ANNOUNCEMENTS

- This is not mandatory but it is quite interesting: https://www.youtube.com/watch?v=GTeb0jVFslA
- Quiz #1 opens on January 22nd.
  - Quiz questions not released until AFTER the quiz closes (a few days after)
- Office hour days
  - Jan. 29th, Feb.11, Feb. 26th (exam return day), March 12th, March 18th, March 28th (exam handback)
    - These days will have no course material but we for asking questions in class

Tsunamis

Chapter 4

Learning Objectives

1. Know what a tsunami is
2. Understand the process of tsunami formation and propagation
3. Understand the effects of tsunamis and the hazards they pose to coastal regions
4. Know what geographic regions are at risk from tsunamis

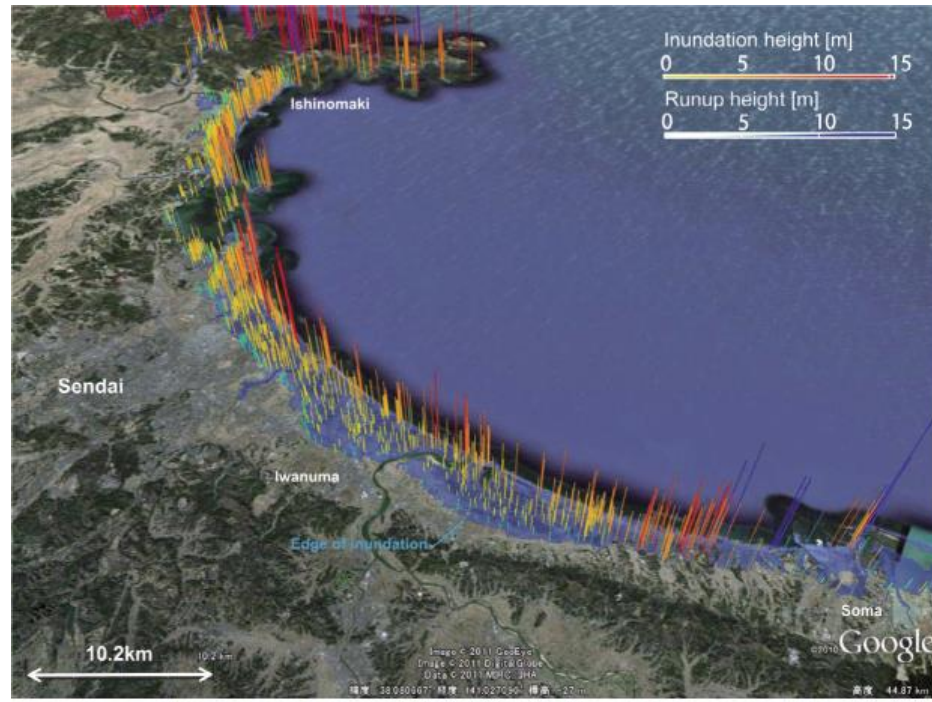
Learning Objectives

5. Recognize the links between tsunamis and other natural hazards

6. Know what national, regional, and local governments, and individuals can do to reduce the tsunami risk

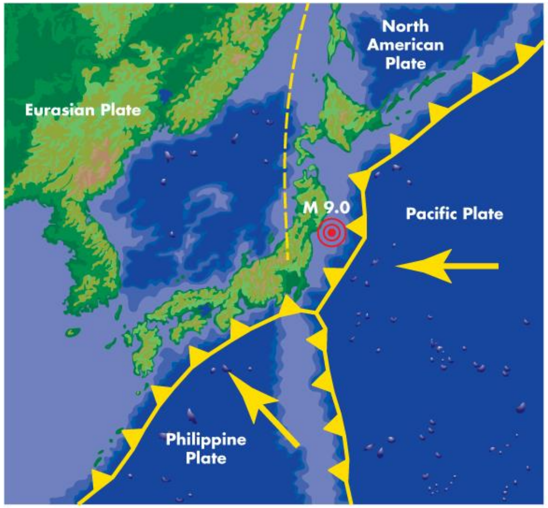
Japan Tsunami

- Occurred on March 11, 2011, killing ~ 16,000 people
- Source was a **M** 9.0 earthquake beneath the seafloor
  - Subduction zone east of Honshu Island
- The direct damage from the earthquake and tsunami was U.S. $235 billion
  - Most expensive natural disaster in history*



Japan Tsunami

- Three nuclear reactors were damaged which led to their meltdown
  - Thousands of residents were forced to evacuate
- The tsunami propagated throughout the Pacific Ocean, causing 2 m high waves in Chile
- Only 58% of people in highest impacted areas heeded the tsunami warnings and evacuated to higher ground



◄ **FIGURE 4.1 TSUNAMI STRIKES JAPAN** A surging mass of muddy, debris-laden water races across the coastal plain at Natori, near Sendai, Japan, on March 11, 2011. The tsunami destroyed nearly everything in its path and killed more than 16 000 people in coastal communities on Honshu. *(Reuters/Kyodo)*

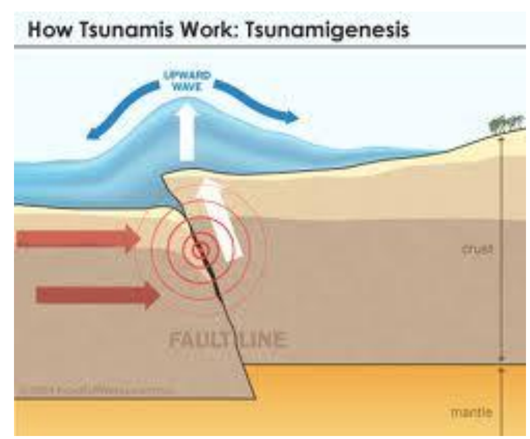
Lessons from the Japan Tsunami

- Japan was unprepared for the size of the tsunami
- Earthquake and tsunami education is necessary for people who live on or visit coastlines
- Tsunamis can have unanticipated secondary effects
  - Destruction of nuclear reactors
- Scientific research on historic tsunamis has not yet found its way into the decision-making process
  - A warning system alone is not enough

Introduction

- A **tsunami** is a series of waves caused by the displacement of a large volume of water.

