.94	18.4	1.44	0.00	101	2.92	52.04	45.04
	51.4	0.17	0.39	0.13	28.5	0.93	18.5	0.91	0.01	101	1.85	52.66	45.48
	51.6	0.12	0.17	0.11	27.8	0.94	18.9	1.51	0.03	101	3.05	53.13	43.82
	51.7	0.12	0.41	0.09	28.3	0.96	18.7	0.98	0.00	101	1.99	52.98	45.04
	51.5	0.16	0.40	0.08	27.6	0.98	18.8	0.92	0.00	100	1.90	53.82	44.28
	51.5	0.16	0.40	0.14	28.8	0.91	18.7	0.86	0.00	102	1.75	52.74	45.51
	51.5	0.14	0.42	0.11	28.6	0.87	18.5	0.90	0.01	101	1.83	52.60	45.57
	51.5	0.14	0.33	0.08	28.5	0.93	18.8	0.85	0.02	101	1.74	53.10	45.17
	51.1	0.14	0.38	0.14	28.0	0.90	18.6	1.81	0.01	101	3.65	52.17	44.18
	51.4	0.11	0.38	0.11	28.3	0.95	18.9	0.92	0.03	101	1.88	53.30	44.82
	51.7	0.13	0.37	0.12	27.9	0.89	18.7	1.11	0.02	101	2.27	53.23	44.51
	51.5	0.14	0.39	0.13	27.8	0.91	18.6	1.75	0.00	101	3.54	52.42	44.04
	51.3	0.13	0.39	0.13	28.5	0.88	18.8	0.88	0.00	101	1.80	53.01	45.19
	51.8	0.13	0.33	0.13	26.8	0.95	18.0	3.27	0.02	101	6.64	50.81	42.55
	51.7	0.15	0.37	0.10	25.6	0.90	17.9	4.18	0.01	101	8.52	50.74	40.74
	51.3	0.15	0.32	0.08	28.4	0.99	18.6	0.89	0.00	101	1.82	52.92	45.25
	51.8	0.11	0.38	0.15	27.6	0.96	18.8	0.89	0.04	101	1.83	53.83	44.35
average	51.8	0.13	0.36	0.14	28.3	0.94	18.6	0.97	0.01	101	1.98	52.86	45.16
2 s.d.	51.5	0.14	0.36	0.12	28.0	0.93	18.6	1.45	0.01	101	2.95	52.62	44.44
	0.5	0.03	0.11	0.06	1.5	0.07	0.6	1.85	0.02	0.5	3.76	1.73	2.37

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
EET 92003	49.8	0.35	1.15	0.47	29.3	0.88	13.5	6.86	0.06	102	14.12	38.70	47.17
	49.4	0.42	1.20	0.37	30.2	0.93	13.1	5.85	0.05	102	12.28	38.21	49.51
	48.5	0.67	0.89	0.37	30.1	0.89	12.8	6.29	0.01	101	13.22	37.31	49.47
	49.9	0.40	1.36	0.49	26.9	0.85	13.3	8.87	0.09	102	18.34	38.27	43.40
	49.3	0.49	0.92	0.28	30.3	0.91	12.9	6.57	0.04	102	13.65	37.18	49.17
	49.6	0.27	1.18	0.42	30.3	0.90	13.0	5.92	0.04	102	12.41	38.00	49.59
	49.8	0.40	1.35	0.44	29.0	0.84	13.2	6.32	0.04	101	13.34	38.88	47.78
	49.2	0.49	1.02	0.29	30.9	0.97	12.1	6.78	0.05	102	14.20	35.30	50.50
	49.9	0.54	1.11	0.30	29.9	0.93	12.6	7.02	0.06	102	14.65	36.67	48.68
	49.4	0.44	1.11	0.39	30.4	0.93	12.9	6.13	0.05	102	12.81	37.61	49.57
	49.1	0.65	1.11	0.31	30.5	0.89	10.9	8.58	0.05	102	18.04	31.89	50.06
	49.1	0.60	1.04	0.23	32.5	1.04	10.9	6.78	0.04	102	14.33	32.04	53.64
	50.0	0.32	1.11	0.47	29.7	0.90	13.8	5.97	0.03	102	12.37	39.64	47.99
	49.5	0.45	1.18	0.38	30.6	0.91	12.1	7.34	0.04	103	15.27	34.98	49.75
	49.3	0.45	1.17	0.41	30.2	1.03	11.1	8.22	0.04	102	17.41	32.70	49.89
	49.0	0.51	1.09	0.36	30.8	0.94	11.7	7.19	0.04	102	15.13	34.34	50.53
	49.6	0.25	1.12	0.47	29.4	0.89	13.4	6.65	0.05	102	13.79	38.61	47.60
	49.0	0.73	1.11	0.31	31.1	0.99	10.5	8.81	0.05	103	18.48	30.60	50.93
	49.1	0.37	1.26	0.44	29.2	0.91	12.2	7.67	0.03	101	16.17	35.77	48.06
average	49.4	0.46	1.13	0.38	30.1	0.92	12.4	7.04	0.04	102	14.74	36.14	49.12
2 s.d.	0.8	0.27	0.24	0.15	2.2	0.10	2.0	1.95	0.03	1.0	4.09	5.42	4.04
EET 92023	50.0	0.60	1.45	0.57	21.9	0.71	14.2	8.79	0.09	98.3	19.26	43.28	37.47
	49.7	0.61	1.58	0.64	21.8	0.68	14.3	9.03	0.10	98.4	19.68	43.24	37.08
	49.9	0.30	1.22	0.49	26.2	0.82	15.4	4.47	0.04	98.7	9.66	46.18	44.16
	50.1	0.38	0.97	0.40	28.1	0.85	15.8	2.85	0.01	99.5	6.10	46.95	46.96
	49.6	0.61	1.50	0.44	24.8	0.75	14.3	6.90	0.07	98.9	14.95	43.13	41.92
	49.4	0.76	1.82	0.64	22.5	0.69	13.9	9.20	0.08	98.9	19.97	41.93	38.10
	49.3	0.58	1.15	0.45	25.6	0.80	14.8	6.07	0.06	98.7	13.02	44.06	42.92
	49.6	0.55	1.44	0.51	24.8	0.77	14.3	6.46	0.06	98.6	14.11	43.54	42.35
	50.2	0.51	1.36	0.59	25.6	0.79	14.9	5.86	0.06	99.8	12.58	44.46	42.96
average	49.7	0.54	1.39	0.53	24.6	0.76	14.6	6.62	0.06	98.9	14.37	44.09	41.55
2 s.d.	0.6	0.27	0.50	0.18	4.3	0.12	1.2	4.30	0.06	1.0	9.47	3.16	6.68

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRA 98005	49.5	0.12	0.28	0.10	35.5	1.11	12.1	1.00	0.03	99.8	2.19	36.96	60.86
	49.3	0.11	0.18	0.07	35.8	1.22	12.2	0.79	0.00	99.7	1.73	37.13	61.14
	49.3	0.08	0.16	0.07	35.4	1.09	12.3	0.96	0.00	99.3	2.10	37.41	60.50
	49.4	0.08	0.26	0.04	33.9	1.03	12.7	1.84	0.03	99.2	4.00	38.39	57.61
	49.1	0.14	0.78	0.11	34.0	1.09	12.4	1.50	0.05	99.2	3.30	38.06	58.64
	49.6	0.13	0.15	0.07	35.2	1.12	12.7	0.84	0.03	99.7	1.83	38.37	59.80
	49.5	0.08	0.25	0.04	35.0	1.14	12.6	0.91	0.00	99.6	1.98	38.41	59.61
	49.5	0.08	0.16	0.03	34.4	1.02	12.8	1.27	0.00	99.2	2.75	38.84	58.41
	49.7	0.09	0.19	0.06	35.0	1.11	12.5	0.87	0.00	99.6	1.90	38.21	59.89
	49.4	0.10	0.14	0.06	35.4	1.15	12.3	0.74	0.02	99.3	1.62	37.60	60.78
average 2 s.d.	49.4	0.12	0.62	0.05	35.1	1.17	12.1	1.12	0.02	99.6	2.47	37.12	60.41
	49.4	0.10	0.29	0.06	35.0	1.11	12.4	1.07	0.02	99.5	2.35	37.86	59.79
GRA 98033	0.3	0.05	0.43	0.05	1.3	0.11	0.5	0.67	0.03	0.4	1.48	1.28	2.27
	49.1	0.12	0.20	0.05	35.7	1.14	11.8	1.37	0.03	99.6	2.99	35.97	61.04
	49.3	0.07	0.14	0.08	34.3	1.09	11.9	2.71	0.01	99.6	5.89	36.04	58.07
	49.1	0.10	0.14	0.04	34.9	1.07	12.0	1.79	0.01	99.1	3.91	36.57	59.52
	49.4	0.06	0.15	0.05	33.8	1.07	11.9	2.82	0.02	99.3	6.16	36.27	57.57
	49.2	0.07	0.15	0.02	35.7	1.11	11.9	1.13	0.01	99.3	2.47	36.45	61.08
	49.3	0.11	0.69	0.10	34.7	0.99	12.4	1.11	0.15	99.5	2.44	37.86	59.70
	49.0	0.07	0.16	0.04	35.7	1.10	12.3	1.00	0.02	99.3	2.17	37.25	60.58
	50.1	0.09	0.21	0.07	31.1	0.96	11.7	6.01	0.03	100.2	12.92	34.89	52.19
	49.3	0.07	0.14	0.10	33.4	1.00	12.0	3.52	0.02	99.5	7.60	36.03	56.36
average 2 s.d.	49.4	0.09	0.15	0.05	35.8	1.16	11.9	1.33	0.00	99.8	2.90	36.19	60.92
	49.3	0.08	0.21	0.06	34.5	1.07	12.0	2.28	0.03	99.5	4.95	36.35	58.70
GRA 98043	0.6	0.04	0.34	0.05	2.9	0.13	0.4	3.15	0.09	0.7	6.74	1.58	5.61
	49.4	0.07	0.17	0.03	36.7	1.20	10.9	0.76	0.00	99.3	1.69	34.07	64.24
	48.5	0.07	0.21	0.04	36.1	1.13	10.7	1.90	0.00	98.7	4.21	33.12	62.67
	50.0	0.13	0.22	0.05	36.9	1.25	11.5	0.85	0.01	100.9	1.86	35.02	63.12
	49.2	0.17	0.15	0.04	36.6	1.33	11.0	1.44	0.00	99.9	3.17	33.80	63.03
	48.4	0.12	0.12	0.07	36.9	1.26	11.2	1.02	0.00	99.0	2.26	34.24	63.50
	48.7	0.12	0.17	0.07	37.1	1.29	10.9	0.98	0.01	99.3	2.17	33.65	64.18
	48.5	0.11	0.12	0.05	36.5	1.22	10.9	1.09	0.03	98.6	2.44	33.89	63.67
	48.7	0.10	0.27	0.08	36.3	1.08	11.4	0.90	0.02	98.9	1.99	35.21	62.81
	48.5	0.08	0.14	0.03	36.5	1.14	10.8	1.00	0.00	98.2	2.24	33.82	63.94
average 2 s.d.	48.9	0.11	0.17	0.05	36.6	1.21	11.0	1.10	0.01	99.2	2.45	34.09	63.46
	1.1	0.07	0.10	0.04	0.6	0.16	0.5	0.71	0.02	1.6	1.57	1.32	1.18

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRA 98055	49.0	0.11	0.14	0.03	36.0	1.20	11.8	0.98	0.02	99.3	2.16	36.10	61.74
	48.8	0.13	0.17	0.04	35.2	1.10	11.9	1.48	0.01	98.8	3.25	36.35	60.39
	49.2	0.12	0.17	0.03	34.8	1.16	12.1	1.72	0.01	99.3	3.76	36.77	59.47
	48.5	0.14	1.31	0.07	34.6	1.12	11.3	0.94	0.00	98.0	2.14	36.06	61.80
	48.9	0.11	0.15	0.01	36.2	1.15	11.7	0.90	0.04	99.2	1.98	35.85	62.17
	48.9	0.13	0.11	0.02	36.0	1.19	11.7	1.02	0.00	98.9	2.24	35.78	61.98
	48.9	0.13	0.20	0.04	33.3	1.01	12.0	2.83	0.01	98.5	6.22	36.71	57.07
	48.9	0.18	0.26	0.05	33.9	1.09	11.7	2.70	0.02	98.8	5.94	35.75	58.31
	48.9	0.16	0.22	0.10	35.6	1.07	12.0	0.87	0.02	98.9	1.91	36.86	61.24
	48.8	0.16	0.18	0.07	35.8	1.16	11.7	0.99	0.00	98.9	2.19	36.04	61.78
average	48.9	0.14	0.29	0.05	35.1	1.12	11.8	1.44	0.01	98.8	3.18	36.23	60.59
2 s.d.	0.3	0.04	0.72	0.05	1.9	0.12	0.4	1.50	0.02	0.8	3.28	0.84	3.52
GRA 98114	49.0	0.16	0.19	0.06	36.0	1.23	11.9	0.91	0.00	99.4	1.99	36.34	61.67
	49.1	0.21	0.39	0.12	36.1	1.20	11.7	0.84	0.03	99.7	1.85	36.01	62.14
	49.3	0.13	0.20	0.09	33.5	1.03	11.7	3.38	0.00	99.4	7.36	35.53	57.10
	49.0	0.11	0.18	0.08	36.3	1.16	11.8	0.96	0.04	99.7	2.10	35.85	62.05
	49.5	0.11	0.14	0.05	35.3	1.14	12.4	0.95	0.00	99.6	2.07	37.80	60.13
	49.2	0.15	0.17	0.10	35.2	1.20	12.0	0.98	0.01	99.0	2.17	37.07	60.76
	49.0	0.14	1.11	0.05	35.4	1.18	11.4	0.80	0.00	99.1	1.81	35.89	62.30
	49.2	0.19	0.26	0.09	29.2	0.95	11.6	6.53	0.02	98.0	14.38	35.41	50.22
	49.1	0.17	0.13	0.06	36.3	1.19	11.8	0.80	0.00	99.6	1.75	35.98	62.27
	49.6	0.15	0.51	0.05	35.8	1.16	11.9	0.88	0.03	100.1	1.94	36.53	61.53
average	49.2	0.15	0.33	0.07	34.9	1.14	11.8	1.70	0.01	99.3	3.74	36.24	60.02
2 s.d.	0.4	0.06	0.60	0.05	4.3	0.18	0.6	3.74	0.03	1.1	8.21	1.46	7.57

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
LAP 031062	51.8	0.17	0.95	0.53	24.7	0.78	20.5	0.54	0.01	100.0	1.11	59.01	39.87
	52.2	0.15	0.84	0.53	25.3	0.81	19.8	0.59	0.01	101.2	1.20	58.72	40.08
	51.7	0.35	0.95	0.39	22.6	0.74	19.8	3.88	0.03	100.5	7.91	56.12	35.97
	52.7	0.29	0.91	0.29	22.7	0.74	20.0	3.02	0.01	100.7	6.22	57.34	36.44
	51.2	0.31	0.82	0.29	22.7	0.71	19.4	4.65	0.04	100.2	9.42	54.63	35.95
	51.3	0.32	0.99	0.34	24.0	0.81	20.3	1.50	0.00	99.6	3.10	58.31	38.59
	51.5	0.31	0.71	0.30	24.1	0.77	20.2	1.48	0.01	99.4	3.06	58.11	38.83
	50.8	0.24	0.77	0.45	25.1	0.79	19.9	0.81	0.01	98.8	1.69	57.56	40.75
	50.4	0.36	1.03	0.46	23.2	0.77	18.9	4.00	0.04	99.2	8.26	54.33	37.41
	50.6	0.31	0.72	0.47	23.5	0.78	19.5	2.47	0.01	98.4	5.15	56.69	38.17
	51.1	0.26	0.71	0.33	24.5	0.78	19.7	1.58	0.03	99.0	3.28	56.94	39.79
average	51.4	0.28	0.85	0.40	23.9	0.77	19.9	2.23	0.02	99.7	4.58	57.07	38.35
2 s.d.	1.4	0.14	0.24	0.19	1.9	0.06	1.1	2.93	0.03	1.8	5.97	3.09	3.43
LAR 06875	49.6	0.10	0.34	0.04	33.8	1.11	12.0	2.64	0.13	99.7	5.78	36.44	57.78
	49.4	0.37	1.53	0.14	30.3	0.91	12.6	4.72	0.03	100.0	10.28	38.19	51.53
	49.2	0.15	0.36	0.04	33.8	1.02	12.3	2.04	0.01	99.0	4.47	37.56	57.96
	49.3	0.07	0.48	0.06	35.6	1.09	11.8	0.89	0.00	99.2	1.97	36.32	61.71
	49.6	0.13	0.16	0.13	35.8	1.11	11.8	0.98	0.00	99.6	2.16	36.27	61.57
	49.6	0.08	0.15	0.05	35.2	1.05	12.3	1.05	0.04	99.5	2.30	37.50	60.20
	49.5	0.11	0.31	0.07	34.9	1.07	12.1	1.39	0.02	99.4	3.06	36.94	60.00
	49.3	0.08	0.13	0.05	35.8	1.10	12.1	0.78	0.00	99.4	1.71	36.93	61.36
	49.5	0.07	0.44	0.07	35.3	1.06	12.2	1.22	0.01	99.9	2.66	37.13	60.22
	49.0	0.95	1.51	0.11	31.7	0.98	10.7	4.21	0.01	99.1	9.61	33.96	56.43
average	49.4	0.21	0.54	0.07	34.2	1.05	12.0	1.99	0.02	99.5	4.40	36.72	58.88
2 s.d.	0.4	0.55	1.06	0.08	3.8	0.13	1.0	2.86	0.08	0.7	6.36	2.29	6.26
LEW 85305	48.4	0.37	0.09	0.16	36.4	1.09	11.3	1.54	0.01	99.3	3.37	34.37	62.26
	48.8	0.32	0.06	0.15	35.7	1.12	11.4	1.79	0.00	99.2	3.95	34.78	61.27
	48.8	0.37	0.06	0.19	35.6	1.11	11.0	1.99	0.01	99.1	4.41	33.92	61.66
	49.5	0.27	0.06	0.13	35.4	1.12	11.5	1.81	0.01	99.8	3.98	35.16	60.86
	49.0	0.36	0.07	0.16	35.4	1.06	11.2	2.42	0.02	99.8	5.30	34.20	60.51
	49.3	0.33	0.09	0.16	35.7	1.08	11.2	1.80	0.02	99.7	3.98	34.44	61.58
	49.2	0.29	0.06	0.15	35.8	1.08	11.2	1.65	0.00	99.5	3.65	34.45	61.89
	49.1	0.39	0.08	0.15	36.1	1.13	11.0	1.62	0.02	99.6	3.59	34.01	62.40
average	49.0	0.34	0.07	0.15	35.8	1.10	11.2	1.83	0.01	99.5	4.03	34.42	61.55
2 s.d.	0.7	0.09	0.03	0.03	0.6	0.05	0.3	0.55	0.01	0.5	1.21	0.81	1.31

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
LEW 87002	52.9	0.18	0.64	0.26	20.2	0.59	23.8	1.07	0.01	99.6	2.13	66.32	31.54
	52.8	0.12	0.68	0.30	19.8	0.53	24.2	0.85	0.02	99.4	1.69	67.34	30.97
	52.0	0.21	0.74	0.21	20.0	0.58	23.3	1.61	0.03	98.7	3.24	65.26	31.50
	51.6	0.27	0.84	0.24	20.0	0.60	23.5	1.54	0.01	98.6	3.09	65.58	31.32
	52.4	0.19	0.65	0.18	19.8	0.57	23.3	1.49	0.00	98.7	3.01	65.68	31.31
	52.2	0.25	0.85	0.27	20.2	0.59	23.2	1.59	0.00	99.1	3.21	65.06	31.73
	52.3	0.15	0.87	0.32	20.0	0.56	23.7	0.85	0.00	98.8	1.71	66.71	31.58
	52.1	0.18	0.73	0.21	20.0	0.56	23.9	1.04	0.00	98.8	2.07	66.64	31.29
	52.5	0.12	0.89	0.38	19.6	0.53	24.1	0.77	0.01	98.9	1.54	67.62	30.84
	52.8	0.13	0.74	0.31	19.8	0.53	24.3	0.84	0.02	99.5	1.68	67.49	30.83
	51.9	0.18	0.91	0.50	20.2	0.59	23.6	0.96	0.00	98.8	1.93	66.25	31.83
average	52.3	0.18	0.78	0.29	20.0	0.57	23.7	1.14	0.01	99.0	2.30	66.36	31.34
2 s.d.	0.9	0.10	0.20	0.18	0.4	0.05	0.8	0.68	0.02	0.7	1.38	1.79	0.68
PCA 91193	51.2	0.21	0.42	0.13	27.4	0.89	17.2	2.08	0.02	99.6	4.39	50.44	45.17
	50.8	0.22	0.47	0.16	28.0	0.88	17.5	1.16	0.00	99.2	2.44	51.40	46.16
	51.1	0.26	0.59	0.15	27.2	0.91	18.3	1.34	0.02	99.9	2.78	53.06	44.16
	51.4	0.25	0.57	0.16	27.7	0.86	18.1	1.18	0.00	100.3	2.46	52.55	44.99
	52.4	0.23	0.49	0.14	28.2	0.85	18.0	1.69	0.06	102.0	3.47	51.33	45.20
	51.4	0.23	0.57	0.18	27.6	0.85	17.9	1.33	0.00	100.1	2.78	52.11	45.12
	51.2	0.23	0.52	0.17	27.1	0.90	18.3	1.31	0.02	99.7	2.74	53.07	44.19
	51.2	0.22	0.45	0.18	28.4	0.88	18.0	0.91	0.00	100.3	1.88	52.02	46.09
	50.7	0.22	0.51	0.15	28.1	0.87	17.7	1.24	0.01	99.5	2.59	51.45	45.96
average	51.3	0.23	0.51	0.16	27.8	0.88	17.9	1.36	0.01	100.1	2.84	51.94	45.23
2 s.d.	0.9	0.03	0.12	0.03	0.9	0.04	0.7	0.68	0.04	1.7	1.43	1.75	1.49
QUE 97014	49.0	0.10	0.15	0.05	36.3	1.10	12.1	0.86	0.00	99.7	1.86	36.51	61.63
	49.0	0.11	0.23	0.07	36.2	1.10	12.1	1.05	0.02	99.9	2.27	36.38	61.35
	48.2	0.12	0.27	0.13	35.4	1.04	11.7	2.35	0.05	99.3	5.06	35.22	59.71
	48.2	0.11	0.18	0.05	36.3	1.08	11.7	1.22	0.00	98.8	2.66	35.62	61.72
	48.5	0.11	0.17	0.08	37.2	1.14	11.6	0.88	0.01	99.6	1.90	35.02	63.08
	47.8	0.11	0.12	0.04	37.0	1.12	11.8	0.84	0.00	98.7	1.81	35.59	62.60
average	48.4	0.11	0.18	0.07	36.4	1.10	11.8	1.20	0.01	99.3	2.59	35.72	61.68
2 s.d.	1.0	0.01	0.10	0.06	1.2	0.07	0.4	1.16	0.04	0.9	2.50	1.21	2.33

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
QUE 99055	49.1	0.10	0.31	0.09	35.6	1.09	12.0	0.83	0.03	99.1	1.82	36.76	61.42
	49.7	0.10	0.28	0.17	35.5	1.11	12.7	0.75	0.02	100.3	1.62	38.32	60.07
	50.2	0.11	0.33	0.22	35.2	1.07	13.1	1.29	0.02	101.6	2.74	38.78	58.48
	49.5	0.10	0.27	0.10	36.1	1.10	12.1	0.72	0.02	100.0	1.58	36.73	61.69
	50.7	0.10	0.26	0.13	34.5	1.07	12.1	2.85	0.02	101.8	6.10	36.10	57.79
	48.8	0.10	0.26	0.12	35.7	1.04	11.9	0.82	0.02	98.8	1.81	36.66	61.52
	49.2	0.14	0.38	0.41	36.4	1.08	11.9	0.80	0.02	100.4	1.74	36.22	62.04
	49.5	0.08	0.28	0.18	36.2	1.06	12.0	0.73	0.02	100.0	1.59	36.54	61.87
average	49.6	0.10	0.30	0.17	35.6	1.08	12.2	1.10	0.02	100.2	2.38	37.01	60.61
2 s.d.	1.3	0.03	0.08	0.21	1.2	0.05	0.9	1.46	0.00	2.1	3.10	1.97	3.30
RKPA 80204	50.2	0.08	0.17	0.04	36.0	1.14	12.2	1.13	0.00	100.9	2.45	36.77	60.79
	49.4	0.09	0.27	0.08	34.2	1.02	11.8	2.47	0.03	99.4	5.42	36.11	58.47
	49.8	0.08	0.18	0.11	35.7	1.10	12.4	0.86	0.00	100.2	1.87	37.46	60.68
	50.2	0.08	0.16	0.08	35.9	1.10	12.0	1.44	0.00	101.0	3.11	36.23	60.67
	49.1	0.06	0.18	0.03	35.9	1.11	11.9	0.92	0.01	99.3	2.02	36.41	61.57
	50.3	0.08	0.16	0.09	36.3	1.11	12.4	0.84	0.01	101.2	1.81	37.10	61.08
	50.5	0.09	0.24	0.06	36.1	1.11	12.4	1.21	0.01	101.7	2.59	36.94	60.47
	50.6	0.07	0.19	0.04	35.8	1.05	12.3	1.71	0.01	101.7	3.66	36.61	59.74
	50.1	0.07	0.13	0.06	36.7	1.13	12.2	1.19	0.01	101.5	2.54	36.24	61.23
average	50.0	0.08	0.19	0.07	35.8	1.09	12.2	1.31	0.01	100.8	2.83	36.65	60.52
2 s.d.	1.0	0.02	0.09	0.05	1.4	0.08	0.4	1.04	0.02	1.8	2.28	0.91	1.85
SCO 06041	49.6	0.18	0.11	0.15	26.8	0.93	20.0	0.78	0.00	98.6	1.57	56.13	42.29
	49.3	0.21	0.14	0.21	25.7	0.85	19.0	2.74	0.02	98.1	5.57	53.67	40.76
	51.1	0.07	0.05	0.06	26.9	0.90	19.7	0.78	0.00	99.6	1.58	55.75	42.68
	51.0	0.13	0.14	0.14	26.8	0.89	19.5	0.80	0.03	99.4	1.63	55.54	42.83
	50.4	0.13	0.14	0.19	26.5	0.91	19.2	0.78	0.00	98.2	1.62	55.46	42.92
	50.7	0.10	0.12	0.17	26.4	0.86	19.1	0.87	0.02	98.3	1.81	55.31	42.88
	52.5	0.10	0.04	0.05	26.6	0.85	19.3	1.29	0.02	100.8	2.64	54.95	42.41
	51.9	0.11	0.12	0.16	26.8	0.93	18.9	0.84	0.00	99.7	1.75	54.75	43.50
	51.5	0.20	0.12	0.22	26.4	0.88	18.7	0.90	0.02	99.0	1.90	54.71	43.39
average	50.9	0.14	0.11	0.15	26.5	0.89	19.3	1.09	0.01	99.1	2.23	55.14	42.63
2 s.d.	2.1	0.10	0.07	0.12	0.8	0.06	0.8	1.28	0.02	1.8	2.59	1.45	1.61

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRO 95533	49.1	0.16	0.02	0.07	36.2	1.19	11.9	0.83	0.02	99.4	1.81	36.23	61.96
	49.4	0.12	0.00	0.11	35.8	1.14	12.0	1.00	0.00	99.6	2.18	36.63	61.19
	49.8	0.12	0.02	0.09	34.6	1.08	12.1	2.34	0.01	100.1	5.06	36.40	58.54
	49.9	0.09	0.03	0.08	35.5	1.12	12.1	1.13	0.04	100.0	2.48	36.97	60.55
	50.1	0.14	0.02	0.05	33.3	1.04	11.8	3.27	0.02	99.7	7.15	35.93	56.92
	49.3	0.17	0.05	0.09	35.7	1.17	11.2	1.43	0.03	99.1	3.18	34.68	62.15
	49.4	0.17	0.02	0.11	35.4	1.21	11.6	1.03	0.01	98.9	2.30	36.01	61.70
	49.5	0.13	0.03	0.09	32.3	1.02	11.3	4.38	0.03	98.8	9.67	34.76	55.56
average	49.5	0.14	0.02	0.09	34.8	1.12	11.8	1.92	0.02	99.5	4.23	35.95	59.82
2 s.d.	0.7	0.05	0.03	0.04	2.8	0.14	0.7	2.59	0.03	1.0	5.70	1.66	5.02
Millbillillie	47.0	1.10	0.06	1.34	32.7	1.04	11.0	4.47	0.02	98.8	9.85	33.84	56.31
	49.3	0.16	0.03	0.12	35.1	1.09	12.1	0.76	0.00	98.6	1.69	37.40	60.91
	49.5	0.11	0.05	0.07	34.3	1.09	12.4	1.30	0.02	98.8	2.88	38.01	59.11
	49.8	0.14	0.03	0.09	34.3	1.01	12.3	2.08	0.02	99.7	4.52	37.20	58.28
	49.6	0.14	0.05	0.18	35.5	1.07	12.4	0.90	0.00	99.7	1.96	37.59	60.46
	49.0	0.23	0.03	0.32	35.3	1.09	12.3	1.21	0.01	99.5	2.65	37.26	60.09
	49.6	0.08	0.04	0.10	35.7	1.09	12.6	0.69	0.01	99.9	1.48	38.13	60.39
	49.5	0.11	0.04	0.08	35.1	1.10	12.3	0.80	0.01	99.0	1.77	37.83	60.40
	49.1	0.06	0.08	0.06	35.0	1.08	12.3	0.71	0.02	98.4	1.58	37.88	60.54
average	49.1	0.23	0.04	0.26	34.8	1.07	12.2	1.43	0.01	99.2	3.15	37.24	59.61
2 s.d.	1.7	0.65	0.03	0.82	1.8	0.06	0.9	2.44	0.02	1.1	5.38	2.63	2.97
Dhofar 007	50.6	0.38	0.71	0.40	27.0	0.77	17.8	2.36	0.05	100.0	4.89	51.30	43.81
	50.7	0.36	0.69	0.42	27.5	0.90	17.7	1.52	0.03	99.9	3.18	51.77	45.05
	50.3	0.34	0.88	0.47	26.8	0.84	17.6	2.17	0.06	99.4	4.57	51.49	43.94
	50.6	0.24	0.55	0.42	27.4	0.83	18.1	1.40	0.06	99.6	2.91	52.56	44.53
	50.5	0.22	0.32	0.47	26.3	0.84	18.1	1.96	0.01	98.7	4.11	52.79	43.10
average	50.5	0.31	0.63	0.44	27.0	0.84	17.9	1.88	0.04	99.5	3.93	51.98	44.09
2 s.d.	0.3	0.15	0.42	0.07	1.0	0.09	0.5	0.82	0.04	1.0	1.72	1.32	1.48

