Part One

Accretion and Differentiation of the Earth

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Composition of the Silicate Earth: Implications for Accretion and Core Formation

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Our knowledge of the constitution and composition of the Earth's mantle has advanced enormously during the last 30 years.... As a result of these developments many new and important boundary conditions for the origin of the Earth have emerged. I do not believe that the significance of these boundary conditions, mainly of a geochemical nature, [has] been adequately recognised in many recent discussions of the origins of terrestrial planets in general and of the Earth in particular.

— A. E. Ringwood (1979)

1.1. Introduction

The formation of our solar system followed the collapse and fragmentation of a dense interstellar molecular cloud. As interstellar matter always has some angular momentum, the development of a central star by direct infall was not possible, and instead a rotating disk resulted. Material within the disk lost angular momentum through viscous dissipation or other processes, leading ultimately to the growth of a central star, our Sun. Only a tiny fraction of the mass of the solar system (~0.1%) was left behind in the disk, eventually to form the planets and asteroids.

The duration of the initial collapse phase was short, less than 1 million years. After this phase, the remnants of the accretion disk may have persisted for as long as 10 million years before the planets were assembled. This history derives from astronomical observations and is consistent with isotopic evidence from meteorites (Podosek and Cassen, 1994). The mixture of gas and grains that made up the proto-solar accretion disk is known as the *solar nebula*. The solar nebula plays a key role in our understanding of the chemical compositions of the Earth, the planets, the asteroids, and other constituents of the solar system. Many of the important and distinctive features of the Earth's composition that are responsible for its structure and evolution were inherited from the processes that operated during the condensation of the solar nebula into solid matter.

The growth of solid bodies in the solar nebula began with the aggregation of tiny dust grains that either formed by condensation or were of interstellar origin. The

small, micrometer-size dust particles suspended in the nebula tended to settle to the midplane. Grains then grew by coagulation due to different settling rates and because of turbulent motion in the nebula. This produced centimetre-size bodies that in turn grew to metre- and kilometre-size blocks by collisional coagulation, produced by gas drag on particles of different sizes (Weidenschilling, 1988). Once the diameters of the planetesimals had reached 1–10 km, gravitational forces determined further growth. Computer simulations show that fast runaway accretion will produce planetary 'embryos', bodies of some 10^{23} kg (i.e., about 2% of the mass of the Earth), within about 10^5 years (Wetherill, 1990, 1994). Three major conclusions derived from this model are pertinent to the growth of the Earth and other planets: (1) Planetesimals appear to grow from small particles through a hierarchy of increasingly larger bodies – an evolving size distribution. Planetesimals (or planets) do not grow by accreting dust onto a single nucleus. (2) Bodies up to kilometre size are composed of material derived from 'local feeding zones' and thus should retain chemical signatures that are characteristic of the heliocentric distances at which they formed. (3) At some point there was clearing of the nebula through intense activity of the early Sun (e.g., T-Tauri phase), leading to removal of gas and fine dust. Metre-size and kilometre-size bodies were not affected. This is potentially an effective mechanism for fractionation of volatile elements. However, it is not known how far accretion had proceeded when the clearing of the nebula took place.

The next step, formation of the inner planets by accumulation of embryos, took millions of years to complete. At this stage, some radial mixing of embryos formed at different heliocentric distances would be expected, so that material formed far out in the asteroid belt may have made significant contributions to the growing Earth. Such components may have been very different in volatile-element content and oxidation state compared with the material in the 'indigenous' embryos at 1 AU (Wetherill, 1994). Clearly, this may have had important consequences not only for the bulk composition of the Earth but also for any differentiation that may have accompanied accretion, particularly core formation. This model for planetary accretion is depicted in Figure 1.1.

