# 1

# Introduction to Plate Boundaries and Natural Hazards

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**ABSTRACT**

A great variety of natural hazards occur on Earth, including earthquakes, volcanic eruptions, tsunamis, landslides, floods, fires, tornadoes, hurricanes, and avalanches. The most destructive of these hazards, earthquakes, tsunamis, and volcanic eruptions, are mostly associated with tectonic plate boundaries. Their occurrence has stimulated scientists to think about their spatial and temporal distribution, and their physical causes, within the atmosphere, in the oceans, or deep within the Earth's interior. It is no coincidence that two of the greatest earthquakes ever recorded occurred at the start of the decade in which the theory of plate tectonics, the grand unifying theory of the solid Earth sciences, was developed. In this chapter, we introduce the different natural hazards associated with plate boundaries, including a discussion of one of the greatest natural disasters in history, the 1755 great Lisbon earthquake that stimulated research into the internal workings of our planet and the development of seismology.



## 1.1. THE AFTERMATH OF THE 1755 GREAT LISBON EARTHQUAKE

The 1755 great Lisbon earthquake was one of the most powerful seismic events ever documented. With an estimated magnitude ($M_w$) of 8.5 to 9, it shocked Lisbon on the morning of All Saints Day while many residents were in churches [*Martinez-Solares and Arroyo*, 2004; *Gutscher et al.*, 2006; *Oliveira*, 2008 and references therein]. Forty minutes after the main shock, three giant waves came up the Tagus River, flooding the harbor and the downtown area [*Baptista et al.*, 1998; 2003]. The tsunami destroyed several buildings along the west coast of the United Kingdom and spread across the Atlantic pounding the east coast of the Americas [*Lyell*, 1830; *Batista et al.*, 2003]. Casualty estimates from the ground shaking, the tsunami, and the resulting fires ranged from 60,000 to 100,000 people, leaving Portugal devastated [*Pereira*, 2006; *Oliveira*, 2008]. The visionary Portuguese minister Marquês de Pombal immediately ordered a survey with 13 questions to be sent around the country. Today, this survey allows us to understand much of what happened that day [*Oliveira*, 2008].

Some of the questions were amazingly prescient for 1755 and opened the door to modern seismology. Among these were: "At what time did the earthquake begin and how long did the earthquake last? Did you perceive the shock to be greater from one direction than another? Number of houses ruined in each parish; Were there any special buildings and what is their state now? Did the

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tide get low or high first; How much did it grow more than normal …?" [*Oliveira*, 2008]. Even though the main objective of the survey was to understand the magnitude of the damage, it is clear from the questions that the Marquês also aimed to understand the characteristics of the event. Similar queries were made by king Fernando VI of Spain [*Martinez-Solares*, 2000; *Oliveira*, 2008].

Today it is possible to construct maps of the intensity of ground shaking from the surveys, and place the source approximately 200 km southwest off the Cape Saint Vincent, the southwest corner of the Iberian Peninsula, and somewhere along the diffuse Azores-Gibraltar plate boundary zone [*Martinez-Solares et al.*, 1979; *Oliveira*, 2008 and references therein]. Nonetheless, the specific structure that generated the quake is still debated [*Zitellini et al.*, 2001; *Gutscher et al.*, 2006; *Rosas et al.*, this volume].

The great Lisbon earthquake was significant not only for its enormous societal impact. As mentioned above, the 1755 event was also essential to the development of modern seismology and in many ways it changed the way people saw the world [*Lyell*, 1830]. The 1755 event attracted the widespread attention of the main thinkers of the then current epoch of enlightenment. Philosophers such as Voltaire, Rousseau, Kant, and many others realized that, contrary to what was previously thought, earthquakes were not a punishment from God [*Zitellini et al.*, 2009]. Instead, they suspected, earthquakes and tsunamis had natural causes! Immanuel Kant wrote three essays in 1756 in which he developed a theory of the causes of earthquakes and gets close to recognizing some of the main characteristics of plate boundaries, more than 200 years before the theory was born [*Kant*, 2012]. The rationalization that the "firm ground" could actually move in such a tremendous way enlightened the minds of many thinkers of the time and contributed to shaking the widely held belief in a solid, immobile, unchanging Earth.