Table A1: Low-Ca major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
Juvinas	50.3	0.10	0.32	0.18	31.6	1.05	13.7	3.02	0.00	100.2	6.48	40.73	52.79
	50.1	0.15	0.30	0.46	33.0	1.09	13.4	1.91	0.04	100.4	4.13	40.36	55.51
	49.9	0.16	0.32	0.53	31.9	1.06	13.6	2.46	0.00	99.9	5.32	40.91	53.77
	50.4	0.11	0.26	0.17	32.0	1.00	13.5	2.45	0.01	100.0	5.30	40.72	53.98
	50.5	0.13	0.34	0.23	30.2	1.02	13.2	4.67	0.02	100.3	10.01	39.48	50.50
	49.9	0.10	0.31	0.27	33.3	1.06	13.4	1.75	0.02	100.1	3.78	40.24	55.98
	49.3	0.21	0.48	1.09	32.1	1.04	13.6	1.86	0.00	99.7	4.05	41.33	54.62
	50.1	0.12	0.29	0.19	33.0	1.08	13.7	1.52	0.03	100.1	3.28	41.11	55.60
	49.4	0.11	0.35	0.23	32.0	1.08	13.1	2.38	0.00	98.6	5.23	39.92	54.85
	50.1	0.12	0.26	0.13	33.4	1.11	13.4	1.02	0.00	99.5	2.23	40.73	57.04
	47.7	0.30	0.75	1.86	33.5	1.08	13.0	0.72	0.00	98.9	1.60	40.33	58.07
	49.8	0.10	0.32	0.18	32.6	1.13	13.4	1.71	0.06	99.3	3.72	40.78	55.51
	48.7	0.21	0.60	1.26	32.5	1.08	13.2	2.12	0.02	99.6	4.63	39.97	55.40
	49.6	0.12	0.36	0.43	32.1	1.05	13.6	2.47	0.07	99.8	5.31	40.77	53.91
	49.7	0.12	0.34	0.27	29.7	1.00	13.6	4.35	0.03	99.2	9.36	40.67	49.97
	50.0	0.12	0.33	0.13	31.2	1.03	13.2	3.45	0.02	99.5	7.47	39.79	52.74
	48.9	0.22	0.62	1.29	31.4	1.03	13.1	3.04	0.03	99.6	6.66	39.79	53.55
average	50.2	0.12	0.37	0.20	31.4	0.99	12.7	4.55	0.04	100.5	9.74	37.87	52.39
2 s.d.	49.7	0.15	0.39	0.50	32.0	1.05	13.4	2.53	0.02	99.7	5.46	40.31	54.23
	1.4	0.11	0.27	1.02	2.1	0.08	0.6	2.29	0.04	1.1	4.88	1.58	4.15
Camel Donga	50.0	0.14	0.06	0.10	33.5	1.40	13.6	1.83	0.00	100.6	3.90	40.26	55.84
	49.6	0.08	0.04	0.09	31.0	1.19	13.5	3.52	0.00	99.0	7.58	40.36	52.05
	49.2	0.15	0.04	0.12	33.5	1.33	13.3	1.86	0.03	99.6	4.00	39.87	56.12
	49.9	0.13	0.07	0.06	30.9	1.29	13.1	4.28	0.02	99.8	9.16	39.13	51.71
	49.6	0.07	0.01	0.08	34.5	1.40	13.6	0.91	0.00	100.1	1.94	40.38	57.67
	50.1	0.11	0.01	0.09	34.2	1.34	13.6	0.76	0.01	100.2	1.63	40.80	57.57
	50.1	0.11	0.05	0.10	32.6	1.32	13.0	2.59	0.01	99.9	5.61	39.26	55.14
	49.7	0.16	0.04	0.12	32.8	1.26	12.4	3.36	0.03	99.9	7.28	37.26	55.46
	50.2	0.16	0.05	0.08	31.8	1.27	13.1	3.33	0.02	100.1	7.16	39.39	53.45
	49.6	0.14	0.04	0.18	33.8	1.35	13.2	0.88	0.00	99.3	1.93	40.23	57.85
	50.1	0.08	0.03	0.05	33.9	1.36	13.6	0.96	0.00	100.0	2.08	40.78	57.14
average	50.1	0.06	0.03	0.02	32.9	1.29	13.5	1.63	0.00	99.5	3.53	40.76	55.72
2 s.d.	49.9	0.11	0.04	0.09	33.0	1.32	13.3	2.16	0.01	99.8	4.65	39.87	55.48
	0.61	0.07	0.04	0.08	2.4	0.12	0.7	2.44	0.02	0.9	5.25	2.02	4.19

Table A2: High-Ca pyroxene major element concentrations in wt%

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo%	En%	Fs%
EET 832227	49.7	0.90	2.75	0.72	13.2	0.45	12.7	19.4	0.04	99.8	40.97	37.30	21.73
	49.3	0.81	2.86	0.62	14.7	0.50	11.8	19.3	0.04	100	40.96	34.70	24.34
	49.7	0.98	2.92	0.72	12.9	0.43	12.7	19.8	0.14	100	41.64	37.13	21.23
	49.1	0.91	2.80	0.63	14.2	0.49	11.9	19.5	0.05	99.6	41.37	35.11	23.52
	48.9	1.22	3.06	0.91	12.6	0.39	12.4	20.1	0.07	99.8	42.52	36.61	20.86
	49.4	1.11	2.96	0.80	12.8	0.41	12.8	19.4	0.06	99.7	41.19	37.60	21.21
	48.2	1.07	4.08	0.94	13.3	0.44	11.8	18.6	0.03	98.5	41.01	36.14	22.85
	48.7	0.88	4.89	1.15	14.2	0.51	11.2	18.4	0.06	100	40.77	34.63	24.59
	48.8	0.60	4.44	0.92	13.0	0.48	10.9	19.8	0.03	99.0	43.91	33.61	22.48
	49.4	0.97	2.79	0.72	13.8	0.44	12.4	19.3	0.05	99.8			
	48.9	1.14	2.83	0.68	14.1	0.53	11.5	19.8	0.04	99.7	40.82	36.46	22.72
	48.8	1.03	2.92	0.70	14.1	0.53	11.5	20.0	0.03	99.7	42.44	34.09	23.47
	49.1	0.90	3.13	0.49	14.1	0.50	11.5	19.6	0.04	99.4	41.98	34.39	23.63
	49.0	0.94	2.77	0.59	14.3	0.47	11.7	19.3	0.06	99.1	41.27	34.85	23.89
	49.3	0.94	2.81	0.56	14.0	0.49	12.0	19.7	0.02	99.8	41.65	35.26	23.09
	49.0	0.93	2.64	0.74	13.8	0.48	11.3	20.4	0.06	99.3	43.62	33.47	22.92
	49.7	0.87	1.67	0.36	15.9	0.52	11.9	18.2	0.05	99.0	38.59	35.10	26.31
	49.6	0.69	1.67	0.35	15.9	0.58	12.4	17.5	0.05	98.7	37.17	36.49	26.33
average	50.1	0.56	2.23	0.23	16.0	0.58	12.2	16.3	0.05	98.3	35.64	37.03	27.33
2 s.d.	49.2	0.92	2.96	0.67	14.1	0.48	11.9	19.2	0.05	99.5	40.97	35.55	23.47
	0.9	0.34	1.59	0.45	2.03	0.10	1.1	2.0	0.05	1.09	4.09	2.62	3.62
EET 87548	51.9	0.20	0.68	0.18	10.1	0.38	13.5	22.2	0.05	99.3	45.41	38.53	16.06
	51.5	0.22	1.02	0.25	11.7	0.42	12.9	21.0	0.09	99.1	43.64	37.38	18.98
	51.8	0.21	0.71	0.24	10.1	0.42	13.5	22.2	0.06	99.3	45.39	38.54	16.07
	52.2	0.21	0.60	0.17	10.1	0.38	13.6	22.5	0.05	99.8	45.59	38.37	16.04
	52.0	0.26	0.83	0.27	10.7	0.43	13.4	22.0	0.06	99.9	44.96	38.05	16.99
	51.9	0.22	0.80	0.23	10.3	0.42	13.6	22.1	0.08	99.7	45.10	38.56	16.34
	51.8	0.19	1.44	0.20	10.1	0.42	13.2	21.5	0.06	99.0	44.91	38.53	16.56
	50.7	0.24	2.10	0.19	10.3	0.41	13.2	21.4	0.04	98.6	44.85	38.42	16.73
	51.7	0.21	0.86	0.17	10.1	0.39	13.6	22.2	0.06	99.2	45.29	38.59	16.11
average	51.7	0.22	1.00	0.21	10.4	0.41	13.4	21.9	0.06	99.31	45.02	38.33	16.65
2 s.d.	0.9	0.04	0.96	0.07	1.05	0.04	0.5	1.0	0.03	0.83	1.15	0.79	1.87

Table A2: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRA 98006	50.2	0.34	0.73	0.24	23.5	0.70	10.6	14.6	0.04	101	30.55	30.94	38.51
	50.2	0.29	0.85	0.27	17.0	0.50	10.1	20.3	0.06	99.6	42.53	29.63	27.84
	51.1	0.32	0.92	0.23	17.8	0.50	10.3	19.9	0.06	101	41.47	29.67	28.87
	50.1	0.32	0.93	0.29	16.5	0.50	10.0	20.5	0.07	99.2	43.29	29.41	27.30
	50.4	0.25	0.91	0.27	16.8	0.55	10.1	20.7	0.08	99.9	43.27	29.28	27.44
	49.9	0.27	0.65	0.24	17.7	0.49	10.4	19.7	0.09	99.4	41.00	30.24	28.77
	49.9	0.25	2.70	0.21	15.9	0.53	9.8	19.7	0.03	99.0	43.07	29.78	27.15
	50.4	0.30	0.86	0.25	17.1	0.46	10.2	20.2	0.07	99.8	42.36	29.67	27.97
	50.3	0.21	0.71	0.14	16.3	0.51	10.3	20.9	0.04	99.5	43.56	29.95	26.49
	49.9	0.34	0.90	0.30	16.4	0.47	10.0	20.8	0.10	99.2	43.76	29.33	26.92
average	50.2	0.29	1.01	0.24	17.5	0.52	10.2	19.7	0.06	99.8	41.49	29.79	28.72
2 s.d.	0.7	0.08	1.20	0.09	4.4	0.13	0.5	3.7	0.04	1.41	7.89	0.99	7.04
GRA 98033	50.0	0.30	0.73	0.26	16.6	0.51	10.0	20.7	0.08	99.3	43.49	29.34	27.17
	50.3	0.21	0.58	0.19	17.1	0.48	10.0	20.5	0.07	99.5	42.87	29.16	27.97
	49.9	0.27	0.72	0.18	18.4	0.55	9.9	19.4	0.07	99.4	40.80	29.03	30.17
	49.8	0.34	1.13	0.21	17.1	0.49	9.8	20.6	0.07	99.6	43.31	28.60	28.09
	50.2	0.27	0.73	0.23	17.0	0.53	10.0	21.0	0.09	100	43.54	28.88	27.58
	49.8	0.35	0.88	0.25	16.4	0.47	9.8	21.1	0.09	99.1	44.34	28.66	27.00
	50.3	0.20	0.59	0.20	17.2	0.53	10.3	21.0	0.08	100	43.07	29.42	27.52
	49.2	0.27	1.05	0.19	16.6	0.48	9.7	20.2	0.12	97.8	43.39	28.82	27.79
	49.5	0.22	0.67	0.18	17.5	0.52	10.2	20.5	0.07	99.3	42.34	29.30	28.35
	49.7	0.17	0.71	0.12	16.5	0.49	10.0	20.8	0.04	98.6	43.59	29.35	27.06
average	49.9	0.26	0.78	0.20	17.1	0.50	10.0	20.6	0.08	99.3	43.07	29.05	27.87
2 s.d.	0.7	0.12	0.37	0.08	1.2	0.06	0.4	1.0	0.04	1.46	1.90	0.60	1.85
GRA 98043	50.0	0.26	0.70	0.22	17.9	0.54	9.7	20.5	0.07	99.9	42.71	28.08	29.21
	49.7	0.24	0.67	0.21	17.6	0.55	9.8	20.8	0.07	99.63	43.14	28.28	28.57
	50.3	0.26	0.81	0.24	19.0	0.58	9.7	19.1	0.04	100	40.36	28.38	31.26
	50.5	0.26	0.87	0.26	18.2	0.52	9.5	20.0	0.08	100	42.23	27.92	29.86
	50.4	0.33	0.70	0.21	17.1	0.52	9.8	20.8	0.06	99.9	43.49	28.59	27.92
	49.6	0.42	1.05	0.29	24.1	0.68	9.6	15.4	0.04	101	32.34	28.21	39.45
	49.7	0.22	0.63	0.24	18.2	0.56	9.6	20.4	0.05	100	42.49	27.96	29.55
	50.0	0.31	0.73	0.20	20.1	0.51	9.6	18.3	0.07	100	38.71	28.17	33.12
	50.5	0.36	1.04	0.25	18.5	0.54	9.5	19.4	0.09	100	41.16	28.17	30.67
	50.8	0.17	0.64	0.21	18.7	0.59	9.8	19.7	0.10	101	41.09	28.51	30.40
average	50.2	0.28	0.78	0.23	18.9	0.56	9.7	19.4	0.07	100.13	40.77	28.23	31.00
2 s.d.	0.8	0.14	0.31	0.05	3.9	0.10	0.2	3.2	0.04	1.04	6.59	0.44	6.61

Table A2: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRA 98055	49.9	0.38	0.77	0.20	17.7	0.50	10.1	20.2	0.07	99.9	41.98	29.26	28.76
	48.9	0.41	1.31	0.22	17.1	0.52	9.9	20.0	0.06	98.5	42.53	29.13	28.34
	50.0	0.37	0.66	0.22	18.4	0.53	10.2	19.6	0.09	100	40.75	29.45	29.80
	48.8	0.36	0.74	0.23	22.5	0.58	10.1	15.2	0.09	98.7	32.40	30.09	37.51
	50.0	0.32	0.68	0.24	17.1	0.51	10.2	20.5	0.06	99.5	42.75	29.50	27.75
	49.6	0.43	0.92	0.27	16.9	0.51	10.0	20.2	0.10	99.0	42.68	29.45	27.87
	50.1	0.41	0.85	0.25	17.4	0.50	10.0	20.2	0.08	99.7	42.36	29.08	28.55
	50.2	0.37	0.74	0.22	16.8	0.49	10.0	20.8	0.07	99.7	43.44	29.12	27.44
	49.6	0.47	1.07	0.33	17.3	0.55	9.9	20.1	0.07	99.4	42.41	29.13	28.46
	49.9	0.37	0.86	0.23	23.7	0.69	10.5	14.7	0.06	101.1	30.79	30.49	38.71
average	49.7	0.39	0.86	0.24	18.5	0.54	10.1	19.2	0.07	99.6	40.21	29.47	30.32
2 s.d.	0.9	0.08	0.40	0.07	5.0	0.12	0.4	4.5	0.03	1.48	9.21	0.94	8.33
GRA 89114	50.2	0.41	1.18	0.25	17.3	0.53	9.9	20.0	0.07	99.8	42.32	29.08	28.60
	49.4	0.38	0.91	0.28	18.0	0.52	10.1	19.6	0.10	99.4	41.02	29.54	29.44
	49.7	0.28	0.71	0.18	17.1	0.51	10.2	20.8	0.06	99.5	43.06	29.33	27.61
	49.6	0.37	0.93	0.24	22.3	0.65	10.3	16.5	0.05	101	34.22	29.64	36.14
	49.8	0.36	1.04	0.24	17.6	0.54	9.4	20.3	0.08	99.3	43.11	27.68	29.21
	49.7	0.36	0.75	0.18	17.6	0.50	9.6	20.8	0.09	99.5	43.49	27.83	28.68
	49.0	0.35	0.86	0.28	18.3	0.52	9.5	19.8	0.08	98.6	41.82	28.02	30.16
	49.1	0.41	1.02	0.24	21.6	0.65	10.2	15.9	0.06	99.2	33.92	30.27	35.81
	49.2	0.37	0.80	0.22	19.1	0.55	9.5	19.2	0.08	99.0	40.58	27.91	31.50
	49.9	0.33	0.71	0.19	17.1	0.56	10.1	20.5	0.07	99.4	42.76	29.43	27.81
average	49.6	0.36	0.89	0.23	18.6	0.55	9.9	19.3	0.07	99.5	40.63	28.87	30.50
2 s.d.	0.8	0.08	0.31	0.07	3.8	0.11	0.7	3.4	0.03	1.22	7.16	1.85	6.20
LAP 031062	51.7	0.34	1.27	0.41	12.2	0.44	14.5	19.5	0.09	101	39.54	41.09	19.37
	50.5	0.57	1.63	0.50	10.3	0.41	14.2	21.2	0.14	99.3	43.27	40.27	16.46
	49.2	4.40	1.22	0.73	16.2	0.49	16.9	11.4	0.11	101	24.00	49.40	26.61
	49.4	2.41	1.18	0.40	17.2	0.56	17.0	11.6	0.06	100.0	23.87	48.53	27.60
	51.2	0.61	1.82	0.64	11.9	0.42	14.5	19.8	0.15	101	40.11	41.07	18.81
	50.5	0.72	2.19	0.76	11.4	0.42	13.7	20.2	0.14	100	41.96	39.58	18.46
	50.3	0.51	1.40	0.49	11.2	0.40	14.7	19.5	0.14	98.6	40.09	41.99	17.92
average	50.4	1.37	1.53	0.56	12.9	0.45	15.1	17.6	0.12	100.03	36.12	43.13	20.75
2 s.d.	1.8	3.03	0.75	0.29	5.4	0.12	2.7	8.4	0.06	1.71	16.84	8.12	8.89

Table A2: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
LAR 06875	46.6	1.53	2.21	0.14	19.2	0.58	8.9	17.9	0.07	97.1	39.57	27.31	33.12
	49.8	0.32	0.87	0.26	16.4	0.48	10.1	20.7	0.10	99.0	43.55	29.58	26.87
	50.2	0.25	1.01	0.20	16.8	0.48	10.1	20.4	0.07	99.5	42.90	29.57	27.53
	50.3	0.29	0.72	0.16	16.6	0.50	10.1	20.8	0.08	99.5	43.46	29.42	27.12
	50.1	0.39	0.92	0.30	16.9	0.51	10.1	20.5	0.07	99.8	42.94	29.37	27.69
	50.3	0.20	0.64	0.16	18.0	0.52	10.4	19.2	0.06	99.6	40.22	30.41	29.37
	50.6	0.21	0.57	0.18	17.6	0.55	10.4	19.5	0.07	99.8	40.88	30.31	28.82
	50.2	0.45	1.14	0.18	17.9	0.48	10.8	19.1	0.10	100	39.65	31.26	29.09
	50.0	0.34	0.90	0.26	16.9	0.55	10.1	20.3	0.07	99.5	42.68	29.54	27.78
	50.6	0.24	0.74	0.16	16.0	0.50	10.1	21.1	0.05	99.5	44.27	29.52	26.21
average	49.9	0.42	0.97	0.20	17.2	0.51	10.1	20.0	0.07	99.4	42.01	29.63	28.36
2 s.d.	2.3	0.80	0.93	0.11	1.9	0.07	1.0	2.0	0.03	1.74	3.51	2.03	3.90
LEW 85305	49.0	0.60	0.99	0.31	18.7	0.59	9.2	18.8	0.12	98.3	40.57	27.79	31.63
	49.1	0.70	1.24	0.33	21.0	0.63	9.5	16.4	0.10	99.0	35.62	28.63	35.75
	48.8	0.62	1.15	0.30	22.5	0.73	9.2	15.4	0.08	98.9	33.66	28.02	38.32
	48.9	0.62	1.18	0.33	22.5	0.68	9.3	15.5	0.07	99.2	33.72	28.11	38.17
	48.6	0.62	1.24	0.40	22.7	0.71	9.2	14.8	0.12	98.4	32.60	28.34	39.06
	49.7	0.66	1.25	0.31	19.7	0.57	9.3	17.7	0.12	99.3	38.49	28.12	33.39
	49.7	0.64	1.19	0.31	21.4	0.64	9.6	16.3	0.11	99.9	35.15	28.84	36.01
average	49.1	0.64	1.18	0.33	21.2	0.65	9.3	16.4	0.10	99.0	35.69	28.26	36.05
2 s.d.	0.9	0.07	0.18	0.07	3.1	0.12	0.3	2.8	0.04	1.10	5.74	0.73	5.50
PCA 91193	50.9	0.58	1.24	0.44	11.9	0.52	13.0	20.7	0.10	99.3	43.11	37.56	19.33
	50.6	0.52	1.19	0.34	14.4	0.53	12.8	18.5	0.08	98.9	38.92	37.43	23.64
	50.6	0.42	1.05	0.37	11.5	0.45	12.6	21.0	0.07	98.2	44.20	36.88	18.92
	50.5	0.53	1.21	0.39	12.1	0.45	13.0	20.1	0.12	98.5	42.20	38.00	19.80
	50.6	0.51	1.10	0.42	11.7	0.49	12.7	20.8	0.10	98.4	43.66	37.23	19.11
	50.8	0.49	1.15	0.37	12.4	0.49	12.8	19.6	0.16	98.2	41.70	37.78	20.53
	50.6	0.49	1.15	0.38	13.1	0.46	12.7	19.8	0.11	98.7	41.55	37.04	21.41
average	50.7	0.51	1.15	0.39	12.4	0.48	12.8	20.1	0.10	98.6	42.19	37.42	20.39
2 s.d.	0.3	0.10	0.13	0.07	2.0	0.06	0.3	1.8	0.06	0.79	3.50	0.80	3.36

Table A2: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
QUE 97014	49.8	0.29	0.72	0.22	19.4	0.66	10.2	17.4	0.05	98.77	37.15	30.37	32.48
	50.1	0.27	0.65	0.20	15.3	0.51	10.0	21.1	0.08	98.23	44.94	29.57	25.48
	50.3	0.21	0.58	0.20	15.9	0.53	10.1	20.9	0.08	98.77	44.16	29.57	26.27
	50.6	0.28	0.72	0.25	16.1	0.53	10.1	20.8	0.08	99.45	43.91	29.56	26.53
	50.2	0.25	0.70	0.24	15.7	0.47	10.2	20.8	0.11	98.66	44.07	30.03	25.90
	50.3	0.21	0.63	0.19	16.0	0.54	10.1	21.0	0.07	99.00	44.26	29.47	26.27
average	50.2	0.25	0.67	0.21	16.4	0.54	10.1	20.3	0.08	98.81	43.08	29.76	27.15
2 s.d.	0.5	0.07	0.12	0.05	3.0	0.13	0.2	2.9	0.03	0.80	5.86	0.72	5.27
QUE 99055	50.3	0.13	0.49	0.47	22.9	0.74	10.5	13.9	0.03	99.40	29.94	31.42	38.65
	45.5	4.12	0.67	0.32	22.5	0.68	9.2	15.1	0.03	98.08	33.14	28.26	38.60
	51.7	0.09	0.43	0.06	20.9	0.63	10.2	14.3	0.05	98.30	32.02	31.58	36.41
	49.4	0.21	0.65	0.18	23.9	0.73	10.3	12.9	0.01	98.31	28.21	31.14	40.65
	51.2	0.08	0.55	0.10	23.4	0.65	10.2	12.9	0.02	99.10	28.51	31.17	40.32
average	49.6	0.92	0.56	0.22	22.7	0.69	10.1	13.8	0.03	98.64	30.36	30.71	38.93
2 s.d.	4.9	3.57	0.21	0.34	2.3	0.09	1.0	1.8	0.03	1.15	4.32	2.76	3.38
RKPA 80204	51.0	0.16	0.47	0.15	24.2	0.78	11.2	13.4	0.05	101.37	27.94	32.57	39.48
	50.5	0.12	0.38	0.15	16.6	0.52	10.5	19.8	0.06	98.61	41.82	30.85	27.33
	50.9	0.22	0.66	0.17	15.7	0.51	10.4	20.8	0.08	99.47	43.87	30.34	25.79
	50.6	0.16	0.45	0.16	19.6	0.62	10.8	16.6	0.06	99.13	35.41	31.96	32.63
	50.8	0.13	0.31	0.06	23.0	0.71	11.2	14.2	0.05	100.39	29.73	32.65	37.62
	50.7	0.18	0.54	0.15	15.4	0.52	10.4	20.9	0.06	98.94	44.13	30.59	25.28
	50.0	0.16	0.54	0.16	15.6	0.48	10.4	20.9	0.05	98.39	43.93	30.48	25.59
	50.3	0.21	0.76	0.14	15.6	0.46	10.3	20.8	0.05	98.63	43.91	30.30	25.79
	49.9	0.20	0.69	0.24	16.3	0.51	10.7	20.1	0.05	98.61	42.15	31.12	26.73
average	50.5	0.17	0.53	0.15	18.0	0.57	10.6	18.6	0.06	99.28	39.21	31.21	29.58
2 s.d.	0.8	0.07	0.30	0.09	6.9	0.22	0.7	6.1	0.02	1.99	12.98	1.89	11.15
SCO 06041	51.9	0.42	0.16	0.23	9.8	0.39	13.5	22.3	0.05	98.77	45.80	38.54	15.66
	51.8	0.23	0.13	0.16	11.4	0.38	14.1	20.5	0.03	98.64	41.85	40.04	18.11
	51.9	0.34	0.16	0.29	9.9	0.37	13.4	22.2	0.06	98.49	45.70	38.45	15.85
average	51.9	0.33	0.15	0.23	10.3	0.38	13.7	21.7	0.04	98.63	44.45	39.01	16.54
2 s.d.	0.1	0.19	0.03	0.13	1.8	0.02	0.7	2.0	0.03	0.28	4.50	1.79	2.72

Table A2: High-Ca pyroxene major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Wo %	En %	Fs %
GRO 95533	50.2	0.37	0.14	0.21	18.9	0.58	10.1	17.8	0.08	98.41	38.19	30.12	31.70
	50.4	0.29	0.14	0.28	16.6	0.51	10.0	20.2	0.08	98.57	42.93	29.59	27.48
	49.6	0.35	0.16	0.30	17.6	0.52	10.1	19.4	0.11	98.11	41.10	29.70	29.20
	50.0	0.38	0.11	0.24	15.5	0.49	10.3	21.0	0.10	98.14	44.22	30.24	25.54
	52.2	0.27	0.11	0.18	16.1	0.53	10.7	20.5	0.06	100.66	42.79	31.09	26.12
	50.4	0.27	0.08	0.15	16.0	0.46	10.4	21.0	0.05	98.85	43.78	30.10	26.13
average	50.5	0.32	0.12	0.23	16.8	0.51	10.3	20.0	0.08	98.79	42.17	30.14	27.70
2 s.d.	1.8	0.10	0.05	0.11	2.5	0.08	0.5	2.4	0.05	1.92	4.45	1.07	4.73
Milbillillie	50.4	0.11	0.06	0.10	24.4	0.70	11.6	12.2	0.04	99.68	25.84	33.94	40.22
	50.3	0.22	0.12	0.20	16.3	0.50	10.5	20.5	0.04	98.59	42.91	30.50	26.59
	50.2	0.33	0.16	0.16	18.0	0.56	10.5	18.3	0.04	98.24	38.97	31.14	29.88
	50.7	0.23	0.10	0.15	15.2	0.45	10.2	21.6	0.07	98.61	45.34	29.73	24.93
	50.7	0.28	0.10	0.20	15.6	0.48	10.1	21.2	0.04	98.82	44.67	29.70	25.63
	46.3	5.36	0.08	0.19	19.0	0.55	9.9	18.3	0.07	99.73	39.13	29.28	31.59
average	49.8	1.09	0.10	0.17	18.1	0.54	10.5	18.7	0.05	98.95	39.48	30.72	29.81
2 s.d.	3.4	4.19	0.07	0.08	6.9	0.18	1.2	6.9	0.03	1.24	14.41	3.43	11.43
Camel Dongi	50.5	0.25	0.12	0.23	14.8	0.59	11.3	20.7	0.06	98.56	43.16	32.78	24.06
	50.0	0.36	0.15	0.24	16.6	0.65	11.4	18.8	0.05	98.27	39.39	33.35	27.26
	50.3	0.25	0.14	0.22	14.8	0.63	11.1	20.7	0.07	98.23	43.38	32.47	24.15
	51.2	0.28	0.11	0.24	15.1	0.62	11.4	20.3	0.05	99.21	42.46	32.99	24.55
	50.5	0.39	0.14	0.33	15.5	0.59	10.7	20.1	0.08	98.32	42.73	31.58	25.69
average	50.5	0.30	0.13	0.25	15.4	0.62	11.2	20.1	0.06	98.52	42.22	32.63	25.14
2 s.d.	0.9	0.13	0.04	0.09	1.6	0.05	0.6	1.6	0.03	0.81	3.25	1.34	2.70

