Bulk element compositions of meteorites: A guide for interpreting remote-sensing geochemical measurements of planets and asteroids

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Abstract: We report a large database of bulk meteorite elemental abundances, compiled to aid in the interpretation of elemental abundance data determined by remote-sensing instrumentation on planetary missions. A custom user interface was developed for easy access and manipulation of the abundance data. The database contains almost 3000 individual analyses of more than 1000 individual meteorites. Most major and minor elements are included, as well as small number of trace elements measurable by remote-sensing gamma-ray spectroscopy (notably Th and U). All meteorite classes show variability in bulk compositions between individual analyses. Some of this spread is intrinsic to the parent bodies of the meteorites. However, some variability is undoubtedly due to systematic uncertainties, caused by inter-laboratory bias, misclassification, effect of weathering, and unrepresentative sampling. We use the database here to investigate both how well different meteorite groups can be distinguished on the basis of bulk compositions and how bulk compositions can be related to the cosmochemical and geological processes that produced them. The major elements measurable by X-ray and gamma-ray remote-sensing—oxygen, magnesium, aluminum, silicon, sulfur, calcium and iron—reflect to differing degrees nebular elemental fractionations and parent-body igneous processes and can be used together to distinguish most classes and sub-classes of meteorites. Potassium is potentially useful as a tracer of thermal processes in the early solar system. Thorium and uranium abundances could be used to trace igneous processes on differentiated asteroids.

key words: chemical compositions, remote-sensing, meteorite classification

1. Introduction

Since the inception of meteoritics as a scientific discipline, chemical analyses have played a key role in understanding the origin and evolution of these extraterrestrial

rocks and the relationships between the diverse array of meteorites now held in the world's collections. Widespread acceptance of the extraterrestrial origin of meteorites stemmed in large part from the occurrence of observed meteorites falls such as those in Siena and L'Aigle in the late 18th and early 19th centuries and their analyses by the most prominent chemists of the period. The differences in chemical compositions between meteoritic and terrestrial rocks and the similarities between meteorites recovered in widely separated regions led credence to the proposed extraterrestrial origin (Sears, 1975).

Classical wet chemical analyses of major and minor elements has long been a staple of meteoritics (Jarosewich, 1990). Urey and Craig (1953) separated H and L chondrites on the basis of "superior" chemical analyses, setting the stage for the idea of separate parent bodies for these two groups of ordinary chondrites. Since the 1960s, many new analytical techniques have become available, allowing us to determine a broader range of elements in much lower concentrations in smaller samples. Today, the majority of new geochemical data on meteorites is for trace elements at the level of parts per billion to million, often on single mineral grains. Yet, as we enter a new era in space exploration, we find that many of our new geochemical data for planetary bodies (*e.g.*, Moon, Mars, and asteroids) are limited to major elements that can be measured remotely. For this reason, there is renewed interest in bulk major element compositions of meteorites.

To prepare for the analysis of geochemical data from the Near Earth Asteroid Rendezvous (NEAR)-Shoemaker mission to the asteroid 433 Eros, we compiled a large database of bulk compositions of meteorites. This database (and an associated graphical user interface developed to allow easy access and manipulation of the data) proved extremely useful in interpreting the elemental data returned by the NEAR-Shoemaker X-ray (XRS) and γ-ray (GRS) spectrometers (Trombka *et al*., 2000; Evans *et al*., 2001; Nittler *et al*., 2001). We believe it has great potential utility for future asteroid and planetary missions as well, including HAYABUSA (formerly MUSES-C; Fujiwara *et al*., 1999), DAWN (Russell *et al*., 2003), and MESSENGER (Solomon *et al*., 2001). Meteorite classification in the laboratory is based on a number of complementary observations (composition, mineral abundances and compositions, petrography, *etc.*). A critical question for remote-sensing experiments is how well different groups can be distinguished from one another, based solely on their bulk major-element compositions. This depends not only on differences in average composition but also largely on the scatter observed between individual meteorites of a given group. The database described here helps both to answer this question and to relate bulk compositions of meteorites to the underlying cosmochemical and geochemical processes which led to compositional variability.

Here, we describe our compositional database and illustrate its utility for interpreting remote-sensing geochemical data. With the exception of our NEAR-Shoemaker papers, we are not aware of any prior work comparing bulk major abundances for all meteorite classes side-by-side and relating them to cosmochemical and geologic processes. Thus, this paper also serves a pedantic purpose for planetary scientists by illustrating the relationships of different meteorite classes to each other. Because the main purpose of this work is to provide "ground truth" for spacecraft observations, we

include a brief discussion of the spacecraft measurements themselves and associated uncertainties (Section 3). The reader is referred to papers for specific missions for additional details (*e.g.*, Trombka *et al.*, 1997; Evans *et al.*, 2001; Nittler *et al.*, 2001; Okada *et al.*, 2002; Russell *et al.*, 2004).

2.   The database

The primary goal of compiling this database was for direct comparison with the chemical composition of 433 Eros from the NEAR X-ray/γ-ray spectrometers. Similar instruments are being flown on the HAYABUSA mission to the near-earth asteroid 25143 Itokawa (X-ray), the SMART-1 mission to the Moon (X-ray), the DAWN mission to the large asteroids 4 Vesta and 1 Ceres (γ-ray), and the MESSENGER mission to Mercury (X-ray and γ-ray). These instruments sample the composition of planetary surfaces at depths ranging from less than $100\,\mu$m (X-ray) to ~10 cm (γ-ray); the spatial resolution depends on the instrument and orbital characteristics, but was ~2–3 km for the NEAR XRS. Elements that can be measured include Si, Al, Mg, S, Ca, Fe, O and K and, depending on their abundance, possibly Ti, Cr, Mn, H, U and Th. For this reason, we have primarily limited our database to these elements, plus a small number of other minor elements (*e.g.*, Ni, Na, P) that are routinely measured during bulk chemical analyses of meteorites. All elements except Th and U are reported as weight percent of the element and elemental ratios are weight percent ratios. Th and U abundances are reported as ng/g.

The database is freely obtainable from the authors (as a comma-separated-variables file) and contains ~2800 analyses of >1000 distinct meteorites taken from >200 published references. The references report data from 48 different laboratories utilizing at least 9 methods for bulk chemical analyses. The majority of these data was acquired using standard wet-chemistry techniques (*e.g.*, Jarosewich, 1990; Yanai and Kojima, 1995) and neutron activation (*e.g.*, Kallemeyn *et al.*, 1989). We do not repeat the details of these analyses here, but complete references are available in the database. We note that many of our data are taken from large compilations, including those of Wiik (1956), Haramura *et al.* (1983), Jarosewich (1990), Yanai and Kojima (1995), Mittlefehldt *et al.* (1998) and Garrison *et al.*, (2000). In addition, G.W. Kallemeyn generously provided a compilation of neutron-activation chondrite data that has been published in a series of papers on the compositional classification of chondrites (*e.g.*, Kallemeyn *et al.*, 1989). In several cases, data were corrected for errors in transcription (*e.g.*, original references to compilations), conversion (*e.g.*, oxide to element) or calculation (*e.g.*, modes and mineral chemistries combined to determine bulk chemistry; Buseck, 1977).

In compiling this database, we tried to include as many data from the peer-reviewed literature as possible. We specifically avoided making value judgments on the quality of data from specific analysts or institutions (as was demanded by a reviewer of an earlier version of this paper) for inclusion in the overall database. Such categorical judgments are beyond our expertise and would remove from consideration most of the extant data for some rare meteorite classes. However, as discussed below, we did make judgments as to which data from the database to include in our plots and discussion here. By

making the database all-inclusive, other researchers will be able to use their own judgment, informed by their own knowledge and experience, as to which data to consider for a specific application.

