Geohazards are the manifestations of geological and environmental conditions caused by short-term and long-term earth processes, and commonly result in catastrophic damage, casualties and destruction of social infrastructure (Figure 1; McGuire et al. 2000). Earthquakes and tsunamis are two of the most devastating geohazards (Table 1; Bolt 2004; de Boer and Sanders 2005; Guidoboni and Ebel 2009; Plag 2014; Scourse et al. 2018) because they are generally linked in space and time and they commonly occur along the most densely populated coastal corridors and industrial centres of continents (e.g. Pacific Rim) and countries (e.g. those around the Aegean and Mediterranean seas). The examples of such catastrophic geohazard events that we witnessed in the Indian Ocean earthquake and tsunami in Indonesia (December 2004), on the Tohoku coast, Japan (March 2011, Tohoku-oki Earthquake and Great Tsunami), in Italy (August 2014), in Nepal (April 2015, the Gorkha Earthquake) and in Sulawesi–Indonesia (September 2018) are some of the most salient reminders of how devastating and destabilizing the manifestations of these natural disasters can be (Plag 2014). History also reminds us that the demise of some of the most important civilization centres in the world was accelerated and completed by major earthquakes, tsunamis, volcanic eruptions and floods/droughts (McGuire et al. 2000;
Their impacts on local and global economies, on the stability of nations and societies and on world geopolitics are immense (Stein and Mazzotti 2007).

Despite all this knowledge, educational and scientific research programmes dealing with risk assessment, prediction and mitigation and management still remain elusive for most nations and organizations. There is also a strong need for better awareness of the existence of geohazards (where and why they occur) and their role in the lives and functions of future generations, developing nations and developing economies. Therefore, informed and systematic efforts for global geohazard safety through education and training, risk assessment, preparedness and mitigation–management are much needed. To this end, we have convened two large meetings on global geohazards during the last four years, bringing together groups of geoscientists, policy makers, government regulators and administrators of some professional organizations to talk to each other and find effective ways to raise public awareness of geohazard risks. The first scientific session was part of the Japan Geoscience Union–American Geophysical Union Joint Meeting, held in Makuhari Messe, Chiba, Japan, on 25 May 2017. The Session H-DS11 was entitled: ‘Enhancing Scientific and Societal Understanding of Geohazards in an Engaged Global Community’. The other meeting took place at an international conference on Resources for Future Generations 2018 (RFG 2018), held in Vancouver, Canada, during the week of 16–21 June, 2018. The related session was entitled ‘EA1: Convergent Margin Geohazards and Geodisasters: Present Understanding, Mitigation, and Long- and Short-term Preparedness’. Both sessions were well attended and the discussions pertaining to geohazard risk assessment techniques and efforts in different countries were particularly
Table 1. Types, the natural causes, the dates and locations, and the social, economic and political consequences of the top ten geohazard occurrences in history. The ranking is based on the magnitude and intensity of earthquakes, the number of fatalities, and the extent of economic losses (data from Pappas and Means 2020, and this study).

| Ranking Among the Top 10 | Geohazard Category | Geohazard Event | Date | Geographic Location | Natural Cause | Social, Economic & Political Consequences |
|--------------------------|--------------------|-----------------|------|---------------------|---------------|---------------------------------------|
| 3                        | Earthquake         | Shaanxi Eq      | 23 January 1556 | Shaanxi Province, Wei River Valley, China | Slip along the Weihe Basin Fault, with a slip rate of 2–25 mm/yr. Mw = 8.0 to 8.3. Intensity = XI on the Mercalli Scale (catastrophic) | Deadliest earthquake in the recorded human history. Nearly 830 thousand people died, as their ‘yaodong’ (cave) houses carved into the loess plateau collapsed during & after the quake. Strong aftershocks followed causing further damage & casualties. It occurred during the reign of the Emperor Jiajing in the Ming Dynasty. The quake triggered massive landslides. Nearly 40 out of 140 Tang Stone Classics were broken. |
| 5                        | Earthquake         | Haiti Eq        | 12 January 2010 | NW of Port-au-Prince, Haiti | Seismic slip along a blind thrust fault, associated with the left-lateral, Enriquillo-Plantain Garden Fault Zone, which takes up half of the relative motion between the North American and Caribbean plates. Mw = 7.0; Focal depth = 13 km. Intensity = IX on the Mercalli scale. | One of the three deadliest earthquakes of all time. 100 to 160 thousand people died. Nearly 250 thousand residential and 30 thousand commercial buildings collapsed. Triggered a local tsunami event. One third of the total population (3 million) of Haiti were affected. The Presidential Palace, the National Assembly and the main cathedral in the capitol city were destroyed. Overall $7-10 Billion in losses and damages. The lack of evacuation plans, failed electrical power system and interrupted communication lines caused the fatalities to rise. More than $16 Billion total aid by the international agencies between 2010 and 2020. |
| 7                        | Earthquake         | Haiyuan Eq      | 16 December 1920 | Haiyuan County, Ningxia Hui Autonomous Region in NW China | Left-lateral seismic slip along the Haiyuan Fault at the NE end of the Tibetan Plateau. Surface rupture after the quake = 200 km. Total left-lateral offset after the quake = 10 m. The average slip rate along this fault = 5–10 mm/yr. Mw = 7.8 (USGS) to 8.5 (China). Intensity = XII on the Mercalli scale (extreme) | Total of 2273,400 people died. Felt in many provinces in China, all the way to Beijing. Massive, co-seismic landslides (total of 7151) in loess deposits triggered by the quake. Near the epicentre of the quake some rivers were dammed. More than 70% of structures in 14 counties collapsed. Many people were perished because of extreme cold weather in the winter time. |
Table 1. Continued.