Immanuel Kant clairvoyantly argued that earthquakes are caused by sudden ground movements triggered by the abrupt displacement of gases in the interior of "interconnected" caverns: "The first thing to be observed is that the ground under us is hollow and its caverns extend very widely, almost in a single interconnected system, even under the floor of the sea" [*Kant*, 1756a]. Inspired by Athanasius Kircher's *Mundus Subterraneus* [1664], he suggests that earthquakes occur along a network of "caverns" and "vaults" [*Kant*, 1756b]. This was in part a result of the recognition that there were other earthquakes in Iceland the same day the 1755 earthquake struck: "the continued effect [felt] simultaneously in widely separated places, including Iceland and Lisbon, which are separated by more than a half hundred German miles of sea and were set in motion on [the] same day, deliver irrefutable testimony, all these phenomena confirming the interconnections of these subterranean caverns"[*Kant*, 1756a]. It is also fascinating to note that Kant associated these "veins" with topography: "one thing is certain, namely that the direction of the caverns is to the mountain ranges…. For these occupy the lowest parts of long valleys bounded sides by parallel mountains…. This is why Peru and Chile are more subject to frequent tremors than any other countries in the world" [*Kant,* 1756a].

Kant was strongly inspired by Newton's theory of the physical world and used logical reasoning and experimentation to understand the causes of earthquakes. Based on the work by Nicolas Lemery and some of his experimental knowledge, he ascribed those causes to the "conflagration" of fires (chemical reactions) and "emission of flammable vapors trapped inside subterranean regions…that break out in flames at the orifices of the volcanoes" [*Kant*, 1756a]. He also recognized that the subsequent tsunami was caused by the "sudden movement of the seafloor" that "set the water in motion." Already in 426 BC the Greek philosopher Thucydides suggested that tsunamis were associated with earthquakes [*Smid*, 1970]. Much of this knowledge was forgotten, especially during medieval times, to be later revived during the Renaissance and the Age of Enlightenment. Kant, by investigating the propagation of the tsunami with the arrival times and intensity at certain points of the European shores, calculated the pressure required to put the water in motion and the area of seafloor that was suddenly uplifted [*Kant*, 1756b]. Although Kant's ideas were far removed from the modern concepts of plate tectonics, he recognized that earthquakes occurred along linear-like features that move causing tremors and topography. He also noted that some of these linear structures seem to strike along the continental margins, but, interestingly, not in all cases. He understood that the Mediterranean shores seemed to be much more prone to earthquakes and tsunamis than northern Germany [*Kant*, 1756a,b]. We now know that the Mediterranean is an active margin corresponding to the plate boundary between Africa and Eurasia, which is marked by many earthquakes, while the northern shores of Europe are passive margins in plate interiors and thus are much less prone to seismic events. However, Kant did not have the necessary data to recognize the existence of plate boundaries as we know them today. It took two centuries for such ideas to mature.

## 1.2. PLATES AND PLATE BOUNDARIES

The concept of rigid plates and associated plate boundaries only started to emerge almost 200 years after the 1755 events. The rigidity and fragmentation of the Earth's outer shell, at least of the continents, was implicit in the ideas of continental drift of *Wegener* [1912] and

*Holmes* [1931] and in early works on seafloor spreading [*Hess*, 1962; *Dietz*, 1961; *Wilson*, 1963]. However, Wilson's 1965 seminal paper introduced plates for the first time: "mobile belts, which may take the form of mountains, mid-ocean ridges and major faults with large horizontal movements…are connected into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates." The transform faults newly identified in Wilson's paper were the last piece of the puzzle, connecting ridges to orogenic belts, and thereby closing the circumference of plates. Wilson also briefly associated the type of earthquakes and the type of movement along the plate boundaries. In a 1967 meeting of the American Geophysical Union, Jason Morgan presented a global tectonic model including 12 rigid lithospheric plates, and that was published the following year in June 1968 [*Morgan*, 1968]. Two months after that *Le Pichon* [1968] introduced a simplified model with only six plates. Those works were largely inspired by a paper published the previous year [*McKenzie and Parker*, 1967] describing how "aseismic areas move as rigid plates on the surface of a sphere." Those authors also made a clear connection between the three types of plate boundaries and their associated three types of focal mechanisms: normal, thrust, and transform.

