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Stuart Ross Taylor and Scott M. McLennan
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Prologue

> We are apt to judge the great operations of Nature on too confined a plan.
> *(Sir William Hamilton) [1]*

It seems inevitable that rocky planets, like bakers, cannot resist making crusts, heat being the prime cause in both cases. Although trivial in volume relative to their parent planets, crusts often contain a major fraction of the planetary budget of elements such as the heat-producing elements potassium, uranium and thorium as well as many other rare elements while the familiar continental crust of the Earth on which most of us live is of unique importance to *Homo sapiens*. It was on this platform that the later stages of evolution occurred and so has enabled this enquiry to proceed.

Planetary crusts in the Solar System indeed have undeniable advantages for scientists: they are accessible. Unlike the other regions of planets that we wish to study, such as cores and mantles, you can walk on crusts, land spacecraft on them, collect samples from them, measure their surface compositions remotely, study photographs, or use radar to penetrate obscuring atmospheres. Despite this accessibility, the problems both of sampling or observing crusts are non-trivial: most of our confusion in deciphering the history of crusts ultimately turns on our ability to sample them in an adequate fashion. We discuss these diverse problems in the appropriate chapters.

This advantage of relatively easy access to crusts is also offset by the distressing tendency for crusts to be complex, so that one may easily become lost in the detail, failing to see the forest for the trees. This is particularly true of the continental crust of the Earth that is sometimes heterogeneous on a scale of meters. One consequence of this myopia is that one sometimes encounters claims that extrapolate from a small region to produce a world-embracing model. The furore over whether there was an early granitic continental crust during the Hadean is a familiar example of the perils of extrapolation from a handful of zircon grains preserved in younger sedimentary

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rocks. As Charles Gillispie has remarked "the inherent difficulties of the science, Lyell thought, had rendered it peculiarly susceptible to the interpretations of ancient miraclemongers and their modern successors" [2]. Moreover the fundamental lesson from comparative planetology is that each rocky planet and satellite has some significant variation from the geological insights gained by studying our own planet.

Another major problem besets attempts to understand the origin and evolution of planetary crusts. Just as it is difficult to trace back the orbit of a near-Earth asteroid that was thrown into an Earth-crossing orbit by Jupiter, or to decipher the oceanic source of an ore deposit that is now outcropping in the middle of a continent, so planetary crusts, that are the final products of extensive planetary differentiation, mostly conceal their previous history.

We usually see only the end product, the classic problem in geology. The upper continental crust of the Earth, that we can investigate so readily, is the product of intra-crustal melting within a crust derived by three stages of remelting of rocks derived from a mantle with a complex history. The other solid bodies in the Solar System display crusts that are often equally complicated, the results of planetary differentiation processes that, although following the laws of physics and chemistry, differ in detail from one body to another.

These are some of the reasons that the development of the geological sciences lagged behind that of most other sciences. Contrary to popular mythology, they are amongst the most difficult and complicated of subjects. This is readily demonstrated by considering the historical development of the various sciences. Thus classical physics was well established by Newton, with the publication of the *Principia* in 1687. Biology was set upon the right track by Darwin in 1859 when he published *The Origin of Species*. The underlying basis of chemistry became understood with the formulation of the Periodic Table of the Elements by Dmitri Ivanovich Mendeleev in 1869. The fundamental nature of atoms was established nearly a century ago in 1911 by Ernest Rutherford. Even the origin of the chemical elements themselves was understood following the work of the Burbidges, Willy Fowler, Fred Hoyle and independently by Al Cameron in 1956.

However, it was only as late as 1963, three centuries after Newton's physical insights, that Fred Vine and Drum Matthews hit upon the fundamental process of plate tectonics. Then geologists finally understood what was going on under their feet. This mechanism explained the architecture of the surface of the Earth that had been painfully established in the previous 150 years following the pioneering works of James Hutton, William Smith and Charles Lyell.