In deciding the best way to compare the chemical composition determined by spacecraft to recovered meteorites, we considered the option of using group averages (with 1 or 2 sigma standard deviations) or envelopes representing the range of the data for individual groups. In the end, the general consensus was that the best comparison is between data plotted for individual meteorites and 433 Eros. This allows the reader to view both the full range of compositions present in the group and the distribution of points within that range.

A large database is only as useful as the tools used to extract and manipulate data from it. We have also developed a custom software package for interfacing to the meteorite composition database, written in the IDL programming language (Research Systems, Inc.). This interface is freely available from the lead author (though it requires an IDL license). It allows easy access to and manipulation of the database, including tools for extracting sub-sets of data (*e.g.*, meteorite classes, fall versus find, ...), performing statistical analyses, and producing publication-quality plots (scatter and histogram). A point-and-click feature allows the user to select individual data points from a plot and have displayed the meteorite name, chemical analyses, type of analyses, laboratory and literature reference. This allows the user to quickly assess any outlier data points for suitability for the intended purpose.

3. Spacecraft planetary abundance measurements

Three methods are in common use for remotely determining elemental abundances from planetary and asteroidal surfaces: X-ray (XRS), γ-ray (GRS), and neutron spectrometry. Both XRS and GRS were used on the NEAR-Shoemaker mission to Eros. In XRS, X-rays emitted by high-temperature plasma in the Sun's corona interact with the planetary surface, inducing fluorescent X-ray emission with energies characteristic for the elements present. The fluorescent X-rays are produced in the top $100\,\mu$m and are detected by an orbiting spectrometer, together with solar X-rays scattered from the surface. Gamma-rays (~1–10 MeV) and neutrons are produced in the top several tens of cm of planetary surfaces by cosmic-ray interactions with constituent nuclei. Gamma-rays are also emitted by decay of naturally occurring radioactive isotopes.

In principle, any element with characteristic X-ray emission in the energy range of an orbiting XRS should be detectable, but in practice detection limits are set by several factors, including detector background and counting statistics. Moreover, quantification of X-ray spectra is complicated by a rapidly changing and uncontrolled excitation source (the Sun) and the lack of standards. The NEAR XRS included a solar-pointing detector in order to record the solar X-ray spectrum simultaneously with spectra from Eros. Unfortunately, the efficiency of this solar monitor was not accurately determined prior to launch, making accurate quantification of the X-ray spectra difficult. Nonetheless, Nittler *et al*. (2001) performed a detailed analysis of spectra acquired during five solar flares and two long integrations under more quiescent solar conditions to determine average Mg/Si, Al/Si, S/Si, Ca/Si and Fe/Si ratios for Eros. The uncertainties

on these ratios (illustrated on Figs. 7 and 9), based on counting statistics and estimated systematic uncertainty from deconvolving solar spectra, are relatively large (~10–30%, 1σ). Moreover, grain size effects and regolith processing could potentially introduce additional systematic uncertainty, especially for Fe/Si ratios. Despite the large errors, the NEAR XRS data were still of sufficient precision and accuracy to indicate un-ambiguously that Eros is a primitive undifferentiated body, with an average surface composition similar to ordinary chondrites (except for a depleted S/Si ratio, probably due to surface space weathering). However, systematic uncertainties have thus far precluded investigation into surface elemental heterogeneity, despite the ~3 km spatial resolution of the NEAR XRS.

It is expected that XRS instrumentation on current and future missions will provide more accurate and precise element data from planets and asteroids than were obtained by the NEAR XRS, due both to improvements in instrument design and to more favorable orbital conditions. For example, the XRS on the MESSENGER mission to Mercury should have a higher signal-to-noise ratio (R. Starr, pers. comm.) than the NEAR instrument and will greatly benefit from the close proximity to the Sun and hence higher flux of solar X-rays. The XRS on the Hayabusa mission to asteroid 25143 Itokawa has several potential advantages over NEAR, including higher energy resolu-tion, a lower background detector, and an onboard standard for quantification (Okada *et al*., 2002).

Gamma-ray spectroscopy can in principle provide compositional information for most rock-forming elements, including O, Si, Mg, Al, Fe, Ti, and Ca, as well as radioactive, K, Th and U. Neutron spectrometry is sensitive to H and C. Unfortu-nately, for a number of reasons (Trombka *et al*., 2001), the signal-to-noise ratio for the NEAR-Shoemaker GRS was far less favorable than expected, with the result that no compositional data have to date been derived from GRS spectra obtained during the year of orbital measurements. However, following a controlled descent to the surface of Eros at the end of the mission, about seven days of high signal-to-noise ratio GRS data were obtained from the surface. Evans *et al*. (2001) derived Fe, Si, O and K abundances from these data, albeit with large errors (~40%). The GRS-derived K abundance and Si/O ratio are consistent with Eros having an ordinary chondrite composition, but the Fe/Si ratio is much lower than that found by the XRS (Nittler *et al*., 2001). Because the XRS and GRS data were obtained on very different spatial scales (global average *versus* a single $< 1\,m^3$ spot, respectively), it is difficult to compare them. Evans *et al*. (2001) favored an explanation for the Fe/Si discrepancy based on physical separation of metal from silicates at the NEAR landing site, perhaps due to electrostatic levitation of fine-grained silicate dust on the asteroid (Robinson *et al*., 2001).

The DAWN mission will visit the asteroids Vesta and Ceres early in the next decade and the spacecraft will include a γ-ray spectrometer (Russell *et al*., 2004) for determin-ing surface element composition. The DAWN GRS is an improved version of the GRS on Lunar Prospector, which was highly successful in mapping elemental abundances on the Moon (*e.g*., Lawrence *et al*., 2002). It is anticipated that this instrument will provide high-precision abundance measurements of all of the elements listed above from the two asteroids, with hemispheric spatial resolution (Russell *et al*., 2004). The

uncertainties in ratios such as Mg/Si, Al/Si and Fe/Si are predicted to be smaller than those derived for the NEAR XRS data from Eros.

An important question is how much elemental heterogeneity might be expected on asteroids on spatial scales resolvable by orbiting X-ray and/or γ-ray spectrometers. *A priori*, one would expect a primitive, chondritic asteroid to be relatively uniform in composition. As shown in Section 4, individual meteorites from a given chondrite group do show elemental heterogeneity, leading to some blurring of group distinctions on element abundance plots. Some of this heterogeneity is undoubtedly real. However, this heterogeneity is observed in the laboratory on a spatial scale of cm (typical of individual chondrites) or smaller and would likely be averaged out when considering km-sized regions of a chondritic asteroid. Even an initially uniform chondritic asteroid could obtain surface element heterogeneity, however, from regolith processing (*e.g.* physical separation of metal from silicates) and/or from impact mixing of different materials. Igneous differentiation processes on asteroids could lead to significant compositional km-scale heterogeneity. McCoy *et al*. (2000) argued on the basis of bulk compositions, mineralogies and isotopic compositions of the acapulcoite and lodranite meteorites that a partially melted and differentiated asteroid could have significant chemical heterogeneity on a scale >200 m. A fully differentiated asteroid like Vesta might be expected to be even more heterogeneous, given the broad range of compositions of eucrites, howardites and diogenites, all believed to have originated on this asteroid (Drake, 2001). On the other hand, regolith processing could in principle erase surface heterogeneities by mixing materials from different regions. Clearly, the question of the spatial homogeneity of asteroids cannot be definitively answered without direct spacecraft measurements.

