

DEEP EARTHQUAKES

This is the first book to present a comprehensive description and discussion of ‘deep earthquakes’ – earthquakes with origins deeper than 60 km, including some with depths as great as 650–700 km. Deep earthquakes are scientifically important because they account for approximately one-quarter of all earthquakes; because a few are very large and damaging; because they provide much of the data that constrain our knowledge of Earth structure and dynamics; and because scientists still don’t fully understand the mechanical processes that allow them to occur.

The first three chapters explain what deep earthquakes are, why they are important, and how they were first discovered. The next three chapters describe the distributions of their depths and size, evaluate how they cluster in both time and space, and review observation about their source properties. There are then three chapters that discuss theories for the origin of deep earthquakes and the significance of deep earthquakes for contemporary science. The final chapter is a comprehensive geographic summary of the literature about deep seismicity for 27 individual terrestrial regions and the Earth’s Moon.

Deep Earthquakes presents a comprehensive, topical, historical, and geographical summary of deep earthquakes and related phenomena. It will be of considerable interest to researchers and graduate students in the fields of earthquake seismology and deep Earth structure.

CLIFF FROHLICH received a Ph.D. in physics from Cornell University in 1976. Since 1978 he has been employed as a research scientist at the University of Texas at Austin where he is now Associate Director of the Institute for Geophysics. The majority of his many scholarly publications concern deep earthquakes, the statistical analysis of earthquakes catalogs, and regional tectonics. His first book, *Texas Earthquakes*, coauthored with Scott D. Davis, was published in 2002. Dr Frohlich also has a keen interest in the physics of sport and is the author of a paper on the physics of diving and gymnastics for *Scientific American*.

Cambridge University Press
0521828694 - Deep Earthquakes
Cliff Frohlich
Frontmatter
[More information](#)

DEEP EARTHQUAKES

CLIFF FROHLICH

*Institute for Geophysics, Jackson School of Geosciences
University of Texas at Austin*



Cambridge University Press
0521828694 - Deep Earthquakes
Cliff Frohlich
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo
Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK
Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521828697
© C. Frohlich 2006

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2006

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN-13 978-0-521-82869-7 hardback
ISBN-10 0-521-82869-4 hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page viii</i>
I Background and introductory material	
1 The big, the bad, and the curious	3
1.1 The big: 9 June 1994 Bolivia	4
1.2 The bad: 4 March 1977 Romania and 25 January 1939 Chile	13
1.3 The curious: 29 March 1954 Spain	21
1.4 What we know and what we don't know	25
1.5 References	27
2 What, where, how, and why?	30
2.1 What are deep-focus and intermediate-focus earthquakes?	30
2.2 Where are deep earthquakes?	34
2.3 How are deep and shallow earthquakes different?	36
2.4 How cool is it where deep earthquakes occur?	38
2.5 Why study deep earthquakes?	46
2.6 Previous reviews of deep earthquake literature	47
2.7 References	49
3 The history of deep earthquakes	53
3.1 Solid earth geophysics in 1900	53
3.2 The depth of normal earthquakes	54
3.3 The discovery of deep earthquakes	59
3.4 The discovery of Wadati–Benioff zones	66
3.5 The deep earthquake source	73
3.6 The deep earthquakes of history	84
3.7 References	88
II Properties of intermediate- and deep-focus earthquakes	95
4 The distributions of depth and size	97
4.1 What is focal depth?	97
4.2 The global distribution of earthquake focal depths	101

