EARTHQUAKES AND GEOLOGICAL DISCOVERY

Bruce A. Bolt

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Library of Congress Cataloging-in-Publication Data

Bolt, Bruce A., 1930–
Earthquakes and geological discovery / Bruce A. Bolt.
p. cm.
Includes bibliographical references and index.
ISBN 0-7167-5040-6: $32.95
1. Seismology. 2. Earthquakes. 3. Earthquake prediction.
I. Title.
QE534.2.B65 1993
551.2'2—dc20 93-12636
CIP

ISSN 1040-3213

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PRINTED IN THE UNITED STATES OF AMERICA

Scientific American Library
A division of HPHLP
New York

Distributed by W. H. Freeman and Company
41 Madison Avenue, New York, NY 10010
20 Beaumont Street, Oxford OXI 2NQ, England

2 3 4 5 6 7 8 9 0 KP 9 9 8 7 6 5 4 3

This book is number 46 of a series.

EARTHQUAKES AND GEOLOGICAL DISCOVERY

According to ancient Japanese folklore, a great catfish (*namazu*) lying beneath the ground caused earthquakes by thrashing its body. In this woodblock print, c. 1855, the god-superior from the Kashima shrine tells the lesser god, or daimyojin, to drive down the pivot stone hard on the Edo (Tokyo) earthquake namazu to warn other catfish. Each of the onlooking namazu is a historical earthquake.

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PREFACE

When the Earthquake Strikes, Flee to the Bamboo Forest.
—Japanese proverb

As an educator in seismology (the science of earthquakes) for over thirty years, I have had the opportunity to reach many audiences. One of my hopes has been that people will come to understand that earthquakes are dangerous chiefly because we do not take adequate precautions against their effects. Indeed, the evidence is clear that, with serious preparation, seismic risk to both life and property can be made acceptably small, even in the largest earthquakes. This message is being spread more vigorously than ever during the last decade of the twentieth century, a period designated The International Decade of Natural Disaster Reduction by the United Nations.

Another aspect of seismology, however, goes well beyond the treatment of earthquake dangers and has contributed crucially to some of the most basic discoveries in all of geology. During this century, for example, earthquake measurements have provided fundamental information on global deformations such as the building of mountain ranges and the movement of the continents. Recordings of earthquakes have also exposed the mysteries of the deep interior of the Earth, especially the structure of its rocks and their elastic properties. Seismological observations have even provided clues to the chemical constitution and dynamic evolution of the Earth's whole interior. Modern technology, particularly high-speed computers, is now supplying this seismological information at a greater and greater pace and in finer detail.

This book is designed for the reader who would like to know how earthquake recordings, which appear on visual displays as wiggly lines, can provide answers to basic questions about the Earth's character far from the places where the recordings are made. Although it is not possible here to give complete coverage of all important geological work in which earthquakes now play a central role, the earthquake case histories and geophysical studies discussed give a realistic flavor of the broad scientific accomplishments of seismology and should satisfy the curious reader. I hope that some of the excitement of the process of geological discovery is also conveyed. The creative spirit of scientific inquiry is perhaps nowhere better exemplified than in the search for physical knowledge of our own planet.

As a quantitative observational science, seismology started in a small way about the end of the last century and has now grown into a major enterprise with applications to geology and geophysics; to seismic exploration in the oil industry; to seismic hazard assessment by geotechnical companies and government laboratories; and to the planning of land use, including the siting of critical structures such as nuclear power plants, large dams, and bridges. The simple mechanical seismographs of the last century have given way to the delicate and sensitive digital recording instruments used today.

I have been fortunate to know a number of the scientific pioneers of earthquake studies, including Professor Hugo Benioff, Professor K. E. Bullen, Professor Perry Byerly, Professor Maurice Ewing, Professor Beno Gutenberg, Sir Harold Jeffreys, Dr. Inge Lehmann, and Professor Charles Richter, all now deceased. I was introduced to seismology in 1949 when Bullen, then Professor of Applied Mathematics at the University of Sydney, Australia, suggested for my Ph.D. thesis that I examine the inferential basis for a transition shell that, it had been hypothesized, surrounds the inner core of the Earth. This mathematical application of earthquake measurements to remote geological sensing evolved into more immediately practical pursuits after I came to the University of California at Berkeley in 1963 as Professor of Seismology. My engineering and geology colleagues expected me to answer questions, not on properties near the center of the Earth, but on the vagaries of earthquake occurrence in California and other seismic regions. They seemed surprised when I had to tell them that their seemingly simple questions did not have reliable answers. Some still do not. Fortunately, the last three decades have seen much progress in the geological basis for the prediction of strong ground motion, and this knowledge has been applied to the design of earthquake-resistant structures and land-use zoning.