In addition to samples from the Earth and the Moon, a wide variety of other solar-system material has been delivered to the Earth as meteorites and is accessible for laboratory study. Some rare types of meteorites (the 'SNC' meteorites, discussed later) are believed to be samples from Mars, and a few have come from the Moon. Most meteorites, however, are thought to be derived from asteroids (Wood and Morfill, 1988). Asteroids are small planetary bodies, or planetesimals, many of which are concentrated in the gap between Mars and Jupiter at 2–3.2 AU, which interrupts the regular spacing of the planets as described by the Titius–Bode law. They are remnants from the era during which the planets of the inner solar system, including the Earth, formed. Accretion of a planet in the position of the present

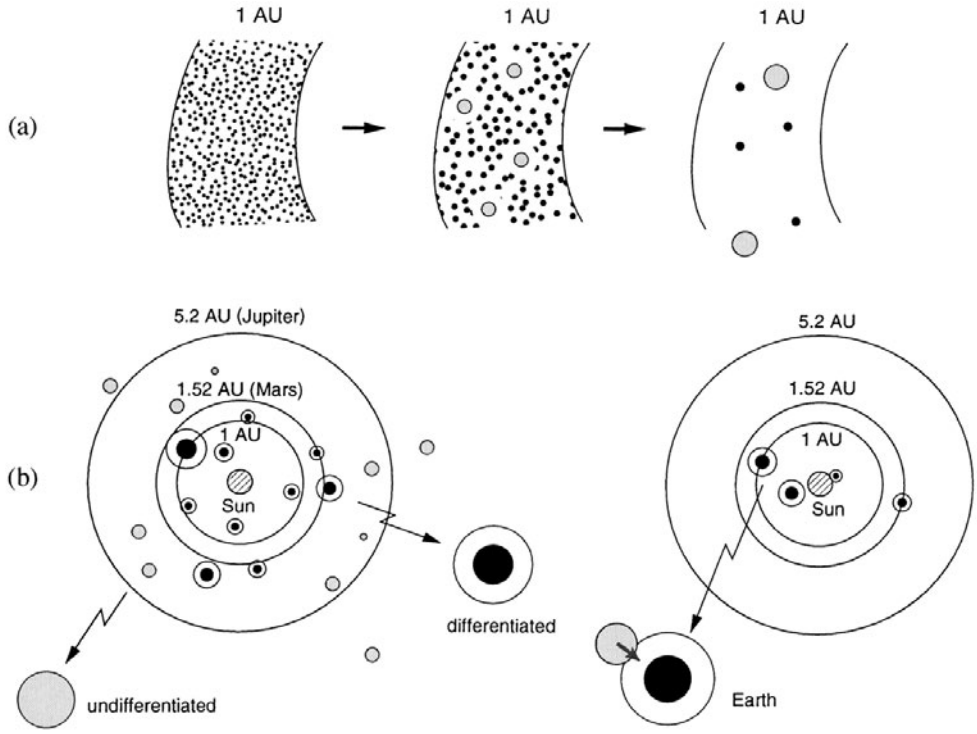


Figure 1.1. Formation of the Earth involved two major steps: (a) Within the local feeding zone of the Earth, at 1 AU (astronomical unit, the distance from the Earth to the Sun), bodies the size of the Moon or Mars ('planetary embryos') were formed within 10^5 years by collisions among kilometre-size planetesimals. (b) In the second step, the terrestrial planets grew by collisions among these embryos. This step took much longer (millions of years) and may have involved bodies formed at distances ranging from 0.5 to more than 3 AU, leading to substantial mixing of materials originating at different heliocentric distances (Wetherill, 1994). Whether or not a planetesimal or planetary embryo was differentiated (i.e., had been heated sufficiently to undergo partial melting and core formation) probably was a function of the size of the body, the timing of the accretion process, and its bulk composition. All of those factors may have depended on heliocentric distance. Thus, both differentiated and undifferentiated planetesimals and planetary embryos may have contributed to the growing Earth, depending on the heliocentric distances at which they formed. Bodies originating from the asteroid belt beyond 2.5 AU may have added undifferentiated, oxidized, and volatile-rich components late in the accretion process, as required by heterogeneous-accretion models.

asteroid belt probably was hindered by the early growth of Jupiter, so that accretion did not progress past the planetesimal stage (i.e., bodies of $\sim 10^{21}$ kg). The spectral properties of the asteroid Vesta suggest that it could have been the parent body for the 'HED' suite (howardites, eucrites, diogenites) of meteorites (Binzel and Xu, 1993).

