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978-0-521-84186-3 - Planetary Crusts: Their Composition, Origin and Evolution
Stuart Ross Taylor and Scott M. McLennan
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# PLANETARY CRUSTS: THEIR COMPOSITION, ORIGIN AND EVOLUTION

*Planetary Crusts* is the first book to explain how and why solid planets and satellites develop crusts. This extensively referenced and annotated volume presents a geochemical and geological survey of the crusts of the Moon, Mercury, Venus, the Earth and Mars, as well as the distinct crusts of the asteroid Vesta and the satellites Io, Europa, Ganymede, Callisto, Titan and Triton.

Spanning a much wider compass than mere descriptions of the diverse crusts encountered throughout the Solar System, the book begins with a discussion of the nature of Solar System bodies and their formation. The authors then adopt a comparative approach to investigate the many current controversies surrounding the development and evolution of planetary crusts. These include the origin of the Moon and Mercury, the nature of the Mercurian plains, the exotic chemistry of Mars, differences in the geological histories of Venus and Earth, the significance of the rare earth element europium, the primitive crusts on the Earth, the onset of plate tectonics, the composition of the mantle, the origin of granites, why Ganymede differs from Callisto, and many other debated topics. The authors conclude that stochastic processes dominate crustal development, and the book ends with a discussion of the likelihood of Earth-like planets and plate tectonics existing elsewhere in the cosmos.

Written by two of the world's leading authorities on the subject, this book presents an up-to-date survey of the numerous scientific problems surrounding crustal development. It is a key reference for researchers and students in geology, geochemistry, planetary science, astrobiology, and astronomy.

STUART ROSS TAYLOR was born in New Zealand and is now an Emeritus Professor at the Australian National University. He is a trace element geochemist and carried out the initial analysis of the first lunar sample returned to Earth at NASA, Houston in 1969. He has a D. Sc. from the University of Oxford, is a Foreign Member of the US National Academy of Sciences, and has received the Goldschmidt Medal of the Geochemical Society, the Leonard Medal of the Meteoritical Society, and the Bucher Medal of the American Geophysical Union. He is the author of 6 other books including *Solar System Evolution,* Second edition (Cambridge University Press, 2001). Asteroid 5670 is named Rosstaylor in his honour.

SCOTT M. MCLENNAN is Professor of Geochemistry at the State University of New York at Stony Brook. He conducts research into the geochemistry of sedimentary rocks, and has published 140 papers in the fields of geochemistry, planetary science and sedimentology. Since 1998, he has applied laboratory experiments and data returned from missions to Mars to understand the sedimentary processes of that planet, and is on the science teams of the 2003 Mars Exploration Rover and 2001 Mars Odyssey missions. He received a Presidential Young Investigator Award from the National Science Foundation in 1989 and a NASA Group Achievement Award as part of the Mars Exploration Rover Science Operations Team in 2004.

Professors Taylor and McLennan are also the authors of *The Continental Crust: Its Composition and Evolution* (1985).

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Ross dedicates this book to Angelo in the hope that he will find the planets just as interesting as has his grandfather.

Scott dedicates the book to his wife Fiona and daughter Kate.

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# Preface

This work is not intended as a textbook, or as a review, but represents an enquiry into the problem of how and why solid planets produce crusts. As this seems to have happened at many different scales throughout the Solar System, we were curious to see whether some general principles might emerge from the detail. The formation of the planets themselves is the outcome of essentially random processes, constrained mainly by the history of the inner nebula and by the cosmochemical abundances of the chemical elements. But perhaps the production of crusts might be a simpler or more uniform process, a notion supported by the frequent appearance of basaltic lavas of assorted types on the surfaces of rocky bodies.

This book is also written from geochemical and geological perspectives, the areas with which the authors are most familiar. We were immediately faced with the problems of ordering the discussion in a logical sequence because "good reasons could be found for placing every chapter before every other chapter" [1]. Although one might reasonably expect to begin such a book with a discussion of the continental crust on which we are standing, this useful feature, like the Earth itself in a wider planetary context, is one of the least enlightening places from which to discover how planets form crusts. For this reason, our familiar continental crust appears late in the discussion. We decided instead to begin with simpler examples.

