The Solid Earth

From the citation for the Prestwich Medal of the Geological Society, 1996 (awarded for the contribution made by *The Solid Earth* to geophysics teaching and research) by the then President Professor R. S. J. Sparks F.R.S.

The Prestwich Medal is given for major contributions to earth science, and provides an opportunity for the Society to recognise achievements in areas that can lie outside the terms of reference of its other awards. This year, the Prestwich Medal has been given to Mary Fowler for the contribution of her book, *The Solid Earth*, which has had an enormous impact. The book has been acclaimed by today's leading geophysicists. There is consensus that, although there are many books covering various aspects of geophysics, there are only a small number that can be seen as landmarks in the subject. Mary's book has been compared to Jeffreys's *The Earth* and Holmes's *Physical Geology*.

The Solid Earth is recognised by her peers as a monumental contribution. In this book she displays a wide knowledge of a very broad range of geological and geophysical topics at a very high level. The book provides a balanced and thoroughly researched account which is accessible to undergraduates as well as to active researchers.

The book has been described as one of the outstanding texts in modern earth sciences.

(*Geoscientist*, Geological Society, 1996, Vol. **6**, No. 5, p. 24.)

MARY FOWLER is Professor of Geophysics and Head of the Earth Sciences Department at Royal Holloway, University of London. She studied Mathematics at the University of Cambridge, as a student of Lady Jeffreys, and was then taken on as a PhD student by Sir Edward Bullard. Her thesis was on the structure of the Mid-Atlantic Ridge, supervised by Drummond Matthews and Brian Kennett. Seismological research at ETH Zurich, Switzerland followed and then adjunct status at the University of Saskatchewan, Canada where she taught, wrote the first edition of *The Solid Earth* and participated in Lithoprobe studies. For ten years her involvement with science was largely honorary while she raised her family.

In 1992 she moved to Royal Holloway. Since then she has served as Vice-President of the Royal Astronomical Society, as a Member of the Bureau of the International Lithosphere Program ILP, and on the Council of the Royal Astronomical Society, Council of the Geological Society, and the Governing Board of the School of Cosmic Physics in the Dublin Institute for Advanced Studies. In addition, she has been a member of various advisory panels for the UK Natural Environment Research Council and the Research Assessment Exercise of the Higher Education Funding Council for England. She has served as an Associate Editor for the *Journal of Geophysical Research* and *Reviews of Geophysics*. Her edited books are *Heat*, *Metamorphism and Tectonics* (Nisbet and Fowler, 1988) and *The Early Earth: Physical, Chemical and Biological Development* (Fowler, Ebinger and Hawkesworth, 2002).

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An Introduction to Global Geophysics

Second Edition

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TO MY FAMILY

Magna opera domini exoquisita in omnes voluntates ejus.

The works of the Lord are great, sought out of all them that have pleasure therein.

Psalm 111.2: at the entrance to the old Cavendish Laboratories, Cambridge.

Contents

The colour plates are situated between pages 398 and 399.

Preface to the first edition

Geophysics is a diverse science. At its best it has the rigour of physics and the vigour of geology. Its subject is the Earth. How does the Earth work? What is its composition? How has it changed? Thirty years ago many of the answers to these questions were uncertain. We knew the gross structure of our planet and that earthquakes occurred, volcanoes erupted and high mountains existed, but we did not understand why. Today we have a general knowledge of the workings of the planet, although there is still much to be discovered.

My aim in writing this book was to convey in a fairly elementary way what we know of the structure and dynamics of the solid Earth. The fabric of geophysics has changed dramatically in the decades since the discovery of plate tectonics. The book places a strong emphasis on geophysical research since the initial formulation of plate theory, and the discussion centres on the crust and upper mantle. It also outlines the recent increases in our knowledge of the planet's deeper interior.

To whom is this book addressed? It is designed to serve as an introduction to geophysics for senior undergraduates in geology or physics and for graduate students in either subject who need to learn the elements of geophysics. My hope is that the book will give them a fairly comprehensive basis on which to build an understanding of the solid Earth.

Part of the challenge in writing a geophysics text is to make the book accessible to both types of student. For instance, some students enter the study of geophysics from a background in the Earth sciences, others from physics or mathematics: only a few enroll directly in geophysics programmes. Geology students tend to know about rocks and volcanoes, but possess only the basics of calculus. In contrast, students of physics have good mathematical skills, but do not know the difference between a basalt and a granite. I have attempted throughout the book to explain for the geologists the mathematical methods and derivations and to include worked examples as well as questions. I hope that this will make the book useful to students who have only introductory calculus. For the non-geologists, I have tried to limit or explain the abundant geological terminology. There is a glossary of terms, to rescue physics students lost in the undergrowth of nomenclature.