vi	<i>Contents</i>	
	4.3 What is earthquake size?	116
	4.4 The global distribution of deep earthquake sizes	123
	4.5 References	133
5	Spatial and temporal clustering	138
	5.1 Spatial clustering	138
	5.2 Temporal clustering	162
	5.3 Correlations with other phenomena	175
	5.4 References	177
III	The mechanism of deep earthquakes	
6	The deep earthquake source	191
	6.1 Source duration and size	191
	6.2 Directional properties of seismic radiation	222
	6.3 Focal mechanisms and Wadati–Benioff zone geometry	235
	6.4 References	244
7	The mechanics of deep earthquakes	252
	7.1 Fracture, friction, and flow	252
	7.2 Mechanisms that won’t work	256
	7.3 Mechanisms that might work	267
	7.4 Are deep quakes caused by more than one mechanism?	292
	7.5 References	294
IV	Why bother about deep earthquakes?	
8	Are deep earthquakes useful?	305
	8.1 Structure of the Earth	305
	8.2 Dynamics of the crust and mantle	315
	8.3 The earthquake source	321
	8.4 Perhaps deep earthquakes aren’t the whole answer	325
	8.5 References	328
9	Answered and unanswered questions	339
	9.1 What we know and what we don’t know	339
	9.2 How we came to know what we think we know	348
	9.3 References	361
V	Geographic summary	
10	A geographic summary of deep earthquakes	365
	10.1 Hjort Trench	372
	10.2 New Zealand	374
	10.3 Tonga–Kermadec	384
	10.4 Vitiaz Cluster and South Fiji Basin	395
	10.5 Vanuatu (New Hebrides)	399
	10.6 New Guinea–Solomons	402
	10.7 Indonesia (Sunda–Banda Arc)	409

Cambridge University Press
0521828694 - Deep Earthquakes
Cliff Frohlich
Frontmatter
[More information](#)

<i>Contents</i>	vii
10.8 Philippines	421
10.9 Ryukyu–Taiwan	427
10.10 Mariana–Bonin	431
10.11 Japan	439
10.12 Kuril–Hokkaido	449
10.13 Alaska and the Aleutians	462
10.14 Western North America	470
10.15 Central America	474
10.16 The Caribbean	482
10.17 Colombia–Venezuela–Panama	487
10.18 South America	493
10.19 South Shetland Islands	513
10.20 Scotia Arc	515
10.21 Spain and Morocco	520
10.22 Italy and the Tyrrhenian Sea	525
10.23 Greece and Turkey	530
10.24 Romania	535
10.25 The Middle East	541
10.26 Pamir–Hindu Kush	545
10.27 Burma	553
10.28 Other	557
10.29 Deep moonquakes	560
 <i>Earthquake index</i>	 568
<i>Index</i>	571

Preface

Why write a book on deep earthquakes?

On 21 January 1906 an earthquake with M_W of 7.4 occurred at a depth of 340 km beneath Japan. Fusakichi Omori, one of the world's finest seismologists of that time, located the event using (S-P) intervals, and concluded that at several Japanese seismograph stations the P waves were transverse and the S waves were longitudinal. This puzzled Omori, so he published a paper about this a year later (see Fig. 0.1 and Chapter 3). So began the story of deep earthquakes – Omori's (1907) paper is among the earliest publications in my collection of references on deep earthquakes.

Of course, for many reasons, Omori wouldn't have told the story of the beginning quite this way. In 1907 the magnitude scale hadn't yet been invented, and Omori's paper never uses the terms “P”, “S”, or “(S-P) interval”; rather, it mentions the “1st displacement,” the “2nd displacement,” and the “duration of 1st preliminary tremor.” Omori also didn't know that the earthquake was deep; indeed, he didn't even know that “normal” earthquakes occurred at depths of 40 km or less. Our perspective on earthquakes has changed considerably since 1907; my collection of references on deep earthquakes now has more than 2000 entries. We have learned a great deal about earthquakes over the past 100 years. For example, one thing we have learned is that deep earthquakes are quite common – nearly a third of all earthquakes located by the International Seismological Centre have focal depths exceeding 60 km; of these, about one fifth exceed 300 km.

The purpose of this book is to summarize what a century of research has taught us about deep earthquakes, i.e., earthquakes with focal depths of 60 km and greater. As far as I can tell, no one has written a summary book about deep earthquakes – ever. Thus, I submit that the passage of 100 years, the appearance of 2000 publications, and the absence of any other book marks a good time to review what we now know about deep earthquakes.