| Ranking Among the Top 10 | Geohazard Category | Geohazard Event | Date | Geographic Location | Natural Cause | Social, Economic & Political Consequences |
|-------------------------|--------------------|----------------|------|---------------------|---------------|------------------------------------------|
| 8                       | Earthquake         | Antioch Eq     | May, AD 526 | Ancient City of Antioch in the Byzantine Empire (today’s Antakya in Turkey) | Dead Sea Transform Fault plate boundary between the Arabia and Africa tectonic plates. Ms = 7.0 (based on surface wave magnitude scale). Intensity = VIII (severe) to XI (violent) on the Mercalli scale. Antioch was built within the Orontes River valley, filled with unconsolidated silt and sand that amplified the quake damage. Aftershocks followed during the next 8 months. | The earthquake took place during the week (25–29 May) of the Christian celebration of “Ascension Day”, which had brought in many people to Antioch. Nearly 250 thousand people died because of the collapsed building and widespread fires afterwards. A local tsunami triggered by the quake destroyed the the harbour at Caesarea Maritima along the Lebanese coast to the south. The church built by Emperos Constantinus II 200 years ago was destroyed. The Emperor Justin I sent money and ambassadors for the reconstruction of Antioch immediately after the earthquake. The newly built city was destroyed again during the November 28th Earthquake. The significantly weakened city was sacked by the Persians in AD538. |
| 9                       | Earthquake         | Tangshan Eq    | 7/28/1976 (3:42 am in the morning) | City of Tangshan, Hebei Province, China | Seismic slip along a subvertical, right-lateral strike-slip fault (N40°E) with extensional component. Nearly 2.7 m vertical offset after the quake. Focal depth = 15 km. Mw = 7.8. Intensity = XI on the Mercalli scale (catastrophe). No foreshocks were felt. | 250 thousand people, out of the 1 million residents of the city, died due to the quake, which was felt in Beijing, 180 km away. Nearly 85% of the city’s buildings collapsed. The Beijing–Shanhaiguan Railway (built in 1887) was seriously damaged, affecting domestic travel. The quake occurred towards the end of the Cultural Revolution (1966–1976) and tested the government’s power and efficiency. Prior to this quake, the Chinese government led the society believe that the Chinese scientists were able to predict earthquakes; it did not happen in this case. Economic loss is estimated to be ~10 Billion Yuan. |
| 10                      | Earthquake         | Aleppo Eq, Syria | 11 October 1138 | NW Syria | Seismic slip along the left-lateral Dead Sea Transform Fault plate boundary between the Africa and Arabia plates. | The quake occurred during the second military campaign of the Crusades to the Eastern Mediterranean region in the period between 1096 and 1271, and weakened the position of the Christian armies. The citadel in the Principality of Antioch was destroyed, along with the Castle of Harim, occupied at the time by the Franks. Nearly 230 thousand people died. The quake was felt in the city of Damascus, 350 km away. |
| 10 | Earthquake, followed by a tsunami | Indian Ocean Earthquake & Tsunami | 12/26/2004 (7:59 am in the morning) | West Coast of the Island of Sumatra (Aceh Province), Indonesia | Subduction zone fault near the Sumatra Trench, east of the Indian Ocean. Mw = 9.1. Focal depth = 30 km. The rupture front during this quake moved at a speed of ~2.5 km/s. It took approximately 8 minutes for the rupture front to propagate ~1200 km northwards, away from its focal point. Followed by a giant tsunami (with a wave speed of 800 km/hr) that affected the entire peri-Indian ocean territories, particularly the Indian subcontinent, Indonesia and Africa. This Indian Ocean Earthquake represents the 3rd largest earthquake (in terms of its magnitude) in the world since 1900. Nearly 230 thousand people died and 2 million people were displaced. Tsunami waves locally reached 30 metres in runup height on the Sumatra coast. Within 20 minutes of the earthquake, the first of several 100-foot waves hit the shoreline of Banda Aceh, killing more than 100,000 people. Many tourist resorts, farmland, and fishing grounds were destroyed or inundated with tsunami debris. Salt-water invasion was devastating for drinking water supplies and plants. The total damage was estimated at $10 Billion. Three weeks after the tsunami, representatives of 168 nations agreed to the Hyogo Framework for Action, for global cooperation for disaster risk reduction. In addition, the Indian Ocean Tsunami Warning and Mitigation System was established to monitor seismological changes in the region. |
| 1 | Floods | Yangtze River Floods, “Central China Floods” | July-August 1931 | Wuhan- Nanjing and Gaoyou Lake, Southern China | Extreme rainfall and cyclonic activities during the summer of 1931, after 3 years of severe drought. 600 mm of rainfall received only in July. The entire region (~180 thousand square km) was inundated. Recent (calibrated) estimates of the fatalities caused by this flood are between 2 million to 3.7 million people. The flood water level was 16 meters above the normal on August 20th. Nearly 25 to 53 million people were affected by the flood. The devastating and far-reaching results of this flood further fueled the ongoing civil war during the reign of Kuomintang of the Republic of China. Almost 15% of the rice and wheat crops in the country was destroyed by flood waters, resulting in widespread famine. Diseases Malaria, dysentry and cholera became rampant in the remainder of 1931, followed by a cholera epidemic in 1932 that killed further 32 thousand people. Manchuria was invaded by the Japanese in September 1931, following the devastating flood disaster. |
| Ranking Among the Top 10 | Geohazard Category | Geohazard Event | Date       | Geographic Location | Natural Cause | Social, Economic & Political Consequences |
|-------------------------|--------------------|----------------|------------|---------------------|---------------|-----------------------------------------|
| 2                       | Flood              | Yellow River (Huang He) Flood | September 1887 | Zhengzhou City, Henan Province, China | Rising water level within the exceedingly silted and filled up channel of the Yellow River overflow its banks and man-made dikes to flood the entire region of northern China. | The farmers living near the Yellow River for many centuries built dikes to contain the rising river waters that in turn caused silt- sand accumulation on the riverbed. His elevated riverbed and many days of heavy rain caused the river flow to overcome the dikes on September 28th, 1887, resulting in a massive flood. Flood waters inundated nearly 13 thousand square km, leaving 2 million people homeless, and 90 thousand to 2 million people dead. After this flood and the several major other floods in 1931 (4 million dead) and 1938 (1 million dead), Westerners dubbed the Yellow River “China’s Sorrows”. |
| 4                       | Cyclone & Flood    | Bhol Cyclone and Flood | 12–13 November 1970 | East Pakistan (today’s Bangladesh) | A tropical cyclone with wind speeds of 205 km/hr and a storm surge of 10.6 m hit the northern coast of the Bay of Bengal. | It was the deadlist cyclone in the recorded history. Widespread flooding of the northern Bay of Bengal and its islands caused the deaths of of 300 to 500 thousand people. More than 45% of the population living in the city of Tazumuddin in the Bhola district perished. The Gangdese Delta was entirely flooded and under water. Estimated cost of the disaster was $86 Billion, and its socio-economic impact led to the Bangladesh Liberation War, and eventually resulted in the independence of Bangladesh in December 1971, after the Indo-Pakistani war. |
| 6                       | Cyclone & Flood    | Coringa Cyclone | 25 November 1839 | Coringa port city in the Andra Pradesh Province of India | A tropical cyclone, developed over the Bay of Bengal, where warm sea surface temperatures create the right atmospheric conditions for cyclones. The Bay of Bengal is warmer than the Arabia Sea to the west, and hence it promotes the formation and intensification of cyclonic systems. Hurricanes formed in the South Pacific and Indian Oceans are called ‘cyclones’, whereas those formed in the Pacific Ocean are called ‘typhoons’. | The cyclone produced a storm surge of 12 metres that destroyed the entire city, its port and about 20 thousand ships; the port was never re-built again and the people moved inland, turning the previous city to a small village. This 1839 cyclone hit the exact same place (Coringa) as the previous 1789 cyclone. Nearly 300 thousand people died. The term ‘cyclone’ was coined by Henry Piddington 1848 in the second edition of his book, called “The Horn-Book for the Law of Storms for the Indian and China Seas”, following this Coringa Cyclone event. |
A very strong tropical storm that escaped any land or mountain barriers on its pathway before it landed in the Red River Delta in the Gulf of Tonkin in the South China Sea where the port town of Haip Hong was situated. “Hai Phong” means sea defence in Vietnamese. The typhoon gained strength over the Gulf and produced a very strong storm surge as it landed in Haip Hong. The port and the town were very young, established by the French only in 1874. They were entirely destroyed, and the rice fields were flooded. The typhoon killed 20 thousand people in Luzon (the deadliest typhoon in the history of the Philippines) and then 3000 people in Haip Hong. The town was rebuilt afterwards; it is now the outport of the capital city of Hanoi, with flood defense system including dykes and levees, a flood warning service provided by the Meteorological Service of the country, and evacuation plans. However, international organizations point out that Hai Phong port lacks a comprehensive and integrated floodwater management plan or strategy. Therefore, considering its economic importance in the region, resilient urban planning capacity, infrastructure management and emergency response of Hai Phong need to be developed effectively and urgently against future and likely typhoons.
interesting and inspiring. The international Union of Geological Sciences set up a Geohazards Task Group in 2016, which provided financial help and opportunities to organize these meetings and to galvanize the collective efforts of the global Earth sciences community to invest in the education and training of vulnerable societies and nations for the manifestations of geohazards events.

This book contains mainly the papers presented at these two meetings on some of the case studies of earthquake and tsunami events, their origins, sources and consequences and ensuing efforts made by different nations and countries towards more effective practices of risk assessment and disaster management. We have decided to concentrate on these two types of geohazards rather than covering all types of other natural hazards (i.e., volcanic eruptions, hurricanes and floods, landslides) to keep the volume internally coherent and manageable in length. Unlike some other thematic volumes on the similar topics, the contents of this volume bridge the gap between the science of earthquakes and tsunamis and the societal implications of and national and international efforts on the development and implementation of geohazard disaster and risk management by integrating discussions on: (1) how to build global capacity to mitigate earthquakes and tsunamis, (2) how to promote global take-up of local best practice in management of these natural events and (3) how to transfer knowledge and skills for increased preparedness for such geohazards to developing countries and all georisk stakeholders. Thus, this book makes a unique contribution to both science and society, and therefore it is a timely endeavour to present the most up-to-date information to the global community that can be used for developing strategic plans and objectives by international organizations and intergovernmental agencies for the safety infrastructure of society.

