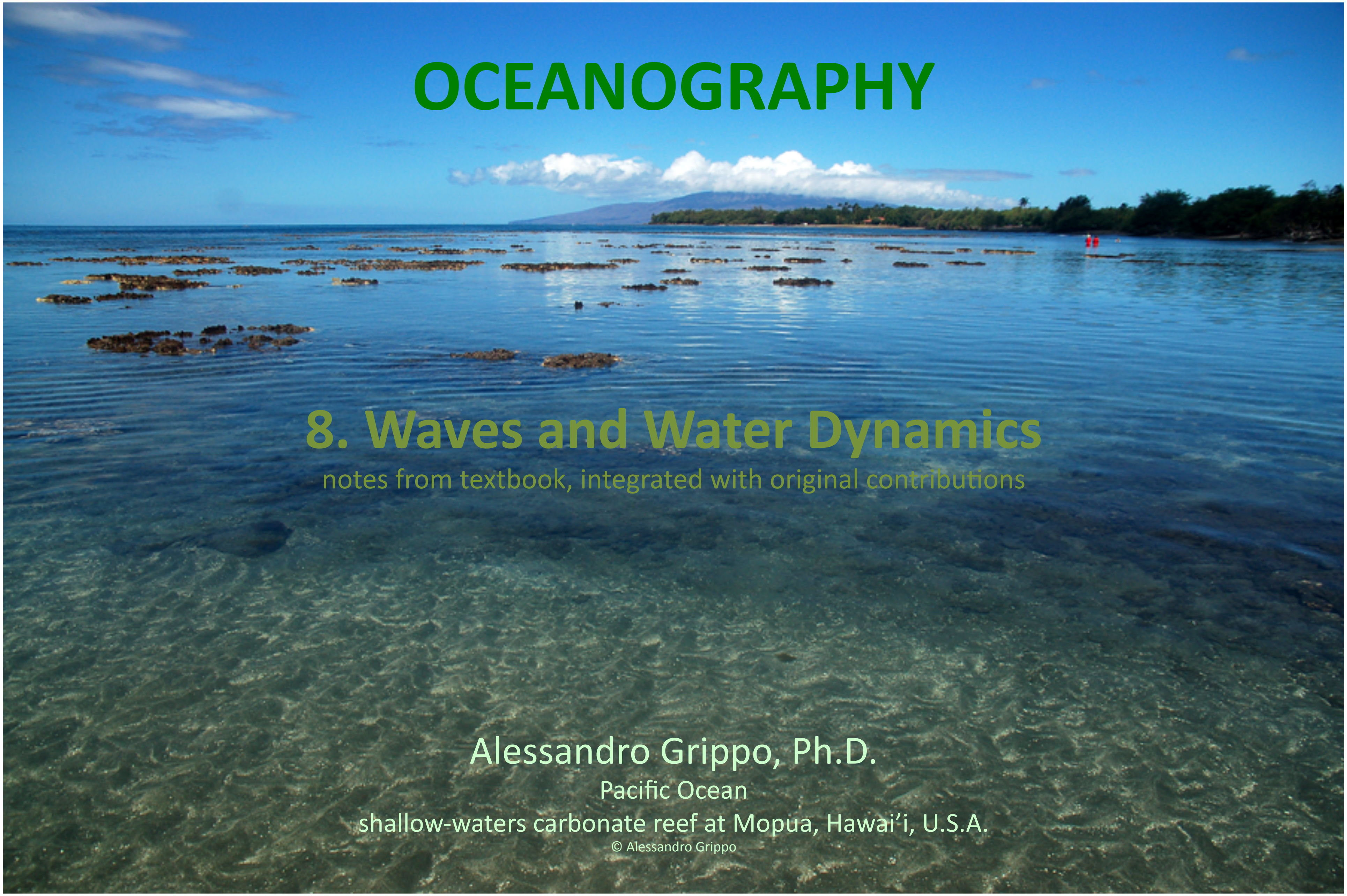
OCEANOGRAPHY
8. Waves and Water Dynamics
notes from textbook, integrated with original contributions
Alessandro Grippo, Ph.D.
Pacific Ocean
shallow-waters carbonate reef at Mopua, Hawai'i, U.S.A.
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introduction

- most waves are generated by winds, during storms
- waves transfer energy across the ocean surface
- tsunamis are fast, long waves generated mostly by seismic events

coastal waves

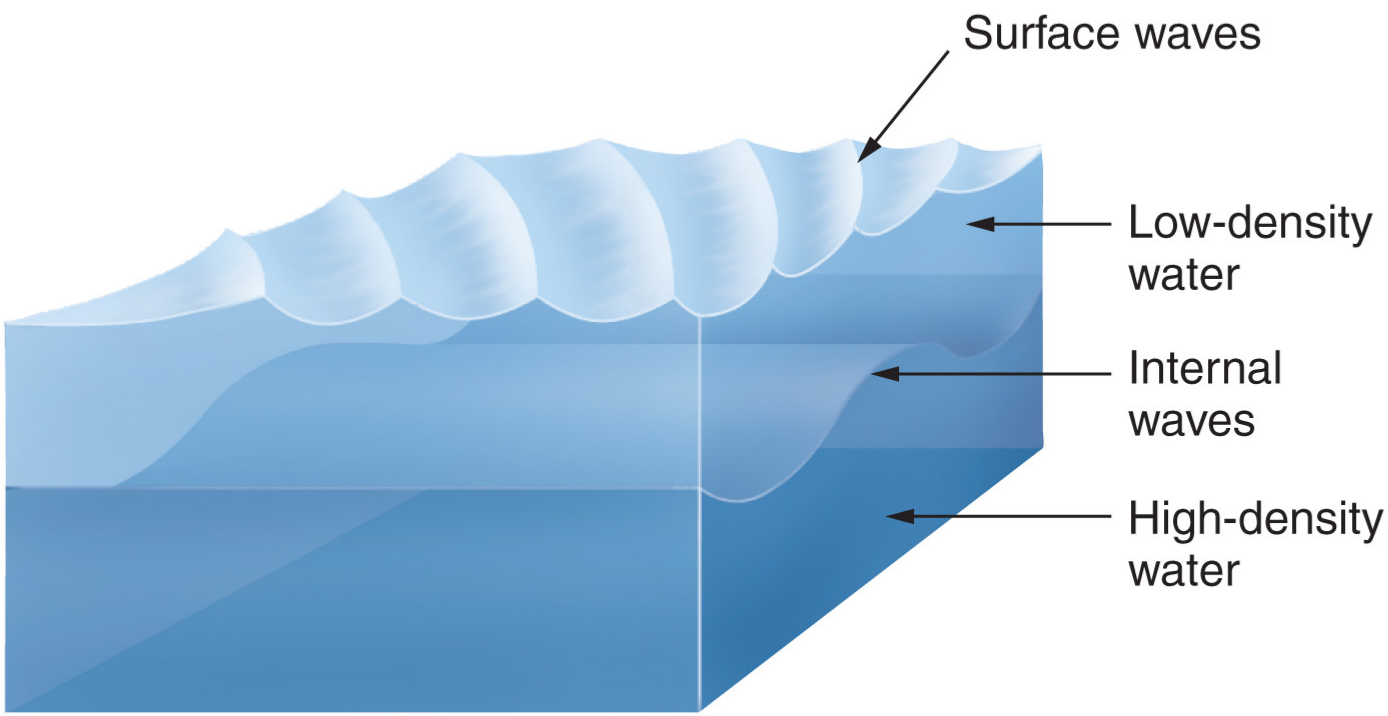
San Juan del Sur, Nicaragua

8.1 – How Are Waves Generated, and How Do They Move?

- all waves begin as a disturbance
- wind blowing across the surface of the ocean generates most ocean waves, which then radiate in all directions
- in general, waves are created by the movement of fluids with different densities

Wave Generation

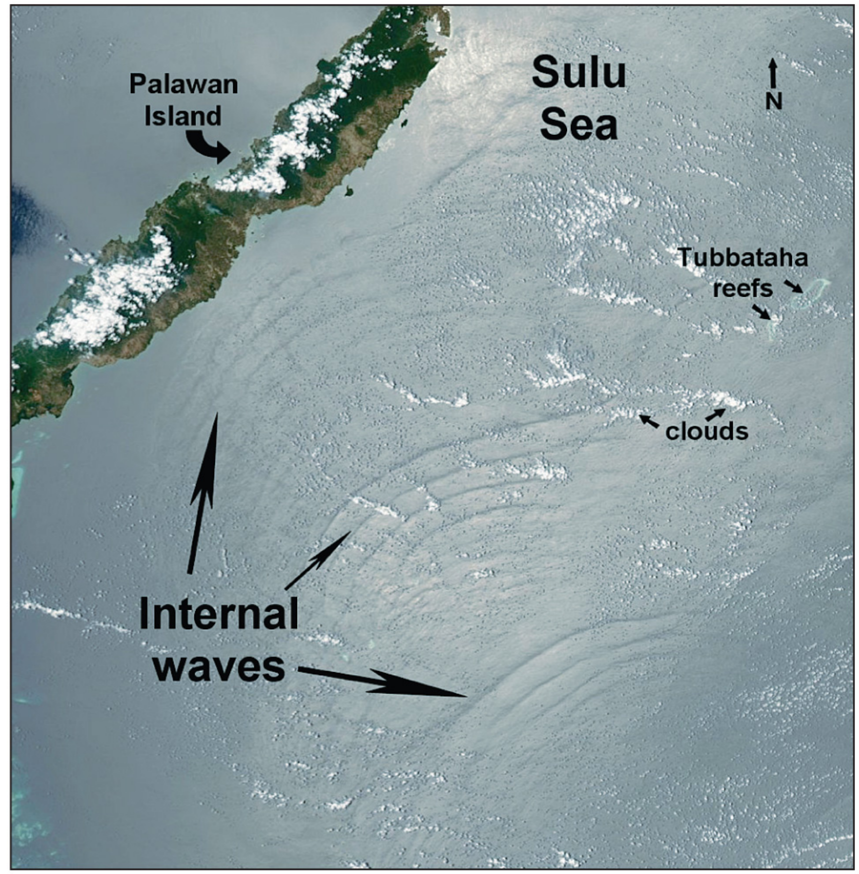
- Air/ocean interface
  - Ocean waves
- Air/air interface
  - Atmospheric waves
- Water /water interface
  - Internal waves (often associated with a pycnocline)



(a)

Internal Waves

- Associated with a pycnocline
- Larger than surface waves (heights exceeding 100 m)
- Caused by tides, turbidity currents, winds, ships
- Possible hazard for submarines