Analyses of all these different kinds of solar-system materials demonstrate that the solar nebula was rather homogeneous in isotopic composition. Exceptions to that rule are provided by rare exotic grains of pre-solar origin found in the most primitive of the chondritic meteorites (e.g., Anders and Zinner, 1993), some isotopic

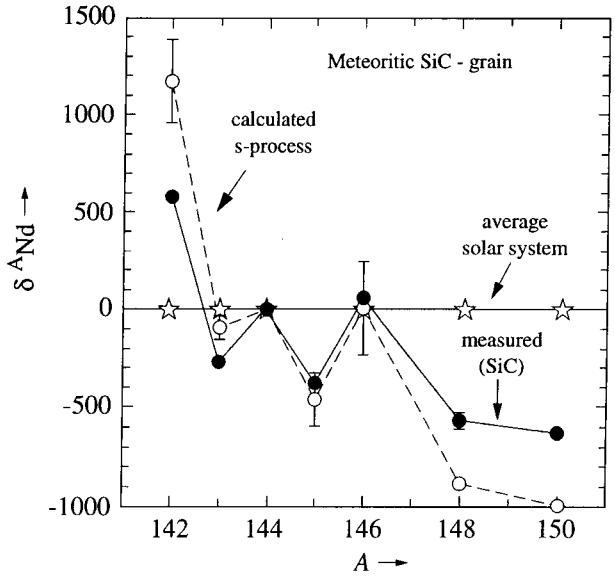


Figure 1.2. The isotopic composition of solar-system Nd, as found in terrestrial and lunar rocks and all bulk samples of meteorites, is uniform to better than one part in 10^4 (after allowing for variable ^{143}Nd from the decay of ^{147}Sm). This contrasts dramatically with the isotopic composition of Nd in a pre-solar SiC grain. The deviation of its Nd isotopic composition from the terrestrial ratio is given in parts per million and all ratios are normalized to ^{144}Nd. Full symbols are measured values (see Richter, Ott, and Begemann, 1992). Error bars are, in most cases, smaller than symbol sizes. The calculated s-process production ratios are also indicated. The important implication is that if the solar nebula had not been well mixed, bodies originating from different parts of it would have consisted of materials with different isotopic compositions for Nd, and, by analogy, for most other elements. From Palme and Beer (1993), with permission.

anomalies in Ca- and Al-rich inclusions in carbonaceous chondrites (e.g., Lee, 1988), and certain enigmatic variations in oxygen isotopes (Clayton, 1993) and noble-gas isotopic compositions (McDougall and Honda, Chapter 3, this volume). In view of the huge isotopic anomalies found in pre-solar grains, it is of great significance that the isotopic compositions of well-studied elements such as Sr, Nd, Hf, and Os (and, by inference, of most other elements) are, within 0.01%, identical in all bulk samples of solar-system material that are available for analysis.

An example of an isotopic anomaly is given in Figure 1.2, in which the isotopic composition of Nd in a pre-solar SiC grain is compared with the isotopic composition of solar-system Nd (i.e., from terrestrial, lunar, and bulk samples of the many different types of meteorites, which differ by less than one part in 10^4). The Nd isotopic composition of the SiC grain is derived from a specific nucleosynthetic source, the s-process, as indicated by comparison with calculated s-process yields (Palme and Beer, 1993). This grain was formed in the interior of a star and was ejected into the interstellar medium, and it finally found its way into a meteorite, more or less undisturbed. By contrast, solar-system Nd must have been