Table A3: Plagioclase major element concentrations in wt%

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
EET 83227	48.88	0.00	33.70	0.22	0.00	0.00	16.25	1.83	0.21	101	81.07	18.09	0.83
	44.94	0.03	36.25	0.97	0.04	0.10	18.91	0.62	0.04	102	93.69	6.14	0.18
	46.76	0.02	35.17	0.37	0.02	0.03	17.71	1.13	0.10	101	88.41	11.18	0.41
	47.90	0.03	33.99	0.38	0.02	0.04	17.17	1.48	0.13	101	84.93	14.56	0.51
	46.89	0.05	34.80	0.37	0.01	0.02	17.70	1.23	0.11	101	87.53	12.04	0.43
	47.27	0.00	34.47	0.20	0.01	0.01	17.41	1.29	0.12	101	86.81	12.72	0.47
	46.09	0.06	35.23	0.53	0.01	0.01	17.86	0.97	0.07	101	90.04	9.69	0.27
	48.39	0.02	33.52	0.67	0.02	0.05	16.73	1.72	0.18	101	82.51	16.79	0.70
	44.97	0.00	35.93	0.83	0.03	0.09	18.74	0.60	0.07	101	93.76	5.97	0.28
	44.91	0.08	36.00	0.80	0.04	0.15	18.85	0.50	0.06	101	94.80	4.94	0.26
average	46.70	0.03	34.91	0.53	0.02	0.05	17.73	1.14	0.11	101	88.36	11.21	0.43
2 s.d.	2.92	0.05	1.96	0.54	0.02	0.10	1.80	0.93	0.10	0.63	9.52	9.13	0.41
EET 87458	45.82	0.00	35.82	0.12	0.01	0.01	18.39	0.91	0.06	101	90.85	8.89	0.25
	45.47	0.00	35.73	0.12	0.01	0.00	18.48	0.87	0.04	101	91.34	8.50	0.16
	45.27	0.00	36.03	0.25	0.00	0.00	18.95	0.74	0.05	101	92.63	7.16	0.21
	45.52	0.01	36.17	0.13	0.01	0.00	18.71	0.76	0.05	101	92.39	7.41	0.20
	45.77	0.00	36.19	0.17	0.02	0.01	18.60	0.83	0.06	102	91.64	8.13	0.23
	45.57	0.00	36.01	0.16	0.00	0.01	18.65	0.79	0.05	101	92.05	7.76	0.19
	45.68	0.00	35.78	0.16	0.00	0.00	18.40	0.86	0.06	101	91.28	8.49	0.23
	45.49	0.00	35.99	0.18	0.00	0.01	18.76	0.84	0.04	101	91.73	8.10	0.16
	45.56	0.05	36.05	0.17	0.00	0.00	18.61	0.84	0.06	101	91.53	8.22	0.25
	45.43	0.00	36.05	0.19	0.00	0.00	18.48	0.80	0.06	101	91.87	7.90	0.23
average	45.56	0.01	35.98	0.17	0.01	0.00	18.60	0.82	0.05	101	91.73	8.06	0.21
2 s.d.	0.33	0.03	0.31	0.07	0.01	0.01	0.35	0.10	0.02	0.53	1.06	1.05	0.06
EET 92003	46.68	0.04	35.33	0.26	0.00	0.02	18.14	1.06	0.09	102	89.31	10.33	0.36
	47.76	0.00	34.33	0.46	0.00	0.02	17.14	1.58	0.16	101	84.02	15.35	0.63
	46.13	0.06	35.24	0.29	0.02	0.01	18.13	1.11	0.08	101	88.87	10.80	0.34
	47.22	0.04	34.67	0.59	0.02	0.03	17.37	1.39	0.19	102	85.66	13.57	0.78
	47.21	0.05	34.87	0.75	0.01	0.05	17.40	1.42	0.15	102	85.58	13.84	0.58
	47.80	0.07	34.61	0.77	0.00	0.07	17.20	1.52	0.13	102	84.62	14.86	0.52
	49.21	0.00	33.57	0.54	0.02	0.04	16.37	2.01	0.24	102	79.68	19.38	0.94
	46.45	0.00	35.29	0.31	0.00	0.02	18.05	1.15	0.11	101	88.42	11.15	0.43
	46.28	0.00	35.36	0.33	0.01	0.02	18.04	1.09	0.09	101	88.97	10.67	0.35
average	47.19	0.03	34.81	0.48	0.01	0.03	17.54	1.37	0.14	102	86.12	13.33	0.55
2 s.d.	1.94	0.05	1.19	0.39	0.02	0.04	1.20	0.62	0.11	0.73	6.31	5.94	0.41

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
EET 92023	46.70	0.05	34.78	0.23	0.00	0.04	17.85	1.14	0.11	101	88.34	11.22	0.45
	46.78	0.08	35.78	0.44	0.02	0.02	17.95	1.12	0.08	102	88.73	10.96	0.31
	47.14	0.06	35.71	0.52	0.02	0.03	17.85	1.10	0.12	103	88.71	10.82	0.47
	47.18	0.07	35.50	0.56	0.00	0.02	17.88	1.10	0.10	102	88.82	10.80	0.38
	46.49	0.04	34.88	0.21	0.00	0.04	17.91	1.19	0.10	101	88.02	11.59	0.38
	46.66	0.04	35.54	0.30	0.00	0.02	18.03	1.09	0.10	102	88.91	10.68	0.41
	47.06	0.04	35.38	0.29	0.00	0.05	17.51	1.26	0.14	102	87.01	12.43	0.56
	47.54	0.00	36.08	0.21	0.00	0.04	17.76	1.20	0.11	103	87.83	11.74	0.43
	46.17	0.02	35.21	0.17	0.00	0.04	18.02	1.13	0.11	101	88.51	11.04	0.45
average	46.86	0.04	35.43	0.33	0.01	0.03	17.86	1.15	0.11	102	88.32	11.25	0.43
2 s.d.	0.83	0.05	0.85	0.29	0.02	0.02	0.31	0.11	0.03	1.58	1.22	1.14	0.14
GRA 98006	45.51	0.02	35.10	0.50	0.02	0.00	18.04	0.94	0.18	100	89.95	9.34	0.70
	45.88	0.01	35.48	0.09	0.01	0.01	18.04	1.03	0.06	101	89.59	10.18	0.23
	44.20	0.02	35.47	0.40	0.00	0.00	18.36	0.85	0.07	99.35	91.38	8.35	0.26
	45.33	0.00	34.30	0.35	0.01	0.06	17.67	1.11	0.11	98.95	88.49	11.05	0.46
	45.80	0.00	34.58	0.43	0.00	0.01	17.48	1.23	0.14	99.67	87.24	12.18	0.58
	44.72	0.00	35.33	0.34	0.00	0.00	18.25	0.86	0.08	99.58	91.19	8.51	0.31
	44.49	0.03	35.01	0.37	0.01	0.01	18.15	0.88	0.08	99.02	90.89	8.78	0.33
	47.23	0.01	36.05	0.29	0.00	0.01	17.94	1.13	0.10	103	88.55	11.03	0.42
	44.54	0.00	35.10	0.18	0.02	0.01	17.94	0.99	0.13	98.90	89.71	9.79	0.51
	45.58	0.00	34.25	0.21	0.02	0.00	17.36	1.19	0.13	98.74	87.56	11.90	0.54
average	45.33	0.01	35.07	0.32	0.01	0.01	17.92	1.02	0.11	99.79	89.46	10.11	0.43
2 s.d.	1.79	0.02	1.13	0.25	0.02	0.04	0.65	0.28	0.08	2.42	2.93	2.78	0.31
GRA 98033	46.12	0.00	35.47	0.11	0.01	0.00	17.98	1.19	0.12	101	87.96	11.58	0.46
	46.50	0.00	35.74	0.16	0.02	0.01	18.06	1.19	0.11	102	88.06	11.52	0.42
	46.21	0.02	35.37	0.06	0.00	0.02	17.80	1.22	0.11	101	87.62	11.94	0.44
	46.24	0.00	35.83	0.12	0.00	0.01	17.99	1.20	0.11	102	87.90	11.65	0.45
	46.07	0.00	35.69	0.13	0.00	0.01	17.86	1.19	0.13	101	87.91	11.57	0.51
	46.10	0.00	35.63	0.15	0.01	0.01	17.82	1.19	0.11	101	87.90	11.65	0.45
	46.29	0.01	35.39	0.12	0.00	0.00	17.93	1.22	0.12	101	87.66	11.87	0.47
	46.29	0.00	35.68	0.11	0.01	0.00	17.91	1.21	0.14	101	87.65	11.79	0.56
	46.19	0.00	35.55	0.22	0.00	0.00	18.02	1.19	0.13	101	87.95	11.53	0.52
	46.39	0.00	35.56	0.16	0.00	0.01	17.87	1.26	0.15	101	87.25	12.17	0.58
average	46.24	0.00	35.59	0.14	0.01	0.01	17.92	1.21	0.12	101	87.79	11.73	0.49
2 s.d.	0.27	0.01	0.30	0.08	0.01	0.01	0.18	0.04	0.03	0.58	0.48	0.43	0.10

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
GRA 98043	47.03	0.00	35.68	0.82	0.00	0.01	17.69	1.23	0.12	103	87.43	12.07	0.50
	46.72	0.00	35.58	0.37	0.01	0.00	17.77	1.10	0.11	102	88.65	10.90	0.45
	46.61	0.02	35.23	0.27	0.00	0.01	17.85	1.20	0.11	101	87.82	11.73	0.45
	46.22	0.00	35.03	0.34	0.00	0.02	17.06	1.13	0.12	99.9	87.96	11.53	0.51
	44.90	0.00	35.86	0.55	0.04	0.02	17.21	1.07	0.10	99.8	88.62	10.98	0.40
	47.08	0.00	35.72	0.64	0.01	0.01	17.18	1.14	0.11	102	87.95	11.60	0.45
	47.26	0.01	35.45	0.56	0.03	0.01	17.40	1.22	0.11	102	87.43	12.15	0.43
average	45.69	0.00	34.82	0.87	0.04	0.02	17.34	1.12	0.11	100	88.21	11.35	0.44
2 s.d.	46.44	0.00	35.42	0.55	0.02	0.01	17.44	1.15	0.11	101	88.01	11.54	0.45
	1.61	0.01	0.73	0.44	0.04	0.01	0.59	0.11	0.02	2.20	0.94	0.91	0.07
GRA 98055	46.50	0.00	35.54	0.25	0.00	0.01	17.68	1.23	0.15	101	87.40	12.02	0.58
	46.50	0.00	35.24	0.20	0.01	0.01	17.89	1.26	0.11	101	87.40	12.18	0.42
	46.46	0.02	35.17	0.59	0.02	0.00	17.50	1.30	0.13	101	86.68	12.81	0.50
	46.60	0.03	35.44	0.46	0.00	0.00	17.72	1.29	0.11	102	86.99	12.56	0.45
	46.68	0.00	35.50	0.38	0.02	0.00	17.70	1.20	0.11	102	87.76	11.79	0.45
	46.51	0.00	35.21	0.32	0.00	0.01	17.79	1.19	0.11	101	87.87	11.69	0.44
	46.59	0.00	35.35	0.43	0.02	0.01	17.78	1.20	0.10	101	87.86	11.73	0.41
	46.57	0.00	35.34	0.41	0.01	0.01	17.92	1.24	0.11	102	87.49	12.06	0.45
	46.27	0.01	35.28	0.25	0.01	0.00	17.95	1.11	0.12	101	88.63	10.89	0.49
	46.71	0.01	35.23	0.19	0.02	0.00	17.69	1.27	0.12	101	87.07	12.45	0.49
average	46.54	0.01	35.33	0.35	0.01	0.00	17.76	1.23	0.12	101	87.51	12.02	0.47
2 s.d.	0.25	0.02	0.25	0.26	0.02	0.01	0.27	0.11	0.03	0.45	1.10	1.09	0.10
GRA 98114	46.32	0.00	35.21	0.08	0.00	0.00	17.84	1.19	0.10	101	87.98	11.60	0.42
	45.46	0.00	35.10	0.23	0.00	0.01	16.35	0.98	0.12	98.3			
	46.07	0.00	35.73	0.33	0.00	0.00	17.88	1.11	0.11	101	88.60	10.96	0.45
	46.24	0.00	35.10	0.26	0.02	0.00	17.84	1.22	0.12	101	87.60	11.90	0.50
	45.93	0.01	35.36	0.23	0.00	0.01	17.94	1.21	0.12	101	87.79	11.75	0.46
	45.91	0.02	35.50	0.36	0.01	0.00	17.83	1.22	0.11	101	87.64	11.93	0.43
	45.73	0.00	35.36	0.18	0.02	0.01	17.95	1.11	0.10	100	88.72	10.87	0.41
	45.93	0.00	35.23	0.45	0.02	0.01	17.85	1.22	0.11	101	87.64	11.91	0.44
	46.15	0.00	35.43	0.21	0.02	0.01	17.82	1.21	0.10	101	87.75	11.87	0.39
	45.83	0.13	35.53	0.14	0.00	0.01	17.71	1.16	0.12	101	88.08	11.44	0.49
average	45.96	0.02	35.35	0.25	0.01	0.01	17.70	1.16	0.11	101	87.98	11.58	0.44
2 s.d.	0.51	0.08	0.40	0.22	0.02	0.01	0.96	0.16	0.02	1.68	0.84	0.82	0.07

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
LAP 031062	49.83	0.00	33.17	0.43	0.00	0.06	15.90	2.03	0.14	102	79.31	20.14	0.55
	45.67	0.00	36.10	0.14	0.00	0.04	18.63	0.84	0.06	101	91.56	8.21	0.23
	49.55	0.04	33.57	0.39	0.00	0.07	16.03	2.01	0.13	102	79.67	19.79	0.54
	49.74	0.05	33.33	0.47	0.01	0.08	15.90	1.97	0.17	102	79.68	19.64	0.69
	50.30	0.06	32.96	0.59	0.01	0.07	15.89	2.04	0.16	102	79.22	20.15	0.63
	48.00	0.01	34.60	0.52	0.02	0.05	17.14	1.46	0.08	102	85.24	14.42	0.34
	46.36	0.01	35.75	0.42	0.00	0.04	18.17	1.03	0.06	102	89.64	10.13	0.23
	45.99	0.03	34.76	0.85	0.00	0.05	17.00	1.12	0.09	100	88.15	11.49	0.36
	46.48	0.01	35.56	0.42	0.00	0.04	18.21	1.06	0.09	102	89.35	10.31	0.35
	46.85	0.05	35.77	0.38	0.01	0.06	18.31	1.15	0.06	103	88.71	11.05	0.24
average	47.88	0.03	34.56	0.46	0.01	0.06	17.12	1.47	0.10	102	85.05	14.53	0.42
2 s.d.	3.64	0.04	2.43	0.36	0.01	0.03	2.28	0.98	0.08	1.41	10.11	9.78	0.34
LAR 06875	46.46	0.00	35.98	0.74	0.03	0.01	17.86	1.11	0.07	102	88.76	10.96	0.28
	47.00	0.00	35.89	0.33	0.02	0.00	17.90	1.19	0.09	102	88.05	11.60	0.35
	48.17	0.06	34.33	1.10	0.04	0.08	17.58	0.96	0.10	102	89.91	9.70	0.39
	46.86	0.00	35.45	1.04	0.02	0.04	17.74	1.11	0.09	102	88.64	11.01	0.35
	46.67	0.02	35.39	0.71	0.01	0.02	17.94	1.03	0.07	102	89.52	10.19	0.30
	47.15	0.01	34.90	1.19	0.05	0.13	18.05	1.00	0.05	103	89.92	9.87	0.21
	45.80	0.01	35.56	0.75	0.03	0.07	18.08	1.05	0.05	101	89.52	10.28	0.20
	46.28	0.01	35.51	1.07	0.02	0.05	17.99	1.01	0.10	102	89.66	9.96	0.38
	46.22	0.07	35.22	0.90	0.02	0.03	18.05	1.01	0.09	102	89.72	9.93	0.35
	46.71	0.00	34.70	0.89	0.06	0.06	17.70	1.20	0.09	101	87.82	11.82	0.36
average	46.73	0.02	35.29	0.87	0.03	0.05	17.89	1.07	0.08	102	89.15	10.53	0.32
2 s.d.	1.29	0.05	1.04	0.51	0.03	0.08	0.34	0.17	0.03	0.87	1.55	1.52	0.14
LEW 85305	46.96	0.01	35.22	0.21	0.00	0.01	17.50	1.37	0.12	101	86.15	13.38	0.47
	46.40	0.00	35.19	0.19	0.00	0.02	17.81	1.24	0.11	101	87.43	12.11	0.45
	46.72	0.00	35.25	0.11	0.00	0.01	17.77	1.31	0.15	101	86.75	12.65	0.60
	46.32	0.00	34.94	0.13	0.01	0.03	17.44	1.40	0.10	100	85.93	13.67	0.40
	46.29	0.04	35.07	0.15	0.00	0.02	17.43	1.34	0.13	100	86.35	13.14	0.51
	46.84	0.00	35.20	0.17	0.00	0.00	17.72	1.41	0.08	101	86.08	13.62	0.30
	46.36	0.00	35.24	0.14	0.00	0.02	17.52	1.24	0.11	101	87.33	12.23	0.45
	46.64	0.00	35.29	0.15	0.00	0.01	17.71	1.25	0.11	101	87.31	12.24	0.45
	46.27	0.03	35.10	0.18	0.00	0.02	17.76	1.23	0.11	101	87.54	12.04	0.42
	46.40	0.00	34.79	0.14	0.02	0.02	17.53	1.38	0.11	100	86.07	13.48	0.45
average	46.52	0.01	35.13	0.16	0.00	0.02	17.62	1.32	0.11	101	86.70	12.85	0.45
2 s.d.	0.50	0.03	0.32	0.06	0.01	0.01	0.30	0.14	0.04	0.86	1.30	1.34	0.15

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
LEW 87002	46.39	0.00	35.57	0.23	0.02	0.05	18.11	1.03	0.11	102	89.52	10.06	0.42
	46.20	0.00	35.25	0.17	0.00	0.04	18.24	1.04	0.10	101	89.45	10.16	0.39
	45.86	0.00	35.66	0.29	0.00	0.05	18.35	0.99	0.11	101	89.91	9.65	0.44
	45.91	0.00	35.65	0.19	0.01	0.08	18.50	0.95	0.07	101	90.45	9.25	0.30
	44.38	0.00	34.96	0.19	0.00	0.03	18.19	0.84	0.11	98.7	91.15	8.40	0.45
	45.93	0.00	34.98	0.29	0.00	0.04	18.00	1.10	0.10	100	88.79	10.81	0.39
	45.40	0.00	35.84	0.56	0.04	0.23	18.85	0.70	0.06	102	92.92	6.82	0.26
	45.27	0.02	35.27	0.37	0.02	0.04	18.05	1.00	0.11	100	89.71	9.85	0.44
	44.76	0.01	35.64	0.35	0.01	0.02	18.62	0.78	0.06	100	92.06	7.70	0.25
	46.07	0.01	35.59	0.43	0.00	0.04	18.28	1.03	0.11	102	89.57	10.00	0.43
	44.95	0.01	36.05	0.15	0.02	0.03	18.84	0.79	0.08	101	92.03	7.66	0.30
	45.97	0.03	35.25	0.38	0.00	0.29	18.76	0.90	0.08	102	91.01	8.68	0.32
average	45.59	0.01	35.48	0.30	0.01	0.08	18.40	0.93	0.09	101	90.55	9.09	0.37
2 s.d.	1.26	0.02	0.67	0.25	0.02	0.17	0.61	0.25	0.04	1.75	2.57	2.46	0.15
PCA 91193	46.4	0.0	35.4	0.5	0.0	0.1	17.9	1.2	0.1	101	88.1	11.4	0.5
	45.4	0.0	34.7	0.4	0.0	0.1	17.6	1.1	0.1	99.3	88.7	10.9	0.4
	46.8	0.0	36.2	0.3	0.0	0.0	18.1	1.1	0.1	103	89.3	10.3	0.4
	46.5	0.0	35.5	0.2	0.0	0.0	18.1	1.1	0.1	102	88.7	10.9	0.4
	46.6	0.0	35.6	0.3	0.0	0.0	17.9	1.1	0.1	102	88.5	11.1	0.4
average	46.3	0.0	35.5	0.3	0.0	0.0	17.9	1.1	0.1	101	88.7	10.9	0.4
2 s.d.	1.1	0.0	1.1	0.2	0.0	0.0	0.4	0.1	0.0	2.4	0.9	0.8	0.1
QUE 97014	46.10	0.03	35.69	0.19	0.02	0.01	17.89	1.15	0.11	101	88.31	11.25	0.44
	46.37	0.00	35.30	0.25	0.03	0.01	17.81	1.29	0.11	101	87.00	12.55	0.45
	45.87	0.00	35.67	0.25	0.02	0.01	17.78	1.24	0.11	101	87.49	12.08	0.43
	45.77	0.00	35.49	0.36	0.02	0.00	17.91	1.19	0.09	101	88.08	11.58	0.34
	46.03	0.00	35.72	0.43	0.01	0.00	18.00	1.19	0.11	102	87.98	11.58	0.44
	45.76	0.00	35.30	0.48	0.00	0.01	17.74	1.26	0.12	101	87.22	12.30	0.47
	46.00	0.04	35.46	0.25	0.00	0.00	17.83	1.20	0.10	101	87.86	11.73	0.41
	45.96	0.00	34.22	1.15	0.04	0.16	17.72	1.13	0.10	100	88.45	11.16	0.39
	46.07	0.00	35.86	0.39	0.02	0.01	17.89	1.23	0.11	102	87.64	11.92	0.44
	46.01	0.00	35.39	0.17	0.00	0.01	17.84	1.19	0.14	101	87.79	11.64	0.56
average	45.99	0.01	35.41	0.39	0.02	0.02	17.84	1.21	0.11	101	87.78	11.78	0.44
2 s.d.	0.35	0.03	0.92	0.57	0.03	0.10	0.17	0.10	0.03	0.72	0.92	0.88	0.12

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %	
QUE 99055	46.68	0.00	35.28	0.30	0.03	0.01	17.91	1.18	0.12	101	88.06	11.47	0.47	
	45.28	0.00	34.99	0.29	0.01	0.03	17.58	0.95	0.09	99.23	90.03	9.61	0.37	
	45.64	0.00	35.39	1.07	0.06	0.16	18.37	0.75	0.06	102	92.28	7.50	0.23	
	46.20	0.00	35.45	0.31	0.02	0.10	17.92	1.15	0.10	101	88.31	11.29	0.41	
	46.32	0.00	35.48	0.31	0.01	0.01	17.66	1.29	0.12	101	86.96	12.58	0.46	
	47.08	0.00	34.98	0.60	0.00	0.01	17.35	1.43	0.14	102	85.47	13.97	0.57	
	45.83	0.00	35.28	0.12	0.00	0.00	17.91	1.19	0.12	100	87.89	11.63	0.48	
	45.85	0.00	35.31	0.72	0.00	0.08	18.11	1.09	0.09	101	89.03	10.63	0.35	
average	46.11	0.00	35.27	0.47	0.02	0.04	17.85	1.13	0.10	101	88.50	11.08	0.42	
2 s.d.	1.16	0.00	0.38	0.62	0.04	0.11	0.64	0.41	0.05	1.59	4.07	3.88	0.21	
RKPA 80204	47.28	0.00	34.64	0.29	0.00	0.02	17.01	1.63	0.15	101	83.49	15.89	0.61	
	46.41	0.02	35.99	0.85	0.00	0.05	17.73	1.15	0.09	102	88.29	11.34	0.37	
	46.78	0.00	34.96	0.45	0.03	0.00	17.25	1.34	0.14	101	86.18	13.25	0.56	
	47.09	0.02	35.22	0.71	0.04	0.10	17.41	1.18	0.12	102	87.69	11.81	0.50	
	53.37	0.00	30.14	0.55	0.00	0.01	15.23	0.94	0.10	100				
	46.19	0.03	35.41	0.66	0.02	0.01	17.61	1.30	0.12	101	86.81	12.72	0.46	
	average	47.86	0.01	34.39	0.59	0.01	0.03	17.04	1.26	0.12	101	86.49	13.00	0.50
	2 s.d.	5.47	0.03	4.27	0.39	0.03	0.07	1.84	0.46	0.05	1.40	3.72	3.56	0.19
SCO 06041	44.88	0.00	35.96	0.08	0.01	0.01	19.00	0.85	0.04	101	92.25	7.49	0.25	
	45.29	0.00	35.59	0.10	0.00	0.01	18.50	1.06	0.07	101	90.26	9.36	0.38	
	44.79	0.00	35.49	0.10	0.00	0.00	18.93	0.86	0.06	100	92.12	7.55	0.34	
	44.47	0.04	36.05	0.23	0.00	0.02	18.97	0.87	0.06	101	92.01	7.61	0.37	
	44.67	0.00	35.39	0.12	0.00	0.00	18.52	0.95	0.06	99.7	91.20	8.47	0.33	
	43.57	0.01	34.87	0.14	0.00	0.01	18.66	0.89	0.05	98.2	91.73	7.96	0.32	
	44.41	0.00	36.19	0.10	0.02	0.00	18.79	0.89	0.06	100.5	91.82	7.84	0.34	
	43.15	0.00	35.51	0.10	0.02	0.02	18.78	0.82	0.05	98.4	92.44	7.28	0.29	
average	43.94	0.02	35.77	0.15	0.00	0.00	18.57	0.86	0.05	99.4	91.94	7.74	0.31	
	43.89	0.01	35.79	0.16	0.00	0.00	18.53	0.89	0.05	99.3	91.77	7.95	0.28	
	44.31	0.01	35.66	0.13	0.01	0.01	18.72	0.89	0.06	99.8	91.75	7.92	0.32	
2 s.d.	1.31	0.02	0.76	0.09	0.02	0.01	0.39	0.14	0.01	1.89	1.25	1.20	0.08	

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
GRO 95533	44.49	0.01	35.08	0.05	0.00	0.03	18.65	0.93	0.06	99.31	91.38	8.25	0.37
	44.61	0.00	35.20	0.05	0.00	0.00	18.64	0.92	0.05	99.47	91.52	8.17	0.32
	45.29	0.01	35.35	0.08	0.01	0.02	18.39	1.11	0.07	100.31	89.82	9.79	0.39
	46.07	0.00	35.79	0.12	0.00	0.02	18.06	1.17	0.09	101.31	89.03	10.46	0.51
	45.66	0.00	35.36	0.12	0.02	0.00	18.02	1.24	0.08	100.50	88.49	11.04	0.48
	43.38	0.00	35.53	0.08	0.01	0.00	18.20	1.05	0.06	98.31	90.21	9.42	0.37
	44.05	0.00	35.39	0.08	0.01	0.00	17.96	1.11	0.06	98.66	89.63	10.00	0.37
	43.68	0.00	35.18	0.14	0.00	0.00	18.07	1.11	0.07	98.26	89.60	9.97	0.43
	44.65	0.00	35.36	0.09	0.01	0.01	18.25	1.08	0.07	99.52	89.96	9.64	0.40
	1.91	0.01	0.45	0.07	0.01	0.02	0.56	0.22	0.02	2.22	2.11	2.01	0.13
Millilitlie	45.57	0.00	34.96	0.73	0.02	0.37	18.32	0.93	0.06	100.96	91.27	8.37	0.35
	45.37	0.00	35.55	0.22	0.01	0.00	18.71	0.92	0.08	100.87	91.39	8.17	0.44
	45.52	0.02	34.73	1.70	0.07	0.42	18.19	1.01	0.06	101.72	90.54	9.11	0.35
	46.12	0.00	33.99	0.69	0.01	0.21	17.94	1.23	0.09	100.28	88.50	10.98	0.52
	47.95	0.00	33.88	0.39	0.01	0.00	16.59	1.99	0.16	100.96	81.43	17.64	0.93
	47.22	0.00	34.40	0.25	0.02	0.00	17.04	1.77	0.12	100.82	83.60	15.70	0.70
	45.76	0.00	35.60	0.22	0.00	0.00	18.25	1.15	0.08	101.05	89.38	10.17	0.44
	45.08	0.00	35.55	0.55	0.01	0.00	18.31	1.13	0.06	100.69	89.64	10.01	0.35
	45.50	0.00	34.99	0.28	0.00	0.02	18.10	1.11	0.06	100.06	89.68	9.95	0.37
	46.01	0.00	34.85	0.56	0.02	0.11	17.94	1.25	0.08	100.82	88.38	11.12	0.50
average 2 s.d.	1.91	0.01	1.32	0.94	0.04	0.35	1.36	0.75	0.07	0.95	6.98	6.61	0.40
Juvinas	45.28	0.00	35.43	1.01	0.05	0.32	18.77	0.67	0.04	101.56	93.68	6.07	0.25
	44.63	0.00	35.62	0.15	0.00	0.02	18.75	0.86	0.07	100.09	91.93	7.67	0.40
	45.04	0.00	36.09	0.29	0.00	0.00	19.37	0.76	0.03	101.58	93.23	6.58	0.19
	44.53	0.00	35.38	0.48	0.03	0.13	19.06	0.69	0.06	100.36	93.54	6.11	0.35
	44.45	0.00	35.09	0.67	0.02	0.25	18.85	0.77	0.06	100.14	92.83	6.83	0.34
	44.48	0.00	36.15	0.33	0.01	0.11	19.10	0.62	0.04	100.84	94.21	5.54	0.25
	44.73	0.00	35.70	0.72	0.02	0.19	18.53	0.86	0.07	100.82	91.88	7.71	0.40
	43.88	0.00	35.86	0.29	0.01	0.09	19.04	0.71	0.05	99.93	93.42	6.31	0.27
	44.91	0.00	36.30	0.55	0.01	0.17	18.89	0.60	0.06	101.48	94.28	5.39	0.33
	44.94	0.00	35.75	0.55	0.02	0.20	18.93	0.63	0.06	101.07	93.98	5.69	0.33
average 2 s.d.	44.69	0.00	35.54	0.14	0.00	0.04	19.04	0.76	0.06	100.28	92.90	6.74	0.36
	45.10	0.00	35.42	0.19	0.01	0.08	18.68	0.91	0.07	100.46	91.48	8.10	0.42
	46.56	0.00	34.68	0.13	0.00	0.01	17.78	1.37	0.12	100.64	87.21	12.11	0.67
average 2 s.d.	44.86	0.00	35.62	0.42	0.01	0.12	18.83	0.79	0.06	100.71	92.66	6.99	0.35
	1.25	0.00	0.88	0.54	0.03	0.20	0.76	0.40	0.04	1.14	3.73	3.52	0.24

Table A3: Plagioclase major element concentrations in wt% (continued).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	An %	Ab %	Or %
Dhofar 007	45.74	0.02	35.30	0.25	0.01	0.21	17.99	1.08	0.14	100.74	89.43	9.73	0.84
	45.74	0.01	35.29	0.23	0.02	0.04	18.39	0.99	0.07	100.77	90.79	8.82	0.39
	45.45	0.01	35.60	0.28	0.00	0.07	18.56	1.00	0.06	101.02	90.84	8.82	0.34
	45.41	0.01	35.38	0.19	0.00	0.05	18.14	1.09	0.07	100.33	89.83	9.76	0.41
	45.19	0.02	35.02	0.20	0.00	0.09	18.23	1.17	0.07	100.00	89.21	10.39	0.41
	44.77	0.02	35.32	0.21	0.00	0.07	18.40	0.96	0.07	99.80	91.02	8.60	0.39
	44.74	0.02	35.06	0.31	0.02	0.01	18.24	1.08	0.07	99.54	89.98	9.64	0.39
average	45.29	0.01	35.28	0.24	0.01	0.08	18.28	1.05	0.08	100.31	90.16	9.39	0.45
2 s.d.	0.83	0.01	0.39	0.09	0.02	0.13	0.37	0.15	0.06	1.11	1.45	1.31	0.34
Camel Donga	45.63	0.01	35.38	0.08	0.00	0.00	18.46	1.03	0.15	100.72	90.08	9.07	0.85
	45.15	0.01	35.60	0.14	0.00	0.02	18.69	0.94	0.05	100.60	91.37	8.35	0.28
	45.37	0.00	35.82	0.08	0.01	0.02	18.81	0.98	0.06	101.15	91.04	8.62	0.34
	46.03	0.00	35.22	0.18	0.00	0.00	17.95	1.31	0.08	100.76	87.95	11.60	0.45
	45.80	0.00	34.63	0.15	0.01	0.01	17.58	1.42	0.10	99.71	86.72	12.68	0.61
	45.42	0.00	34.72	0.23	0.00	0.00	17.97	1.23	0.07	99.65	88.59	11.00	0.41
	46.69	0.01	33.87	0.35	0.02	0.03	17.29	1.71	0.12	100.09	84.20	15.09	0.71
	44.31	0.00	35.38	0.18	0.01	0.02	19.08	0.79	0.04	99.81	92.77	6.98	0.25
	44.16	0.00	35.74	0.31	0.02	0.00	18.98	0.80	0.05	100.06	92.68	7.02	0.30
	43.11	0.00	35.38	0.20	0.00	0.00	19.19	0.73	0.04	98.65	93.38	6.39	0.24
average	45.17	0.00	35.17	0.19	0.01	0.01	18.40	1.09	0.08	100.12	89.88	9.68	0.44
2 s.d.	2.09	0.01	1.20	0.18	0.01	0.02	1.33	0.64	0.07	1.45	5.95	5.66	0.42

Table A4: Repeat measurements of the major element standards Natural Bridge diopside, Johnstown hypersthene and Plagioclase (Labradorite) Lake County, OR. Concentrations in wt%.