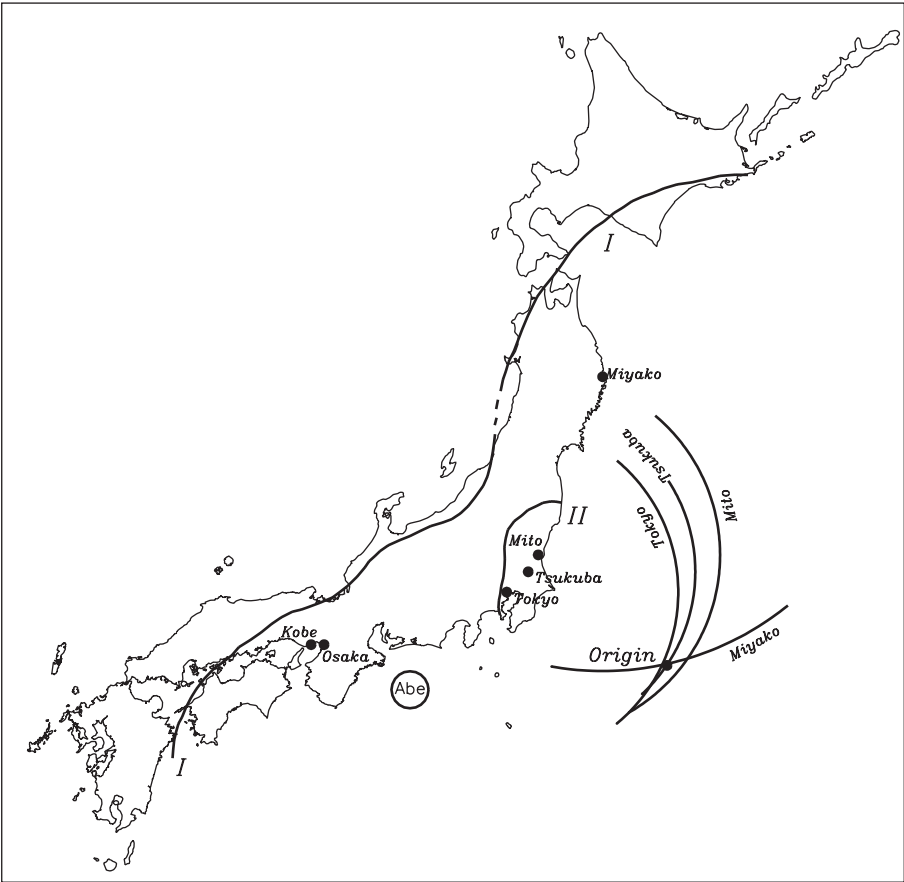


Fig. 0.1 Reproduction of Omori’s 1907 figure summarizing his observations of the Japan earthquake of 21 January 1906. The arcs indicate event-station distances determined from (S-P) intervals recorded at Tokyo, Mt. Tsukuba, Mito, and Miyako. Omori assumed that the earthquake was shallow and occurred east of Japan where the arcs crossed; a modern location (Abe, 1985) finds that it was deep and 360 km further west (circle labeled “Abe”). Roman numerals I and II show the boundaries of the area of “slight motion” and “strong motion,” respectively.

So, what do we know, and what don’t we know? Even if you take the time to read all those 2000 publications, the answers aren’t straightforward. This is because research papers don’t report only established facts or observations; they also interpret these observations and attempt to explain them with models and speculation. Thus, much that the literature reports isn’t well established – it often isn’t even true. For example, for the 1906 earthquake Omori concluded that P waves were transverse and S waves were longitudinal because he believed all earthquakes occurred at shallow depths and thus the (S-P) intervals proved his event occurred

east of his seismograph station, offshore of Japan (see Fig. 0.1). He was wrong, of course, because his model of earthquake location was wrong; in fact the earthquake was deep and situated almost directly beneath the recording stations.¹

Omori's mistake exemplifies a central theme of this book – that basic observations are the true essence of what we know. A model only helps us organize our observations; we simply throw it away when it doesn't serve us. Because one is never sure which models will survive, in this book I strive to distinguish between what the observations teach us about deep earthquakes, and what we think we know from models.