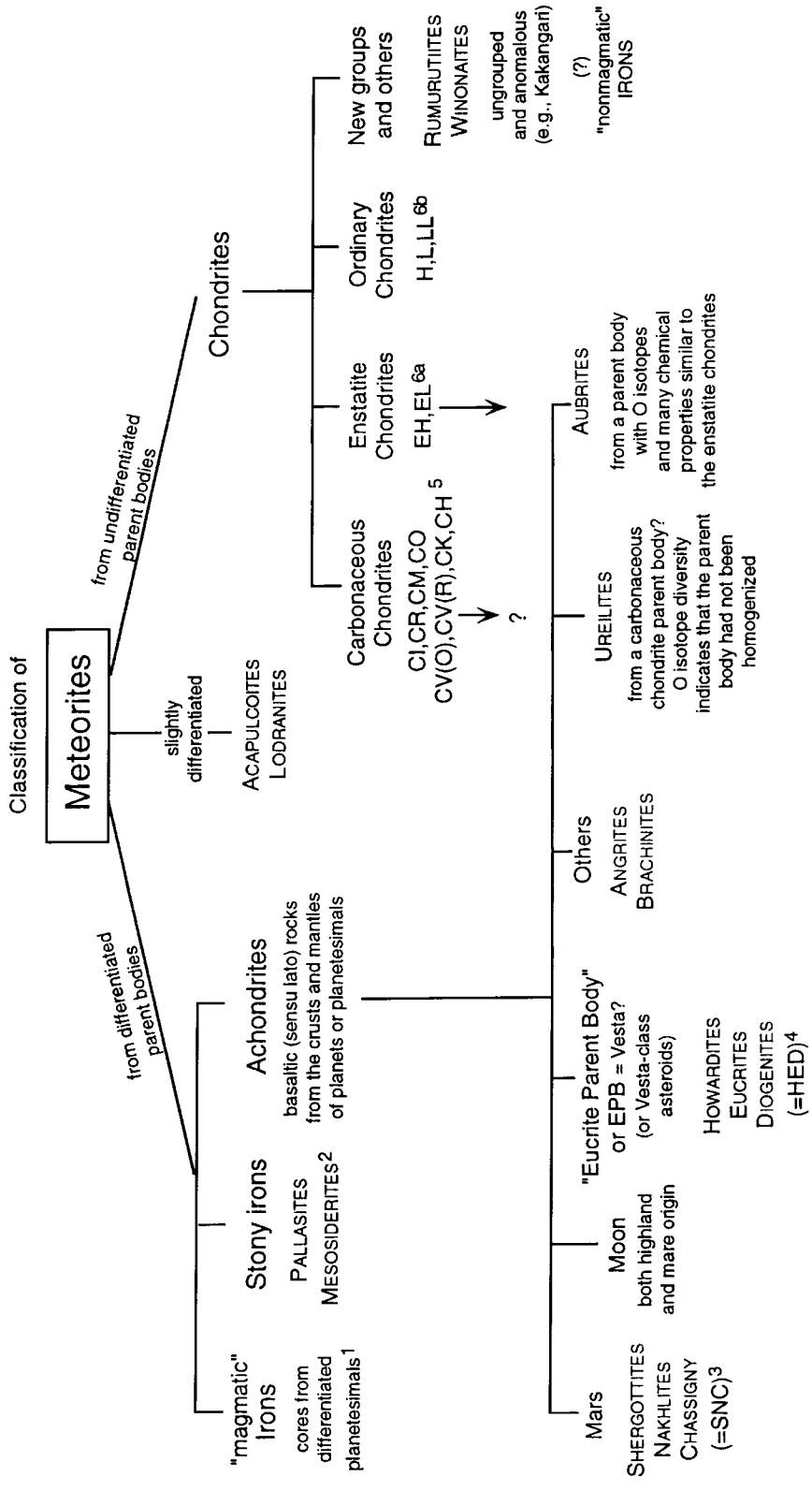
derived by mixing of Nd from more than one nucleosynthetic process and thus has a distinctive isotopic composition. This is probably true of many elements. Thus, the rare interstellar grains, with their huge isotopic anomalies (not, of course, confined to Nd), are truly 'exceptions that prove the rule', the rule being that the materials now in the inner solar system share a common origin, consistent with derivation from a homogenized nebula that was efficiently mixed on the usual scale at which meteorites are sampled for conventional isotopic analysis.