There is a further philosophical problem that bedevils geology, a term that we use here in its broadest sense to encompass the study of the "origin, structure and history" of planets. Planets differ from stars, whose classification and evolution

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have been understood for nearly a century. Thus the Hertzsprung–Russell diagram, fundamental to astrophysics, dates from 1913. It is nearly a century old, as is the robust OBAFGKM classification of stars [3]. In contrast to stars, the planets, including the terrestrial planets and the Earth and indeed most of the geological record, are essentially the end result of the operation of stochastic processes. Planets are individuals that refuse to be placed into neat pigeonholes, unlike stars.

Thus it is difficult to find geological laws or generalizations of general applicability such as the Hertzsprung–Russell diagram or the Periodic Table of the Elements that enabled the rapid development of astronomy and chemistry. Such problems are responsible for the lengthy development of geology and of the continual appearance of bizarre theories to account for geological phenomena.

So we need to heed the wise advice of Sir William Hamilton that heads this section and that of Al Hofmann, who, in studying the mantle of the Earth, employed "a simple-minded, uniformitarian approach that uses known geological processes and avoids exotic processes wherever possible" [4].

It is only occasionally that the investigation of geological details has led to insights into fundamental processes, examples being the unconformities in Scotland at Jedburgh and more famously at Siccar Point that enabled Hutton to develop the concept of deep time. The K-T boundary outcrop at Gubbio, in Tuscany, Italy is another such that led to the recognition of the catastrophic impact of a 10 km diameter asteroid that ended the Cretaceous Period. But much of the rock record that has been painstakingly assembled over the past two centuries reflects localized events. Standing on the Earth, it is difficult to appreciate the slow process of plate tectonics: it was the data from marine geophysics, not surface outcrops, road-cuts or drill cores, that provided the compelling evidence for sea-floor spreading that was the key to understanding the mobile nature of the surface of the Earth [5].

Early attempts to decipher the geological record were bedevilled by the occurrences of similar-looking rocks that turned out to be of different ages. The study of individual ore deposits that we find so useful for our technical civilization reveals that they form mostly as a consequence of local geological conditions. So they provide only indirect evidence of the processes that have resulted in the concentration of the ore elements by many orders of magnitude from those of the bulk planet. Venus, in contrast to the Earth, has a totally different geological history. Like Mercury and perhaps Mars, all seem unlikely to have much in the way of ore deposits.

Another problem is that geology has had to wait for the development of specialized techniques, from marine magnetometers to mass spectrometers, in order to resolve its problems. As Bill Menard [6] has remarked "geology was moribund during the period from about 1860 to about 1940 because it lacked the techniques to solve its important problems … (and) the geologists … were inevitably doomed to working on trivia until new tools were forged”. In the meantime, according to Stephen Brush, “Geologists in the 20th century became accustomed to carrying on interminable controversies about problems that they were unable to solve” [7]. Such debates have often reached levels reminiscent of medieval religious disputes, a classic example, that is worthy of historical study, being the question whether tektites originated from the Moon or the Earth. The wrangle over the reality of mantle plumes forms a current instance.

Fortunately, the advent of sophisticated analytical techniques has helped to resolve many of the problems raised by the field observations and so has enabled us to embark on this discussion.

Notes and references

1. Hamilton, W. (1773) *Observations on Mt. Vesuvius, Mt. Etna and other volcanoes*, T. Cadell, p. 161. Better known to history as the husband of Emma, Lady Hamilton, who was the mistress of Admiral Lord Nelson, this distinguished naturalist and Fellow of the Royal Society was one of the first modern students of volcanoes.
2. Gillispie, C. C. (1951) *Genesis and Geology*, Harvard University Press, p. 127.
3. To which L and T classes have been added for the recently discovered brown dwarfs, thus spoiling the famous mnemonic “Oh be a fine girl kiss me”.
4. Hofmann, A. (1997) Mantle geochemistry: the message from oceanic volcanism. *Nature* **385**, 219–22.
5. Earlier attempts to understand the architecture of the surface of the Earth are the classic accounts by Suess, E. (1904) *The Face of the Earth* (trans. H. B. C. Sollas), Clarendon Press (3 volumes) and Umbgrove, J. H. F. (1947) *The Pulse of the Earth* (2 ed.), Nijhoff.
6. Menard, H. (1971) *Science Growth and Change*, Harvard University Press, p. 144. Relevant to this comment is the proliferation of edited volumes on many topics of which the Archean and the early Solar System are favorites. Despite heroic efforts by editors, such collections of papers from disparate authors with varying opinions and styles are rarely successful, while their reference lists extend into the thousands. Much of this material could equally well appear in the normal refereed scientific literature. Indeed attempts to enshrine a topic in a definitive work such as the ten-volume *Treatise on Geochemistry* seem pointless in an active science where any publications rarely survive more than five years. For example, our estimates given in this book, both for the composition of the Earth (Chapter 8) and for the continental crust (Chapter 12), differ significantly from those given in the *Treatise*.
7. Brush, S. G. (1996) *Transmuted Past*, Cambridge University Press, p. 55.