(b) Internal waves, Sulu Sea

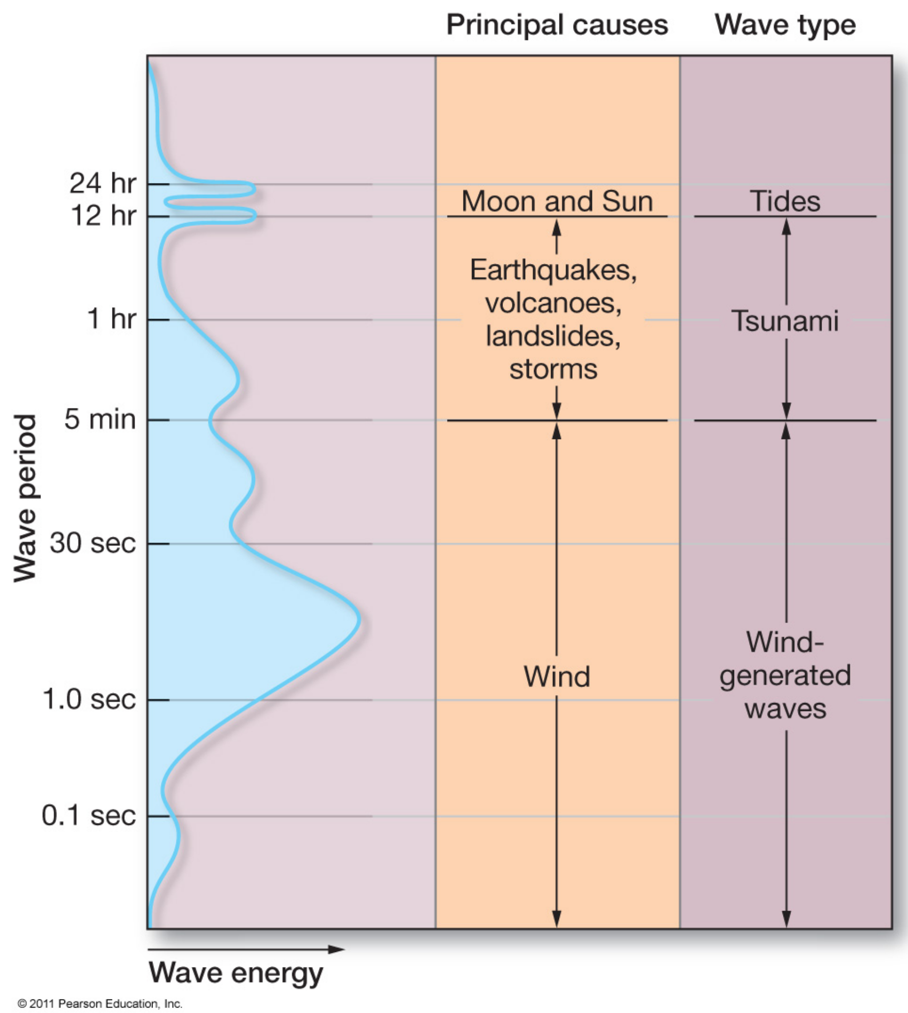
Other Types of Waves

- Splash wave
  - from mass movement into the ocean:
    - Coastal landslides, calving icebergs
- Seismic sea wave, or tsunami
  - Sea floor movement
    - uplifting or downdropping of ocean floor (plate tectonics)
    - turbidity currents
    - volcanic eruptions
    - fault slippage
- Tides
  - Gravitational attraction among Moon, Sun, and Earth
    - very predictable
- Wake
  - Ships

boat wake developing upon leaving Los Angeles Harbor

Palos Verdes and San Pedro to the left, Vincent Thomas Bridge in the background, harbor cranes to the right

Energy in Ocean Waves



Waves as energy in motion

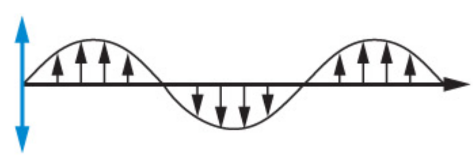
Wind blowing across a field of California poppies:
waveform moves as the flowers sway, but the plants stay in the same location

California Poppy Preserve, Lancaster, Los Angeles County, CA

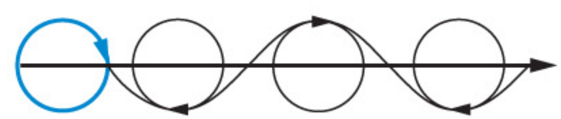
Wave Movement

- Different waves move in different ways
- Progressive waves are waves that oscillate uniformly and progress (or travel) without breaking
- Progressive waves can be:
  - longitudinal
  - transverse
  - orbital (a combination of longitudinal and transverse)

(1) LONGITUDINAL WAVE
Particles (color) move back and forth in direction of energy transmission. These waves transmit energy through all states of matter.



(2) TRANSVERSE WAVE
Particles (color) move back and forth at right angles to direction of energy transmission. These waves transmit energy only through solids.



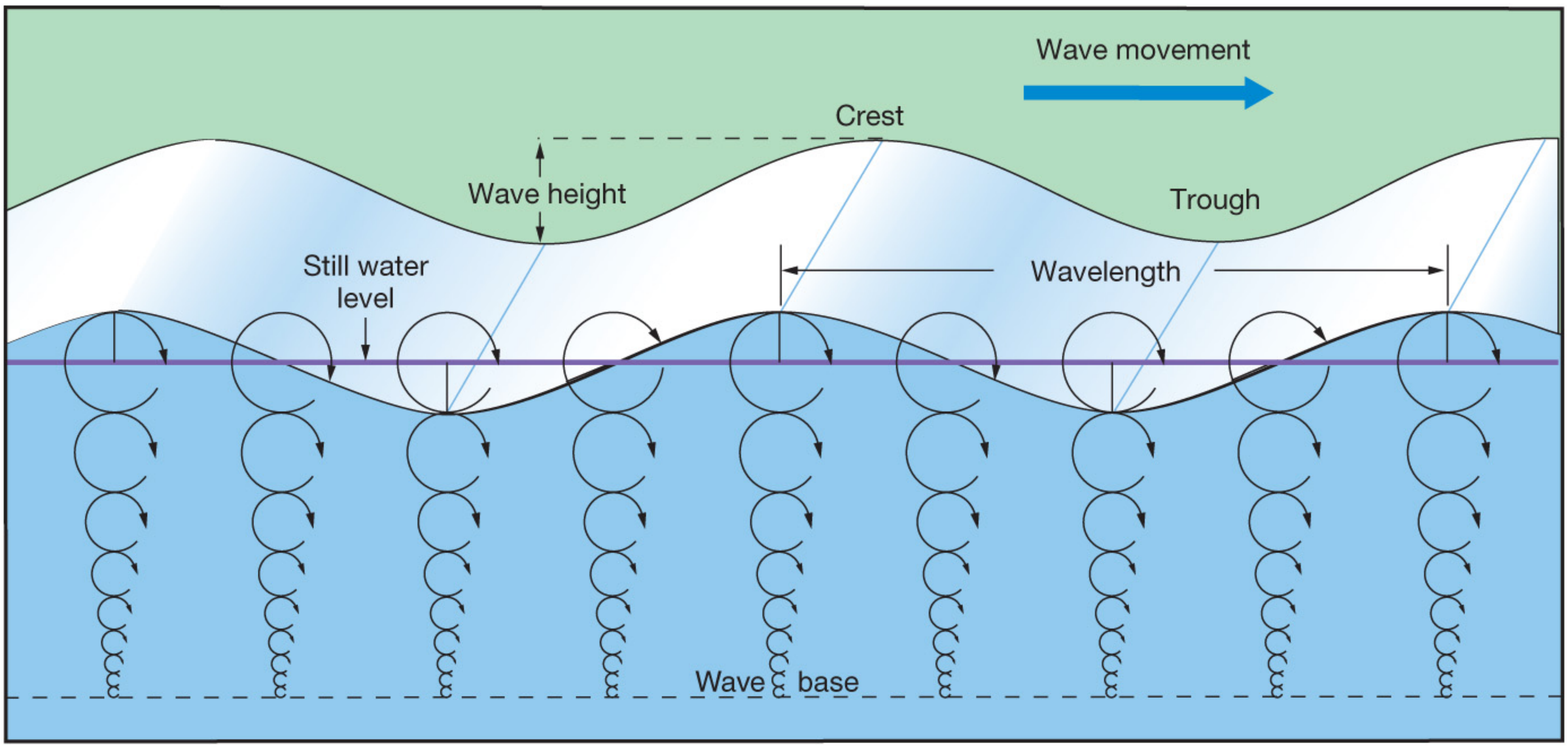
(3) ORBITAL WAVE
Particles (color) move in orbital path. These waves transmit energy along interface between two fluids of different density (liquids and/or gases).

Longitudinal Waves and Transverse Waves

- Longitudinal Waves are those where particles vibrate in the same direction the wave is travelling
  - like pulling and letting a spring go, or clapping
  - energy is transmitted through all states of matter: solid, liquid, and gas
- Transverse Waves are those where particles vibrate perpendicularly to the direction of the travelling wave
  - like a rope tied to a knob on a door and made to oscillate up and down
  - energy is transmitted only through solids
- Longitudinal and Transverse Waves are considered Body Waves
  - they transfer energy through a body of matter
- Ocean Waves instead are considered Surface Waves
  - energy is transferred along the interface between two fluids
  - movement involves components that are both longitudinal and transverse, so particles move in circular orbits
  - thus, waves at the ocean surface are Orbital Waves (or Interface Waves)

8.2 – What Characteristics Do Waves Possess?

Crest, Trough, Wave Height (H), Wavelength (L), Still Water Level

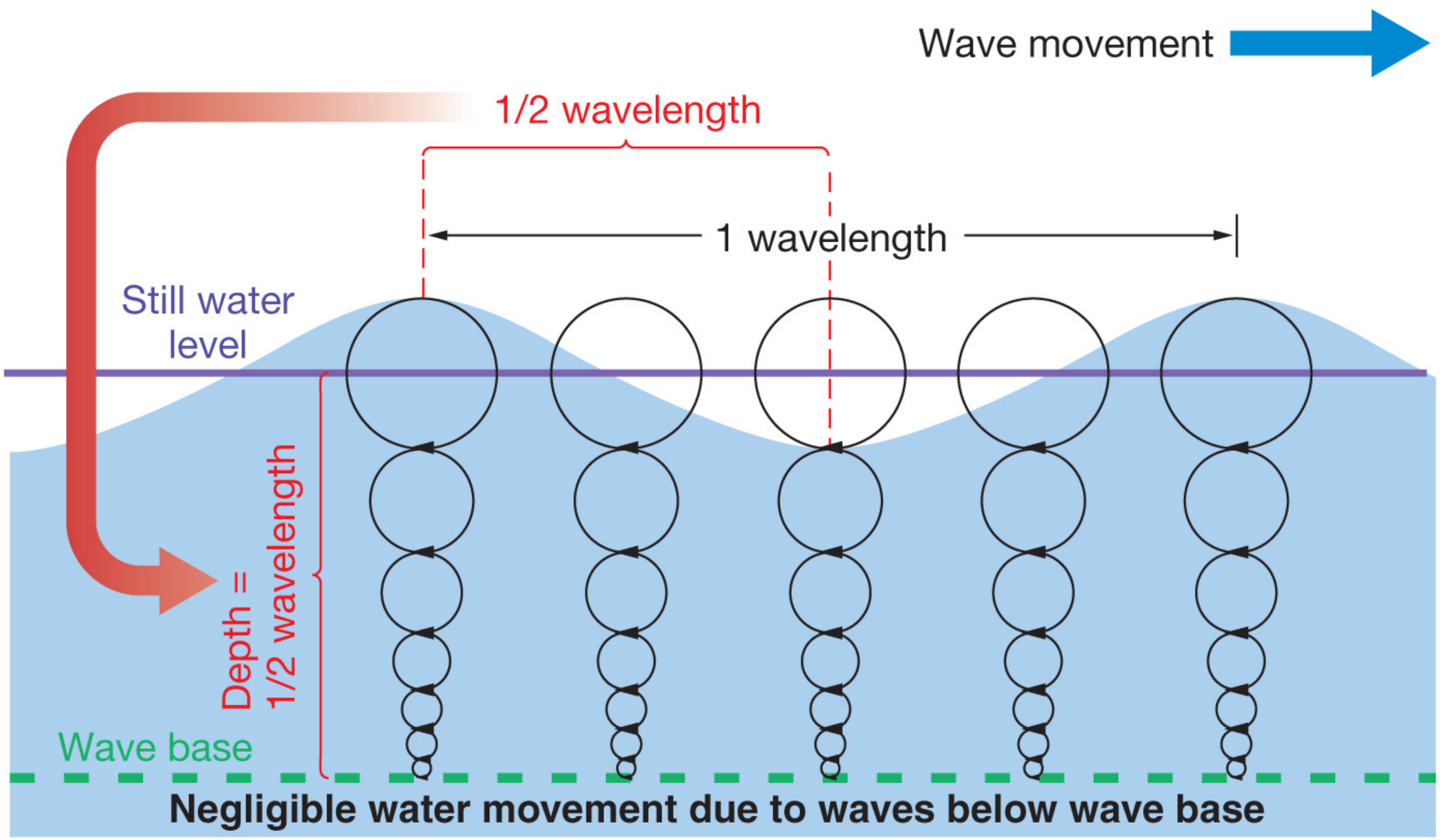


(a) Wave characteristics

Orbital Wave Characteristics

- Wave steepness = H/L
  - If wave steepness > $^1/_7$, wave breaks
- Wave period (T) = time that it takes for one wavelength to pass a fixed point
- Wave frequency = inverse of period or 1/T: number of wave crests passing a fixed location per unit of time

