As much as they enjoyed exploring Kirk Point, Roxanne and Gemma knew there was a lot more to see in the Cape Enterprise area. They rock-hopped from the point around to Balon beach (Figure 15), a long sandy beach they loved to visit. Hiking westwards along the beach to Blackwater Estuary they discovered some interesting objects along the way.

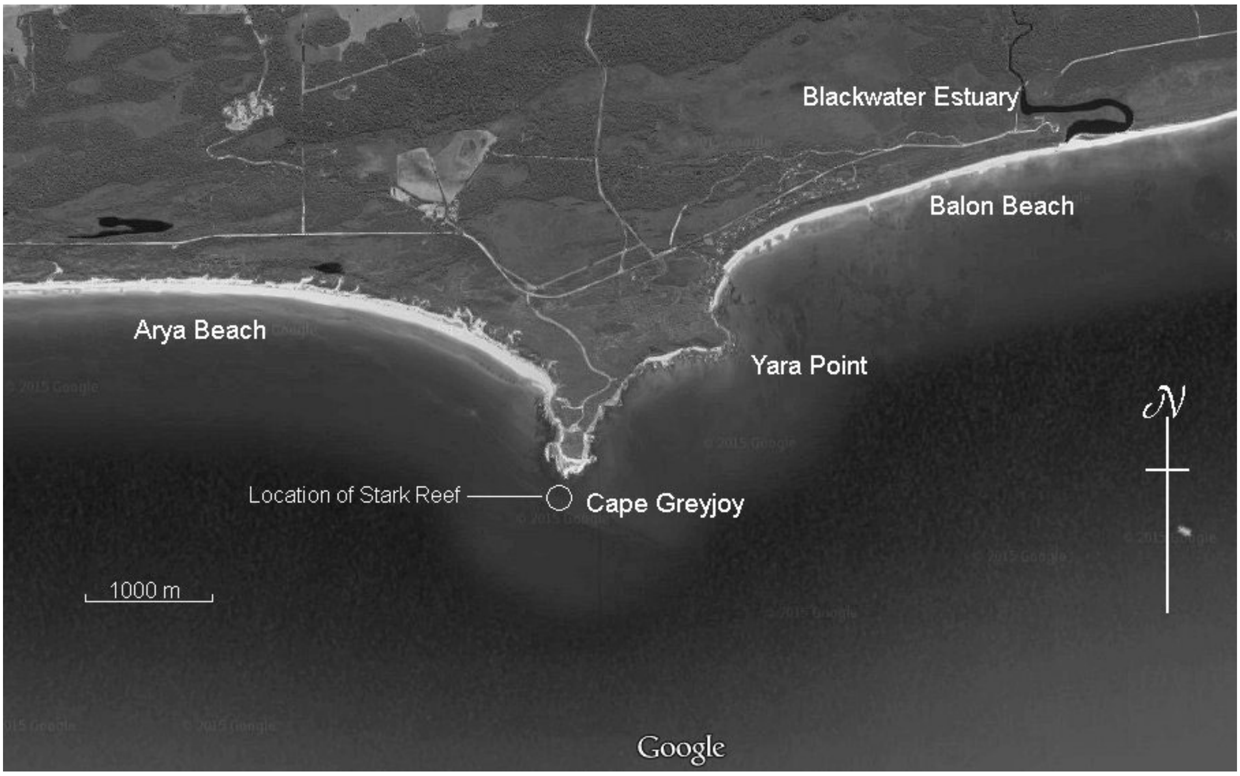


Figure 15: Geography of the Cape Greyjoy area. Cape Enterprise is further to the East and not shown here. Modified image courtesy of Google Maps.

The first object they picked up was one of many similar objects found amongst the flotsam washed up by waves and left behind on the upper part of the beach as the tide receded (Figure 16 on the next page). Documenting everything on social media as they went, one of their friends, marine biologist Shelly Waters, immediately commented…

> *… I find that stuff on beaches everywhere! I know you have told me before that it's an igneous rock called pumice but I have never really understood how it ends up on beaches.*

Figure 16: The first object collected on Balon beach. Roxanne noted the barnacle remnants indicated the pumice spent a long time in the water prior to being beached.