I have had help from many people in writing this book. I owe a great debt to friends in the earthquake profession in California with whom I continue to work as a consultant on practical aspects of earthquake risk. A number of colleagues and students read or commented on portions of the draft, and I am grateful to them. In particular, I thank N. A. Abrahamson, A. Becker, P. Dehlinger, J. Dewey, N. Gregor, J. Litehiser, A. Lomax, T. Tanimoto, B. Tucker, Y. B. Tsai, and A. Udias for valuable help with the book's content.

Many colleagues suggested and supplied fine illustrations; unfortunately, limited space dictated a winnowing from among those available. My wife, Beverley Bolt, helped in crucial ways: spotting errors and compiling the index. Claire Johnson, of the Earthquake Engineering Research Center at the University of California at Berkeley, applied her word processing skills under the considerable pressure of deadlines. I also thank the Scientific American Library staff at W. H. Freeman and Company. The editor, Susan Moran, delved deeply into the subject matter with me and made many improvements. It was a pleasure to share the search for enlightening color photographs with Travis Amos, who made some delightful artistic discoveries.

Bruce A. Bolt
Professor of Seismology
March 1993

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THE ORIGINS OF SEISMOLOGY

CONTENTS

IN THE LAST five hundred years, more than 7 million people have died from earthquakes, and many millions more have seen their food sources and local economies destroyed. The hazard earthquakes present to a growing world population has often been the first concern motivating the scientists and engineers who study them. Yet earthquakes have proved to be not only a source of destruction but a source of geological knowledge. The analysis of seismic waves has provided geologists with detailed and often unique information about the Earth. The discovery of earthquake properties has gone hand in hand with our exploration of the constitution and restless reworking of our planet.

Seismology, the scientific study of earthquakes, is a young subject compared with chemistry, physics, or geology; yet in only one hundred

An artist's conception of the City Hall in the aftermath of the 1906 earthquake and fire in San Francisco.

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years it has made remarkable strides in explaining the causes of earthquakes, the nature of seismic waves, the considerable variation in their intensity, and the remarkable patterns of earthquake activity around the globe. Although seismology has been recognized as a separate field of study only in the last century, people have been speculating about the causes of earthquakes for thousands of years. As early superstitions gave way to more scientific attempts to analyze these natural events, the inexorable succession of large earthquakes stimulated ever more sophisticated thinking about the origins of the shakings, until early in this century scientists reached the modern understanding of the immediate source of powerful ground motions.

THE EARLIEST RECORDS

The Earth has suffered earthquakes throughout geological time, and written accounts date back several millennia. In China, scholars have culled the ancient dynastic and literary works, temple records, and other sources for evidence of earthquakes from long ago. The oldest have been traced back to 1831 B.C. in Shandong province (the record states merely, "shaking of Taishan mountain"), but the record is fairly complete only from 780 B.C., the period of the Zhou Dynasty in northern China.