The formation of the two types of crust on the Moon, the highlands and the maria, indeed form the clearest and best understood examples of the complex processes that lead solid bodies in the Solar System to form crusts. So after considering the formation of the Solar System, we open the debate with the interesting and well-resolved example of primary and secondary crusts on the Moon. Next we describe what little is known about the crust of Mercury, that forms at present the closest analogue to the well-studied lunar example.

The recent investigations of the martian crust provide an excellent example of the complexities of crustal development on a more evolved planet. Mars is one of the few planetary bodies for which samples, in the form of martian meteorites,

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are available for study. The amount of information now available for Mars is substantial enough to warrant two chapters. The strange case of Venus, our "twin planet", discussed next, shows bizarre contrasts to the familiar geology of the Earth and provides a sobering insight into how similar planets can develop in different directions throughout geological time.

The five chapters on terrestrial crusts that follow illustrate the unique importance of water in crustal development. Beginning with the oceanic crust, another example of a secondary crust, we discuss in the following four chapters, the development of our useful continental crust. These latter chapters illustrate the complexities of terrestrial crustal development, the onset of plate tectonics and the slow evolution of the present continental crust from its enigmatic beginning in the Hadean.

In the penultimate chapter, some readers may be surprised to find a discussion about the crust of an asteroid and of some of the major satellites of the giant planets. However, these provide further examples of crustal diversity, as well as providing insights into early planetary evolution. Their crusts likewise provide interesting contrasts with those in the familiar inner Solar System. We conclude with some speculations on the likelihood of extra-solar examples of geological processes such as plate tectonics and of the possible presence of Earth-like planets with benign crusts elsewhere. We close each of the major chapters with a synopsis of the salient points.

We hope that the broader perspective adopted in this book will encourage our more terrestrially oriented colleagues to consider the interesting and unusual scientific problems presented by other bodies in the Solar System. Here we are mainly concerned with why and how crusts develop on planets in the Solar System rather than with local geological details that are unique to each planet. While interesting in their own right, the details on the Earth, for example of the formation of mountain ranges, or the location of subduction zones, belong in another treatise. Thus while continent–continent collisions may be broadly similar, the resulting geology exposed for our observation may be strikingly different. For example the European Alps, derived from the collision between Africa and Europe, differ in much tectonic detail from the Himalaya and the Tibetan Plateau, that formed from the collision of India with Asia during the Tertiary.

The operations of these stochastic processes mimic, on a smaller scale, the larger-scale sequence of random events that led to the accretion of the terrestrial planets. Thus readers seeking enlightenment on topics such as the tectonic evolution of the Archean crust of the Earth or the manner of the accretion of terranes to cratons during the assembly of continents on the Earth will need to look elsewhere [2].

The proliferation of planetary missions over the past decade, especially to Mars, has resulted in a tidal wave of spectral data and truly spectacular images. Although some of these results are of direct interest to our enquiry, most shed light more on

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surface processes and geological phenomena. Accordingly, we have resisted the temptation to focus too much of our attention on these pictures, stunning as they may be. We use planetary images sparingly, mostly where they illustrate specific points being discussed.

Although we try to refer to much of the relevant literature, the book is not intended as a review, but reflects our assessment of the evidence. Here we have chosen to take a broad overview so that many may become irritated by a perceived cavalier treatment of their specialty. However, specialist treatises often suffer from the Law of Diminishing Returns (witness the proliferation of multi-author volumes on the Archean or on the early Solar System) and we make no apology for this attempt to widen horizons.

Here we have attempted to give references to all sources of fact, information, opinion and interpretation other than our own. The rapidly increasing number of papers on all topics has made it inevitable that we have missed some significant contributions. We apologize for such omissions and have found the existence of “invisible colleges”, within which authors circulate their preprints, to be a partial solution in dealing with the deluge.

We list references by number in order of appearance in each chapter, rather than break up the continuity of the text with lists of names and dates. Except for two-author papers, first authors only followed by *et al.* are given, as it is pointless in a work such as this to provide lists of authors that on occasion extend to 50 or more names [3]. Most material is easily accessible on the Smithsonian/NASA ADS Abstract Service or Georef (the premier database from the American Geological Institute).

