CHAPTER

3

The Geological Perspective

Hazards in the Oceanic Environment from a Dynamic Earth

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INTRODUCTION

In the theory of plate tectonics, the Earth's rigid outer shell is considered a series of "plates," approximately 100 km thick, moving relative to one another in response to convection in the underlying mantle. Convection in the Earth's mantle is driven by the planet's internal heat, some of it left over from the considerable temperatures reached during its accretion from the solar nebula and some being generated by the natural radioactive decay of uranium, thorium, and an unstable isotope of potassium, all present in small concentrations in mantle rocks. Mantle convection and the corresponding plate motion and volcanism are the main ways that the Earth dissipates both its primordial and its radiogenic heat.

Part of the success of the plate tectonics theory lies in its simplicity: most of the main geological processes at the Earth's surface can be described by a system of slightly more than a dozen such plates (Fig. 3-1). The largest is the Pacific plate, which makes up most of the floor of the Pacific Ocean, west of the East Pacific Rise. The North American plate is a medium-sized plate, comprising the continent of North America east of the San Andreas Fault and the northwestern Atlantic Ocean.

Most active geological processes, including ones that affect human health, occur on or near the boundaries between plates. The San Andreas Fault in California is the boundary between the Pacific and North American plates. Relative motion between the Pacific and North American plates occurs at a rate of 4 to 5 cm/yr, of which about 3 cm/yr occurs on the San Andreas Fault. If the fault were a frictionless boundary, this motion would occur as continuous creep. Unfortunately, along most of its segments, the fault is not frictionless and strain builds up, releasing every few hundred years in a process known as an earthquake, with obvious impacts on human health.

Most plate boundaries, however, are located in the ocean basins, so it is appropriate to discuss the impact of geological processes on human health in this textbook. The eastern boundary of the North American plate is the Mid-Atlantic Ridge, a mountain chain (with a cleft in the middle) that runs more or less up the middle of the Atlantic Ocean, separating the North American plate from the Eurasian plate. The reason for the cleft in the middle of the ridge is that North America and Eurasia plates are pulling apart at a rate of about 2 cm/yr, and volcanism does not quite fill the resulting gap. Although most of this boundary is submarine, a small part of it is exposed in Iceland. As a direct result of their proximity to this plate boundary, Icelanders are exposed to many volcanic eruptions and earthquakes, can make power from geothermal sources, can smelt aluminum from bauxite ore (a hydrated oxide of aluminum) economically, and have an ever-expanding supply of real estate (literally). They also have to be concerned with excess natural fluorine in their environment, which can lead to fluorosis. Thus, the Earth's geological processes play both positive and negative roles in human health and welfare.

The goal of this chapter is to give the reader a deeper understanding of these roles. We provide a basic background in marine geology and highlight a few examples where marine and coastal geological processes have direct and indirect impacts on human health.

Plate Boundaries and Hazards

There are three types of plate boundary, classified by the three types of relative motion that are possible (Fig. 3-2):

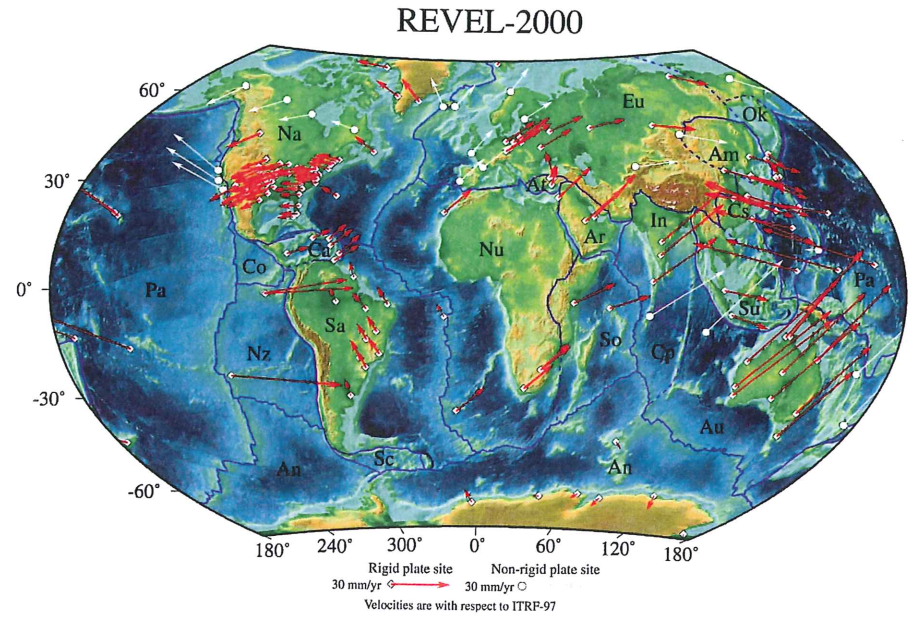

FIGURE 3-1. Map of Earth's major plates. Arrows indicate motion of selected sites, as measured by high precision GPS, relative to an arbitrary global reference frame. Red arrows are plate interior sites, white arrows are sites near plate boundaries. Plate names are abbreviated, (e.g., Pa is Pacific, Na is North America, Sa is South America, Co is Cocos). From Sella *et al.*, 2007.

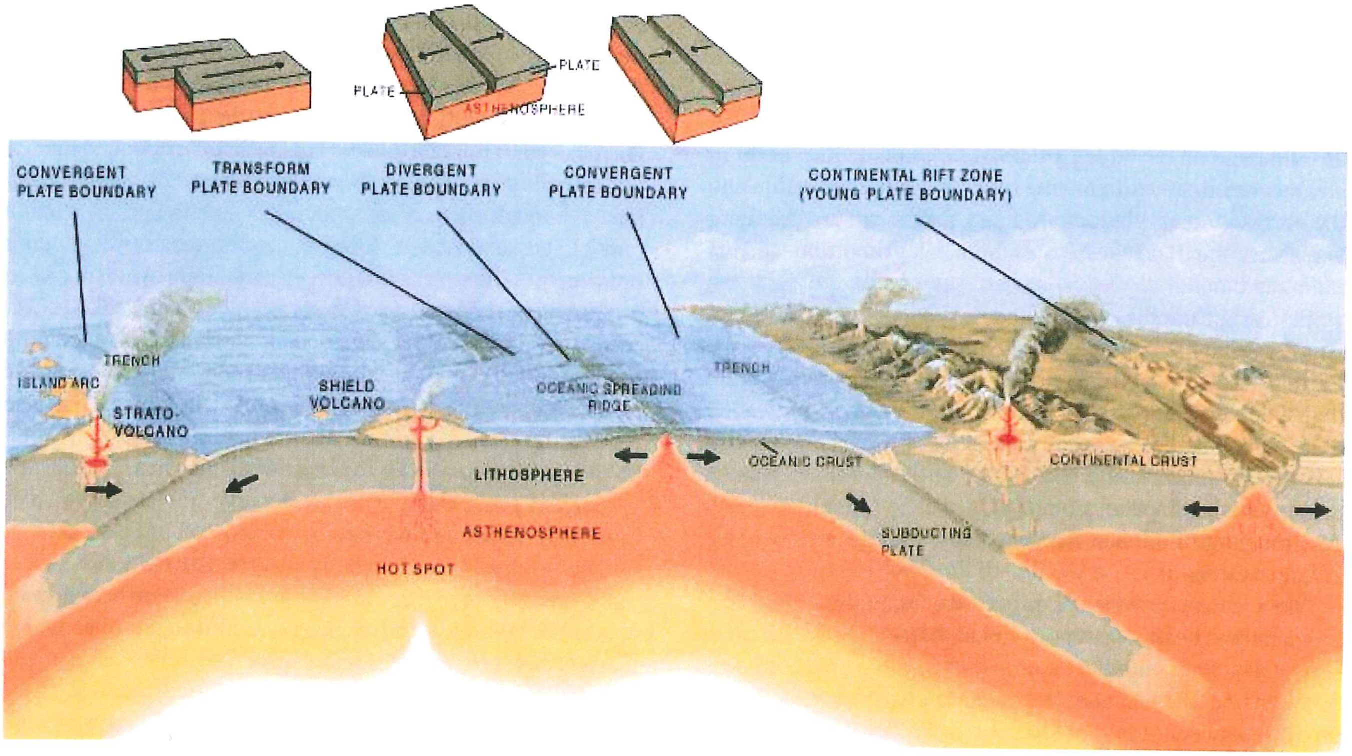

FIGURE 3-2. Cartoon illustrating the three types of plate boundaries. Note that convergent plate boundaries include both ocean-continent boundaries (right-hand side) resulting in volcanoes on the continental edge, as in Central and South America, or ocean-ocean boundaries (left-hand side) resulting in island arc volcanoes, as in the western Pacific. In both cases, a deep trench marks the surface expression of the convergent boundary. Courtesy of U.S. Geological Survey.

1. Plates can move away from one another, at a boundary termed a rift or spreading ridge (e.g., the Mid-Atlantic Ridge). This is the process by which new sea floor is formed: upwelling magma (molten rock) is extruded and cools along the spreading ridge, then it moves away as the plates separate as if the cooled magma were on a conveyor belt.
2. One plate can move toward another plate, termed a convergent or subduction zone boundary (e.g., the Middle America Trench and the Peru-Chile Trench, on the west coasts of North and South America, respectively). This is the process by which seafloor is destroyed.
3. Plates can move past each other, termed a transform boundary (e.g., the San Andreas Fault).

Because of their potential for large-scale destruction of infrastructure, the principal geological hazards that most directly affect human health are earthquakes, tsunamis, and volcanic eruptions. Health effects of these processes may be direct (e.g., death by drowning in a tsunami) or indirect, (e.g., disease and malnutrition associated with loss of crops, livestock, and civil infrastructure as a result of a tsunami).