The modern conception of plate tectonics is that the surface of the Earth is composed of rigid lithospheric plates (Fig. 1.1) that incorporate the crust and the upper (strong) portion of the mantle and move coherently relative to one another over the asthenosphere through geological time, such that deformation, seismicity, and volcanism occur at their boundaries [e.g., *Wilson*, 1963,1965; *Mckenzie and Parker*, 1967; *Morgan*, 1968; *Isacks*, 1968; *Le Pichon*, 1968; *Jacoby*, 1970; *DeMets et al.*, 1990; *Gordon and Stein*, 1992; *Stein and Sella*, 2003; *Kreemer et al.*, 2003]. The asthenosphere is the hot, low-viscosity portion of the uppermost mantle, which can flow readily and offers low mechanical resistance to movement of the plates over geological time periods (millions of years). On average, plates are ~100 km thick, and move very slowly, at centimeters per year with respect to one another. The rigid plate model immediately proved a powerful tool for computing present and past plate motions [e.g., *Gordon and Jurdy*, 1986; *Morgan*, 1968; *Le Pichon and Hayes*, 1971; *Wilson*, 1966; *Muller et al.*, 1993] and, in particular, for constructing global plate kinematic models [*Chase*, 1978; *Minster and Jordan*, 1978; *DeMets et al.*, 1990; 2010; *Kreemer et al*., 2003; 2014].

Notwithstanding, it was soon recognized that in a number of regions, plate boundaries are broad regions of deformation several hundreds of kilometers wide rather than narrow regions that are at least an order of magnitude smaller. *Isacks* [1968] was among the first to show that on a global scale earthquakes are distributed along "narrow seismic belts that outline aseismic blocks" and that focal mechanisms of more than 100 earthquakes remarkably correlate with the geometry and kinematics of the plates as proposed by Wilson, Le Pichon, Morgan, and McKenzie. Isacks noted that these belts are narrower in spreading zones (e.g., mid-Atlantic), broader in convergent regions (e.g., Andes), and diffuse within continents (e.g., Himalayas). *Morgan* [1968] also noted this divergence from an idealized rigid plate model. Later, *Gordon and Stein* [1992] showed that such broad regions of seismic deformation occur not only in continents but also within the oceanic lithosphere (e.g., the Indian Ocean region of the Indo-Australian-Capricorn composite plate and at the eastern Azores-Gibraltar plate boundary).

Although the rigidity of plates is still a useful concept used in many studies, modern space geodetic techniques can use intraplate stations to quantify intraplate strain. Such approaches thus allow us not only to quantify directly the relative motion of the tectonic plates within and outside the plate boundary zones but also to compute their internal deformation [*Stein and Sella*, 2003].

Plate boundaries cover 15% of the Earth's surface and cover a spatial range that spans from a single fault system to diffuse regions of deformation sometimes with stranded microplates [e.g., *Gordon and Stein*, 1992; *Stein and Sella*, 2003; *DeMets et al.*, 2010; *Kreemer et al.*, 2014]. To accommodate such diversity, Gordon and Stein [1992] use the term "plate boundary zones," defined as a "zone of active deformation that takes up the motion between nearly rigid plate(s)." Such zones vary in width from a few hundreds of meters (e.g., oceanic transforms) to thousands of kilometers (e.g., in areas of continental collision such as in the Himalaya-Tibet mountain belt).

Plate boundaries are commonly divided into three types: divergent, convergent, and transform [Fig. 1.2; e.g., *Wilson*, 1965]. At divergent plate boundaries, plates move away from each other such as at oceanic spreading ridges (see Chapter 11 by Dziak and Merle, this volume). They are characterized by low to moderate seismicity and volcanism. Divergent movement can also occur inside the continents producing rift systems, such as the East African Rift, which are bounded by extensional normal faults (see Chapter 2 by Brune, this volume). Divergent plate boundaries are generally thought of as regions of plate construction, where new tectonic plate material (lithosphere) is created.