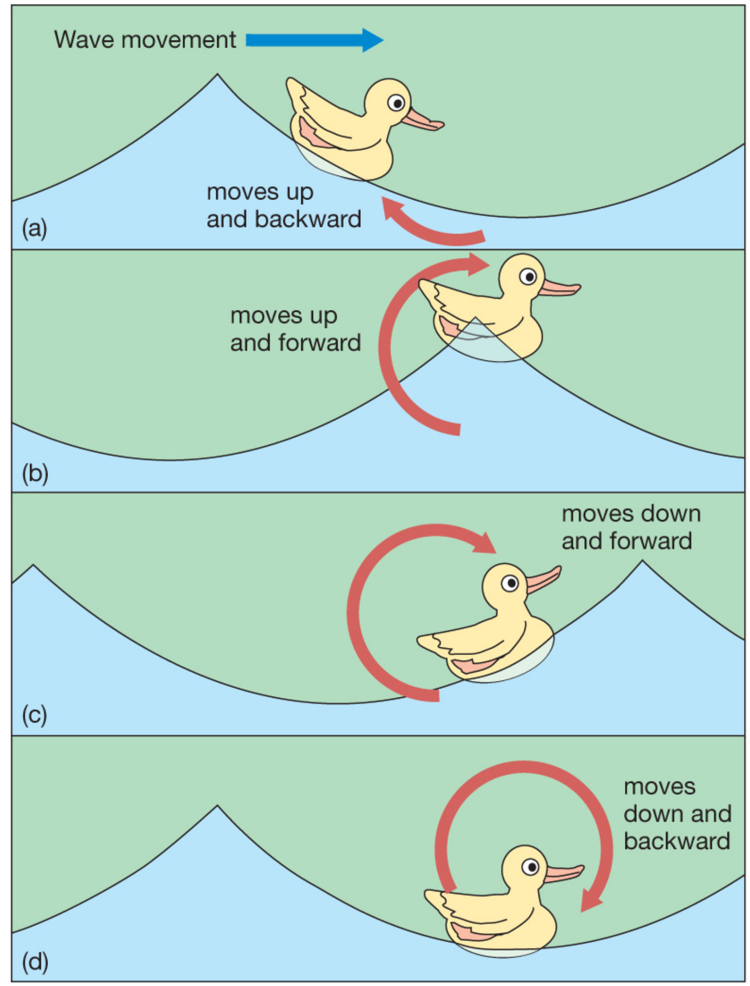
- the Diameter of orbital motion decreases with depth
- Wave base = ½ L
- There is hardly any motion below wave base that is caused by wave activity



(b) Calculation of wave base

Circular Orbital Motion

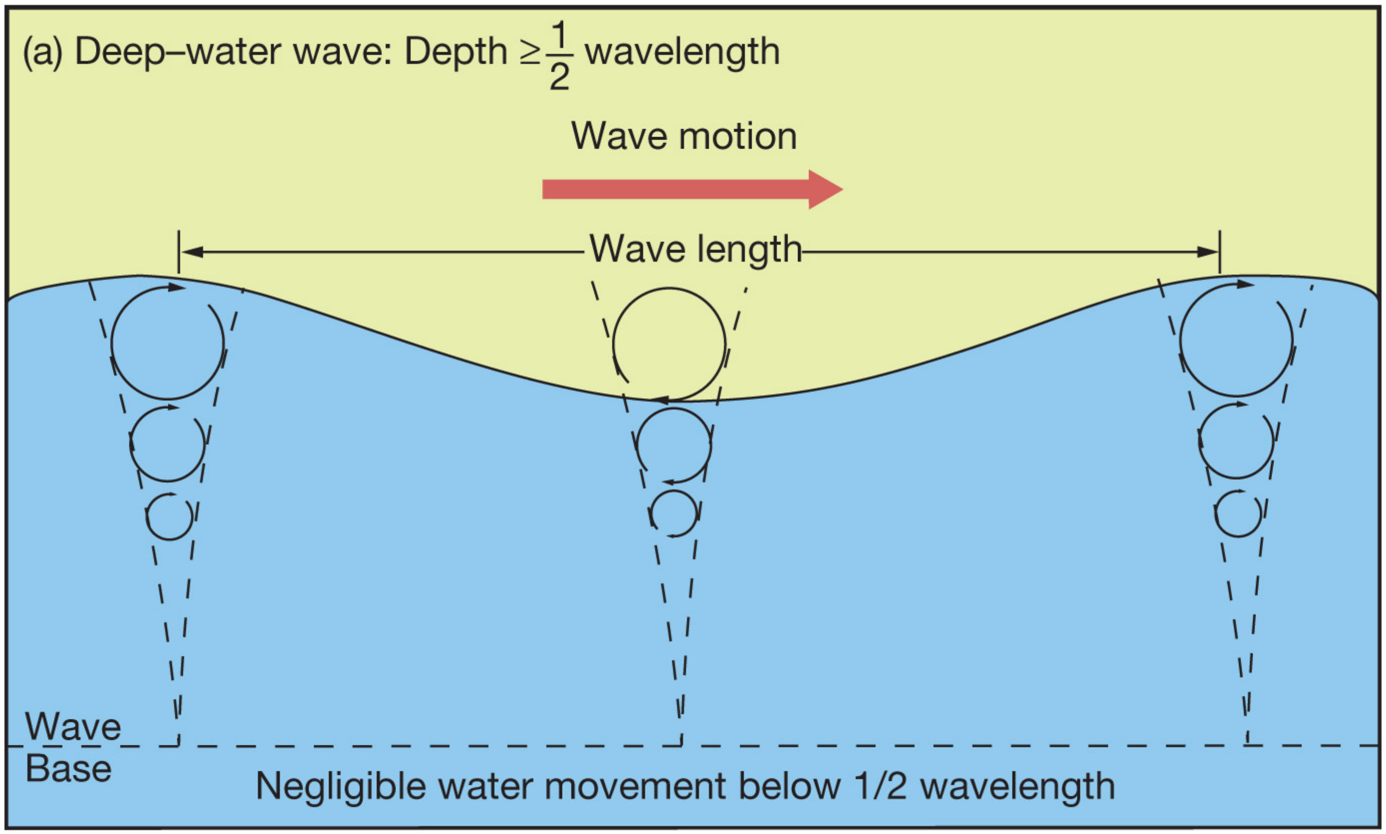
- During orbital motion, wave particles move in a circle
- There is no net transportation of water in the direction of the wave*
- The circle diameter is equal to the wave height at the surface, and it decreases to zero at a depth = ½ WL (measured from still water level)



*The circular orbit does not quite return the floating object to its original position because the half of the orbit accomplished in the trough is slower than the crest half of he orbit.
This results in a slight forward movement (net mass transport), which is called *wave drift*

Deep-Water Waves

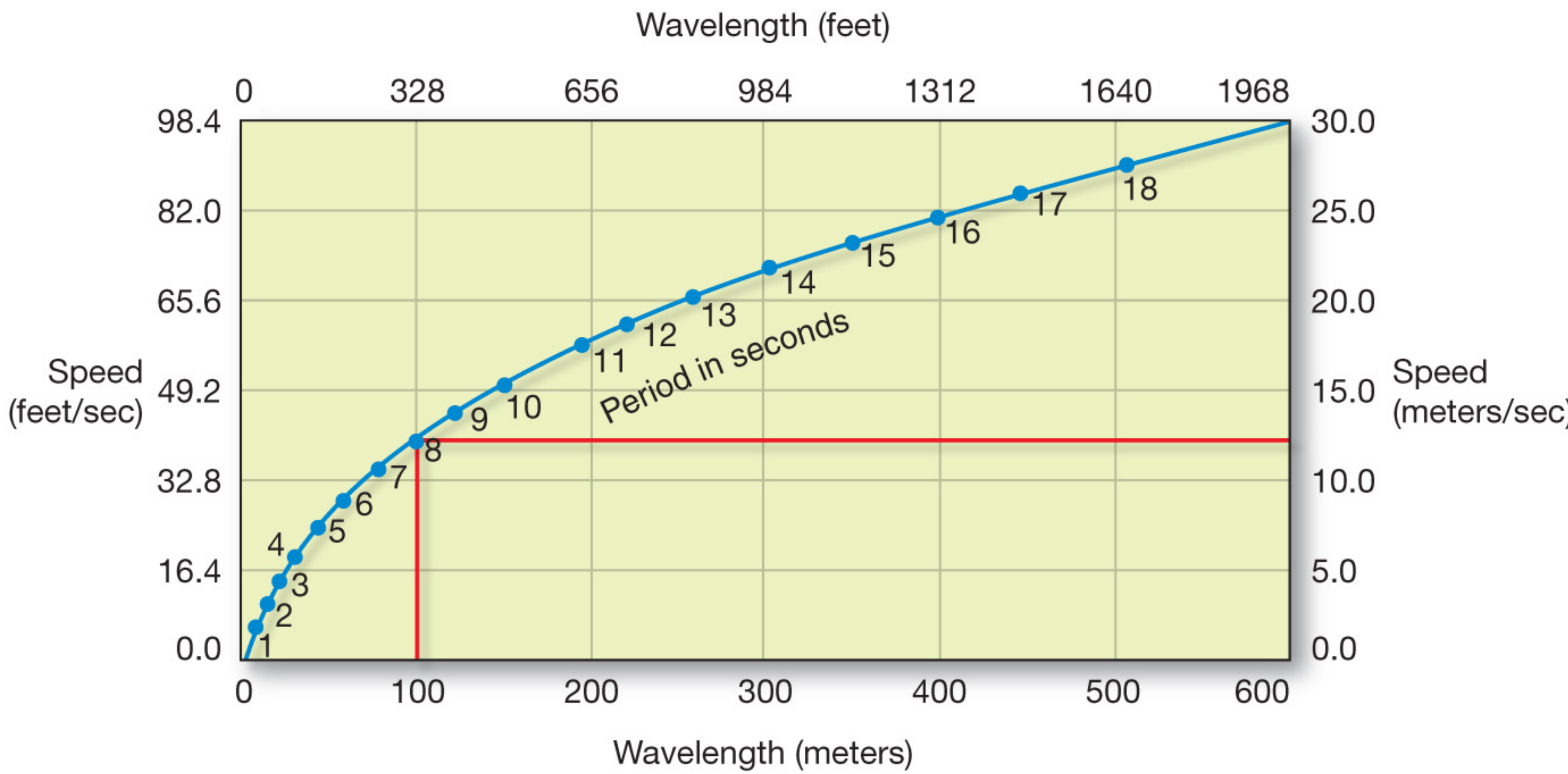
- Water depth is greater than wave base ($\geq$½L)
- Wave speed = celerity (C)
- C = WL/T