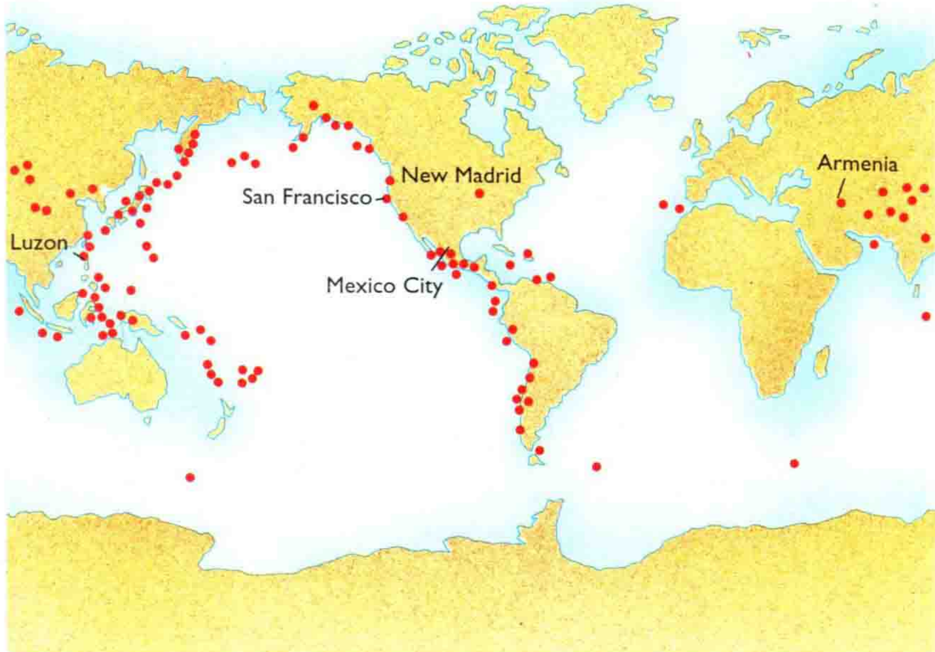
These historical reports are so detailed that from them modern studies have been able to establish the distribution of damage and, hence, the size of the earthquakes. For example, the San-ho earthquake of September 2, 1679, the greatest known near Beijing, was mentioned in the records of 121 cities. When modern researchers compared the descriptions of building damage, ground cracks, and other geological features near the source, together with reports of shaking from distant places, with earthquakes of recent times, they concluded that its size was similar to that of the San Francisco earthquake of 1906.

Despite their careful documentation of earthquakes, Chinese scholars were unable to achieve any real insight into the causes of catastrophic ground shaking. The prevailing thinking linked earthquakes with other natural afflictions such as floods, droughts, and pestilence and sought the origins of all these disasters in supernatural intervention.

The religious interpretation of earthquakes was shared by peoples in seismic regions throughout the ancient world. Many allusions to ancient earthquakes are found in the Bible and other religious writings of the time. Some notable events, such as the falling of the walls of Jericho and the parting of the Red Sea, have been explained as the effects of earthquakes by those who are not prepared to allow for miraculous intervention. The Book of Zechariah even has a remarkably modern description of a section of slipping rock at an earthquake source:

> The Mount of Olives shall cleave in the midst thereof towards the East and towards the West and there shall be a very great valley; and half of the mountain shall remove towards the North and half of it towards the South.

It was not until the twentieth century that the physical connection between rock slip and earthquakes, suggested by this passage, was understood. But the first steps toward a more physical understanding of the origins of earthquakes had been taken long ago by the ancient Greeks.

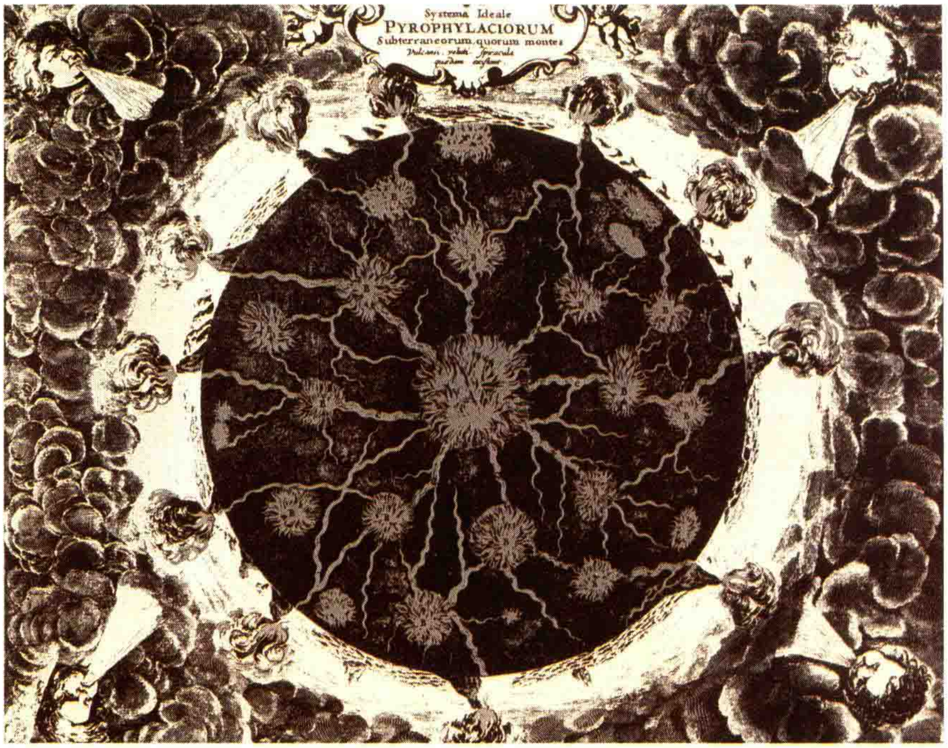


The epicenters of large-magnitude earthquakes that occurred from 1897 through 1992.