28. Q: What did Roxanne say in response to Shelly's puzzlement? (1 mark)

Pumice on the beach is the result of several factors, principally …

a. …submarine volcanoes erupting very frothy lava that has a very high porosity but near zero permeability allowing it to float. Surface conditions raft the pumice around until it washes on shore.
b. … submarine volcanoes erupting frothy lava that has a very high permeability but near zero porosity allowing it to float. Surface conditions raft the pumice around until it washes ashore.
c. … submarine volcanoes erupting lava that flows across the ocean floor forming pillow basalt. Sometimes bits of pillow break off and float to the surface where they are rafted around until they wash on shore.
d. … submarine volcanoes erupting lava that flows across the ocean floor forming pillow basalt. Sometimes bits of pillow break off and are rolled around by marine currents until they are pushed ashore in storms.
e. …submarine volcanoes exploding violently, showering the local area with pyroclastic debris, including pumice. Pumice is all that remains on the beach because it is made of silica (microcrystalline quartz) and resists weathering.
f. … submarine volcanoes exploding violently, showering the globe with pyroclastic debris, including pumice. Pumice is all that remains on the beach because it is made of olivine [$(Fe,Mg)_2SiO_4$] and resists weathering.

Roxanne also sent the group an ancient graphic (from the early 21st century), showing what a pumice raft looks like (Figure 17). Gemma's friend, Jean Luc Bringuebaler, was very excited to see mention of pumice in the chat and immediately contacted everybody to share some fun facts related to pumice-forming events in the Pacific region where he has been researching historical seismic events and tsunami. He was in a very playful mood so he challenged them to answer some questions based on some interesting information and images* associated with an historical event from various global sources:

Figure 17: Raft of pumice clasts resulting from an eruption in the South Pacific. Image courtesy of NOAA.

*Figure 18 - The event's air pressure wave arrival times in Auckland, New Zealand.

*Figure 19 - Pressure and sound wave arrival in Southern Alaska, Kenai Peninsula.

*Figure 22 - Tsunami wave arrival times on the US and Canadian coast.

*Figure 23 – Passage of waves across Britain.

Along with the images he added:

There are lots of different ways volcanoes can produce tsunami such as earthquakes, caldera and flank collapses, pyroclastic flows, or underwater explosions, but these kinds of events rarely displace enough water to trigger tsunami that cross oceans. Violent volcanic explosions, however, can cause global tsunami by triggering acoustic-gravity waves that excite the atmosphere-ocean interface. These are low-frequency compression sound waves propagating under gravity at speeds very close to the speed of sound for the medium (e.g. ~340 m/s in air and 1500 m/s in water). This allows them to travel significant distances before they start to dissipate. For comparison a seismic wave in rock like granite travels at about 5000 m/s.

The only additional help he gave them was to say the historical event occurred at around 4:15 UTC on the day in question and the air wave speed did not slow down much over open water in the South Pacific so the Auckland data is a reliable means of calculating distance.

29. Jean Luc's first question, related to Figure 18, was:
How far from Auckland is the volcano that caused this event?

Q: Gemma correctly calculated … (1 mark)

a. … ~796 km.
b. … ~1,999 km.
c. … ~2,142 km.
d. … ~3,574 km.
e. … ~3,876 km.
f. … ~9,450 km.