Speed of Deep Water Waves

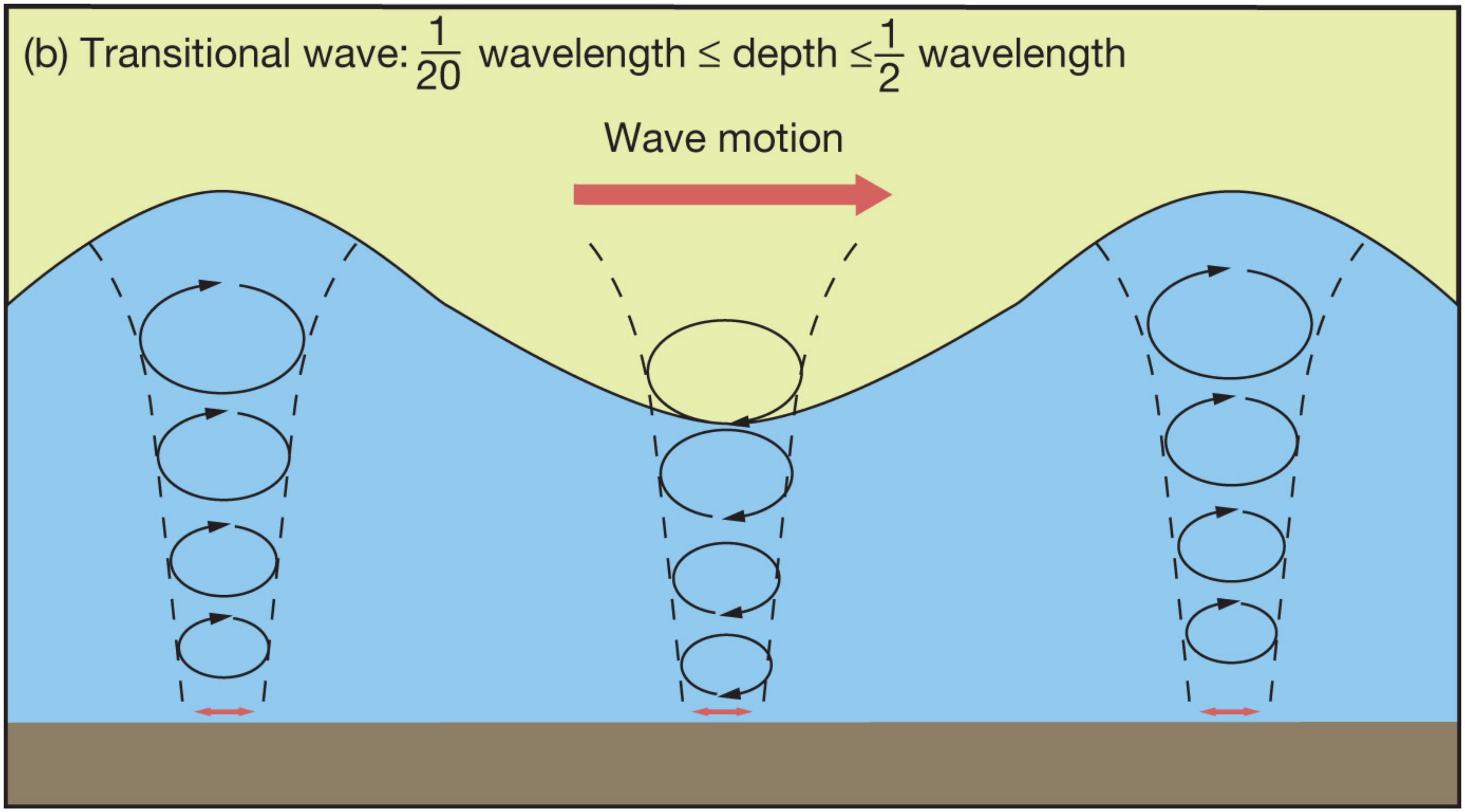
The speed of progressive waves, in the case of deep-water waves, is dependent upon wavelength and other variables that remain constant. Replacing the constants with numbers, we have that Celerity (in m/s) = $1.25\sqrt{L} = 1.56T$

So, we can build a curve that relates the three variables (wavelength, period, speed)



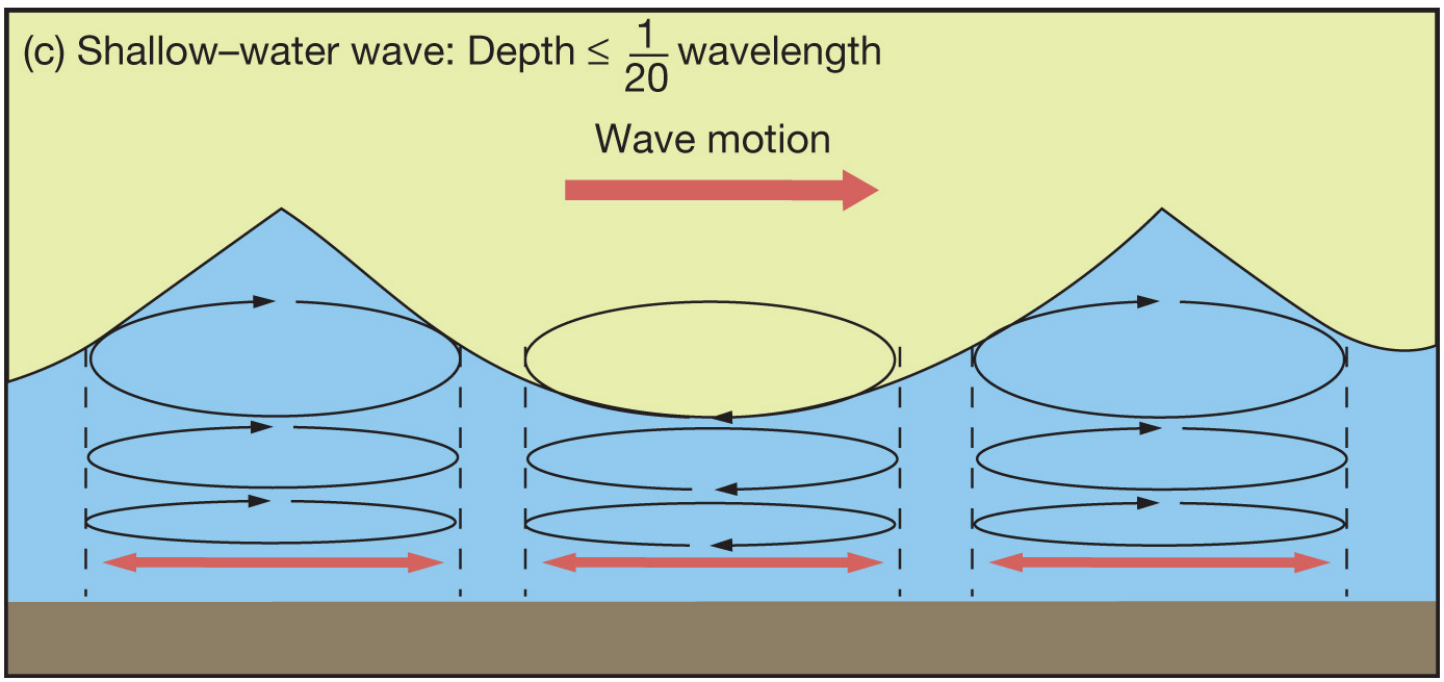
Transitional Waves

- Characteristics of both deep- and shallow-water waves
- Celerity depends on both water depth and wavelength



Shallow-Water Waves

- Shallow water waves occur if water depth is $\leq$ 1/20L
- These waves have flattened orbital motion and are said to *"feel the bottom"*
- C is influenced only by gravitational acceleration (g) and water depth (d)
- C = 3.13 √d(m): as a consequence, the deeper the water, the faster the wave
- Tides, and tsunamis can be seen as shallow water waves



8.3 – How Do Wind-Generated Waves Develop?

- Most ocean waves are generated by the wind
- A wind-generated wave
  - forms in a windy area
  - travels across the ocean without the need of further wind action
  - it eventually breaks and releases its energy
    - in the open ocean
    - against the shore

Wind-Generated Wave Development

- Capillary waves (ripples)
  - Wind generates stress on sea surface
  - WL < 1.74 cm
  - round crests, V-shaped troughs

Gravity waves

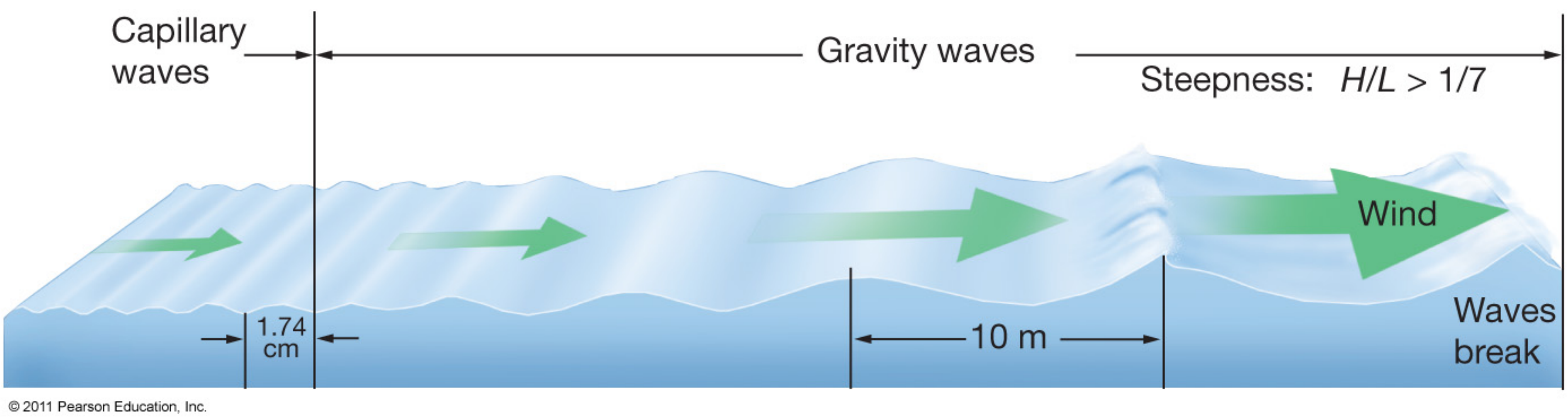
Increasing wave energy

First wavelength increases, then wave height, finally developing

Trochoidal waveforms

Furtherly Increased energy

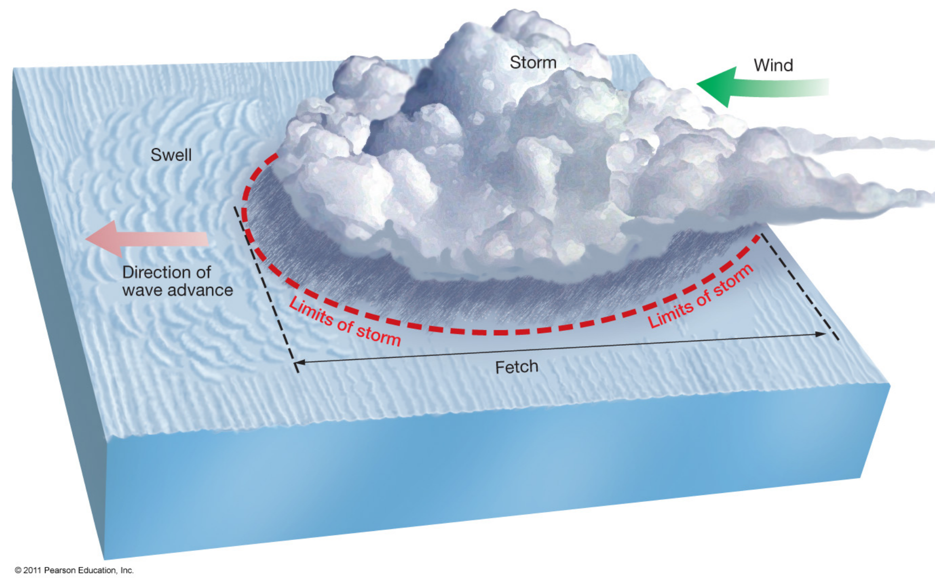
Round troughs, pointed (V-shaped) crests



Sea and Swell

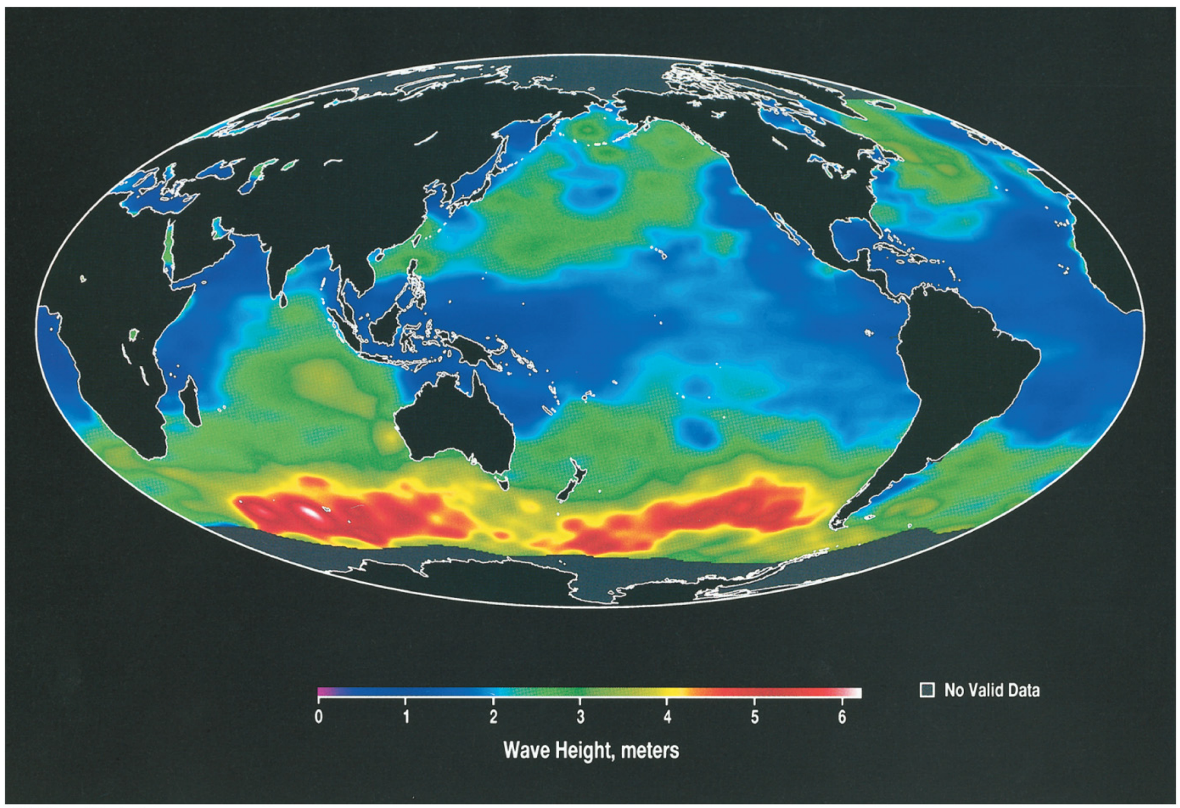
- Sea or sea area – where wind-driven waves are generated
- characterized by choppiness and waves moving in many directions