	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total
Hypersthene standard	53.3	0.06	1.21	0.70	14.9	0.47	27.15	1.28	0.00	99.0
	53.5	0.07	1.18	0.74	14.9	0.51	26.85	1.31	0.04	99.1
	53.5	0.08	1.22	0.73	14.7	0.49	26.99	1.31	0.04	99.1
	53.9	0.07	1.16	0.71	14.7	0.51	27.26	1.30	0.02	99.6
	54.0	0.08	1.20	0.73	14.8	0.50	27.29	1.25	0.02	99.9
	53.8	0.07	1.19	0.71	15.2	0.48	27.02	1.29	0.02	99.8
	53.8	0.07	1.19	0.69	14.8	0.52	27.00	1.33	0.00	99.4
	54.1	0.06	1.21	0.71	14.9	0.46	27.22	1.24	0.01	99.9
	53.9	0.06	1.19	0.72	14.8	0.47	27.32	1.28	0.00	99.8
	53.4	0.07	1.16	0.69	14.6	0.50	27.16	1.27	0.03	98.9
	53.7	0.06	1.17	0.74	15.0	0.47	27.36	1.28	0.03	99.8
	54.1	0.05	1.24	0.69	14.9	0.50	27.07	1.28	0.01	99.8
	54.3	0.07	1.20	0.77	15.0	0.51	26.83	1.27	0.01	100
	54.0	0.04	1.18	0.72	14.9	0.50	26.71	1.30	0.01	99.3
	53.7	0.04	0.26	0.71	14.7	0.52	27.25	1.33	0.02	98.5
	53.8	0.07	0.23	0.69	15.0	0.50	27.21	1.27	0.00	98.7
	53.2	0.06	1.21	0.67	14.9	0.46	27.42	1.27	0.03	99.2
	53.5	0.08	1.13	0.69	14.8	0.48	27.82	1.24	0.00	99.8
	53.5	0.06	0.20	0.74	15.0	0.51	27.77	1.26	0.04	99.0
	53.6	0.08	0.21	0.72	15.0	0.50	27.89	1.26	0.02	99.3
	54.1	0.07	0.21	0.72	15.0	0.49	27.46	1.25	0.01	99.3
	54.1	0.05	0.21	0.72	14.8	0.49	27.25	1.30	0.01	98.9
	53.8	0.07	0.19	0.75	15.0	0.47	27.47	1.32	0.02	99.1
average	53.8	0.06	0.89	0.72	14.9	0.49	27.25	1.28	0.02	99.4
2 s.d.	0.6	0.02	0.92	0.05	0.27	0.04	0.60	0.05	0.02	0.87
	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total
Diopside standard	54.7	0.03	0.30	0.00	0.22	0.03	18.5	25.6	0.19	99.5
	54.8	0.01	0.33	0.00	0.25	0.04	18.5	25.6	0.18	99.7
	54.7	0.01	0.29	0.00	0.24	0.02	18.5	25.7	0.20	99.7
	55.0	0.02	0.29	0.02	0.20	0.02	18.8	25.6	0.18	100
	55.1	0.02	0.34	0.00	0.29	0.01	18.9	25.7	0.20	101
	54.8	0.01	0.28	0.01	0.24	0.04	18.4	25.6	0.17	99.6
	55.2	0.01	0.30	0.02	0.22	0.00	18.6	25.7	0.19	100
	54.7	0.00	0.29	0.00	0.19	0.04	18.7	25.5	0.18	99.6
	54.7	0.00	0.30	0.00	0.27	0.02	18.6	25.5	0.19	99.6
	55.0	0.00	0.31	0.03	0.27	0.03	18.7	25.5	0.22	100
	55.0	0.01	0.27	0.00	0.24	0.01	18.7	25.6	0.15	100
	54.9	0.01	0.26	0.00	0.08	0.04	18.7	25.6	0.18	99.7
	54.9	0.01	0.29	0.01	0.22	0.06	18.5	25.5	0.20	99.7
	55.1	0.01	0.29	0.00	0.24	0.04	18.7	25.5	0.20	100
	55.1	0.00	0.30	0.00	0.23	0.04	18.4	25.8	0.19	100
	55.2	0.01	0.30	0.01	0.24	0.03	18.5	25.6	0.19	100
	55.0	0.02	0.30	0.00	0.24	0.03	18.6	25.6	0.17	100.0
	54.9	0.02	0.29	0.00	0.24	0.02	18.3	25.5	0.18	99.4
	54.6	0.01	0.30	0.00	0.22	0.04	18.2	25.5	0.19	99.0
	55.0	0.00	0.25	0.00	0.20	0.02	18.5	25.5	0.18	99.7
	55.0	0.01	0.28	0.00	0.25	0.05	18.6	25.6	0.17	100
	55.2	0.00	0.27	0.00	0.12	0.00	18.7	25.8	0.17	100
	55.0	0.01	0.30	0.00	0.24	0.04	18.6	25.5	0.20	99.9
	54.7	0.00	0.31	0.01	0.29	0.04	18.6	25.6	0.20	99.7
	54.7	0.00	0.32	0.00	0.23	0.04	18.6	25.6	0.20	99.6
	54.7	0.00	0.30	0.00	0.20	0.04	18.4	25.5	0.18	99.2
	55.0	0.01	0.31	0.00	0.23	0.01	18.5	25.5	0.17	99.8
	55.1	0.00	0.28	0.00	0.22	0.01	18.7	25.5	0.19	100
	55.1	0.02	0.29	0.01	0.21	0.02	18.3	25.4	0.19	99.5
	54.7	0.00	0.05	0.00	0.27	0.04	18.5	25.4	0.18	99.2
	54.4	0.01	0.05	0.00	0.28	0.00	18.6	25.5	0.16	99.1
	54.9	0.01	0.06	0.00	0.22	0.03	18.5	25.4	0.18	99.3
	54.4	0.00	0.04	0.00	0.25	0.02	18.8	25.5	0.17	99.2
	54.9	0.01	0.04	0.00	0.24	0.02	18.7	25.6	0.20	99.7
	53.8	0.01	0.26	0.00	0.26	0.01	18.7	25.3	0.17	98.5
	53.1	0.01	0.29	0.00	0.23	0.02	18.8	24.8	0.19	97.5
	54.6	0.00	0.05	0.00	0.21	0.02	18.7	25.3	0.18	99.0
	53.8	0.00	0.06	0.04	0.21	0.04	18.4	25.2	0.21	98.0
	54.6	0.02	0.07	0.00	0.25	0.04	18.5	25.3	0.18	99.1
average	54.8	0.01	0.24	0.00	0.23	0.03	18.6	25.5	0.19	99.6
2 s.d.	0.8	0.02	0.20	0.02	0.08	0.03	0.33	0.33	0.03	1.21

Table A4: Repeat measurements of major element standards (continued). Concentrations in wt%.

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total
Plagioclase standard	51.9	0.05	31.3	0.43	0.03	0.14	3.54	13.6	0.18	101
	50.8	0.04	30.3	0.46	0.00	0.15	3.30	13.5	0.16	98.8
	49.8	0.08	29.5	0.43	0.02	0.17	3.35	13.7	0.23	97.3
	49.7	0.05	29.6	0.40	0.00	0.18	3.42	13.7	0.24	97.3
	50.6	0.04	30.5	0.48	0.00	0.16	3.44	13.5	0.20	99.0
	51.8	0.08	31.5	0.44	0.01	0.14	3.53	13.7	0.16	101
	50.0	0.06	30.0	0.46	0.00	0.14	3.40	13.7	0.22	97.9
	49.3	0.05	29.9	0.45	0.00	0.13	3.39	13.4	0.18	96.8
	51.1	0.08	31.5	0.46	0.01	0.14	3.61	13.6	0.18	101
	50.2	0.03	30.8	0.45	0.00	0.14	3.44	13.7	0.19	98.9
	52.4	0.09	31.5	0.45	0.00	0.13	3.24	13.7	0.18	102
	52.0	0.04	31.4	0.52	0.00	0.12	3.51	13.7	0.16	101
	50.6	0.04	30.4	0.44	0.01	0.17	3.38	13.6	0.18	98.8
	50.1	0.06	29.9	0.44	0.01	0.19	3.31	13.5	0.19	97.8
	51.2	0.02	30.7	0.44	0.00	0.14	3.47	13.6	0.17	99.7
	50.9	0.01	30.4	0.44	0.02	0.14	3.39	13.6	0.21	99.1
	52.1	0.08	31.3	0.47	0.02	0.13	3.47	13.8	0.18	102
	51.9	0.04	31.1	0.50	0.01	0.13	3.48	13.6	0.17	101
	49.8	0.03	29.8	0.43	0.01	0.15	3.40	13.6	0.22	97.4
	51.0	0.04	30.6	0.43	0.02	0.14	3.42	13.6	0.17	99.5
	49.1	0.10	29.6	0.45	0.02	0.12	3.37	13.6	0.21	96.6
	51.0	0.06	30.7	0.47	0.00	0.16	3.44	13.5	0.16	99.5
average	50.8	0.05	30.6	0.45	0.01	0.15	3.42	13.6	0.19	99.2
2 s.d.	1.93	0.05	1.36	0.05	0.02	0.04	0.17	0.16	0.05	3.34

Appendix B

Trace element data

The following are tables of all of the LA-ICPMS trace element data acquired for eucrite samples and geostandards in this study.

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	
EET 87548	2.96	11.6	97900	1706	5510	35.4	894	58.9	833	6390	2.52	0.85		
	2.91	16.3	100500	2028	5540	34.4	812	55.0	703	6400	5.91	0.33		
	2.66	22.0	101900	2597	5630	36.0	1008	64.4	914	6330	4.93	0.46		
	3.73	15.5	99730	1953	6330	35.3	985	67.4	968	6480	2.92			
	3.46	15.9	96800	1711	6570	36.1	928	59.9	838	6350	4.05	0.74		
	3.54	24.9	100700	1901	9800	38.9	1045	65.8	889	6450	3.97	0.44		
average	3.21	17.7	99588	1983	6563	36.0	945	61.9	858	6400	4.05	0.56		
2 s.d.	0.85	9.7	3801	656	3293	3.1	170	9.5	182	115	2.51	0.44		
EET 92003	8.46	173	71400	2814	33500	42.8	2580	90.3	2150	6450	13.28	8.35		
	9.30	187	72000	2803	33800	40.7	2582	107.4	3081	6440	15.47	14.20		
	average	8.88	180	71700	2809	33650	41.8	2581	2616	6445	14.38	11.28		
	2 s.d.	1.19	19.2	849	16	424	3.0	3	24.2	14	3.10	8.27		
	GRA 98006	0.32	120	71100	1686	8810	43.0	924	44.9	478	7520	10.00	0.67	
		0.92	92.9	67800	1590	10800	33.4	1090	57.1	1560	7560	10.70		
0.82		134	75700	2540	11520	42.4	2050	203.0	7600	8000	11.00	1.52		
0.90		125	83000	1790	15030	38.4	670	51.0	650	9900	14.10	1.59		
0.58		125	62500	1379	15890	37.5	662	41.0	578	7060	8.40	0.68	4.60	
0.50		156	76500	1752	17430	35.0	614	37.1	411	8100	11.30	0.70	1.90	
average	0.80	128	70300	1679	19740	41.6	779	43.0	592	7230	9.80	0.25	3.50	
2 s.d.	0.69	126	72414	1774	14174	38.8	970	68.2	1696	7910	10.76	0.90	3.33	
	0.46	37.4	13300	728	7851	7.5	1010	119.7	5265	1909	3.52	1.07	2.72	
GRA 98033	5.92	43.3	64000	909	9210	34.0	620	34.8	424	7520	7.59	0.58		
	4.77	16.4	60000	620	10900	34.0	683	37.2	450	7640	7.13			
	4.86	18.4	62700	677	13640	37.6	438	42.6	387	7110	6.59	0.13		
	6.01	120	60600	1078	23470	46.3	745	53.7	586	7540	7.69	0.03		
	average	5.39	49.5	61825	821	14305	38.0	622	42.1	462	7453	7.25	0.25	
	2 s.d.	1.33	97.1	3711	424	12754	11.6	265	16.8	174	469	1.01	0.59	
GRA 98043	2.77	93.0	58900	880	16480	41.3	511	38.7	429	8017	13.40	0.90		
	3.38	96.5	57560	1933	22660	51.4	698	49.2	490	7874	5.07	0.19	0.80	
	3.52	73.2	57930	1709	15310	39.2	964	29.8	369	7811	2.75	0.80	1.30	
	3.77	50.0	56230	1516	15250	45.2	1141	35.1	485	7880	2.10	0.22		
	4.63	96.1	57000	1564	28700	43.7	1007	36.6	480	7490	2.17	0.26		
	6.19	109.0	56200	1216	33800	47.3	1134	43.3	596	7060	2.25			
average	4.04	86.3	57303	1470	22033	44.7	909	38.8	475	7689	4.62	0.47	1.05	
2 s.d.	2.43	42.4	2092	746	15629	8.7	506	13.5	151	709	8.89	0.69	0.71	

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
GRA 98055	2.63	50.9	60920	1297	19700	40.5	1065	39.9	704	7150	6.45	0.46	
	4.29	71.8	60690	1866	14400	43.3	1259	45.4	533	7690	7.88	0.23	
	2.47	87.8	61490	2610	13090	35.2	835	28.9	369	7328	8.41	0.09	
	6.23	58.5	61480	1133	17980	48.9	1154	39.8	463	7447	8.46	0.38	
	4.85	48.6	60030	1005	24200	50.5	728	61.2	502	7236	8.01	0.10	
	3.12	55.7	60740	1089	17180	41.9	915	43.8	461	7320	7.58	0.04	
average	6.00	62.7	59300	1340	19340	47.2	1213	49.2	558	7150	7.84	0.14	
2 s.d.	4.23	62.3	60664	1477	17984	43.9	1024	44.0	513	7332	7.80	0.21	
	3.10	27.3	1567	1148	7342	10.7	404	19.8	208	380	1.35	0.32	
GRA 98114	6.19	83.5	55550	2602	12110	41.1	1190	39.9	532	7720	3.37		
	3.52	59.4	60620	1885	17720	39.0	1027	35.2	456	7100	6.00		
	4.77	44.2	57400	1149	10200	34.5	1017	36.7	407	7360	4.83		
	6.90	132	56830	2257	13890	36.0	1001	38.5	508	7390	7.18		
	3.09	66.5	58700	2009	15730	34.3	986	33.2	412	7070	5.96		
	4.89	77.1	57820	1980	13930	37.0	1044	36.7	463	7328	5.47		
average	3.30	67.5	3863	1079	5902	5.9	166	5.3	112	526	2.87		
LAR 06875	5.20	690	56500	12400	25020	29.6	815	46.7	1470	6630	5.23	0.39	
	4.65	155	59500	2200	14260	32.5	1303	77.4	3190	6760	6.30	0.96	
	2.90	490	59400	9060	16600	30.3	987	75.4	3210	6990	5.30	0.35	
	3.53	251	59700	3200	13590	31.8	787	37.3	657	7070	5.20	0.64	
	2.30	361	59900	6760	19220	30.6	722	54.9	1770	6600	5.15	0.37	
	4.26	541	58400	8720	25890	34.6	1750	42.5	678	6490	4.72	0.85	
average	3.81	414.7	58900	7057	19097	31.6	1061	55.7	1829	6757	5.32	0.59	
2 s.d.	2.20	394.5	2571	7688	10628	3.6	795	34.1	2296	460	1.05	0.53	
LEW 85305	3.53	244	58890	2651	34580	46.7	2422	61.8	1568	6770	7.37	0.63	
	3.05	319	58770	3328	42660	54.3	2983	74.0	1777	6460	7.04	0.25	
	3.39	344	57800	3708	45900	57.3	3206	81.1	1958	6260	6.87	0.38	
	3.28	217	60160	2598	32430	44.1	2497	49.3	1435	6850	8.29	0.03	
	3.48	237	59790	2841	33680	45.7	2568	64.4	1568	6712	7.67	0.11	
	3.53	259	60300	3001	34910	47.3	2740	63.8	1608	6680	9.27	1.43	
	3.74	191	58910	2181	28720	40.1	1959	52.2	1300	6851	8.18	1.00	
	3.30	152	59560	1882	24960	38.3	1835	44.8	1210	7050	8.52	0.70	
	3.29	200	59650	2285	29670	40.2	2130	49.5	1282	6810	8.04	0.83	
	2.94	196	59580	2310	29400	42.4	2313	51.6	1381	6850	7.92	0.00	
average	3.35	235.8	59341	2679	33691	45.6	2465	59.2	1509	6729	7.92	0.54	
2 s.d.	0.47	118.3	1503	1114	12804	12.3	868	23.7	470	447	1.44	0.94	

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
LEW 87002	4.48	38.6	124500	2806	5023	14.0	869	59.0	2819	3605	14.00	7.22	
	5.04	30.6	123100	2806	5889	15.0	897	57.5	2135	3686	13.89	8.22	
	4.74	27.5	123000	2861	6229	15.7	1042	57.7	2233	3823	13.65	7.88	
	3.92	32.2	121700	2574	6620	14.7	1123	52.9	1715	3775	13.93	7.21	
	3.77	17.2	123900	3192	7529	16.2	1201	76.7	5033	3852	14.78	8.31	
average	4.39	29.2	123240	2848	6218	15.1	1026	60.8	2787	3748	14.05	7.77	
2 s.d.	1.08	15.7	2115	444	1894	1.8	286	18.4	2632	204	0.86	1.06	
PCA 91193	4.13	99.4	94860	3052	19580	41.3	2081	79.2	1425	5570	8.63		
	4.65	108	94000	1873	20590	40.6	1383	63.7	1054	5722	7.27	0.38	
	4.23	104	95900	2177	20400	37.7	1666	65.8	1394	5558	10.27	0.35	
	3.63	67.1	96900	2115	10290	36.1	1820	72.2	1525	5917	5.21		
	4.01	74.7	93000	1551	15740	30.5	1408	54.6	1092	5898	5.56		
	3.45	86.6	92760	1702	16640	31.8	1521	60.5	1214	5698	7.61	0.01	
average	4.02	90.0	94570	2078	17207	36.3	1647	66.0	1284	5727	7.43	0.25	
2 s.d.	0.86	33.2	3268	1066	7879	8.9	538	17.4	384	309	3.79	0.41	
QUE 97014	5.02	80.0	63390	1340	23550	42.6	1008	43.9	990	7648	1.10		
	5.54	50.3	65030	942	20420	43.6	1760	77.3	3090	7320	0.94	0.10	
	7.19	111.7	63970	932	34180	49.8	815	47.8	566	6872	1.44	0.01	
	7.15	79.6	64230	973	35310	49.5	1760	54.7	1380	6996	0.84	0.03	
	4.24	56.5	64100	945	21000	45.7	519	43.0	524	7504	0.78	0.41	
average	5.83	75.6	64144	1026	26892	46.2	1172	53.3	1310	7268	1.02	0.14	
2 s.d.	2.62	48.4	1180	352	14552	6.6	1128	28.3	2109	658	0.53	0.37	
QUE 99005	2.47	38.9	66100	1334	5069	36.5	883	110.0	3500	7610	7.87	2.24	
	2.87	28.9	69380	1209	4974	35.7	724	88.2	2053	7280	8.10	2.53	
	2.46	20.2	63000	1489	4924	38.1	891	126.2	5340	7730	7.50	2.44	
	2.72	22.0	67800	1456	5370	38.2	1090	120.6	4480	7630	8.34	2.23	
	2.56	27.0	64600	1362	4880	35.1	811	103.4	3470	7540	7.90	2.26	
average	2.62	27.4	66176	1370	5043	36.7	880	109.7	3769	7558	7.94	2.34	
2 s.d.	0.35	14.7	5048	221	391	2.8	271	29.9	2466	339	0.62	0.27	

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
RKPA 80204	4.84	103	64200	952	15800	34.9	745	50.0	1280	6980	7.39	0.37	
	3.72	27.8	64500	948	10840	34.2	919	92.1	4210	7000	7.00	0.76	
	5.05	111	64100	2449	13370	36.1	653	40.6	855	7070	8.08	0.58	
	4.84	43.1	67200	736	18920	37.9	673	45.9	1081	6890	6.13	0.67	
	5.14	49.7	64400	865	13040	36.3	740	43.6	991	7150	6.82	0.44	
	2.99	56.5	66200	1351	11000	35.8	1793	93.5	4040	7480	6.89	0.63	
average	4.43	65.3	65100	1217	13828	35.9	921	61.0	2076	7095	7.05	0.58	
2 s.d.	1.74	67.9	2574	1276	6169	2.6	875	49.7	3188	416	1.30	0.29	
SCO 06041	3.28	86.6	100800	3083	17720	31.8	1478	107.3	4090	5740	11.30	4.29	
	2.45	57.5	100700	2801	13250	33.4	989	87.5	1208	5864	10.18	3.77	
	3.53	87.0	99300	3226	16750	32.9	1199	129.2	4910	5839	10.54	5.09	
	4.05	28.0	100600	2916	13890	28.1	1479	105.6	3740	5639	11.32	4.05	
	3.59	64.8	103400	2884	18800	25.5	2080	131.7	6540	5229	12.98	3.91	
	3.20	50.9	100400	2332	17220	27.7	1117	84.0	1817	5623	10.70	4.20	
average	3.35	62.5	100867	2874	16272	29.9	1390	107.6	3718	5656	11.17	4.22	
2 s.d.	1.06	45.0	2712	612	4420	6.5	782	40.1	3943	463	1.98	0.93	
GRO 95533	4.91	42.2	63990	826	14850	35.6	978	42.5	585	7670	4.02		
	5.77	40.1	65440	729	15150	33.9	951	34.3	435	7445	2.92	0.42	
	3.88	47.6	63700	919	21510	38.5	2530	83.0	2650	7638	2.88	0.17	
	5.27	34.4	63200	795	13590	35.3	880	44.1	509	7270	3.19		
	3.74	22.5	62860	623	12800	31.0	1107	37.8	865	7710	2.65		
	4.71	37.4	63838	778	15580	34.9	1289	48.3	1009	7547	3.13	0.30	
average	4.71	37.4	63838	778	15580	34.9	1289	48.3	1009	7547	3.13	0.30	
2 s.d.	1.76	19.1	1993	221	6897	5.5	1397	39.5	1864	370	1.06	0.35	
Camel Donga	6.15	87.5	75000	1331	21700	41.4	1165	69.0	1180	9500		0.61	
	4.92	89.2	74000	907	20000	38.9	1027	61.3	844	9440	0.20	0.51	
	4.70	88.2	73900	1111	20880	41.2	935	67.6	973	9050	0.03	0.39	
	7.19	105.9	70230	1214	22050	40.3	1220	57.9	1083	9150	0.58	0.43	
	7.77	121.5	70800	1368	25700	39.5	1404	58.6	1010	9170	0.45		
	5.83	75.3	76230	1049	21070	39.9	996	55.4	803	9580	0.29		
average	6.09	94.6	73360	1163	21900	40.2	1125	61.6	982	9315	0.31	0.49	
2 s.d.	2.43	32.8	4731	351	3984	1.9	347	11.0	285	437	0.43	0.19	

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	⁸⁶ Sr	⁸⁸ Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	¹⁵¹ Eu	¹⁵³ Eu
EET 87548	2.56		0.80	0.08	1.61	0.03	0.04	0.13	0.02	0.17	0.13	0.00	0.01
	3.05	0.03	2.80	0.24	1.54	0.08	0.05	0.15	0.02	0.10	0.02	0.04	0.02
	1.54	0.05	1.50	0.10	1.65	0.05	0.09	0.24	0.04	0.18	0.13	0.04	0.03
	1.75	0.02		0.01	0.99	0.01	0.04	0.05	0.01	0.08	0.08	0.01	
	1.21			0.05	0.76	0.01	0.04	0.06	0.03	0.17	0.10	0.04	
average	1.47	0.02	1.30	0.13	1.45	0.04	0.08	0.19	0.06	0.23	0.23		0.02
	1.93	0.03	1.60	0.10	1.33	0.04	0.06	0.14	0.03	0.16	0.11	0.03	0.02
2 s.d.	1.43	0.03	1.70	0.15	0.74	0.05	0.04	0.15	0.03	0.11	0.14	0.04	0.02
EET 92003	5.32	0.01	2.30	0.61	22.10	0.07	0.14	0.45	0.10	0.87	0.47	0.04	0.04
	6.10	0.02	2.10	0.50	13.28	0.19	0.05	0.28	0.08	0.77	0.50	0.04	0.01
	average	5.71	0.02	2.20	0.55	17.69	0.13	0.09	0.37	0.09	0.82	0.04	0.03
	2 s.d.	1.10	0.02	0.28	0.16	12.47	0.12	0.24	0.02	0.14	0.04	0.00	0.05
	GRA 98006	1.83	0.14	0.20	0.36	0.91	0.07	0.13	0.99	0.08	0.37	0.14	0.03
2.43		0.07		0.31	1.27	0.10	0.09	1.54	0.13	0.45	0.33	0.03	0.01
2.61		0.17	1.50	0.34	7.00	0.24	0.17	0.60	0.07	0.40	0.25	0.02	0.00
2.26		0.11		0.48	5.60	0.22	0.18	3.59	0.08	0.54	0.31	0.03	0.02
4.03		0.17	1.20	0.36	1.33	0.20	0.17	3.61	0.11	0.50	0.37	0.01	0.01
average	4.78	0.19		0.59	1.90	0.28	0.18	2.76	0.12	0.56	0.36	0.04	0.01
	3.09	0.12	0.90	0.77	3.12	0.27	0.20	1.28	0.14	0.69	0.50	0.05	0.02
	2 s.d.	0.14	0.95	0.46	3.02	0.20	0.16	2.05	0.10	0.50	0.32	0.03	0.01
	2.17	0.08	1.11	0.34	4.77	0.16	0.08	2.50	0.05	0.22	0.22	0.03	0.01
	GRA 98033	2.52	0.01	0.30	0.16	1.54	0.06	0.10	1.16	0.06	0.59	0.31	0.01
1.98		0.04	0.20	0.08	1.35	0.04	0.03	0.62	0.02	0.19	0.18	0.02	0.01
1.85		0.00		0.15	3.06	0.04	0.08	0.99	0.05	0.24	0.16	0.02	0.00
2.58		0.01	1.20	0.50	3.97	0.04	0.16	1.87	0.11	0.73	0.41	0.01	0.01
average		2.23	0.02	0.57	0.22	2.48	0.05	0.09	1.16	0.06	0.44	0.27	0.02
2 s.d.	0.74	0.03	1.10	0.38	2.51	0.02	0.11	1.05	0.07	0.53	0.23	0.02	0.04
GRA 98043	2.82	0.07	2.60	0.62	1.11	0.22	0.92	0.87	0.35	2.00	0.79		0.01
	2.78	0.11	1.30	0.68	2.32	0.21	0.97	2.34	0.47	2.34	1.12	0.04	0.05
	5.11	0.14	0.50	0.59	1.87	0.35	0.23	3.23	0.12	0.68	0.38	0.02	0.04
	3.67	0.10	1.80	0.09	2.18	0.04	0.17	0.71	0.05	0.36	0.21	0.02	0.01
	3.05	0.11	2.10	0.45	2.53	0.10	0.13	0.75	0.09	0.42	0.28	0.03	0.01
average	2.09	0.04	0.20	0.55	4.70	0.03	0.12	0.59	0.08	0.45	0.45	0.03	0.03
	3.25	0.09	1.42	0.50	2.45	0.16	0.42	1.42	0.19	1.04	0.54	0.03	0.02
2 s.d.	2.08	0.07	1.87	0.43	2.42	0.25	0.81	2.20	0.35	1.77	0.70	0.02	0.03