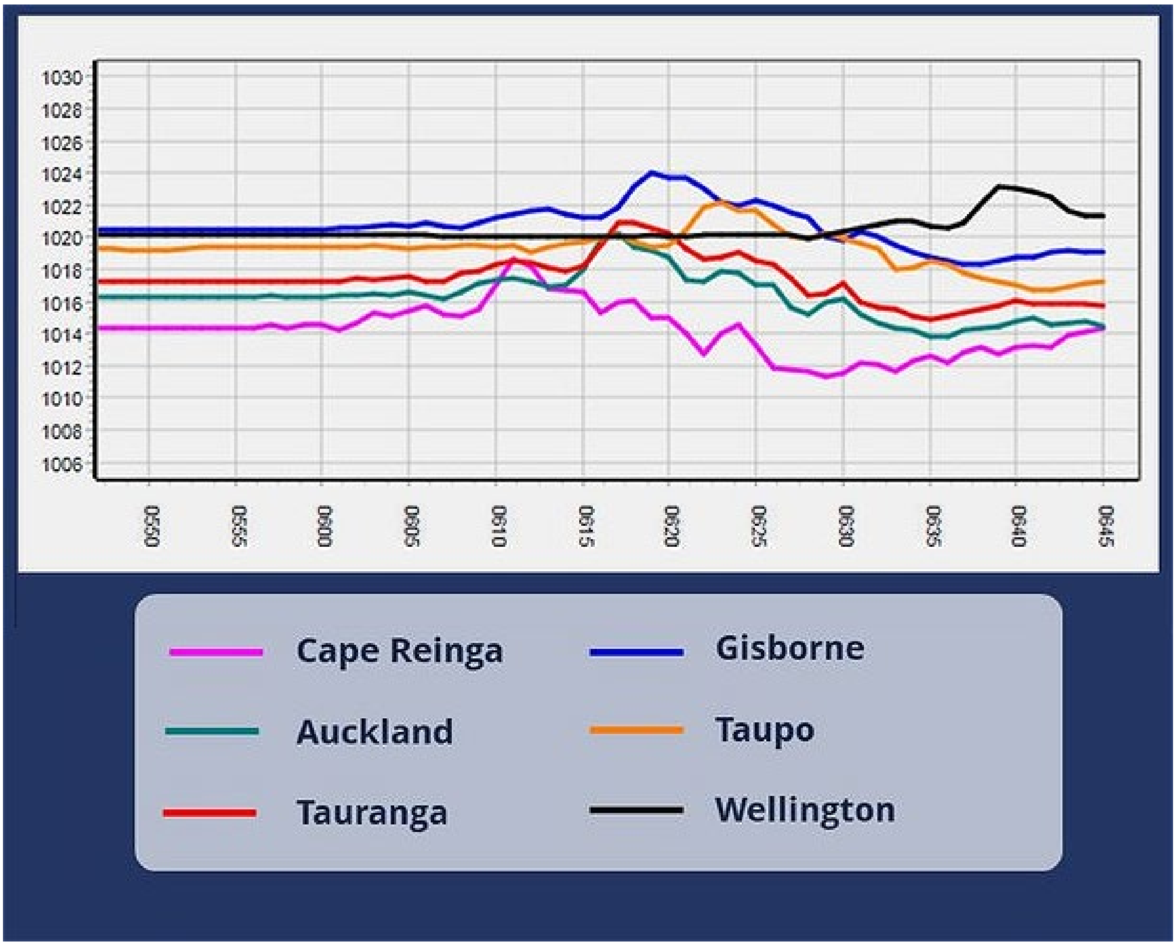


Figure 18: Air Pressures recorded at 6 New Zealand stations on the day in question. Times are UTC. The NZ MetSerive advise they take the wave's arrival time to be marked by the first "disturbance in the force" registering as a departure from the steady state recorded prior to arrival. Modified image courtesy New Zealand MetService

30. Jean Luc predicted the air wave would arrive at Kenai, Alaska, about 7.5 hours after the eruption. However, Gemma was doubtful this could be the case given how far Auckland is from Alaska (Figures 19a and 19b on the next page). She calculated the actual travel time from Auckland should be ~ 9 hours 10 minutes.

Q: What explanation for the 7.5 hour prediction did Jean Luc give her? (1 mark)

a. The volcano is ~2040 km closer to Alaska than Auckland is to Alaska.
b. The volcano is ~2040 km further from Alaska than Auckland is to Alaska.
c. The volcano is ~2142 km closer to Antarctica than Auckland is to Alaska.
d. The volcano is ~2142 km closer to Antarctica than Alaska is.
e. The volcano is ~796 km due west of Auckland.
f. The volcano is ~796 km due east of Auckland.