We have referenced mostly more recent works, except where older papers have acquired classic status, remain the sole source of information or provide cautionary tales. The average lifetime of a scientific paper rarely exceeds five years. After that period, the results are either incorporated into the general corpus or, if erroneous, are mostly ignored. We have excluded all references to conference abstracts and other grey literature except in a few cases where the information is not available elsewhere. We rarely include references to websites and the like, regarding them as too ephemeral for incorporation here. We have attempted to survey the literature through 2007.

In attempting such a broad synthesis, we are conscious of the risks either of offending the specialist or of boring the general reader. The individual chapters and sections could be the subject of books in their own right (and in many cases have become so). In trying to solve this problem, extensive use has been made of notes and comments that attempt to steer a course between the Scylla of minutiae and the Charybdis of lack of precision. However, the huge amount of literature that we feel requires comment means that the material in the notes sometimes exceeds the length of the discussion in the main text.

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We have endeavoured, not always successfully in such a seriously overloaded discipline, to avoid jargon and acronyms, which continue to spread like a virus. Among much bad usage, it seems impossible to read anything about Precambrian geology without encountering those terrible twins, autochthonous and allochthonous. These have displaced the basic English terms, native and foreign, with words that demonstrate the erudition of the writer and send the less erudite searching for their dictionaries. However, like much jargon (delamination is another example), such usage casts a veneer of understanding that serves to obscure the underlying complexities. Sophistication should not be confused with explanation.

Elemental abundances, as in the vast majority of the geochemical literature, are given in wt%, ppm, ppb or ppt rather than as wt%, mg/g, ng/g, μg/g or pg/g. We regard the latter convention as likely to lead to error and confusion, as well as having elements of scientific pretension. As wt% (parts per 100) has been retained in this latter usage, it even lacks the pedantic excuse of consistency. Density is expressed in units of $g/cm^3$ rather than $kg/m^3$ because most of the geological and geophysical literature continues to use these units. We list units of pressure as kilobars (kbar) or gigapascals (GPa) as appropriate [4]. We apologize that in the absence of better alternatives for these stupendous periods of time, millions of years are abbreviated to Myr and billions of years to Gyr.

Books should reflect the opinions of the authors. It is no service to readers to provide a list of ongoing controversies or of problems without making some assessment of a likely resolution or outcome. This is indeed not without hazard. Here we have attempted to give our own judgment on such controversial matters as the existence of plate tectonics in the Archean, the nature of the Hadean crust of the Earth, the value of the decay constant for $^{176}$Lu, the stratigraphic record on Venus, the evolution of Mars, the age of martian meteorites, the composition of the continental crust and of the Earth and many other difficult topics. On occasion, as in the discussion of mantle plumes, the origin of eucrites or the source of the bodies responsible for the lunar "cataclysm", we have preferred to wait for new evidence.

Meanwhile, as Francis Bacon remarked, we remain conscious of "the subtilty (sic) of Nature, the secret recesses of truth, the obscurity of things, the difficulty of experiment, the implication of causes and the infirmity of man's discerning power" [5].

## Notes and references

1. Kerridge J. F. (1988) *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), University of Arizona Press, p. xvi.
2. Among the masses of literature on these subjects, excellent expositions can be found in Cloud, P. (1988) *Oasis in Space: Earth History from the Beginning*, W.W. Norton; and (2002) in *The Early Earth: Physical, Chemical and Biological Development* (eds.

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C. M. R. Fowler *et al*., 2002), Geological Society of London Special Publication 199. The assembly of the terrestrial continents, is well treated in Rogers, J. J. W. and Santosh, M. (2004) *Continents and Supercontinents*, Oxford University Press; and in Bleeker, W. (2003) The late Archean record: a puzzle in *c*. 35 pieces. *Lithos* **71**, 99–134. A good example of the problems involved in such reconstructions can be found in Windley, B. F. *et al*. (2007) Tectonic models for accretion of the Central Asian orogenic belt. *J. Geol. Soc. London* **164**, 31–47.