Convergent plate boundaries are regions where plates move toward each other (see Chapter 4 by Stern et al., this volume). At subduction zones, an oceanic plate dives (subducts) below another plate, which can be continental or oceanic. At collisional boundaries, two continents or a continent and an arc collide, and one plate is often forced below the other in a process called continental subduction. Convergent plate boundaries are the loci of

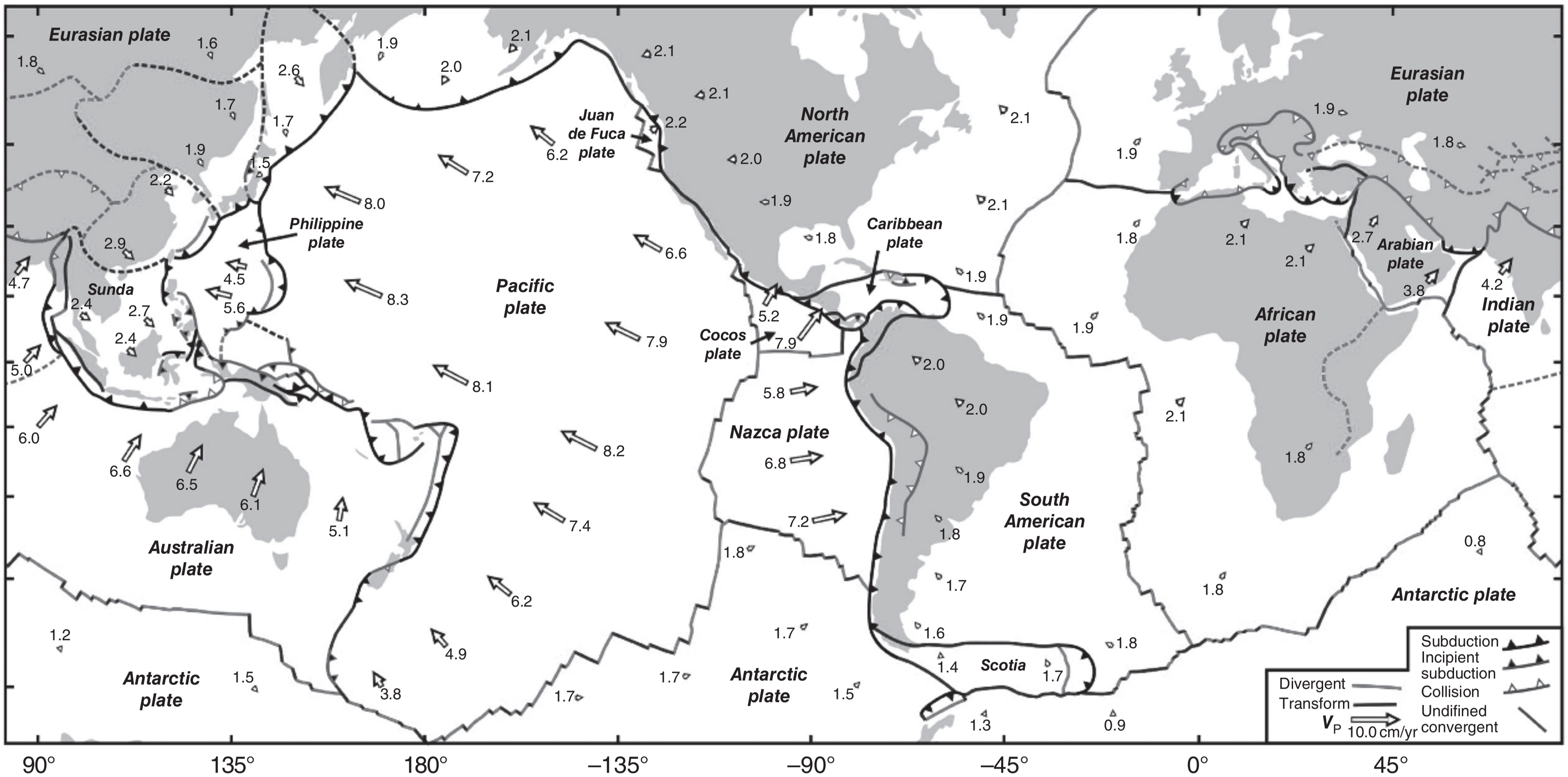


**Figure 1.1** Global plate tectonic map illustrating the major tectonic plates, their velocities (in cm/yr), and the major plate boundaries: convergent plate boundaries (black and grey segments with triangles), divergent plate boundaries (grey segments), and transform plate boundaries (black segments). Velocities were calculated in the Indo-Atlantic hot spot reference frame from *O'Neill et al.* [2005] using the geophysically constrained relative plate motion model from *DeMets et al.* [1994], in which relative plate motions have been averaged for the last ~3 Myr. Figure modified from *Schellart et al.* [2011].