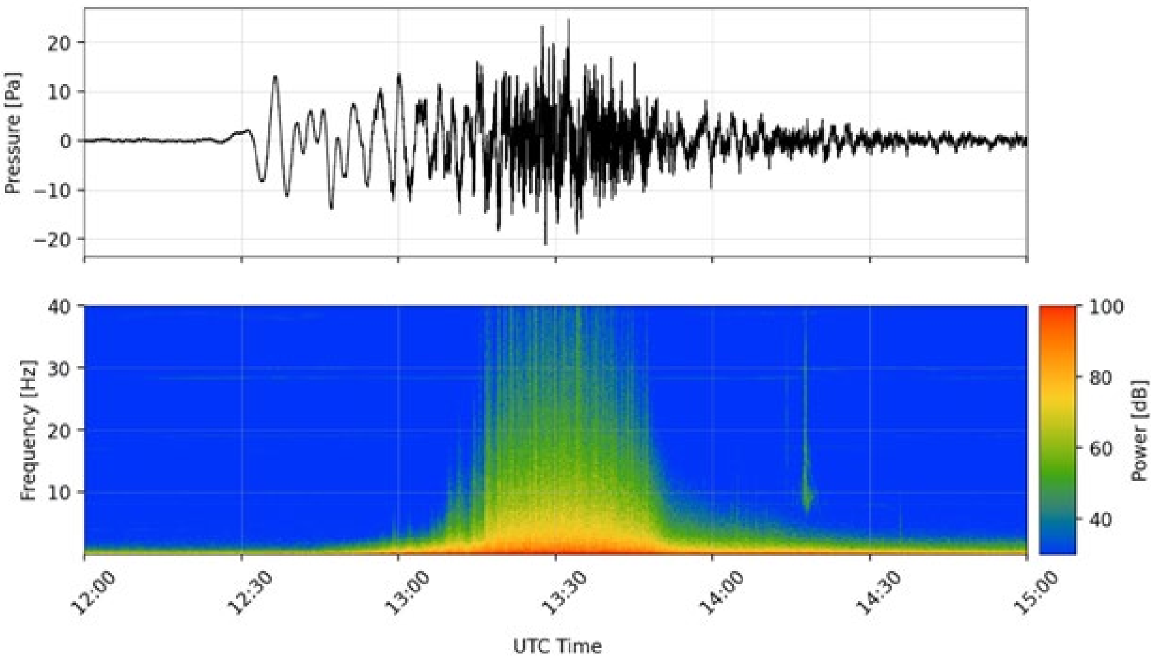


Figure 19a: Pressure and sound wave arrival time (UTC) Southern Alaska, Kenai Peninsula (11,234 km from Auckland, NZ) . Modified image courtesy of the UAF Geophysical Institute

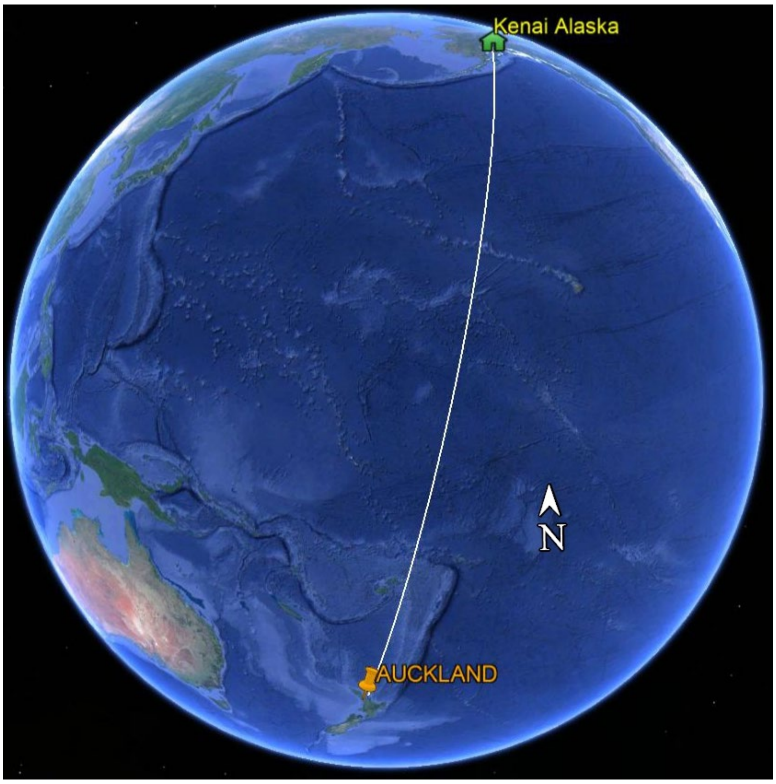


Figure 19b: Geographic location of Kenai, Alaska relative to Auckland, New Zealand. The line across the globe represents a distance of 11,234 km.

31. Looking at the graph supplied by Jean Luc (Figure 19a), Gemma noted that the actual arrival time did not correspond with the predicted 7.5 hour travel time or the travel time she calculated earlier.

Q: When she challenged Jean Luc to explain the discrepancy, what did he say?

a. The actual travel time of 7 hours 05 minutes is best explained by the wave slowing down as it travelled through warm, moist tropical air.
b. The actual travel time of 8 hours 05 minutes is best explained by the wave slowing down as it travelled through warm, moist tropical air.
c. The actual travel time of 9 hours 05 minutes is best explained by the wave slowing down as it travelled through warm, moist tropical air.
d. The actual travel time of 7 hours 05 minutes is best explained by the wave reaching Alaska via a route over Antarctica faster than via the Pacific route.
e. The actual travel time of 8 hours 05 minutes is best explained by the wave reaching Alaska via a route over Antarctica faster than via the Pacific route.
f. The actual travel time of 9 hours 05 minutes is best explained by the wave reaching Alaska via a route over Antarctica faster than via the Pacific route.

32. Sandra commented on the graph shown in Figure 19a, saying: *I read an historical news report that people in Alaska actually heard this eruption. How is that even possible?* Jean Luc said his colleagues assured him it was possible because most adult humans can detect sounds in a frequency range from about 20 Hz to 20 kHz as long as the intensity (power) is above about 80 decibels (dB) for low frequencies.

Q: What did Jean Luc add to his comment about the event's audibility in Alaska? (1 mark)

a. Most adults in Kenai Alaska could have heard this event at 14:17 UTC.
b. Most adults in Kenai Alaska could have heard this event between 13:15 & 13:45 UTC.
c. The sound frequency recorded between 13:15 & 13:45 UTC is too high to be heard.
d. The sound frequency recorded at between 13:15 and 13:45 UTC is too low to be heard.
e. The sound frequency between 13:15 and 13:45 UTC wasn't powerful enough to be audible.
f. The range of sound frequencies recorded at between 13:00 and 14:00 UTC are all inaudible.