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{88}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
GRA 98055	3.24	0.08		0.30	2.33	0.09	0.13	0.66	0.06	0.37	0.25	0.02	0.00
	3.25	0.01		0.10	1.53	0.06	0.11	0.81	0.07	0.13	0.16	0.03	0.01
	2.62	0.05	0.40	1.76	1.60	0.57	0.08	0.45	0.05	0.39	0.15	0.00	0.03
	2.74		0.10	0.08	1.79	0.02	0.03	0.48	0.04	0.27	0.31	0.02	0.03
	2.19			0.10	1.20	0.01	0.05	0.25	0.05	0.39	0.35	0.03	0.03
	3.10		0.40	0.19	1.06	0.03	0.06	0.61	0.06	0.40	0.23	0.03	
average	2.17			0.09	2.22	0.02	0.04	0.68	0.03	0.36	0.20	0.02	0.02
2 s.d.	2.76	0.04	0.30	0.38	1.68	0.11	0.07	0.56	0.05	0.33	0.23	0.02	0.02
	0.92	0.07	0.35	1.23	0.96	0.40	0.08	0.37	0.02	0.19	0.15	0.02	0.02
GRA 98114	2.92	0.07		0.08	1.63	0.06	0.01	7.48	0.03	0.14	0.09	0.00	
	2.10	0.06		0.12	1.26	0.04	0.04	5.98	0.04	0.32	0.20	0.01	0.03
	3.46	0.02		0.08	1.35	0.09	0.02	0.49	0.03	0.21	0.13	0.03	0.03
	2.80	0.14		0.03	2.11	0.05	0.05	7.72	0.04	0.28	0.18	0.02	0.02
	3.06	0.01		0.07	1.70	0.06	0.08	7.97	0.04	0.26	0.24	0.01	0.03
	2.87	0.06		0.08	1.61	0.06	0.04	5.93	0.04	0.24	0.17	0.01	0.03
average	2.87	0.06		0.08	1.61	0.06	0.04	5.93	0.04	0.24	0.17	0.01	0.03
2 s.d.	0.99	0.10		0.06	0.67	0.04	0.06	6.28	0.01	0.14	0.12	0.03	0.01
LAR 06875	2.19	0.07	13.60	13.40		5.73	0.81	1.78	0.26	1.39	0.65	0.12	0.13
	2.04	0.07	0.90	1.84	1.14	2.30	1.94	5.08	0.73	3.75	1.19	0.05	0.06
	1.81	0.09	8.90	10.81	2.23	4.32	0.45	1.37	0.20	0.92	0.44	0.09	0.08
	3.18	0.22	4.90	2.85	8.77	2.29	0.84	2.36	0.38	1.94	0.85	0.06	0.04
	2.68	0.04	4.40	7.37	1.52	2.31	0.36	0.99	0.14	0.75	0.25	0.07	0.09
	2.05	0.16	10.90	11.40	5.58	6.93	1.26	3.15	0.46	2.07	0.74	0.09	0.16
average	2.33	0.11	7.27	7.95	3.85	3.98	0.94	2.46	0.36	1.80	0.69	0.08	0.09
2 s.d.	1.02	0.14	9.40	9.53	6.53	4.03	1.17	2.99	0.43	2.18	0.65	0.06	0.09
LEW 85305	2.87	0.01		0.44	42.50	0.04	0.11	0.60	0.17	1.31	1.00	0.02	0.02
	2.76	0.08	2.40	0.95	63.50	0.07	0.23	1.17	0.29	1.96	1.15	0.03	0.03
	2.37	0.02		0.96	75.00	0.02	0.18	1.26	0.36	2.70	1.63	0.02	0.03
	2.57	0.03		0.46	36.10	0.08	0.13	0.48	0.13	1.12	0.75	0.02	0.02
	3.32	0.03		0.45	46.10	0.07	0.18	0.59	0.17	1.52	1.09	0.02	0.02
	2.80	0.09		0.57	45.60	0.01	0.17	0.69	0.21	1.67	1.22	0.03	0.04
	3.22	0.03		0.25	26.20	0.03	0.04	0.30	0.04	0.77	0.53	0.03	0.02
	3.34		2.00	0.18	21.40	0.04	0.02	0.26	0.06	0.56	0.39	0.04	0.03
	3.38	0.04	1.00	0.44	28.70	0.05	0.09	0.42	0.13	1.01	0.61	0.04	0.03
	2.31	0.06	1.20	0.30	32.60	0.02	0.12	0.47	0.14	0.95	0.74	0.04	0.03
average	2.89	0.04	1.65	0.50	41.77	0.04	0.13	0.62	0.18	1.36	0.91	0.03	0.03
2 s.d.	0.81	0.06	1.32	0.53	33.70	0.05	0.13	0.68	0.18	1.27	0.75	0.01	0.02

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{88}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
LEW 87002	1.86	0.00	0.10	0.16	7.50	0.04	0.04	0.05	0.03	0.17	0.12	0.03	0.03
	2.18		3.40	0.04	6.96	0.03	0.02	0.04	0.01	0.17	0.14	0.02	0.04
	2.05			0.03	7.55	0.04	0.02	0.02	0.02	0.24	0.14	0.04	0.03
	1.77	0.02	2.00	0.07	6.96	0.04	0.03	0.03	0.02	0.15	0.20	0.03	0.03
	2.15	0.04		0.08	8.01	0.04	0.02	0.06	0.01	0.17	0.13	0.05	0.02
average	2.00	0.03	1.83	0.08	7.40	0.04	0.03	0.04	0.02	0.18	0.15	0.03	0.03
2 s.d.	0.36	0.07	3.31	0.10	0.89	0.01	0.02	0.03	0.01	0.07	0.06	0.02	0.02
PCA 91193	2.08	0.02		0.57	13.26	0.11	0.08	0.29	0.12	0.88	0.55	0.05	0.03
	3.13	0.12		0.75	7.53	0.13	0.15	0.49	0.12	0.72	0.49	0.04	0.04
	3.09	0.10	3.80	0.60	18.38	0.18	0.07	0.22	0.05	0.50	0.51	0.04	0.03
	4.68	0.08		0.63	8.93	0.16	0.15	0.30	0.06	0.44	0.17	0.02	0.03
	1.93	0.10		0.47	4.63	0.11	0.19	0.59	0.11	0.71	0.37	0.04	0.03
average	2.78	0.01	2.90	0.52	6.51	0.12	0.27	0.62	0.11	0.78	0.35	0.04	0.02
2 s.d.	2.95	0.07	3.35	0.59	9.87	0.14	0.15	0.42	0.09	0.67	0.41	0.04	0.03
	1.97	0.09	1.27	0.19	10.16	0.06	0.15	0.34	0.06	0.34	0.28	0.01	0.02
QUE 97014	2.33	0.01	2.10	1.00	2.28	0.26	0.08	0.23	0.06	0.33	0.30	0.03	0.04
	3.44	0.08	1.00	0.48	3.73	0.11	0.11	0.32	0.08	0.47	0.35	0.04	0.02
	3.09	0.07	4.40	1.10	5.30	0.15	0.25	0.45	0.14	0.87	0.51	0.03	0.03
	2.34	0.03		0.43	3.12	0.07	0.10	0.23	0.07	0.54	0.32	0.03	0.03
	2.18	0.06	1.20	0.50	2.53	0.13	0.11	0.25	0.08	0.40	0.22	0.00	0.03
average	2.68	0.05	2.18	0.70	3.39	0.15	0.13	0.30	0.09	0.52	0.34	0.03	0.03
2 s.d.	1.11	0.05	3.12	0.64	2.41	0.14	0.13	0.18	0.06	0.42	0.21	0.03	0.02
QUE 99005	3.52	0.01		0.10	4.37	0.29	0.19	0.22	0.10	0.54	0.28	0.00	0.00
	3.62	0.07		0.06	5.80	0.28	0.15	0.29	0.09	0.51	0.21	0.01	0.00
	4.04	0.06		0.13	5.26	0.65	0.22	0.46	0.22	1.01	0.44	0.03	0.01
	3.66	0.01		0.10	6.38	0.45	0.20	0.25	0.08	0.41	0.11	0.00	0.02
	3.71			0.09	4.44	0.39	0.27	0.31	0.14	0.58	0.19	0.00	0.00
average	3.71	0.03		0.10	5.25	0.41	0.27	0.31	0.13	0.61	0.25	0.01	0.01
2 s.d.	0.39	0.07		0.05	1.73	0.30	0.34	0.18	0.12	0.46	0.25	0.03	0.02

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{88}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
RKPA 80204	2.32	0.06		0.55	1.02	0.15	0.26	5.57	0.15	0.98	0.31	0.00	0.01
	2.30	0.01		0.14	1.10	0.07	0.09	1.62	0.05	0.45	0.17	0.00	0.02
	2.27			2.09	1.56	0.75	0.21	2.06	0.09	0.49	0.27	0.03	0.03
	1.98			0.28	1.03	0.09	0.16	2.18	0.10	0.53	0.29	0.02	0.01
	3.44	0.03		0.48	0.63	0.10	0.18	1.56	0.09	0.55	0.32	0.01	0.03
	2.12	0.03		0.58	0.90	0.29	2.06	6.30	0.70	3.70	1.17	0.03	0.01
average	2.41	0.03		0.69	1.04	0.24	0.49	3.22	0.20	1.12	0.42	0.01	0.02
2 s.d.	1.05	0.04		1.42	0.61	0.52	1.54	4.27	0.50	2.56	0.74	0.03	0.02
SCO 06041	5.33	0.06	2.10	0.62	3.42	0.57	0.09	0.43	0.08	0.71	0.49	0.05	0.02
	5.49	0.05	0.30	0.37	4.01	0.71	0.08	0.26	0.05	0.39	0.22	0.04	0.02
	6.30	0.05	1.30	0.50	6.48	0.48	0.14	0.44	0.06	0.67	0.24	0.03	0.05
	2.26		2.30	0.24	5.84	0.04	0.08	0.28	0.06	0.34	0.32	0.05	0.03
	5.43	0.03		0.44	12.58	0.33	0.10	0.31	0.05	0.49	0.27	0.02	0.02
	4.10	0.06	2.00	0.34	6.94	0.26	0.07	0.32	0.08	0.55	0.35	0.03	0.02
average	4.82	0.05	1.60	0.42	6.55	0.40	0.09	0.34	0.06	0.53	0.31	0.04	0.03
2 s.d.	2.88	0.02	1.64	0.26	6.53	0.48	0.05	0.15	0.03	0.30	0.20	0.02	0.02
GRO 95533	2.36	0.09	1.30	0.10	1.72	0.05	0.05	0.11	0.04	0.18	0.12	0.04	0.02
	4.07	0.03	2.30	0.26	2.92	0.17	0.11	0.31	0.08	0.30	0.32	0.03	0.03
	3.50	0.02	2.10	0.33	3.90	0.07	0.10	0.34	0.08	0.53	0.36	0.03	
	2.08			0.14	2.19	0.11	0.07	0.28	0.06	0.36	0.35	0.03	0.02
	2.98	0.04		0.09	1.55	0.03	0.05	0.16	0.03	0.25	0.29	0.03	
average	3.00	0.04	1.90	0.18	2.46	0.09	0.07	0.24	0.06	0.32	0.29	0.03	0.02
2 s.d.	1.63	0.07	1.06	0.21	1.93	0.11	0.06	0.20	0.05	0.26	0.19	0.01	0.01
Camel Donga	1.14	0.07		0.22	3.57	0.14	0.05	0.16	0.04	0.38	0.25		
	2.06			0.45	2.93	0.40	0.06	0.17	0.03	0.26	0.10		
	1.70	0.00		0.31	3.56	0.29	0.07	0.22	0.04	0.26	0.34		
	1.47	0.03		0.33	4.68	0.15	0.03	0.16	0.06	0.41	0.36		
	1.90	0.01		0.45	5.78	0.20	0.09	0.37	0.08	0.71	0.41		
	1.69	0.07		0.40	2.99	0.23	0.08	0.23	0.05	0.34	0.22		
average	1.66	0.04		0.36	3.92	0.23	0.06	0.22	0.05	0.39	0.28		
2 s.d.	0.65	0.07		0.18	2.22	0.20	0.04	0.16	0.04	0.33	0.23		

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
EET 87548	0.12	0.06	0.21	0.09	0.27	0.05	0.50	0.12	0.06	
	0.29	0.05	0.25	0.08	0.34	0.06	0.54	0.08	0.12	0.07
	0.38	0.06	0.32	0.10	0.36	0.07	0.67	0.12	0.16	0.06
	0.14	0.04	0.21	0.11	0.28	0.09	0.61	0.08	0.06	0.05
	0.12	0.03	0.21	0.09	0.36	0.07	0.49	0.08	0.05	
	0.22	0.06	0.40	0.11	0.51	0.09	0.63	0.11	0.07	0.06
average	0.21	0.05	0.27	0.10	0.35	0.07	0.57	0.10	0.09	0.06
2 s.d.	0.22	0.02	0.16	0.03	0.17	0.03	0.15	0.04	0.09	0.01
EET 92003	1.10	0.20	1.33	0.40	1.41	0.19	1.37	0.22	1.03	0.06
	0.83	0.19	1.39	0.33	1.18	0.12	1.24	0.23	0.79	0.10
average	0.97	0.20	1.36	0.37	1.30	0.16	1.31	0.23	0.91	0.08
2 s.d.	0.38	0.01	0.08	0.11	0.33	0.09	0.18	0.00	0.34	0.05
GRA 98006	0.41	0.10	1.12	0.29	1.25	0.21	2.06	0.36	0.09	0.08
	0.22	0.09	0.85	0.27	0.95	0.17	1.46	0.25	0.11	0.05
	0.42	0.10	1.00	0.21	0.74	0.14	1.48	0.20	0.38	0.07
	0.70	0.18	1.39	0.41	1.47	0.27	2.43	0.39	0.16	0.03
	0.51	0.20	1.39	0.44	1.50	0.29	2.47	0.41	0.13	0.05
	0.70	0.14	1.13	0.29	1.10	0.21	1.74	0.28	0.09	0.13
	0.67	0.14	1.50	0.39	1.49	0.25	1.94	0.34	0.30	0.02
average	0.52	0.14	1.20	0.33	1.21	0.22	1.94	0.32	0.18	0.06
2 s.d.	0.36	0.08	0.47	0.17	0.60	0.11	0.82	0.16	0.23	0.08
GRA 98033	0.50	0.12	1.14	0.35	1.39	0.26	1.87	0.39	0.15	0.11
	0.34	0.15	1.15	0.34	1.51	0.24	1.88	0.42	0.15	0.09
	0.53	0.10	1.00	0.32	1.25	0.25	2.08	0.36	0.16	0.08
	0.96	0.20	1.93	0.51	1.66	0.32	2.58	0.44	0.51	0.06
average	0.58	0.14	1.31	0.38	1.45	0.27	2.10	0.40	0.24	0.08
2 s.d.	0.53	0.09	0.84	0.18	0.35	0.08	0.67	0.07	0.36	0.04
GRA 98043	1.47	0.31	2.64	0.65	2.34	0.38	2.95	0.51	0.16	0.10
	1.61	0.42	3.26	0.83	3.02	0.50	4.24	0.83	0.22	0.10
	0.71	0.15	1.16	0.29	1.22	0.24	1.74	0.35	0.14	0.08
	0.36	0.14	1.35	0.39	1.30	0.25	1.88	0.36	0.17	0.03
	0.51	0.17	1.18	0.29	1.23	0.21	1.79	0.32	0.24	0.03
	0.65	0.16	1.53	0.34	1.49	0.25	1.83	0.35	0.47	0.01
average	0.89	0.23	1.85	0.47	1.77	0.31	2.41	0.45	0.23	0.06
2 s.d.	1.05	0.23	1.76	0.44	1.49	0.23	2.02	0.39	0.24	0.08

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
GRA 98055	0.37	0.10	1.25	0.30	1.10	0.19	1.81	0.34	0.27	0.12
	0.44	0.09	0.99	0.38	1.12	0.21	2.00	0.39	0.25	0.06
	0.45	0.10	0.78	0.26	0.85	0.16	1.68	0.34	0.13	0.04
	0.64	0.14	1.40	0.35	1.57	0.27	2.07	0.46	0.23	0.06
	0.56	0.19	1.57	0.39	1.53	0.30	2.34	0.46	0.16	0.01
	0.73	0.13	1.33	0.32	1.13	0.28	2.02	0.44	0.09	0.08
	0.60	0.16	1.30	0.39	1.64	0.32	2.37	0.41	0.23	0.06
average	0.54	0.13	1.23	0.34	1.28	0.25	2.04	0.40	0.19	0.06
2 s.d.	0.25	0.07	0.53	0.10	0.60	0.12	0.51	0.10	0.14	0.06
GRA 98114	0.34	0.11	1.08	0.33	1.31	0.29	2.05	0.41	0.17	0.05
	0.59	0.12	1.06	0.33	1.07	0.23	1.84	0.24	0.13	0.04
	0.44	0.10	0.80	0.31	1.17	0.26	1.59	0.34	0.16	0.05
	0.45	0.15	1.04	0.29	1.23	0.24	1.61	0.30	0.18	0.04
	0.59	0.13	1.10	0.38	1.41	0.29	1.71	0.34	0.15	0.00
average	0.48	0.12	1.02	0.33	1.24	0.26	1.76	0.33	0.16	0.04
2 s.d.	0.22	0.04	0.25	0.06	0.26	0.05	0.38	0.12	0.04	0.04
LAR 06875	0.88	0.20	1.45	0.36	1.22	0.24	1.83	0.25	0.51	0.04
	1.94	0.36	2.76	0.75	2.30	0.37	2.46	0.42	0.08	0.06
	0.61	0.14	0.96	0.36	1.01	0.17	1.60	0.31	0.12	0.05
	1.06	0.23	1.57	0.44	1.57	0.26	2.03	0.32	0.28	0.03
	0.45	0.13	0.86	0.33	0.86	0.24	1.67	0.28	0.13	0.07
	1.09	0.25	1.73	0.42	1.28	0.29	2.08	0.28	0.30	0.00
average	1.01	0.22	1.56	0.44	1.37	0.26	1.95	0.31	0.24	0.04
2 s.d.	1.04	0.17	1.37	0.31	1.03	0.13	0.63	0.12	0.32	0.05
LEW 85305	2.17	0.42	3.52	0.79	2.33	0.43	2.83	0.44	1.02	0.01
	2.32	0.52	4.25	0.91	3.01	0.53	3.10	0.53	1.86	0.05
	2.71	0.62	4.82	1.11	3.43	0.55	3.21	0.56	2.20	0.03
	1.75	0.42	3.27	0.81	2.45	0.41	2.90	0.41	0.99	0.01
	1.79	0.47	3.77	0.92	2.80	0.44	2.93	0.48	1.31	
	2.46	0.55	4.09	1.15	3.39	0.61	3.35	0.51	1.58	
	1.36	0.31	2.58	0.58	2.19	0.38	2.29	0.39	0.77	0.03
	1.20	0.26	2.49	0.60	2.19	0.30	2.58	0.46	0.71	0.03
	1.41	0.35	3.00	0.76	2.57	0.38	3.06	0.56	0.87	
	1.46	0.38	2.85	0.73	2.32	0.46	2.95	0.54	1.09	
average	1.86	0.43	3.46	0.84	2.67	0.45	2.92	0.49	1.24	0.03
2 s.d.	1.04	0.22	1.54	0.38	0.94	0.18	0.61	0.12	0.99	0.04

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
LEW 87002	0.23	0.08	0.62	0.15	0.58	0.07	0.63	0.10	0.21	0.03
	0.32	0.06	0.58	0.16	0.65	0.12	0.57	0.12	0.21	0.08
	0.42	0.08	0.48	0.19	0.71	0.11	0.71	0.13	0.20	0.04
	0.33	0.07	0.67	0.14	0.61	0.09	0.72	0.13	0.25	0.09
	0.47	0.09	0.65	0.18	0.62	0.11	0.76	0.11	0.26	0.06
average	0.35	0.08	0.60	0.16	0.63	0.10	0.68	0.12	0.23	0.06
2 s.d.	0.18	0.03	0.15	0.04	0.10	0.04	0.15	0.02	0.05	0.05
PCA 91193	0.95	0.23	1.82	0.48	1.41	0.25	1.61	0.29	0.45	0.05
	1.02	0.18	1.62	0.39	1.51	0.23	1.56	0.25	0.32	0.04
	0.71	0.16	1.37	0.35	1.10	0.19	1.34	0.22	0.57	0.06
	0.45	0.13	1.07	0.25	0.90	0.18	1.12	0.20	0.27	0.09
	0.61	0.13	0.99	0.24	0.90	0.16	1.06	0.16	0.26	0.06
average	0.59	0.12	1.14	0.26	0.91	0.20	0.92	0.18	0.22	0.08
2 s.d.	0.72	0.16	1.34	0.33	1.12	0.20	1.27	0.22	0.35	0.06
0.44	0.08	0.08	0.66	0.19	0.55	0.06	0.56	0.09	0.27	0.03
QUE 97014	0.67	0.18	1.35	0.40	1.49	0.27	2.09	0.46	0.28	0.04
	0.76	0.16	1.33	0.37	1.50	0.28	1.84	0.44	0.23	0.02
	0.82	0.26	1.81	0.43	1.72	0.35	2.25	0.49	0.34	0.00
	0.76	0.20	1.44	0.39	1.71	0.31	1.99	0.40	0.31	0.02
	0.50	0.15	1.50	0.39	1.79	0.34	2.41	0.49	0.20	0.08
average	0.70	0.19	1.49	0.40	1.64	0.31	2.12	0.45	0.27	0.03
2 s.d.	0.25	0.08	0.39	0.05	0.28	0.07	0.44	0.08	0.11	0.06
QUE 99005	0.27	0.09	0.62	0.17	0.56	0.12	1.49	0.19	0.13	0.03
	0.28	0.08	0.44	0.14	0.54	0.11	1.16	0.16	0.24	0.06
	0.70	0.14	0.85	0.26	1.05	0.16	1.32	0.22	0.17	0.01
	0.17	0.06	0.59	0.15	0.59	0.10	1.07	0.19	0.26	0.07
	0.51	0.09	0.77	0.19	0.74	0.12	1.24	0.17	0.17	0.08
average	0.39	0.09	0.65	0.18	0.70	0.12	1.26	0.19	0.19	0.05
2 s.d.	0.43	0.06	0.32	0.10	0.43	0.05	0.32	0.05	0.11	0.06

Table B1: Low-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
RKPA 80204	0.65	0.12	1.17	0.30	0.94	0.17	1.72	0.30	0.08	0.06
	0.37	0.10	0.68	0.21	0.82	0.14	1.28	0.28	0.06	0.00
	0.49	0.12	1.26	0.25	1.10	0.24	1.83	0.28	0.09	0.00
	0.48	0.13	1.16	0.29	1.00	0.23	1.55	0.30	0.10	0.04
	0.41	0.09	0.85	0.22	0.94	0.21	1.38	0.29	0.09	0.08
	1.72	0.40	2.82	0.54	1.70	0.31	2.52	0.41	0.07	0.03
average	0.69	0.16	1.32	0.30	1.08	0.22	1.71	0.31	0.08	0.04
2 s.d.	1.03	0.24	1.53	0.24	0.63	0.12	0.89	0.10	0.03	0.06
SCO 06041	0.78	0.21	0.99	0.30	1.27	0.17	1.32	0.26	0.25	0.13
	0.69	0.13	1.01	0.26	1.08	0.19	0.89	0.20	0.25	0.09
	0.69	0.14	1.39	0.25	0.97	0.18	1.05	0.24	0.35	0.06
	0.40	0.09	0.76	0.22	0.74	0.15	1.00	0.15	0.39	0.06
	0.57	0.13	0.92	0.18	0.68	0.12	0.87	0.14	0.34	0.05
	0.60	0.12	0.92	0.21	0.77	0.12	1.04	0.18	0.32	0.07
average	0.62	0.13	1.00	0.24	0.92	0.15	1.03	0.19	0.32	0.08
2 s.d.	0.26	0.08	0.42	0.09	0.46	0.06	0.32	0.09	0.11	0.06
GRO 95533	0.54	0.17	1.38	0.39	1.47	0.22	1.91	0.32	0.13	0.05
	0.72	0.18	1.33	0.34	1.48	0.22	1.51	0.33	0.18	0.02
	0.65	0.15	1.55	0.41	1.62	0.30	2.30	0.36	0.32	-0.01
	0.58	0.16	1.28	0.40	1.37	0.21	1.72	0.35	0.14	0.01
	0.45	0.12	1.33	0.34	1.30	0.24	1.97	0.28	0.16	-0.01
	0.59	0.16	1.37	0.38	1.45	0.24	1.88	0.33	0.19	0.01
average	0.59	0.16	1.37	0.38	1.45	0.24	1.88	0.33	0.19	0.01
2 s.d.	0.21	0.04	0.21	0.07	0.24	0.07	0.59	0.06	0.15	0.05
Camel Donga	0.73	0.17	1.64	0.44	1.57	0.28	2.02	0.41	0.25	0.00
	0.29	0.19	1.62	0.41	1.36	0.27	1.79	0.28	0.18	0.02
	0.79	0.14	1.61	0.35	1.35	0.19	1.73	0.26	0.18	0.02
	0.67	0.23	1.88	0.54	1.99	0.38	2.29	0.41	0.33	0.04
	0.98	0.26	2.24	0.56	1.96	0.35	2.53	0.38	0.30	0.01
	0.59	0.15	1.60	0.38	1.67	0.34	2.38	0.41	0.16	0.04
average	0.68	0.19	1.77	0.45	1.65	0.30	2.12	0.36	0.23	0.02
2 s.d.	0.46	0.09	0.51	0.17	0.56	0.14	0.65	0.14	0.14	0.03

Table B2: High-Ca pyroxene trace element concentrations in µg/g

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
EET 87548	3.39	103	94400	2263	37900	46.3	1108	84.4	1009	5620	2.17	1.00	
	3.51	157	93500	2467	56800	46.0	980	81.4	1280	5380	10.88	1.08	0.90
	3.66	221	90600	3952	59100	51.8	1126	91.3	1103	5050	12.23	2.05	3.60
average	3.52	160	92833	2894	51267	48.0	1071	85.7	1131	5350	8.43	1.38	2.25
2 s.d.	0.27	118	3972	1844	23266	6.5	159	10.2	275	572	10.92	1.17	3.82
EET 92003	6.72	309	62800	5005	42180	50.3	2070	111.0	3007	6470	9.36	8.02	
	13.3	224	78800	5182	43450	51.0	2842	122.8	3333	5926	16.14	5.53	
	15.3	256	71900	5027	44680	52.0	1971	128.4	3773	6500	6.90	2.10	
	12.2	332	66470	5332	50050	55.8	3254	112.4	3171	6582	6.84	3.22	
	9.30	399	62790	5155	51760	56.6	3522	103.1	2817	6746	6.38	5.39	
	10.7	323	59260	5117	52590	57.5	3664	100.0	2824	6630	6.89	2.83	
	15.0	325	66300	5601	53400	59.9	4530	132.1	4480	6320	5.85	2.17	
average	11.77	310	66903	5203	48301	54.7	3122	115.7	3344	6453	8.34	4.18	
2 s.d.	6.19	113	13146	413	9435	7.3	1819	24.8	1202	536	7.23	4.41	
GRA 98006	0.89	242	70000	2200	47000	54.3	890	76.0	730	6300	8.90	0.44	
	2.07	427	77000	2430	63800	59.6	2480	186.0	4900	7000	10.00	0.41	
	1.56	338	63900	2624	73500	67.2	2470	127.0	3790	5400	8.58	0.49	
	1.47	340	61500	2576	80300	81.1	2440	148.0	3580	5400	9.40	0.89	
average	1.50	337	68100	2458	66150	65.6	2070	134.3	3250	6025	9.22	0.56	
2 s.d.	0.97	151	13857	381	28902	23.3	1574	91.7	3554	1552	1.24	0.45	
GRA 98033	7.78	236	61600	1584	48500	57.8	1202	80.1	1360	6750	8.19	0.83	
	7.38	195	60600	1388	53500	57.6	1010	72.3	1290	6190	5.75	0.42	
	8.18	190	60500	1246	55900	65.8	735	74.8	699	6220	6.50	0.62	
	9.16	310	59500	2660	74200	73.6	1000	93.1	902	6100	6.00	0.08	
	9.60	372	62600	1878	74400	75.2	1053	94.0	944	5850	6.80	0.45	
	9.31	288	60200	1539	93500	86.8	840	107.1	972	5140	5.27	0.93	
	10.9	437	55300	2420	115800	104.0	1365	128.6	1375	3890	5.22	0.69	
	13.7	581	58800	2663	127200	109.2	2030	158.4	2860	3800	5.87	0.96	
average	9.50	326	59888	1922	80375	78.8	1154	101.1	1300	5493	6.20	0.62	
2 s.d.	4.08	267	4385	1158	58705	39.4	808	59.3	1352	2223	1.94	0.60	
GRA 98043	13.8	606	51660	4680	131700	133.4	2439	140.9	1830	3850	2.93	0.67	0.10
	9.05	310	54130	1952	98600	91.1	1610	87.6	1015	5480	1.52	0.56	
	15.7	613	51860	3585	129900	121.5	2242	128.4	1642	3682	1.96	1.17	2.20
	14.75	576	51100	4271	129300	122.4	2393	131.6	1921	3740	3.18		2.00
average	13.3	526	52188	3622	122375	117.1	2171	122.1	1602	4188	2.40	0.80	1.43
2 s.d.	5.88	290	2669	2403	31766	36.3	767	47.2	816	1728	1.57	0.65	2.32

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
GRA 98055	13.03	553	54290	3607	127700	122.9	2494	132.6	1891	3554	5.46	0.52	
	15.11	561	54580	3898	125700	109.0	2649	137.0	1718	3704	5.59	0.48	
	16.17	579	54090	4100	124900	114.8	2655	148.1	1827	3580	5.55	0.41	
	15.23	598	50830	4873	122900	123.7	3051	160.3	2187	3596	5.93		
average	14.9	573	53448	4120	125300	117.6	2712	144.5	1906	3609	5.63	0.47	
2 s.d.	2.65	40	3513	1083	3973	14.0	476	24.8	401	132	0.41	0.11	
GRA 98114	7.52	172	60900	2382	42390	50.5	1276	59.1	787	6630	8.26		
	8.84	346	57700	3340	66100	66.2	1429	78.3	1024	5420	6.99		
	6.24	162	58200	2681	46800	52.8	2760	155.5	5030	5790	7.83		
	7.53	227	58933	2801	51763	56.5	1821.7	97.6	2280.3	5946.7	7.7		
average	7.53	227	58933	2801	51763	56.5	1821.7	97.6	2280.3	5946.7	7.7		
2 s.d.	2.60	207	3443	980	25220	17.0	1632.4	102.1	4768.5	1240.1	1.3		
LAR 06875	5.40	900	56700	13300	55900	47.8	2280	62.2	754	5620	5.08	1.47	
	5.15	1340	50500	24600	32700	28.8	1829	43.3	1210	5610	3.95	0.81	
	3.52	747	35733	12633	29533	25.5	1370	35.2	655	3743	3.01	0.76	
	0.35	622	8768	15981	32810	26.9	637.8	26.7	644.9	14.1	1.6	0.9	
LEW 85305	4.01	776	52500	4190	107400	91.7	3497	127.2	2450	4470	6.38	1.07	
	4.60	818	53200	4669	105100	90.4	3576	134.1	2626	4475	6.61	0.77	
	4.31	797	52850	4430	106250	91.1	3537	130.7	2538	4473	6.50	0.92	
	0.83	59	990	677	3253	1.8	111.7	9.8	248.9	7.1	0.3	0.4	
LEW 87002	3.50	17	121600	3183	9720	20.3	1711	64.3	2040	3929	12.81	4.32	
	3.49	14	121000	2446	9810	16.6	1377	49.1	1429	3883	13.56	4.51	
	3.62	17	122500	3179	10180	19.9	1683	62.3	2120	3929	12.65	3.58	
	3.09	24	122300	3168	11610	19.0	1716	64.1	2215	3989	19.90	87.00	
average	3.02	34	124300	3215	14300	23.5	1766	66.9	2120	3888	14.80	23.50	
	3.34	21	122340	3038	11124	19.9	1651	61.3	1985	3924	14.74	24.58	
	0.54	17	2492	663	3862	5.0	311.7	14.1	633.6	85.2	6.0	71.8	
PCA 91193	7.22	445	79250	3550	100700	67.0	2104	128.8	1891	4020	7.30	0.02	
	7.38	813	76700	11700	101900	70.9	3138	140.4	2550	4010	8.07	0.38	
	9.40	774	71330	5450	128500	89.2	3685	209.8	2968	3380	6.41	0.25	
	8.00	677	75760	6900	110367	75.7	2976	159.7	2470	3803	7.26	0.22	
2 s.d.	2.43	404	8086	8528	31431	23.7	1605.8	87.6	1086.0	733.3	1.7	0.4	