All three types of plate boundaries can generate earthquakes, whereas type 2 generates most tsunamis. Both types 1 and 2 can generate volcanoes. Volcanoes that are not associated with a plate boundary (midplate or "hot spot" volcanoes such as Hawaii or Yellowstone) may also occur (Fig. 3-2).

Sea level rise and coastal subsidence are not generally related to plate boundary processes (with a few notable exceptions) but are geological processes that can have profound effects on human health through their role in exacerbating flooding during tropical storms and hurricanes. This was demonstrated most recently in August 2005 when Hurricane Katrina struck New Orleans. The geological background to these issues is discussed at the end of this chapter.

EARTHQUAKES

Earthquakes are brittle ruptures between or inside blocks of rock in the Earth's crust or upper mantle. They occur when stress accumulated by the planet's tectonic forces overcomes the local strength of rocks. Most faults (e.g., at plate boundaries) are locked, meaning that rather than being able to accommodate plate motion through continuous creep or sliding, the two walls of the fault remain attached (locked) while deforming, locally accumulating tectonic stresses that build up with time. When this deformation becomes too large, the rock cracks (as would a window pane if pressure were applied from the edges toward the middle), the two sides of the fault slip past one another (this constitutes the earthquake), and then the rock returns to an undeformed state. The process is then repeated to build the next earthquake, resulting over long timescales in a *stick-and-slip* phenomenon analogous in some ways to the screeching of a car's tires around a corner. The recurrence time between major earthquakes at plate boundaries is a complex, irregular, and poorly understood function of the geological environment, ranging typically between 100 and 10,000 years.

In the oceanic environment, the largest earthquakes occur at subduction boundaries (type 2), such as the western coast of South America and the Japanese and Indonesian arcs in the western Pacific. At such locations, an oceanic plate penetrates down ("subducts") into the mantle beneath an overlying plate that can be continental (e.g., in Chile) or oceanic (e.g., at the Tonga-Kermadec arc). Along midoceanic spreading centers (type 1 boundaries), earthquakes occur only on slow-spreading segments, such as the Mid-Atlantic Ridge; they are absent from fast spreading ones, such as the East Pacific Rise. Even so, only moderate earthquakes, not exceeding magnitude 6, take place along slow-spreading centers. In general, they carry little hazard to humans because of their small size and underwater locations. Earthquakes at type 3 boundaries occur along large lateral offsets in the midoceanic ridge system, called transform faults, which can occasionally extend onto land, as in the case of the San Andreas Fault, which connects spreading centers at the opposite ends of California, or the Sumatra Fault, which helps partition (with the nearby subduction zone) the oblique convergence between the Australian and Eurasian plates. Transform fault earthquakes can reach magnitude 8 both on land (e.g., San Andreas, 1857) and at sea (Southwest Indian Ocean Ridge, 1942). Finally, earthquakes can occur inside rather than between plates. Such events have been documented at the magnitude 7 level in the Pacific Basin, and complex earthquakes occurring in the vicinity of plate boundaries (but not exactly along them) regularly reach magnitude 8. The destructive earthquakes at the Sanriku coast of Japan in 1933 and at Sumbawa, Indonesia, in 1977 were of that type.

The hazardous nature of earthquakes rests in their ability to inflict damage or destroy buildings and infrastructure. An earthquake source does not change the physical parameters of the environment to an extent that constitutes a health hazard to humans. The maximum accelerations of the Earth's surface created by earthquakes remain on the order of 1 *g* (or about 10 m/s^2), much less than those experienced by a fighter pilot. In this respect, *earthquakes do not kill people*; their combined effects, primarily building collapses but also fires, landslides, or tsunamis, do. Table 3-1 lists events with the greatest reported death tolls. Although most casualties in the 2004 Sumatra, 1755 Lisbon, and 1896 Sanriku events were victims of the tsunami triggered by the earthquake, building and infrastructure collapse remain the greatest

TABLE 3-1. Death toll in major earthquakes.

		Death Toll	
Year	**Region**	**Absolute**	**Scaled to Global Population**
1556	Shansi, China	800,000	1/625
1780	Iran	280,000	1/3000
1976	Tangshan, China	250,000	
2004	**Sumatra**	**250,000**	**1/24,000**
1920	Kansu, China	200,000	
1923	Tokyo, Japan	200,000	
1927	Tsinghai, China	200,000	
2005	**Pakistan**	**80,000**	**1/75,000**
1755	Lisbon	70,000	1/10,000
1908	Messina, Sicily	70,000	
1970	Ancash, Peru	66,000	
1999	Izmit, Turkey	40,000	
2003	Bam, Iran	40,000	
1896	Sanriku, Japan	30,000	
1989	Armenia	30,000	
1939	Chillan, Chile	25,000	
1906	Valparaiso, Chile	20,000	
2001	Bhuj, India	20,000	
.....			
1906	San Francisco	3,000	
.....			
1989	Loma Prieta, California	68	
For reference:	Hiroshima:	200,000	
	WWI + Influenza epidemic:	30,000,000	1/60

hazard induced by most earthquakes, especially moderate ones. Damage to buildings and their eventual collapse results from the shaking and deformation they undergo during the earthquake, processes that are controlled by the ground acceleration provoked by the earthquake waves. This acceleration is a function of the earthquake's source (principally its "size," which can be expressed as a magnitude) and of the history of the seismic waves as they travel along the path between the source and the receiver (a building), as well as the site response at the location of the individual building. Other things being equal, an earthquake wave reaching soil with poor mechanical properties (sand, mud, clay) will displace it more efficiently than a stiffer geological structure, such as a hard rock made of granite. This enhanced site response in loose sedimentary environments was illustrated in a spectacular fashion during the 1989 Loma Prieta earthquake: the Golden Gate Bridge in San Francisco, solidly anchored in strong plutonic and metamorphic rock formations, was unaffected by the shaking, whereas a section of the Oakland Bay Bridge just a few kilometers away collapsed, because it was built on mud flats at the bottom of the bay.

In addition, a phenomenon known as liquefaction can result in the loss of rigidity when soils contain a significant amount of water. Under the shaking created by the earthquake, the solid sedimentary matrix loses its cohesion, and the soil then behaves essentially as a liquid. The soil becomes unable to support structures because it loses its shear strength; unlike solids, liquids, by definition, have no shear strength (i.e., no resistance to sideways forces). Figure 3-3 shows a spectacular example of soil liquefaction during the 1964 Niigata, Japan, earthquake. Note that the building at the center has no structural damage from the earthquake; it simply tipped over on its side when the liquefied soil could no longer support its foundation. Such soil conditions are especially common in low-lying coastal areas, such as river deltas (described later in this chapter) and in former lake beds, such as Mexico City.

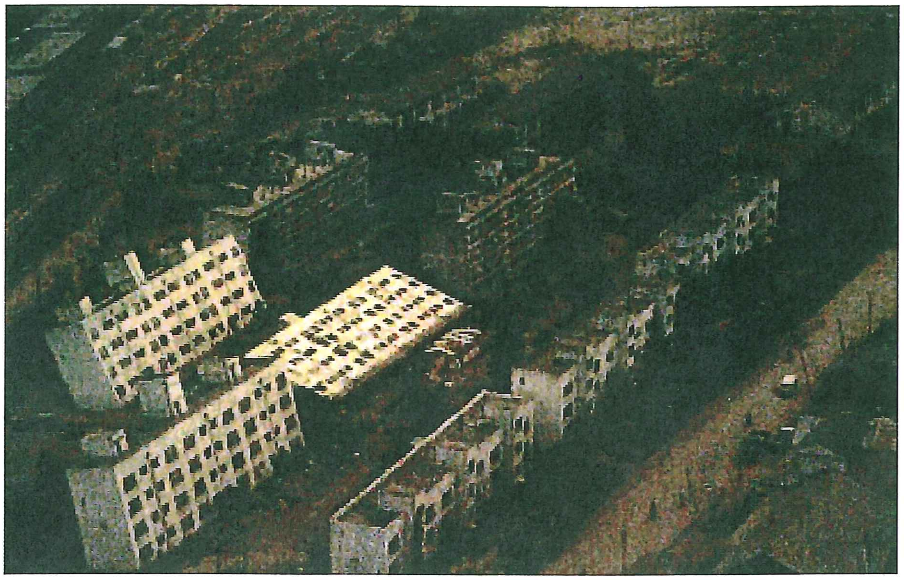

FIGURE 3-3. Example of damage caused by soil liquefaction, following the 1964 earthquake in Niigata, Japan. Note that the buildings are structurally intact but have tipped over because the liquefied soil failed to support their foundations. From the National Geophysical Data Center.

These kinds of hazards can be mitigated through the use of appropriate zoning and building codes, the latter concept having been introduced in California following the 1925 Santa Barbara and 1933 Long Beach earthquakes [both magnitude (*M*) = 6.3; with 10 and 120 deaths, respectively] and systematically revised since then following each significant earthquake. Ideally, building on soils with poor mechanical properties or easily subject to liquefaction (e.g., landfills) should be prohibited and construction should use designs and materials minimizing the risk of structural collapse. Solutions can be as simple as triangular bracing or as innovative as decoupling the building from the ground and letting it ride the earthquake on an isolating rubber cushion, as pioneered at the National Museum of New Zealand in Wellington. In practice, many existing buildings and structures can and must be retrofitted to higher standards, which in itself constitutes a separate engineering discipline. As a rule of thumb, the most hazardous building structure is the rural adobe house whose walls fail during shaking, provoking the collapse of the roof on the occupants. Brick and unreinforced concrete buildings in urban areas are also dangerous. In contrast, simple dwellings woven from tree branches and leaves can provide surprisingly good protection, as their flexibility accommodates torsion during the impact of the most destructive shear waves.