4. Meteorite groupings and processes

We focus our discussion on using the bulk compositions of these meteorites to (1) determine how well different groups of meteorites can be distinguished on the basis of both element-element and element ratio-element ratio plots and (2) investigate the extent to which the range of bulk chemistries can be related to the cosmochemical and geologic processes that are known to produce them from decades of detailed laboratory and theoretical research. Our goal is not to provide a comprehensive review of meteorite element compositions. We recognize that many of our interpretations rest on existing understanding of meteorite petrogenesis. Much of this work has been reviewed in the Planetary Materials book (Papike, 1998), which incorporates major element chemistry as part of a synthetic approach to unraveling meteorite origins. In this work, we focus our attention on a few elements that best illustrate the broad scope of the database and its utility for our purposes. The plots and discussion presented here only scratch the surface of the wealth of data contained within the database itself.

4.1. Caveats and cautionary notes

Because the database is designed to be all-inclusive, it contains a comprehensive compilation of meteorite compositions, including ones that are aberrant for the classification given. Such anomalies can result from a number of factors, including mis-

classification of a meteorite (*e.g.*, an L chondrite mislabeled as an H), analysis of an unrepresentative small mass, unreliable chemical analyses, or extreme weathering of a meteorite. Chemical analyses of meteorites are complex and differences between the results from different analysts, laboratories and analytical techniques can be attributed to systematic errors. Unfortunately, there have been very few systematic inter-laboratory comparisons of the quality of chemical data for meteorites, with the exception of an Allende meteorite powder (Jarosewich *et al.*, 1987). In that study, the data for bulk chemical analyses, particularly those done by classical wet chemical methods, were in close agreement. In a smaller study of separate samples of the Leedey meteorite (McCoy *et al.*, 1997), four analyses from separate laboratories showed significant discrepancies, primarily for sulfur and metallic iron. These differences were attributed to sampling. The lack of representative sampling, both in the analysis of unrepresentatively small samples and in the inadequacy of sampling representative proportions of silicate, metal and sulfide, is the major cause of disagreement between analysts. The amount of material required for a representative sample for chemical analysis is a complicated issue and depends both on the concentrations of elements of interest and on the detailed mineralogical makeup of the rock (*e.g.*, grain sizes of different phases, spatial correlations of minerals, *etc.*; see Haas and Haskin, 1991 for a good discussion). Unfortunately, most of the analyses cited in our database do not have accompanying information about the size of the sample powdered or of the aliquot of that powder actually analyzed, so it is difficult to assess sampling errors from a purely sample size point of view.

     Several of these issues can be illustrated using our database.   An excellent example of inter-laboratory bias is illustrated by Figs. 1 and 2, which show Fe plotted *vs.* Mg for H, L and LL chondrites analyzed by E. Jarosewich (Smithsonian Institution; Jarosewich, 1990) and H. Haramura (NIPR; Haramura *et al.*, 1983; Yanai and Kojima, 1995).   These data were obtained using similar but not identical wet-chemical techniques.   Although the data largely overlap, it is apparent that the Jarosewich (1990) data are systematically offset to lower Fe and Mg concentrations than that of Haramura *et al.* (1983) and Yanai and Kojima (1995) for both meteorite finds (Fig. 1) and falls (Fig. 2).   The compositions of Jarosewich (1990) also exhibit a systematic enrichment in Si (less than 1 wt%) relative to those of Haramura *et al.* (1983) and Yanai and Kojima (1995).   Differences in analytical technique are probably responsible, although the exact cause remains uncertain.

     A meteorite's composition can be altered by weathering after it falls.   Considering the Jarosewich (1990) data in Fig. 2, it is apparent that the H, L and LL chondrite finds exhibit significantly greater scatter and tend towards lower Fe and Mg concentrations than fresh falls of the same groups.   Indeed, while data for falls clearly distinguish H and L chondrites, this compositional gap is somewhat blurred if finds are considered. The tendency for finds to exhibit greater scatter probably results from the weathering of metal, sulfides and silicates, in approximately that order, and the associated hydration of the meteorites.   Note that there is no systematic difference in major element abundances between the Antarctic and non-Antarctic finds analyzed by Jarosewich (1990), despite the expectation that Antarctic meteorites experience less terrestrial weathering than other finds.   Moreover, the clear difference between the Jarosewich and Haramura
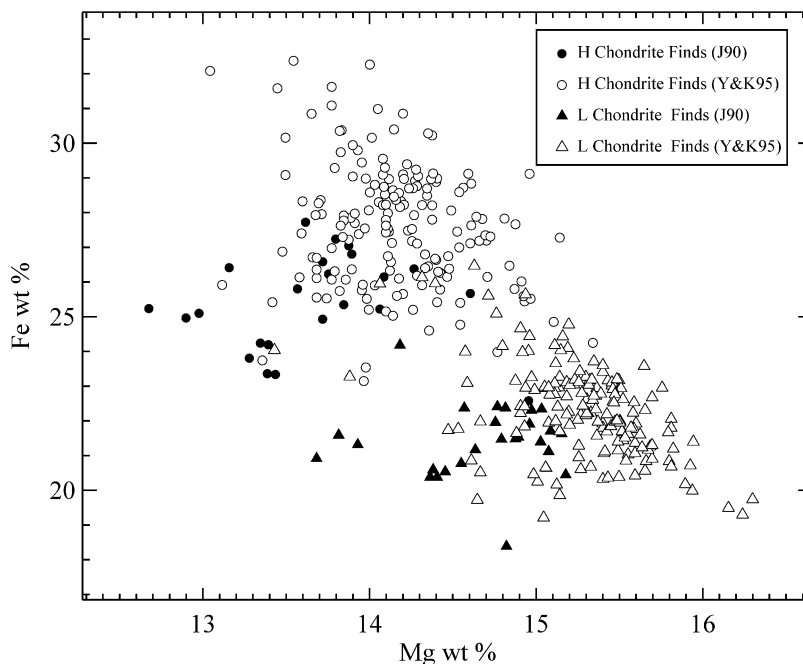
Fig. 1. *Fe and Mg abundances, plotted for H and L chondrite finds. Filled circles are data from Jarosewich (1990), unfilled circles from Yanai and Kojima (1995), both obtained using similar wet chemistry techniques. Note the systematic offset between Mg (~1%) and Fe (~3%) abundances for both H and L chondrites between the two laboratories. Evidently, inter-laboratory biases may account for much of the variation between analyses of meteorites in the same subclasses, and must be taken into account when attempting to ascertain intrinsic variations.*

data for H and L meteorite falls indicates that the differences in data between these two laboratories is not due to differences in terrestrial weathering (*e.g.*, differences in terrestrial residence ages between the Yamato and US Antarctic meteorite collection sites). On subsequent plots in this and other papers (*e.g.*, Trombka *et al*., 2000; Nittler *et al*., 2001), we have chosen to include only data for ordinary chondrite falls analyzed by Jarosewich (1990). These falls provide (1) a clearer sense of the intrinsic range of compositions of these groups, (2) a better comparison to airless planetary bodies, which are obviously unaffected by terrestrial weathering, and (3) adequate statistical representation of their groups, given the significant number of analyses. Exclusion of the data of Haramura *et al*. (1983) and Yanai and Kojima (1995) simply reflects that nearly their entire databases are finds from Antarctica. We do include data from these researchers when discussing meteorites other than ordinary chondrites.