Interestingly, current research is increasingly revealing isotopic inhomogeneity on a finer scale, and it seems that in some primitive meteorites different nucleosynthetic sources are still discernible in individual mineral grains. For example, the Cr isotopic composition of the Cr-bearing phases of carbonaceous chondrites is highly variable, although the average isotopic compositions of the bulk meteorites are identical with those of terrestrial rocks and other solar-system samples (Rotaru, Birck, and Allègre, 1992). Nonetheless, on all except this smallest of sampling of scales, the dominant picture remains one of essential uniformity in isotopic constitution.

The major deduction from the hypothesis of a well-mixed nebula is that all solar-system material, including that forming the Earth, was derived from a nebula material that had a uniform, characteristic *chemical* and isotopic composition. This is the solar composition as observed in the solar photosphere.

Variations in the oxygen isotopic compositions of solar-system materials (Clayton, 1993) might appear to contradict this hypothesis of a homogeneous nebula. However, the pattern of these variations has not been satisfactorily explained, and it now seems likely that the mass-independent isotopic fractionation observed in meteoritic oxygen may have resulted from physical processes within the solar nebula (e.g., condensation) (Thiemens, 1988). This is supported by recent findings of such effects in stratospheric and mesospheric CO_2 (Thiemens et al., 1995).

Although the solar nebula was essentially homogeneous in composition, the compositional diversity of the bodies in the inner solar system (especially as sampled by meteorites) indicates that a substantial amount of chemical differentiation must have taken place either during its condensation or subsequently during accumulation of the condensed matter into planetesimals and planetary embryos. The material that now forms asteroids and the material that formed the precursors to the larger planets can reasonably be supposed to have shared a common early history, so that meteorites derived from asteroids should document the type and extent of the fractionation processes that occurred during these early stages of planet-building and affected the Earth-forming precursor materials. Identifying the fundamental chemical fractionation processes responsible for the surprisingly large compositional diversity of meteorites provides the framework not only for constraining compositional models of the Earth but also for appreciating the significance of the Earth's composition in chronicling the history of its accretion and early differentiation.



1.2. The Meteorite Record

1.2.1. Classification of Meteorites and the Diversity in Their Chemical Compositions

Most meteorites formed around 4.5 billion years ago, as revealed by the standard radiogenic-isotope geochronometers. Only for a comparatively short fraction of the time since then (i.e., on the order of a few million years) do they show evidence of having been exposed to cosmic rays. For most of their existence, therefore, the fragments of rocks that we now find as meteorites were buried in the interiors of their parent planetesimals. That there were variations in the chemical compositions and thermal histories of these parent bodies is evidensed by the many different types of meteorites. A classification scheme for meteorites is depicted in Figure 1.3.

The fundamental distinction among meteorites is between those derived from parent bodies that had undergone igneous differentiation and metal segregation, leading to core formation, and those derived from essentially undifferentiated parent bodies. The latter are particularly useful, because they preserve directly the chemical compositions of their parent bodies.

The meteorites from differentiated bodies include the products of partial melting (e.g., the basaltic meteorites, such as the eucrites), residues from partial melting (lodranites and ureilites), the metallic cores of planetesimals (the 'magmatic' irons), samples from the core–mantle boundaries of the planetesimals (the pallasite stony