Because earthquakes cannot be predicted, the population at risk must rely on individual reaction to shaking for personal mitigation; this includes taking refuge under tables from falling objects, avoiding crossing entryways in or out of buildings, as well as adequate preparedness in areas at risk, such as advance stocking of food, water, and first-aid supplies.

Other effects of earthquakes include large-scale fires, set up in urban areas by the often simultaneous rupture of gas and power lines, with the most tragic examples being San Francisco (1906) and Tokyo (1923). This hazard remains present in modern times, as experienced in Kobe (1995), and mitigation efforts can aim, for example, at shutting off gas lines automatically above a predetermined threshold of shaking, as recorded by strong motion detectors.

In addition, earthquakes can trigger landslides in gravitationally unstable environments. In high relief terrains, earthquake shaking can induce landslides either directly or by the liquefaction process described earlier. Landslides can be subaerial (i.e., taking place above sea level), submarine, or a combination of both (the subaerial material falling into the sea at the shore line). Subaerial landslides constitute a separate hazard, as they not only destroy impacted structures but can simply bury them, causing immediate death to any occupants. Their dynamics, comparable to those of snow avalanches, fall into the realm of fluid dynamics. The most catastrophic example of an earthquake-triggered landslide took place on May 31, 1970, in the Ancash district of northern Peru, leading to the eradication of the city of Huaraz with a death toll of 70,000. Significant landslides were also observed during the 1999 Chi-chi earthquake in Taiwan and the 2001 event in El Salvador. Underwater landslides are, of course, much less well known but can lead to lethal tsunamis, such as in Papua New Guinea in 1998 (2200 deaths; see the following discussion).

TSUNAMIS

General Properties

Tsunamis (a Japanese idiom literally meaning "harbor wave") are gravitational oscillations of the entire body of an oceanic basin following the deformation of the sea floor (or exceptionally of the surface). They take the form of waves propagating at a speed c controlled by the depth h of the water column according to the formula $c \cong \sqrt{gh}$, where g is the Earth's gravity. In a 5-km deep ocean, this amounts to 220 m/s, or the speed of a modern jetliner.

Generation

Tsunamis are most often triggered by major earthquakes and are capable of exporting death and destruction to distant shores, their propagation being limited only by the size of the oceanic basin. For example, the 1960 Chilean earthquake resulted in upward of 150 deaths in Japan, 24 hours after the origin of the earthquake. Tsunamis can also be generated by landslides (e.g., Papua New Guinea, 1998), volcanic eruptions in the sea (e.g., Santorini, 1650 B.C.; Krakatau, 1883), and even bolide impacts (e.g., Chicxulub, Yucatan, 65 million years ago).

Tsunamis generated by major earthquakes result from the displacement of large masses of rock (and consequently of large volumes of water) over relatively small distances. For example, during the 2004 Sumatra event, the fault extended for 1200 km north of the epicenter, but the seismic slip on that fault (the amount of displacement on the fault that occurred during the earthquake) did not exceed 20 m. As a result, a tsunami wave on the high seas, far from its source and from any shoreline, has a small amplitude (70 cm according to a satellite measurement during the 2004 event) spread out over a considerable wavelength (typically on the order of 300 km). As the tsunami approaches a coastline, it *shoals*—that is, its energy is concentrated over a shallower water column, its propagation speed slows down considerably, its wavelength shortens, and the amplitude of the wave is increased many times. In Sumatra, waves coming ashore reached 32 m locally, whereas the corresponding water currents reached 30 m/s or 100 km/h. Even in the far field, many thousands of kilometers from the source, runup amplitudes (flood heights) of 10 m are not uncommon. In the Sumatra example, even the coast of Somalia, more than 5000 kilometers across the Indian Ocean from Indonesia, was affected by the tsunami wave.

Such runup amplitudes and current velocities give tsunamis exceptional powers of devastation. In addition to drowning, tsunami fatalities come from the complete destruction of buildings and infrastructure on the affected shores, with masonry walls obstructing the wave's flow being destroyed systematically. Furthermore, tsunami waves can lift objects as large as buses, locomotives, and small boats, and transform them into projectiles inflicting further damage onshore. During the 2004 Sumatra tsunami, many victims were run over by vehicles moving with the tsunami at speeds comparable to highway traffic; in Banda Aceh, a 10,000-ton barge was moved 3 km inland. Once the tsunami reaches its maximum penetration inland, the water regresses back to the sea, and the draw-down currents can be devastating also because as soil is eroded, roadbeds are further scoured, and debris and people are simply washed out to sea. Finally, during the shoaling process, the wave erodes the sea floor, occasionally transforming the underwater landscape and affecting fisheries for considerable periods of time thereafter.

Underwater landslides can also generate locally devastating tsunamis. These processes differ from earthquakes in that they move volumes of rock with much smaller horizontal dimensions (rarely exceeding 30 km in linear dimension) over considerable distances. For example, a landslide at the head of a canyon may be several tens of kilometers in lateral dimension but flow several hundred kilometers. Large underwater flows of such sediments are sometimes called turbidity currents. The waves of such tsunamis have considerable heights but much shorter wavelengths than those generated by earthquakes, and as a result, they do not propagate efficiently to the far field. Examples include the 1929 Grand Banks tsunami whose waves ran up to 27 m and killed 27 people on the nearby coast of Newfoundland, and the dramatic 1998 event that caused 2200 deaths along the Northern coast of Papua New Guinea. That tsunami reached 15 m and eradicated several villages, but its effects were confined to a 35-km stretch of shoreline, and the tsunami was hardly noticed elsewhere in the Pacific Basin. Tsunamigenic landslides are generally triggered by earthquakes, but their mechanism can involve a delay, expressing the nonlinearity inherent in the release of the precarious material. In the case of the Papua New Guinea tsunami, Synolakis *et al.* (2002) established that the slide took place 13 minutes after the seismic source. In other cases, there may be no delay, and the evidence for the landslide rests in occurrences of dramatic, locally enhanced waves, as for example during the 1946 Aleutian tsunami where a 42-m runup eradicated the lighthouse at Scotch Cap (Okal *et al.*, 2003).

Note also that even earthquakes whose rupture occurs on land can generate tsunamis by triggering submarine landslides through the shaking of underwater sedimentary structures located at some distance from the seismic source. Examples include the 1989 Loma Prieta earthquake, which generated a local tsunami at Moss Landing, California (40 km away), and reportedly the 1910 Rukwa earthquake along the African Rift, which triggered a landslide in the Indian Ocean more than 800 km away.

When its seismic trigger is too small to be recorded, the landslide appears "aseismic," as was the case for example in 1994, when a 3 million-m^3 underwater landslide generated an 11-m wave a few km away in Skagway, Alaska, killing one dock worker. Subaerial landslides falling into the sea have also given rise to damaging tsunamis that can reach gigantic proportions when the landslide falls into a shallow body of water. The record for this type of tsunami is the 525-m runup at Lituya Bay, Alaska, following a major strike-slip earthquake on the Fairweather fault on July 10, 1958. This tsunami, however, failed to penetrate the body of the Pacific Ocean with a meaningful amplitude (Miller, 1960). Tsunamis generated by volcanic explosions or bolide impacts share the characteristics of landslide-generated ones. For example, the 1883 Krakatau tsunami was devastating locally (with waves reaching 15 m and killing 34,000 people), but it did no damage in the far field, even though it was recorded worldwide on tidal gauges.

Mitigation

Direct mitigation of tsunami damage generally involves building seawalls specifically engineered to reflect the waves back to sea; such structures are used systematically along the coast of Japan. However, they are only as good as their maximum height; 6-m walls were ineffective against the 10-m waves hitting Okushiri Island in 1993 (Fig. 3-4).

The only way for humans to avoid the effects of tsunamis is to take refuge away from the wave's reach. In areas where it is difficult to reach more inshore of the inundation line (isthmi, land spits, congested urban areas), the concept of vertical evacuation must be emphasized; it can be as simple as climbing up deeply rooted trees (in general, palm trees are to be avoided), a strategy saving many lives in Papua New Guinea in 1998, or taking shelter atop high-rise buildings (of course, not using elevators, which are at risk for getting trapped at inundated levels). In this respect, pillared structures are particularly valuable, as they provide essentially free passage to the waves through the first floors of construction, offering no cross-section for destructive impact. This concept is being used in the building of evacuation platforms in Japanese harbors.

Tsunami Warning

As tsunami waves propagate relatively slowly (about 200 m/s) and in particular much slower than seismic waves (typically several km/s), it may be possible to provide advance notice of the existence and progress of the tsunami to distant shores. The efficiency of such warnings obviously increases with distance, as more time becomes available for the evacuation of threatened shores.

In practice, a tsunami-warning center analyzes seismic data from the parent earthquake and advises government officials when the event's magnitude exceeds a particular threshold, depending on regional conditions. Regardless of the intrinsic difficulty of measuring in real time the size of the greatest earthquakes, special challenges are posed by certain earthquakes featuring an anomalously slow release of energy, which makes their conventional seismic waves deceptively weak (e.g., Nicaragua, 1992; Java, 1994 and 2006), or by contrast by events such as the large 2005 Nias,

FIGURE 3-4. View of the small town of Aonae, on the island of Okushiri, Japan, in the aftermath of the Japan Sea tsunami of July 12, 1993. Note the devastation wrought by the tsunami wave; all housing in the left part of the photograph has been destroyed and the rubble washed out into the harbor. Note also the fishing boats carried inland and the fires, still burning in this next-day photograph. From Y. Tsuji.

Indonesia earthquake, whose far-field tsunami turned out to be unexpectedly small because of shallow bathymetry and the presence of large islands in its source rupture area.

