

Racing Across the Ocean: Does Depth Set a Tsunami's Speed?

Learning target: I can use tide-gauge travel-time data to argue what controls a tsunami's speed, and use that claim to forecast when waves will reach a coast and how much warning people will have.

Claim, evidence, reasoning

About 45 min

Individual

MS-ESS3-2 · assesses

writing

data analysis

Standards connections

MS-ESS3-2 (assesses, analyzing tsunami travel data to forecast arrival times and warning time): Students analyze distances, travel times and wave heights from past tsunamis to establish that ocean depth sets speed, then forecast arrival times for two towns and explain what each forecast means for warnings and mitigation. This matches the clarification's emphasis on hazards whose timing can be forecast once a triggering event is detected. The data are simulated.

Purpose: practice · **Time:** about 45 minutes · **Format:** individual

Answers with reasoning

The question

A tsunami warning center keeps records from tide gauges, instruments that measure sea level at harbors around an ocean. For past tsunamis from one undersea fault, scientists know where each tsunami started, how far the waves traveled to each gauge, how long they took, and how high the water rose. A new forecaster asks a simple question: what sets how fast a tsunami travels? One coworker says it is the size of the earthquake. Another says it is the depth of the ocean along the path. Your job is to decide from the data.

Background you can use — A tsunami moves the whole column of water from the seafloor to the surface. Its crests are often more than 100 km apart, which is far longer than the ocean is deep (about 4 km on average). Ordinary wind waves have crests only meters apart and move only water near the surface.

Dataset 1: One tsunami reaching six tide gauges (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Tide gauge	Path mostly over	Average depth along path (m)	Distance from source (km)	Travel time to first wave (h)
A	Deepest open-ocean basin	5000	4000	5.0
B	Open ocean	4000	2850	4.0
C	Ocean with undersea ridges	3000	1850	3.0
D	Edge of the basin and continental slope	1000	700	2.0
E	Wide continental shelf	200	320	2.0
F	Shallow inland sea	50	120	1.5

Simulated data for teaching. Distances and times are realistic for a large ocean basin; average depth is the typical depth along each path.

Dataset 2: Two different earthquakes on the same fault, measured at gauge B (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Earthquake	Magnitude	Travel time to gauge B (h)	Highest water rise at gauge B (m)
Earthquake 1	7.7	4.0	0.2
Earthquake 2	8.9	4.0	1.8

Simulated data for teaching. Both tsunamis followed the same 2,850 km path averaging 4,000 m deep.

Warm-up: organize the evidence

1. Calculate the average speed to each gauge: speed = distance ÷ time. Round to the nearest whole number and show one calculation below the table.

Answer: A: 5,000 m, $4,000 \div 5.0 = 800$ km/h. B: 4,000 m, $2,850 \div 4.0 = 713$ km/h (712.5). C: 3,000 m, $1,850 \div 3.0 = 617$ km/h. D: 1,000 m, $700 \div 2.0 = 350$ km/h. E: 200 m, $320 \div 2.0 = 160$ km/h. F: 50 m, $120 \div 1.5 = 80$ km/h.

Why: Speed is distance divided by time for each row. The simulated values were built to match the long-wave speed relationship.

Also acceptable: Accept 712 or 713 for B and 616 or 617 for C.

2. Describe the pattern between depth and speed in your table. Does each extra 1,000 m of depth add the same amount of speed? Use gauges A, C and D to check.

Answer: The deeper the water along the path, the faster the tsunami: speeds fall from 800 km/h over 5,000 m to only 80 km/h over 50 m. Each extra 1,000 m does not add the same speed: from D (1,000 m) to C (3,000 m) the speed rises by 267 km/h, about 133 km/h per 1,000 m, but from C to A (5,000 m) it rises by only 183 km/h, about 92 km/h per 1,000 m. The speed keeps rising with depth, but more slowly in deeper water.

Why: Speed increases with the square root of depth, so the gains shrink as depth grows. Students do not need the square root to see the pattern.

Also acceptable: Accept 'deeper means faster' with numbers for partial credit if the second question is not addressed.