- Triggered by:
  - Large earthquakes that cause uplift or subsidence of the sea floor
  - Underwater landslides
  - Volcano flank collapse
  - Submarine volcanic explosion
  - Asteroids
    - Can produce [mega tsunami]



Some Historic Tsunamis

Date	Cause	Damage
1755	Earthquake (**M** 8-9) in Lisbon, Portugal	20,000 people killed
1883	Krakatoa volcano eruption	>36,000 people killed, 35 m high waves
1946	Earthquake (**M** 8.1) near the Aleutian Islands	~160 people killed in the Hawaiian Islands
1960	Earthquake (**M** 9.5) in Chile	61 people killed in Hawaii
1964	Earthquake (**M** 9.2) in Alaska	~130 people killed in Alaska and California
1993	Earthquake (**M** 7.8) in the Sea of Japan	120 people killed in Okushiri Island, Japan
1998	Submarine landslide triggered by an earthquake (**M** 7.1) in Papua New Guinea	>2100 people killed
2004	Earthquake (**M** 9.1) in Sumatra	Killed ~ 230,000 people
2010	Earthquake (**M** 8.8) in Chile	~150 people killed
2011	Earthquake (**M** 9.0) in Japan	>16,000 people killed in Honshu

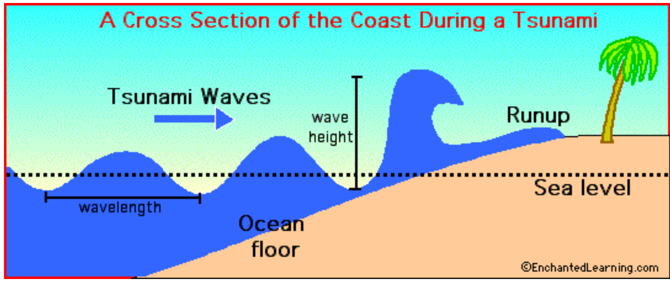
Earthquake–Triggered Tsunamis

- Earthquake rupture in the seafloor pushes water upwards
  - Generally Requires > **M** 7.5 earthquake

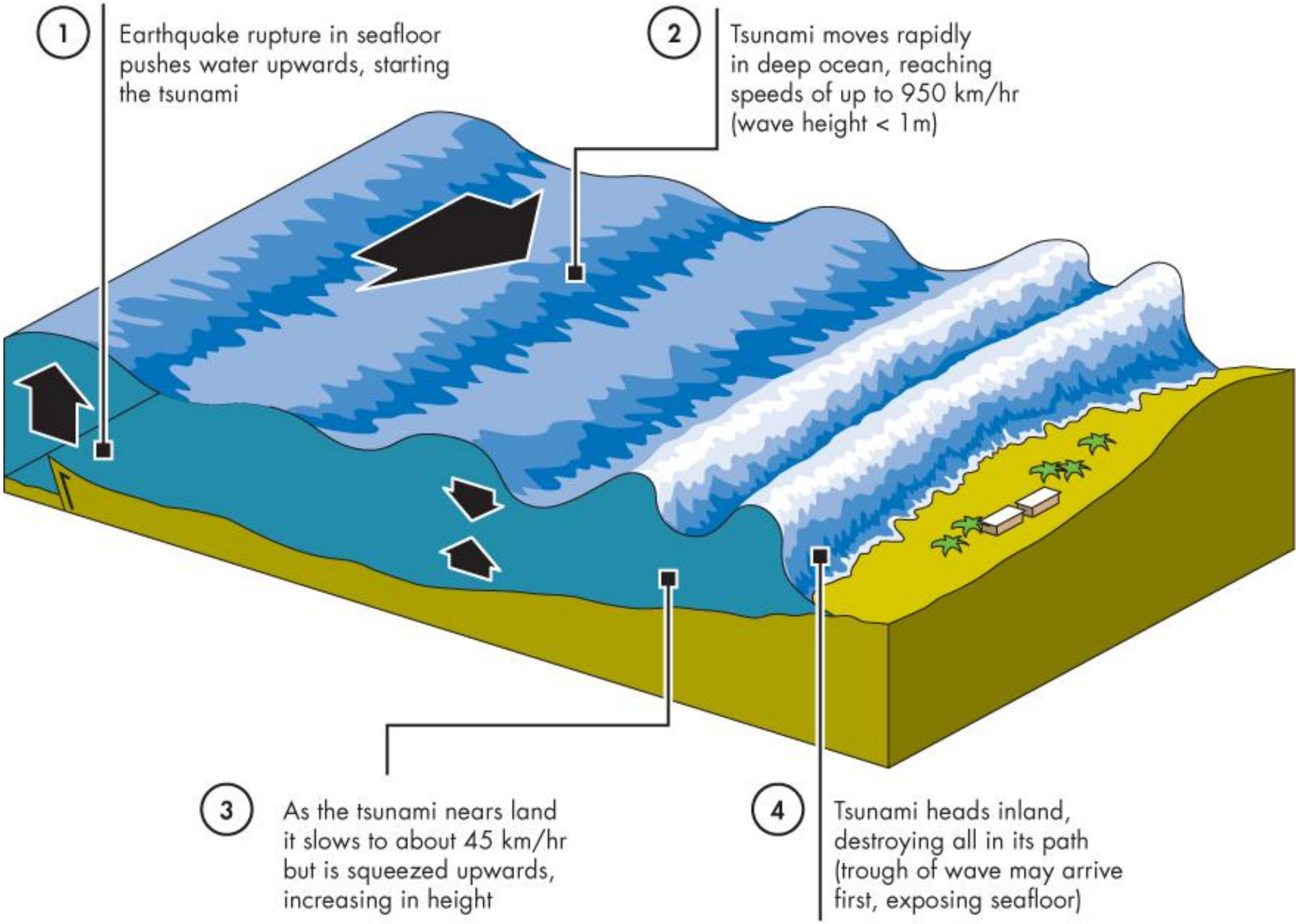
- Tsunamis move rapidly in the deep ocean
  - Can typically travel up to and over 500 km/h
  - Spacing (frequency) of crests is large and amplitude is small; people on large boats do not notice tsunami waves