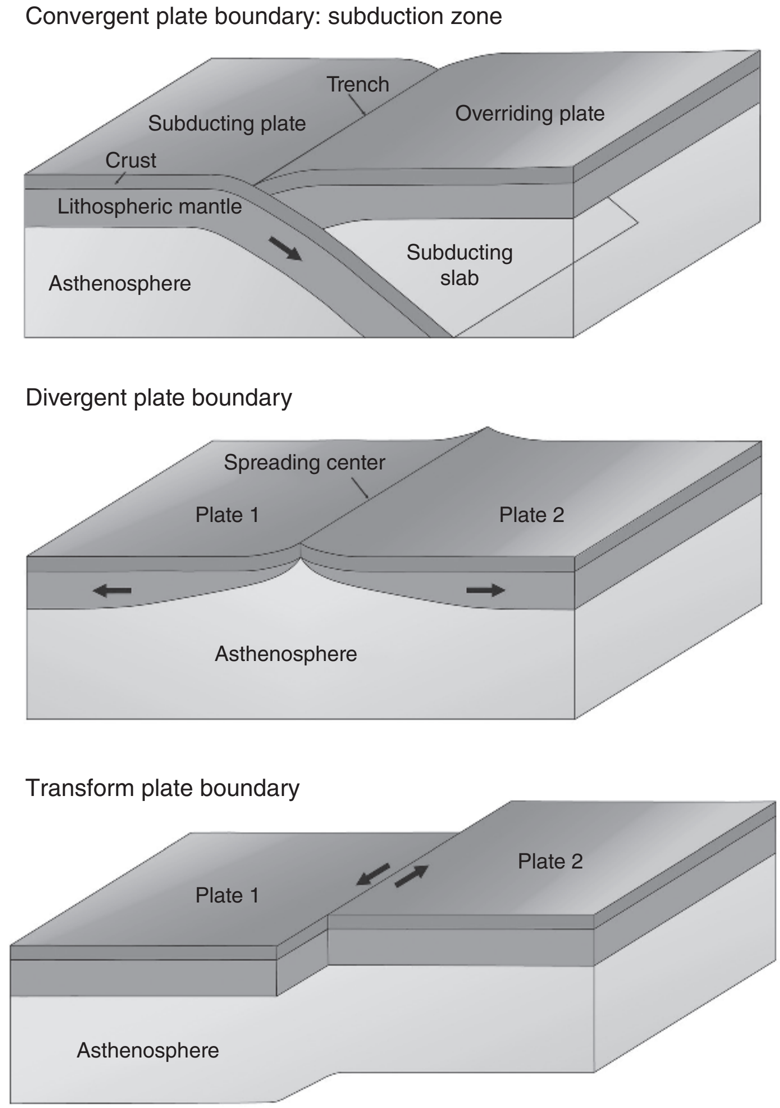


**Figure 1.2** Schematic representation of the three types of plate boundaries: convergent (top), divergent (center), and transform (bottom).

high to very high magnitude seismicity, thrust faulting and volcanism (see Chapter 7 by Ye, et al. and Chapter 8 by Lei and Zhao, this volume). Recent examples include the 2004 Sumatra-Andaman earthquake and associated tsunami at the Sunda subduction zone, the 2011 Japan (Tohoku) earthquake and associated tsunami at the northwest Pacific subduction zone, and the 2015 Nepal earthquake in the Himalayan collision zone. Convergent plate boundaries are sometimes referred to as destructive plate boundaries, as plate material is destroyed and lost as it disappears into the mantle.