These remarks illustrate the difficulty of assessing, especially in real time, the tsunamigenic character of a large earthquake. For this reason, efforts aim at incorporating direct observations of the tsunami wave itself into the warning algorithms. In addition to shore-based records on tidal gauges (which suffer from the nonlinear response of these devices and the often nonoptimal ports where they are deployed), a number of modern technologies are starting to provide direct measurements of the waves on the high seas. These technologies include (1) detection by ocean-bottom microbarographs of the overpressure created by the wave and the relaying of this information via offshore buoys, of which a growing number are being deployed in the aftermath of the Sumatra event; (2) direct imaging of the wave at the surface of the sea by satellite altimetry (a proven technique suffering from the aleas of geographic sampling); and (3) over-the-horizon radar exploiting the subtle coupling of the tsunami wave to the overlying atmospheric column (still at the prototype level). Once a warning is issued, evacuation procedures become the responsibility of civil defense authorities and must have been properly designed and tested in advance of the event. The catastrophic death toll of the 2004 Sumatra tsunami in the far field was due principally to the lack of established communication channels between the Pacific Tsunami Warning Center in Hawaii and the authorities of the countries at risk, and of appropriate response procedures in those countries.

Because of the limited amount of time available, centralized warnings are of limited value to humans in the near field, where self-evacuation must be the rule for any individual feeling an earthquake on the shoreline or observing any anomalous behavior of the sea, in particular a large draw down that exposes the sea floor beyond the line of lowest tides. As a gross rule of thumb, and barring exceptionally large tsunamis, evacuation to an altitude of 15 m for at least several hours following the maximum disturbance of the sea is appropriate. Automatic actions, including the closing of sluices where rivers enter the sea, remain valuable mitigation options in the near field.

Finally, we wish to emphasize the value of education of populations at risk as an effective way to minimize the impact of tsunamis on humans. Education can be formal in the classroom, parental through the transmission of ancestral knowledge, or highlighted by media programs and drills. In all cases, education should emphasize a few simple points. Tsunamis are natural phenomena occurring as part of the geological activity of the Earth, and as such they can and will recur; an orderly evacuation following either an official warning or the feeling of shaking along the water line or the observation of any anomalous behavior of the sea will save lives. Success stories as diverse as the evacuation of the village of Baie Martelli in Vanuatu in 1999 (Caminade *et al.*, 2000), the case of the Moken tribe in the Andaman Islands in 2004, or the well-publicized story of Tilly Smith, a 10-year English girl vacationing in Phuket, all confirm, if need be, that education *does* indeed work.

VOLCANOES

Volcanoes are the surface manifestation of a process that caused melting of rock at depth. Molten rock (magma) tends to be less dense than its surroundings and hence rises. Volcanoes represent surface accumulation of erupted magmatic products, which include lava (magma at the surface) and volcanic ash resulting from explosive eruptions, particles of rapidly quenched magma, and particles of the surrounding "country rock." Though midocean ridges are volumetrically the largest form of volcanism on the planet, they have little short-term impact on human health. For this chapter, we will consider volcanoes in two other geological settings, namely hot spots and subduction zones

Hot Spots

As the name implies, a hot spot is a region in the mantle that is anomalously hot. It need not be associated with a plate boundary, and in fact the best-known example of hot spot volcanism is Hawaii, near the middle of the Pacific plate (Fig. 3-5). Although the details of what makes and maintains a hot spot are not well known, they likely represent regions in the mantle that are undergoing focused convective upwelling, which provides a way for the Earth to dissipate radioactively generated heat (broader scale convection also drives plate motion). Because the viscosity (resistance to flow) in the mantle is a strong function of temperature, once established, a hot spot plume will tend to stay focused in one region for long periods of time. The Hawaiian plume is known to have been active for more than 50 million years, resulting in an age-progressive chain of islands (hot spot track) across the Pacific sea floor, aligned in the direction of plate motion. A change in the trend of the island/seamount chain, from west-northwest to northwest, is interpreted to indicate a change in the direction of Pacific plate motion ~40 million to 50 million years ago (e.g., Clague and Dalrymple, 1989). The total age of the chain and hot spot is unknown, since the distal end of the chain may have been subducted near Kamchatka (Fig. 3-5).

In a long-term geological sense, one implication of hot spot volcanism for human health is overwhelmingly positive: it provides land surface within a large ocean for many new species (including humans) to colonize, evolve, and take holidays. On short timescales, of course, lava flows, as well as landslides, tsunamis, and earthquakes associated

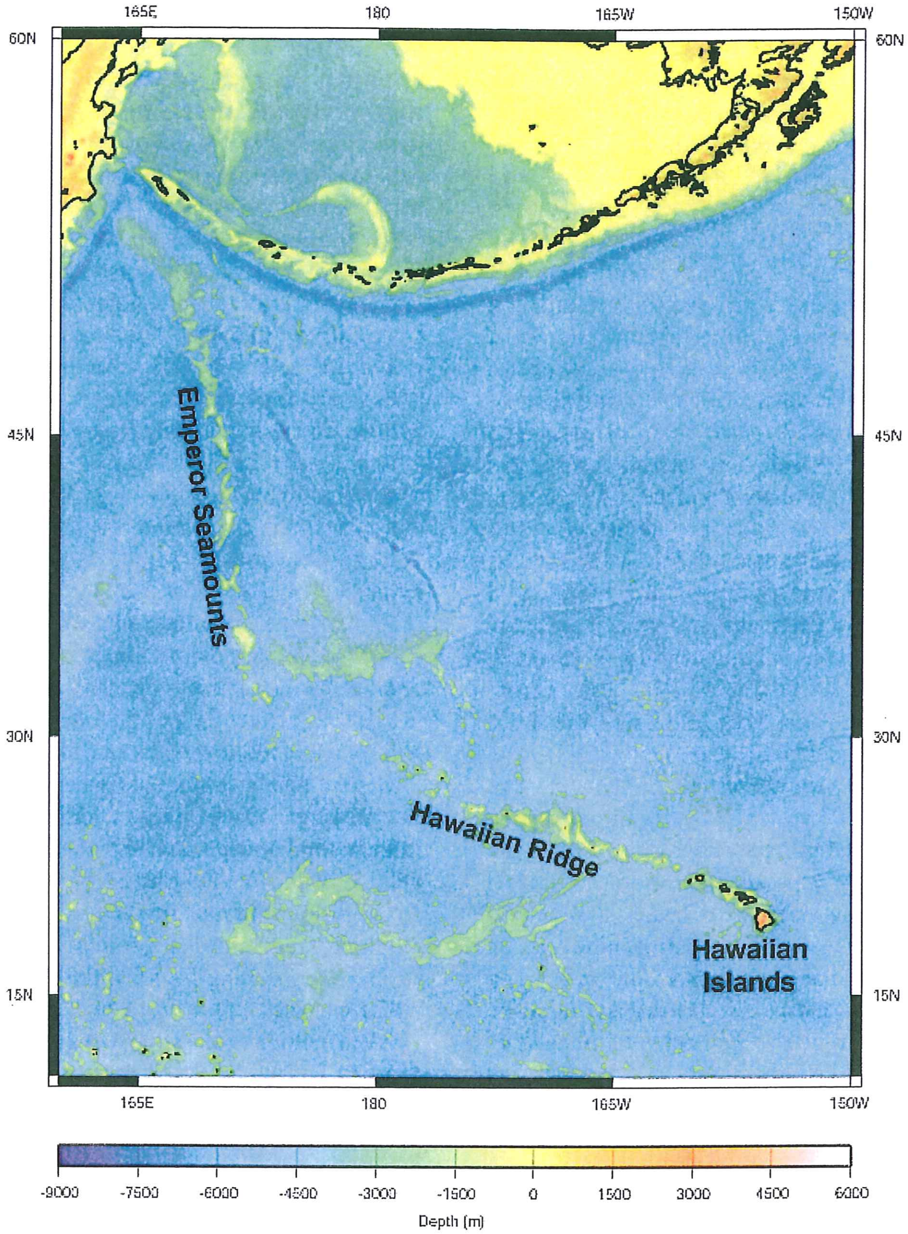

FIGURE 3-5. Bathymetric map of the Hawaii-Emperor seamount chain. The bend between the Hawaiian and Emperor chains occurred at about 43–50 Ma (*Clague and Dalrymple,* 1989; *Clague*, personal communication). Image courtesy of D. Clague and the Monterey Bay Aquarium Research Institute.

with volcanic processes can prove deleterious to human health. Lava flows themselves are not particularly hazardous: they are generally slow moving, and there is usually sufficient warning of their approach. Landslides, tsunamis, and associated earthquakes (e.g., Amelung *et al.*, 2007; Owen and Bürgmann, 2006) can be more disruptive, and on "hot spot" volcanoes such as Hawaii, generally result from the topographic instability associated with a growing volcanic pile and related dike intrusion. A dike is a volcanic formation that results from the intrusion of magma in a vertical wall. In the case of Hawaii, dike growth may indicate seaward motion of a large block of rock on the flank of the volcanic cone because of gravitational sliding; magma fills the resulting vertical crack. Landslides extending up to 80 km offshore suggest that this process can occur catastrophically and lead to locally generated tsunamis (Moore *et al.*, 1995). Problems associated with the large 1783 Lakagigar eruption on Iceland in 1783, another hot spot, caused numerous deaths between 1783 and 1785, primarily the result of starvation. This occurred both from direct effects of the eruption as well as contamination of ground water and pasture land, with subsequent loss of livestock upon which many early settlers depended (Stothers, 1996; Thordarson and Self, 1993; Vasey, 1991). Studies of the livestock remains and graves of the settlers killed during this period suggest that the effect of fluorosis from excess fluorine emissions from the volcano was a contributing factor (Pain, 2005).