For more advanced students of either geological or physical training I have in places included more mathematical detail than is necessary for a basic

introductory course. This detail can easily be by-passed without either interrupting the continuity of the text or weakening the understanding of less mathematical students. Throughout the book I have attempted to give every step of logic so that students can understand why every equation and each conclusion is valid.

In general, I have tried to avoid the conventional order of textbooks in which geophysical theory comes first, developed historically, followed in later sections by interesting and concrete examples. For instance, because the book focuses to a large extent on plate-tectonic theory, which is basic to the study of the crust and mantle, this theory is introduced in its proper geophysical sense, with a discussion of rotation, motions on plate boundaries and absolute plate motions. Most geological texts avoid discussing this, relying instead on two-dimensional cartoons of ridges and subduction zones. I have met many graduate students who have no idea what a rotation pole is. Their instructors thought the knowledge irrelevant. Yet understanding tectonics on a sphere is crucial to geophysics because one cannot fully comprehend plate motion without it.

The next chapters of the book are concerned with past plate motions, magnetics, seismology and gravity. These are the tools with which plate tectonics was discovered. The exposition is not historical, although historical details are given. The present generation of geophysicists learned by error and discovery, but the next generation will begin with a complete structure on which to build their own inventions.

These chapters are followed by discussions of radioactivity and heat. The Earth is a heat engine, and the discovery of radioactivity radically changed our appreciation of the physical aspects of the planet's history, thermal evolution and dynamics. The study of isotopes in the Earth is now, perhaps unfairly, regarded as an area of geochemistry rather than of geophysics; nevertheless, the basic tools of dating, at least, should be part of any geophysics course. Understanding heat, on the other hand, is central to geophysics and fundamental to our appreciation of the living planet. All geology and geophysics, indeed the existence of life itself, depend on the Earth's thermal behaviour. Heat is accordingly discussed in some detail.

The final chapters use the knowledge built up in the earlier ones to create an integrated picture of the complex operation of the oceanic and continental lithosphere, its growth and deformation. The workshops of geology – ridges and subduction zones – are described from both geophysical and petrological viewpoints. Sedimentary basins and continental margins employ most of the world's geophysicists. It is important that those who explore the wealth or perils of these regions know the broader background of their habitat.

SI units have been used except in cases where other units are clearly more appropriate. Relative plate motions are quoted in centimetres or millimetres per year, not in metres per second. Geological time and ages are quoted in millions or billions of years (Ma or Ga) instead of seconds. Temperatures are quoted in

degrees Centigrade (°C), not Kelvin (K). Seismic velocities are in kilometres per second, not in metres per second.

Most geophysicists look for oil. Some worry about earthquakes or landslips, or advise governments. Some are research workers or teach at universities. Uniting this diversity is a deep interest in the Earth. Geophysics is a rigorous scientific discipline, but it is also interesting and fun. The student reader to whom this book is addressed will need rigour and discipline and often hard work, but the reward is an understanding of our planet. It is worth it.

Preface to the second edition

Since the first edition was published in 1990 computers have revolutionized geophysics and all of the Earth sciences just as they have our daily lives. Huge datasets can be manipulated, complex computations performed and detailed colour images plotted. An understanding of the fine details of the workings of the many processes taking place within the Earth is becoming achievable and a synthesis of the interactions of the hitherto rather separate disciplines of geochemistry, dynamics, heat and seismology has become possible. This has been an exciting decade for advances in our comprehension of the interior working of the Earth.

I have kept the overall format and structure of the book unchanged from the first edition. Many people have contacted me and seemed to like the approach that I used. I have taken many of their detailed suggestions into consideration when preparing this new edition. Changes have not been made for the sake of using the latest publications, but where there have been significant advances. Older references and sources have been retained in order to lead students to papers of value that they would not otherwise meet, and to show how major steps in understanding were achieved. The major change from the first edition is that the deep internal structure of the Earth and mantle and core processes are now covered in a separate chapter rather than being included in the chapters on seismology and heat. The other substantial change is the addition of a section of colour plates.

Acknowledgements to the first edition

Textbooks are not easy to write. They need to have an author, of course, but much of the work is done by an array of encouragers, teachers and critics. Lady Jeffreys introduced me to Sir Edward Bullard, who made geophysics sound fun. To Drummond Matthews, Dan McKenzie and Brian Kennett, as well as to those who were students with me, I owe much. Ships and rocks are much more exciting than a life crouched over computers and equations.