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The planets: their formation and differentiation

> Alphonso, King of Castille, …was ill seconded by the astronomers whom he had assembled at considerable expence (sic)…. Endowed with a correct judgement, Alphonso was shocked at the confusion of the circles, in which the celestial bodies were supposed to move. 'If the Deity' said he, 'had asked my advice, these things would have been better arranged'
>
> *(Pierre-Simon Laplace) [1]*

1.1 Planetary formation

Although this book is concerned with the crusts of the solid bodies in the Solar System, it is necessary to delve a little deeper into the interiors of the planets, to see how the planets themselves came to be formed and why they differ from one another. It is only possible to understand why and how crusts form on planets if we understand the reasons how these bodies came to be there in the first place and why they are all different from one another. Following 40 years of exploration of our own Solar System, the discovery of over 200 planets orbiting stars other than the Sun has brought the question of planetary origin and evolution into sharp focus. The detailed study of planets is in fact a very late event in science and has required the prior development of many other disciplines.

This highlights a basic problem in dealing with planets, at least in our Solar System, that are all quite different, so that it is difficult to extract some general principles that might be applicable to all of them.

Stars, although they vary in mass, have similar compositions and so are amenable to mathematical and physical laws, a feature that has led to the thriving field of astrophysics. But there is a fundamental difference between stars and planets. Stars form "top-down" by condensation, essentially of hydrogen and helium gas, from dense cores in molecular clouds. Their major differences in mass, luminosity and surface temperature are well displayed on the celebrated Hertzsprung–Russell diagram that is nearly a century old. The success of the Hertzsprung–Russell

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representation is that the luminosity and surface temperatures of stars are underpinned by the basic nuclear physics of stellar processes, just as the Periodic Table of the Elements is based on the electronic structure of atoms, something of which the originators of both classifications were unaware.

Planets, in contrast to stars, were assembled randomly, "bottom-up" from leftover material in the nebular disk, at least in our Solar System but likely elsewhere. They are all distinct, forming from a complex mixture of components that can be loosely labeled as gases, ices and rock. From our observations both of our own and extra-solar planets, these bodies may form from any combination of these three components. There is no equivalent of the Hertzsprung–Russell diagram for planets or much sign of one appearing.

It is even difficult to arrive at a satisfactory definition of a planet; witness the furore over the status of Pluto or its larger colleague Eris, that are eccentric dwarfs when placed among the planets, but are the largest icy planetesimals in the Kuiper Belt in their own right [2]. As Confucius remarked "the beginning of wisdom is to call things by their right names".

In our Solar System, we have eight planets, all of them distinct from one another in mass, density, composition, obliquity and rotation rates. Their only common properties are near-circular orbits and low inclinations to the plane of the ecliptic (the Earth–Sun plane), characteristics that enabled Laplace to conclude in 1796 that they had originated from a rotating disk of gas and dust, the solar nebula.

While we still have only one planetary system to examine closely, it includes over 160 satellites [3] but of these, none resemble one another, even among the "regular" satellites. Like the planets, each satellite exhibits some peculiarities of composition or behavior. This tells us that there is no uniformity in the processes of planetary or satellite formation from the gases, ices and rocky components of the primordial nebula. Clones of our planets or our Solar System are consequently expected to be rare.