Subduction Zones

Volcanoes associated with subduction zones are common along the circum-Pacific "ring of fire." Along the west coast of North and South America, these volcanoes occur exclusively on land, but in the western Pacific and Aleutian Islands, they occur as discrete islands, often in an arc-shaped chain, and for this reason are sometimes termed *island arc volcanoes* (Fig. 3-2). They probably represent the greatest volcanic hazard to human health, for several reasons. First, they are more numerous than other types of volcanoes, at least in terms of subaerial volcanoes (volcanoes located on the sea floor, associated with spreading ridges, are probably more numerous but pose essentially no health risk). Second, for reasons that will be discussed, these volcanoes can erupt catastrophically with large explosions, affecting large areas. Large intracontinental calderas such as Yellowstone may impact even larger areas, but these are thought to erupt rarely, perhaps once in 10^6 years, and are not considered here. In contrast, a typical island arc volcano may erupt every few hundred years. Depending on the criteria used for assessing activity, there are approximately 500 to 1000 such volcanoes that are considered active, meaning that, on average, we can expect one or more such eruptions per year on the Earth. Not all of these will be major eruptions, however. Although we review the human health impacts of such eruptions, it should be noted that from a long-term environmental and geological perspective, this class of volcanism is important for the growth of continental crust, the maintenance of soil fertility in many agricultural regions, and generation of numerous natural resources, especially base metals.

How does subduction generate volcanoes? The subducting plate, which is relatively cool, tends to cool the surrounding mantle, so at first glance it seems counterintuitive that volcanoes, which require melting of mantle material, should form here at all. The cause is melting point depression. Recall that subducted oceanic plates include seafloor formed many million of years before subduction, back at the midocean ridge (Fig. 3-2). During their long journey across the ocean to a subduction zone, and especially shortly after formation at the midocean ridge, the rocks that constitute the upper few kilometers of the oceanic plate become hydrated, as new minerals form that incorporate H_2O into their mineral structure (the original minerals formed at the ridge are anyhydrous). As the plate is subducted, these hydrated minerals are subjected to great pressures and release their water, much as water is squeezed from a sponge. Much of this water is squeezed out within the first 5 to 10 kilometers depth, thereby returning to the ocean, but some is released at greater depths, becoming entrained in the surrounding mantle and moving downward with the plate. This entrained water then lowers the melting temperature of the mantle rocks, much in the same way as salt is used to melt snow on roads, and the ambient mantle conditions can be hot enough for partial melting of hydrated rock even though the temperatures would be insufficient to melt dry rock. The newly generated melt is less dense that its surroundings and rises, eventually erupting to form a volcano. Most subduction zone volcanoes occur directly above the point where the surface of the subducting plate reaches a depth of 100 ± 10 km.

It should come as no surprise that the resulting magmas are water rich. This is one of the main reasons why these volcanoes are so hazardous. Like bubbles in a corked bottle of champagne, the water and other gases in the magma (including CO_2 and SO_2) remain dissolved in the magma at depth, where the confining pressure is high. As the magma approaches the surface, however, the pressure lessens, allowing the gases to come out of solution, forming bubbles that may not be able to escape the magma because of its high viscosity. In the last few kilometers of the magma's rise, as pressure falls rapidly, additional gases are released (their solubility decreases with decreasing pressure), and the volume of existing bubbles expands dramatically, leading to an explosive eruption. The explosion and resulting fragmentation of the lava leads to formation of pyroclastic deposits (from *pyro* meaning fire), including fine ash and a range of larger materials.

Volcanologists classify pyroclastic deposits in a number of ways, including particle size, composition, whether they are deposited as air-fall or as landslides, and whether they are deposited hot or cold. Lahars, for example, are generally fine-grained deposits, representing ash and other pyroclastic debris that initially accumulates on the upper slopes of the volcano from explosive eruptions but then gets saturated with rainfall or melted snow and begins to move downslope, to be redeposited at lower elevations. Lahars can be quite fast moving (they have consistencies that range from thin slurries to that of wet cement) and can quickly entomb entire towns and villages unfortunate enough to be located in the lahar channel, typically an existing river or stream channel. A relatively small eruption of Nevado del Ruiz volcano in Colombia in 1985 killed approximately 23,000 people as a result of erupted ash and lava mixing with snow and ice at the volcano summit (Pierson *et al.*, 1990). The lahars impacted populated areas several hours after the main eruption began. People died both directly from the lahar (by suffocation or internal injuries from the initial flow and devastation) and indirectly by dehydration or infection within several days of the event, as they were trapped in the warm, sticky deposit, and rescuers were unable to reach them.

Lahars are a largely avoidable hazard, in the sense that they usually come with some long-term warming (they typically occur days to months after the initial volcanic eruption), they occur in predictable places (often an existing channel), and while they can be fast-moving (up to ~50 km/hr), there is generally some short-term warning. In the case of Nevado del Ruiz the initial eruption was felt by inhabitants, but civil and religious authorities had assured them that all was well. Previous lahars had occurred in essentially the same location, in 1595 and 1845. Hazard maps warned of the danger of lahars for the town of Armero, destroyed by the 1985 flow (Fig. 3-6). The town was actually built on top of the previous town destroyed by the 1845 lahar.

In contrast, pyroclastic deposits that are a direct result of an eruption may come with much less warning, other than general signs of volcanic unrest, such as local earthquakes. Although volcanologists recognize many different types, all such deposits result from several characteristics of arc volcanoes. First, these volcanoes represent stratified layers of older lava and pyroclastic deposits that can build to high elevation, resulting in the classic "Mount Fuji" conical profile. These may be considered gravitationally unstable piles of relatively weak material, prone to landslides. Second, if such a volcano is active, it can have a large mass of molten, gas-charged rock perched in a magma chamber at relatively high elevation, just beneath the summit of the volcano. A large landslide from such an edifice can flow out many tens of km from the edifice. Moreover, if such a landslide happens to de-pressurize ("uncork") a gas-charged volume of magma, the magma can erupt violently. This happened at Mt. St Helens in 1980. The resulting mass of hot magma, ash, and rock debris initially erupts upward, then falls to Earth and down the slopes of the volcano, again for many tens of kilometers. The resulting flow of hot, gas-charged ash and debris moves quite rapidly, killing everything in its path. Such an event occurred on the island of Martinique in the Caribbean in 1902 when Mt. Pelée erupted, killing 29,000 people. The phenomenon is termed *nuées ardentes* (literally, "searing cloud"), also known as a pyroclastic flow. A similar phenomenon destroyed the city of Pompeii, in Italy in 79 A.D., when Mount Vesuvius erupted near the modern city of Naples.

FIGURE 3-6. Lahar from Nevado del Ruiz, Colombia. The former town of Armero is located beneath the lahar, approximately in the image center. Approximately three quarters of the town's original 29,000 inhabitants were killed by the lahar and lie entombed within it. Photo by J. Marso, taken in late November of 1985.

A longer-term health effect from such eruptions is the formation and widespread dispersion of fine-grained volcanic ash, which can travel hundreds of even thousands of kilometers from the eruption site. Certain components in the ash, especially the mineral cristobalite, a polymorph of quartz (SiO_2), are known to be highly irritating to lung tissue and may contribute to chronic lung diseases such as silicosis (Baxter *et al.*, 1999; Horwell *et al.*, 2003; Housley *et al.*, 2002; Wilson *et al.*, 2000).

COASTAL SUBSIDENCE AND FLOODING

It is generally agreed that sea level is rising in response to global warming, because of a combination of thermal expansion (ocean volume increase) and melting of land ice (ocean mass increase). The rate of increase averaged over the past hundred years is ~2 mm/yr (e.g., Miller and Douglas, 2004), although this is likely to increase in the future as melting of land ice (Greenland, Antarctica, and mountain glaciers) accelerates. As discussed elsewhere in this volume, global sea level rise will have several deleterious impacts on human populations, especially in coastal areas, including loss of freshwater aquifers because of saltwater intrusion and increased susceptibility of coastal infrastructure to flood damage associated with tropical storms and hurricanes. As tragically demonstrated in New Orleans in the aftermath of Hurricane Katrina in 2005, such flooding, although predictable, can nevertheless have catastrophic consequences, leading to immediate death by drowning and subsequent fatalities from dehydration, disease, untreated chronic conditions, and other causes associated with the breakdown of infrastructure and civil society.

Certain coastal areas are at much greater risk from these processes because of land subsidence; they are experiencing higher rates of *relative* sea rise because of a *combination* of rising ocean levels *and* falling land levels. Such regions are in some ways like the proverbial canary in a coal mine, illustrating what may happen to many areas in a few hundred years when global sea level rise results in widespread inundation of highly populated coastal regions. Before considering these impacts further, we need to consider the geological and anthropogenic causes of subsidence and the technical challenges involved in measuring land subsidence and sea level rise.