EARLY GREEK IDEAS

Seismic activity is high in parts of the Mediterranean Sea and surrounding countries, and it is there that natural explanations for earthquakes were first attempted. As Greek science dawned, its practitioners began to consider physical causes for earthquakes in place of the divine causes suggested by folklore and myth. One of the earliest Greek writers on scientific subjects (about 580 B.C.) was Thales, known for his discussions of magnetism. Thales was much impressed by the destructive power of the sea, clearly in evidence from his island home of Miletes. He believed that the globe of the Earth floated on the oceans and that movements of the water produced the seismic shaking. In contrast, Anaximenes, who died about 526 B.C., thought that the rocks of the Earth were the cause of the shaking. As masses of rock fell in the Earth's interior, they would strike other rocks, producing reverberations. Another school, typified by the ideas of Anaxagoras (428 B.C.), saw fire as the cause of at least some earthquakes.

None of these seminal Greek commentaries, however, contained a general, rational theory of earthquake genesis. The first such account was developed by the Greek philosopher Aristotle (384–322 B.C.). The crucial importance of Aristotle's writings was that he did not seek an explanation in religion or astrology, such as that earthquakes are caused by the conjunction of planets or comets, but instead drew on the pragmatic background of his times. He discussed the



An early view of the Earth's interior, from about 1678. The writer Athanasius Kircher conceived the Earth as a ball of solid material fissured by tubes of magma, which connected pockets of eruptive gases to volcanic vents on the surface.

generation of earthquakes by drawing analogies first with frequently observed atmospheric events, such as thunder and lightning, and second with subterranean events associated with rising vapors from the Earth and volcanic activity. Like many of his contemporaries, Aristotle was convinced that there existed "a central fire" inside the Earth, although Greek thinkers differed as to its cause. Aristotle's theory held that caverns underground would produce fire in the same way as storm clouds produce lightning. This fire would rise rapidly and, if obstructed, would burst violently through the surrounding rocks, causing vibrations and noise. A later modification of this theory held that subterranean fires would burn away the supports of the outer parts of the Earth. The ensuing collapse of the cavern roofs would create the shocks experienced as earthquakes. Aristotle's linking of subterranean and atmospheric events and his view that dry and smoky vapors cause earthquakes under the Earth, although incorrect, were widely accepted until the eighteenth century.

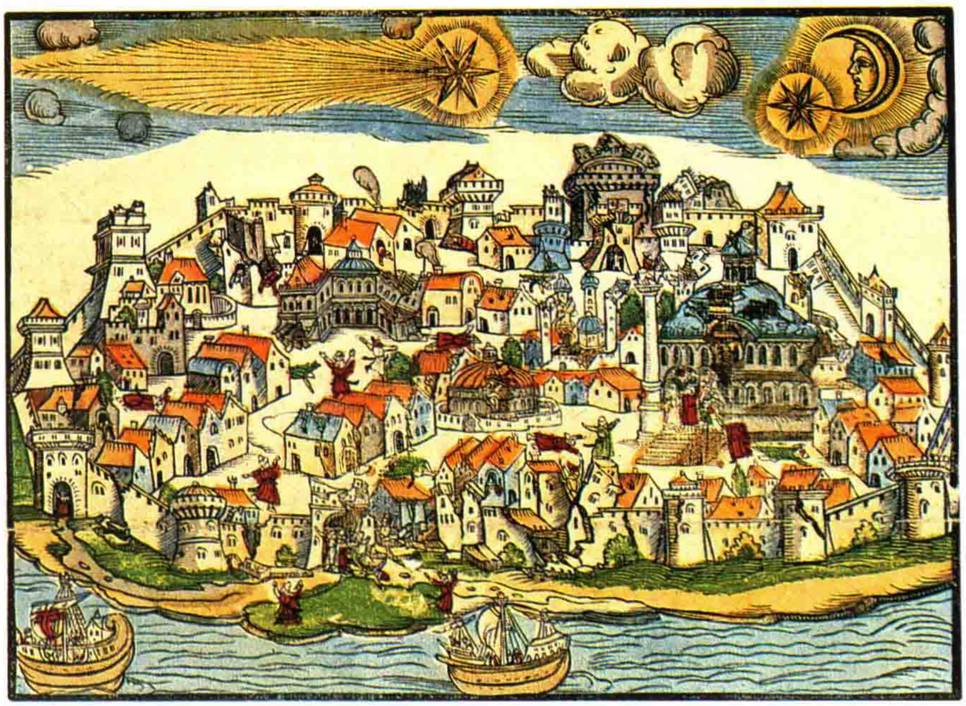
In an important step toward a physical explanation of the ground shaking, Aristotle also classified what he regarded as different types of earthquakes in terms of whether they shook structures and people in mainly vertical or diagonal directions and whether they were associated with the escape of vapors. According to Aristotle in his *Meteorologica,* in which he explained a wide variety of natural phenomena, "Places whose subsoil is poor are shaken more because of the large amount of wind they absorb."