Earthquake–Triggered Tsunamis

- Tsunami nears land, loses speed, gains height
  - Depth of ocean decreases, slowing tsunami waves to 45 km/h
  - More water piles up, increasing amplitude and frequency



- Tsunami moves inland, destroying everything in its path
  - Can be metres to tens of metres high
  - Trough may arrive first, exposing the seafloor
  - **Run up** - furthest horizontal and vertical distance of the largest wave
  - More waves likely to follow



▲ **FIGURE 4.4 FORMATION AND DEVELOPMENT OF A TSUNAMI** Idealized diagram showing the process of how a tsunami is produced by an earthquake and travels away from the source toward a coastline. *(Adapted from the United Kingdom Hydrographic Office)*

Indonesia Tsunami

- Occurred on December 26, 2004, killing ~ 230,000 people
- Source was a **M** 9.1 earthquake off west coast of Sumatra
  - Subduction zone between Burma and Indian and Australian plates
- No tsunami warning system in the Indian Ocean at the time
- Few people knew tsunami warning signs
- https://www.youtube.com/watch?v=Aq0v4Qlghnk

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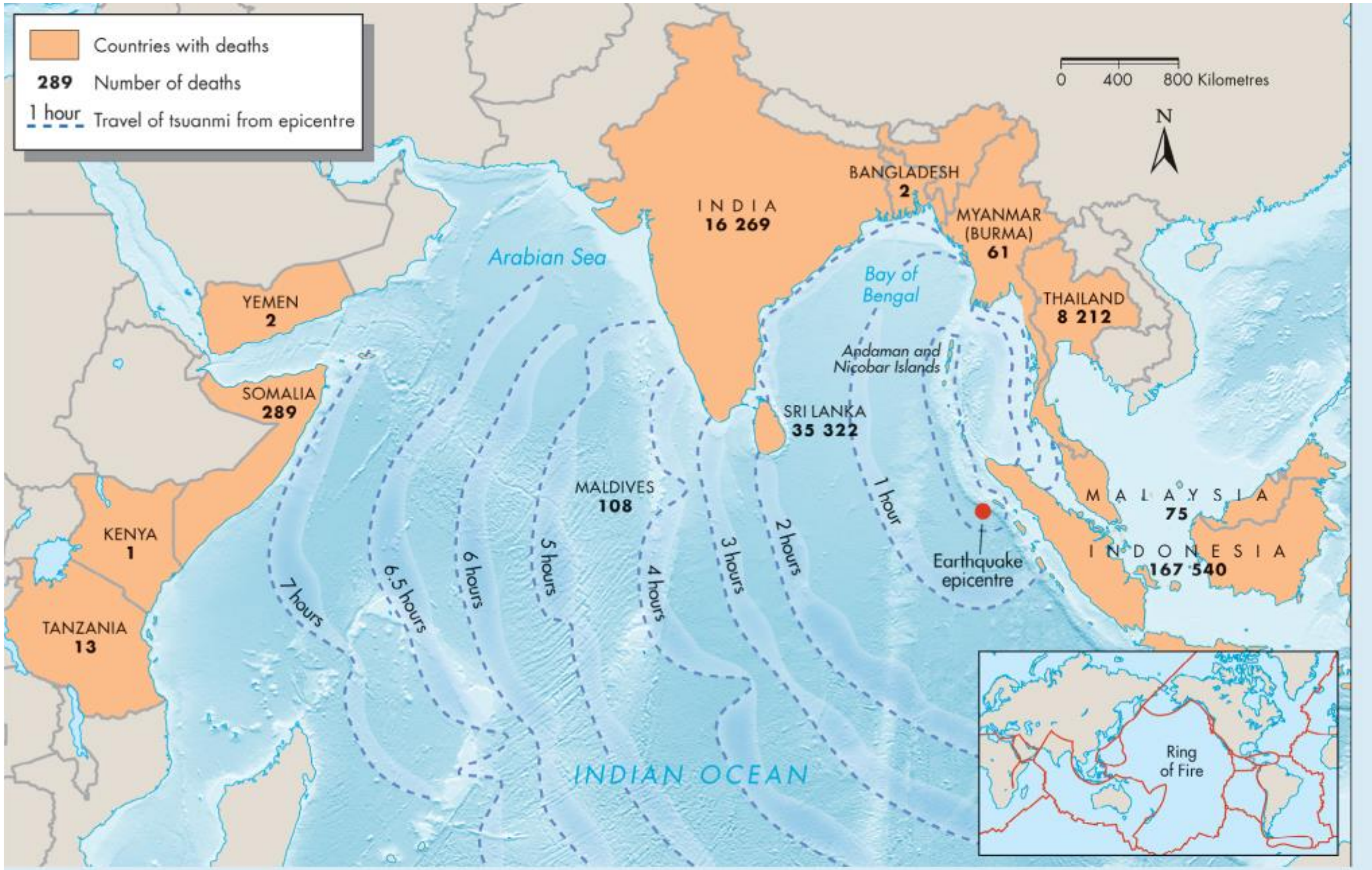