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Cu
QUE 97014	11.4	273	60140	1609	76900	74.7	1175	81.3	1127	5550	1.27	0.43	
	9.83	267	60840	1542	87100	79.0	1081	84.1	1160	5426	1.73		
	11.4	317	59260	1774	88800	78.4	926	92.6	1217	5102	0.92	0.07	
	13.5	509	57680	3800	98500	85.6	1466	108.7	2081	4710	1.25		
average	11.5	341	59480	2181	87825	79.4	1162	91.7	1396	5197	1.29	0.25	
2 s.d.	3.02	228	2726	2167	17693	9.1	454	24.7	916.0	751.2	0.7	0.5	
QUE 99005	3.39	69	62900	2710	16320	36.3	1341	128.2	5410	7510	7.61	2.42	
	2.24	106	60200	6040	16610	31.1	1184	130.3	6780	7210	7.87	2.01	
	2.82	87	61550	4375	16465	33.7	1263	129.3	6095	7360	7.74	2.22	
	1.63	51	3818	4709	410	7.3	222.0	3.0	1937.5	424.3	0.4	0.6	
RKPA 80204	7.40	275	60600	3210	50200	49.6	1104	88.5	2540	6100	6.70	0.71	
	6.24	247	64000	4350	41010	47.5	971	73.8	2170	6270	6.01	0.39	
	6.82	261	62300	3780	45605	48.6	1038	81.2	2355	6185	6.36	0.55	
	1.64	39	4808	1612	12997	3.0	188	20.8	523.3	240.4	1.0	0.5	
SCO 06041	3.60	42	102100	3190	22110	36.4	2060	100.7	2232	5370	10.52	3.54	
	3.83	50	103000	3153	22090	36.0	1911	110.8	3120	5247	11.83	3.48	
	3.42	90	97200	2147	22200	29.3	1134	91.4	2740	5740	10.62	3.84	
	3.54	85	103600	3083	27970	33.3	1891	124.6	3800	5180	12.43	4.55	
average	3.60	67	101475	2893	23593	33.7	1749	106.9	2973	5384	11.35	3.85	
2 s.d.	0.34	48	5832	999	5837	6.6	833.7	28	1321	500	1.9	1.0	
GRO 95533	5.62	74	63850	908	26560	38.7	959	49.5	686	7378	3.20	0.00	
	5.53	57	64040	829	25870	39.8	905	39.5	475	7428	2.30	0.40	
	4.84	71	63420	831	25400	40.7	913	38.3	492	7404	3.13		
	5.33	67	63770	856	25943	39.7	926	42.4	551	7403	2.88	0.20	
2 s.d.	0.85	17	635	90.1	1167	2.0	58.3	12.3	234	50.0	1.0	0.6	
Camel Donga	10.5	302	69200	2378	77600	61.5	2167	117.4	3036	6920	0.37	0.75	
	6.75	189	71080	1832	57300	54.3	1340	90.0	1211	7470	0.20	0.90	
	6.92	350	71700	7140	53600	52.8	1441	105.6	3390	8210	0.42	1.03	
	8.07	281	70660	3783	62833	56.2	1649	104.3	2546	7533	0.33	0.89	
2 s.d.	4.28	165	2603.7	5839.5	25842.9	9.3	902.3	27.5	2338.7	1294.7	0.2	0.3	

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{87}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
EET 87548	1.22	0.07	3.30	0.88	4.93	0.01	0.08	0.38	0.08	0.60	0.29	0.06	0.03
	1.75	0.01	0.00	1.12	4.91	0.07	0.21	0.57	0.13	0.77	0.36	0.04	0.04
	1.01	0.02	2.10	1.58	6.40	0.06	0.24	0.66	0.17	0.95	0.31	0.06	0.06
average	1.33	0.04	1.80	1.19	5.41	0.05	0.18	0.54	0.13	0.77	0.32	0.05	0.04
2 s.d.	0.76	0.07	3.34	0.71	1.71	0.06	0.17	0.28	0.09	0.35	0.07	0.02	0.03
EET 92003	3.29		0.40	0.87	5.09	0.16	0.13	0.48	0.12	0.89	0.57	0.03	0.06
	5.00		2.20	0.61	4.06	0.02	0.06	0.31	0.07	0.76	0.49	0.04	0.04
	4.11		2.00	0.75	2.28	0.02	0.06	0.23	0.06	0.45	0.29	0.03	0.04
	4.27	0.03	0.60	1.11	6.73	0.04	0.14	0.66	0.18	0.91	0.61	0.06	0.04
	6.55	0.02	3.20	1.61	8.41	0.27	0.22	0.96	0.20	1.40	0.77	0.06	0.07
	2.71	0.01	2.50	1.10	7.25	0.03	0.09	0.46	0.14	1.11	0.72	0.04	0.06
	2.65	0.00	3.60	1.02	5.34	0.02	0.12	0.54	0.16	1.08	0.46	0.04	0.04
average	4.08	0.02	2.07	1.01	5.59	0.08	0.12	0.52	0.13	0.94	0.56	0.04	0.05
2 s.d.	2.77	0.03	2.42	0.65	4.13	0.19	0.11	0.48	0.10	0.60	0.33	0.03	0.03
GRA 98006	3.90	0.14	2.80	1.62	7.30	0.21	0.21	1.73	0.11	0.71	0.48	0.06	0.02
	2.36	0.29	4.90	2.90	14.30	0.29	0.29	1.02	0.28	1.79	1.09	0.05	0.01
	2.40	0.08	3.70	3.09	19.00	0.51	0.46	1.37	0.42	2.36	1.14	0.04	0.06
	2.15	0.07	3.50	3.50	27.60	0.09	0.34	1.25	0.44	2.70	1.41	0.09	0.05
average	2.70	0.14	3.73	2.78	17.05	0.27	0.32	1.34	0.31	1.89	1.03	0.06	0.04
2 s.d.	1.61	0.21	1.75	1.62	17.04	0.35	0.21	0.59	0.30	1.74	0.79	0.05	0.04
GRA 98033	2.57	0.03	2.70	1.53	10.40	0.08	0.22	2.50	0.20	1.38	1.02	0.05	0.03
	1.74	0.02	0.80	1.38	9.39	0.14	0.12	1.56	0.21	1.34	0.76	0.04	-0.01
	1.74	0.04	4.30	1.44	9.95	0.05	0.16	1.32	0.16	1.07	0.74	0.02	0.03
	1.56	0.06	2.50	3.09	13.30	0.46	0.16	2.22	0.25	1.63	1.14	0.04	0.04
	2.29	0.17	2.10	2.01	15.70	0.06	0.35	3.16	0.31	2.32	1.21	0.04	0.03
	1.42	0.01	2.20	2.57	16.70	0.04	0.21	1.59	0.27	2.09	1.12	0.04	0.04
	0.47	0.01	4.90	3.83	25.60	0.06	0.36	2.61	0.52	3.78	2.26	0.07	0.05
	1.34	0.09	4.60	3.98	24.20	0.11	0.41	5.63	0.56	3.59	2.30	0.08	0.05
average	1.64	0.05	3.01	2.48	15.66	0.12	0.25	2.57	0.31	2.15	1.32	0.05	0.03
2 s.d.	1.27	0.11	2.88	2.12	12.60	0.28	0.22	2.77	0.30	2.06	1.23	0.04	0.04
GRA 98043	3.13	0.06	7.40	5.51	32.56	0.14	0.76	3.89	0.61	4.12	2.38	0.09	0.08
	3.41	0.00	2.90	3.19	13.96	0.06	0.20	1.16	0.25	1.87	1.05	0.05	0.08
	2.50	0.19	7.50	4.82	25.18	0.09	0.50	2.26	0.50	3.87	2.18	0.11	0.07
	2.14	0.13	6.10	5.53	27.33	0.11	0.80	4.55	0.72	4.07	2.21	0.10	0.11
average	2.80	0.10	5.98	4.76	24.76	0.10	0.56	2.97	0.52	3.48	1.96	0.09	0.08
2 s.d.	1.16	0.16	4.29	2.20	15.67	0.07	0.55	3.08	0.40	2.16	1.22	0.05	0.03

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{87}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
GRA 98055	1.29	0.04	6.30	4.66	29.20	0.03	0.65	3.18	0.73	5.11	2.41	0.07	0.06
	1.66	0.05	4.50	5.22	28.91	0.05	0.68	3.55	0.65	4.75	2.56	0.04	0.06
	1.14	0.02	6.00	5.08	32.23	0.03	0.68	3.58	0.73	6.27	3.11	0.04	0.05
	1.23	0.01	3.80	4.98	42.40	0.06	0.91	5.51	1.06	7.52	4.06	0.10	0.06
average	1.33	0.03	5.15	4.99	33.19	0.04	0.72	3.96	0.79	5.91	3.04	0.06	0.06
2 s.d.	0.46	0.04	2.39	0.48	12.65	0.03	0.25	2.11	0.36	2.51	1.49	0.06	0.01
GRA 98114	2.41	0.02		0.93	12.97	0.07	0.19	5.45	0.21	1.56	0.70	0.04	0.02
	3.73	0.07	6.10	2.12	17.10	0.12	0.20	10.10	0.26	1.71	0.96	0.03	0.05
	4.02	0.04	11.9	1.21	8.15	0.08	0.20	4.18	0.15	0.89	0.51	0.02	0.04
average	3.4	0.0	9.0	1.4	12.7	0.1	0.2	6.6	0.2	1.4	0.7	0.0	0.0
2 s.d.	1.7	0.1	8.2	1.2	9.0	0.1	0.0	6.2	0.1	0.9	0.5	0.0	0.0
LAR 06875	1.61	0.16	15.9	18.80	14.00	11.00	2.60	7.40	1.12	5.82	1.88	0.19	0.13
	2.35	0.13	31.8	31.40	16.99	9.70	3.28	8.60	1.27	6.48	1.88	0.25	0.26
average	1.32	0.10	15.9	16.73	10.33	6.90	1.96	5.33	0.80	4.10	1.25	0.15	0.13
2 s.d.	1.0	0.1	22.5	17.8	4.2	1.8	1.0	1.7	0.2	0.9	0.0	0.1	0.2
LEW 85305	1.90		6.70	5.01	83.40	0.07	1.54	6.76	1.56	9.85	4.46	0.10	0.12
	1.90		4.10	5.56	122.50	0.21	1.17	5.18	1.19	7.30	3.37	0.12	0.12
average	1.90		5.40	5.29	102.95	0.14	1.36	5.97	1.38	8.58	3.92	0.11	0.12
2 s.d.	0.0		3.7	0.8	55.3	0.2	0.5	2.2	0.5	3.6	1.5	0.0	0.0
LEW 87002	1.90			0.03	9.88	0.04	0.02	0.04	0.03	0.14	0.15	0.02	0.01
	1.71			0.04	6.64	0.05	0.02	0.02	0.02	0.10	0.08	0.05	0.03
	1.62			0.06	11.13	0.05	0.03	0.04	0.01	0.13	0.18	0.01	0.04
	1.88	0.02		0.12	10.44	0.11	0.03	0.06	0.02	0.14	0.18	0.04	0.03
	1.75	0.02		0.38	15.50	0.14	0.09	0.22	0.06	0.33	0.18	0.03	0.03
average	1.77	0.02		0.13	10.72	0.08	0.04	0.07	0.03	0.17	0.15	0.03	0.03
2 s.d.	0.2	0.0		0.3	6.4	0.1	0.1	0.2	0.0	0.2	0.1	0.0	0.0
PCA 91193	1.50	0.07	3.70	3.91	44.20	0.22	0.62	2.64	0.70	5.21	2.90	0.04	0.04
	1.95	0.12	13.6	10.90	68.60	1.89	0.77	3.85	0.87	7.52	3.43	0.11	0.17
	1.69	0.08	5.30	5.54	79.80	0.27	0.52	3.14	0.87	5.88	3.39	0.11	0.09
average	1.71	0.09	7.53	6.78	64.20	0.79	0.64	3.21	0.81	6.20	3.24	0.09	0.10
2 s.d.	0.5	0.1	10.6	7.3	36.4	1.9	0.2	1.2	0.2	2.4	0.6	0.1	0.1

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Zn	Rb	^{86}Sr	^{87}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu
QUE 97014	2.06	0.05	0.00	2.26	10.98	0.10	0.16	0.69	0.21	1.59	0.88	0.06	0.04
	1.80	0.02	4.80	2.74	9.96	0.17	0.31	0.86	0.24	1.89	1.21	0.07	0.06
	2.44	0.04	1.80	2.75	11.94	0.10	0.19	0.91	0.26	1.79	1.23	0.06	0.04
	1.75	0.08	3.30	5.46	14.32	0.62	0.29	0.97	0.33	2.12	1.29	0.07	0.08
average	2.01	0.05	2.48	3.30	11.80	0.25	0.24	0.86	0.26	1.85	1.15	0.06	0.05
2 s.d.	0.6	0.0	4.1	2.9	3.7	0.5	0.1	0.2	0.1	0.4	0.4	0.0	0.0
QUE 99005	3.73	0.10		1.57	6.50	0.65	0.47	0.56	0.18	1.01	0.37	0.04	0.04
	4.41	0.09		5.19	4.63	1.51	0.34	0.37	0.15	0.76	0.17	0.03	0.05
average	4.07	0.09		3.38	5.57	1.08	0.40	0.47	0.17	0.89	0.27	0.03	0.04
2 s.d.	1.0	0.0		5.1	2.6	1.2	0.2	0.3	0.1	0.4	0.3	0.0	0.0
RKPA 80204	1.96	0.09	3.50	3.04	2.74	0.45	0.26	2.80	0.16	1.01	0.50	0.04	0.05
	2.19	0.05	6.40	4.32	2.95	0.75	0.10	1.52	0.10	0.61	0.38	0.06	0.03
average	2.08	0.07	4.95	3.68	2.85	0.60	0.18	2.16	0.13	0.81	0.44	0.05	0.04
2 s.d.	0.3	0.1	4.1	1.8	0.3	0.4	0.2	1.8	0.1	0.6	0.2	0.0	0.0
SCO 06041	3.80	0.06		0.47	14.24	0.19	0.09	0.36	0.08	0.73	0.31	0.04	0.05
	2.14	0.01		0.41	14.46	0.03	0.08	0.28	0.08	0.69	0.45	0.03	0.02
	4.87	0.13		0.55	3.22	0.52	0.13	0.45	0.07	0.64	0.49	0.03	0.03
	4.15	0.03		0.54	30.80	0.16	0.10	0.35	0.09	0.48	0.28	0.05	0.04
average	3.74	0.06		0.49	15.68	0.22	0.10	0.36	0.08	0.64	0.38	0.04	0.04
2 s.d.	2.3	0.1		0.1	22.7	0.4	0.0	0.1	0.0	0.2	0.2	0.0	0.0
GRO 95533	2.46			0.24	2.14	0.04	0.05	0.22	0.06	0.43	0.22	0.03	0.04
	1.28			0.44	3.21	0.06	0.06	0.31	0.06	0.49	0.32	0.00	0.05
	2.06			0.35	3.12	0.02	0.11	0.51	0.12	0.69	0.33	0.02	0.04
average	1.93			0.34	2.82	0.04	0.07	0.35	0.08	0.54	0.29	0.02	0.04
2 s.d.	1.2			0.2	1.2	0.0	0.1	0.3	0.1	0.3	0.1	0.0	0.0
Camel Donga	1.24		2.70	2.48	17.12	0.30	0.25	1.44	0.38	2.29	1.29	0.00	0.01
	1.16	0.10	0.40	2.15	12.80	1.07	0.24	1.02	0.27	1.63	1.04	0.03	0.03
	2.09	0.13	6.30	7.44	6.60	2.58	0.13	0.42	0.10	0.66	0.65	0.03	0.07
average	1.50	0.12	3.13	4.02	12.17	1.32	0.20	0.96	0.25	1.53	0.99	0.02	0.04
2 s.d.	1.0	0.0	5.9	5.9	10.6	2.3	0.1	1.0	0.3	1.6	0.6	0.0	0.1

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
EET 87548	0.68	0.11	0.70	0.13	0.67	0.10	0.42	0.10	0.18	0.03
	0.54	0.12	0.97	0.23	0.76	0.12	0.50	0.11	0.21	0.09
	0.67	0.15	0.96	0.21	0.69	0.10	0.69	0.13	0.35	0.05
average	0.63	0.13	0.88	0.19	0.71	0.11	0.54	0.11	0.25	0.05
2 s.d.	0.16	0.04	0.31	0.11	0.09	0.02	0.28	0.02	0.18	0.07
EET 92003	1.24	0.31	2.55	0.63	2.05	0.38	2.20	0.34	0.20	0.05
	0.76	0.22	1.82	0.45	1.40	0.24	1.68	0.23	0.14	0.07
	0.50	0.14	0.85	0.26	0.79	0.12	1.03	0.17	0.14	0.06
	1.11	0.28	1.77	0.46	1.31	0.21	1.68	0.23	0.36	0.08
	1.39	0.33	2.48	0.66	2.15	0.29	2.03	0.32	0.31	0.05
	1.32	0.26	2.16	0.58	1.75	0.32	1.87	0.36	0.32	0.04
average	1.26	0.27	1.99	0.51	1.70	0.29	1.70	0.28	0.29	0.06
2 s.d.	1.08	0.26	1.95	0.51	1.59	0.26	1.74	0.27	0.25	0.06
	0.66	0.13	1.14	0.27	0.94	0.17	0.74	0.14	0.19	0.03
GRA 98006	1.12	0.25	2.82	0.56	1.92	0.25	2.11	0.40	0.47	0.05
	2.18	0.59	3.95	0.82	2.22	0.32	1.89	0.35	0.73	0.06
	2.46	0.45	3.72	0.86	2.59	0.36	2.96	0.46	0.76	0.14
	2.84	0.61	4.42	1.11	2.76	0.45	3.33	0.55	1.11	0.09
average	2.15	0.47	3.73	0.84	2.37	0.35	2.57	0.44	0.77	0.09
2 s.d.	1.48	0.34	1.34	0.45	0.75	0.17	1.37	0.17	0.53	0.08
GRA 98033	1.89	0.36	3.53	0.79	2.53	0.40	2.87	0.47	0.75	0.05
	1.56	0.37	2.85	0.70	2.37	0.40	2.50	0.45	0.63	0.02
	1.67	0.33	3.05	0.71	2.21	0.37	2.45	0.43	1.08	0.04
	1.96	0.45	3.22	0.84	2.43	0.33	2.68	0.47	1.01	0.06
	2.14	0.58	4.40	1.15	3.31	0.48	3.25	0.52	1.11	0.10
	2.50	0.55	4.19	0.91	3.12	0.44	3.01	0.47	1.18	0.04
	3.59	0.79	6.38	1.28	3.56	0.50	3.78	0.52	1.78	
	4.23	0.91	7.48	1.42	4.37	0.63	3.83	0.62	2.06	0.07
average	2.44	0.54	4.39	0.98	2.99	0.44	3.05	0.49	1.20	0.05
2 s.d.	1.93	0.42	3.37	0.55	1.49	0.18	1.07	0.12	0.97	0.05
GRA 98043	3.07	0.75	5.64	1.35	3.73	0.60	3.99	0.61	2.11	0.07
	1.78	0.35	3.57	0.78	2.45	0.34	2.56	0.40	1.27	0.07
	2.87	0.67	5.01	1.10	3.02	0.45	2.88	0.56	2.06	0.10
	3.45	0.79	5.50	1.20	3.10	0.48	3.43	0.57	1.86	0.06
average	2.79	0.64	4.93	1.11	3.08	0.47	3.22	0.53	1.83	0.07
2 s.d.	1.43	0.40	1.89	0.48	1.05	0.21	1.26	0.18	0.77	0.03

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
GRA 98055	3.88	0.85	6.18	1.30	3.69	0.52	3.63	0.60	2.06	
	4.08	0.84	6.29	1.29	3.75	0.61	3.48	0.58	2.34	0.02
	4.68	0.89	6.97	1.48	4.62	0.60	4.58	0.66	2.51	0.03
	5.29	1.21	9.52	2.04	5.85	0.84	5.66	0.85	2.81	0.06
average	4.48	0.95	7.24	1.53	4.48	0.64	4.34	0.67	2.43	0.03
2 s.d.	1.27	0.35	3.12	0.71	2.02	0.27	2.01	0.24	0.63	0.04
GRA 98114	1.51	0.35	2.70	0.72	2.14	0.35	2.58	0.45	0.79	0.08
	2.24	0.45	3.14	0.74	2.63	0.39	2.50	0.37	1.13	0.05
	0.95	0.25	2.17	0.48	1.57	0.27	1.76	0.30	0.56	0.03
	1.6	0.4	2.7	0.6	2.1	0.3	2.3	0.4	0.8	0.1
2 s.d.	1.3	0.2	1.0	0.3	1.1	0.1	0.9	0.2	0.6	0.1
LAR 06875	2.35	0.54	3.78	0.90	2.61	0.35	2.89	0.38	0.64	0.09
	2.72	0.42	2.82	0.76	2.14	0.41	2.29	0.34	0.53	0.14
	1.69	0.32	2.20	0.55	1.58	0.25	1.73	0.24	0.39	0.08
	0.5	0.2	1.4	0.2	0.7	0.1	0.8	0.1	0.2	0.1
LEW 85305	5.79	1.12	7.14	1.39	4.45	0.48	4.02	0.61	3.10	
	5.12	1.14	6.95	1.53	5.00	0.66	4.06	0.59	4.15	
	5.46	1.13	7.05	1.46	4.73	0.57	4.04	0.60	3.63	
	0.9	0.0	0.3	0.2	0.8	0.3	0.1	0.0	1.5	
LEW 87002	0.39	0.10	0.62	0.17	0.67	0.14	0.84	0.14	0.32	0.08
	0.27	0.07	0.61	0.16	0.60	0.11	0.67	0.12	0.28	0.07
	0.33	0.09	0.88	0.23	0.67	0.12	0.91	0.18	0.45	0.10
	0.37	0.08	0.85	0.22	0.77	0.12	0.80	0.16	0.39	0.06
	0.40	0.10	0.95	0.25	0.81	0.12	0.86	0.15	0.60	0.05
average	0.35	0.09	0.78	0.20	0.70	0.12	0.82	0.15	0.41	0.07
2 s.d.	0.1	0.0	0.3	0.1	0.2	0.0	0.2	0.0	0.3	0.0
PCA 91193	4.41	0.81	5.52	1.13	2.76	0.36	2.03	0.33	1.56	0.05
	5.43	1.01	6.49	1.30	3.61	0.47	2.65	0.36	2.17	0.06
	5.26	0.86	6.18	1.22	3.50	0.41	2.50	0.34	1.97	0.06
	5.03	0.89	6.06	1.22	3.29	0.41	2.39	0.34	1.90	0.06
2 s.d.	1.1	0.2	1.0	0.2	0.9	0.1	0.6	0.0	0.6	0.0

Table B2: High-Ca pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
QUE 97014	1.98	0.47	3.44	0.78	2.60	0.47	2.26	0.48	0.91	0.02
	2.07	0.45	3.51	0.85	3.04	0.47	2.75	0.48	0.83	0.04
	2.27	0.50	3.66	0.89	2.79	0.46	2.80	0.47	0.94	0.01
	2.78	0.53	4.30	1.01	3.10	0.48	3.08	0.58	1.25	
average	2.28	0.49	3.73	0.88	2.88	0.47	2.72	0.50	0.98	0.02
2 s.d.	0.7	0.1	0.8	0.2	0.5	0.0	0.7	0.1	0.4	0.0
QUE 99005	0.70	0.18	1.53	0.31	1.17	0.21	1.60	0.22	0.39	0.12
	0.45	0.14	1.07	0.24	0.89	0.15	1.52	0.21	0.20	0.00
	0.58	0.16	1.30	0.28	1.03	0.18	1.56	0.22	0.30	0.06
	0.4	0.1	0.7	0.1	0.4	0.1	0.1	0.0	0.3	0.2
RKPA 80204	0.98	0.25	1.88	0.43	1.41	0.24	1.68	0.35	0.24	0.00
	0.59	0.15	1.39	0.39	1.33	0.22	1.75	0.32	0.24	0.00
	0.79	0.20	1.64	0.41	1.37	0.23	1.72	0.34	0.24	0.00
	0.6	0.1	0.7	0.1	0.1	0.0	0.1	0.0	0.0	0.0
SCO 06041	0.83	0.16	1.62	0.32	0.98	0.16	1.22	0.20	0.67	0.03
	0.87	0.19	1.69	0.34	1.37	0.18	1.39	0.20	0.77	0.04
	0.61	0.13	1.23	0.27	1.16	0.14	1.15	0.19	0.20	0.09
	0.66	0.15	1.26	0.22	0.83	0.14	0.90	0.11	0.79	0.05
average	0.74	0.16	1.45	0.29	1.09	0.15	1.17	0.17	0.61	0.05
2 s.d.	0.3	0.1	0.5	0.1	0.5	0.0	0.4	0.1	0.6	0.1
GRO 95533	0.75	0.17	1.63	0.38	1.30	0.26	1.67	0.29	0.22	0.07
	0.76	0.18	1.34	0.29	1.38	0.22	1.53	0.33	0.20	0.03
	1.10	0.25	1.99	0.48	1.85	0.28	1.87	0.36	0.23	
	0.87	0.20	1.65	0.38	1.51	0.25	1.69	0.32	0.22	0.05
average	0.87	0.20	1.65	0.38	1.51	0.25	1.69	0.32	0.22	0.05
2 s.d.	0.4	0.1	0.7	0.2	0.6	0.1	0.3	0.1	0.0	0.1
Camel Donga	2.15	0.53	3.85	0.85	2.39	0.38	2.67	0.40	0.97	0.01
	1.57	0.45	3.47	0.73	2.45	0.37	2.29	0.40	0.73	0.03
	0.78	0.26	2.10	0.50	1.79	0.29	2.11	0.33	0.39	0.05
	1.50	0.41	3.14	0.69	2.21	0.35	2.36	0.38	0.70	0.03
average	1.50	0.41	3.14	0.69	2.21	0.35	2.36	0.38	0.70	0.03
2 s.d.	1.4	0.3	1.8	0.3	0.7	0.1	0.6	0.1	0.6	0.0

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn
EET 83227	8.98	97.3	110600	7550	18290	33.7	32	182	4460	5570	11.4	5.35	1.95
	5.27	118	119400	6744	21770	29.4	922	133	5899	4547	10.8	4.24	1.56
	6.38	136	98600	4640	27780	42.3	2345	138	3872	5500	9.76	5.24	2.70
	5.56	121	97700	4553	28010	42.1	2360	139	3862	5400	9.13	5.23	1.79
	8.28	118	86000	5499	31970	46.2	698	153	4380	6230	7.94	6.31	1.96
	6.57	148	86680	6344	33800	50.9	1076	158	4644	5988	7.56	5.17	4.95
	6.85	179	88600	5733	34060	49.5	1031	153	4457	6079	12.4	6.40	4.60
	5.30	127	77500	5752	38500	46.1	3031	101	2950	5382	6.93	5.27	5.13
	4.85	116	83900	5479	41260	48.6	3194	106	3610	5300	8.45	5.12	1.90
	5.62	121	76400	6320	47500	51.8	3650	110	3146	5643	5.70	4.64	2.71
	7.62	185	64230	4871	54250	66.2	4226	85	2078	7310	6.56	6.44	2.79
average	6.48	133	89965	5771	34290	46.1	2051	132	3942	5723	8.78	5.40	2.91
2 s.d.	2.69	54.1	31581	1841	21349	19.4	2750	57.9	2026	1391	4.25	1.42	2.68
EET 92023	7.31	344	82900	4626	34660	41.5	2515	111	3437	5260	23.6	24.0	7.56
	5.49	337	77900	4460	35500	42.0	2736	99.1	3030	5090	27.3	137	7.90
	7.18	345	81600	4790	35750	41.7	2520	114	3650	5500	26.6	27.2	7.82
	6.79	362	80700	4552	36010	42.9	2916	108	3182	5380	27.5	33.6	8.75
	6.93	409	84700	5200	36150	41.3	2210	119	4020	5460	28.7	30.0	8.44
	5.49	400	81900	4729	37130	41.7	3330	105	3360	5410	29.3	538	8.21
	7.10	539	83300	4774	38370	43.3	3400	102	3240	5310	75.5	497	10.0
	6.62	406	83600	4882	39220	46.1	3143	111	3624	5380	55.7	230	8.89
	7.45	486	77500	4578	39220	44.0	3515	99.1	3075	5110	24.7	52.4	9.70
	7.42	355	82200	4773	39420	43.4	2936	106	3560	5340	27.3	28.8	9.24
	5.96	369	82000	4764	40060	45.8	3164	110	3390	5490	28.7	30.9	9.07
	6.70	431	83600	4778	40970	44.8	3630	105	3270	5560	25.5	32.8	9.16
average	6.70	399	81825	4742	37705	43.2	3001	107	3403	5358	33.4	138	8.73
2 s.d.	1.40	124	4411	377	4167	3.4	884	11.7	559	294	31.5	375	1.52