3. Workers in particle physics are even less (or more) fortunate with lists of authors often exceeding 500.
4. As 10 kbar equals one GPa, we wonder about the necessity for this change, apart from the need to celebrate the life of that distinguished French scientist, Blaise Pascal (1623–1662). Bars bear an obvious relationship to atmospheric pressure, just as cycles per second seem more understandable than Hertz. We deplore the attempts of committees to force-feed the use of "international units". It is interesting that that useful unit, the Angstrom ($10^{-8}$ cm, about the size of an atom) has survived the attempts of such committees to order the universe in multiples of 1000 from an essentially arbitrary base.
5. This translation from Latin of aphorism 92 from "*Novum organum*" by Francis Bacon (1620) is from Peter Medawar (1979) in *Advice to a Young Scientist*, Pan Books, p. 6.

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First we wish to acknowledge the continued support and patience of our families during the writing of this book. Ross thanks Richard Arculus and David Ellis of the Department of Earth and Marine Sciences at the Australian National University for much encouragement and advice. Ross also wishes to thank Brian Harrold (Department of Earth and Marine Sciences, Australian National University) for crucial assistance with computing and the Australian National University for the award of a Visiting Fellowship that has enabled this book to be written. We are highly appreciative of the assistance of Dr Judith Caton (Department of Earth and Marine Sciences, Australian National University) who has transformed many of our rough drafts of the figures and tables.

Scott wishes to thank his graduate students, past and present, for helping to create a rich and exciting environment for studying crustal processes on both Earth and Mars. He is also grateful to the entire Mars Exploration Rover and Mars Odyssey science teams who, over the past four years, have brought to life in exquisite detail the geology of another planet.

We are grateful to Simon Mitton and particularly to Susan Francis of Cambridge University Press for their encouragement to write this book, for the assistance of Diya Gupta and Eleanor Collins during production, to Zoë Lewin for meticulous copy-editing and all for their patience in dealing with contrary authors.

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Chapter 2 Lunar highlands and Chapter 3 Lunar maria: Marc Norman (Australian National University).

Chapter 4 Mercury: Bob Strom (University of Arizona).

Chapter 5 Mars: planetary composition: Jeff Taylor (University of Hawaii).

Chapter 6 Mars: crustal composition: Hap McSween (University of Tennessee) and Jeff Taylor (University of Hawaii).

Chapter 7 Venus: Ellen Stofan (Proxemy Research, VA).

Chapter 8 Oceanic crust: Mike Perfit (University of Florida).

Chapter 9 The Hadean: Balz Kamber (Laurentian University, Sudbury, Canada).

Chapter 10 The Archean: Stephen Moorbath (University of Oxford).

Chapter 11 The Post-Archean and Chapter 12 The continental crust: Richard Arculus (Australian National University).

Chapter 13 Minor bodies: Brett Gladman (University of British Columbia) and Bill McKinnon (Washington University, St Louis).

They have performed an invaluable service, saving us from various misinterpretations and errors. We remain completely responsible for any mistakes and omissions.

# Abbreviations

Here we list those that appear commonly throughout the text and that may not be familiar to some readers.

| | |
|---|---|
| Å: | Ångstrom unit ($10^{-8}$ cm) |
| AGU: | American Geophysical Union |
| AU: | Astronomical unit (149 597 871 km) |
| CI: | Type 1 carbonaceous chondrites |
| EPSL: | Earth and Planetary Science Letters |
| GCA: | Geochimica et Cosmochimica Acta |
| GRL: | Geophysical Research Letters |
| GSA: | Geological Society of America |
| HREE: | Rare earth elements Gd through to Lu |
| JGR: | Journal of Geophysical Research |
| KREEP: | Acronym from potassium, rare earth elements and phosphorus |
| LIL: | Large ion lithophile |
| LPI: | Lunar and Planetary Institute, Houston, Texas |
| LPSC: | Lunar and Planetary Science Conference |
| LREE: | Rare earth elements La through to Sm |
| MORB: | Mid-ocean ridge basalt |
| MPS: | Meteoritics and Planetary Science |
| OIB: | Oceanic island basalt |
| PEPI: | Physics of the Earth and Planetary Interiors |
| ppb: | Parts per billion ($10^9$, hg/g) |
| ppm: | Parts per million ($10^6$, μg/g) |
| ppt: | Parts per trillion ($10^{12}$, pg/g) |
| REE: | Rare earth elements |