Transform plate boundaries are where two plates move past one another without significant convergence or divergence and where slip along the plate boundary fault predominantly has a horizontal movement (see Chapter 3 by Gerya, this volume). They are sometimes referred to as conservative plate boundaries because plate material is neither created nor destroyed. Seismicity in these regions is generally of moderate to high magnitude. However, these areas can also produce very high magnitude events. Examples include the M = 8.4 earthquake of 25 November 1941 in the Gloria strike-slip fault in the Azores-Gibraltar plate boundary [*Buforn et al.*, 1988] and the 11 April 2012 $M_w$ 8.6 and 8.2 events oceanward of the Sumatra subduction zone segment [*Delescluse et al.*, 2012; *McGuire and Beroza*, 2012].

## 1.3. NATURAL HAZARDS ASSOCIATED WITH PLATE BOUNDARIES

Of the world's population, 40% lives within plate boundary zones, which are the loci of some of the most powerful natural hazards on Earth [*Gordon and Stein*, 1992; *Stein and Sella*, 2003]. A natural hazard can be defined as a naturally occurring event that can have a damaging effect on humans or the environment. Natural hazards are generally subdivided in two main groups: geophysical and biological [*Burton et al.*, 1993]. Geophysical natural hazards include earthquakes, tsunamis, hurricanes, floods, and fires, whereas biological hazards include pandemic spreading of viruses or the contamination of watercourses and reservoirs by harmful organisms. Here, we focus on the geophysical natural hazards, in particular those associated with tectonic events at plate boundary zones, which include most of what we could call "tectonic hazards" [*Smith*, 2013]. Nevertheless, it should be noted that many natural hazards are interrelated and may follow one another, such that biological hazardous events may occur after a geophysical event. For example, large-scale soil contamination and spreading of epidemic diseases may occur after a tsunami.

### 1.3.1. Earthquakes

Earthquakes are one of the most common and most damaging natural hazards occurring at plate boundary zones. It is estimated that more than 2 million deaths in the twentieth century were earthquake related [*Smith*, 2013]. The stick-slip movement of plates at their boundaries releases large amounts of elastic energy that are radiated in the form of seismic waves that move through the Earth and across its surface [*Yeats et al.*, 1997]. The energy of an earthquake is expressed by its moment magnitude that depends on the average slip along the fault, the rupture area of the fault, and the rigidity of the affected rocks [*Hanks and Kanamori*, 1979; *Kanamori*, 1978]. The larger the fault slip, the larger the rupture area, and the higher the rigidity, the larger the earthquake and the higher the moment magnitude.

Most earthquakes are not damaging and, in general magnitudes lower than 3, are imperceptible. Earthquakes of magnitude equal or higher than 7 may cause significant damage over vast areas, depending on the depth of the hypocenter. In general, the shallower the earthquake, the larger the damage. It is estimated that nearly 500,000 instrumental earthquakes occur every year, from which around 100,000 can be felt and 100 cause damage (see http://earthquake.usgs.gov/earthquakes/world/events/1755_11_01.php). Most of these earthquakes occur along plate boundaries and their mechanisms generally correlate with the plate boundary fault type: normal fault earthquakes at divergent plate boundaries, thrust mechanisms at convergent boundaries, and strike-slip mechanisms at transform-transcurrent boundaries [*Mckenzie and Parker*, 1967; *Yeats et al.*, 1997]. The most powerful earthquakes (megathrust earthquakes) occur at subduction zones and can have magnitudes higher than 9. The greatest earthquake recorded was the magnitude 9.5 Valdivia earthquake in 1960, also know as the great Chilean earthquake [*Barrientos and Ward*, 1990]. The deadliest recorded earthquake, the 1556 Shaanxi quake in central China, killed more than 800,000 people [*Jing-Ming*, 1990; http://earthquake.usgs.gov/earthquakes/world/events/1755_11_01.php].

### 1.3.2. Tsunamis

When an underwater earthquake strikes, sudden movement of the seafloor can produce a tsunami [*Smith*, 2013]. Earthquake-related tsunamis consist of a series of long wavelength–long period waves produced by the displacement of a large volume of the water [*Voit*, 1987]. Most tsunamis (in particular the most devastating ones) are associated with convergent plate boundaries, in particular subduction zones, as earthquakes there produce both large uplift and subsidence of the seafloor vertically displacing the water column. In contrast, transform plate boundaries in the oceans do not produce tsunamis because their strike-slip motion does not result in significant uplift and/or subsidence of the seafloor. Normal faulting at divergent plate boundaries below sea level also generally does not produce significant tsunamis, because these earthquakes are generally of low to moderate magnitude with relatively minor vertical displacement of the seafloor. Earthquakes with magnitude 7.5 or higher can give rise to tsunamis with wavelengths of the order of tens of kilometers, and periods varying from minutes to hours, traveling in the open sea at several hundred kilometers per hour [*Noson et al.*, 1988].