The first section is on earthquakes, related hazards and risk assessment, and includes 10 chapters with case studies from Turkey, Iran, Japan, Myanmar, Indonesia, South America, and the Azores (Portugal). The flow of papers on earthquakes in this section follows an order from the geological causes and mechanisms of earthquake events and related studies on their modern and palaeoseismological characteristics to how to predict future earthquake events, new methods for computing probabilistic seismic hazard risks and the significance of seismic monitoring networks and surveillance systems in earthquake-prone regions. The following section is focused on tsunami hazards and their sources, risk assessment and disaster management. The nine chapters in this section examine historical and modern tsunami events and their societal consequences in Japan, Thailand, Indonesia, Sri Lanka and the Azores (Portugal). Different techniques to recognize potential tsunami sources, to implement more accurate evacuation procedures before and during tsunami events and to improve pre-existing disaster risk reduction programmes are introduced and explained in this section. The last two sections in the volume involve: (1) typhoons and river floods, and their effects on sediment distribution at continental margins; and (2) building earthquake resilience in societies of seismically active regions. Science and Society in Geohazard Investigations finally highlights some of the most important ‘take-home’ observations and knowledge gained from the case studies covered in this book.

### Earthquakes, related hazards and risk assessment

The North Anatolian Fault (NAF) in Turkey is a major continental transform fault plate boundary in the eastern Mediterranean region and is one of the most seismically active fault zones in the Alpine–Himalayan orogenic belt. This, nearly 1500 km-long, dextral strike-slip fault zone extends from the Karliova Triple Junction in eastern Turkey to the northern Aegean Sea through the Sea of Marmara to the south of the megapolis of Istanbul. Episodic slips along the NAF have been responsible for large (Mw > 7) seismic events during the twentieth century with a pattern of earthquake sequences migrating from east to west through time. Historical records and radiocarbon chronology data show that nearly seven very large earthquakes occurred over the past 3000 years prior to the mid-twentieth century, with an average interevent time of 385–166 years (Fraser et al. 2009, 2010). Large earthquakes during the past 75 years have resulted in thousands of casualties and major damage to infrastructures and housing in urban areas. The 1939 Erzincan earthquake along the eastern segment of the NAF was responsible for 33 000 fatalities and c. 100 000 injuries, and for the destruction of c. 120 000 houses, making this seismic event the costliest in terms of the loss of life and property in Turkey in the twentieth century. These numbers and the intensity of total destruction in the region prompted the policy makers and government officials to outline and adopt, for the first time in the country, seismic building regulations. Emre et al. (2020) document the fault geometry, segmentation and slip distribution associated with the 1939 Erzincan earthquake along the eastern NAF. They show that the total surface rupture during this event was 330 km, with nearly 250 km of it developed on the main strand of the NAF, whereas the remaining amount was distributed along the major fault splays. Slip distribution occurred in five segments, 42–90 km in length and separated by step-overs and bends that are 1–7 km in length and 1–3
km in width along-strike of the NAF. The maximum dextral slip measured on the 1939 rupture was 10.5 m. Based on palaeoseismological and geodetic survey results, previous researchers inferred a slip rate of 20 mm a\(^{-1}\) along the eastern segment of the NAF, between the Karliova Triple Junction and the town of Niksar (see Emre et al. 2020 for references). The authors conclude that the variable slip along the 1939 surface rupture in different segments of the NAF probably resulted from different amounts of strain accumulated on them since the last major earthquake prior to 1939. They also report that fault geometry, the level of stress transformed at segment boundaries and rupture direction were the main factors controlling the mode and nature of the rupture propagation from the main strand of the NAF. These are important parameters for source-fault characterization of strike-slip fault systems with multiple segments. The available palaeoseismological data suggest a nearly 900–1500 year interval between the two large multisegment earthquakes on the eastern NAF. Given the strong seismic record of the NAF, it is extremely important to prepare improved seismic hazard risk assessment through Global Positioning System measurements, seismological data production, geodetic surveys and geological mapping conducted along all of its segments in order to identify low- and high-potential zones for future earthquakes (Akkar et al. 2018; Dogru et al. 2018).

Like the adjacent Turkey, Iran is also one of the most seismically active areas in the Alpine–Himalayan orogenic belt, and its southern tectonic domain, the Zagros fold and thrust belt (ZFTB), is home to a dense population of tectonically active thrust and strike-slip fault systems, which produce frequent and destructive earthquakes. The ZFTB is nearly 1800 km long in a NW–SE direction and marks the foreland of the continental collision zone between the NE-moving Arabian plate and the Eurasian continent (Dilek 2006). Previous studies have shown that the seismogenic depth in the ZFTB is c. 20 km, although most of the moderate earthquakes (Mw 5–6) take place at depths of 5–10 km within the sedimentary cover (Nissen et al. 2011). Larger-magnitude earthquakes (Mw 6.7 and higher) commonly involve both the sedimentary cover and the crystalline basement. The majority of seismically active faults are south-vergent thrust faults that are compatible with the collision geometry and under-plating of the Arabian continent in this broad zone of oblique convergence. Some of these thrust faults never make it to the surface and are lacking coseismic surface ruptures, forming blind faults, which are highly problematic in seismic hazard assessment. Khalili and Dilek (2021) present a geological and geophysical evaluation of the source of the 9 April 2013, Kaki Earthquake in the ZFTB and discuss its origin and implications for seismic risk assessment in this part of Iran. Using surface and subsurface distributions and focal mechanism solutions of the aftershocks of this earthquake, the authors determine that the fault responsible for the Kaki earthquake was a NE-vergent backthrust, opposite to the general tectonic fabric and transport direction within the ZFTB. The seismic slip occurred between 7 and 17 km at depth along this reverse fault, which also represents a blind fault with no surface rupture. The Kaki Earthquake was responsible for the deaths of 37 people and the injuries of 850, and it occurred extremely close to the Bushehr nuclear power plant in SW Iran. The city of Kaki was ruined, and the other nearby cities of Kormouj, Dayer and Kargan were severely damaged. The Kaki earthquake displays the typical and significant threat of blind faults in actively deforming areas and underscores the importance of systematic geological and geophysical studies and surveys in identifying and evaluating such blind faults for more effective seismic assessment and management efforts in SW Iran and elsewhere, particularly when the construction and maintenance of nuclear and hydraulic power plants are involved.

Active convergent margins and collision zones are primary geological environments, where both high-magnitude seismicity and destructive, explosive volcanism commonly occur in tandem. Central Japan has a unique tectonic setting, which is (a) situated in the upper plate of four subduction zones, (b) adjacent to two triple junctions and (c) adjoined by at least four tectonic plates. The Izu Peninsula jutting out to the Philippine Sea is a site of an arc–arc collision zone, surrounded to the east and the west by two trenches, the Sagami and Surunga troughs, and to the north by the collisional Tanzawa Mountains. Mori and Ogawa (2020) examine the geohazard potential in the Sagami Bay coastal area on the eastern flank of the Izu arc collision zone based on recent onshore and offshore neotectonics activities in the area and on the archaeological and historical records from the region. This area with a great seismic potential is home to two megacities, Tokyo and Yokohoma, which experienced large earthquakes and ensuing fires that resulted in major damage and loss of life in 1703 (Genroku–Kanto Earthquake with Mw 8.2) and in 1923 (Great Kanto Earthquake with Mw 7.9). The Oiso Hills just to the north of the Sagami Bay are delineated by active faults and folds on all sides and are undergoing rapid uplift as evidenced by the tilted and uplifted coastal terraces. The progressive uplift of these coastal terraces seems to have accelerated during the last 6.5 kyr, with average uplift rates ranging from 1.3 (Oiso town) to 3.1 m ka\(^{-1}\) (Nakamura-hara terrace). In addition to these convergent margin tectonics-related seismic events and crustal deformation, the area is also a home to two large, active (c. 1 myr old)
volcanoes, Hakone and Fuji, whose eruptions during the last 10 kyr have affected people’s lives significantly. Archaeological evidence suggests that inversion of stream and river channels as a result of the deposition of ash deposits and pyroclastic flows resulted in major floods of cities and agricultural fields, and in widespread famines. Volcanic winters caused by eruptions also induced colder climates and contributed to these prolonged famines. Historical records indicate that seismicity and volcanism were intimately related in space and time in the area, and that one was usually a precursor for the other. For example, the 1703 Genroku–Kanto earthquake (Mw 8.2) was followed by the 1707 Hoei eruption of Mount Fuji that caused significant damage in the greater Tokyo area (known as Edo at the time), which had the largest population (estimated at 1 million) in the world then. Historical documents indicate that three major eruptions of Mount Fuji were nearly contemporaneous with large subduction-related earthquakes, and that the potential for such dual geohazards is pre-eminent in the near future.