Figure 1.3. The diversity of meteorites.
[1]There are approximately 12 major groups of irons, plus anomalous or ungrouped examples. Originally, four major groups of irons were recognized on chemical grounds (I, II, III, and IV). Further work led to subdivision (e.g., IVA, IVB). Some of these subdivisions have subsequently been recombined (e.g., IAB) and recombined again (IAB + IIICD). However, the fundamental division of the irons is into 'magmatic' types (which show chemical evidence for differentiation by fractional crystallization in the core of an asteroid-size parent body) and 'nonmagmatic' types (at least some of which may be close to being compositionally primitive condensates from the solar nebula, and therefore of chondritic affinity).
[2]Mesosiderites are breccias involving a mixture of iron meteorites with material of possible HED origin. Main-group pallasites may come from the core–mantle boundary of the EPB (O isotopes). Pallasites of the Eagle Station type come from a body with a different O isotope signature.
[3]Shergottites are (presumably) Martian basalts; nakhlites and Chassigny are cumulate rocks of hypabyssal origin.
[4]Eucrites are basalts; diogenites are hypabyssal cumulates. Most eucrites and diogenites are breccias. Howardites are polymict breccias of eucrites and diogenites.
[5]The second letter usually stands for the name of a representative member of the class (e.g., I for Ivuna); see Table 1.1. The H in CH is an exception.
[6a]H is for high Fe, and L is for low Fe.
[6b]H is for high Fe, L is for low Fe, and LL is for (very) low total Fe and low metallic Fe. Currently, chondrite groups are always referred to by their letter(s), except anomalous meteorites and the newly defined groups (rumurutiites, winonaites). Rumurutiites are now R chondrites.

irons), and so forth. The meteoritic record probably samples a continuum in the differentiation of planetesimals, ranging from the completely undifferentiated, through those that had just begun to melt and show the traces of incipient differentiation (e.g., acapulcoites), to the completely differentiated, of which the eucrite parent body (EPB) is thought to be an example.

Meteorites from undifferentiated bodies are termed *chondrites*. Meteorite nomenclature is encumbered with some interesting but potentially confusing historical baggage, of which the term "chondrite" is a good example. The term comes from *chondrules*, the name given to near-spherical objects typically of sub-millimetre-to-millimetre dimensions that are interpreted to be agglomerations of nebula dust that were melted by rapid heating and then were rapidly cooled. That much about the origin of chondrules was discovered by Sorby (1877), using a petrologic microscope and thin-section process that he himself had invented. Although, some 120 years later, the cause of the melting still is not generally agreed upon, it evidently was a common process, at least in the inner solar system, as chondrules are major components of many chondritic meteorites. For example, chondrules and chondrule fragments account for 65–75%, by volume, of ordinary chondrites with primitive (unmetamorphosed) textures, much of the remainder being *matrix*. In many chondrites, however, chondrules are difficult to recognize, because subsequent recrystallization accompanying thermal metamorphism in the meteorite parent body has obscured their shapes. Even more extensive metamorphism has led to complete erasure of chondrules in some groups of chondritic meteorites. The CI carbonaceous chondrites do not contain chondrules – they are composed mostly (>95%) of matrix. Thus the presence of chondrules plays no part in the current definition of a chondritic meteorite.

Meteoriticists recognize three major groups of chondritic meteorites, the ordinary chondrites (OCs), the enstatite chondrites (ECs), and the carbonaceous chondrites (CCs), plus a number of minor groups and a few anomalous individuals. These major groups are further subdivided on the basis of their chemistry and textures. A brief overview of chondritic-meteorite classification is given in Table 1.1, and some of the key chemical characteristics of the chondrite groups are listed in Table 1.2. In keeping with other irregular aspects of meteorite nomenclature, most of the carbonaceous-chondrite subgroups are not particularly rich in carbon. An indication of the relative abundances of the different types of meteorites, as sampled here on the Earth, is provided by the statistics in Table 1.3.

Chemically, the most primitive chondrites are thought to be the CI carbonaceous chondrites, which are the richest in volatile elements. The chemical composition of this group of meteorites is accorded special significance, as it appears to be the same as that in the solar photosphere (Figure 1.4) for all elements except the most volatile (the 'ice-forming elements' H, C, O, and N, and the rare gases) and the light elements actively being consumed by nuclear reactions in the interior of the Sun (Li, Be, and B). Because the present mass of the solar system is almost completely contained in the Sun, the solar photosphere, being representative of the Sun, also