- Wind speed
- Wind duration
- Fetch
  – distance over which wind blows



Wave Height

- Directly related to wave energy
- Wave heights usually is less than 2 meters (6.6 feet)
- Breakers called whitecaps form when wave reaches critical steepness (1/7 WL)
- Beaufort Wind Scale describes appearance of sea surface



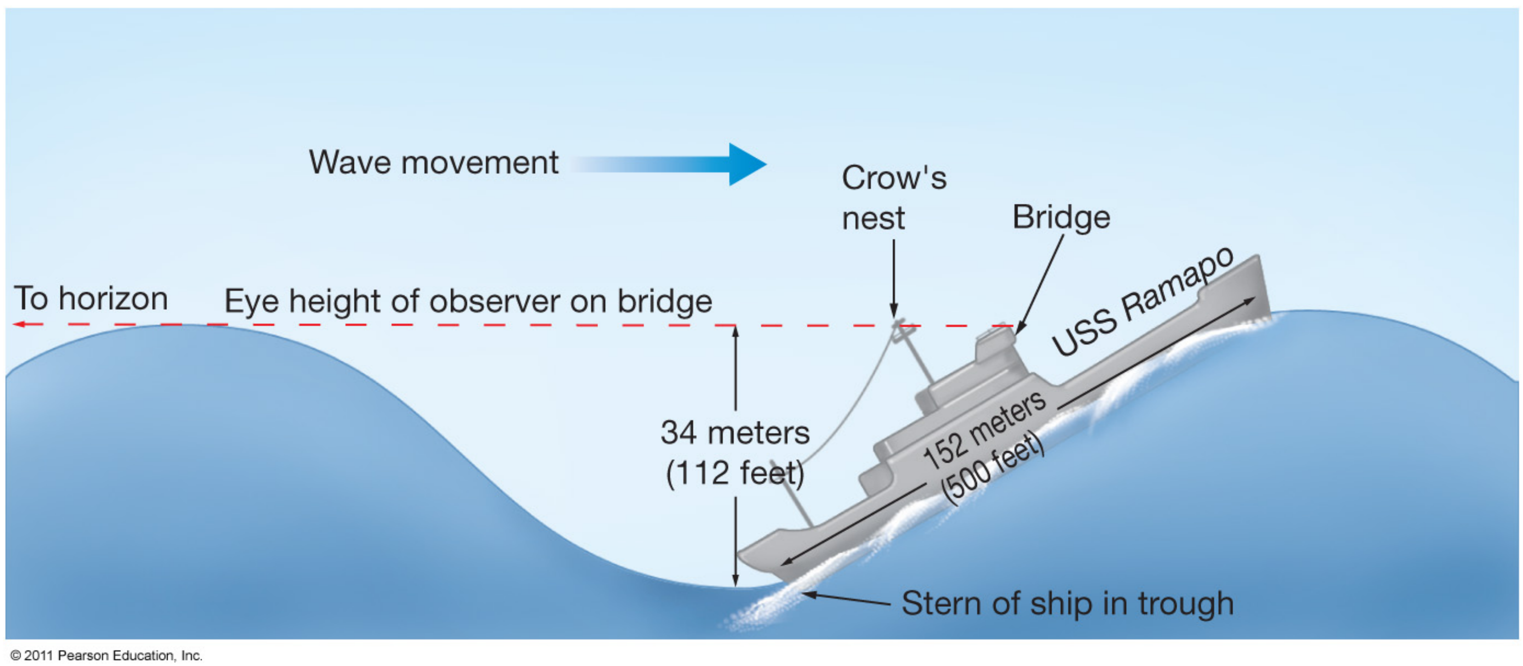
Beaufort Wind Scale

TABLE 8.1 BEAUFORT WIND SCALE AND THE STATE OF THE SEA

Beaufort number	Descriptive term	Wind speed (km/hr)	Wind speed (mi/hr)	Appearance of the sea
0	Calm	<1	<1	Like a mirror
1	Light air	1–5	1–3	Ripples with the appearance of scales, no foam crests
2	Light breeze	6–11	4–7	Small wavelets; crests of glassy appearance, no breaking
3	Gentle breeze	12–19	8–12	Large wavelets; crests begin to break, scattered whitecaps
4	Moderate breeze	20–28	13–18	Small waves, becoming longer; numerous whitecaps
5	Fresh breeze	29–38	19–24	Moderate waves, taking longer form; many whitecaps, some spray
6	Strong breeze	39–49	25–31	Large waves begin to form, whitecaps everywhere, more spray
7	Near gale	50–61	32–38	Sea heaps up and white foam from breaking waves begins to be blown in streaks
8	Gale	62–74	39–46	Moderately high waves of greater length, edges of crests begin to break into spindrift, foam is blown in well-marked streaks
9	Strong gale	75–88	47–54	High waves, dense streaks of foam and sea begins to roll, spray may affect visibility
10	Storm	89–102	55–63	Very high waves with overhanging crests; foam is blown in dense white streaks, causing the sea to appear white; the rolling of the sea becomes heavy; visibility reduced
11	Violent storm	103–117	64–72	Exceptionally high waves (small and medium-sized ships might for a time be lost from view behind the waves), the sea is covered with white patches of foam, everywhere the edges of the wave crests are blown into froth, visibility further reduced
12	Hurricane	118+	73+	The air is filled with foam and spray, sea completely white with driving spray, visibility greatly reduced

Maximum Wave Height

- USS Ramapo (1933): 152-meters (500 feet) long ship caught in Pacific typhoon
- Waves 34 meters (112 feet) high



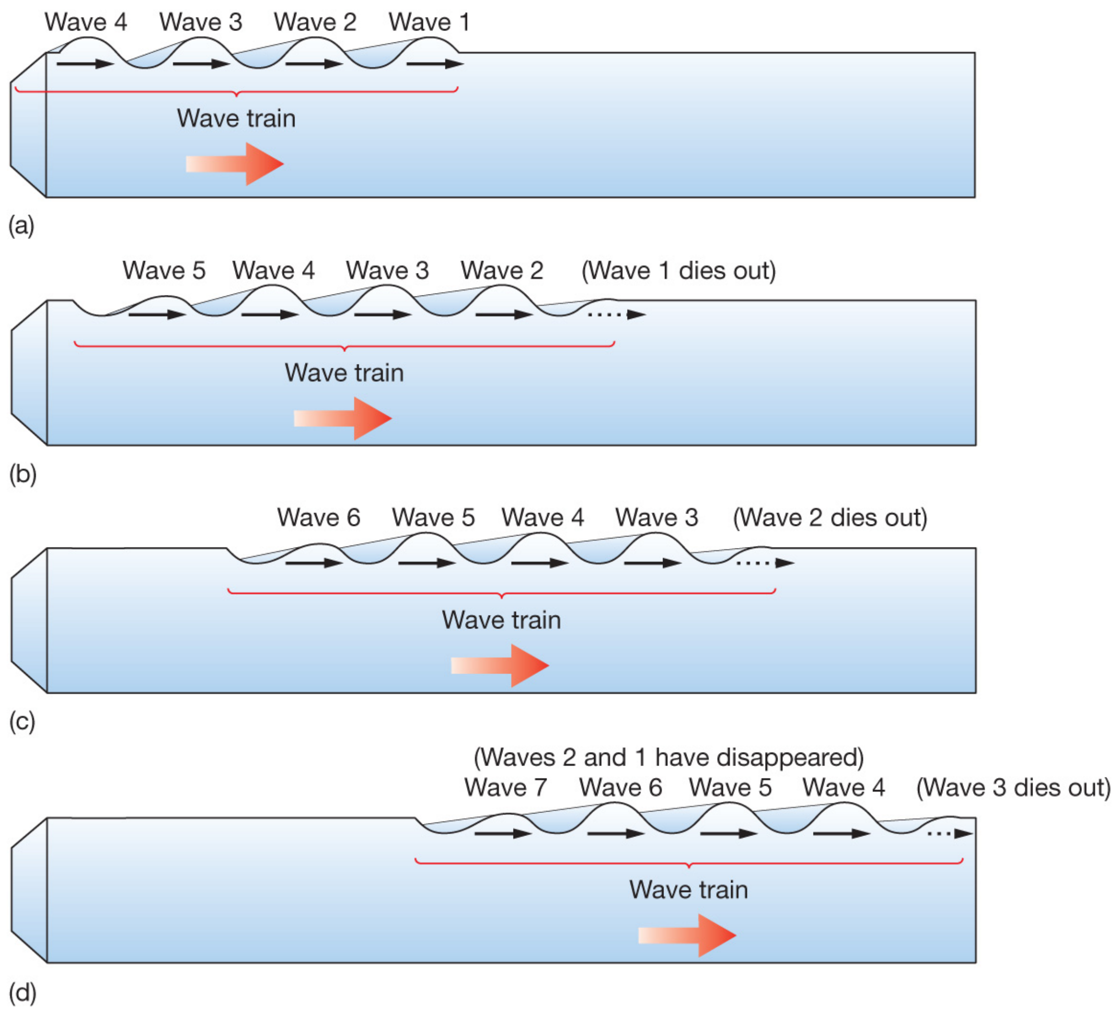
Wave Energy

- Fully developed sea
  - Maximum wave height, wavelength for particular fetch, speed, and duration of winds at equilibrium conditions
  - Waves cannot grow any further because of the loss of energy when they break as whitecaps
- Swell
  - Uniform, symmetrical waves that travel outward from storm area (at that point, faster than wind)
  - Long crests
  - Transport energy long distances

Swells

- Longer wavelength waves travel faster and outdistance other waves
  - Wave train – a group of waves with similar characteristics
  - Wave dispersion – sorting of waves by wavelengths
- Wave train speed is ½ speed of individual wave