Compositional differences arising both from the use of different techniques and from sample heterogeneity are apparent in Fig. 3, which plots Fe *vs*. Mg for seven analyses of the Acapulco meteorite and ten analyses of other acapulcoites. These analyses show a broad range of compositions, varying by nearly 8 wt% (~35% relative) in Fe and 2 wt% (~13% relative) in Mg. These seven analyses are from four separate
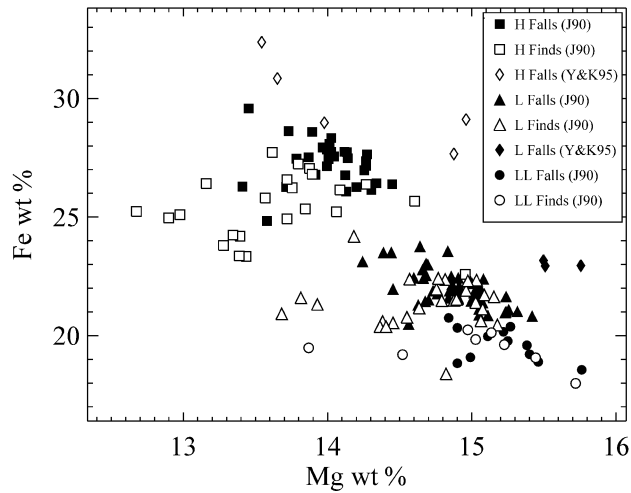
Fig. 2. *Fe versus Mg abundances for H, L, and LL chondrite finds and falls. Most data were obtained by a single analyst (Jarosewich, 1990), but a few H and L falls analyzed by Haramura (Yanai and Kojima, 1995) are also shown.   Despite a high degree of overlap, there is a small systematic loss of Mg and Fe in meteorite finds, due to terrestrial weathering.   Finds also show a somewhat greater degree of scatter than fresh falls.   Note that the systematic differences between falls and finds analyzed by Jarosewich (1990) and shown here are smaller than that for the finds analyzed in two different laboratories shown in Fig. 1.*
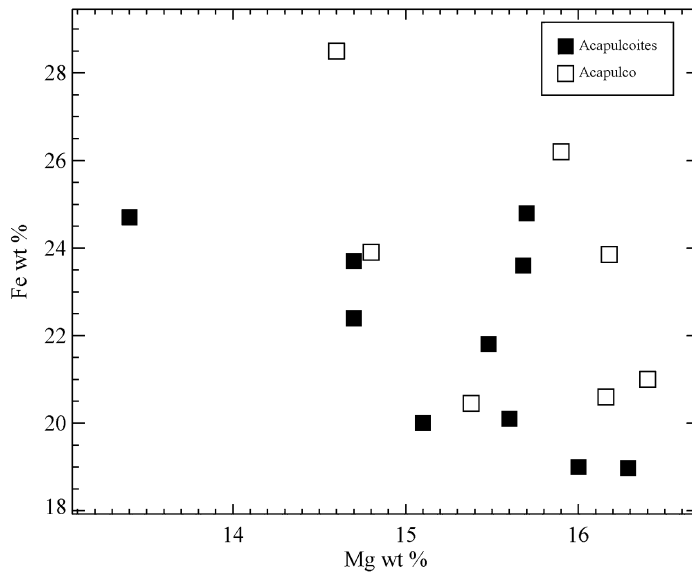
Fig. 3. *Fe and Mg abundances of several acapulcoite samples, including seven separate analyses of the Acapulco meteorite.   The range of reported compositions is probably due to inter-laboratory bias and sampling errors, in addition to intrinsic variability of this class of primitive achondrites.*

sources (Palme *et al.*, 1981; Kimura *et al.*, 1992; Yanai and Kojima, 1995; Zipfel *et al.*, 1995), three of which reported replicate analyses.   The differences between replicates of a single author were substantially less (up to 2.9 wt% Fe and 1.6 wt% Mg) than the differences between analysts.   This suggests that both sample heterogeneity and inter-laboratory bias are contributors to this range of compositions.   In this case, the range of compositions shown for Acapulco rivals that for the entire acapulcoite group.   Thus, determining a single, representative analysis for a meteorite, especially a metal-rich one, can prove difficult.

4.2.   Fe-Mg systematics

Iron and magnesium are two of the most useful major elements to determine both meteorite groupings and geologic processes.   Their concentrations within mafic silicates vary systematically throughout the solid solution series (*e.g.*, fayalite to forsterite, enstatite to ferrosilite).   Magnesium is partitioned solely into mafic silicates in most meteorites, while iron occupies a variety of valence states and occurs in mafic silicates, metal and sulfides.   Urey and Craig (1953) first used the concentration of total iron to delineate chondrite groups.

Chondritic meteorites exhibit a range of iron (~18–34 wt%) and magnesium (~8–16 wt%) concentrations (Fig. 4).   Ordinary chondrites exhibit a trend of decreasing magnesium with increasing iron in the order LL→L→H, although some scatter exists within these groups.   (Note that some care must be taken when considering absolute
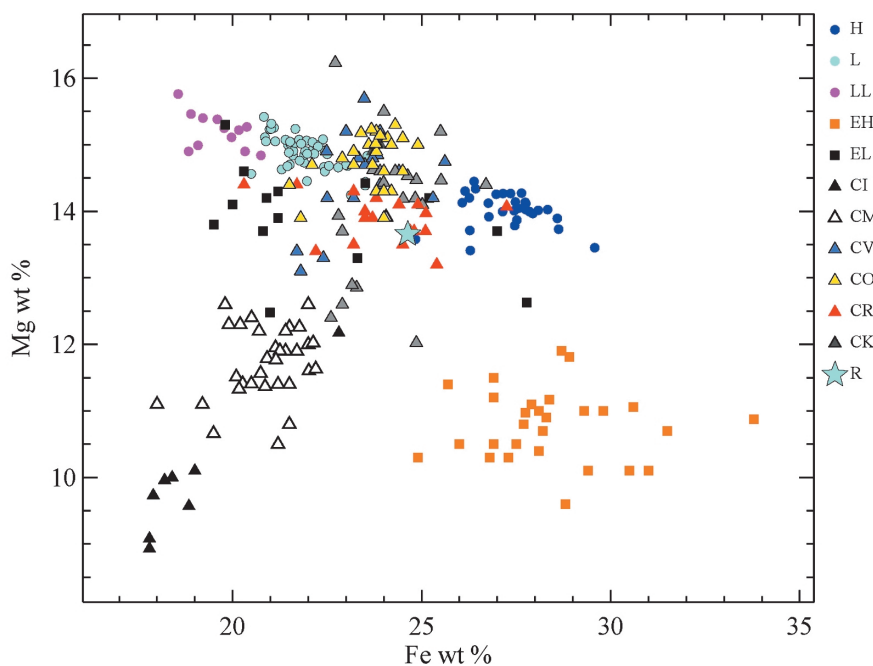

Fig. 4.   Plot of Fe-Mg systematics in major classes of chondrites.   Systematic differences between classes are apparent, though there is significant overlap between several classes.

abundances, as opposed to abundance ratios. Much of the change in the Mg along this sequence is due to the need to measure abundances in relation to the total mass of a rock: as the wt% of Fe goes up, the fractional abundances of other elements must go down. In fact, the Mg/Si ratio is basically identical for L and LL chondrites, but slightly higher for H chondrites.) Carbonaceous chondrites exhibit a trend of increasing Mg concentration with increasing Fe concentration in the sequence CI→CM→CR≈CO≈CV≈CK. This trends reflects both changes in modal mineralogy and the decrease in water content from CI to CM to the dominantly anhydrous carbonaceous chondrite groups. The latter point is supported by the general trend of increasing H concentration with decreasing Mg concentration in the same sequence. Not surprisingly, EH chondrites have higher Fe and lower Mg abundances than do EL chondrites, reflecting higher metal and/or sulfide abundances in EH compared to EL chondrites. The only R chondrite in our database, Rumuruti (E. Jarosewich, unpublished data), plots within the range of H and CR chondrites.