In his *Quaestiones naturales,* Seneca (4 B.C. to A.D. 65) presented his theory of the cause of earthquakes and contrasted it with the theories of his predecessors. His work was inspired in part by the major earthquake that shook Compaigne, Italy, in A.D. 63. Seneca conjectured that the shaking was the result of air finding its way into underground passages. As this air became compressed, it produced violent storms, which created widespread devastation when they broke to the surface.

All the Greek explanations lacked a theoretical conception of the mechanical forces needed to produce the energy in earthquakes. The strength of Greek science was the curiosity of its practitioners, which led them to classify and speculate. Its weakness was its lack of experimentation and instrumentation for making quantitative observations of natural phenomena.

MODERN ENLIGHTENMENT

Many records of building damage in medieval times have come to us through artists' impressions on woodblock prints and through descriptions from diaries, letters, and travel logs. But as the centuries passed, the relationship between geological movements and earthquakes became understood only slowly. Geology remained throttled by the deep deficiency in the appreciation of physical principles. A new era dawned in the eighteenth century under the powerful influence of Sir Isaac Newton's writings on waves and mechanics. Newton's *Principia mathematica* at last provided a formulation capable of unifying all terrestrial motions, including earthquakes. His laws of motion provided the physical theory needed to explain earthquake waves, and his law of gravitation provided the basis for understand-



A woodcut by Herman Gall depicts a comet seen at Constantinople in 1556, said to be the wondrous sign portending two earthquakes.

ing the geological forces that shape the Earth. This sudden advance is illustrated by his incisive proposition on Earth tides: "The flux and reflux of the sea arise from the [gravitational] actions of the Sun and Moon."

Nevertheless, the ancient attribution of earthquakes to supernatural causes died hard. Even in A.D. 1750, a writer in the Philosophical Transactions of the Royal Society of London apologized "to those who are apt to be offended at any attempts to give a natural account of earthquakes."

By the middle of the eighteenth century, scientists and engineers under the influence of Newtonian mechanics began to publish memoirs that associated earthquakes with waves traveling through rocks in the Earth. These memoirs gave a great deal of attention to the geological effects of earthquakes, including landslides, ground movements, changes of sea level, and damage to buildings. For example, some observers noted, as the Greeks had, that structures on soft ground were usually more damaged by earthquakes than those on hard ground. Interested persons began to keep and regularly publish lists of earthquakes, so that in 1840 K. E. A. Von Hoff was able to publish an earthquake list for the whole world.

Even as the age of reason spread across Europe and scientific inquiry grew apace, earthquakes were still usually ascribed to either supernatural causes or causes hypothesized by the Greek scholars of long ago. The attachment to the ancient theories can be illustrated by the reactions of men of letters in 1750 to "the year of the earthquakes," when London was jolted several times by seismic shocks. On February 8, people were sent into the streets by a foreshock that rattled windows and shook furniture. A month later, a more powerful tremor knocked down chimneys, collapsed buildings, and rang church bells. These earthquakes stimulated the writing of more than fifty papers for presentation to the Royal Society of London.