- States that speed increases with depth
- Uses numbers from the table
- Notices that the increase per 1,000 m gets smaller in deeper water

3. Using Dataset 2, calculate the speed of each tsunami to gauge B. Then calculate how many times higher the water rose for Earthquake 2 than for Earthquake 1.

Answer: Both tsunamis: $2,850 \text{ km} \div 4.0 \text{ h} = 713 \text{ km/h}$ (712.5). Height: $1.8 \text{ m} \div 0.2 \text{ m} = 9$, so Earthquake 2's tsunami raised the water 9 times higher.

Why: Same path, same speed, very different heights: the earthquake's size changed the height but not the speed.

Also acceptable: Accept 712 or 713 km/h.

Your argument

Answer: Claim: The depth of the ocean along the path sets a tsunami's speed; the size of the earthquake does not change the speed, but a bigger earthquake makes a taller tsunami. Evidence: Over the 5,000 m path to gauge A the tsunami averaged 800 km/h, over the 1,000 m path to gauge D only 350 km/h, and over the 50 m path to gauge F only 80 km/h. A magnitude 7.7 and a magnitude 8.9 earthquake both sent tsunamis to gauge B in 4.0 hours (713 km/h), but the water rose 1.8 m for the bigger one and only 0.2 m for the smaller one, 9 times higher. Reasoning: A tsunami moves the whole column of water, and its crests are far longer than the ocean is deep, so the seafloor affects the entire wave; in shallower water the wave is held back and slows down, while in deep water it can travel faster. The earthquake's size decides how much water is lifted, which sets the height and energy of the wave, but once the wave is moving its speed depends on the depth it is traveling through. Because depth along every path is known from seafloor maps, a warning center that knows where and when an earthquake happened can calculate arrival times at every coast.

Why: This is the core relationship the chapter needs: speed depends on depth, height depends on the source and on shallowing near shore. See the rubric for scoring.

Also acceptable: A claim that 'both matter' earns partial credit only if the student correctly assigns depth to speed and magnitude to height.

- Claim names depth as the control on speed and separates speed from height
- At least three numeric pieces of evidence from both datasets
- Reasoning explains the whole-column, long-wave idea
- Reasoning explains why magnitude changes height, not speed
- Connects the claim to forecasting arrival times

Use your claim to forecast

4. A large earthquake strikes on this fault at 2:00 a.m. A harbor town lies 3,600 km away across open ocean averaging about 4,000 m deep. Use the speed you found for gauge B to forecast when the first wave should arrive. Show your calculation and give the arrival time to the nearest 5 minutes.

Answer: $3,600 \text{ km} \div 712.5 \text{ km/h} = 5.05 \text{ hours}$, about 5 hours and 3 minutes. 2:00 a.m. + 5 h 3 min $\approx$ 7:05 a.m. (to the nearest 5 minutes).

Why: Arrival time = distance $\div$ speed, added to the time of the earthquake. $0.05 \text{ h} \times 60 = 3 \text{ minutes}$.

Also acceptable: Accept 7:00 to 7:05 a.m. if a rounded speed of 700 to 720 km/h is used with the calculation shown.

5. A second town is only 120 km from the fault, across water averaging about 2,000 m deep. Use your table to estimate the tsunami's speed on that path, then estimate how many minutes the town would have before the first wave. Explain what that means for how the town must prepare **before** any earthquake happens.

Answer: At 2,000 m the speed should fall between gauge D (350 km/h at 1,000 m) and gauge C (617 km/h at 3,000 m), roughly 480 to 500 km/h. Time = $120 \text{ km} \div \text{about } 500 \text{ km/h} = 0.24 \text{ h}$, about 14 to 15 minutes. That is too little time for a distant warning center to detect, confirm and broadcast a warning and for everyone to hear it, so the town must prepare beforehand: mapped tsunami hazard zones, marked evacuation routes to high ground, signs, practice drills, and teaching residents that strong, long shaking near the coast is itself the warning to move to high ground. Buildings or hills reachable on foot within that time matter more than any siren.

Why: A near-source tsunami leaves only minutes, as northeastern Japan saw in 2011 and as California's North Coast would see from a Cascadia earthquake, so mitigation must be in place before the event.

Also acceptable: Accept a speed estimate from 450 to 520 km/h and times from 13 to 16 minutes.