▲ **FIGURE 4.6 DEADLIEST TSUNAMI IN HISTORY** The Indian Ocean tsunami of December 26, 2004, was by far the deadliest tsunami in history. It formed off the northwest coast of the island of Sumatra and spread death and destruction across the Indian Ocean to the east coast of Africa. Dashed lines are the approximate positions of the lead wave or trough of the wave train at different times after the earthquake. *(Data from Casualties summarized in Telford, J., and J. Cosgrave. 2006.* Joint Evaluation of the International Response to the Indian Ocean Tsunami: Synthesis Report. *London: Tsunami Evaluation Coalition; Tsunami travel time data from NOAA)*

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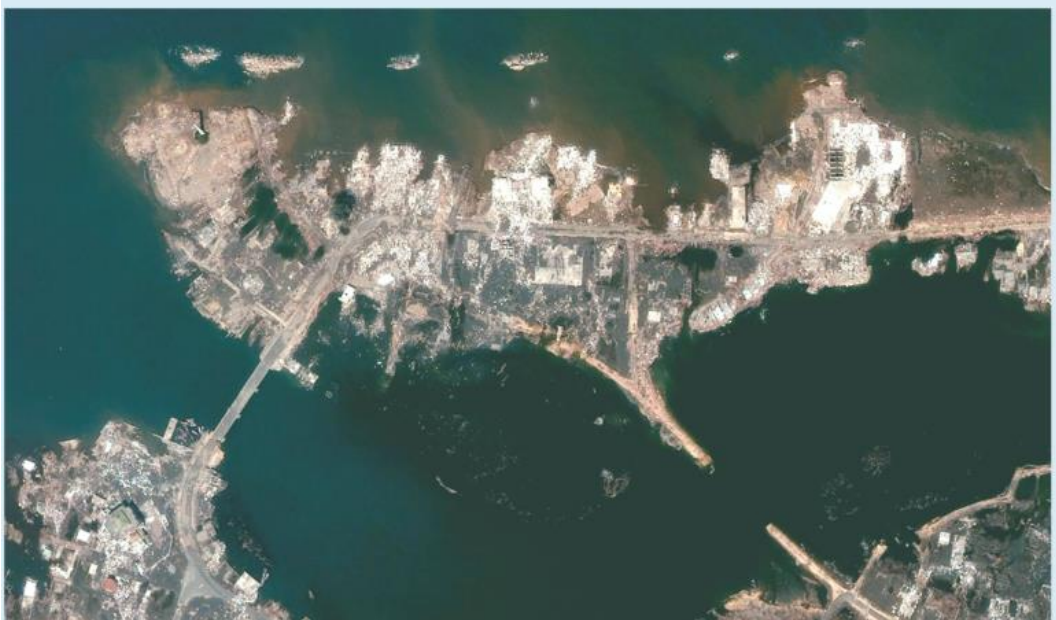


(b)

◄ **FIGURE 4.7 BANDA ACEH BEFORE AND AFTER THE 2004 TSUNAMI** QuickBird satellite images of Banda Aceh, a provincial capital on Sumatra (a) on June 23, 2004, before the tsunami, and (b) on December 28, 2004, two days after the tsunami. All the buildings in this area were destroyed, including part of the bridge at the lower right. *(Digital Globe)*

Positive Stories from the Indonesia Tsunami

- In Thailand, a 10-year-old British girl saved people by recognizing the signs of the tsunami
- A port official on the Nicobar Islands warned people to go to higher ground after the earthquake
- Native peoples in some regions recognized the danger and moved to higher ground
- In Thailand, elephants sensed the tsunami and aided in moving handlers and tourists to higher ground

▲ **FIGURE 4.9 TSUNAMI SURVIVOR** Christine Lang was engulfed in the great Indian Ocean tsunami when it struck Phi Phi Island, Thailand, on December 26, 2004. She survived the terrifying ordeal. *(Courtesy of Christine Lang)*

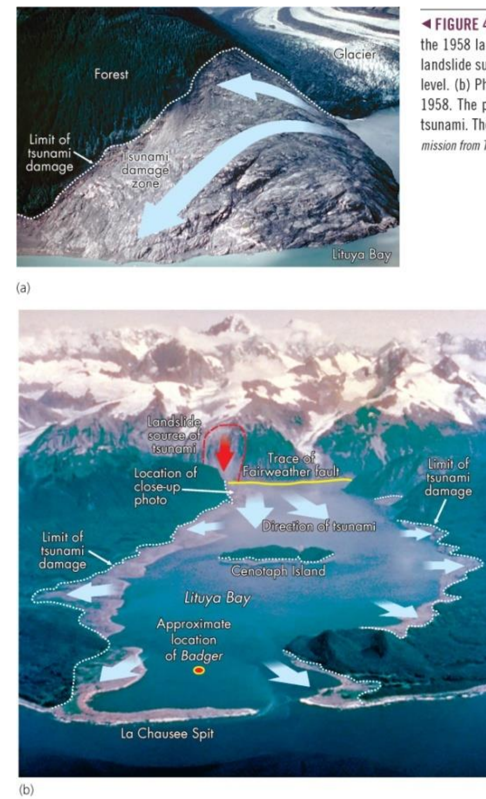
Landslide-Triggered Tsunamis

- Submarine landslides cause water to become displaced in lakes or oceans

- Landslides can fall into the ocean from mountains, causing waves to form
  - Ex: Lituya Bay, Alaska
  - Bay water surged to a level 525 m above normal