If we expand our view to include the achondrites (Fig. 5), the picture becomes somewhat more complex. The basaltic-pyroxenitic suite of rocks sampled by the howardites, eucrites and diogenites occupy a region at lower Fe concentrations than chondrites and with a broad range of magnesium concentrations. Several primitive
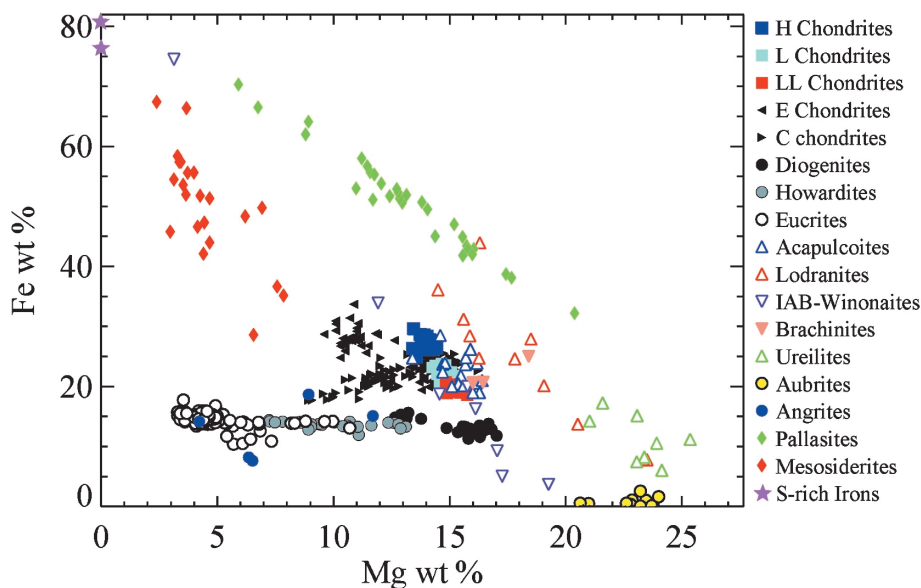

Fig. 5. *Fe and Mg abundances from a wide range of meteorite classes and sub-classes. Most classes have distinctive characteristics, and can be clearly distinguished from each other and from chondritic classes. Basaltic achondrites (diogenites, howardites, eucrites and angrites), have distinctively low Fe and variable Mg. Irons, mesosiderites, and pallasites have distinctively higher iron abundances. The stony-irons fall along linear trends indicating metal-silicate mixing. Primitive achondrites that are depleted in plagioclase (e.g., lodranites) plot outside of chondritic compositions, whereas others (e.g., Acapulcoites) have approximately chondritic compositions. Generally, E and C chondrites are distinguishable from ordinary chondrites (H, L, LL).*

achondrites, including the winonaites and silicate inclusions in IAB irons, acapulcoites and brachinites plot near the chondrites. Plagioclase-depleted rocks thought to sample residues of partial melting (*e.g.*, ureilites, lodranites, aubrites) have generally lower Fe and higher Mg. Mesosiderites and pallasites stretch along distinct trends towards a high Fe and low Mg metallic iron end member.

The compositions of these groups can be easily understood in the context of geologic processes that have operated on asteroids (Fig. 6). Rocks of broadly chondritic composition (not distinguishing between E, O and C chondrites) were almost certainly the precursors to the groups of igneous meteorites. Very low degrees of partial melting (less than a few %) most likely produced the primitive achondrites (acapulcoites, winonaites) with roughly chondritic compositions, whereas higher degrees of melting produced a range of partial melts and residues (Mittlefehldt *et al.*, 1998; and references therein). These include (1) an Fe- and Mg-poor silicate partial melt depleted in metal, rich in feldspar and with FeO-rich silicates (eucrites, angrites), (2) an Fe, Ni-FeS partial melt (troilite-rich iron meteorites), and (3) plagioclase-depleted residues rich in Mg and with a range in iron depending on the concentration of residual metal and composition of the mafic silicates (ureilites, lodranites). Fractional crystallization of silicate partial melts produces silicate-dominated rocks enriched in Mg relative to the host, such as the diogenites and possibly the aubrites. Other groups owe
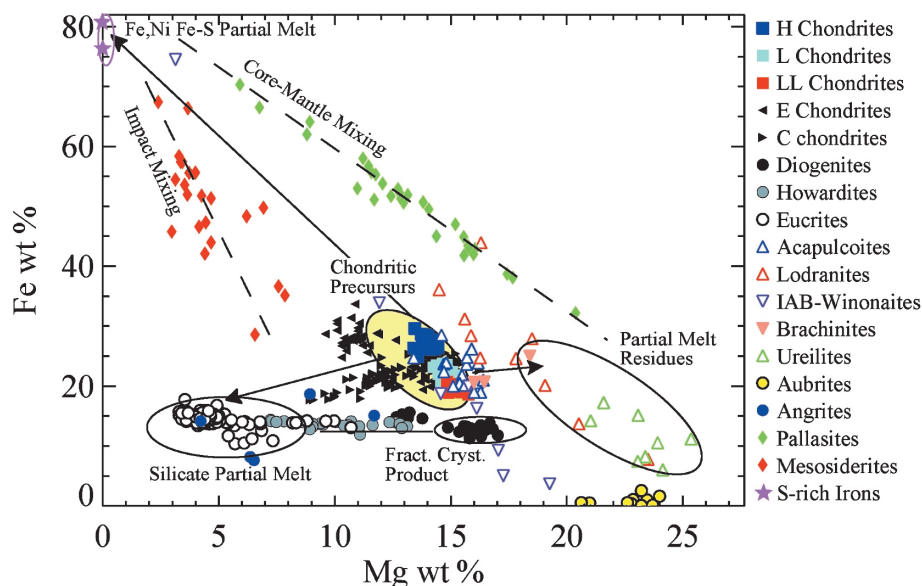

Fig. 6. *Trends resulting from geochemical processes superimposed on Fe-Mg plot of Fig. 5. Starting with chondritic precursors (central ellipse), varying degrees of silicate partial melting, melt segregation and fractional crystallization result in the production of basaltic achondrites (diogenites, howardites, eucrites, and angrites) and primitive achondrites (e.g., acapulcoites, lodranites, ureilites, winonaites). Physical mixing processes of metallic Fe-Ni and silicates result in the stony iron compositions (e.g., mesosiderites, pallasites). Fe,Ni-FeS partial melts and asteroidal cores are represented by S-rich iron meteorites.*

their composition primarily to mixing between these or similar lithologies and metal, such as the mesosiderites (mixtures of metal and basalts or pyroxenites) and the pallasites (olivine-metal mixtures).   That these various processes produced the various meteorite classes is well-established in the literature, but it is interesting how clearly this can be seen on a plot of just two major elements (Fig. 6).   Thus, bulk compositions of remotely-sensed asteroidal lithologies can in principle provide not only relationships to known groups of meteorites, but also insights into the underlying geologic processes that formed those lithologies.
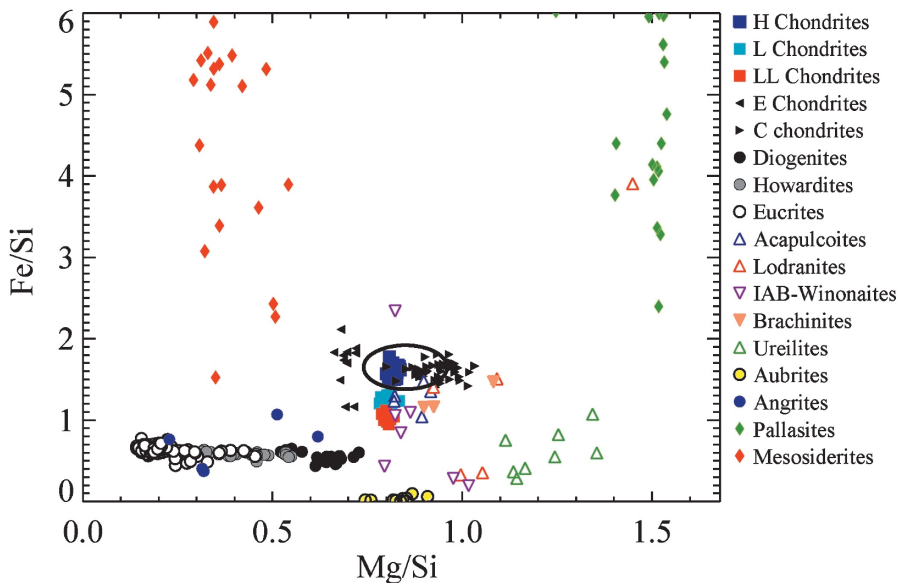