Our limited sampling of extra-solar planets displays much wider variations from our own system in terms of mass and spacing of planets while, to add additional complexity, many of these newly discovered planets are in highly elliptical orbits. It appears likely that we will find planets forming from Keplerian disks around young stars that will occupy all possible niches available within the limits imposed by the cosmochemical abundances of the elements and the laws of physics and chemistry (Fig. 1.1).

The Earth is the unique planet. No hard-won geological or geophysical truths discovered about our own planet, or even the detailed sequence of geological events, has much applicability elsewhere in the Solar System. Indeed, the sequence of geological processes on Earth has little predictive power. If one had visited the Earth during the Permian, one would not have foreseen the world of the Triassic with its

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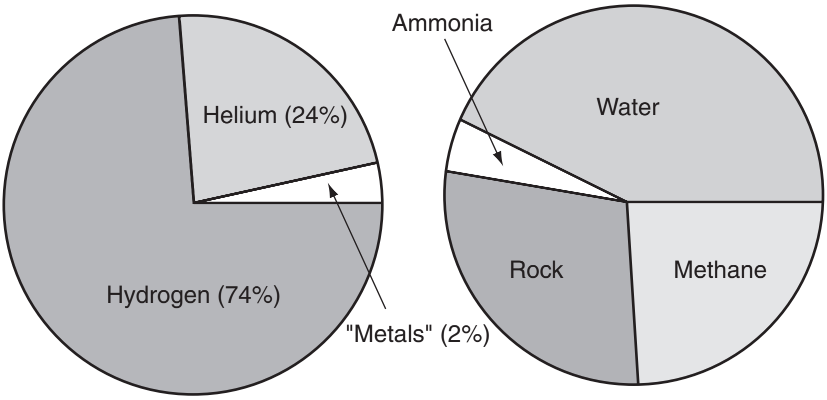

Fig. 1.1 The pie diagram on the left shows the composition of the primordial solar nebula, constituted of 98% gases (H and He) and 2% “metals” (in astronomical jargon). The right-hand pie diagram breaks down the “metals” sector into “ices” (mostly water, ammonia and methane) and “rock” (the remaining elements). Planets may form from any combination of gases, ices and rock. Thus Jupiter and Saturn are dominantly hydrogen and helium (“gas giants”), Uranus and Neptune are “ice giants” while the terrestrial planets are formed from rock.

completely different fauna. To a visitor in the warm Cretaceous, it would have been difficult to imagine the cooling throughout the Tertiary or the onset of the ice ages. Even more unpredictable was the catastrophe that would end that benign period, remove the giant reptiles and lead to the dominance of mammals. That event, that has now resulted in the Earth being overrun by one species, was one consequence of the great K-T boundary collision of the Earth with a 10 km diameter asteroid. Nor could a visitor to Venus a billion years ago have foreseen the total resurfacing of the planet that was to occur shortly thereafter. Planetary history, like planetary formation, is dominated by stochastic and unpredictable events.

The problems of studying planets are well illustrated by the history of attempts to understand the Earth. Often beset by the notions of miracle mongers, the consequence was that geology was a latecomer among the sciences. Even so, it took 150 years following the insights into deep time by James Hutton in 1788 to understand that plate tectonics is the mechanism responsible for the architecture of the Earth’s surface. But the Earth is an unusual planet even by the standards of the Solar System. The geological, geochemical and geophysical truths extracted from over 200 years of study are not easily applied to other planets.

Plate tectonics has the useful property both of building continents and of forming ore deposits useful for advanced civilizations and so enabling this discussion to take place. However, this process is unique to the Earth among our planets. The trivial terrestrial water content of a few hundred parts per million, responsible for plate tectonics and the growth of continents, was a late stochastic addition to the planet.

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Many of the difficulties in trying to understand the petrology and evolution of the Moon arose from uncritical attempts to apply our hard-won experience with wetter terrestrial rocks to our bone-dry satellite.