Rising to the challenge, two mutual friends, Andy Sight & Ashleigh Hammer, decided to help Gemma locate the event by creating a table of known sea wave travel times from the time of eruption at 4:15 UTC. The wave was recorded at South Pacific tsunami detection buoys and Australian coastal tide gauges. Jean Luc quickly added a bit more historical data to help everybody figure out where the event occurred (Table 2) then Gemma graphed the data and posted for everyone to see (Figure 20 on the next page).

Buoys and tide gauges (shown in Figure 21)	**Time of sea wave arrival** (since eruption at 4.15 UTC, hh:mm)	**Distance of buoy or gauge from eruption site** (as supplied by Jean Luc to help)
Buoy NZG	0.27	~375 km
Buoy NZF	1:10	~1, 041 km
Buoy NZK	1:38	~1,656 km
Norfolk Island TG	1:45	~1,993 km
Buoy NZL	1:53	~2,095 km
Buoy NZJ	2:09	~2,256 km
Gold Coast, QLD TG	3:00	~3,312 km
Port Kembla, NSW	3:45	~3,699 km
Twofold Bay, NSW	4:00	~3,887 km

Table 2: Water wave travel times between the eruption site, four tsunami detection buoys and three Australian coastal tide gauges plus the distances from each site to the eruption site.

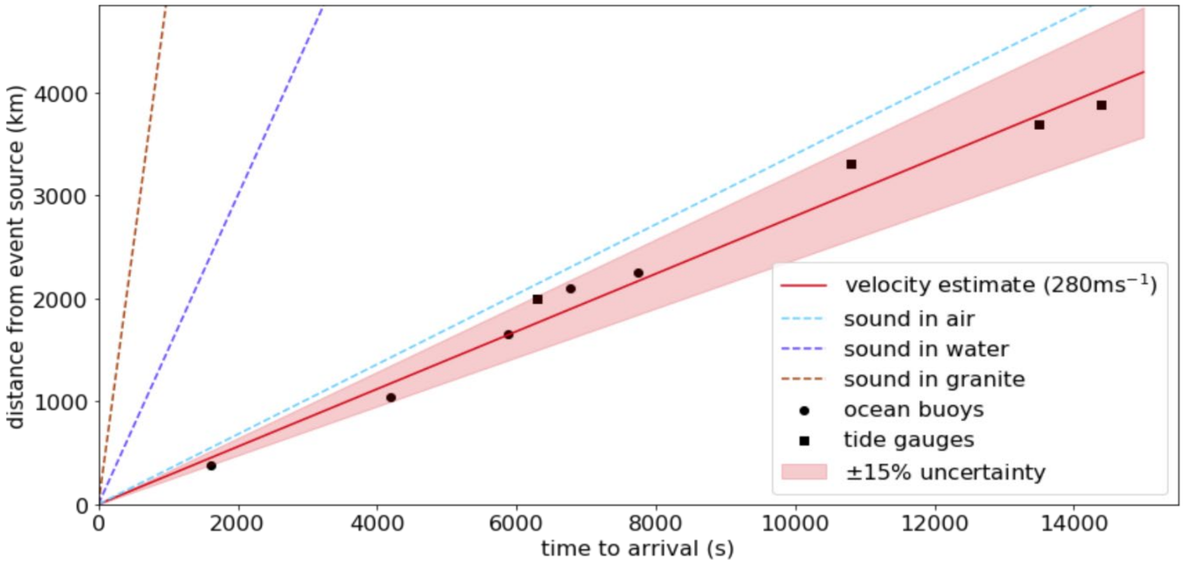


Figure 20*:* Water wave velocity estimate based upon recorded arrival times and distances from each gauge or buoy to the eruption site (as supplied by Jean Luc).

33. Andy and Ashleigh made some observations about the data and Gemma's graph (Table 2, Figure 20).

Q: Which observation below did Gemma agree was correct?

a. The wave's velocity increased with distance from the source due to lower friction at the water-air interface.
b. The wave's velocity was controlled by water temperature, travelling slower in tropical waters.
c. The wave's velocity was controlled by air temperature, travelling slower in the tropics.
d. The wave's velocity was erratic outside of the range of measurement uncertainty, apparently influenced by unknown variables (more research is needed).
e. The wave's velocity decreased overtime in response to increased incoming radiation as the sun rose after the 4.15 UTC eruption.
f. The wave's velocity is neither increasing nor decreasing over the Tasman Sea (that part of the South Pacific Ocean between Australia and New Zealand).