Of course, models are wonderfully useful for organizing data, for helping us recognize which observations are ordinary and which are interesting. For example, a few years after H. H. Turner announced that some earthquakes appeared to have depths as great as 400 km (Turner, 1922; see Chapter 3), Harold Jeffreys published a characteristically thorough analysis demonstrating why this wasn't possible (Jeffreys, 1928), asserting that "most earthquakes, including all large earthquakes, have focal depths not exceeding about 35 km." Jeffreys, besides being an earthquake seismologist, was an authority on isostasy and the thermal history of planets. His models explaining how the lithosphere supported mountains told him that the Earth's lithosphere could only be 30–100 km thick. How then can earthquakes occur at depths where the Earth doesn't maintain stresses? In particular, if increasing temperature at depth cause this lack of strength, how can earthquakes occur where it is so warm?

Jeffreys' arguments illustrate a second theme of this book: that temperature is an important parameter controlling how and where deep earthquakes do occur. Does the fact that Jeffreys was wrong and deep quakes really do occur mean that temperatures where they occur are very low? Or do they represent a mechanical phenomenon that is fundamentally different from earthquakes that occur in the lithosphere?

This book is organized into five sections; the first four sections present a topical review of deep earthquake phenomena. The first section presents background information and consists of three chapters:

- Chapter 1 introduces deep earthquakes by presenting observations about several large and significant twentieth century deep earthquakes;
- Chapter 2 defines what "deep" is, presents a simple model to estimate temperature within subducted lithosphere, and discusses why deep earthquakes are worth studying;
- Chapter 3 describes the discovery of deep earthquakes and explores their early history, concentrating primarily on the period prior to 1970.

¹ We mustn't be too hard on Omori. His research was extraordinary enough that I found it worth reading almost 100 years later. If anybody bothers to read this book a century from now, please contact my descendants and tell them I said "Hello."

The second section, with two chapters, focuses on the properties of earthquake catalogs:

- Chapter 4 looks at the distributions of focal depths, magnitudes, and scalar moments;
- Chapter 5 evaluates spatial and temporal clustering of hypocenters.

The third section addresses the mechanism of deep earthquakes:

- Chapter 6 reviews observations of source properties;
- Chapter 7 considers various mechanical models that explain the occurrence of deep earthquakes.

The fourth section considers why deep earthquakes have been and still are worth studying:

- Chapter 8 shows how the analysis of deep earthquake signals has provided key information about a great many features of Earth structure and dynamics;
- Chapter 9 considers what we have learned over the past 100 years, what we have still to learn, and deep earthquake research’s place in the history of the science.

Absent from these four sections is any sense of the character of deep seismicity in specific geographic regions; this is the topic of the fifth and last section – a single chapter – Chapter 10. This presents maps, cross sections, focal mechanisms, and a review of the literature for deep-focus and intermediate earthquakes in each of 28 geographic regions. The reader of Chapter 10 will learn that there are decided differences in the “flavor” of research in the various regions. For example, the majority of the literature concerning South America (Section 10.18) appears in well-known journals and concentrates on variations in the geometry of Wadati–Benioff zones, and also on the source properties of a number of extraordinarily large deep-focus earthquakes. In contrast, much of the literature on Romania (Section 10.24) appears in books, technical reports, and regional publications, and concerns models for evaluating hazard. Finally, many papers concerning Greek deep seismicity (Section 10.23) appear in European journals and focus on time-dependent trends in seismic activity or relations between deep seismicity and other phenomena, such as volcanism of geoelectric signals. Chapter 10 also includes descriptions of 58 individual deep earthquakes which are unusually large, important historically, or otherwise remarkable.

Each of the first nine chapters and each geographic summary in Chapter 10 is self-contained; i.e., mostly you can read them independently without reading preceding material. However, a few abbreviations that appear regularly throughout the book (see Table 0.1) won’t be explained repeatedly in each chapter. Separate reference lists follow each of the first nine chapters and each geographic summary. Some of these lists are quite long; thus, for readers desiring further guidance I have