Doke et al. (2020) report on the velocity vectors and strain rate fields of the region in and around the Izu arc collision zone in the Izu Peninsula in central Japan, based on their Global Navigation Satellite System observation data. Seismic slip and crustal deformation along the NNE–SSW–oriented, sinistral Kita–Izu Fault Zone in the north-central Izu Peninsula have produced numerous large earthquakes throughout the recorded history. Three major earthquakes in 1633, 1782 and 1853, known as the ‘Odawara Earthquakes’, were spatially associated with shear deformation along this fault and damaged the Odawara city significantly. The subduction-related earthquakes in the Suruga and Sagami Troughs with the recurrence intervals of c. 400–500 years were particularly damaging in the region. The 1923 Taisho Kanto earthquake (Mw 7.9) beneath the Sagami Bay resulted in >105 000 fatalities, the largest ever recorded in Japan. The Global Navigation Satellite System velocity vector calculations by the authors show that strain rate fields in the northern Izu Peninsula are complex and inhomogeneous. The crustal block east of the Kita–Izu Fault Zone displays larger northward velocities in comparison with the fault block to the west. Interestingly, the deformation rate calculated based on the authors’ GNNS data is locally twice the geologically determined deformation rate, indicating that the surface evidence does not reflect the cumulative deformation in the region; some of the observed geodetic displacement may be released by interplate earthquakes at the Sagami Trough. This is a major concern because geoscientists cannot correlate the accumulated total strain (and the related strain energy) within and along the Kita–Izu Fault Zone with the occurrence of large earthquakes to the west of the Sagami Bay. Potentially larger-magnitude earthquakes may occur in the northern Izu Peninsula in the future.

Nanayama (2020) reviews the geological evidence for seventeenth-century-type giant earthquakes and tsunamis along the southern Kuril subduction zone in eastern Hokkaido, northern Japan. Earthquakes with magnitudes of 7 and 8 occur with recurrence intervals of 70–100 years, and those with magnitudes of 8.8 take place at 400–500 year intervals in the southern Kuril Trench off eastern Hokkaido. These are interplate earthquakes that are generally associated with giant tsunamis. Here, the Pacific plate subducts beneath the North America plate (or the Okhotsk plate) at a rate of 73–75 mm a⁻¹, whereas in northern Hokkaido the Kuril arc, specifically its forearc region, has been colliding with the Northeast Japan Arc along a NNW–SSE-trending collision front since 12 Ma (Kusunoki and Kimura 1998). The southern Kuril trench plate interface is divided into a series of segments, each of which experiences Mw 7–8 earthquakes that cause coastal surface uplifts of 0.5–2 m as well as subsidence in coastal plains at a rate of 8–9 mm a⁻¹ since the mid-1800s. Radiocarbon evidence from peat layers interlayered with brackish water mud layers deposited in coastal marshes of eastern Hokkaido indicate four discrete sea-level falls that were associated with seismic uplifts during the last 3 kyr. The 1637 giant earthquake was a result of a multisegment, interplate earthquake (Mw 8.8) with a large slip near the trench axis. However, this area overlaps with the Kuril forearc sliver collision zone, which is affecting the current topography in eastern Hokkaido. Therefore, the possible effects of the collision and the related extrusion tectonics must also be considered in better understanding the seismicity of this region and predicting future seismic events and associated tsunamis. Nanayama (2020) points out that the Headquarters for Earthquake Research Promotion discussed in its recent report (2018) the occurrence probability of a large, seventeenth-century-type (i.e. Mw 8.8) earthquake in the region within the next 30 years, as it has been nearly 400 years since the last great earthquake of 1637. This warning has prompted the local governments in eastern Hokkaido to prepare new hazard maps complete with evacuation sites and routes at an accelerated pace during the last 2 years.

The NW–SE-striking, left-lateral Nam Ma Fault in Indochina is a nearly 215 km-long fault in the region of the Laos–Myanmar border. It is one of many subparallel fault systems in the broad region between the lithospheric-scale Red River and Sagamit faults to the east and the west, respectively. The Mekong River is offset sinistrally for 12–14 km by the central segment of this fault, which terminates at both ends in currently deforming,
trastensional pull-apart basins (Wang et al. 2014). These geomorphic and geological features indicate that the Nam Ma Fault is an active, seismogenic fault. Okubo et al. (2020) present the results of their field surveys along the Nam Ma Fault exposed in Myanmar and document the nature of its segmentation. Their mapping of the entire fault system and its segments was done using ASTER GDEM data and a series of geological maps, which were harmonized to eliminate cross-border inconsistencies and discontinuities arising from different methodology and mapping techniques of various organizations and their geoscientists. Through a combination of remote sensing data mapping and field surveys, a harmonized geological map of the Indochina Peninsula has been published. An earthquake with a magnitude of Mw 6.8 occurred as a result of rupture on a 30 km segment at the west end of the Nam Ma Fault on 24 March 2011, near the town of Tarlay in Myanmar; the death toll was 104. More detailed field surveys need to be completed both in Myanmar and in Laos to better understand the segmentation and slip characteristics of this fault in order to assess future seismic risk hazards in the region more effectively.

The 2018 Hokkaido Eastern Iburi Earthquake in central Hokkaido triggered more than 6000 landslides and 259 rockslides in the area. Of the total of 44 fatalities resulted from this earthquake, 36 were caused by earthslides and rockslides in Atsuma town. Ito et al. (2020) document the distribution of both landslides and rockslides in and near Atsuma and Mukawa towns, using high-resolution aerial laser survey data and field survey after the earthquake. They report that, while it was possible to identify and map shallow landslides on satellite images owing to heavy vegetation. Rockslides can block rivers, causing major floods and hence economic damage, as well as fatalities. Therefore, surveying potential sites of rockslides in topographically unstable areas in earthquake-prone regions is a significant and urgent undertaking.

Seismic slips, amplified ground motions and landslides are real potential hazards for any society situated along active faults and fault systems in and along Tertiary terrestrial basins. However, two aspects of such settings are particularly dangerous for much higher disaster risk potential: (1) buried active faults beneath Plio–Quaternary and unconsolidated clastic sediments; and (2) liquefaction processes in water-saturated ground. Active subsurface faults are difficult to survey and monitor through conventional geological methods, and hence their historical records are not immediately accessible to develop effective hazard prediction and mitigation plans. Liquefaction occurs, as water-saturated sediments at or near the ground surface lose their shear strength in response to strong ground shaking during earthquakes, and they behave like fluid and flow. This process results in sudden collapse of buildings and is hence a major contributor to urban seismic risk. The 2018 Sulawesi Earthquake (Mw 7.5) occurred along the buried Palu–Koro Fault (PKF) in north-central Sulawesi (Indonesia) that ruptured along a 180 km segment beneath Palu City, located in and across a north–south-trending Plio–Quaternary sedimentary basin, and caused widespread liquefaction, severe damage to infrastructures, and significant destruction of many residential buildings. Cipta et al. (2020) used microtremor time series recorded prior to the 2018 earthquake to analyse the subsurface structure of the PKF and the velocity structure within the basin fill. They were able to locate the orientation, geometry and dip direction of the PKF through inversion of horizontal-to-vertical spectral ratio curves and to detect the existence of a subsurface pond and water-saturated sandy soil beneath the neighbourhood of Balanoa, where mega-liquefaction and thus the highest level of subsidence and damage took place. This study shows the significance of investigating both surface and subsurface geology of active faults and fault systems in and around major urban centres and cities where water-saturated Plio–Quaternary deposits in sedimentary basins cover such faults and their seismic history. More effective seismic risk assessment methods and plans can be implemented through such studies.