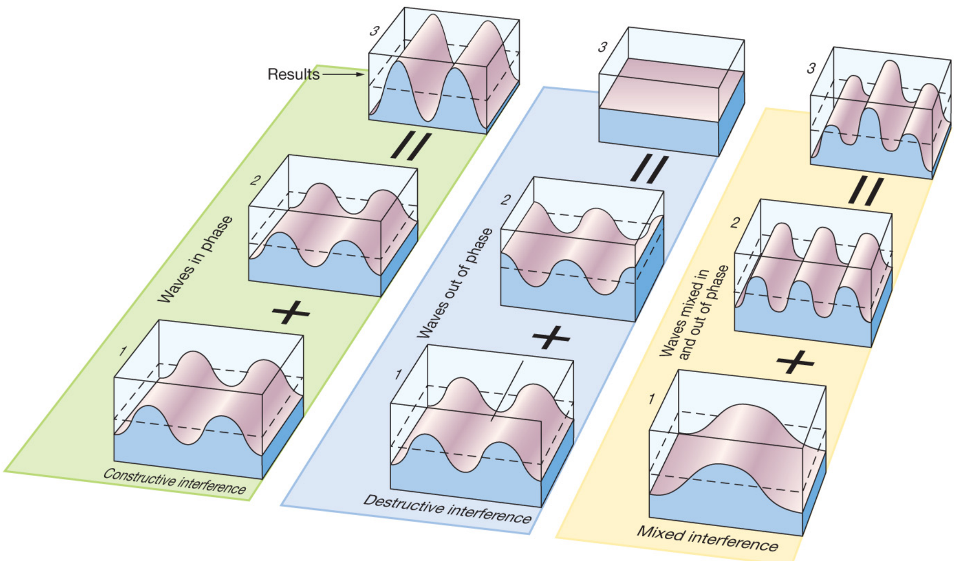
Wave Train Movement

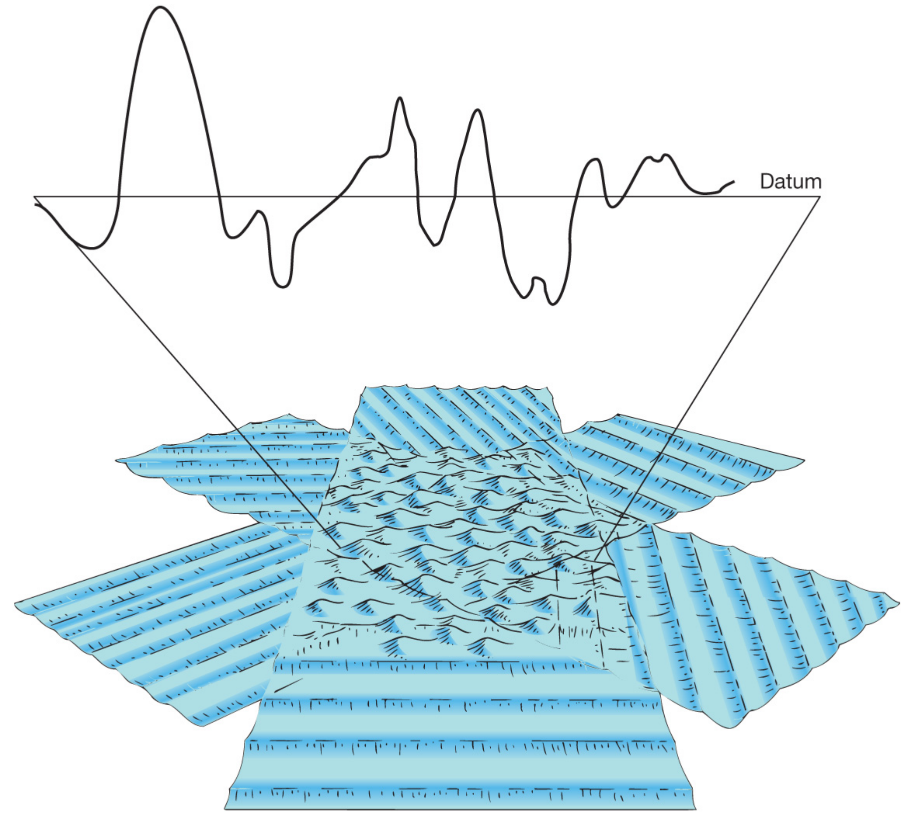


Wave Interference Patterns

- Collision of two or more wave systems
- Constructive interference
  - In-phase wave trains with about the same wavelengths
- Destructive interference
  - Out-of-phase wave trains with about the same wavelengths
- Mixed interference
  - Two swells with different wavelengths and different wave heights

Wave Interference Patterns





Rogue Waves

- Massive, solitary, spontaneous ocean waves that can reach enormous heights and often occur at times when normal ocean waves are not unusually large
- Statistically they are very rare but on average there are more than 10 at any time in the ocean
- Special ocean conditions are necessary for their formation
- In general, constructive interference is necessary, but scientists are still not exactly sure about what causes these interferences

8.4 – How Do Waves Change in the Surf Zone?

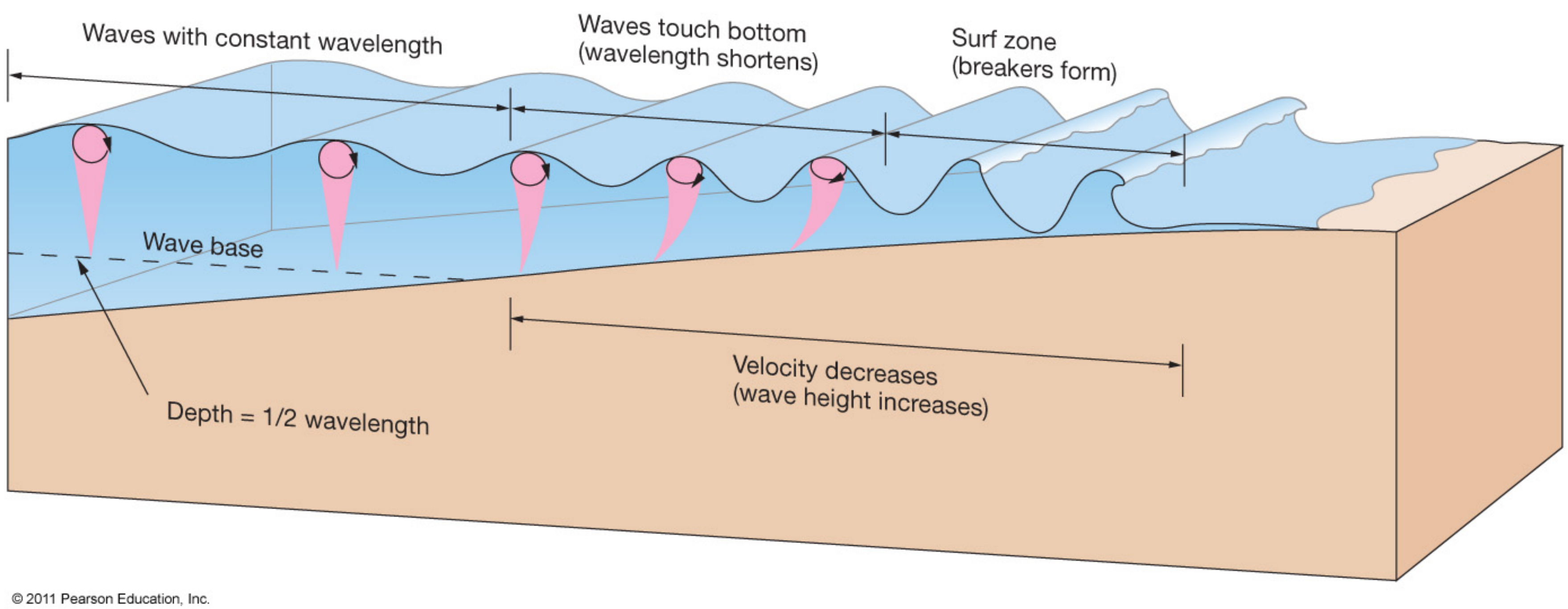
- Waves release their energy near shore, in what is called the surf zone
- Waves travel in shoaling waters, eventually encountering depths of less than ½ their wavelength, thus becoming transitional waves
- Any underwater obstacle would cause a wave to behave like this: if waves break (not randomly), then there are shallow waters

Waves breaking at a distance from the coast because of the presence of a coral reef barrier
Lahaina, Maui, Hawai'I

Physical Changes as Waves Approach Shore

- As a deep-water wave becomes a shallow-water wave:
  - Wave speed decreases
  - Wavelength decreases
  - Wave height increases
  - Wave steepness (height/wavelength) increases
  - When steepness $\geq$ $^{1}/_{7}$, wave breaks

Waves Approaching Shore



Breakers in the Surf Zone

- Surf as swell from distant storms
  - Waves break close to shore
  - Uniform breakers
- Surf generated by local winds
  - Choppy, high energy, unstable water
- Water depth < $\frac{1}{20}$ wavelength, waves act as shallow-water waves
  - Wave particles “feel” sea floor

Types of Breakers:

spilling, plunging, surging

Spilling Breakers

- Gently sloping sea floor
- Wave energy expended over longer distance
- Water slides down front slope of wave

(a)

Plunging Breakers

- Moderately steep sea floor
- Wave energy expended over shorter distance
- Best for board surfers
- Curling wave crest

(b)

Surging Breakers

- Steepest sea floor
- Energy spread over shortest distance
- Best for body surfing
- Waves break on the shore

(c)

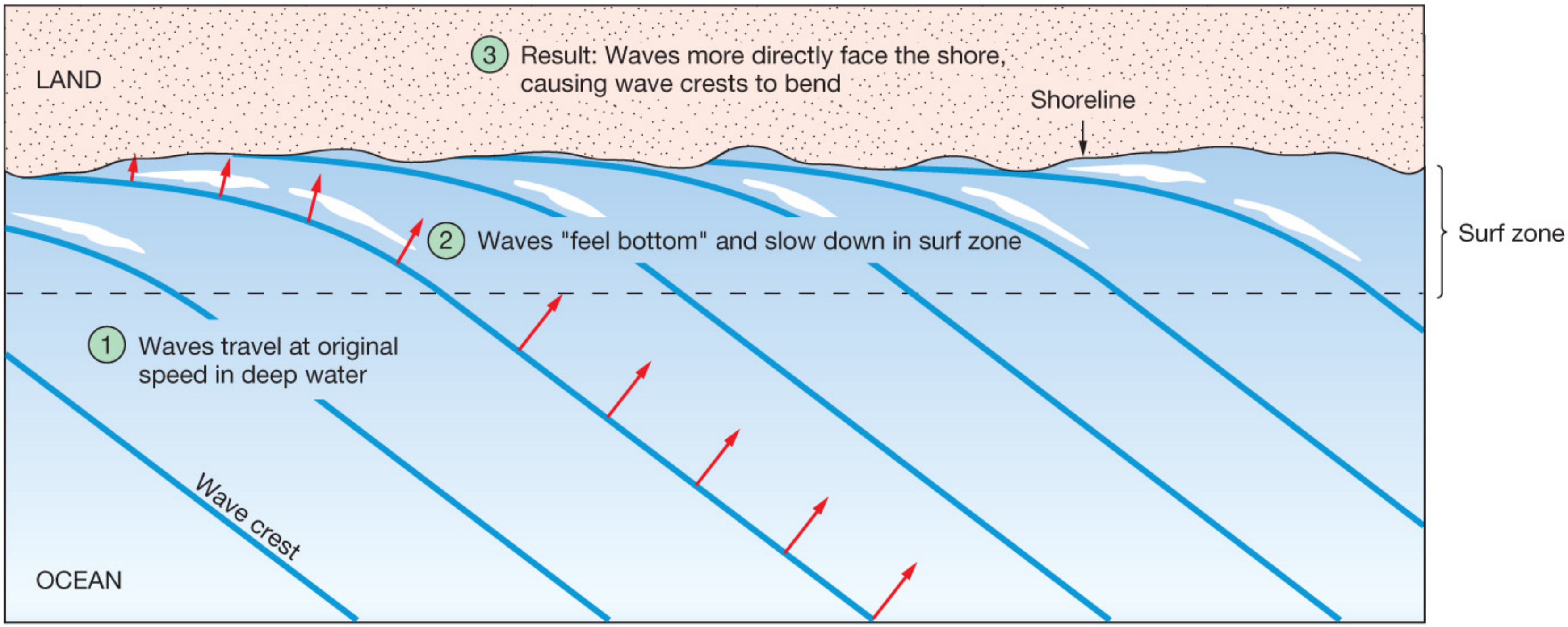
Surfing

- Like riding a gravity-operated water sled
- Balance of gravity and buoyancy
- Skilled surfers position board on wave front
  - Can achieve speeds up to 40 km/hour (25 miles/hour)

Wave Refraction

- Waves rarely approach shore at a perfect 90 degree angle.
- As waves approach shore, they bend so wave crests are nearly parallel to shore.
- Wave speed is proportional to the depth of water (shallow-water wave).
- Different segments of the wave crest travel at different speeds.