Fig. 7.   Plot of Mg/Si versus Fe/Si ratios for meteorite samples representing major classes.   The various meteorite groups plot largely in the same relative regions of the plot as they do in Figs. 5 and 6.   One exception is the mesosiderites and pallasites that now form vertical lines, owing to their relatively constant silicate compositions.   The ellipse indicates the one-sigma errors of the composition of asteroid Eros, measured by the NEAR-Shoemaker X-ray spectrometer (Nittler et al., 2001).

It is common practice in meteorite studies to consider element ratios, rather than absolute abundances and this is preferable for remotely-sensed spacecraft data as well (Nittler *et al*., 2001).   Figure 7 includes the same meteorites plotted in Figs. 5 and 6, but for Mg/Si *vs*. Fe/Si weight ratios.   In large part, the various groups populate the same relative regions of the plot as before.   Notable exceptions are the trends defined by the mesosiderites and pallasites, which now exhibit nearly uniform Mg/Si ratios but with large ranges in Fe/Si.   Varying the mafic silicate compositions can cause large shifts in Mg/Si and small shifts in Fe/Si (*e.g.*, the ureilites), while varying the metal abundance causes pronounced ranges in Fe/Si with small ranges in Mg/Si (*e.g.*, mesosiderites and pallasites).

4.3. O-Fe-Si systematics

Oxygen is the most abundant element by weight in all stony meteorites, but it is very difficult to accurately determine using standard chemical analysis techniques.   Thus, in most discussions of meteorite abundances, it is determined by difference and reported combined with other elements as oxides.   The bulk abundance of O can be determined by remote-sensing gamma-ray spectroscopy, however.   Thus, it is instructive to examine the variability of O between meteorite classes.   Figure 8 shows Fe/Si and O/Si ratios for different meteorite groups; all three of these elements can be determined for asteroid surfaces using remote-sensing gamma-ray spectrometry (Trombka *et al*., 1997; Evans *et al*., 2001).   Note that although a few of the plotted O values were directly determined, most were determined by difference; only analyses which included both FeO and total Fe were used for the difference calculation.   Because totals for these analyses are usually close to 100%, the uncertainties on the difference-determined O abundances should be relatively small.   For example, the standard deviation of O abundances determined for the H chondrites of Jarosewich (1990) is 2.3% relative, indicating that the uncertainty is no greater than this.

Most meteorites have O/Si ratios between those of pure pyroxene (1.7) and olivine (2.3).   The only meteorites with higher O/Si ratios are CI and CM chondrites; the excess O in these is carried by water of hydration.   Mesosiderites, pallasites and enstatite meteorites (aubrites and E chondrites) plot along vertical lines corresponding to mixing of metal and a constant silicate composition.   In contrast, the relatively large
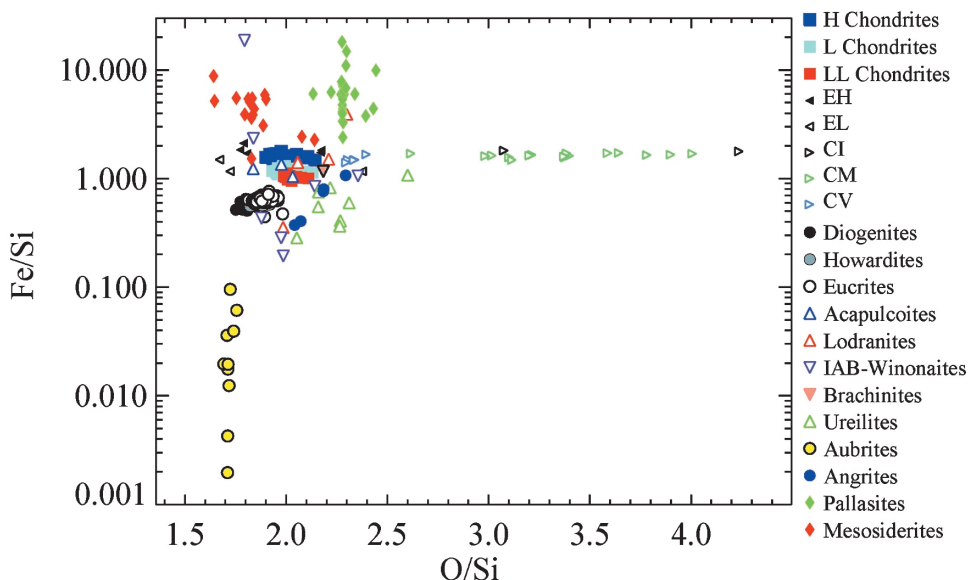

Fig. 8.   Plot of O/Si versus Fe/Si ratios for meteorites from major classes and sub-classes.   Most meteorites have O/Si ratios between those of olivine and pyroxene; exceptions are the CM and CV chondrites which contain significant water.   Constant O/Si ratios and varying Fe/Si ratios reflect metal-silicate mixing (e.g., pallasites), whereas variable O/Si ratios reflect varying silicate abundances or compositions.

range in both Fe/Si and O/Si ratios for ureilites and winonaites probably reflects variations in silicate compositions, in addition to metal-silicate mixing.

4.4.   Al-Mg-Ca systematics

Chondrites exhibit low Al concentrations, ranging from ~0.7–2 wt% (Al/Si~0.045–0.19).   Ordinary and enstatite chondrites are essentially indistinguishable on the basis of Al contents and Al/Si ratios.   Carbonaceous chondrites are slightly more Al-rich on average than other chondrite groups, but there is some overlap between individual meteorites from the different groups.   Moreover, the low absolute abundance makes it difficult for spacecraft data to accurately distinguish chondrite groups on the basis of Al. However, the Al-Mg system is quite useful for tracking partial melting and melt migration, as aluminum is hosted almost exclusively in plagioclase and magnesium almost exclusively in mafic silicates in meteorites.