– Volcano flank collapse may also cause tsunami

– Lose energy over distance



◄ FIGURE 4.13 LI
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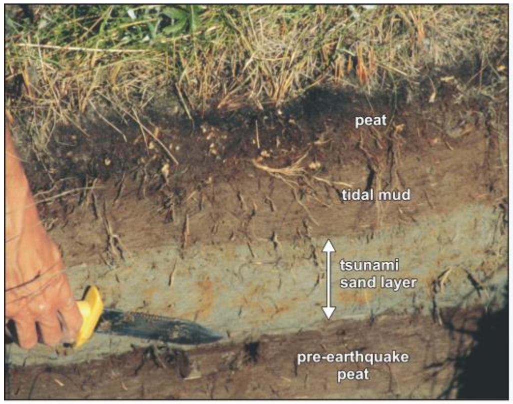
Volcanic-Triggered Tsunamis

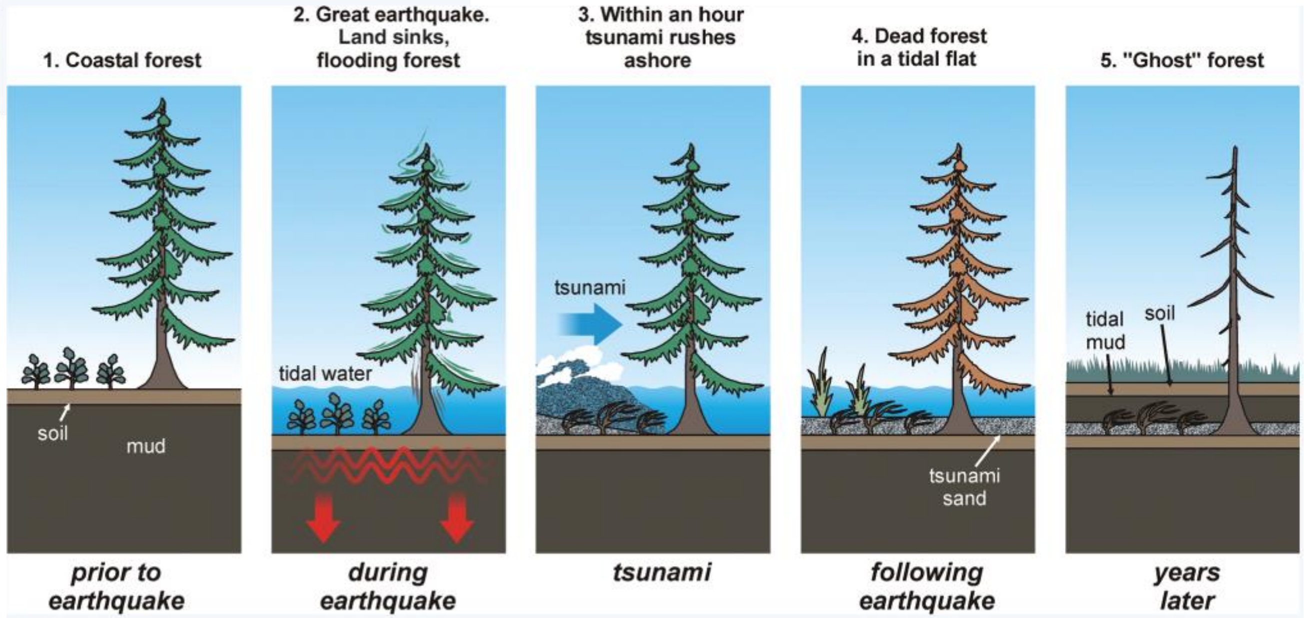
- Less common than earthquake-triggered

- The second most deadly tsunami was triggered by the Krakatoa eruption
  - Between Java and Sumatra
  - Eruptions on August 26 and 27, 1883
  - Explosion heard 5000 km away

Geologic Evidence



◄ FIGURE 4.10 **TSUNAMI SAND** This layer of sand in a tidal marsh near Tofino on the west coast of Vancouver Island was deposited by a tsunami generated by a great earthquake at Cascadia subduction zone in 1700. The sand layer becomes thinner and finer with increasing distance inland. It overlies peat and is overlain by tidal mud, both of which are the normal sediments that accumulate in the marsh. *(Tricouni Press tricouni@telus.net/Vancouver, City on the Edge)*