Surface ruptures and strong ground motions caused by large earthquakes (Mw >6) commonly result in widespread property damage and fatalities. The timing and magnitude of an earthquake, its seismic wave characteristics, epicentre location and the hypocentre (or focal) depth, and the geology of an area (hard rock basement v. alluvial fill), play a significant role in the extent of damage and casualties. With the exception of the geology of an earthquake-prone region, the other parameters listed here are generally unpredictable, making earthquake hazard
assessment difficult. Jin and Kim (2020) discuss the use of fault damage zones and respect distances along active faults in earthquake hazard estimation. They argue that surface ruptures, main shocks, aftershocks and fault damage zones are spatially and temporally related, and thus careful structural and palæo-seismic investigations and analyses of faults and fault zones can be used for predicting future earthquakes. A ‘fault damage zone’ is the volume of deformed wall rocks around a fault plane that developed as a result of the inception, propagation, interaction and build–up of slip along a fault (Jin and Kim 2020, and references therein). Damage zones provide valuable information regarding fault propagation and growth, and are therefore helpful for predicting the locations of future surface ruptures along active faults. Respect distance delineates permanent deformation zone(s) and expected deformation types along active faults, and critical facilities, infrastructures and buildings must be located outside of the respect distance of such active faults. Determining respect distances is, hence, important in assessing earthquake hazards of specific sites and identifying safe areas for developing nuclear facilities and high-level waste disposal sites.

Slab interface and intraslab earthquakes in subduction zone environments generally result in the highest magnitude and the highest impact seismic events in earthquake history. Therefore, the occurrences of such earthquakes must be considered carefully in seismic source characterization and seismic hazard analysis. Pagani et al. (2020) introduce a new methodology for constructing subduction interface and intraslab earthquake sources in computing probabilistic seismic hazard risks at regional and local scales. In this method, the authors define the geometry of a subducting slab and the slab interface to model the maximum magnitude earthquake allowed by that interface segment. They utilize cross-sections of earthquake catalogues, focal mechanisms and geophysical models to define the locked subduction interface and slab volume, and to classify seismicity. They use these parameters to identify segment boundaries along a slab. They also present a methodology for classifying subduction zone seismicity towards modelling subduction sources. The authors show the application of their methods for probabilistic seismic hazard analysis to the Nazca subduction zone off the coast of South America and demonstrate that the obtained magnitude-frequency distributions present a better fit for the observed occurrences in comparison with other traditional approaches. However, slab segmentation inferences may present inherent errors in identifying the rupture sites and thereby limiting the modelling results. The authors plan on removing this limitation in their future work by implementing a smoothing procedure and using a new methodology, which assigns spatially variable occurrence rates to earthquake ruptures.

Unlike many of the case studies of seismic events occurring at convergent plate boundaries that are covered in this volume, the seismicity in and around the Azores archipelago (Portugal) in the central North Atlantic Ocean is associated with divergent and transform fault plate boundary processes, involving the Eurasia, North America and Nubia plates. The Azores Islands trend WNW–ESE for a distance of 480 km between the 40 and 37°N latitudes and straddle the Mid–Atlantic Ridge spreading axis. They form a volcanic plateau, characterized by a bathymetric swell, a gravity anomaly and characteristic ocean island basalt geochemistry of their rocks that is a manifestation of their melt evolution above the Azores hotspot. Thus, the magmatic development of the Azores archipelago has been spatially and temporally associated with mid-ocean ridge and triple junction (Azores Triple Junction) tectonics. The nearly east–west-trending plate boundary between the Eurasia and Nubia plates is defined by the Azores–Gibraltar Fracture Zone (AGFZ), which encompasses the Terceira Rift and the Gloria Fault. The majority of the Azores Islands occur along and to the south of the AGFZ. Geohazard risks in the Azores, thus, involve both earthquakes and volcanic eruptions. Silva et al. (2020) summarize the characterization of the origin, the intensity and the effects of both historical and modern seismic events since the settlement of the islands in the 1500s. Almost all major and destructive earthquakes took place along the AGFZ, ranging in magnitude from 4.8 to 7.3, and triggered landslides, debris flows, major ruptures and tsunamis. The first reported destructive earthquake with an intensity of X on the Mercalli Scale occurred on the São Miguel Island on 22 October 1522 and resulted in the total destruction of the capital city of Vila Franca do Campo and the deaths of 5000 people (Caldeira et al. 2017). The majority of the casualties were due to the debris flows and major landslides that followed the earthquake. The strongest earthquake in the Azores occurred on 9 July 1787, with its epicentre near São Jorge Island, and caused more than 1000 casualties. Some other earthquakes in the Azores were associated with submarine volcanic eruptions. The 1958 and 1964 earthquakes on the islands of Faial and São Jorge (respectively) were triggered, for example, by volcanic eruptions, and also resulted in the development of major landslides that caused severe damage. The instrumental data gathered since 1997 indicate that most of the seismic activity in the Azores occurs along the transtensional Terceira Rift, which defines the modern plate boundary between the Eurasia and Nubia plates. The authors emphasize the significance of having a seismic monitoring network and a surveillance system in and across the archipelago in...
order for the civil protection agencies to develop more effective strategic plans for hazard assessment, land-use and emergency situations.

**Tsunami hazards: sources, risk assessment and disaster management**

Tsunamis are one of the most devastating natural hazards and cause extraordinarily large numbers of casualties, vast property damage and significant economic loss on both regional and global scales (Figure 1), as the world has witnessed during the last 20 years (December 2004 Indonesia and March 2011 Tohoku-oki, Japan tsunami events). What sets tsunamis apart from earthquakes is that they can cause major damage and casualties thousands of kilometres away from their causative sources. Tsunami waves are commonly triggered by sudden displacement of the seafloor as a result of seismic slips, but massive landslides on the seafloor, large submarine volcanic eruptions and meteorite impacts in the oceans can also generate tsunami waves. Unlike wind-generated surface waves, tsunami waves encompass the entire water column regardless of ocean depth and they reach even greater speeds in deeper ocean waters. Their speed may reach 900 km h$^{-1}$ (faster than a passenger jetliner) and their wavelengths can be as much as 500 km. When they approach the shorelines, they start interacting with the sea bottom and their speed decreases suddenly, transferring their energy to wave height (amplitude). This process of ‘wave shoaling’ with suddenly increased height of a water wall (sometimes 20 m high) is responsible for the extreme inundation of coastal areas. Rivers and stream channels with estuaries at appropriate angles to the incoming tsunami waves may facilitate the propagation of these waves further inland, amplifying tsunami effects and damage on land, as experienced on the NE coast of the Island of Honshu, Japan, during the 2011 Tohoku-oki tsunami. The destructive power of tsunamis is largely a result of inundation, wave impact on human-made structures, large volumes of water draining off the land and erosion. Floating debris in tsunami flood waters causes further damage as it crashes into buildings, breaks power lines and gas pipes and starts large fires. Tsunamis also create significant health hazards and environmental problems. Flooding and contamination of drinking water commonly result in the rapid spread of infectious diseases, and solid waste and toxic substance debris become a critical issue for environmental safety. The salination of rivers, water wells, inland lakes and groundwater aquifers is amongst the common consequences of large tsunami events. Significant damage to the infrastructure of nuclear power plants, as was the case in Fukushima Daiichi in Okuma, Japan, in March 2011, can cause radiation pollution, which will have long-lasting effects on people and societies.

Tsunamis cannot be predicted nor prevented as a major type of geohazard. Tsunami risk assessments are, therefore, mostly dependent on the history of past tsunami occurrences and the location of major tsunami-generating active fault systems near coastal areas and offshore. The chapters in this section evaluate tsunami hazards and their impacts on societies and nations. Tetsuka et al. (2020) report that searching for and systematically documenting tsunami deposits associated with past earthquakes using both historical documents and geological evidence are extremely important for more accurately determining future risk potential associated with large earthquake and tsunami events along the Kuril and Japan trenches. Using the AD 1611 Keicho earthquake tsunami that struck the Pacific coast of Tohoku in northern Japan as a case study, the authors argue that one extremely large or two or three closely spaced large earthquakes and tsunamis might have occurred in a short time interval along the adjacent Kuril and Japan trenches in the seventeenth century. Constraining the event ages of tsunami deposits plays a critical role in determining the source of the known tsunami events. The authors use both pre-existing results and their own radiocarbon dating and pollen analyses to distinguish between the AD1454 and AD1611 tsunamis. This approach was in turn very helpful to tie the AD1611 tsunami event to the AD1611 Keicho earthquake. The conclusions and inferences derived from this study are significant in that the 2011 Tohoku-oki earthquake and tsunami events may be followed by a series of large events in the near future, should we consider the AD1611 earthquake and tsunami events as the most recent analogues for such potential hazards.