Both Mg/Si and Al/Si show a broad range when all meteorite groups are considered (Fig. 9).   Most apparent is the presence of high Al, low Mg basalts, including the eucrites, howardite and angrites.   Interestingly, the mesosiderites are indistinguishable from the eucrites and howardites on this plot, despite having lower absolute Mg and Al, since the Si normalization negates the metallic component of these meteorites (they are clearly distinguished on Fig. 7, however).   At low Al/Si are groups depleted in plagioclase, including pallasites, lodranites, ureilites, aubrites and diogenites.   From a petrogenetic viewpoint, this diagram nicely discriminates silicate partial melts (e.g.,
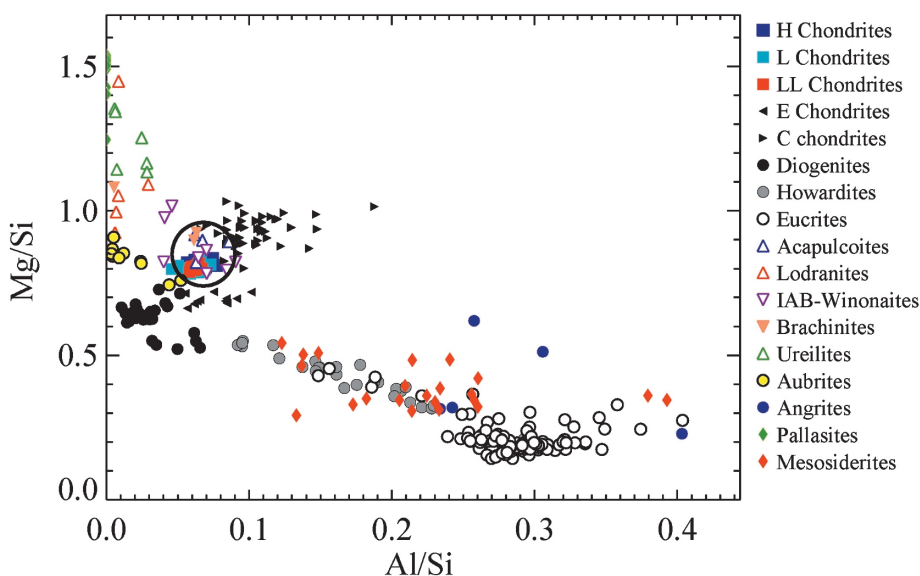

Fig. 9.   *Mg and Al systematics of major meteorite classes and sub-classes.   This plot discriminates well between silicate partial melts (e.g., eucrites) and residues of partial melting (e.g., ureilites, lodranites) as well as between pyroxene-rich groups (diogenites, aubrites) and olivine-rich groups (lodranites, ureilites, pallasites).   The ellipse indicates the one-sigma errors of the composition of asteroid Eros, measured by the NEAR-Shoemaker X-ray spectrometer (Nittler et al., 2001).*

eucrites, angrites) from residues of partial melting (*e.g.*, ureilites, lodranites). More-
over, at the low Al/Si end, the plot also distinguishes the pyroxene-rich groups
(diogenites, aubrites) from the olivine-rich groups (lodranites, ureilites, pallasites),
owing to the much lower Mg/Si ratio in orthopyroxene compared to olivine.

Calcium has a very similar abundance to Al in most meteorite groups, and a plot of
Mg/Si *versus* Ca/Si is very similar to Fig. 9. Thus, the above discussion applies also to
Ca. We note that Nittler *et al*. (2001) also used the Fe/Ca ratio measured by X-ray
spectrometry to help pin down elemental abundances on Eros.

4.5. Mg-S systematics

Sulfur can play an important role in tracing the geologic history of asteroids, since
it is a major component of the Fe, Ni-FeS cotectic melt that forms at ~1000°C as the first
melt in a chondritic system (Kullerud, 1963). To examine the distribution of S in
various types of meteorites, we utilize the Mg/Si-S/Si system (Fig. 10). While ordi-
nary chondrites have a relatively restricted range of S concentrations around 2 wt% (S/
Si~0.1), carbonaceous and enstatite chondrites exhibit a broad range of S concentrations
from less than 1 to nearly 8 wt% (S/Si~0.05–0.4). As we have seen earlier for other
elements, a number of the primitive achondrite groups, including acapulcoites,
winonaites and brachinites have essentially chondritic abundances of both S and Mg.
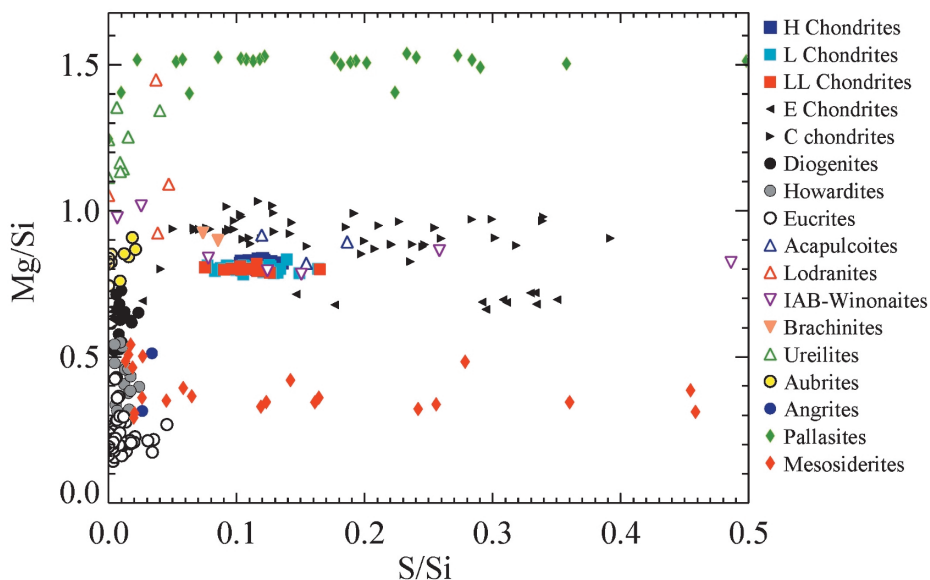In contrast, groups that have experienced significant degrees of melting have low S

Fig. 10. *Mg/Si and S/Si abundance ratios in a wide range of meteorite classes. Sulfur is a good
tracer of igneous processes since it concentrates in early partial melts. Basaltic achondrites
and many classes of primitive achondrites have low S abundances, relative to chondrites,
reflecting loss of an immiscible S-rich metallic melt from silicate melts and residues. The
ordinary chondrites are clearly distinguished from other chondrite groups and separation of
stony irons (e.g., mesosiderites) from other classes is also possible.*

abundances, reflecting efficient separation of the immiscible S-rich metallic melt from the silicate melts and residues.   Important exceptions are the silicate-bearing IAB irons, pallasites and mesosiderites.   Each of these groups plots on horizontal (constant Mg/Si) mixing lines between a low-S component (high-Mg in the case of pallasites, low-Mg for mesosiderites) and a high-S component-the metallic host present in these groups.

4.6.   *Minor and trace element systematics*

Although our database primarily contains major element data, we have included abundances for K, U and Th, since these elements have naturally occurring radioactive isotopes and can be detected by gamma-ray spectroscopy if they occur in sufficient abundances (Fichtel and Trombka, 1997).   The abundances of Al and K for a wide range of meteorite types are shown in Fig. 11.   Most obvious is the low abundance of K in bulk meteorites, seldom exceeding 0.1 wt%.   Data for K is somewhat quantized because of the low concentrations and the reporting of the data (often as K_2O) to only 1 or 2 significant figures.   Compositions on this plot can be broadly grouped into three categories.   Chondrites have ~1–3 wt% Al and 0.02–0.12 wt% K.   Residues from partial melting (*e.g.*, lodranites, ureilites) exhibit both low Al and K.   Since both Al and K are largely contained in feldspar in chondrites, one might expect that melting and crystallization of feldspar-rich basaltic melts would produce enrichment in both Al and K.   However, the basaltic eucrites exhibit relatively low K abundances (less than 0.08
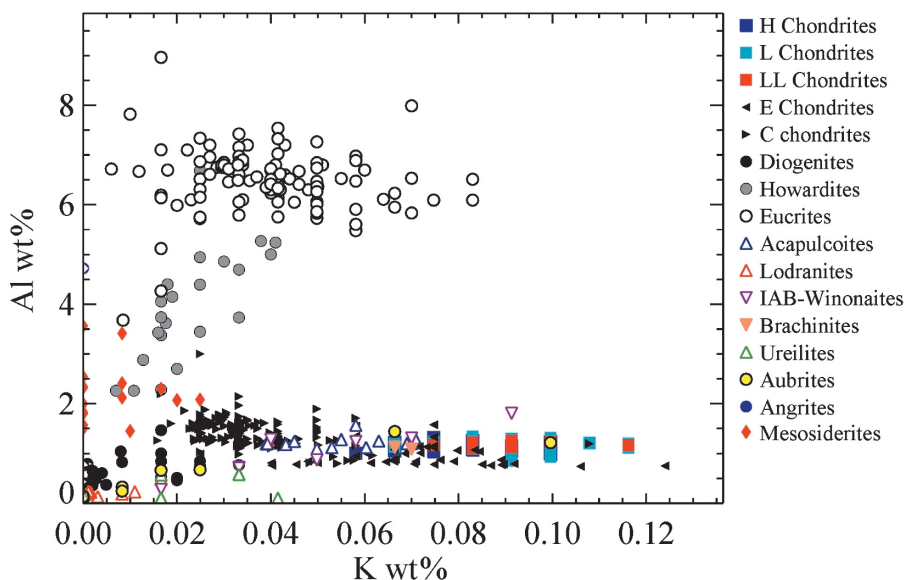