One of these papers, entitled "Some Considerations on the Causes of Earthquakes," was authored by the Reverend Stephen Hales, who was active in church affairs and was associated with the trustees for establishing the colony of Georgia in America. In 1727, he had published *Vegetable Staticks,* the most original work in science to be published in Europe since Isaac Newton's *Optics* and a foundation stone of the model of the flow of sap in plants. Hales was a bold and happy experimenter, and his lively accounts pay all due tribute to Newton. He described the earthquake of March 6, 1750, in personal terms:

> I'd been then awakened there on the ground floor in London, and very sensibly felt the bed heave and consequently the Earth must heave too. There was an obscure rushing noise in the house which ended in a loud explosion up in the air like that of a small cannon. The whole duration from the beginning of the earthquake to the end was 3–4 seconds.

Yet Hales's view of the cause of the London earthquakes was similar to the views expressed by the classical philosophers many centuries before:

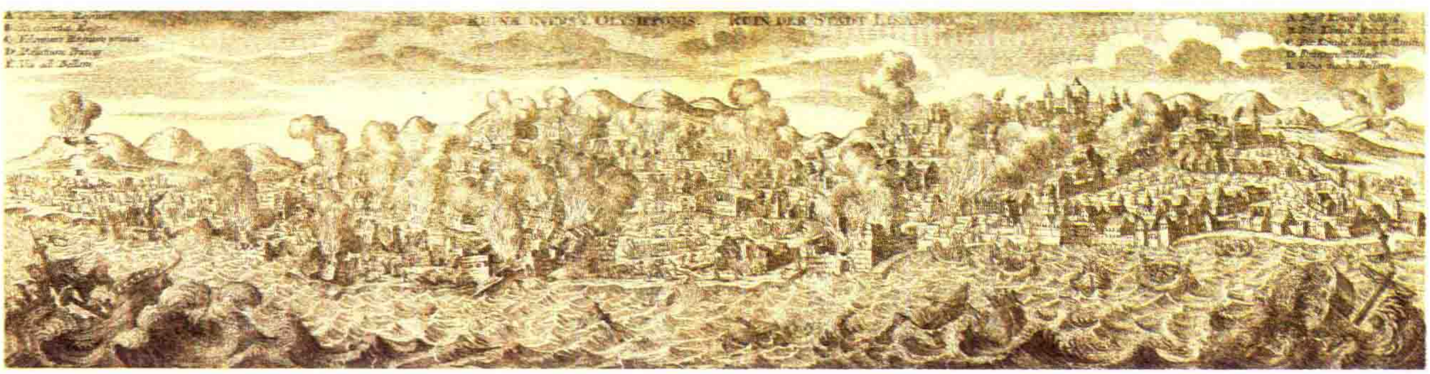
> We find in the late earthquakes in London, that before they happen there is usually a calm air with a black sulfurous cloud which cloud would probably be dispersed like a fog if there were a wind; which dispersion would

> prevent the earthquake which is probably caused by the explosive lightning of this sulfurous cloud; being both near the Earth and coming at a time when sulfurous vapors are rising from the Earth in greater quantity than usual which is often occasioned by a long period of hot and dry weather. Ascending sulfurous vapors in the Earth may probably take fire, and thereby cause Earth lightning which is first kindled at the surface and not at great depths as has been thought whose explosion is the immediate cause of an earthquake.

The scientific study of earthquakes received a critical stimulus in 1755, when a disastrous earthquake struck the Iberian peninsula on November 1. This earthquake was observed over many parts of Europe by people attending religious services who noticed the swinging of church chandeliers. It was felt strongly over Portugal and Spain and less intensely in many other European countries. Lisbon was overwhelmed, and some 60,000 of its residents were killed, many by a series of ocean waves that reached 30 or 40 ft above high tide level and swamped large parts of the city. Modern studies have determined that the site of origin of the great Lisbon earthquake was several hundred kilometers south-southwest of Portugal along a massive geological structure called the East Atlantic rise.

Survivors left accounts of the earthquake's effects in Lisbon. First, the city was said to have shuddered violently, and its tall spires were described as "waving like a corn field in a breeze." Then a second, stronger shaking arrived, sending the facades of the many grand buildings cascading down into the street and leaving a wasteland of broken stones—graves for those who were caught by the falling debris.

> In some places lay coaches with their masters, horses and riders almost crushed to pieces; here mothers with infants in their arms; there ladies richly dressed, gentlemen and mechanics; some had their backs or thighs broken, others vast stones on their breasts; some lay almost buried in the rubbish.



A contemporary fanciful print portraying the destruction of Lisbon by the earthquake and tsunami of 1755.

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