- Estimates a speed between 350 and 617 km/h
- Calculates a time of roughly 12 to 20 minutes
- Explains that there is too little time for an official warning to do all the work
- Names at least two preparations made before the earthquake

6. The warning center can forecast tsunami arrival times very well, but it cannot forecast the date of the next tsunami. Explain why, using what starts a tsunami.

Answer: Most tsunamis are started by large undersea earthquakes, and no one can forecast the date of an earthquake. Once an earthquake happens, seismometers locate it within minutes and sea-level sensors confirm the waves, so the center can calculate arrival times from depth and distance. The forecast can begin only after the triggering event.

Why: This is the contrast in the PE's clarification: earthquakes strike without notice, while a tsunami's arrival can be forecast after the earthquake is detected.

Also acceptable: Accept answers that also mention landslides or eruptions as triggers that give little notice.

- Earthquakes (the usual trigger) cannot be predicted
- Arrival can be forecast once the earthquake and waves are detected

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
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Claim	Names ocean depth as what sets speed, states that earthquake size does not change speed, and states that bigger earthquakes make taller tsunamis.	Names depth as what sets speed and rules out earthquake size, but does not say what earthquake size changes.	Says both depth and earthquake size set speed, or names depth without addressing earthquake size.	Claims earthquake size sets speed, or no claim.
Evidence	Three or more accurate pieces of evidence with numbers, including a comparison across gauges and the two-earthquake comparison.	Three accurate pieces with numbers, but only one dataset is used.	One or two pieces, or evidence described without numbers.	Evidence missing, invented or contradicting the data.
Reasoning	Explains that the whole water column moves and the wave is much longer than the ocean is deep, so depth controls speed; explains that magnitude sets height, not speed; links the claim to forecasting arrival times.	Explains the depth idea and the magnitude idea, but does not connect to forecasting, or the scientific explanation is thin.	Restates the pattern without explaining why it happens.	No reasoning, or reasoning that contradicts the claim.
Forecasting (q4 and q5)	Correct arrival time with work shown; a reasonable near-source time; clear explanation of why the near town must prepare before any earthquake, with two specific preparations.	Correct calculations, with a partial explanation of what the short warning time means.	One calculation correct, or calculations without interpretation.	Forecasts missing or unsupported.

Teacher notes

Both datasets are simulated but follow the long-wave speed relationship, speed = square root of ($9.8 \times$ depth): 797 km/h at 5,000 m, 713 at 4,000, 617 at 3,000, 356 at 1,000, 159 at 200 and 80 at 50 m. At 2,000 m the rule gives 504 km/h and 120 km takes about 14 minutes; students interpolating linearly will get about 480 km/h and 15 minutes, which is fine. The extension's Crescent City figures are real: the 2011 tsunami arrived about 9 hours 48 minutes after the earthquake, and the straight-line distance is about 7,500 km, an average near 770 km/h. Students often expect the bigger earthquake to send faster waves; Dataset 2 is designed to break that idea. The near-source case in q5 reflects real California planning: state tsunami hazard maps and evacuation signs on the North Coast assume that a Cascadia earthquake could send waves ashore within minutes. Keep q5 responses focused on community preparation rather than a personal emergency checklist.

Scaffold offered to students: Evidence sentence frames

Try these frames for your Evidence box: 'Over a path averaging ___ m deep, the tsunami traveled at about ___ km/h, but over a path averaging ___ m deep it traveled at only ___ km/h.' 'Earthquakes 1 and 2 had magnitudes of ___ and ___, yet both tsunamis took ___ hours to reach gauge B, a speed of ___ km/h.' 'The bigger earthquake made the water rise ___ times higher.' For q5, find the two gauges whose depths are on either side of 2,000 m and choose a speed between theirs.

Extension: Find the rule

Physicists have found that for waves much longer than the water is deep, speed in meters per second equals the square root of $(9.8 \times \text{depth in meters})$. Use a calculator to test this rule for gauges A, D and F (multiply meters per second by 3.6 to get km/h). How close are the results to your table? Then use the rule to explain why the tsunami that reached Crescent City, California, about 10 hours after the 2011 earthquake off Japan traveled about 7,500 km in that time.