In writing this book I have been helped by many people. P. H. Fowler, D. P. McKenzie, E. G. Nisbet, A. Prugger, C. Sammis and P. J. Smith, together with several anonymous reviewers, read most or all of the manuscript, making many useful suggestions and pointing out errors. Since the manuscript was long the task was large. I am very grateful. For detailed critiques of individual chapters I am indebted to M. J. Bickle, P. van Calsteren, S. R. Fowler, D. Gubbins, E. Hegner, J. A. Jacobs, T. K. Kyser, J. B. Merriam, B. I. Pandit, J. A. Pearce, G. M. Purdy, G. Quinlan, R. S. White and P. J. Wyllie. The expertise and solid criticism of these kind people helped greatly in my quest for accuracy in so many fields in which I am not a specialist. Many people, including T. Atwater, D. R. Barraclough, R. M. Clowes, R. G. Coleman, A. M. Dziewonski, Sir Charles Frank, R. G. Gordon, A. G. Green, N. B. W. Harris, W. Haxby, E. Irving, J. A. Jackson, C. E. Keen, S. Klemperer, K. D. Klitgord, R. A. Langel, R. D. Lindwall, H. Nevanlinna, N. W. Peddie, J. A. Percival, G. M. Purdy, M. P. Ryan, J. G. Sclater, C. R. Scotese, A. G. Smith, J. F. Sweeney, J. Verrall and M. L. Zoback, have given advice on specific details, and sent prints of their figures or preprints and reprints of their articles. I am very appreciative of their help. The geodynamics lectures given in Cambridge by Geoff King provided the basis for my presentation of relative plate motions in Chapter . Most of all, I wish to acknowledge the generous and painstaking help of Walter Pilant, who read the text not once but twice, and pointed out much error and infelicity. Despite all this help there are bound to be mistakes. For these I apologise; they are entirely my fault, either as errors of understanding or as errors of printing. My hope is that they will be few.

I should like to thank W. G. E. Caldwell and H. E. Hendry, who as respective chairmen of the Department of Geological Sciences at the University of Saskatchewan provided the facilities and encouragement that enabled me to undertake this project. A. Heppner showed immense tolerance and patience in typing many versions of the enormous manuscript, while A. C. Williamson made

it possible for me to write. Lindsay Embree drew many of the figures. Peter-John Leone's enthusiasm and the diligent, careful work of Mary Nevader and Glenn Cochran created a book from a pile of paper. Thank you.

I thank my children for their forbearance over the past few years. In fact, without a family I would probably not have had the opportunity and time to undertake the writing of this book; I would have been too busy doing other things such as writing papers and sitting on committees. Finally, I thank Euan for constant encouragement, help and advice.

Acknowledgements to the second edition

A second edition should, I thought, be much easier to write than the first. Now I am not so sure! Pruning, altering and adding to the first edition of *The Solid Earth* in order to create the second edition has not been easy. I have been helped and encouraged greatly by many friends and colleagues without whom this book would not be the same. Many people have helped enormously by letting me know how they used the book for teaching and which sections they felt could be improved or extended and by pointing out spelling and typographical errors and inconsistency. Some have helped by sending reprints and preprints. Others have provided invaluable assistance by sending data and figures. They include Robin Adams, Falk Amelung, Donna Blackman, Derek Blundell, Carl Bowin, Mike Brudzinski, Peter Bunge, Joe Cann, Rudolphe Cattin, Cindy Ebinger, Cliff Frohlich, Saskia Goes, Steve Grand, Akira Hasegawa, Tim Henstock, Ted Irving, Wilfried Jokat, Hans-Gert Kahle, Dan MacKenzie, Didier Massonnet, Guy Masters, Lisa McNeill, Jim Mechie, Neil Mitchell, Walter Mooney, Christian Mueller, Otto Muller, David Price, Barbara Romanowicz, Peter Shearer, Wim Spakman, Rob van der Hilst, Doug Wiens, Cecily Wolfe and George Zandt. Others have read and commented on chapters and sections for me: J. Baker, M. F. Thirlwall, R. Cattin, C. Chauvel and E. G. Nisbet. Graeme Eagles undertook the huge task of preparing large numbers of figures and plates. Other people who have helped by drafting figures and to whom I am very grateful are James McGrow, Nicola Wilson, Nigel Rata, Louise Anderson, Susan Macmillan, Kylara Martin and Grace Nisbet. Many figures have been produced using the GMT software of Paul Wessel and Walter H. F. Smith (Wessel, P. and Smith, W. H. F. 1991. *EOS Trans. Am. Geophys. Un.*, **72**, 441). I am most grateful to everyone, named and anonymous – thank you all very much indeed for your contributions.

I am indebted to The Geological Society, who awarded me their Prestwich Medal in 1996, its centenary year, for *The Solid Earth*. That was an honour that quite amazed me; I just hope that this new edition continues to be as useful and helpful to students, teachers and researchers as the first edition seems to have been.

As ever, my final thanks must go to my family for their continual encouragement, advice and tolerance.