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn
LAP 031062	5.66	204	105900	4463	22130	31.1	1635	132	3672	4920	10.20		1.19
	6.40	202	105100	4526	22050	31.8	1632	132	3825	4930	10.40		1.81
	7.67	186	104600	4556	20780	30.8	1617	129	3637	4837	9.36		1.47
	2.01	167	104300	3601	22420	32.2	2149	100	2430	5230	7.44		2.03
	1.34	124	108900	4163	25700	36.7	2281	115	2070	5050	5.70		1.65
	2.88	180	102600	3479	22520	29.6	2108	110	2873	5440	8.23		1.82
	5.17	220	111400	3920	22990	32.7	2290	119	3840	5080	9.74		1.44
	3.65	193	103600	3980	22650	35.4	2311	121	3640	5140	9.38		1.63
	4.03	241	103000	4030	24040	34.6	2290	117	3640	5120	12.08		1.59
	1.52	98.0	116000	3520	18600	30.8	1550	131	3160	5380	8.60		1.51
	3.92	196	108600	3610	22080	32.8	1960	122	4150	5020	10.30		1.35
average	4.02	183	106727	3986	22360	32.6	1984	121	3358	5104	9.22		1.59
2 s.d.	4.09	81.9	8258	811	3541	4.3	631	20.5	1297	375	3.40		0.47
Milbillillie	4.34	42.1	73520	1246	23660	53.5	1847	97.9	3260	8059	9.18	0.55	2.37
	4.48	41.8	72360	1154	30870	49.9	2339	101	3410	7729	8.66	0.74	2.48
	5.37	206	71990	6600	34100	45.8	3450	102	4200	8102	9.00	1.07	3.04
	4.85	154	70410	4282	33200	46.4	2857	84.0	3507	7889	8.76	0.77	2.46
	4.15	175	71900	5860	37000	48.5	2530	88.8	3100	7760	8.44	1.10	2.56
	4.41	33.8	76500	1182	31500	59.8	1280	90.0	2100	8000	8.80	0.87	2.18
	5.25	38.8	83800	1488	21800	56.6	1920	145	5260	9500	10.00	0.28	2.03
	4.38	27.5	78900	1353	23400	49.2	3010	128	4780	8130	9.47	0.67	2.62
average	4.65	89.9	74923	2896	29441	51.2	2404	105	3702	8146	9.04	0.76	2.47
2 s.d.	0.90	149.5	9063	4628	11403	10.0	1413	42.3	2012	1135	1.01	0.54	0.61
Juvinas	3.30	31.6	85450	1718	16290	48.8	953	105	2547	8750	4.46	0.25	2.64
	2.52	30.2	84990	1954	16740	44.2	1171	145	5371	8761	5.09	0.03	2.42
	2.89	35.8	82280	1788	18530	38.5	1006	127	4854	8550	5.15	0.62	1.97
	3.27	46.2	82600	2029	19520	41.7	1118	141	5472	8710	5.04	0.01	2.59
	3.24	36.7	82660	2017	21110	39.7	1408	147	6330	8590	5.51		2.23
	2.47	40.5	82660	2130	19380	40.9	1523	161	6856	8660	6.30	0.59	3.30
	3.58	50.7	81220	1833	19140	40.0	1260	137	5500	8820	5.77	0.20	2.37
average	3.04	38.8	83123	1924	18673	42.0	1206	138	5276	8692	5.33	0.28	2.50
2 s.d.	0.84	15.0	3048	297	3348	7.0	414	35.1	2748	194	1.18	0.53	0.83

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Sc	Ti	V	Cr	Mn	Co	Ni	Zn
Dhofar 007	3.49	228.7	95700	3381	29070	36.3	2558	106	3640	5700	26.81	24.8	7.62
	4.37	210.3	96100	3435	26310	35.5	2229	111	3820	5770	26.42	26.5	7.82
	5.32	231.1	96600	3406	28960	36.1	2571	103	3530	5800	26.90	32.3	6.61
	6.49	216.0	98300	3452	28030	35.2	2478	109	4010	5750	29.00	55.6	8.93
	2.95	214.3	95200	3564	25480	35.0	2170	122	4090	5990	30.10	31.1	6.83
	6.29	220.0	97100	3428	24020	33.5	1856	113	3990	5690	28.90	34.4	7.14
	3.53	161.4	96900	3131	20270	32.3	1306	108	4020	5810	45.70	550.0	7.68
	5.05	207.8	95400	3427	26930	35.7	2270	120	4140	6090	29.50	27.6	7.19
	6.20	232.0	97800	3480	26250	33.5	2290	106	3660	5780	28.50	33.3	7.59
average	4.85	213.5	96567	3412	26147	34.8	2192	111	3878	5820	30.20	90.62	7.49
2 s.d.	2.67	42.9	2135	235	5485	2.7	798	12.8	443	267	11.90	345.01	1.35

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Rb	^{86}Sr	^{87}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
EET 83227	0.06	0.40	0.18	0.23	0.09	0.33	1.51	0.16	0.71	0.40	0.05	0.03	0.40
	0.04	1.30	0.17	1.09	0.03	0.03	0.12	0.02	0.18	0.14	0.05	0.03	0.20
			0.19	24.00	0.02	0.05	0.52	0.15	1.21	0.76	0.03	0.04	1.39
	0.01		0.23	24.90		0.10	0.48	0.14	1.14	0.61	0.03	0.01	1.13
	0.01	2.50	0.35	0.21	0.03	0.03	0.36	0.02	0.10	0.11	0.00	0.05	0.09
	0.14	0.90	0.50	0.41	0.19	0.08	1.02	0.05	0.38	0.21	0.05	0.02	0.25
	0.08	1.80	0.65	0.40	0.25	0.06	0.25	0.03	0.38	0.07	0.03	0.03	0.19
	0.10	0.60	1.40	48.60	0.21	0.46	2.57	0.46	3.64	2.01	0.04	0.06	2.80
	0.06	1.60	1.37	57.00	0.07	0.61	2.57	0.74	4.34	2.20	0.05	0.06	4.00
	0.03	3.90	0.96	43.40	0.05	0.58	3.23	0.73	5.42	2.66	0.05	0.07	3.95
	0.06	1.63	0.72	24.35	0.11	0.27	1.39	0.28	2.01	1.05	0.04	0.04	1.65
	0.08	2.29	1.21	51.92	0.18	0.52	2.33	0.58	4.10	2.08	0.03	0.04	3.31
EET 92023	0.08	1.00	0.57	8.08	0.06	0.11	0.46	0.12	0.89	0.63	0.05	0.04	0.88
	0.01		0.50	12.00	0.03	0.10	0.44	0.13	0.96	0.67	0.03	0.04	1.29
	0.05		0.48	22.80	0.04	0.08	0.33	0.13	0.80	0.54	0.06	0.04	1.32
	0.06	1.50	0.55	27.10	0.06	0.10	0.52	0.17	1.12	0.59	0.03	0.04	1.56
	0.12	0.60	0.67	3.64	0.11	0.06	0.24	0.06	0.66	0.54	0.01	0.04	0.98
	0.05		0.55	10.83	0.09	0.09	0.46	0.13	1.29	0.60	0.04	0.04	1.28
	0.33	0.40	0.77	32.40	0.19	0.21	0.84	0.19	1.74	1.12	0.04	0.04	1.81
	0.06	2.30	0.77	6.13	0.02	0.21	0.68	0.17	1.16	0.67	0.05	0.04	1.25
	0.24		0.92	13.52	0.17	0.16	0.82	0.19	1.77	0.89	0.02	0.03	1.37
	0.08		0.63	4.83	0.08	0.08	0.33	0.11	0.72	0.54	0.02	0.01	1.09
	0.00	1.40	0.57	27.00	0.06	0.06	0.46	0.14	1.02	0.66	0.03	0.04	1.55
	0.01	0.00	0.62	24.80	0.08	0.14	0.55	0.17	1.14	0.84	0.04	0.02	1.59
	0.09	1.03	0.63	16.09	0.08	0.12	0.51	0.14	1.11	0.69	0.03	0.03	1.33
	0.20	1.55	0.26	20.21	0.10	0.10	0.38	0.08	0.71	0.35	0.03	0.02	0.54

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Rb	⁸⁶ Sr	⁸⁸ Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	¹⁵¹ Eu	¹⁵³ Eu	Gd
LAP 031062		11.10	0.33	0.78	0.01	0.02	0.05		0.05	0.07	0.03	0.03	0.40
		6.40	0.25	0.93			0.12		0.09	0.11	0.02	0.02	0.25
		4.30	0.23	1.27	0.02	0.04	0.05	0.01	0.18	0.12	0.02	0.02	0.42
		2.40	0.34	14.00	0.04	0.07	0.28	0.07	0.55	0.37	0.01	0.04	0.84
		1.80	0.47	19.80	0.05	0.08	0.44	0.12	0.81	0.56	0.04	0.04	1.32
		3.90	0.24	12.66	0.01	0.05	0.26	0.08	0.51	0.40	0.05	0.01	1.00
			0.26	12.50	0.01	0.06	0.34	0.08	0.80	0.51	0.03		1.35
			0.31	14.60	0.03	0.03	0.27	0.13	0.79	0.59	0.03	0.04	1.07
			0.39	14.70	0.05	0.05	0.51	0.08	0.87	0.49	0.03	0.01	1.02
			0.28	3.64	0.04	0.07	0.21	0.07	0.41	0.29	0.02	0.02	0.58
		2.20	0.23	7.45	0.02	0.04	0.18	0.05	0.41	0.42	0.01	0.01	0.60
average		4.59	0.30	9.30	0.03	0.05	0.25	0.08	0.50	0.36	0.03	0.02	0.80
2 s.d.	#DIV/0!	6.56	0.15	13.47	0.03	0.04	0.30	0.07	0.60	0.37	0.02	0.03	0.76
Millibillillie	0.06	2.50	0.54	4.00	0.30	0.17	0.67	0.15	0.56	0.37		0.02	0.72
	0.05	0.70	0.60	7.46	0.17	0.20	0.75	0.14	0.93	0.44		0.03	0.82
		4.50	6.02	7.95	1.64	0.19	0.45	0.09	0.57	0.35	0.05	0.04	0.64
	0.08	3.30	4.25	11.03	1.35	0.54	1.45	0.29	1.56	0.72	0.04	0.04	1.34
	0.05	6.10	6.48	3.33	1.88	0.24	0.53	0.11	0.80	0.39	0.04	0.06	0.95
		1.20	0.69	4.06	0.20	0.18	0.60	0.14	0.85	0.60	0.02		1.02
		2.50	0.50	5.69	0.28	0.21	0.50	0.10	0.61	0.49			0.81
		2.50	0.56	6.47	0.26	0.34	0.79	0.18	0.97	0.39	0.01	0.02	0.64
average	0.06	2.91	2.46	6.25	0.76	0.26	0.72	0.15	0.86	0.47	0.03	0.04	0.87
2 s.d.	0.03	3.48	5.33	5.12	1.46	0.25	0.64	0.13	0.65	0.26	0.04	0.03	0.47
Juvinas	0.05		0.05	4.73	0.11	0.03	0.07	0.03	0.12	0.19	0.00	0.03	0.36
	0.01	1.30	0.07	4.14	0.04		0.08	0.02	0.17	0.12		0.01	0.23
	0.01	0.70	0.05	3.88	0.02	0.00	0.08	0.02	0.27	0.20			0.53
	0.02	0.60	0.09	4.55	0.02	0.04	0.09	0.01	0.23	0.17	0.03		0.42
		1.20	0.08	4.91	0.03	0.03	0.19	0.04	0.35	0.21	0.00	0.00	0.54
	0.02	2.30	0.09	4.91	0.05	0.05	0.13	0.03	0.16	0.30	0.01	0.00	0.55
			0.10	4.29	0.04	0.04	0.15	0.04	0.33	0.26	0.00	0.03	0.46
average	0.02	1.22	0.07	4.49	0.04	0.03	0.11	0.03	0.23	0.20	0.01	0.01	0.44
2 s.d.	0.03	1.35	0.04	0.80	0.06	0.03	0.09	0.02	0.17	0.12	0.03	0.02	0.23

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Rb	^{86}Sr	^{88}Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
Dhofar 007	0.03	0.20	2.46	25.20	0.53	0.06	0.39	0.09	0.88	0.51		0.02	1.05
	0.08	2.30	1.35	17.97	0.32	0.04	0.38	0.12	0.64	0.44	0.01	0.00	0.92
	0.03	8.70	8.99	27.10	1.68	0.07	0.31	0.12	0.51	0.47	0.01	-0.01	0.75
	0.03	3.80	5.26	23.60	0.67	0.04	0.32	0.07	0.86	0.46		0.01	0.89
	0.03	8.10	7.15	14.10	1.44	0.06	0.33	0.09	0.81	0.35		0.01	1.04
		8.80	9.00	11.68	2.27	0.05	0.24	0.07	0.49	0.29	0.02	0.01	0.90
		0.70	1.28	5.37	0.20	0.04	0.24	0.06	0.55	0.47	0.01	0.01	0.65
	0.02	3.90	3.34	17.10	0.52	0.07	0.34	0.09	0.64	0.40	0.01	0.00	1.04
	0.01	11.70	11.00	16.20	2.13	0.11	0.31	0.06	0.61	0.52	0.01	0.02	0.99
average	0.03	5.36	5.54	17.59	1.08	0.06	0.32	0.09	0.67	0.43	0.01	0.01	0.91
2 s.d.	0.04	8.15	7.29	13.84	1.61	0.04	0.11	0.05	0.30	0.15	0.01	0.02	0.28

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
EET 83227	0.05	0.37	0.07	0.26	0.05	0.15	0.05	0.06	0.07
	0.06	0.37	0.12	0.34	0.08	0.47	0.09	0.09	0.09
	0.24	1.72	0.45	1.34	0.17	1.28	0.18	0.69	0.01
	0.22	1.65	0.38	1.22	0.18	1.16	0.18	0.84	
	0.04	0.07	0.03	0.21	0.05	0.17	0.06	0.05	0.07
	0.05	0.28	0.11	0.37	0.07	0.44	0.06	0.06	0.11
	0.03	0.46	0.12	0.25	0.05	0.46	0.06	0.05	0.05
	0.56	4.88	0.92	3.22	0.42	2.73	0.42	1.42	0.09
	0.70	5.72	1.15	3.64	0.53	2.92	0.38	1.62	0.13
	0.74	6.16	1.27	4.05	0.49	3.42	0.42	1.88	0.08
	0.80	6.07	1.13	4.02	0.57	3.72	0.57	1.63	0.09
average	0.32	2.52	0.52	1.72	0.24	1.54	0.23	0.76	0.08
2 s.d.	0.63	5.20	0.99	3.31	0.43	2.77	0.38	1.50	0.07
EET 92023	0.25	1.71	0.42	1.33	0.22	1.26	0.22	0.34	0.06
	0.27	2.30	0.50	1.67	0.25	1.74	0.23	0.29	0.12
	0.27	1.94	0.49	1.56	0.25	1.67	0.24	0.37	0.09
	0.28	1.86	0.51	1.70	0.24	1.49	0.30	0.41	0.09
	0.17	1.73	0.42	1.33	0.21	1.37	0.23	0.16	0.02
	0.30	2.09	0.55	1.72	0.24	1.65	0.27	0.37	0.05
	0.35	2.43	0.62	2.06	0.32	2.37	0.33	1.05	0.15
	0.25	1.66	0.44	1.27	0.20	1.23	0.24	0.30	0.08
	0.31	2.52	0.59	1.85	0.25	1.89	0.30	0.31	0.06
	0.23	1.93	0.43	1.46	0.22	1.15	0.27	0.29	0.06
	0.25	2.19	0.47	1.75	0.25	1.60	0.32	0.58	0.11
	0.33	2.44	0.51	1.81	0.23	1.63	0.31	0.76	0.08
average	0.27	2.07	0.50	1.63	0.24	1.59	0.27	0.44	0.08
2 s.d.	0.10	0.61	0.13	0.48	0.06	0.67	0.08	0.49	0.07

Table B3: Single phase pyroxene trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	W
LAP 031062	0.06	0.74	0.17	0.70	0.10	0.91	0.15	0.05	0.07
	0.09	0.54	0.14	0.79	0.12	0.77	0.13	0.06	0.03
	0.10	0.84	0.20	0.69	0.15	0.91	0.13	0.04	0.06
	0.22	1.48	0.37	1.15	0.18	1.09	0.19	0.58	0.03
	0.29	2.05	0.52	1.39	0.20	1.27	0.30	0.85	0.04
	0.20	1.54	0.36	1.24	0.18	0.94	0.20	0.59	0.01
	0.21	1.56	0.36	1.19	0.20	1.26	0.23	0.55	0.07
	0.26	1.80	0.38	1.34	0.18	1.16	0.22	0.48	0.09
	0.23	1.39	0.44	1.14	0.16	1.45	0.19	0.56	0.03
	0.09	0.50	0.15	0.61	0.07	0.68	0.12	0.18	0.01
	0.16	1.02	0.32	0.92	0.13	1.06	0.16	0.22	0.05
average	0.17	1.22	0.31	1.01	0.15	1.05	0.18	0.38	0.04
2 s.d.	0.16	1.05	0.26	0.56	0.08	0.46	0.10	0.55	0.05
Millbillillie	0.14	1.62	0.37	1.50	0.27	2.14	0.38	0.40	0.04
	0.18	1.39	0.39	1.52	0.28	2.00	0.38	0.50	0.03
	0.20	1.56	0.38	1.82	0.26	2.03	0.33	0.55	0.03
	0.26	2.35	0.58	1.97	0.28	2.29	0.38	0.46	0.07
	0.15	1.76	0.40	1.53	0.31	2.58	0.44	0.20	
	0.25	1.91	0.46	1.93	0.36	2.59	0.57	0.29	0.00
	0.19	1.96	0.45	1.79	0.30	2.44	0.47	0.54	
	0.22	2.14	0.51	1.99	0.32	2.31	0.46	0.32	
average	0.20	1.84	0.44	1.76	0.30	2.30	0.43	0.41	0.03
2 s.d.	0.09	0.63	0.14	0.42	0.07	0.46	0.15	0.25	0.05
Juvinas	0.16	1.15	0.34	1.48	0.28	1.89	0.36	0.21	0.06
	0.10	1.02	0.36	1.33	0.21	1.92	0.34	0.13	0.00
	0.14	1.27	0.33	1.29	0.26	1.79	0.31	0.21	0.02
	0.13	1.21	0.36	1.25	0.27	2.02	0.32	0.18	
	0.14	1.03	0.30	1.12	0.19	1.57	0.23	0.10	0.01
	0.12	1.14	0.26	1.10	0.21	1.40	0.30	0.13	0.08
	0.09	1.06	0.25	1.16	0.15	1.49	0.22	0.18	0.08
average	0.13	1.13	0.31	1.25	0.22	1.73	0.30	0.16	0.04
2 s.d.	0.05	0.19	0.09	0.27	0.09	0.48	0.11	0.09	0.07

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
EET 83227	11.0	6517	610	200200	128500	217	61.0	0.04	197	197	54.0	1.37	3.12
	10.7	6519	532	196900	128000	98.5	55.2	0.06	188	196	52.7	0.37	0.82
	9.54	6137	415	200800	127400	62.9	30.5	0.07	189	194	52.7	0.27	0.64
	8.82	5704	393	201700	130500	67.6	32.3	0.05	190	194	49.0	0.26	0.68
	8.46	5492	471	207000	131200	59.5	33.8	0.14	192	193	48.7	0.35	0.92
	7.95	5043	265	222900	135400	82.4	25.6	0.16	183	184	46.2	1.04	2.21
average	9.40	5902	448	204917	130167	98.0	39.7	0.09	190	193	50.6	0.61	1.40
2 s.d.	2.43	1186	239	18795	5912	120.3	29.2	0.10	9	9	6.1	0.95	2.05
EET 87548	5.76	6291	105	194000	125700	48.9	15.2	0.08	144	145	12.2	0.29	0.60
	4.78	5826	83	196100	123700	36.2	16.2	0.07	151	151	13.1	0.23	0.46
	5.51	6037	92	202500	126800	45.7	18.0	0.07	152	154	13.0	0.27	0.52
	5.46	6087	95	198700	124400	44.7	18.0	0.05	152	151	13.2	0.28	0.49
	4.99	5478	88	185600	122200	40.6	15.1	0.10	140	143	12.3	0.26	0.47
	6.08	7057	115	201200	125700	46.6	14.4	0.09	157	161	14.8	0.35	0.59
	5.30	6165	97	199000	124900	44.0	13.6	0.08	157	157	14.2	0.30	0.53
	5.37	6120	91	203200	127720	41.2	13.8	0.07	157	159	14.1	0.30	0.53
	5.84	6140	91	195200	124400	30.1	14.6	0.12	146	148	12.5	0.27	0.53
	5.85	6240	102	195300	122600	45.0	14.7	0.07	144	149	13.5	0.33	0.60
	5.74	6097	98	192800	126200	44.4	17.5	0.04	149	151	13.6	0.30	0.59
	5.17	5928	91	189400	125300	35.4	20.0	0.10	145	144	13.3	0.28	0.63
average	5.49	6122.2	95.7	196083.3	124968.3	41.9	15.9	0.08	149	151	13.3	0.29	0.55
2 s.d.	0.77	730.6	17.1	10521.6	3256.1	11.0	3.9	0.04	11	11	1.5	0.06	0.11
EET 92003	10.5	9010	2468	176500	120000	347	196.4	0.20	190	188	73.1	0.65	1.63
	11.0	8823	1380	197100	122400	167	116.0	0.06	205	207	63.2	0.61	1.49
	10.7	8448	484	203600	125400	200	43.2	0.09	208	210	65.3	0.64	1.55
	9.91	8582	375	201100	124800	182	37.1	0.12	216	219	74.4	1.15	2.57
	9.37	6970	235	207700	129600	104	28.5	0.03	200	205	50.1	0.34	0.71
	12.0	9317	354	195900	120600	146	36.5	0.11	208	209	80.4	0.67	1.52
	8.91	6716	1333	197900	124100	123	136.3	0.10	186	188	51.4	0.32	0.85
	7.81	6544	2256	193400	123100	730	223.6	0.17	187	187	58.5	1.11	3.15
	9.17	7320	1720	192100	121000	654	209.0	0.10	187	193	55.5	0.58	1.78
	9.26	7245	419	203400	125700	164	78.5	0.09	202	200	55.2	0.43	1.16
average	9.87	7898	1102	196870	123670	281.8	110.5	0.11	199	200	62.7	0.65	1.64
2 s.d.	2.44	2079	1686	17319	5800	453.4	154.5	0.10	21	22	20.8	0.57	1.48

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
EET 92023	5.49	7800	870	208300	121100	192	59.0	0.29	195	199	62.9	0.75	1.61
	7.42	13240	539	188300	109000	259	19.9	0.43	189	191	73.9	0.84	1.60
	5.19	7410	333	210000	126500	90.4	21.3	0.16	201	203	56.3	0.30	0.76
	5.65	10710	401	191100	114900	209	19.0	0.43	195	191	67.9	0.76	1.40
	5.72	8400	409	204600	120200	213	23.9	0.19	194	192	71.1	1.08	2.13
	6.11	8060	561	202900	120600	239	27.1	0.48	194	191	63.0	1.04	2.27
	5.75	7800	402	201200	122300	210	16.8	0.32	190	188	49.1	0.68	1.72
	5.75	8490	462	216400	124000	172	21.2	0.24	198	196	48.4	0.66	1.48
	5.43	8330	742	206300	122100	212	46.3	0.28	193	191	47.8	0.74	1.67
	5.07	7380	464	212400	129200	117	39.8	0.11	183	180	14.0	0.19	0.40
average	4.98	7110	747	210500	127000	119	23.0	0.22	191	187	28.4	0.23	0.57
2 s.d.	5.69	8612	539	204727	121536	184.8	28.8	0.29	193	192	53.0	0.66	1.42
	1.33	3622	348	17238	11389	108.3	27.1	0.24	10	12	36.8	0.61	1.21
GRA 98006	29.3	7070	36	198300	117400	21.6	9.4	0.44	185	180	63.8	0.52	1.06
	28.0	7680	34	198700	116300	20.6	9.2	0.48	176	171	77.3	0.33	0.74
	20.6	6660	37	198700	115100	26.9	10.1	0.09	170	173	50.8	0.47	0.96
	22.6	6950	35	195100	115600	22.5	8.8	1.97	180	180	193.0	0.47	0.84
	13.0	7100	35	197800	118100	36.3	10.1	0.42	167	179	78.7	0.47	0.83
	23.8	6560	30	199800	115500	31.9	9.6	0.62	178	177	80.9	0.46	0.73
	6.6	6100	36	205500	122400	43.3	10.9	0.09	183	186	50.1	0.39	0.72
average	20.5	6874	35	199129	117200	29.0	9.7	0.59	177	178	84.9	0.44	0.84
2 s.d.	16.3	996	4	6330	5070	17.1	1.4	1.28	13	10	98.7	0.12	0.26
GRA 98033	12.9	8220	1680	199800	120300	81.6	179.0	0.06	185	188	58.4	0.79	1.41
	12.0	8080	2640	194600	117000	95.2	297.0	0.09	188	196	61.2	0.72	1.34
	11.5	7850	914	201800	122000	75.0	101.3	0.07	200	209	66.7	0.74	1.36
	13.5	8360	1675	213600	125800	106	161.2	0.05	207	213	67.2	0.77	1.44
	11.5	7770	3050	199900	120300	153	290.0	0.10	198	203	65.4	0.68	1.29
	12.0	8180	3450	194500	117200	117	264.0	0.09	196	194	63.7	0.57	1.18
	12.2	8410	1790	206100	119200	82.2	193.0	0.06	197	202	65.3	0.67	1.23
	11.2	7537	2510	195700	122300	110	220.0	0.06	189	187	62.4	0.64	1.12
	12.3	8060	2730	200400	120500	112	279.0	0.07	197	196	64.0	0.55	1.00
average	12.1	8052	2271	200711	120511	103.5	220.5	0.07	195	199	63.8	0.68	1.26
2 s.d.	1.5	572	1609	12226	5408	47.8	134.5	0.03	14	18	5.6	0.17	0.29

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
GRA 98043	12.5	7620	2860	200400	120400	109	281.0	0.11	194	199	24.9	0.65	0.88
	11.3	7290	194	192300	112500	78.0	39.2	0.17	188	195	22.8	0.86	1.23
	11.9	7780	1550	206200	121800	92.5	152.0	0.10	208	216	25.4	0.51	0.88
	11.9	8070	4300	188000	115500	74.8	482.0	0.17	183	188	51.9	0.67	0.91
	12.7	8100	3870	186700	117000	166	321.0	0.22	181	189	50.2	0.64	1.15
	13.4	9271	103	204900	120000	41.5	21.6	1.60	193	195	108.1	0.76	1.19
average 2 s.d.	12.2	8560	283	204800	120000	40.6	41.6	0.53	201	205	58.8	0.72	1.04
	12.5	8290	1530	192100	118100	61.6	178.0	0.21	187	190	56.4	0.57	1.02
	12.3	8123	1836	196925	118163	83.1	189.5	0.39	192	197	49.8	0.67	1.04
GRA 98114	1.25	1220	3342	16082	6118	81.9	325.5	1.01	18	19	55.9	0.22	0.28
	11.2	7650	2420	184100	117300	177	321.0	0.35	188	189	70.8	0.80	1.89
	13.5	8420	72	182700	121200	68.2	28.0	0.14	176	177	53.9	0.75	1.90
	13.0	8130	109	185100	117600	57.0	21.8	0.27	185	185	66.4	0.50	1.41
	12.2	7350	3860	183600	118600	250	421.0	0.13	178	180	59.0	0.54	1.40
	13.5	8260	61	192700	121500	54.3	18.6	0.15	184	183	61.2	0.56	1.39
average 2 s.d.	10.6	7608	176	208100	115800	141	28.6	0.65	186	183	75.8	0.93	1.36
	11.8	7942	300	210900	120700	439	59.3	0.61	197	192	81.3	0.87	1.30
	12.2	7909	1000	192457	118957	170	128.3	0.33	185	184	66.9	0.71	1.52
LAP031062	2.30	776	3044	24256	4413	278	337.6	0.44	14	10	19.5	0.35	0.52
	3.94	7260	490	230600	144400	107.1	20.6	0.02	251	258	36.1	0.42	1.00
	4.10	7160	463	233500	145100	128.3	19.3	0.01	251	255	35.8	0.49	1.28
	4.04	7170	517	247200	154600	134.2	20.0	0.02	266	273	41.7	1.05	2.03
	4.11	7050	433	216200	137300	97.0	16.2	0.06	240	233	31.1	0.55	1.11
	4.05	7160	476	231875	145350	116.7	19.0	0.03	252	255	36.2	0.63	1.35
average 2 s.d.	0.16	172	72	25425	14205	35.0	4.0	0.04	21	33	8.7	0.57	0.93
LAR 06875	13.10	8670	847	212400	131800	314.0	112.7	0.04	225	217	68.0	1.12	2.60
	13.16	7650		185700	115100	295.0	1163.0	0.12	201	205	48.9	1.08	2.74
	17.38	8580	1490	215800	132300	337.0	184.0	0.18	225	233	60.9	1.61	4.00
	12.68	8070	3630	223200	136500	251.0	385.0	0.04	223	234	68.8	3.00	7.54
	14.08	8243	1989	209275	128925	299.3	461.2	0.10	218	222	61.7	1.70	4.22
	4.42	950	2914	32701	18909	72.9	963.8	0.13	23	28	18.4	1.80	4.60