In addition to seismic slip on active submarine faults, submarine landslides can also be a major cause of local or regional severe tsunamis (Harbitz et al. 2013). Submarine landslides may occur along both active and passive continental margins (Locat and Lee 2002) and on gentle slopes as low as 1°. They may be triggered by earthquakes, melting ice sheets, gas hydrate disassociation and submarine volcanic eruptions. The very strong 1771 Meiwa tsunami that struck the Sakishima Islands of the Ryukyu island arc chain in the western Pacific Ocean had estimated run-up heights of 30 m and was one of the most devastating tsunami events in Japan during historical times. Some researchers have proposed that the Meiwa tsunami was caused by a massive submarine landslide and related processes. Kana-matsu et al. (2020) investigated the seafloor morphology and sediment magnetic fabrics in the source region of the Meiwa tsunami to test its inferred submarine landslide origin. Although a
detailed bathymetric survey of the Hateruma Basin at the tsunami site displays geometrical features of slope failure, piston core samples of the sedimentary deposits and their magnetic fabrics do not show any evidence for mass-transport deposition; instead, they indicate coherent sediment accumulation. These findings rule out the possibility of a submarine landslide as a trigger for the 1771 Meiwa tsunami. However, the authors caution that the graben structure they observed within the Hateruma Basin may have the potential to generate a tsunami in the future because the rift shoulders and fault blocks are possible sites of slope instability that may create submarine landslides as potential tsunami triggers.

Cabral (2020) presents a revised catalogue for the Azorean tsunamis that is based on a comprehensive review of chronicles and newspaper articles, scientific papers and online international databases, published since 1522. Since their settlement in the fifteenth century, the Azores Islands have experienced major tsunami events, some of which caused major casualties and damage, such as the tsunami triggered by the 1755 Lisbon earthquake. Although most recorded tsunamis are earthquake-induced, the new catalogue shows that some tsunamiic events were produced by major landslides, such as the 9 July 1847 Quebrada Nova tsunami, which killed 10 people on Flores and Corvo islands. Heavy storms with strong winds and intense rainfall over the islands commonly lead to slope instabilities along the shoreline cliffs and massive landslides, which in turn generate tsunamis. Considering the historical records, instrumental information obtained from tide gauges and the spatial distribution of seismic and volcanic activities in the Atlantic Ocean, the author lists six areas and the related sources as the main source of tsunamis. The Gloria fracture zone presents a revised catalogue for the new catalogue shows that some tsunamiic events were produced by major landslides, such as the 9 July 1847 Quebrada Nova tsunami, which killed 10 people on Flores and Corvo islands. Heavy storms with strong winds and intense rainfall over the islands commonly lead to slope instabilities along the shoreline cliffs and massive landslides, which in turn generate tsunamis. Considering the historical records, instrumental information obtained from tide gauges and the spatial distribution of seismic and volcanic activities in the Atlantic Ocean, the author lists six areas and the related sources as the main source of tsunamis. The Gloria fracture zone presents a revised catalogue for the

The Grand Banks domain off the coast of Newfoundland, Canada, is an area far outside of the Azores archipelago where occasional earthquakes generate tsunamis that can reach the Azores, such as the one on 18 November 1929. The seismically and volcanically active Caribbean region also has a great potential for generating tsunamis to affect the Azores. Finally, the Canary volcanic archipelago off the coast of NW Africa is known for the origin of landslide-triggered tsunamis as a result of caldera collapse or eruption-related collapses of the volcanoes. Such landslide-induced tsunamis emanating from the Canary Islands can easily reach the Azores. The installment of the first tide gauges in the Azores archipelago in the second decade of the twentieth century was a major step towards the collection of more reliable and detailed tsunami data. This is an important development in tsunami detection and public preparation because the continued increase in the population of the Azores makes the future tsunami hazards potentially much more impactful, both socially and economically.

Pagnoni et al. (2020) propose a new methodology to assess tsunami risks from the perspective of human damage (HD), which is defined by the quantification of people affected and killed by a tsunami, and economic loss (EL), described as the loss of the economic value of structures damaged and destroyed by a tsunami. The authors utilize the available information on damaged buildings, demography and reasonable inundation heights (IH) in this method. They use the census data for an estimation of HD and real estate data for residential and industrial buildings to estimate EL. When applied to the town of Augusta in eastern Sicily (Italy) based on the historical accounts and past tsunami inundations, the method reveals that the IH is very important as EL increases linearly with IH, and the EL may reach nearly 11% of the GDP of the province if IH reaches 10 m. When the IH is around 6 m or slightly above, partial collapse of residential buildings is common, but with IH exceeding 8 m, industrial buildings experience collapse and destruction. The IH also affects HD, as well; the number of people involved increases linearly with increasing IH numbers, and the number of fatalities goes up following a quasi-quadratic law. In and around the historical city of Augusta, 70% of the people are expected to be exposed and nearly half of them (c. 47%) are expected to die for the highest IH number of around 10 m. The authors plan on refining their method to include more efficient and accurate vertical evacuation procedures and to identify suitable buildings and their locations as possible vertical shelter sites for each IH level.

Kawamura et al. (2020a) propose that burial diagenesis of hemipelagic clayey sediments in trench settings can result in microfabric development at shallow crustal depths, leading to an initiation of a décollement surface prior to subduction. The formation of such diagenetic rock fabric in consolidated shaly rocks can then become an important factor in the locking of shallow tsunami-generating slip in subduction zones. This progressive change from a randomly oriented fabric to a well-developed shaly fabric with increasing burial depth, as part of early-stage diagenetic processes, may play a critical role in the development of slip mechanisms of thrust faults and décollement surfaces, which trigger earthquakes at shallow depths. Kawamura et al. (2020a)
recovered hemipelagic, clay-rich Paleocene–Holocene sedimentary rocks from a depth of c. 1327 m in drill cores obtained from IODP Site U1480 (IODP 362) in the Sunda Trench, south of Sumatra. Alignment of platy minerals (mica and clay flakes) through grain reorientation and sliding along microfaults owing to a rapid increase in pore-fluid pressure during burial consolidation results in the development of slip surfaces. In addition, porewater produced by dehydration of silica minerals can concentrate along the aligned fabric planes, forming a water film or a water-concentrated layer, which creates an effective slip plane. Such slip planes can then be the sites for the initiation of submarine slides and décollement zones, both of which produce tsunamis.

Thailand was one of the most devastated countries during and after the 2004 Indian Ocean tsunami, with nearly 8345 people killed and many more missing. This disaster prompted the authorities in Thailand to introduce several disaster risk reduction programmes and measures. Leelawat et al. (2020) review the main efforts and measures that have been implemented to reduce the natural disaster risks in the country. Specifically, they discuss the tsunami warning systems, evacuation signs, manuals and guidelines, evacuation shelters, housing recovery, hotel business and recovery, public awareness and media, and disaster education in today’s Thailand. The authors also look at the tsunami numerical simulations as part of tsunami hazard evaluation and disaster preparedness. They used TUNAMI, a simulation tool developed by Tohoku University (Sendai, Japan) in 1995, to simulate tsunami hazards associated with a Mw 9.0 earthquake along a fault length of 575 km and a width of 145 km at the Andaman Sea coast and produced detailed inundation maps for the Phang Nga and Phuket Provinces. The results of this study are insightful to spotlight potential areas for the improvement of the existing disaster risk-reduction programmes and the disaster risk-management cycle in Thailand.