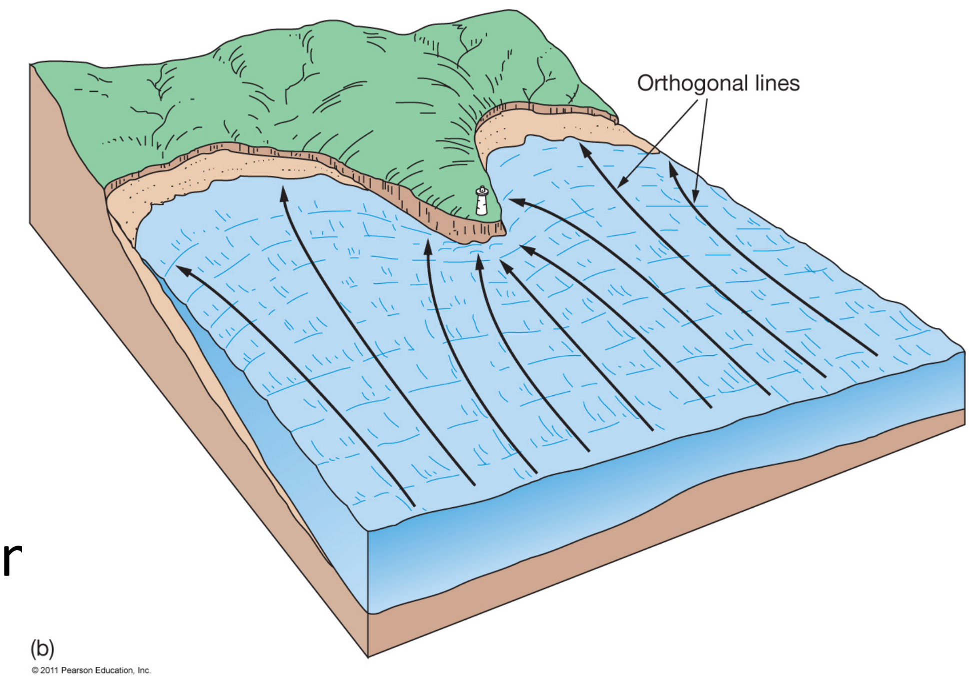
Wave Refraction



(a)

Wave Refraction

- Wave energy unevenly distributed on shore
- Orthogonal lines or *wave rays* – drawn perpendicular to wave crests
  - More energy released on headlands
  - Energy more dissipated in bays



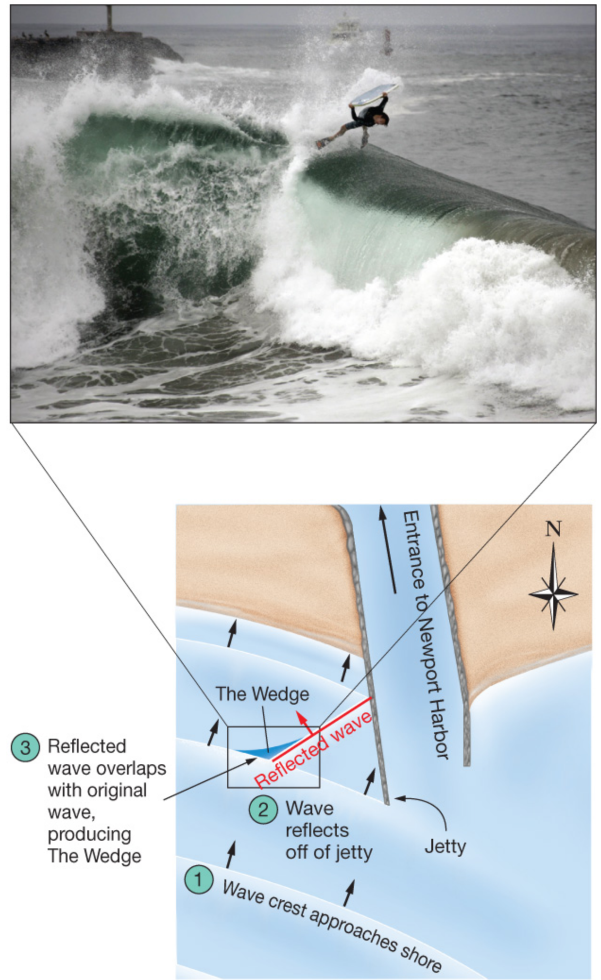
Wave Refraction

- Gradually erodes headlands
- Sediment accumulates in bays

(c)

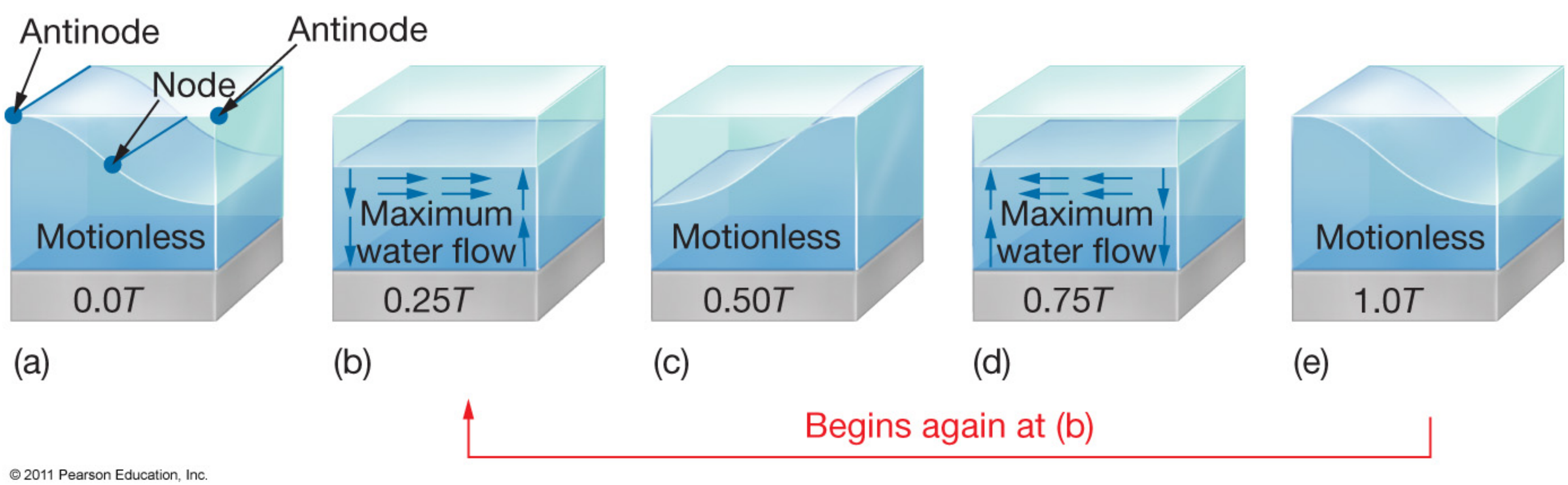
Wave Reflection

- Waves and wave energy bounced back from barrier
- Reflected wave can interfere with next incoming wave
- With constructive interference, can create dangerous plunging breakers



Standing Waves

- Two waves with same wavelength moving in opposite directions
- Water particles move vertically and horizontally
- Water sloshes back and forth



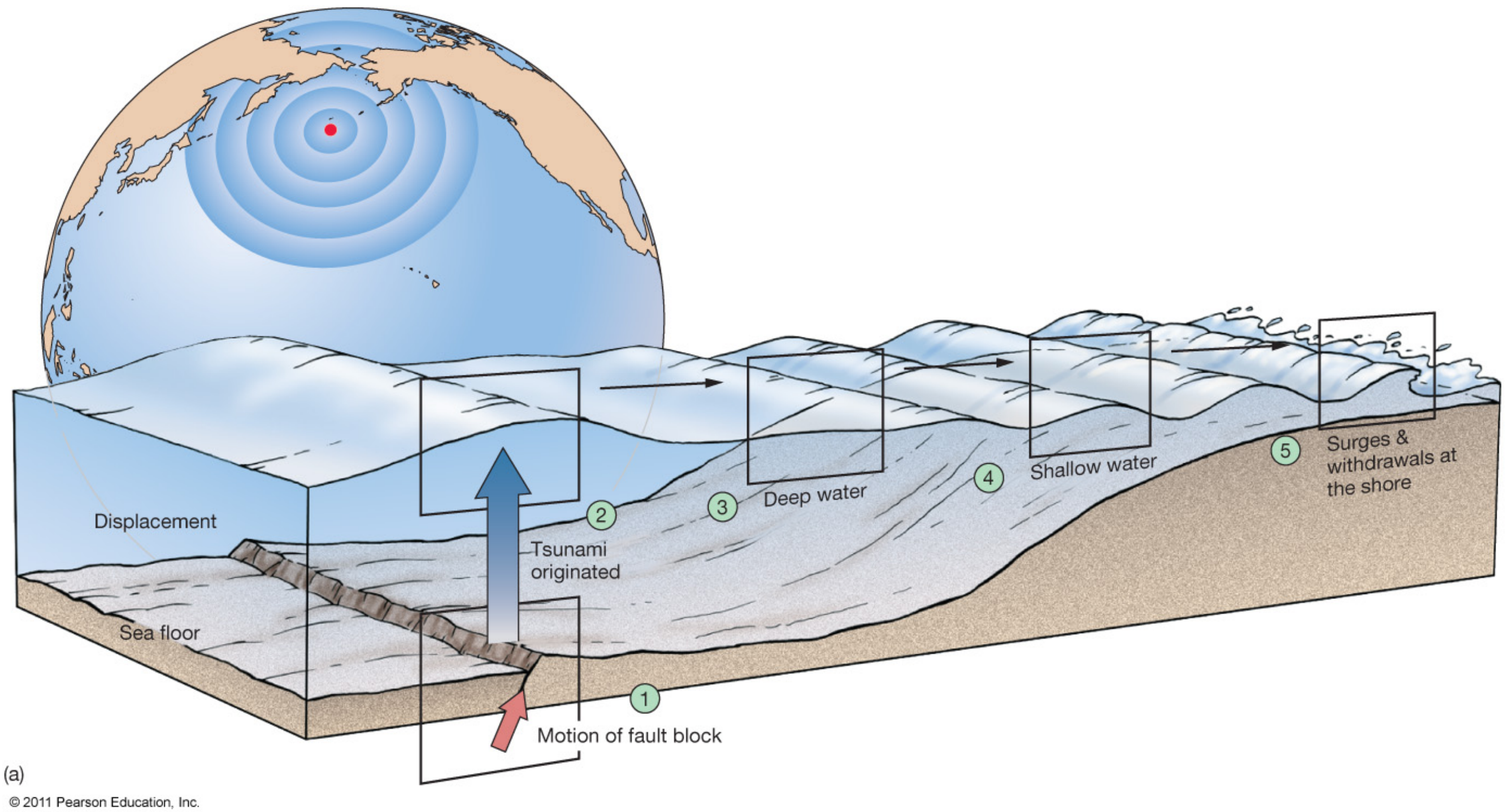
Tsunami

- Seismic sea waves
- Originate from sudden sea floor topography changes
  - Earthquakes – *most common cause*
  - Underwater landslides
  - Underwater volcano collapse
  - Underwater volcanic eruption
  - Meteorite impact – splash waves

Tsunami Characteristics

- Long wavelengths (> 200 km or 125 miles)
- Behaves as a shallow-water wave
  - Encompasses entire water column, regardless of ocean depth
  - Can pass undetected under boats in open ocean
- Speed proportional to water depth
  - Very fast in open ocean

Tsunami


Displacement
Sea floor
Tsunami originated
Motion of fault block
1
2
3
Deep water
4
Shallow water
5
Surges & withdrawals at the shore
(a)
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Tsunami Destruction

- Sea level can rise up to 40 meters (131 feet) when a tsunami reaches shore.