34. Gemma also made some observations.

Q: Which observation below did Andy, Ashleigh and Roxanne all agree was correct?

a. The wave has propagated through the marine environment at a velocity far more like a sound wave in air than a sound wave in water.
b. The wave has propagated through the marine environment at a velocity far more like a sound wave in water than a sound wave in air.
c. The wave has propagated through the marine environment at a velocity far more like a seismic wave in rock than a sound wave in water.
d. The wave has propagated through the marine environment at a velocity far more like a sound wave in space than a sound wave in air.
e. The wave has propagated through the water at a velocity intermediate between a wave in air and a wave in water.
f. The wave has propagated through the wet seafloor sediments at a velocity intermediate between a sound wave in water and a seismic wave in rock.

Andy & Ashleigh offered to make a map showing locations Gemma's friends suggested for the eruption. Gemma was curious to see if the 280 m/s velocity estimate would help them discover the eruption site and asked Andy & Ashleigh to add 280 m/s travel circles to the map for each of the buoys and tide gauges (Figure 21 on the next page).

35. Looking at the map (Figure 21), Sandra wondered why there are no active volcanoes on the South Island of New Zealand, given the North Island has had at least 9 major eruptions in the last 2000 years.

Q: What did Andy Syght post in reply?

a. The South Island sits over a hotspot whereas the North Island sits over a subduction zone.
b. The North Island sits over a hotspot whereas the South Island sits over a subduction zone.
c. The North Island straddles a transform fault whereas the South Island sits over a subduction zone.
d. The North Island rocks must have a lower melting point than South Island rocks.
e. The South Island straddles a transform fault whereas the North Island sits over a subduction zone.
f. The North Island rocks must have a higher volatile content than South Island rocks.