Subsidence can be defined as vertical motion of the land surface toward Earth's center of mass. When we consider tide gauge data (a common method of measuring present-day sea level rise; Fig. 3-7) and geological indicators of past sea level location such as the height and age of coastal geomorphic features (which can give longer term indicators of relative sea level rise or fall; Fig. 3-8), it is important to realize that both are relative sea level indicators and do not directly distinguish land subsidence (a local process) from local and global sea level rise (ocean expansion that results from mass or volume increase, for example, because of glacier melting or

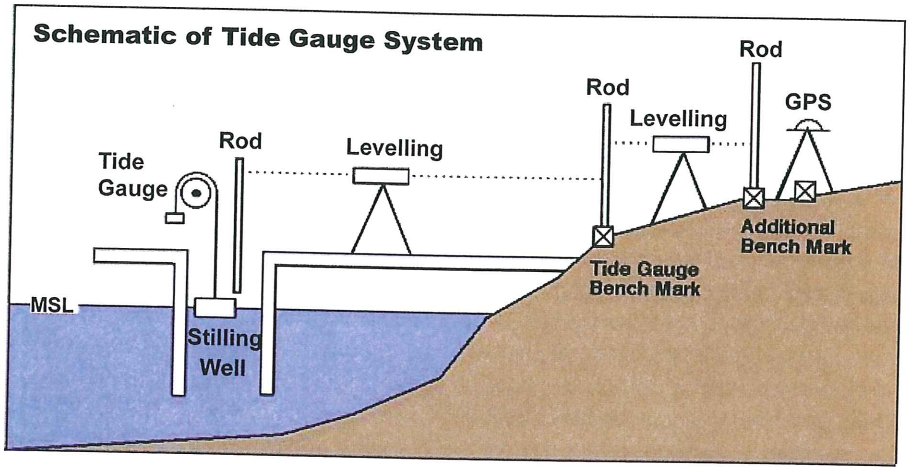

FIGURE 3-7. Tide gauges, precise leveling, and GPS are used to measure changes in sea level and relate these changes to a stable reference, such as Earth's center of mass. The tide gauge can basically be considered a stick that records water level. The system includes a stilling well, to damp out short-term wave motions, and a recording device. Leveling may be performed to connect the tide gauge, often mounted on a dock or pier, to a geodetic benchmark on land. GPS can be used to tie this benchmark to a global reference frame to record long-term changes relative to Earth's center of mass.

FIGURE 3-8. Wave cut coastal terraces at Point Arena, California, marking the positions of former sea level stands. Note the modern coastline at the base of the cliffs. The base of each terrace cliff marks sea level at several times in the past; the "flight" of terraces at this location indicates relative sea level fall over an extended period of time (i.e., land has uplifted at rates greater than the sea level rise because of tectonic forces). Image courtesy of U.S. Geological Survey.

thermal expansion, and changes in coastal currents). All of these processes may contribute to relative sea level rise. It is, of course, the sum of these effects that is important in terms of flood hazard.

Space Geodesy

Distinguishing land subsidence from true sea level rise has been made much easier by the advent of space geodesy. Geodesy is the science of measuring locations on the Earth's surface, and changes in those locations. Space geodesy exploits satellites, both artificial satellites such as the Global Positioning System (GPS) and Earth's natural satellite (the Moon), to establish an external reference frame for such measurements (e.g., Dixon, 1991; Seeber, 2003). For example, we can look at changes of the Earth's surface relative to the center of mass of the Earth, removing the ambiguity inherent in a relative sea level indicator such as a tide gauge. Since the 1990s, GPS measurements of the stability of coastal regions have clarified the relative importance of land subsidence and increasing ocean volume/mass increase in the interpretation of relative sea level rise data from tide gauges (Snay *et al.*, 2007). In effect, the GPS is used to calibrate tide gauges for ground motion (Figs. 3-7 and 3-9).

How It Works

GPS can be thought of as a timing device in the sky, measuring distance between the phase centers of the GPS satellite and ground receiver antennas through measurements of time. In principle, if we know the distance between at least three satellites and a given ground receiver, we can calculate the position of the ground receiver in three dimensions. In practice, at least four satellites are required, because rather than measure distance directly, we measure time (actually time delay, $\Delta\tau$) between the transmission of a satellite signal and its subsequent reception on the ground and use knowledge of the speed of light, c, to estimate the distance d ($d = \Delta t$). Because of the possibility of timing errors, four or more satellites are required to solve for the three position components and the clock offset. In a typical handheld GPS receiver, a simple measurement of "group delay" is performed, using a signal code that is modulated on one of the sinusoidal carrier waves transmitted by the satellite. To achieve the high precision necessary to investigate subsidence and other geophysical phenomena, special GPS receivers and antennas are required. These receivers use two frequencies (to compensate for ionospheric fluctuations that affect the speed of light) and make highly precise time/distance measurements through the use of phase measurements on the carrier itself, in addition to the group delay from the modulated code. Subsequent analysis of the phase and group delay data must account for a number of geophysical effects, such as tides and atmospheric perturbations, which may also cause c to vary, using sophisticated models. Dixon (1991) and Seeber (2003) provided additional details. Figure 3-9 shows an example time series of GPS data spanning several years, showing long-term subsidence at this coastal site near New Orleans, Louisiana, as well as short-term annual and semiannual variations, possibly related to Mississippi River flooding.

Synthetic Aperture Radar (SAR) is an active remote sensing technique that produces its own illumination

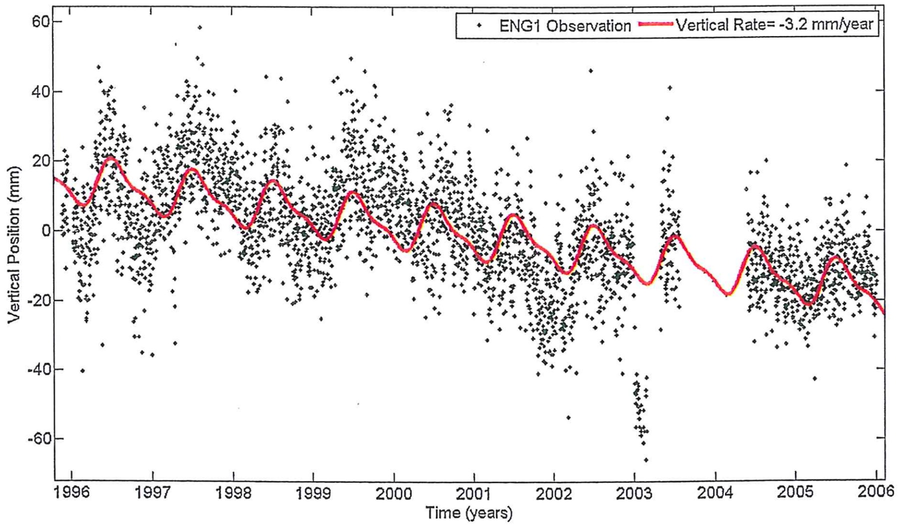

FIGURE 3-9. Example of a high-precision GPS time series, showing daily height estimates (black dots) from a site near English Turn in the Mississippi River, New Orleans. The red line is a model that assumes both annual and semiannual fluctuations, as well as a long-term linear rate. Note the annual fluctuation (probably from loading associated with the annual spring flood of the Mississippi River) and the longer-term trend of subsidence.

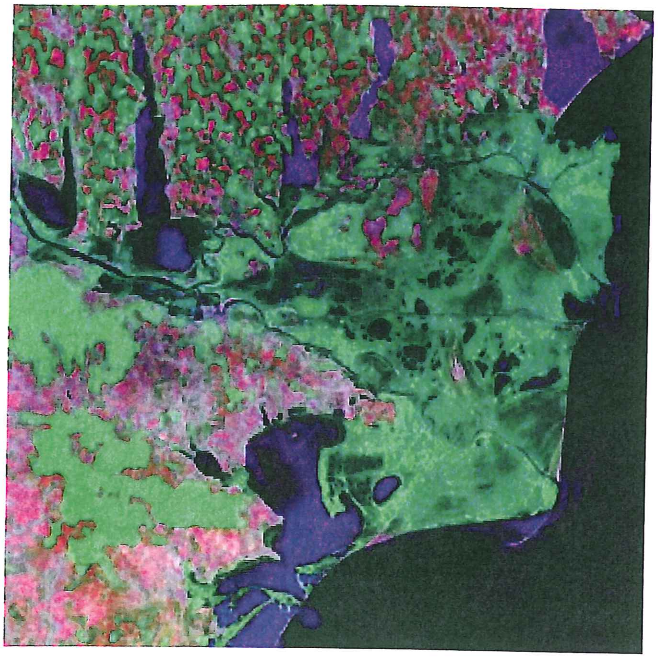

FIGURE 3-10. Danube River delta, imaged by the National Aeronautics and Space Administration's Landsat satellite. Image courtesy of NASA.

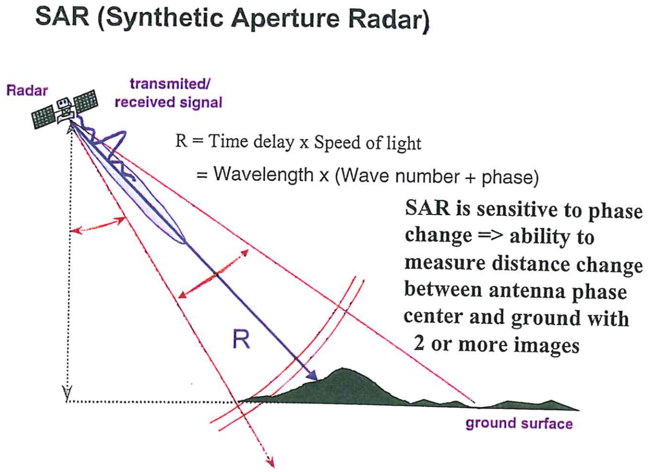

FIGURE 3-11. Principle of Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR). The space-based radar sensor measures both the amplitude and phase of the reflected signal reflected from the ground. By comparing phase change between successive SAR images (which may be acquired several months apart) and having accurate knowledge of the location of the spacecraft, it is possible to detect changes in the ground surface as small as several millimeters, a fraction of the SAR wavelength.

(microwave energy), and hence works in all weather, day or night (Fig. 3-10). SAR is a coherent imaging system, meaning that both amplitude and phase information in the reflected signal can be used in the data analysis. In effect, the original sinusoidal shape of the transmitted pulse is preserved after reflection from the surface and reception at the antenna. Although the amplitude data produces the image, the phase data in SAR are the key to using this technique for more than just imaging, turning it into a precise space geodetic technique analogous in some respects to GPS. Phase comparison of successive SAR images (interferometric SAR, or InSAR) allows an estimate of the change in the position of the surface to an accuracy of about 5% of the SAR wavelength. A typical SAR wavelength is about 6 cm, so the precision of the surface change measurement is several mm.