(b)

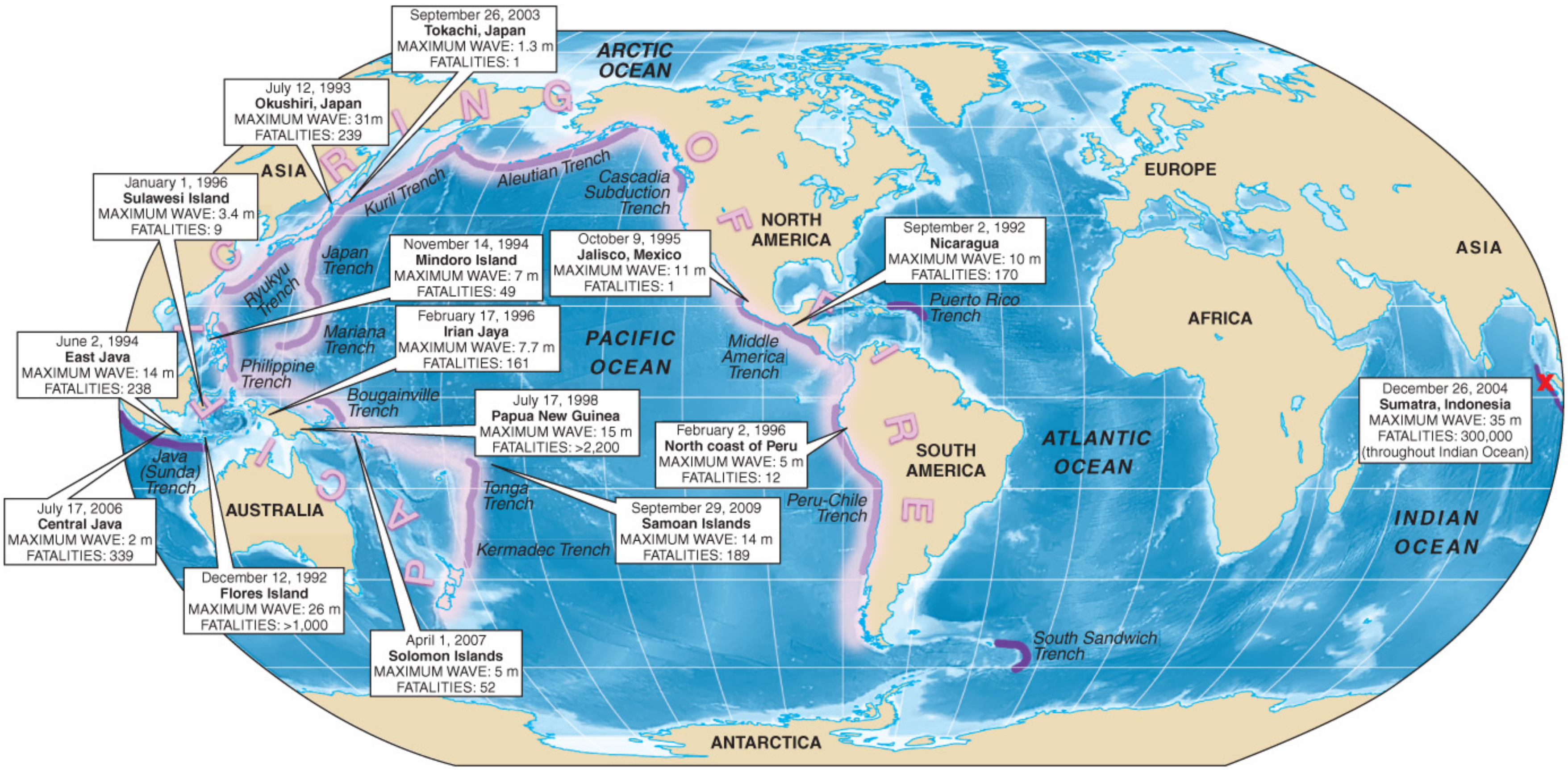
Tsunami

- Most occur in Pacific Ocean
  - More earthquakes and volcanic eruptions
- Damaging to coastal areas
- Loss of human lives

Historical Tsunami

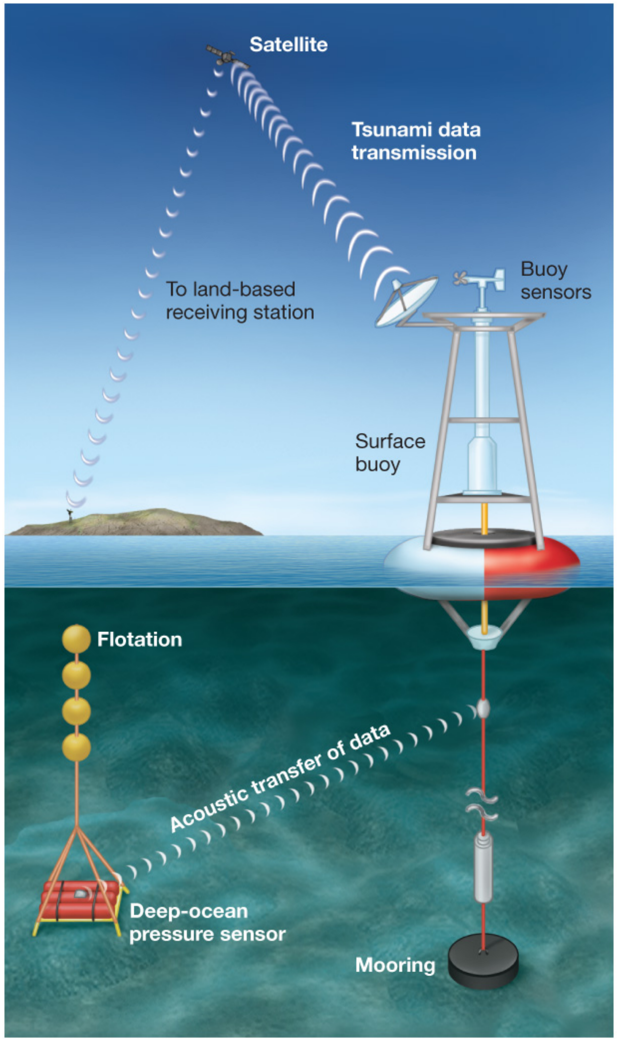
- Krakatau – 1883
  - Indonesian volcanic eruption
- Scotch Cap, Alaska/Hilo, Hawaii – 1946
  - Magnitude 7.3 earthquake in Aleutian Trench
- Papua New Guinea – 1998
  - Pacific Ring of Fire magnitude 7.1 earthquake
- Indian Ocean – 2004
  - Magnitude 9.3 earthquake off coast of Sumatra

Historical LargeTsunami



Tsunami Warning System

- Pacific Tsunami Warning Center (PTWC) – Honolulu, HI
  - Uses seismic wave recordings to forecast tsunami
- Deep Ocean Assessment and Reporting of Tsunami (DART)
  - System of buoys
  - Detects pulse of tsunami passing



Tsunami Watches and Warnings

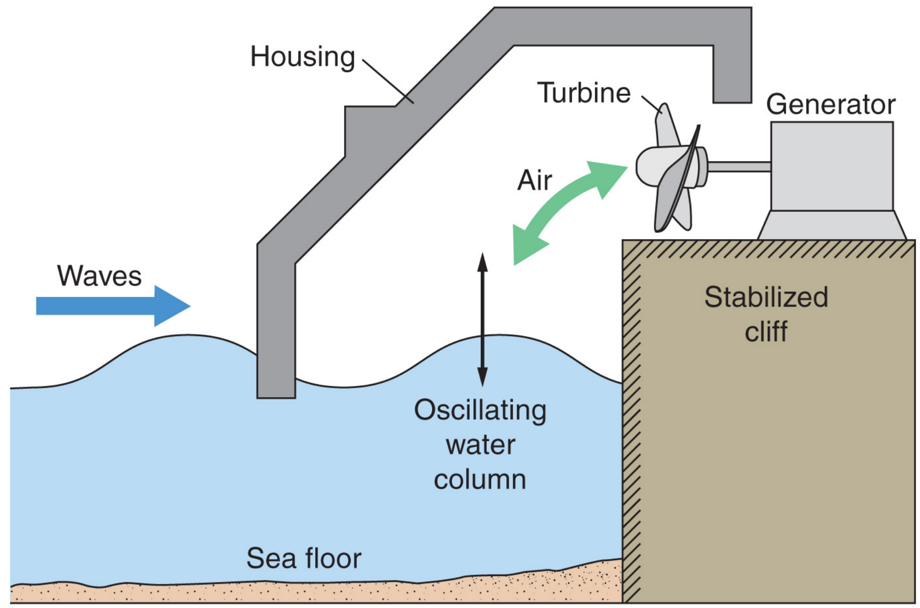
- Tsunami Watch – issued when potential for tsunami exists
- Tsunami Warning – unusual wave activity verified
  - Evacuate people
  - Move ships from harbors

Waves as Source of Energy

- Lots of energy associated with waves
- Mostly with large storm waves
  - How to protect power plants
  - How to produce power consistently
- Environmental issues
  - Building power plants close to shore
  - Interfering with life and sediment movement

Wave Power Plant

(a)



(b)

Wave Power Plants

- First commercial wave power plant began operating in 2000
- LIMPET 500 (Land Installed Marine Powered Energy Transformer)
  - Coast of Scotland
  - 500 kilowatts of power under peak operating capacity

Wave Farms

- Portugal – 2008
  - Ocean Power Delivery
  - First wave farm
- About 50 wave power development projects globally

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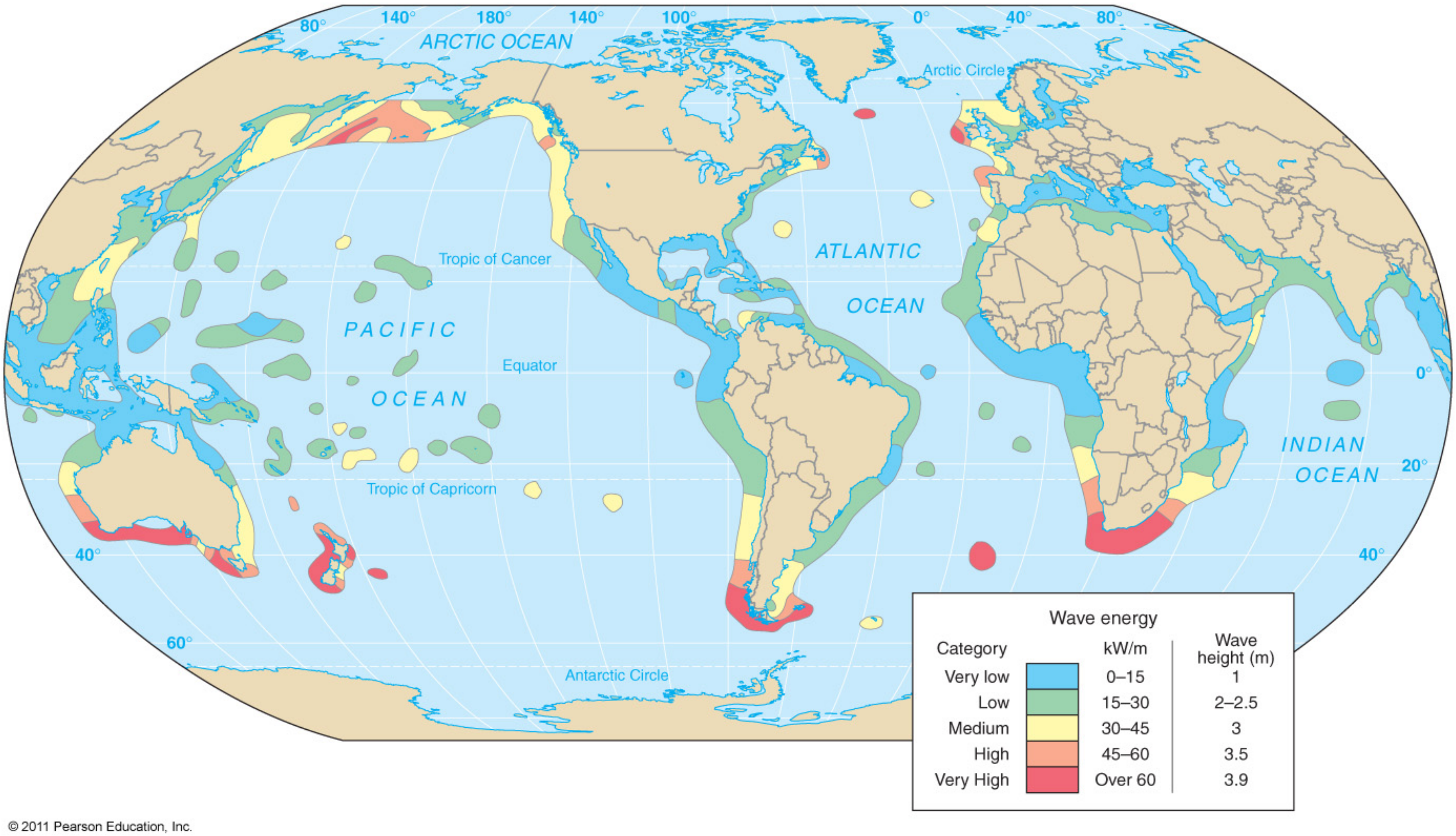
Global Wave Energy Resources



End of CHAPTER 8
Waves and Water Dynamics