Even when nature got around to building two similar planets, it finished up with the Earth and Venus. These twins, unlike Mars and Mercury, are close in mass, density, bulk composition and in the abundances of the heat-producing elements (potassium, uranium and thorium). But Venus is a one-plate planet without a moon and appears to undergo planetary-wide resurfacing with basalt perhaps once every billion years. What causes the difference between the geological histories of these twins? The short answer is water, but much may be due to variations in the early history of impacts during planetary accretion. As the study of Venus shows, similarity is not identity and the Earth resembles Venus much as Dr Jekyll resembled Mr Hyde. As we search for terrestrial-like planets elsewhere, we need to find out the reasons for these differences and the conditions that allow these diverse bodies, or Mercury and Mars for that matter, to form at all. Just as geology arose in the nineteenth century, now the study of planets represents a new area in scientific enquiry.

1.2 The solar nebula and the giant planets

The solar nebula from which the Sun and planets formed had three basic constituents: loosely "gases", "ices" and "rock". The dominant component was gas (98% hydrogen and helium). The heavier elements ("metals" to the astronomers) that amounted to about 2% by mass, had accumulated in the interstellar medium from 10 billion years of nucleosynthesis in previous generations of stars. Abundant elements such as carbon, oxygen and nitrogen were present in the nebula as ices (e.g. as water, methane, carbon monoxide, carbon dioxide and ammonia). The remaining elements, that fill the rest of the periodic table, were present mostly as dust and grains (rock). This rock component had a composition that is given by the CI meteorites, the most primitive stony meteorites (Table 1.1). The rationale for equating their composition to that of the primitive solar nebula is that the composition in this class of meteorites, when ratioed to a common element such as silicon, matches the composition of the solar photosphere. As the Sun contains 99.9% of the mass of the system, their composition is taken to reflect that of the rock fraction of the original solar nebula [4].

Perhaps the most fundamental division in the Solar System is the difference between the giant planets and the small terrestrial planets, although even the giant planets differ significantly among themselves. Jupiter and Saturn, in addition to their massive gaseous envelopes, possess cores of rock and ice that are between 10 and 15 Earth-masses. In contrast, Uranus and Neptune, that are 14 and 17 Earth-masses

Table 1.1 *The composition of the rock fraction of the primordial solar nebula**

Atomic number	Element	Mean CI chondrite		Atomic number	Element	Mean CI chondrite	
		Ref. 1	Ref. 2			Ref. 1	Ref. 2
3	Li (ppm)	1.49	1.50	47	Ag (ppb)	197	199
4	Be (ppb)	24.9	24.9	48	Cd (ppb)	680	686
5	B (ppb)	690	870	49	In (ppb)	78	80
9	F (ppm)	58	61	50	Sn (ppb)	1680	1720
11	Na (ppm)	4982	5000	51	Sb (ppb)	133	142
12	Mg (wt%)	9.61	9.89	52	Te (ppb)	2270	2320
13	Al (ppm)	8490	8680	53	I (ppb)	433	433
14	Si (wt%)	10.68	10.64	55	Cs (ppb)	188	187
15	P (ppm)	926	1220	56	Ba (ppb)	2410	2340
16	S (wt%)	5.41	6.25	57	La (ppb)	245	234.7
17	Cl (ppm)	698	704	58	Ce (ppb)	638	603.2
19	K (ppm)	544	558	59	Pr (ppb)	96.4	89.1
20	Ca (ppm)	9320	9280	60	Nd (ppb)	474	452.4
21	Sc (ppm)	5.90	5.82	62	Sm (ppb)	154	147.1
22	Ti (ppm)	458	436	63	Eu (ppb)	58	56.0
23	V (ppm)	54.3	56.5	64	Gd (ppb)	204	196.9
24	Cr (ppm)	2646	2660	65	Tb (ppb)	37.5	36.3
25	Mn (ppm)	1933	1990	66	Dy (ppb)	254	242.7
26	Fe (wt%)	18.43	19.40	67	Ho (ppb)	56.7	55.6
27	Co (ppm)	506	502	68	Er (ppb)	166	158.9
28	Ni (wt%)	1.08	1.10	69	Tm (ppb)	25.6	24.2
29	Cu (ppm)	131	126	70	Yb (ppb)	165	162.5
30	Zn (ppm)	323	312	71	Lu (ppb)	25.4	24.3
31	Ga (ppm)	9.71	10.0	72	Hf (ppb)	107	104
32	Ge (ppm)	32.6	32.7	73	Ta (ppb)	14.2	14.2
33	As (ppm)	1.81	1.86	74	W (ppb)	90.3	92.6
34	Se (ppm)	21.4	18.6	75	Re (ppb)	39.5	36.5
35	Br (ppm)	3.5	3.57	76	Os (ppb)	506	486
37	Rb (ppm)	2.32	2.30	77	Ir (ppb)	480	481
38	Sr (ppm)	7.26	7.80	78	Pt (ppb)	982	990
39	Y (ppm)	1.56	1.56	79	Au (ppb)	148	140
40	Zr (ppm)	3.86	3.94	80	Hg (ppb)	310	258
41	Nb (ppb)	247	246	81	Tl (ppb)	143	142
42	Mo (ppb)	928	928	82	Pb (ppb)	2530	2470
44	Ru (ppb)	683	712	83	Bi (ppb)	111	114
45	Rh (ppb)	140	134	90	Th (ppb)	29.8	29.4
46	Pd (ppb)	556	560	92	U (ppb)	7.8	8.1