Plate-Boundary-Related Subsidence

Many processes can contribute to ground subsidence. For this discussion we will focus on those likely to affect coastal areas. The major plate boundary process that contributes to coastal subsidence is the cyclical pattern of strain accumulation and release associated with the earthquake cycle at subduction zones. As discussed in a previous section, during the interseismic phase, the down-going (usually oceanic) plate is coupled to the overriding plate, forcing it down and landward. This motion is "recovered" during the subsequent earthquake. The cycle is highly variable in length, but periods in the range 50 to 500 years probably describe most subduction zone earthquake cycles. Vertical motions (mainly down during the long interseismic phase, up during the earthquake) may exceed several meters in amplitude (e.g., Barrientos and Ward, 1990; Holdahl and Sauber, 1994). However, because of the cyclical nature of this motion, the long-term impact is usually small. Exceptions would occur in coastal areas that lack zoning regulations (or have poorly enforced regulations), allowing significant development near the beginning of an earthquake cycle (taking advantage of all the extra coastal area). The region would then experience progressive subsidence in subsequent decades as the shoreline newly created by the previous earthquake is progressively drowned and the region becomes increasingly susceptible to storm-related flooding.

Nonplate Boundary Subsidence

One of the most geologically active coastal areas not associated with plate boundary processes is the deltaic environment, where a river meets the ocean. As the velocity of the river slows upon entering the ocean, suspended sediments are deposited, unless strong ocean currents move and disperse the sediments along the coast. In the absence of such currents, the resulting deposits often have an approximately triangular shape in plan (map) view, hence the term *delta,* named after the Greek letter Δ (Fig. 3-11). Many cities are built on or near deltas, representing the historical importance of transportation hubs that connect oceangoing ship transport with barges and other river vessels that can access continental interiors. Deltas also tend to be fertile regions with abundant fresh water for irrigation, promoting agriculture. For both these reasons, many of the world's deltas are densely populated. Examples include New Orleans, near the mouth of the Mississippi River in the United States; Alexandria, near the mouth of the Nile River in Egypt; Venice, near the mouth of the Po River in Italy, and Calcutta and Dhaka in India/Bangladesh, at the combined mega-delta of the Ganges and Brahmaputra rivers.

Nichols and Leatherman (1995) suggested that a 1-m change in relative sea level will displace 6 million people in the Nile Delta. As populations increase, this number will certainly grow, particularly in third world countries with rapid rates of population increase. Bangladesh has an even greater number of people at risk. One meter of sea level rise will take several hundred years if current rates continue, but there are other factors to consider:

1. Will the current rate of sea level rise remain constant?
2. Will global warming impact the number or intensity of future storms and hurricanes?
3. Will the delta subside independently of sea level rise, increasing the rate of *relative* sea level rise?
4. Will land loss and population displacement take place gradually, or catastrophically? How will society react to these changes in our environment? What are the human health impacts?

The combination of dense population, low elevation, land subsidence, rising sea level, and possibly more frequent, more intense hurricanes and resulting storm surges clearly suggests the potential for the world's densely populated deltas to undergo major disasters in the future, with significant implications for human health. Let us look at these questions in more detail and consider a case history.

With regard to question 1, the rate of sea level rise over the next 50 to 100 years is largely determined by the fate of the Greenland and Antarctic ice sheets, which represent a huge reservoir of freshwater perched above current sea level (Alley *et al.*, 2005). Until recently, it was assumed that the thermal inertia of these large ice bodies was sufficiently high that current global warming would not significantly impact their melting rate for hundreds or even thousands of years. This was based on simple thermal conduction theory, which suggests that it takes a long time for temperature changes at the surface of the ice to impact the main ice mass, because water in all its forms is a poor heat conductor. However, observations of outlet glaciers (e.g., Rignot and Thomas, 2002) and the changing mass of Greenland ice (Velicogna and Wahr, 2006) suggest that Greenland and possibly Antarctica are melting at much faster rates than initially predicted. This may reflect advective (as opposed to conductive) thermal processes, whereby melt water at the surface of the ice penetrates cracks, allowing it to flow to the base of the glacier. In effect, this advects heat deep within the glacier and may even lubricate the basal ice, allowing faster outward flow of ice to the ocean, facilitating more rapid break up of the ice sheet.

With regard to question 2, this is an area of much current research. There are some indications that global warming may lead to both increased numbers of storms (Webster *et al.*, 2005) as well as increased storm intensity (Emanuel, 2005), but these are not settled questions, and more research is needed. What seems clear is that we should not assume that storm statistics based on the record of the past 100 years can be used to predict what will happen in the next 100 years.

With regard to questions 3 (delta subsidence), all deltas subside, for a variety of natural and artificial reasons, as outlined later. However, in a natural delta, subsidence is compensated by ongoing sediment deposition. As the delta subsides, the sediment-water interface is maintained near sea level by seasonal flooding and new sediment deposition, at least averaged over several years. In this way, sedimentary deposits in deltas may accumulate over thousands or millions of years and become thousands of meters thick. However, if this process is interrupted, for example, by channelizing the river with artificial levees to reduce or eliminate seasonal overbank flooding, the surface on which the city is built will continue to subside without compensating sediment deposition. Over time, this can result in extremely low elevations (in some cases several meters below mean sea level) and a consequent extreme flood hazard.

Three natural processes and one anthrogenic process are thought to contribute to delta subsidence:

1. Compaction of sediments by the weight of overburden (younger sediments deposited above) as pore water is gradually expelled and sediment density increases.
2. Isostatic adjustment as the crust and upper mantle of the Earth deflect and adjust to the weight of the delta.
3. Gravity sliding as the mass of recently deposited deltaic sediment slides down the continental slope into deeper water.
4. Fluid pumping (extraction of ground water, oil, or natural gas) may also contribute to localized subsidence as reservoir pressure drops, leading to excess compaction of the material comprising the reservoir.

In addition, sediment compaction may be exacerbated by human activities, especially in the case of organic rich soils that are drained for irrigation or urbanization. At this point, they become dessicated, and carbon-rich material is exposed to air, oxidizing to form CO_2, a gas which diffuses into the atmosphere, with significant mass and volume loss in the soil column.

The rates at which these various processes occur may vary significantly from delta to delta, may vary within a given delta, may also vary with time, and in general are poorly known. Of course, the rates at which these processes happen will affect the extent to which they matter on human timescales. Thus, to address question 4 (human impacts), we need to have some quantitative understanding of these various processes.

Let's look at a recent example from New Orleans and the Mississippi Delta. We have seen that the construction of artificial levees that serve to channel the river and reduce or eliminate overbank flooding, as has been done to the Mississippi River in the vicinity of New Orleans, will eventually lead to low elevation of the delta and increased flood hazard. However, in the short term, there are two advantageous consequences. First, the urban region is temporarily protected from flooding. Second, it provides a stable surface upon which geologists and geodesists can make measurements to quantify and better understand the subsidence process. Of course, the engineers who construct levees and the taxpayers who fund them probably did not intend the second consequence, but scientists play the hand they are dealt!

Current subsidence in the Mississippi Delta was first described by Penland and Ramsey (1990), who presented tide gauge data for Florida and other parts of the Gulf Coast including the Mississippi Delta. Along stable coastal areas with negligible ground subsidence such as Florida, relative sea level rise is occurring at rates of about 2 mm/yr. This presumably represents a global sea level signal associated with warming in the past 50 to 100 years. In contrast, along the Mississippi Delta, higher rates (~10 to 12 mm/yr) are observed, presumably representing a combination of ~2 mm/yr of sea level rise and ~8 to 10 mm/yr of land subsidence. The highest rates of subsidence tend to correlate with known regions of high land loss in the past few decades and of thickest Holocene deposits.

Subsidence in the region is best defined in New Orleans. This large urban area has understandably been the focus of a number of investigations because of the flood hazard facing this vulnerable community. In particular, we can use GPS and InSAR data.

GPS Data

The decade-long GPS time series at ENG-1, a site near New Orleans, reliably characterizes the average rate of surface subsidence at that location since the 1990s (3.1 ± 0.9 mm/yr) within its measurement uncertainty (Fig. 3-9). This time series also exhibits annual fluctuations, which may be related to annual fluctuations of the surface, perhaps because of water table fluctuation, differential seasonal loading of the delta, or unmodeled atmospheric processes that affect the signal.

SAR Data

High subsidence rates are observed today in parts of New Orleans using a variant of the InSAR technique, called PSInSAR (Fig. 3-12, from Dixon *et al.*, 2006). The technique exploits strong radar reflectors in the urban environment, such as buildings, or "Permanent Scatterers," and estimates their motion averaged over several years. The average subsidence rate in the city and surrounding suburban areas based on PSInSAR is 6 ± 2 mm/yr. This is equivalent within uncertainty to the average rate of 5 mm/yr reported by Burkett *et al.* (2003) from leveling data and the average for the larger delta reported by Dokka *et al.* (2006) from GPS (5 ± 2 mm/yr). Parts of New Orleans experience even higher subsidence rates, 20 mm/yr or more. These high subsidence areas tend to be located in former wetlands, drained for agriculture and urbanization, and hence are subject to desiccation and oxidation.

Based in part on the new space geodetic results and comparison to older leveling results, surface elevation data, soil maps, and a variety of other geophysical studies, we can now estimate quantitatively the rates of subsidence associated with individual processes.

Compaction of Young (Holocene; Less Than 10,000 Years Old) Sediments

These comprise the upper few meters to several tens of meters for most parts of the Mississippi Delta; maximum Holocene thickness is about 100 meters. In general, subsidence rates will be highest where the thickness of Holocene sediments is greatest, and they may reach several mm/yr. Older sediments also compact, but in general the rates are lower. Organic-rich marshy sediments may achieve the highest subsidence rates because of oxidation. Rates of compaction in this case can exceed 20 mm/yr, and the process may continue for many decades until a highly compacted, low-carbon state is achieved.