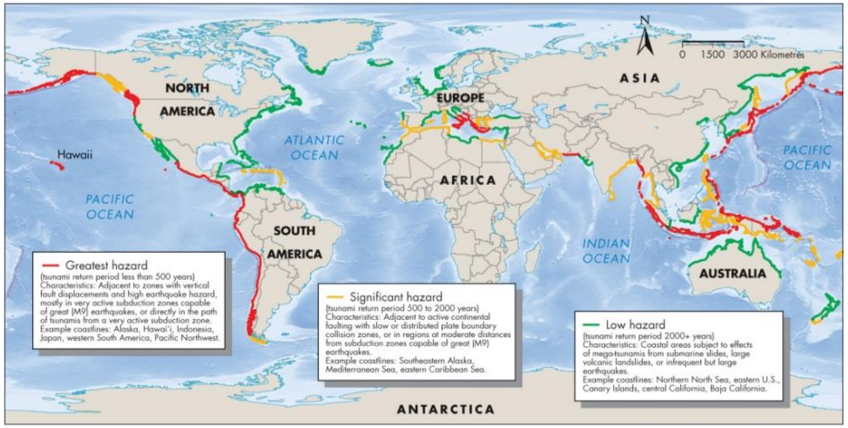


▲ FIGURE 4.11 **GEOLOGIC EVIDENCE FOR SUBDUCTION ZONE EARTHQUAKES AND TSUNAMIS** Schematic diagram of tidal marsh sediments showing the geologic signature of a great Cascadia earthquake and its attendant tsunami. A tidal marsh subsides up to 2 m during a great earthquake, just before it is overrun by the tsunami triggered by the quake. The tsunami leaves a layer of sand on the subsided marsh surface. After the earthquake, the inundated surface becomes a platform on which intertidal silt and clay are deposited. The definitive signature of the earthquake is a marsh peat (the former vegetated marsh surface), abruptly overlain by a sand sheet (the tsunami deposit) that, in turn, is sharply overlain by tidal mud. *(Reprinted with permission from Tricouni Press)*

Regions at Risk

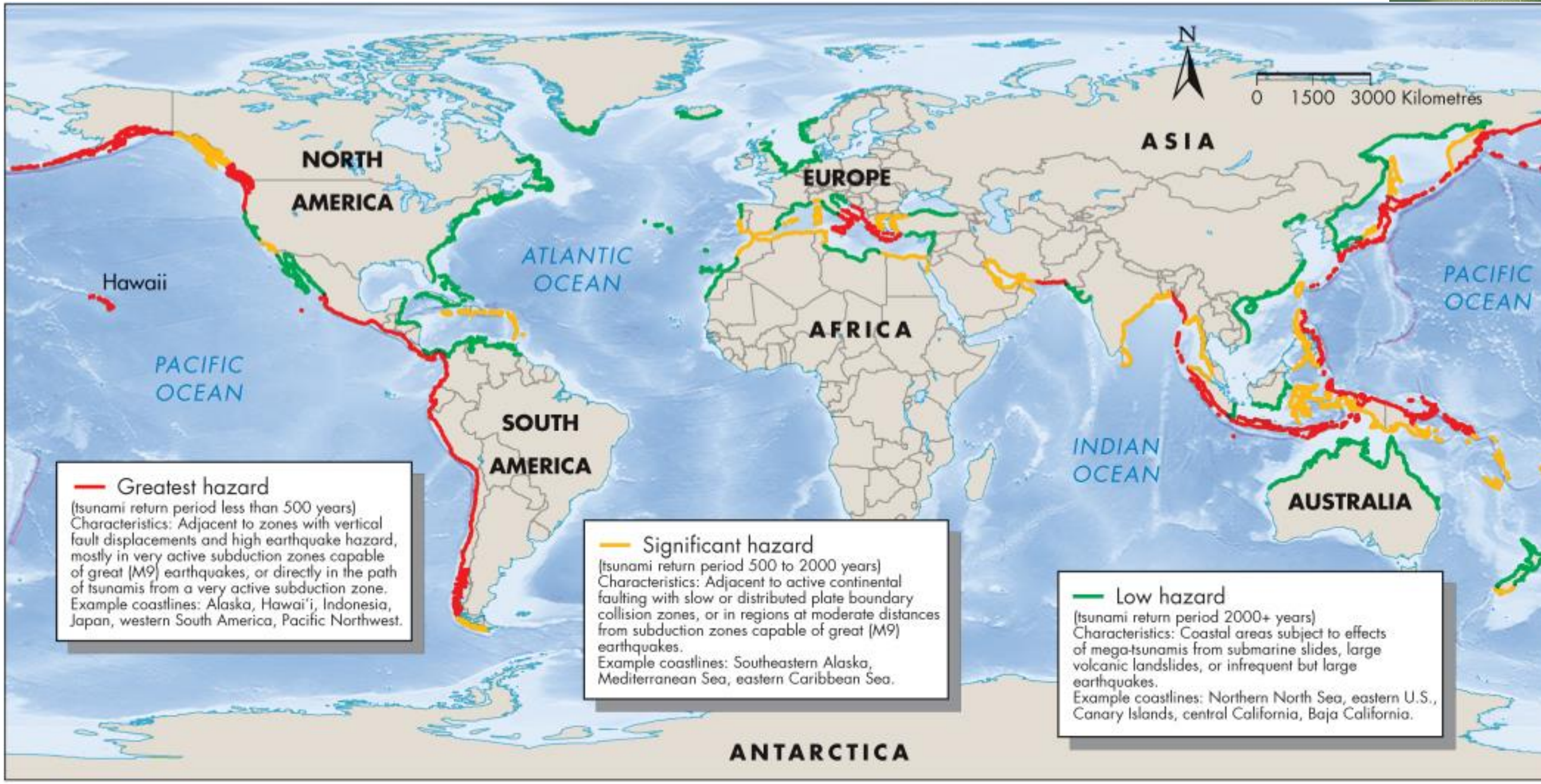
- Most coastlines of all oceans and some lake shorelines