The island of Sri Lanka is situated in the northern Indian Ocean, far from any active plate boundary, and is separated from the Indian subcontinent by the Gulf of Mannar and the Palk Strait. With the exception of major landslides in the central highlands on the island, the country did not experience any significant geohazard threats until 26 December 2004, when the Indian Ocean tsunami struck its eastern and southern coasts. All shorelines of Sri Lanka were hit by the three main waves of this tsunami 2 h after the initial earthquake, resulting in the death of 31 000 people and the displacement of 440 000 people, with 7000 people missing, and in the destruction of 90 000 buildings. The total economic value of the damage caused by the tsunami was estimated at US$900 million. The magnitude of such high loss of both lives and property was staggering, but not necessarily surprising, because an organized disaster management culture and system did not exist in the country owing to the lack of awareness of and experience with major natural hazards. Weththasinghe et al. (2020) report on the Sri Lanka government’s disaster management plan, which was introduced after the 2004 tsunami, and evaluate its effectiveness based on their field observations and surveys of the local people and communities along the tsunami-struck coastal strip of the country. The authors collected data on the preparedness of the society and local communities, the availability of evacuation plans and pre-disaster warning systems. The new Disaster Management Centre, National Building Research Organization and Department of Meteorology were established after the tsunami to function under the Ministry of Disaster Management. With the development of the disaster management plan, an effective disaster response capability was established that provides a better relief distribution mechanism and a reduction of the loss of lives. The survey shows that more than 74% of the tsunami victims have a high level of confidence in the early warning systems. However, the same survey also shows that the degree of participation in disaster awareness training programmes is very low. These findings indicate that the education of the Sri Lankan society regarding the awareness and preparedness for potential natural hazards remains an important task, and that further improvements in the management of such hazards are necessary.

Tsunamis are devastating for coastal communities, local and global economies, the stability of natural environments and ecosystems, and the physical and mental health of the people who experience them. Kawamura et al. (2020b) report on the occurrence of microplastics in sediment deposits in deep-sea environments, and conclude that tsunamis can play a major role in the dispersal of microplastics from coastal areas to the deep sea. Scattering of microplastics at all depths across the global ocean is in turn extremely harmful for ocean life, marine ecosystems and human health. Zooplanktons and fish larvae consume microplastics, and filter-eaters such as scallops, mussels and clams ingest them. Through the food chain, these microplastics are then passed on to the higher trophic levels (i.e. tuna fish and mackerel) in the oceans and eventually to humans. Microplastics could be extremely harmful to marine organisms and humans as they contain toxic chemicals, such as phthalates and bisphenol A, and can also lead to the accumulation of polychlorinated biphenyls, all of which collectively cause various cancers, weakened immune systems and reproductive problems (Smith et al. 2018). The authors collected sediment samples from offshore the Shimokita Peninsula at the very northern end of the Honshu Island (Japan), using a conventional
multicore sampler, 5 months after the March 2011 Tohoku-oki tsunami. The sample collection site is located c. 300 km north of the epicentre of the earthquake. The water depths for the nine stations on the seafloor where the samples were collected ranged from 55 to 1963 m, encompassing the continental shelf and the upper margin of the Japan Trench. The authors point out that the widespread production and use of plastics in Japan goes back to the 1960s, and that sediment layers containing microplastics are contaminated with $^{137}$Cs originating from nuclear tests conducted in Japan in the 1960s. Thus, the microplastic chips in the sedimentary record off the coast of NE Honshu can provide an effective relative dating tool for very recent turbidite deposits. The significance of this finding is that based on the absence or presence of microplastics: (1) it is possible to differentiate 1960–2011 tsunami deposits from 1896–1933 tsunami deposits; and (2) the relative dating of very young, deep-sea sediments below the CCD (carbonate or calcite compensation depth) is possible.

Typhoons, river floods and their effects on sediment distribution at continental margins

River flooding along shorelines is a major geohazard and may affect the distribution of sediments on continental margins when floods transport large quantities of clastic material from land to the sea. Such flood events are commonly associated with heavy rainfall within the watershed areas of rivers. Typhoons and monsoonal precipitation are the primary causes of floods. Ikehara et al. (2020) report on the nature of submarine flood deposits on the slope off the Kumono River on the SE shores of the Kii Peninsula, facing the Pacific Ocean. The authors used in this study four surface sediment cores collected 2 months after the 2011 flood. The September 2011 flood was a once-in-a-century-scale flood, caused by a typhoon, which also triggered numerous landslides that released large amounts of sediments into the Kumono River. The Kumono River is c. 183 km-long and is the largest river in the region based on its drainage area and the mean annual precipitation it receives in its drainage system (c. 1.6 times larger than that of the Japanese islands). The Shingu submarine canyon follows the Kumono River offshore, incising the upper slope of the narrow continental shelf. The authors identified in the sediment cores repeated intercalations of some coarse-grained layers in a bioturbated clayey silt–silt clay material, and each coarse-grained layer was underlain by a sharp basal contact covered by massive mud. The very top sequence was a result of the 2011 flooding event, underlain by two or three other such sequences, corresponding to past historical flood events. The stratigraphy of the discrete flood deposits was significantly different, and the thicknesses and the grain sizes of these flood deposits, which emanated from the same Kumono River, displayed no relationship with the maximum discharge from each flood. These observations have important implications for sediment transport mechanisms within the river’s drainage system and show that there is no linear relationship between the size of the floods (i.e. maximum v. minimum discharge) and the sediment thickness and lithology. The lack of any earthquake-induced turbidite deposit on the slope also indicated that continental shelf and slope deposition in the region was mainly controlled by major flood events during the last several centuries.

Building earthquake resilience in seismically active regions

Building resilience to natural disasters is extremely important in order to strengthen the global capacity to endure disasters and has become a significant component of the global development agenda towards improving the ability of societies and nations to cope with and to recover from the consequences of such disasters (Paton 2015). Because earthquakes, volcanic eruptions, floods, hurricanes and tornadoes cannot be prevented, we must build and strengthen the community resilience so that any community and society facing major natural disasters would be able to maintain vital functions during an emergency event and to recover efficiently within a reasonable time frame after such an event. It is of particular significance that global organizations as well as government agencies provide technical knowledge and expert support for building resilience and disaster preparedness in high-risk countries around the world. Turkey and the surrounding seas straddle multiple tectonic plate boundaries that are seismically very active (Dilek 2006), and routinely experience major earthquakes with high numbers of casualties and infrastructure and property damage. Dogulu et al. (2020) discuss their findings on community resilience and disaster preparedness from two different case studies based on two large-magnitude earthquakes, which occurred in geographically different parts of the country. Their study emphasizes the perceptions of various factors related to resilience of the survivors of the 1999 Düzce earthquake in NW Turkey and the 2011 Van earthquake in SE Turkey. These two regions are very different in terms of their landscapes, geological causes of the seismic events and socioeconomic structures of the local communities. The 1999 Düzce earthquake, which occurred along a splay of the North Anatolian Fault Zone (see Emre et al. 2020), had a magnitude of
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Mw 7.2 and a maximum intensity of IX on the Mercalli Scale, and resulted in 838 known fatalities. It was after this earthquake that the country shifted from a focus on disaster management to a focus on disaster risk management, and that community participation for disaster preparedness and risk communication activities became more important and relevant. Based on their survey results and observations, the authors state that learning through former disaster experiences of the communities is highly valuable for investing in future efforts for disaster-risk management. The survivors of the 1999 Düzce and the 2011 Van earthquakes have different perceptions of resilience for such disasters immediately after the events, and having this knowledge is highly valuable for planning community interventions and initiatives for those people. Capacity building is significant to better prepare for natural disasters, and scientists have a major role and responsibility in developing training programmes in collaboration with other stakeholders towards an effective promotion of preparedness and mitigation. The authors conclude that it is necessary to empower local community resilience and societal preparedness, rather than maintaining highly centralized and hierarchical disaster-management systems in Turkey and elsewhere.

Science and society in geohazard investigations: take-home lessons and future action plan

We highlight and discuss below some of the most important aspects of the science and societal issues pertaining to the occurrences and manifestations of earthquakes and tsunamis, as emerged from the case studies reported in this book. The list is not complete by any means but provides useful talking points for discussions, which would hopefully involve, going forward, many stakeholders in regard to effective risk assessment and hazard management policies and practices around the globe. In the first part, we state some of the important scientific results and their implications, and in the second part we briefly discuss some societal implications of geohazard events and their role in future risk assessment and management plans.