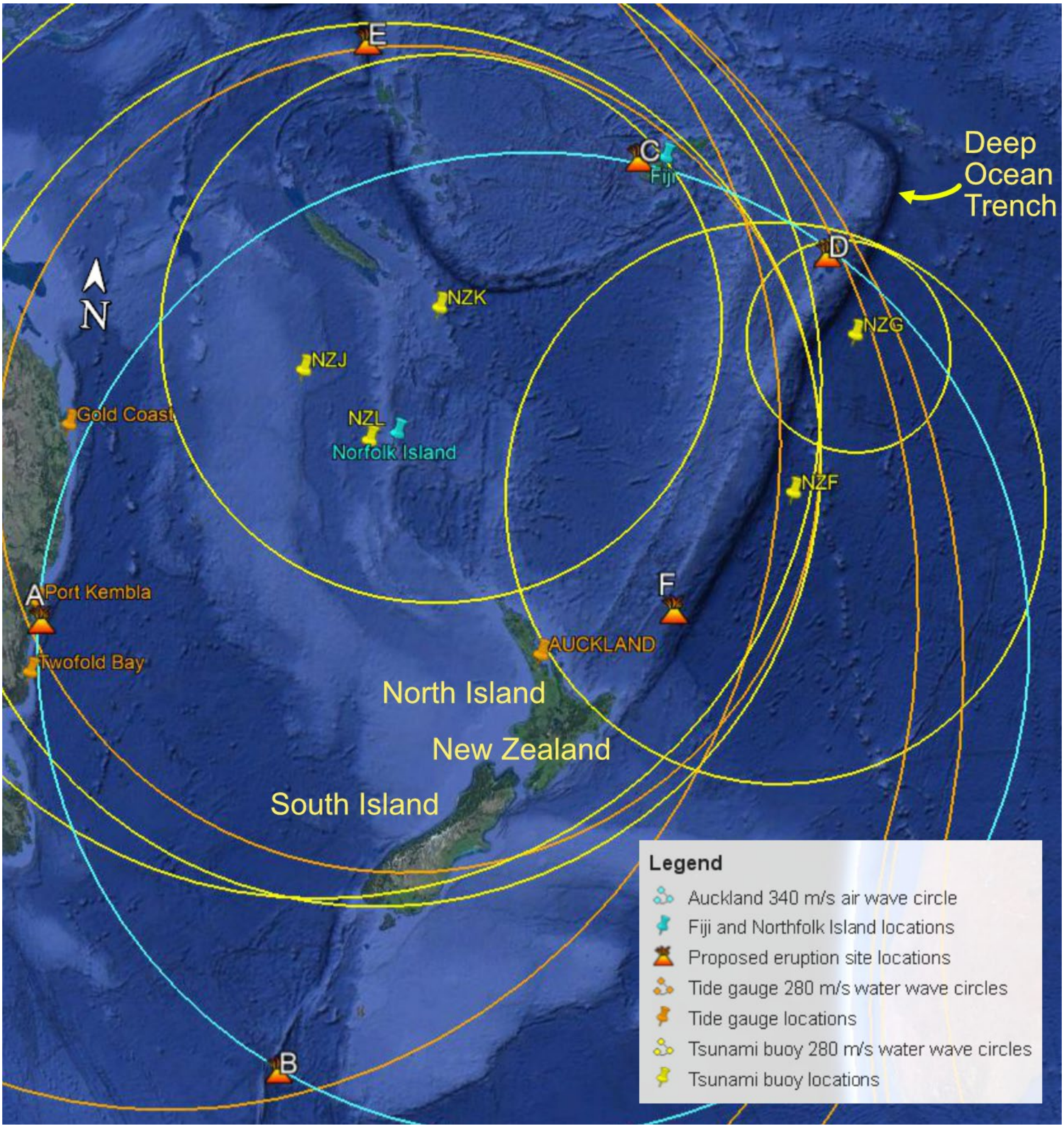


Figure 21*:* Location of tide gauges and tsunami buoys listed in Table 3. The blue circle represents the distance from Auckland for an air wave travelling at 340 m/s. The yellow circles represent the distances travelled for a water wave moving at 280 m/s from each of the five buoys. The orange circles represent the distances travelled for a water wave moving at 280 m/s from each of the four tide gauges. Ocean floor topography is represented in shades of blue. The darker the blue the deeper the water. Volcano icons A, B, C, D E & F represent the eruption sites argued for by Gemma's friends.

Everyone thanked Andy & Ashleigh for the map but each friend suggested a different location for the eruption site based on the same information in Figure 21!

Roxanne argued for Site A because the eruption is most likely somewhere on the Auckland air pressure wave circle and Site A sits over an active subduction zone between the Australian and Pacific Plates.

Rose nominated Site B, arguing the eruption is most likely somewhere on the Auckland air pressure wave circle and Site B sits over an active subduction zone between the Australian and Pacific Plates.

Zoe nominated Site C because the eruption is most likely somewhere on the Auckland air pressure wave circle plus there are many Miocene to Pliocene volcanoes in the area around the island of Fiji. She also noted the complex subduction zones in the South Pacific are well known for explosive submarine volcanoes.

Gabi voted for Site D, arguing that the eruption site is most likely somewhere on the Auckland air pressure wave circle, the location is on a volcanic arc and most water wave circles intersect with the Auckland air wave circle in this region.

Philip pointed to Site E because the volcanoes around Papua New Guinea are notoriously explosive and Site E is located on a subduction zone.

Andy nominated Site F, arguing the eruption is most likely somewhere on a volcanic arc and many water wave circles intersect the region nearby, over the Benioff zone.

36. Gemma carefully considered all five eruption site options shown in Figure 21 and the reasons given by her five friends.