- Coasts near the sources of tsunami
  - Earthquakes, landslides, volcanoes
  - Subduction zones capable of generating **M** 9 earthquakes, such as Cascadia zone, Chilean trench, off coast of Japan



▲ FIGURE 4.14 GLOBAL TSUNAMI HAZARD Map showing the relative risk of the world's coastlines to a tsunami at least 5 m high. The map is generalized because tsunami run-up differs considerably over short distances depending on the form of the seafloor directly offshore and the topography and vegetation landward of the beach. *(Risk Management Solutions. 2006. 2004 Indian Ocean Tsunami Report. Newark, CA: Risk Management Solutions, Inc. Reprinted with permission. All rights reserved.)*

- Areas around the Pacific Ocean, Mediterranean Sea, and northeastern Indian Ocean



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Effects of Tsunamis

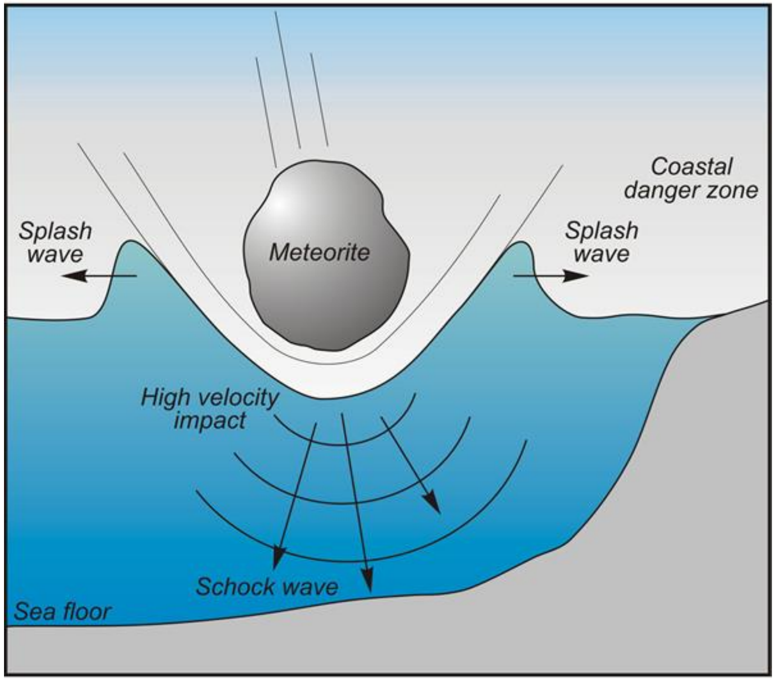
- Primary effects are related to flooding and erosion
  – Shorten the coastline
  – Debris erodes the landscape and damages structures
  – Diminish with distance from the coast
  – Deaths from both drowning and the force of impact of the water

◄ FIGURE 4.19 **TSUNAMI DAMAGE TO TREES** IKONOS satellite images of a low-lying coastal area (a) before and (b) after the 2004 Indian Ocean tsunami. Note the near-total destruction of vegetation by the tsunami. *(IKONOS Satellite images courtesy of the Centre for Remote Imaging, Sensing and Processing (CRISP) and GeoEye. Copyright 2007. All rights reserved)*

- Secondary effects
  – Fires
  – Contaminated water supplies
  – Disease

Links with Other Natural Hazards

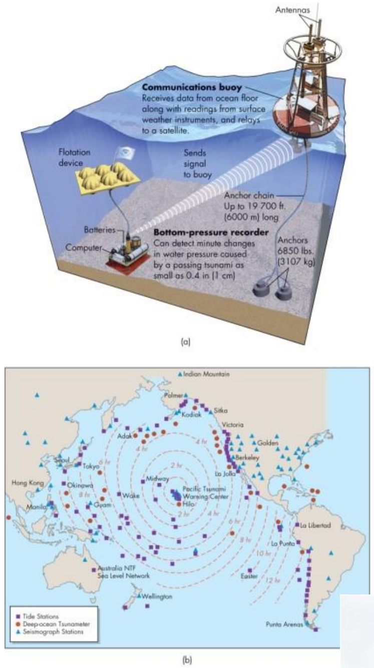
- Causes *of* tsunami
  - Earthquakes
  - Landslides
  - Volcanic explosions
  - Asteroids



- Caused *by* tsunami
  - Coastline erosion and sediment deposition
  - Subsidence of coastlines

Minimizing the Tsunami Hazard

- Detection and warning
  - Monitor earthquake zones
  - **Tsunami warning system**
    - Seismographs to detect earthquakes
    - Tidal gauges to determine sea level changes
    - Buoy sensors to detect tsunami in open ocean