Hence, the impact of a tsunami is not restricted to the plate boundary zones. Instead, tsunamis can cause severe harm to the coastal population of an entire oceanic basin [*Smith*, 2013]. The Boxing Day tsunami in 2004 that spread over the Indian Ocean after the Sumatra-Andaman quake is estimated to have killed nearly 230,000 people in 14 countries [*Smith*, 2013]. This tsunami was produced by a $M_W$ 9.1–9.3 undersea megathrust event at the Sunda subduction zone, one of the largest ever recorded [*Lay et al.*, 2005].

Tsunamis can also be produced by undersea landslides [e.g., *Bondevik et al.*, 2003; *Smith*, 2013; Omira et al., Chapter 13 this volume]. In general, tsunamis produced by landslides have much shorter wavelengths and therefore more localized effects [*Harbitz et al.*, 2006]. Nevertheless, they can be extremely damaging at the local coastlines. An example was the Tafjord event, a rockslide in the Norwegian fiords in 1934, that produced run-up heights of more than 60 m [*Harbitz et al.*, 1993]. Earthquakes can also cause secondary rockslides and landslides, which can themselves produce a tsunami when occurring underwater [e.g., *Harbitz et al.*, 2006; *Keefer*, 1984; *Bommer and Rodríguez*, 2002]. For instance, the 1998 Papua New Guinea tsunami, caused by a slump in the aftermath of an earthquake, produced run-up heights up to 15 m and killed more than 2000 people [*Sweet and Silver*, 2003].

Beyond their tremendous short-term impact on the affected coastlines, tsunamis may also have a long-lived environmental impact, because they displace vast quantities of sediment and flood the coast with salty waters. Only recently, mainly after the Boxing Day 2004 event, have researchers started to investigate such long-term consequences.

### 1.3.3. Volcanoes

Volcanism also poses a serious threat to the human population and the natural environment. Most of Earth's volcanoes occur at plate boundaries [*Lockwood and Hazlett*, 2010; *Smith*, 2013]. The exceptions are intraplate volcanoes, a number of which can be related to mantle plumes that can pierce the lithosphere within a tectonic plate [*Sleep*, 1992]. The classic example is the Hawaiian-Emperor volcano chain in the Pacific [*Macdonald*, 1983]. Plate boundary–related volcanoes occur at divergent boundaries (midoceanic ridges or intracontinental rifts) and at convergent boundaries, notably at subduction zones [see Chapter 12 by Jenkins et al., this volume; *Lockwood and Hazlett*, 2010]. Midoceanic ridge volcanism can be observed in Iceland whereas intracontinental volcanism occurs in the region of the East African Rift. In convergent regions, volcanoes usually occur in the volcanic arc above subduction zones. These make up 80% of the total of the world's active volcanoes [*Smith*, 2013].

There are presently ~500 active volcanoes on Earth and ~500 million people live near them [*Smith*, 2013; http://earthobservatory.nasa.gov/]. These volcanoes pose a significant threat to a substantial fraction of the human population. When an eruption occurs, the pressure accumulated inside the volcano is suddenly released, which can produce a highly energetic blast. Among the documented examples are the Mount St. Helens eruptions in 1980 [*Fisher et al.*, 1998] and the 1883 Krakatoa eruption [*Self and Rampino*, 1981; see also Chapter 12 by Jenkins et al., in this volume, on the 2010 eruption of the Merapi volcano in Indonesia]. Mount St. Helens exploded on 18 May 1980 after an earthquake-generated landslide (the largest ever recorded) released the pressure accumulated on the northern flank of the volcano, killing 57 people [*Fisher et al.*, 1998 and references therein]. The Krakatoa eruption was one of the most destructive volcanic events documented in history, with a death toll of at least 36,000 attributed to the volcanic blast and the associated tsunami [*Self and Rampino*, 1981 and references therein]. The explosion completely destroyed Krakatoa Island. The sound wave produced by the blast reverberated around the world seven times and destroyed the eardrums of sailors in boats 64 km from the volcano [*Winchester*, 2003].