Scientific results and implications

(1) Studies of subduction-related contractional and transform–transcurrent faults with strike-slip displacements show that such faults are commonly segmented, and that fault segments may have different amounts of strain accumulation, variable surface rupture geometries, different rupture propagation rates and different amounts of slip. These parameters make source-fault characterization of segmented faults more challenging and necessitate multi-instrumental and interdisciplinary investigations of them in order to identify high-potential domains for future earthquake events.

(2) Blind faults that do not display surface ruptures are difficult to recognize, detect and incorporate into seismic hazard assessments based solely on surface geology. As a result, they pose serious threats to urban centres, such as the greater Los Angeles metropolitan area (Shaw and Shearer 1999) and the Hawke’s Bay, Napier, on the east side of the North Island of New Zealand (Webb and Anderson 1998). Therefore, it is critical that potential blind faults in seismically active areas be identified and investigated in their three-dimensional extents, and that they be integrated into regional fault databases and seismic hazard calculations.

(3) Large earthquakes with magnitudes higher than Mw 7.5 may cause eruptions of volcanoes within a 200 km distance, as historical and modern examples indicate. Such eruptions result from static and/or dynamic stresses generated by large earthquakes and may be triggered by either dilatational or contractual changes in the stress field, and/or by strong ground motions and large tectonic slip (Nishimura 2017). Mori and Ogawa (2020) discuss how the 1703 Genrouku-Kanto earthquake (Mw 8.2) might have triggered the 1707 Hoei eruption. Another earthquake with a magnitude of Mw 8.7 that occurred only several weeks before the same eruption in 1707 (the fourth year of the Hoei era) further contributed to the triggering mechanism of the eruption of Mount Fuji. Many researchers concur nowadays that these seismic events and the Hoei volcanic eruption were spatially and temporally related. This empirical conclusion was strongly considered by the Japanese geoscientists immediately after the 2011 Tohoku-oki earthquake off the coast of Sendai seeking to determine whether this seismic event may have changed the internal pressure of the Mount Fuji magma chamber significantly, possibly to result in its eruption.

(4) Establishing codes and zones in seismically active urban centres and cities is an integral part of seismic risk assessment plans. Assessing surface faulting, ground shaking and ground failure potentials (liquefaction susceptibility) is critical in evaluating earthquake hazards and in the preparation of hazard zonation maps. Intensity maps based on damage
reported from past earthquakes according to the Modified Mercalli Index can be used effectively to delineate those areas, which may experience the strongest ground shaking in future earthquakes. Respect distance and permanent deformation zone(s) along seismically active faults must be clearly defined and mapped (Jin and Kim 2020), and they should be considered carefully in locating and designing new buildings and construction sites. Rigorous design and construction standards must be established for the development of utility systems across seismically active faults.

Societal implications of geohazard events and their role in future risk assessment and management actions

1. The impact of an extremely devastating geohazard event of a regional scale may potentially extend beyond a humanitarian disaster and may become an event of geopolitical moment in the future. History shows us that such events and their consequences in the past led to significant inflection points in the rise and demise of civilizations (Dilek 2017). Seismic storms of 1225–1175 BC resulted in the collapse of the Bronze Age and trade routes in the Mediterranean region. The 1755 Lisbon Earthquake halted the progress of the Age of Enlightenment in eighteenth century Europe (Wiesner et al. 1989). The 1883 eruption of Krakatoa strengthened the Dutch colonial rule in Indonesia and led to the establishment of one of the most geopolitically significant passages (‘choke points’) in the global ocean system around the world, the Strait of Malacca (Dilek 2017). These are only a few examples of how geohazards and their consequences can have long-lasting effects on societies, nations and civilizations. The highly interconnected global society of today and tomorrow will undoubtedly be more vulnerable to devastating, high-impact geohazard events at different scales.

2. Human casualties and property loss resulting from natural disasters are extremely variable across the world and they inflict disproportionately more devastation and destruction in developing and poorer countries in comparison with developed nations and societies (Figure 2). This phenomenon is mostly a result of weak governments in power, the lack of education and training of the public about geohazards, less effective land use planning and the absence of strategic risk and management regulations, and slow and inefficient disaster recovery.

3. There is a clear interconnectedness amongst some of the most important global organizations whose aims and missions are geared towards the implementation of effective geohazard risk assessment, disaster management and global resilience development plans. Some of these agencies include the United Nations Educational, Scientific and Cultural Organization, the International Union of Geological Sciences, GeoHazards International, the Global Geodetic Observing System and the National Earthquake Hazards Reduction Program. There is a strong need to have such organizations and intergovernmental agencies establish effective and real-time communications and connections on a common electronic platform. Scientists, particularly Earth scientists, have a significant role to play in the success of the fulfillment of the objectives of these organizations, and they must be provided with adequate funds and tools and voice to do it effectively. Governments, international organizations and societies must invest money and human resources in supporting and enabling scientific communities to do more and better in forecasting geohazard risk and disasters, and educating the public in jargon-free and simple but informative narratives.

4. In our globally connected world, technology, particularly satellite and computer technology, has enhanced media coverage significantly by making it instantaneously available and affordable. Thus, the media’s capability to report on the consequences of destructive geohazard events, their causes and human responses from different corners of the world is unparalleled nowadays in comparison with what we were able to do only 20 years ago. However, the media commonly covers the news and the consequences in the aftermaths of earthquakes and tsunamis, but it seldom provides the much-needed information to the public about disaster preparedness and response, and the local or regional sources of potential geohazards and their history. This is highly important because the public need the learned knowledge and information; efficient and effective working relationships between the media and the government offices, relief and emergency organizations and evacuation centres before, during and after geohazard events can speed up the response and recovery processes considerably. Journalists and reporters as part of the media bear their own responsibilities in conveying the information and news about geohazards to the local communities and the global societies in objective, reliable, verified and credible modes.
Nearly 3.6 billion people live along or within 150 km of a coastline, and estimates indicate that almost 75% of the world’s population may be living along coasts within 30 years (The National Academies Report 2009). These numbers are even higher in the developing world in Southeast Asia and Latin America, and hence coastal communities are becoming increasingly more vulnerable to geohazards. The devastations wrought by the 2004 December Indian Ocean tsunami and the 2011 March Tohoku-oki tsunami are strong reminders of the enormous losses that coastal communities in heavily populated areas in both the developing and the developed world endure. As most of the earthquake- and tsunami-prone regions happen to be along the Pacific Rim, the Indian Ocean and the Mediterranean and the Aegean Sea coastlines, there is an ever-increasing need for more effective ways to improve: (a) hazard risk assessment and disaster management plans; (b) the installation of early warning systems and measurement instruments; and (c) societal resilience in coastal regions.

Unlike earthquakes and volcanic eruptions that can strike cities and major population centres instantaneously, tsunami, which form across an ocean, may take hours to reach the shoreline. This time lag is sufficient to warn people to evacuate and move to higher land. However, the early-warning process requires the existence of real-time monitoring systems in place to provide data for forecasting tsunamis. The case study from the Azores archipelago (Cabral 2020) has shown that the tide gauges installed on the islands have been effective in collecting reliable and detailed tsunami data. A more sophisticated tsunami early warning system, Deep-ocean Assessment and Reporting of Tsunamis (DART), was established in the major oceans by the National Oceanic and Atmospheric Administration of the USA in 2001. DART has been providing timely tsunami warning information for global coastal communities since then. DART systems consist of an anchored seafloor
bottom pressure recorder and a surface buoy for real-time communications (González et al. 1998). If the bottom pressure recorder detects changes in water pressure and any seismic activity on the seafloor, the related data are transmitted to the buoy, which signals an alert via satellite to the tsunami warning systems in Alaska and Hawaii. This is one of the most effective and global, early warning systems for tsunami hazard risks, and will continue to save lives with much improved timing of tsunami detection, warning guidance and international coordination. Clearly, more DART stations are needed in the global oceans for better coverage against future tsunami hazards.

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