Fig. 11.   *Plot of Al and K abundances in meteorites from major classes. Potassium abundances are somewhat quantized because of low concentrations and reporting of data to 1 or 2 significant figures. Note the very low abundances of K.   Interestingly, basaltic melts (e.g., eucrites) are rich in Al but not in K, despite the fact that K partitions into feldspar.   This reflects volatile depletion in the early solar system, before the melting processes that formed the eucrites.   The absolute abundance of K is apparently not a good particularly good discriminant of meteorite groups.*

wt%) and the basaltic angrites have even lower K contents (Warren *et al.*, 1995). Low K/U ratios measured in eucrites, as well as Martian, Lunar and terrestrial basalts have been used to argue for a major loss of volatiles in the inner solar system during or before planetesimal assembly (Taylor, 1988). Thus, it appears that K may not be a particularly good discriminant of melting and differentiation of chondritic rocks, but it might be useful as a tracer of volatile depletion processes in the early solar system.

Uranium and thorium are naturally radioactive elements that proved particularly useful in delimiting basaltic *vs.* anorthositic regions on the Moon (Fichtel and Trombka, 1997). One might reasonably ask whether measurement of these elements could distinguish chondritic from differentiated asteroids. Although significant amounts of data exist for both U and Th in meteorites, we have plotted in Fig. 12 only those for which these two elements have been measured in the same aliquot and, thus, relatively few analyses are available. An obvious conclusion is that chondrites exhibit relatively low concentration of both U and Th, typically less than 100 ng/g of Th and 20 ng/g of U. In contrast, basaltic eucrites contain an order of magnitude greater concentrations of both elements. Thus, we might expect non-detection of U and Th for chondritic bodies and detection of these elements on a basaltic asteroid. Further, the low concentrations of U and Th in the pyroxenitic diogenites suggests that basaltic and
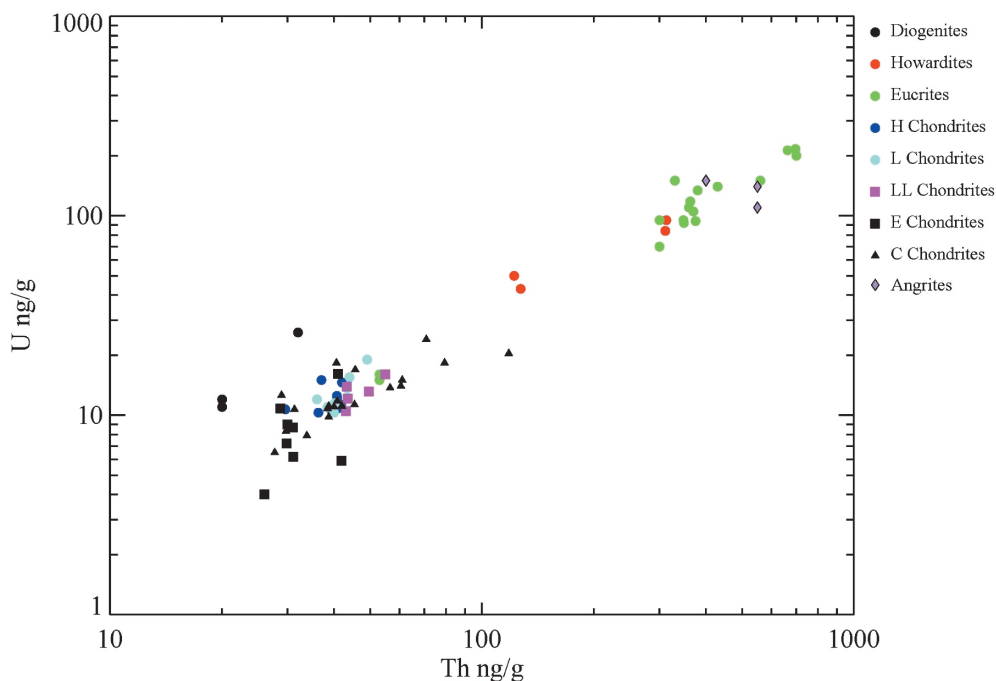

Fig. 12.   *U and Th abundances in meteorites.   Abundances of these elements are low and well correlated. The very low U and Th contents for compositions make detection of these elements by remote-sensing highly improbable from chondritic asteroids.   Basaltic compositions (e.g., eucrites) contain an order of magnitude higher abundances of these elements, and thus have the likelihood of detection.*

pyroxenitic units could be distinguished on an asteroid such as Vesta, if the size of the geologic units exceeds the spatial resolution of the spacecraft-based gamma-ray spectrometer.

5. Summary

The elemental compositions of bulk meteorites reflect both cosmochemical fractionations in the solar nebula and geological processes on meteorite parent bodies. We have compiled a large database of bulk chemical analyses of meteorites and developed a user interface that greatly eases exploration of the data in the database. Both the database and the interface are freely available to meteorite researchers, although the interface software requires an IDL license. Examination of the database reveals a significant level of elemental variability between individual meteorites of any given classification. Some of this spread in the data certainly reflects intrinsic variations on parent bodies, especially for non-chondritic meteorites. However, some of the variability indicates the presence of systematic errors in the literature data, caused by inter-laboratory bias, misclassification of certain samples, weathering, and unrepresentative sampling. These problems indicate that obtaining a representative bulk chemical analysis of a meteorite can be very difficult.

We have presented examples of element-element and element ratio-element ratio plots that can be used to investigate how well different elemental abundances discriminate between different meteorite groups and how bulk compositions are affected by geological processes. The abundances of iron and magnesium discriminate well different meteorite groups, reflecting nebular fractionations, parent-body melting, melt separation, fractional crystallization from partial melts, and impact mixing. Aluminum, calcium, sulfur and magnesium are excellent tracers of igneous processes on asteroids, since the first three elements partition into early partial melts, leaving Mg-enriched residues. The relative abundances of iron, oxygen and silicon reflect the bulk mineralogy of a meteorite. Finally, although trace element data are relatively scarce in our database, the abundances of potassium, thorium and uranium do vary between meteorite groups, reflecting volatile depletion in the case of K and differentiation in the case of Th and U. The elements we chose to discuss here were selected because they can be measured by the X-ray and gamma-ray spectrometers on planetary missions. However, a great deal more information is contained in our database than explicitly discussed here, and the database has great potential as a research tool for meteoritics and planetary science.

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