Table 0.1. *Abbreviations used throughout this book.*

<i>Catalogs of hypocenters:</i> See detailed explanation and references in Chapter 10.	
Abe	Catalog published by Abe (1981) covering the period 1897–1980
CMT	Centroid moment tensor – and the catalog published by Harvard for the period 1977–present
CMT-Hist	Additional centroid moment tensors for the historical period 1906–1976 published by various sources
ISC	International Seismological Centre – and their catalog covering the years 1964–present
EHB	Engdahl, van der Hilst, and Buland (1998) – and their catalog comprised of selected relocations of ISC data 1964–2004
EV Centennial	Engdahl and Villaseñor (2002) – and their catalog covering the period 1900–1999
GR	Gutenberg and Richter (1954) – and their catalog covering the period 1904–1952
<i>Magnitude scales:</i>	
M_W	Moment magnitude determined from scalar moment M_o by the formula $M_W[N-m] = (2/3)\log_{10}M_o - 6$
M_S	Surface wave magnitude; usually as reported in the GR catalog
m_b	Short period body-wave magnitude, usually as reported in the ISC catalog
m_B	Longer-period body-wave magnitude, usually as reported in the Abe catalog
<i>Other abbreviations:</i>	
CLVD	Compensated linear vector dipole; see Section 6.2.1
h	Focal depth estimate for an earthquake
JHD	Joint hypocenter determination
NUVEL	Model describing the relative motions of tectonic plates; developed by DeMets <i>et al.</i> (1990; 1994)
pP depth	Focal depth determined from (pP–P) intervals; see Section 4.1.2
PREM	Preliminary reference earth model – a global model of velocity and elastic parameters proposed by Dziewonski and Anderson (1981)
USGS	United States Geological Survey
WWSSN	World Wide Standardized Seismograph Network

marked a few especially important, interesting, or comprehensive references with a “•”.

Why was this book written, really?

In 1935 Konrad Lorenz published a classic paper on the learning behavior of young ducklings and goslings. He noted that at certain specific developmental periods some animals seemed instinctively primed to learn quite remarkable behaviors. As an example, he observed that soon after hatching, baby ducklings learned to follow the first conspicuous moving object they saw – usually the mother duck. But, they

might also “imprint” on a bird of another species, a bright red ball, a scientist, or almost anything else, if they saw it at the appropriate time. Subsequently, the ducklings would continue to follow this imprint-parent, even if doing so didn’t make much sense.

In my experience, we scholars aren’t all that different from ducklings – at some key time in our university education – usually in graduate school – we open our eyes and imprint on some particular problem that seems interesting to us. Then we follow it blindly through our careers, steadfastly giving it the lion’s share of our attention, even if doing so doesn’t make much sense.

I here confess that, as a graduate student at Cornell University in about 1974, I imprinted on deep earthquakes. Actually, when I began graduate school I worked in a low-temperature laboratory operated by physicists John Reppy, Bob Richardson, and Dave Lee. The graduate student working on the apparatus next to mine was Doug Osheroff. Doug was having all kinds of trouble with a gauge that got stuck every time he tried to cool liquid helium mixtures below a certain temperature. It was clear to me that nothing would come out of this; Doug’s gauge was obviously faulty and everyone knew that near absolute zero nothing much happened.² I became disillusioned with low-temperature physics and soon switched to geophysics and earthquake seismology. Within a year I was studying deep earthquakes.

In the three subsequent decades I have maintained a steadfast and passionate interest in deep earthquakes in spite of distractions provided by numerous wives, children, and research grants which should have encouraged me to focus on something more practical. But, I can’t help myself; I just find deep earthquakes interesting; I am obsessed with deep earthquakes. Why I chose deep earthquakes and not something equally respectable, such as low-temperature physics, is a puzzle.

This book, then, is an attempt to do something useful with my obsession. If you share my interest in deep earthquakes, please use this book to move the subject forward in any way you can. Alternatively, if you are passionate about some other subject but for some reason need to know about deep earthquakes, this book may help you avoid sifting through what has become a considerable literature.

Who is not responsible?