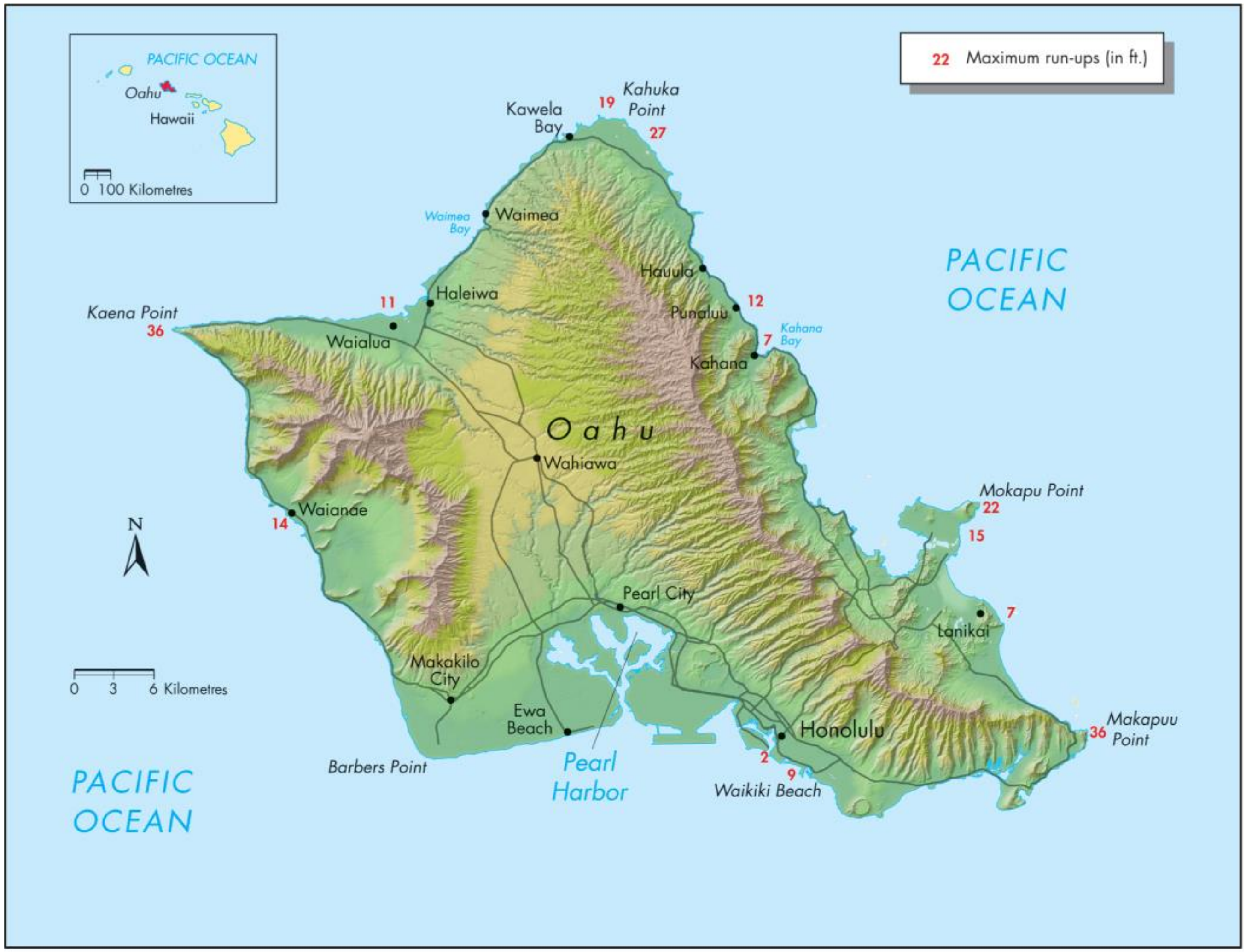


◄ **FIGURE 4.16 TSUNAMI WARNING SYSTEM IN THE PACIFIC** (a) A bottom sensor detects a tsunami and a tethered buoy transmits the information to a tsunami warning centre. (b) The Pacific Tsunami Warning Center in Hawaii acquires information from three sources: a network of seismographs, more than 100 tide gauges, and 30 DART ocean-bottom pressure sensors linked to surface buoys. The dashed lines show the time it would take a tsunami to reach Hawaii from locations in the Pacific Ocean. *(Modified after NOAA National Weather Service)*

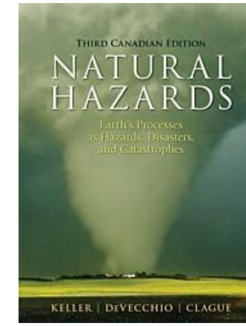
- Structural control
  - Building codes for susceptible coastline areas

▲ **FIGURE 4.17 HOUSE ON STILTS** This house in Hilo, Hawaii, is elevated on posts to provide protection against tsunamis. A small tsunami would pass beneath the living level of the home, leaving it undamaged. *(John J. Clague)*

- Tsunami inundation maps (run-up)
  - Show the height to which water is likely to rise



▲ **FIGURE 4.18 TSUNAMI RUN-UP ON OAHU** Map of Oahu, Hawaii, showing vertical run-up of the 1946 tsunami that originated from an earthquake in the Aleutian Islands, Alaska. Values are in feet. *(Modified after Walker, D. 1994.* Tsunami Facts. *SOEST Technical Report 94-03. School of Ocean and Earth Science and Technology. Reprinted with permission.)*



Minimizing the Tsunami Hazard

- Land use
  - Native vegetation may provide defense
  - Development of land must be monitored
- Probability analysis
  - Similar to earthquake analysis
- Education
  - Educate people on the signs of tsunami
  - Differences between **tsunami watch** and **tsunami warning**

Minimizing the Tsunami Hazard

- Tsunami readiness
  - Establish 24-hour emergency operation centres
  - Be able to receive tsunami warnings
  - Have ways to alert the public
  - Develop a preparedness plan with emergency drills
  - Promote community awareness programs through education

Perception and Personal Adjustment to the Tsunami Hazard

- If you feel an earthquake, leave the beach or low-lying area
- If you see the ocean receding, run from the beach
- A small tsunami in one location may be larger nearby
- Tsunamis have multiple waves

Perception and Personal Adjustment to the Tsunami Hazard

- If you hear a tsunami siren, move to higher ground
- Do <u>not</u> go down to the beach to watch the tsunami. If you can see it, you are already in danger
- https://www.youtube.com/watch?v=Wx9vPv-T51I