* Two estimates of the composition of type CI carbonaceous chondrites. (1) Mean CI abundances from Palme, H. and Jones, A. (2004) in *Treatise on Geochemistry* (eds. H. D. Holland and K. K. Turekian), Elsevier, vol. 1, Section 1.03, Table 3, p. 49. (2) Mean CI chondrite composition from Anders, E. and Grevesse, N. (1989) *GCA* **53**, Table 1, p. 158. Little significant change has occurred in the 15 year interval between the two estimates.

respectively, contain only 1 or 2 Earth-masses of gas and are mostly composed of ice and rock. These ice giants are analogues for the cores of Jupiter and Saturn. The difference is that Jupiter and Saturn have captured much larger amounts of gas. In addition to the distinction in composition between these giants and the terrestrial planets, there is also a major contrast in mass. Mercury, Venus, Earth, the Moon and Mars contain only a trivial amount (2 Earth-masses of rock) compared with the total of 440 Earth-masses of gases, ices and rock that reside in the giant planets.

It was only after the Sun began the hydrogen to helium nuclear reactions that strong solar winds developed, sweeping out the inner nebula, with the ices condensing at 5 AU at a so-called “snow line”. The formation of the planets was thus a very late event in the history of the disk, beginning only after the Sun had entered the T Tauri stage of solar evolution [5]. This enhancement at the snow line of ices and dust, locally increased the density of the nebula by around 5 AU and led to the rapid (10^5 year) runaway growth of bodies of ices and dust of around 10–15 Earth-masses. It is likely that four cores formed of which the ice giants Uranus (14.5 Earth-mass) and Neptune (17.2 Earth-mass) are surviving examples.

The lifetime of the nebula was only a few million years. Disks around stars have lifetimes between three and six million years so that Jupiter and Saturn had to acquire their complement of gases within that period [6]. The early growth of these massive cores enabled them to begin capturing the gases (H and He) before the nebula was dispersed. Perhaps either the core of Jupiter grew faster than the others, or it was closer to the Sun. Whatever the sequence, Jupiter was able to accrete about 300 Earth-masses of gases. This is much less than that present in the original nebula, with the result that Jupiter does not have the composition of the Sun, but is enriched in the ices and rock component, or metals by a factor between 3 and 13 [7]. Saturn, with a similar size core, managed to capture only about 80 Earth-masses of gas and so is more strongly “non-solar” in composition. Uranus and Neptune lost out almost completely and finished up with 1 or 2 Earth-masses of gas.

These non-solar compositions of the giant planets are key evidence for their “bottom-up” or core accretion models of formation from the solar nebula. The core accretion model indeed faces some problems of timing relative to the lifetimes of nebulae, although the times required to form the cores and collapse the gases on to them are not well constrained and probably can be fitted into the few million years of disk lifetimes.

The alternative model for giant planet formation by condensation directly from the gaseous nebula is usually referred to as the disk instability model. Its main attraction is fast formation (a few thousand years), but it also faces theoretical difficulties. Although disks may break up, whether giant planets form from these clumps remains uncertain [8]. Apart from this, there are two fatal flaws. First, the