Pyroclastic flows also pose major hazards to the population living near volcanoes [*Smith*, 2013; see also Chapter 12 by Jenkins et al., this volume]. These fast-moving currents of hot gas and rock can spread away from the volcanoes at up to 700 km/h [*Branney*, 2002]. A well-known case was the 1991 eruption of Mount Pinatubo in the Philippines, the second-largest volcanic eruption of the twentieth century and the most powerful in a highly populated area, which produced destructive high-speed avalanches of hot ash and gas (see http://pubs.usgs.gov/fs/1997/fs113-97/). The pyroclastic flow was not so destructive as it could have been due to a timely forecast of the eruption, leading to evacuation of the surrounding areas. Volcanic eruptions can also emit large clouds of gas, rock, and ash that can ascend to several kilometers into the atmosphere and spread over tens to thousands of kilometers away from the eruptive centre [*Decker and Decker*, 1997; *Smith*, 2013]. In 79 AD, during an eruption of Mount Vesuvius, pyroclastic ashfall and surges buried the city of Pompeii in the Bay of Naples, Italy [*Zanella et al.*, 2007]. The number of deaths is unknown, but thousands of bodies have been recovered. Today nearly 600,000 people live in the shadow of Vesuvius.

Emission of ash and gases into the atmosphere can also have a direct short-term effect on the aviation industry [*Smith*, 2013; Chapter 14 by Prata, this volume]. In 2010 the eruption of the Eyjafjallajökull volcano in Iceland closed the airspace of several European countries to commercial jet traffic for almost 10 days, affecting about 10 million travelers. Such atmospheric emissions can also have a long-term impact on global climate [*Smith*, 2013; Chapter 14 by Prata, this volume]. As an example, around 70,000 years ago the eruption of the Lake Toba supervolcano on Sumatra Island in Indonesia caused a volcanic winter that some believe almost extinguished the human species [*Rampino and Self*, 1993]. Several authors have suggested that large-scale volcanic eruptions, probably associated with the arrival of a plume head, may have contributed to the extinction of the dinosaurs and many other species at the end of the Cretaceous [*Duncan et al.*, 1998].

## 1.4. CONCLUDING REMARKS

The present millennium has been particularly devastating in terms of plate boundary natural hazards. The $M_w$ ~9.1–9.3 Sumatra-Andaman earthquake in 2004, the $M_w$ 8.8 Chilean earthquake in 2010, and the $M_w$ 9 Tohoku earthquake in 2011 (see Chapter 5 by Gutscher, this volume), all with subsequent deadly tsunamis, and the 2010 Haiti earthquake and the 2015 Nepal earthquake all had devastating effects and increased our awareness of the destructive power of natural hazards (see Chapter 4 by Stern et al. and Chapter 6 by Stein et al., this volume). In total, half a million people were killed.

Although we have come a long way in the search for understanding such natural phenomena, in many ways we still feel today as Kant probably felt after the 1755 earthquake: overwhelmed by the events. Although our knowledge of Earth dynamics and plate tectonics has improved enormously, there are still fundamental uncertainties in our understanding of these natural hazards (see Chapter 6 by Stein et al., this volume). Increased understanding is crucial to improve our capacity to predict such natural hazards. Nevertheless, we may have to rely on prevention strategies for the time being. However, we are convinced that more studies and ever-increasing periods of continuous recording and monitoring of the Earth system will allow improvements to be made in natural hazard prediction and mitigation. Progress has been made in predicting volcanic eruptions by monitoring volcano inflation, which allowed a timely evacuation of the surroundings of Mount Pinatubo just before the 1991 eruption.

This book reviews some of the main concepts associated with tectonic plate boundaries and presents new studies on natural hazards associated with such boundaries. The volume was designed to contain different levels of information and complexity so that it can be used not only by scientists but also by students, policy makers, journalists, and the informed public. Our intention was not to cover all the subjects in the field (that would be impossible) but, instead, provide the reader with insight into what is currently being done.

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