Although I must accept full responsibility for the material in this book, numerous individuals helped and encouraged me during its preparation. First, I am indebted

² Time has demonstrated that it was my insight that was faulty, not the gauge. It turned out that Osheroff’s gauge was working fine, but “sticking” as the helium mixture cooled through a previously unknown phase transition. Osheroff, Richardson, and Lee won the Nobel Prize for this experiment in 1996.

to Bryan Isacks and Muawia Barazangi, my earthquake mentors at Cornell when I imprinted on deep earthquakes. Second, I must thank Steve Kirby and Terry Wallace, who each almost coauthored this book with me. In 1995 Kirby and I proposed to write a book on deep earthquakes, but gave up when the book proposal was rejected. Later, Wallace approached me about coauthoring a book, but we both became overwhelmed with other projects and made little progress. The present manuscript came about largely due to encouragement from my wife, Jacqueline Henkel, and from a close friend, Frank Whigham. Both are professors of English, and they managed to convince me that writing a book might be a reasonable thing to do even if the scientific community generally values journal publications more than books.³

Finally, I am grateful to numerous colleagues who were supportive of this project. Those who reviewed various sections of this book and provided thoughtful criticism were: Geoff Abers, Muawia Barazangi, John Cassidy, George Choy, Mike Coffin, Patricia Cooper, Shamita Das, Diane Doser, Bob Engdahl, Xaq Frohlich, Alexei Gorbato, Steve Grand, Jacqueline Henkel, James Jackson, Yan Kagan, Honn Kao, Junji Koyama, Rob McCaffrey, Yosio Nakamura, Jim Ni, Lani Oncescu, Martin Reyners, Ray Russo, David Rubie, Martha Savage, Cezar Trifu, Agustín Udías, Doug Wiens, and Ray Willemann. Scott Davis read a draft of the entire manuscript and caught numerous blunders, subtle and otherwise. I owe special thanks to Bob Engdahl, who sent me a recently updated version of the EHB catalog complete to December 2004. Inés Benlloch and Yosio Nakamura provided helpful assistance with translations. Geoff Abers, Michael Antolik, Shamita Das, Brad Hacker, and Shun-ichiro Karato were kind enough to provide electronic copies of figures. A book like this couldn't happen without access to a good library and professional support from a good librarian; for these I am indebted to Dennis Trombatore and The University of Texas Library.

References

- Abe, K., 1981. Magnitudes of large shallow earthquakes from 1904 to 1980, *Phys. Earth Planet. Int.*, **27**, 72–92.
 1985. Re-evaluation of the large deep earthquake of Jan. 21, 1906, *Phys. Earth Planet. Int.*, **39**, 157–166.
 DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, 1990. Current plate motions, *Geophys. J. Int.*, **101**, 425–478.
 1994. Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, doi:10.1029/94GL02118, 2191–2194.

³ My wife and my friend may be wrong. Indeed, no less an authority on science than Thomas Kuhn, the celebrated inventor of the concept of scientific paradigms, has stated that “The scientist who writes [books] is more likely to find his professional reputation impaired than enhanced” (Kuhn, 1970).

Preface

xv

- Dziewonski, A. M. and D. L. Anderson, 1981. Preliminary reference earth model, *Phys. Earth Planet. Int.*, **25**, 297–356.
- Engdahl, E. R., R. van der Hilst, and R. Buland, 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Amer.*, **88**, 722–743.
- Engdahl, E. R. and A. Villaseñor, 2002. Global seismicity: 1900–1999, In *International Handbook of Earthquake and Engineering Seismology*, San Diego, CA, Academic Press for International Association of Seismology and Physics of the Earth's Interior, 665–690.
- Gutenberg, B. and C. F. Richter, 1954. *Seismicity of the Earth and Associated Phenomena* (2nd edition), Princeton, N.J., Princeton University Press, 310 pp.
- Jeffreys, H., 1928. The times of transmission and focal depths of large earthquakes, *Mon. Not. Roy. Astron. Soc., Geophys. Supp.*, **1**, 500–521.
- Kuhn, T. S., 1970. *The Structure of Scientific Revolutions*, (2nd edition), Chicago, University Chicago Press, 210 pp.
- Omori, F., 1907. Seismograms showing no preliminary tremor, *Bull. Imperial Earthquake Investigation Committee*, **1**, No. 3, 145–154.
- Turner, H. H., 1922. On the arrival of earthquake waves at the antipodes, and on the measurement of the focal depth of an earthquake, *Mon. Not. R. Astron. Soc., Geophys. Supp.*, **1**, 1–13.