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
LEW 85305	3.87	9582	174	230800	142200	83.7	42.5	0.16	240	247	103.6	1.41	2.64
	3.64	10390	171	221600	137300	102.1	47.3	0.12	238	240	106.6	1.88	3.21
	3.85	10190	191	218600	137500	93.9	46.8	0.11	230	236	97.5	1.44	2.90
	4.34	9826	185	222900	137800	76.3	49.9	0.12	236	239	104.3	1.25	2.42
	4.01	9141	165	223400	138100	84.3	41.6	0.12	238	240	102.3	1.22	2.53
	4.02	10088	167	218700	133500	111.8	41.8	0.45	239	237	91.1	1.87	3.64
	3.90	10250	193	226800	139400	139.3	44.6	0.16	250	257	110.2	1.79	3.27
	3.93	10370	179	226300	139500	97.3	45.9	0.11	238	244	110.5	1.54	2.92
	3.49	10090	157	222400	136600	98.9	38.2	0.13	243	240	105.5	1.78	3.09
	3.43	10770	182	221000	135100	127.7	45.5	0.36	240	236	111.7	1.04	1.82
average	3.85	10070	176	223250	137700	101.5	44.4	0.18	239	242	104.3	1.52	2.84
2 s.d.	0.54	917	23	7598	4824	39.7	6.8	0.24	10	13	12.6	0.60	1.03
LEW 87002	6.84	5890	1545	196700	129200	48.8	52.3	0.10	209	209	85.3	0.73	1.50
	7.67	6694	4877	187400	128000	256.0	118.3	0.07	198	204	87.3	0.32	0.71
	8.79	7497	1113	195300	125900	86.1	31.9	0.14	207	211	93.7	0.45	0.98
	6.88	6454	4240	204500	132380	104.9	127.0	0.20	219	222	90.9	0.33	0.62
	8.34	6969	2660	210500	136200	124.0	59.3	0.08	216	220	89.9	0.34	0.62
	7.88	6968	2703	209200	135100	115.1	56.6	0.11	218	221	91.1	0.34	0.68
	5.71	4852	4820	197000	130300	107.3	133.0	0.14	207	207	80.7	0.58	1.19
	7.02	6211	6280	184000	126300	197.8	150.4	0.07	198	202	84.3	0.47	0.93
average	7.39	6442	3530	198075	130423	130.0	91.1	0.11	209	212	87.9	0.45	0.90
2 s.d.	1.96	1624	3607	19157	7706	131.8	91.1	0.09	17	16	8.6	0.29	0.63
PCA 91193	8.82	8329	372	195800	125200	82.2	20.6	0.06	196	197	50.4	0.82	1.52
	7.97	8290	375	211500	133100	133.7	23.1	0.25	211	218	55.6	1.21	2.06
	8.12	8390	396	205300	129070	110.7	17.0	0.10	193	198	35.1	1.25	2.46
	8.60	7932	322	194700	124400	64.7	51.9	0.15	181	184	28.7	0.70	1.45
	8.58	8594	379	191200	122400	90.9	16.0	0.18	201	196	45.7	0.75	1.51
	8.27	8610	390	197400	125300	116.9	17.3	0.27	191	191	37.1	0.84	1.76
	8.01	8052	325	203900	129700	98.6	22.8	0.12	209	207	47.8	1.45	2.85
average	8.34	8314	365	199971	127024	99.7	24.1	0.16	197	199	42.9	1.00	1.94
2 s.d.	0.66	508	60	14271	7431	46.1	25.2	0.15	21	22	19.1	0.59	1.08

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
QUE 97014	13.8	8907	158	185500	117800	43.2	26.9	0.08	188	194	22.2	0.46	0.91
	15.1	9360	1140	203500	128300	52.7	139.0	0.10	200	201	43.8	0.46	0.83
	13.6	8918	289	206600	130800	37.6	35.4	0.06	205	211	41.7	0.46	0.85
	15.6	9290	488	197200	124300	53.8	62.5	0.08	197	199	32.9	0.46	0.92
	14.1	8853	4070	187300	123300	84.6	324.0	0.10	205	204	44.2	0.99	2.29
	14.7	9020	501	186300	118500	45.2	43.8	0.23	202	202	45.2	0.51	0.95
average	14.5	9058	1108	194400	123833	52.9	105.3	0.11	200	202	38.3	0.56	1.12
2 s.d.	1.56	430	2980	18649	10347	33.4	229.1	0.12	13	11	18.2	0.43	1.15
QUE 99005	16.5	8450	1501	204800	129300	71.7	131.7	0.15	214	212	67.8	0.18	0.44
	15.2	8000	1327	205800	128900	67.4	152.2	0.15	208	211	63.7	0.35	0.39
	16.6	8550	1727	205600	130000	60.2	149.3	0.24	215	209	72.7	0.41	0.54
	13.9	7400	1881	206000	131200	66.0	210.5	0.18	207	208	60.4	0.28	0.33
	22.2	12570	2871	175600	107800	187.0	218.1	1.53	209	212	137.3	0.56	0.85
	20.9	11730	2588	188300	116700	124.4	187.6	1.55	217	216	122.2	0.34	0.58
average	17.6	9450	1983	197683	123983	96.1	174.9	0.63	212	211	87.4	0.35	0.52
2 s.d.	6.56	4294	1231	25676	19093	100.7	71.2	1.41	9	6	66.9	0.25	0.38
SCO 06041	9.97	6621	108	207800	132300	94.6	11.6	0.07	175	175	39.8	0.37	0.63
	10.0	6111	83	209600	134300	65.4	10.0	0.07	174	171	38.1	0.39	0.60
	10.4	6752	95	205700	132100	72.2	10.9	0.05	178	172	40.1	0.40	0.67
	11.2	7223	123	207200	131600	180.3	14.8	0.07	173	176	43.8	0.32	0.66
	9.38	5840	102	208500	135400	62.4	13.4	0.20	176	175	42.5	0.63	1.42
	9.25	5814	121	212800	136400	61.3	11.9	0.09	177	176	39.1	0.46	1.03
average	9.55	5883	92	210900	135800	61.2	11.7	0.06	173	178	38.7	0.41	0.71
2 s.d.	12.5	7220	120	203600	129200	93.4	12.4	0.05	173	174	41.6	0.41	0.78
average	10.7	6381	119	208100	131600	126.6	12.5	0.07	170	172	42.7	0.54	0.91
	10.9	6666	111	199100	126400	107.5	11.3	0.13	161	167	41.0	0.73	1.42
	10.4	6451	107	207330	132510	92.5	12.0	0.08	173	174	40.7	0.47	0.88
2 s.d.	1.94	1070	28	7726	6242	76.3	2.7	0.09	10	6	3.8	0.26	0.62

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	^{86}Sr	^{87}Sr	Ba	La	Ce
GRO 95533	11.0	7084	55	211300	135200	60.6	23.3	0.30	184	185	74.0	0.96	1.85
	10.3	7040	65	208700	132300	60.0	21.4	0.08	184	184	63.1	3.16	8.41
	13.5	8484	76	209000	130900	52.2	18.2	0.12	197	199	64.7	0.93	1.67
	12.6	8632	227	203500	127800	65.1	31.8	0.11	203	203	70.7	0.88	1.57
	10.5	7741	77	195300	125500	45.9	17.3	0.07	198	200	78.9	0.82	1.53
	12.0	8272	57	197300	125100	48.9	15.5	0.17	188	190	83.5	0.65	1.19
	10.4	7276	69	212700	133500	59.7	21.5	0.03	191	190	64.0	1.08	2.01
	10.7	7162	95	205500	131200	63.4	22.4	0.23	179	183	64.7	1.00	1.95
average	11.4	7711	90	205413	130188	57.0	21.4	0.14	190	192	70.5	1.18	2.52
2 s.d.	2.39	1330	114	12721	7393	14.1	10.0	0.18	17	16	15.4	1.62	4.79
Milbillillie	19.1	11450	1200	191100	116300	97.1	104.7	2.37	188	192	167.8	0.49	0.86
	21.3	11221	2707	183700	114900	120.2	258.2	0.22	174	178	64.0	0.42	0.77
	21.0	11460	4890	170000	106600	193.0	485.0	0.47	163	163	72.2	0.38	0.70
	16.7	10040	3300	190900	117400	436.0	327.0	0.30	190	185	68.5	0.53	1.00
	18.0	11180	2630	182000	111800	93.8	276.0	0.18	182	186	68.6	0.39	0.96
	15.8	9033	4350	183900	118000	214.0	422.0	0.16	185	184	62.3	0.54	1.04
	15.3	8106	3628	184900	116600	164.3	334.5	0.38	174	174	57.3	0.67	1.42
average	18.2	10356	3244	183786	114514	188.3	315.3	0.58	179	180	80.1	0.49	0.96
2 s.d.	4.84	2678	2439	14109	8090	237.3	244.7	1.59	19	19	78.0	0.21	0.47
Juvinas	8.55	5512	1286	209000	135500	41.7	146.0	0.08	155	153	39.0	0.23	0.63
	9.77	6603	1980	200000	129800	58.2	203.1	0.10	157	156	41.7	0.18	0.57
	10.20	6303	2035	206500	134580	58.3	215.0	0.18	169	165	53.6	0.16	0.37
	9.25	5901	1671	205000	134800	39.7	189.1	0.08	165	166	69.6	0.32	0.88
	8.47	5390	1752	206200	137100	47.5	182.4	0.13	144	146	33.8	0.15	0.39
	8.30	5430	1270	207900	137100	40.5	126.7	0.14	148	148	33.2	0.14	0.28
	8.81	5533	1656	207000	132600	47.8	165.9	0.13	158	153	46.1	0.13	0.31
	8.05	5225	2188	206100	135200	56.3	219.0	0.10	149	148	40.3	0.09	0.23
	9.72	6366	1639	198700	131000	52.2	179.7	0.12	177	178	62.5	0.12	0.37
	9.17	6144	1491	199300	131600	58.0	146.7	0.12	166	167	56.1	0.17	0.46
average	9.03	5841	1697	203940	134028	50.0	177.4	0.12	159	158	47.6	0.17	0.45
2 s.d.	1.42	971	610	7710	5259	15.2	61.8	0.06	21	21	24.7	0.13	0.39

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Li	Na	Mg	Al	Ca	Ti	Mn	Rb	⁸⁶ Sr	⁸⁸ Sr	Ba	La	Ce	
Dhofar 007	5.89	7950	514	215400	134500	163.8	42.8	0.26	191	195	43.0	1.06	2.61	
	6.19	8230	681	221000	149600	197.1	45.7	0.41	211	218	49.2	1.59	3.32	
	6.19	7970	654	221700	138600	193.3	38.9	0.25	202	210	49.0	1.39	2.56	
	6.55	8580	588	214800	131500	202.1	44.7	0.27	192	191	45.2	1.35	2.75	
	6.29	8330	541	211800	130100	213.5	30.0	0.46	195	192	46.1	0.88	2.04	
	5.88	7810	537	213900	131600	131.8	48.1	0.32	189	189	40.0	0.59	1.49	
	4.65	6330	482	219900	140200	51.5	50.6	0.17	178	178	23.9	0.16	0.44	
average	5.95	7886	571	216929	136586	164.7	43.0	0.30	194	196	42.3	1.00	2.17	
2 s.d.	1.24	1469	147	7768	13751	114.2	13.7	0.20	21	27	17.5	1.00	1.91	
Camel Donga	12.1	10230	137	223700	129800	69.8	24.9	0.01	230	223	93.8	1.26	2.34	
	10.1	7970	117	222000	136800	53.2	25.7	0.01	242	232	87.0	1.04	1.98	
	9.44	7580	142	235600	145400	64.4	34.7	-0.01	239	238	88.1	1.17	2.31	
	10.6	9050	234	211200	130700	67.7	33.8	0.01	197	197	80.7	1.45	2.69	
	8.49	8330	231	211300	129700	39.3	14.4	0.21	208	207	75.1	0.51	1.00	
	average	10.2	8632	172	220760	134480	58.9	26.7	0.05	223	219	84.9	1.09	2.06
	2 s.d.	2.70	2089	111	20280	13552	25.4	16.4	0.19	40	34	14.4	0.71	1.29

Table B4: Plagioclase trace element concentrations in µg/g (continued).

Sample	Pr	Nd	Sm	¹⁵¹ Eu	¹⁵³ Eu	Gd
EET 83227	0.37	1.56	0.29	1.53	1.41	0.24
	0.10	0.44	0.12	1.46	1.56	0.09
	0.10	0.38	0.10	1.42	1.47	0.11
	0.09	0.39	0.12	1.42	1.40	0.11
	0.13	0.59	0.27	1.48	1.37	0.20
	0.25	1.24	0.30	1.30	1.32	0.26
average	0.17	0.76	0.20	1.43	1.42	0.17
2 s.d.	0.23	1.02	0.19	0.16	0.17	0.15
EET 87548	0.05	0.29	0.12	0.83	0.84	0.06
	0.06	0.11	0.09	0.92	0.91	0.07
	0.05	0.18	0.09	0.93	0.93	0.06
	0.05	0.27	0.04	0.90	0.90	0.07
	0.05	0.13	0.00	0.88	0.84	0.08
	0.06	0.19	0.03	0.96	1.00	0.09
	0.05	0.21	0.07	0.95	0.99	0.03
	0.05	0.20	0.08	0.96	1.01	0.00
	0.05	0.20	0.01	0.90	0.89	0.00
	0.06	0.22	0.07	0.90	0.90	0.06
	0.06	0.20	0.08	0.94	0.95	0.01
	0.06	0.23	0.10	0.92	0.91	0.03
average	0.05	0.20	0.07	0.92	0.92	0.05
2 s.d.	0.01	0.10	0.07	0.07	0.11	0.06
EET 92003	0.21	1.00	0.28	1.29	1.27	0.24
	0.19	0.83	0.20	1.43	1.54	0.13
	0.19	0.83	0.20	1.43	1.45	0.16
	0.29	1.25	0.25	1.65	1.57	0.27
	0.07	0.26	0.07	1.46	1.37	0.09
	0.18	0.60	0.18	1.51	1.47	0.13
	0.11	0.47	0.15	1.37	1.32	0.12
	0.41	2.07	0.56	1.35	1.37	0.65
	0.25	1.28	0.31	1.41	1.32	0.27
	0.13	0.69	0.20	1.38	1.40	0.14
average	0.20	0.93	0.24	1.43	1.41	0.22
2 s.d.	0.19	1.03	0.26	0.20	0.20	0.33

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
EET 92023	0.20	0.83	0.18	1.41	1.34	0.14
	0.19	0.73	0.10	1.37	1.41	0.11
	0.11	0.41	0.16	1.46	1.38	0.11
	0.15	0.62	0.14	1.37	1.42	0.15
	0.28	1.13	0.18	1.35	1.45	0.13
	0.27	1.28	0.19	1.41	1.46	0.27
	0.22	0.90	0.16	1.32	1.48	0.21
	0.19	0.78	0.19	1.36	1.37	0.16
	0.21	0.80	0.20	1.32	1.40	0.14
	0.05	0.38	0.10	1.21	1.17	0.02
	0.07	0.30	0.13	1.28	1.28	0.14
average	0.17	0.74	0.16	1.35	1.38	0.14
2 s.d.	0.15	0.61	0.07	0.13	0.18	0.13
GRA 98006	0.11	0.54	0.09	1.34	1.22	0.08
	0.08	0.34	0.05	1.23	1.28	0.14
	0.10	0.38	0.10	1.19	1.19	0.02
	0.10	0.40	0.12	1.21	1.28	0.14
	0.10	0.34	0.11	1.22	1.33	0.06
	0.08	0.33	0.12	1.22	1.24	0.05
	0.06	0.27	0.04	1.26	1.35	0.01
average	0.09	0.37	0.09	1.24	1.27	0.07
2 s.d.	0.03	0.17	0.07	0.10	0.11	0.10
GRA 98033	0.14	0.60	0.13	1.47	1.47	0.13
	0.13	0.56	0.13	1.48	1.42	0.13
	0.15	0.50	0.10	1.57	1.58	0.11
	0.16	0.66	0.12	1.61	1.64	0.17
	0.13	0.64	0.15	1.53	1.61	0.15
	0.14	0.63	0.14	1.47	1.43	0.15
	0.12	0.56	0.14	1.51	1.64	0.11
	0.14	0.67	0.18	1.52	1.56	0.11
	0.12	0.52	0.12	1.51	1.52	0.15
average	0.14	0.59	0.13	1.52	1.54	0.13
2 s.d.	0.03	0.12	0.04	0.09	0.17	0.04

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
GRA 98043	0.20	3.20	0.37	1.56	1.56	0.39
	0.27	1.40	0.38	1.45	1.45	0.44
	0.11	0.56	0.13	1.61	1.61	0.15
	0.17	0.72	0.19	1.44	1.41	0.26
	0.17	0.80	0.25	1.46	1.39	0.40
	0.18	0.94	0.31	1.40	1.53	0.32
	0.22	0.96	0.29	1.57	1.52	0.32
	0.15	0.64	0.18	1.54	1.46	0.16
average	0.18	1.15	0.26	1.50	1.49	0.30
2 s.d.	0.09	1.74	0.19	0.15	0.15	0.22
GRA 98114	0.17	0.66	0.16	1.42	1.39	0.13
	0.16	0.53	0.11	1.25	1.35	0.14
	0.09	0.33	0.17	1.42	1.37	0.17
	0.11	0.41	0.12	1.33	1.34	0.14
	0.11	0.40	0.12	1.34	1.34	0.18
	0.23	1.02	0.32	1.36	1.44	0.43
	0.19	0.81	0.24	1.50	1.43	0.27
average	0.15	0.60	0.18	1.38	1.38	0.21
2 s.d.	0.10	0.50	0.15	0.16	0.08	0.22
LAP031062	0.12	0.51	0.19	2.02	2.01	0.18
	0.18	0.71	0.23	2.04	1.99	0.17
	0.39	1.73	0.54	2.15	2.21	0.40
	0.16	0.62	0.16	1.73	1.84	0.09
average	0.21	0.89	0.28	1.99	2.01	0.21
2 s.d.	0.25	1.13	0.35	0.36	0.30	0.26
LAR 06875	0.28	1.40	0.29	1.70	1.84	0.54
	0.33	1.71	0.51	1.64	1.64	0.64
	0.53	2.56	0.75	1.80	1.60	0.80
	1.05	4.61	1.51	1.76	1.85	1.50
average	0.55	2.57	0.77	1.73	1.73	0.87
2 s.d.	0.70	2.89	1.06	0.14	0.26	0.87

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
LEW 85305	0.27	1.16	0.29	1.92	1.93	0.22
	0.37	1.54	0.24	1.85	1.89	0.32
	0.32	1.23	0.22	1.83	1.79	0.20
	0.28	1.12	0.25	1.89	1.85	0.22
	0.28	0.98	0.30	1.88	1.90	0.16
	0.43	1.85	0.25	1.84	1.81	0.30
	0.37	1.49	0.26	1.99	1.99	0.22
	0.37	1.20	0.29	1.99	1.85	0.25
	0.34	1.43	0.44	1.90	1.88	0.21
	0.21	0.84	0.18	1.96	1.83	0.15
average	0.32	1.28	0.27	1.90	1.87	0.23
2 s.d.	0.13	0.59	0.14	0.12	0.12	0.11
LEW 87002	0.14	0.64	0.12	1.46	1.55	0.11
	0.09	0.41	0.17	1.59	1.53	0.18
	0.12	0.56	0.18	1.62	1.52	0.11
	0.06	0.26	0.10	1.54	1.52	0.09
	0.08	0.37	0.13	1.65	1.60	0.14
	0.06	0.39	0.10	1.45	1.52	0.14
	0.12	0.49	0.15	1.53	1.52	0.15
	0.11	0.53	0.19	1.44	1.42	0.24
average	0.10	0.46	0.14	1.53	1.52	0.14
2 s.d.	0.06	0.25	0.07	0.16	0.10	0.09
PCA 91193	0.18	0.56	0.16	1.28	1.38	0.06
	0.23	0.86	0.19	1.51	1.52	0.18
	0.25	0.93	0.22	1.39	1.40	0.15
	0.15	0.56	0.14	1.23	1.22	0.09
	0.16	0.50	0.16	1.36	1.45	0.12
	0.16	0.80	0.14	1.38	1.25	0.08
	0.27	1.05	0.21	1.49	1.50	0.17
average	0.20	0.75	0.17	1.38	1.39	0.12
2 s.d.	0.10	0.43	0.06	0.21	0.23	0.09

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
QUE 97014	0.11	0.44	0.10	1.38	1.45	0.13
	0.10	0.38	0.08	1.62	1.58	0.09
	0.10	0.47	0.12	1.65	1.58	0.14
	0.10	0.41	0.12	1.47	1.45	0.15
	0.26	1.31	0.33	1.53	1.52	0.43
	0.11	0.42	0.15	1.59	1.54	0.11
average	0.13	0.57	0.15	1.54	1.52	0.17
2 s.d.	0.13	0.73	0.18	0.21	0.11	0.26
QUE 99005	0.05	0.26	0.12	1.65	1.60	0.09
	0.10	0.27	0.12	1.68	1.64	0.17
	0.11	0.68	0.22	1.62	1.62	0.19
	0.06	0.43	0.10	1.54	1.59	0.03
	0.19	0.91	0.21	1.67	1.70	0.33
	0.13	0.39	0.22	1.64	1.66	0.13
average	0.11	0.49	0.17	1.63	1.64	0.16
2 s.d.	0.10	0.51	0.11	0.10	0.08	0.21
SCO 06041	0.08	0.30	0.06	1.22	1.26	0.09
	0.07	0.27	-0.02	1.13	1.16	0.07
	0.07	0.28	0.11	1.22	1.21	0.07
	0.06	0.31	0.12	1.20	1.17	0.05
	0.16	0.60	0.16	1.20	1.13	0.10
	0.13	0.44	0.02	1.19	1.22	0.05
	0.08	0.26	0.15	1.08	1.25	0.14
	0.07	0.39	0.07	1.09	1.17	0.12
	0.11	0.38	0.08	1.15	1.15	0.04
	0.13	0.51	0.12	1.09	1.11	0.14
average	0.09	0.37	0.09	1.15	1.18	0.09
2 s.d.	0.07	0.23	0.11	0.11	0.10	0.07

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
GRO 95533	0.18	0.70	0.18	1.31	1.34	0.14
	1.04	4.29	1.00	1.33	1.30	0.69
	0.19	0.66	0.13	1.46	1.57	0.17
	0.16	0.61	0.11	1.55	1.55	0.14
	0.16	0.65	0.11	1.57	1.55	0.10
	0.11	0.51	0.17	1.54	1.46	0.05
	0.20	0.85	0.17	1.39	1.48	0.16
	0.21	0.77	0.17	1.24	1.32	0.08
average	0.28	1.13	0.25	1.42	1.45	0.19
2 s.d.	0.62	2.56	0.61	0.25	0.22	0.41
Millbillillie	0.09	0.52	0.05	1.61	1.50	0.13
	0.09	0.40	0.14	1.36	1.32	0.10
	0.10	0.43	0.11	1.22	1.26	0.13
	0.11	0.51	0.13	1.50	1.55	0.15
	0.11	0.42	0.15	1.36	1.42	0.19
	0.10	0.54	0.13	1.42	1.41	0.12
	0.16	0.62	0.17	1.28	1.27	0.16
average	0.11	0.49	0.13	1.39	1.39	0.14
2 s.d.	0.05	0.16	0.08	0.27	0.23	0.06
Juvinas	0.07	0.33	0.09	1.05	1.06	0.09
	0.07	0.28	0.13	1.03	1.05	0.08
	0.05	0.18	0.01	1.26	1.18	0.00
	0.09	0.39	0.14	1.22	1.17	0.13
	0.04	0.20	0.07	0.91	1.02	0.06
	0.03	0.14	0.02	1.00	0.99	0.08
	0.04	0.11	0.00	1.04	0.99	0.03
	0.03	0.14	0.00	1.01	0.92	0.00
	0.05	0.20	0.11	1.21	1.18	0.00
	0.04	0.27	0.09	1.20	1.17	0.03
average	0.05	0.22	0.07	1.09	1.07	0.05
2 s.d.	0.04	0.18	0.11	0.24	0.19	0.09

Table B4: Plagioclase trace element concentrations in $\mu\text{g/g}$ (continued).

Sample	Pr	Nd	Sm	^{151}Eu	^{153}Eu	Gd
Dhofar 007	0.30	1.22	0.23	1.30	1.25	0.19
	0.35	1.59	0.19	1.35	1.37	0.19
	0.28	1.23	0.15	1.23	1.39	0.17
	0.31	1.29	0.24	1.23	1.27	0.22
	0.23	0.91	0.16	1.25	1.21	0.21
	0.20	0.93	0.19	1.21	1.31	0.23
	0.07	0.28	0.05	1.19	1.29	0.00
average	0.25	1.06	0.17	1.25	1.30	0.17
2 s.d.	0.19	0.83	0.13	0.11	0.13	0.16
Camel Donga	0.27	0.89	0.21	1.43	1.70	0.15
	0.23	0.88	0.22	1.60	1.68	0.20
	0.26	1.06	0.13	1.72	1.79	0.17
	0.29	0.99	0.24	1.42	1.49	0.13
	0.13	0.42	0.09	1.66	1.64	0.05
average	0.23	0.85	0.18	1.57	1.66	0.14
2 s.d.	0.13	0.50	0.13	0.27	0.22	0.12

Table B5: Measured trace element concentrations in the BHVO standard in µg/g

Sample	Li	Na	Mg	Al	Sc	Ti	V	Cr	Mn	Co	Ni	Zn	Rb
BHVO-2G	4.47	17200	38480	64440	28.6	15440	316	302	1271	42.5	115.5	92.6	9.2
	4.57	16830	39160	64280	28.1	15640	315	306	1274	44.0	124.8	91.8	9.1
	4.28	16480	38770	64690	27.2	15570	313	299	1269	43.7	123.7	93.5	9.0
	4.31	16860	38140	63760	27.5	15500	315	303	1282	44.9	126.4	93.8	9.4
	4.66	16600	38820	63700	27.4	15540	320	308	1273	43.7	118.3	96.4	9.0
	4.54	16990	38330	63890	27.7	15480	318	309	1270	43.4	112.1	93.7	8.8
	4.28	16600	38940	64190	27.1	15670	314	309	1282	45.1	122.8	93.1	8.9
	4.24	16590	39650	63780	27.3	15730	320	317	1299	44.6	125.3	92.9	8.5
	4.21	16540	38780	64130	27.1	15390	317	307	1290	45.5	123.3	93.3	8.7
	4.27	16490	39110	64420	27.8	15750	314	320	1306	45.2	126.2	92.7	8.9
average	4.38	16718	38818	64128	27.6	15571	316	308	1282	44.3	121.8	93.4	8.9
2 s.d.	0.32	482.38	875.64	673.88	1.0	245.94	4.81	13.26	25.87	1.93	9.77	2.43	0.47

Sample	Sr	Zr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho
BHVO-2G	374	144	126	13.8	36.2	4.77	22.7	5.38	1.75	5.84	0.697	4.56	0.88
	368	144	125	13.8	35.9	4.73	21.7	5.69	1.88	5.6	0.72	4.46	0.90
	368	143	123	13.5	35.9	4.75	22.1	5.19	1.93	5.74	0.785	4.41	0.82
	376	147	125	13.6	36.2	4.77	21.9	5.62	1.86	5.09	0.774	4.19	0.86
	369	142	126	13.7	37.5	4.91	22.2	6.09	1.74	5.21	0.762	4.51	0.73
	369	141	124	13.2	35.8	4.83	22.2	5.31	2.05	5.61	0.711	4.52	0.84
	365	142	125	13.6	35.9	4.72	22.1	5.41	1.77	5.38	0.768	4.47	0.75
	376	141	126	13.4	37.4	4.89	22.3	5.40	1.83	5.86	0.798	4.47	0.78
	369	141	126	13.4	36.5	4.99	21.7	5.78	1.97	5.42	0.795	4.60	0.79
	366	146	126	13.5	36.3	4.98	21.0	5.29	1.98	5.53	0.789	4.89	0.82
average	370	143	125	13.5	36.4	4.83	22.0	5.52	1.88	5.53	0.760	4.51	0.82
2 s.d.	7.93	4.19	1.92	0.36	1.22	0.20	0.90	0.55	0.21	0.51	0.07	0.35	0.11

Table B5: Measured trace element concentrations in the BHVO standard in $\mu\text{g/g}$ (continued).

Sample	Er	Tm	Yb	Lu	Hf	W
BHVO-2G	2.24	0.27	1.71	0.23	3.61	0.17
	2.20	0.30	1.72	0.23	3.55	0.31
	2.15	0.25	1.75	0.23	3.47	0.18
	2.21	0.26	1.83	0.24	3.55	0.20
	1.99	0.29	1.63	0.22	3.50	0.20
	2.25	0.26	1.79	0.20	3.16	0.27
	2.17	0.28	1.86	0.22	3.78	0.18
	2.12	0.26	1.80	0.24	3.44	0.20
	2.06	0.23	1.89	0.22	3.75	0.14
	1.90	0.24	1.83	0.24	3.90	0.21
average	2.13	0.26	1.78	0.23	3.57	0.21
2 s.d.	0.23	0.05	0.16	0.03	0.42	0.10

Table B6: Measured trace element concentrations in the ATHO-G standard in $\mu\text{g/g}$

Sample	Li	Na	Mg	Al	Ti	Mn	Rb	Sr	Ba	La	Ce
ATHO-G	36.1	38700	806	83700	1897	870	69.4	93.5	561	57.1	133
	36.2	38690	819	85100	1910	886	71.1	97.8	577	57.9	131
	36.3	37880	802	83700	1903	897	71.2	95.9	585	59.0	135
	35.4	37000	789	82900	1921	900	72.0	99.0	589	59.1	135
	35.9	37970	803	82800	1912	900	73.0	98.7	584	57.7	132
	36.5	38600	812	82800	1934	926	73.7	99.5	584	59.0	138
	35.3	36990	787	81000	1870	901	73.4	97.8	594	58.6	135
	36.8	38900	809	83300	1882	886	74.3	97.7	601	59.8	137
	35.1	37400	792	81800	1890	891	73.1	97.1	584	58.6	133
	37.3	37800	792	80900	1895	871	72.3	96.7	574	56.5	136
	36.5	38200	791	80600	1849	864	74.2	93.9	579	56.5	132
	36.5	37900	783	80700	1862	853	71.8	95.1	548	55.1	128
average	36.2	38003	799	82442	1894	887	72.5	96.9	580	57.9	134
2 s.d.	1.3	1296	23	2875	50	40	2.9	3.9	28	2.8	6

Sample	Pr	Nd	Sm	Eu	Gd
ATHO-G	14.8	64.7	15.5	2.93	15.8
	15.0	66.4	15.5	2.90	16.8
	15.1	65.8	16.2	2.87	16.5
	15.5	66.2	16.0	2.83	16.4
	15.0	65.9	15.0	2.76	16.1
	15.1	64.7	15.4	2.75	16.2
	15.0	65.8	15.5	2.72	15.3
	15.4	67.6	15.4	2.78	15.4
	15.0	64.4	15.7	2.82	15.2
	15.0	66.1	15.2	2.66	15.5
	14.5	64.6	15.0	2.79	15.1
	14.0	61.7	15.0	2.63	14.6
average	15.0	65.3	15.4	2.79	15.7
2 s.d.	0.7	2.9	0.7	0.18	1.3

Appendix C

Eucrite sample images

The following are backscattered electron images of each eucrite sample used in this study taken using the JEOL SuperProbe JXA-8230 EPMA at Victoria University of Wellington.

Figure C1: EET83227

Figure C2: EET87458

Figure C3: EET92003

Figure C4: EET92023

Figure C5: GRA98006

Figure C6: GRA98033

Figure C7: GRA98043

Figure C8: GRA98055

Figure C9: GRA98114

Figure C10: LAP031062

Figure C11: LAR06875

Figure C12: LEW85305

Figure C13: LEW87002

Figure C14: PCA91193

Figure C15: QUE97014

Figure C16: QUE99055

Figure C17: RKPA80204

Figure C18: SCO06041

Figure C19: GRO95533

Figure C20: Millbillillie

Figure C21: Juvinas

Figure C22: Dhofar007

Figure C23: Camel Donga