Subsidence of the Delta Because of Mass Loading

If sediment flux is steady, the delta will attain a state close to isostatic equilibrium. However, the Mississippi Delta received a large sediment load near the end of the last pulse of Holocene glaciation. Because of the delayed response of the viscous upper mantle, the delta may still be adjusting to this additional load, with subsidence rates as high as several mm/yr (Ivins *et al.*, 2007). A more recent perturbation may have increased erosion rates within the Mississippi drainage basin and consequent increased deposition in and near the delta, as the continental interior was cleared for agriculture in the past 150 years.

Tectonic Subsidence

Large-scale motion of the delta down and to the south occurs as it undergoes gravity sliding into the Gulf of Mexico. Many deltas probably do this, but for the Mississippi Delta, new GPS data have quantified the rate as ~2 ± 1 mm/yr to the south (Dokka *et al.*, 2006). Subsidence asso-

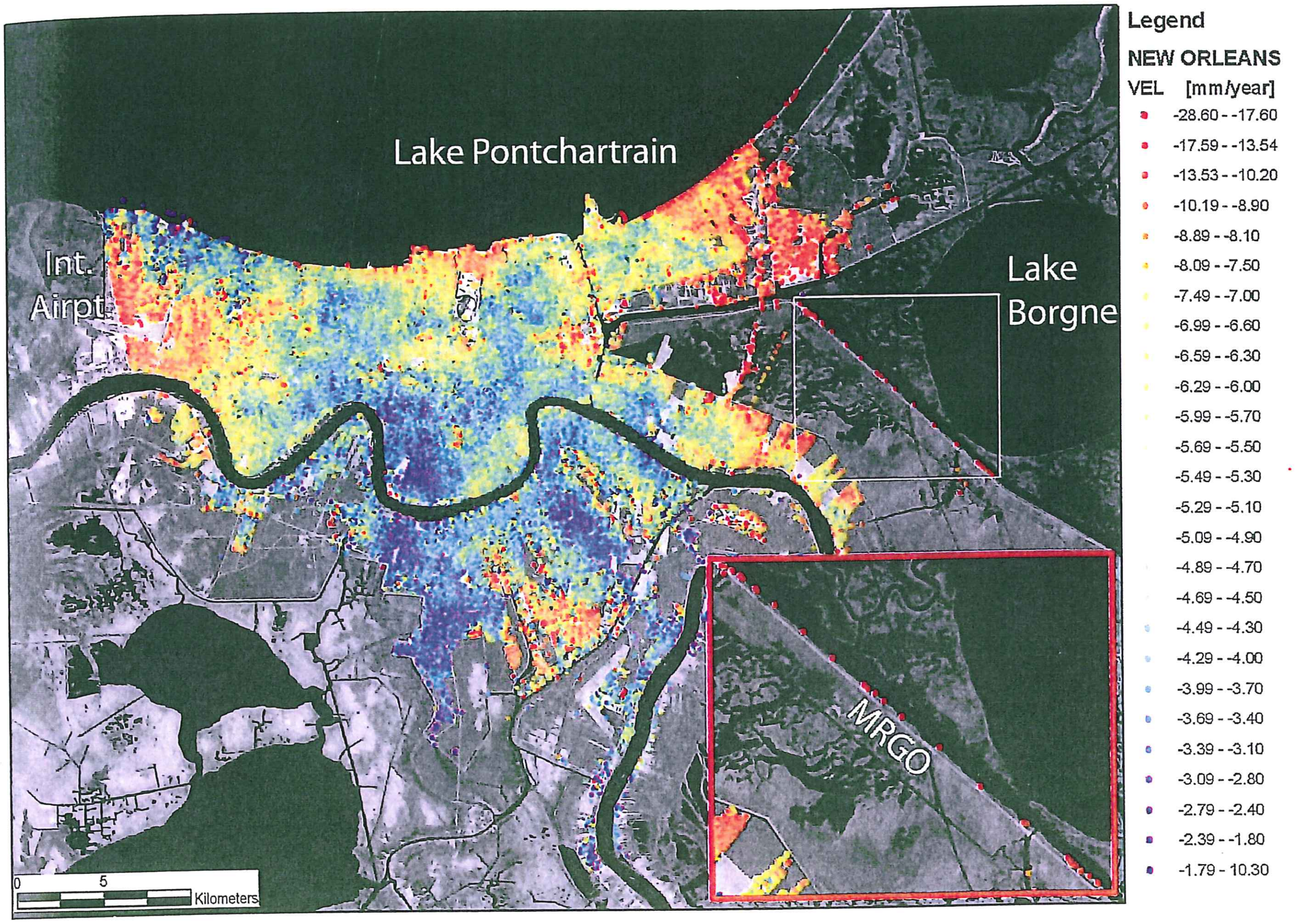

FIGURE 3-12. Subsidence map of New Orleans, Louisiana, based on Radarsat data from 2002–2005. Note high subsidence rates (>15 mm/year) near some coastal areas (recently backfilled), International Airport (town of Kenner, former marshland drained in the 1920s and 1930s for agriculture and urbanization), and adjacent to the Mississippi River-Gulf Outlet (MRGO) canal (inset). From Dixon *et al.* (2006).

ciated with this horizontal motion is less precisely known (and may vary as a function of distance from active normal faults that accommodate the motion) but is probably in the range 2 to 4 mm/yr. Note that the mean rate of GPS-measured delta subsidence reported by Dokka *et al.* (2006) (5 ± 2 mm/yr) represents the sum of several effects, including tectonic subsidence, mass loading, and some sediment compaction.

Fluid Withdrawal

This process typically produces subsidence "cones" within a few kilometers of the point of withdrawal, but it may be more widespread depending on the nature and depth of the reservoir and the rate, magnitude, and timing of production. Onshore hydrocarbon production slowed significantly after the 1970s in Louisiana and is probably not a significant factor in New Orleans or most of the Mississippi Delta.

Elevation and Flooding

Are the high rates of subsidence measured today (e.g., 2002–2005 from the PSInSAR results) typical of subsidence over the past 100 to 150 years? Can they explain the current low elevation of the city? Some parts of New Orleans currently lie 3.0 meters or more below sea level. Major drainage and levee construction in the region began after 1850. Assuming low elevations are somehow related to levee construction and assuming starting elevations close to sea level, average subsidence rates of at least 20 mm/yr over the past 150 years are required to achieve these low elevations. Thus, we conclude that the rapid rates of subsidence measured today in parts of New Orleans could explain the low elevation of parts of the city, especially if the lowest lying areas are characterized by organic rich soils, typical of former marshes. Inspection of soil maps suggests that this is indeed the case.

The main consequence of such high subsidence rates, if sustained over many decades, is, of course, low elevation.

FIGURE 3-13. Flooding in New Orleans Louisiana, approximately 12 hours after passage of Hurricane Katrina, August 29, 2005. Lake Pontchartrain is at the top of the image, the Mississippi River is the dark sinuous band along the bottom third of the image, the white areas are clouds, and the dark areas on land represent flooded areas. The black line marks the approximate maximum flood extent. The yellow numbers show the elevation of the flood line in meters (negative numbers denotes elevations below sea level). Image from SPOT-2 satellite, downloaded and processed at Center for Southeastern Tropical Advanced Remote Sensing (CSTARS), University of Miami. Courtesy of SPOT Image Corp. and D. Whitman, Florida International University.

This was tragically demonstrated in late August and September of 2005 when Hurricane Katrina struck New Orleans, overtopped several levees, and flooded the low-lying parts of the city (Fig. 3-13). Immediate fatalities, largely because of drowning, exceeded 1000 people. Most drowning fatalities were restricted to parts of the city where elevations were more than 2 meters below sea level. By definition, these areas had experienced high subsidence rates for long periods of time (e.g., 20 mm/yr for 100 years). Longer-term health consequences have been profound and are related to loss of infrastructure, loss of livelihood, and consequent loss of access to health care, interruptions to education, increased poverty, and increased susceptibility to disease. As of mid-2007, the population of the city has been reduced by nearly 50% from the prestorm value. On the other hand, immediate health consequences for the survivors were relatively benign. Although floodwaters were highly polluted, with high levels of fecal indicator bacteria and microbial pathogens, concentrations of key indicator bacteria in Lake Pontchartrain, where the floodwaters were eventually pumped, returned to background concentrations within a few months (Sinigalliano *et al.*, 2007).

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STUDY QUESTIONS

1. Assume you own a piece of real estate in Iceland measuring 1 km by 1 km that spans the main boundary between the North American and Eurasian plate. Assuming you hold on to your investment for 50 years, how much area have you gained?
2. Assuming all the ice in Greenland and Antarctica melts, how much would the global sea level rise? Assume Greenland ice is 1 km thick and Antarctic ice is 2 km thick.
3. You have been asked to travel to an oceanic island to investigate an outbreak of fluorosis and recommend solutions. Once you arrive, local authorities assure you that that the problem has been traced to a plant that manufactures toothpaste and has been remedied. However, the island also has an active volcano. How could you determine if fluorosis is actually endemic to the island because of volcanism, but has only recently been recognized and reported?
4. Calculate the time required for an electromagnetic signal to travel from a GPS satellite to a receiver on the Earth's surface. Assume that the satellite is 20,000 km away from the receiver.
5. (a)Assuming a coastline has a constant slope of 1% (1 m vertical drop for each 100 m horizontal distance), how far inland will a 5 m storm surge travel (ignore complexities associated with vegetation or other barriers and wave dynamics)? (b) How much will this answer change in 100 years if sea level rises at an average rate of 5 mm/yr and coastal subsidence occurs at a rate of 10 mm/yr. For part (b), assume that levee construction temporarily holds back the water until the storm surge.