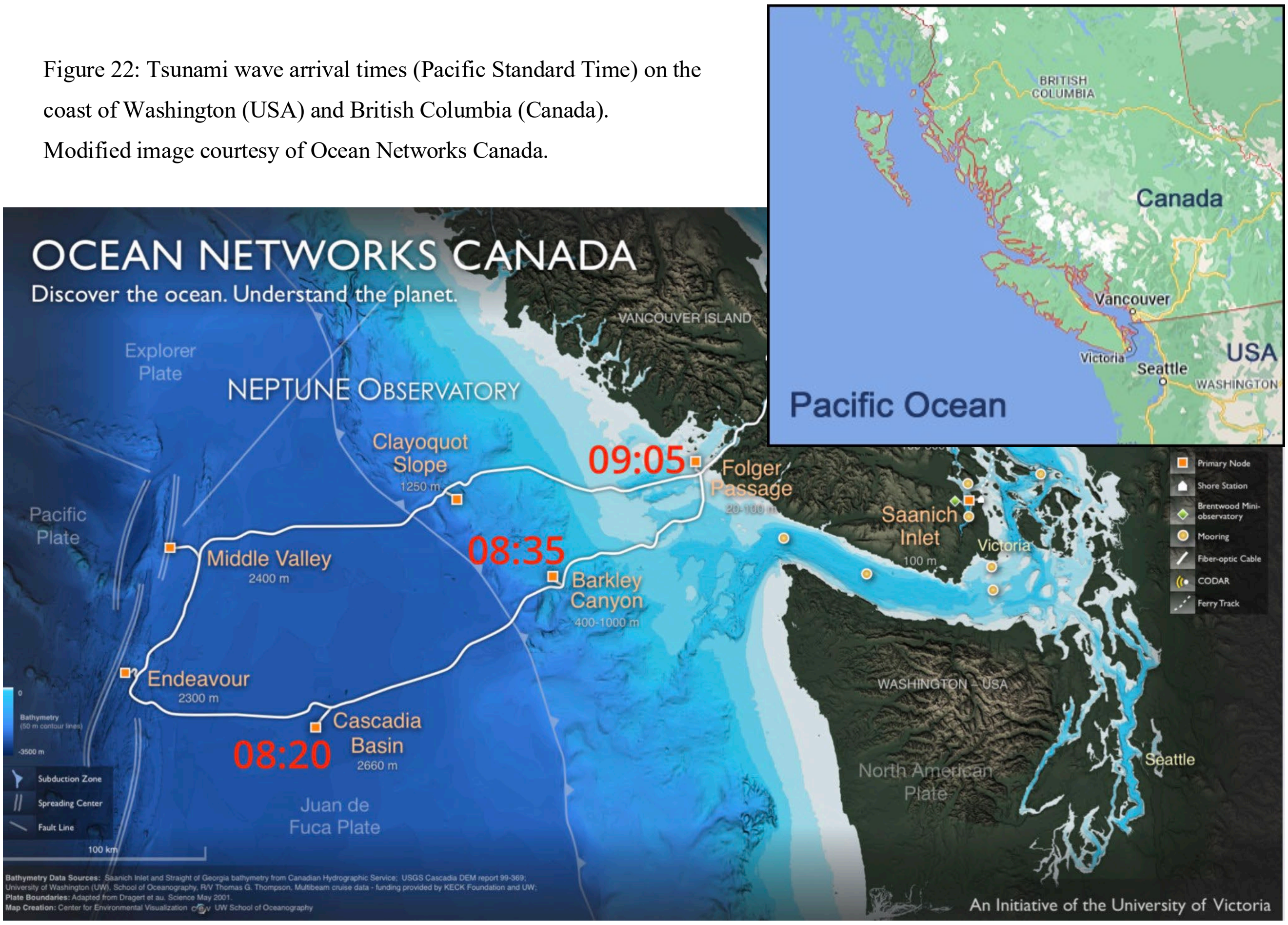
Q: Which option did Gemma correctly select?

a. Roxanne's argument for Site A.
b. Rose's nomination for Site B.
c. Zoe's nomination for Site C.
d. Gabi's vote for Site D.
e. Philip's vote for Site E.
f. Andy's argument for Site F.

Jean Luc kept the conversation going with yet another image (Figure 22), commenting that not only did the northern hemisphere hear the explosion but it also experienced the global tsunami that followed. He also provided this helpful information:

- Distance from Cascadia Basin (CAS) to Barkley Canyon (BAR) ~150 km
    - Tsunami travel time CAS to BAR ~15 minutes
    - Water depth of the Cascadia Basin is ~ 2660 m
- Distance from BAR to Folger Passage (FOL) ~100 km
    - Tsunami travel time BAR to FOL ~30 minutes
    - Water depth of the Barkley Canyon varies from 1,000 m in the west to 100 m depth near-shore

Figure 22: Tsunami wave arrival times (Pacific Standard Time) on the coast of Washington (USA) and British Columbia (Canada). Modified image courtesy of Ocean Networks Canada.



37. Gemma was quick to calculate the wave velocity (V) for each setting.

Q: What did Gemma add when she shared the values for $V_{CB\text{-}BC}$ and $V_{BC\text{-}FP}$ with the group?

We know that tsunami wave speed (W) is dependent upon water depth (h) over which they propagate according to the formula $W=\sqrt{gh}$,, *where g is gravity acceleration (~9.8 m/s).*
Therefore ...

a. … the observed wave speeds are both consistent with those calculated for the ocean depths at these locations, taking into account that $V_{BAR\text{-}FOL}$ is an average.
b. … the observed wave speed $V_{CAS\text{-}BAR}$ is consistent with $W_{CAS\text{-}BAR}$ as calculated for the given depth of CAS but $V_{BAR\text{-}FOL}$ is inconsistent with the calculated $W_{BAR\text{-}FOL}$ values, taking into account that $V_{BAR\text{-}FOL}$ is an average.
c. … the observed wave speed $V_{BAR\text{-}FOL}$ is consistent with $W_{BAR\text{-}FOL}$ as calculated for the given depths of FOL but $V_{CAS\text{-}BAR}$ is inconsistent with the calculated $W_{CAS\text{-}BAR}$ value, suggesting the ocean depth for CAS is far more variable than indicated.
d. … the observed wave speeds are both inconsistent with those calculated for the ocean depths at these locations, taking into account that $V_{BAR\text{-}FOL}$ is an average.
e. … the observed wave speeds are both inconsistent with those calculated for the ocean depths at these locations because the bathymetry depth figures vary with tidal flux and were not necessarily taken at a point consistent with the tidal point during the tsunami event.
f. … the depth measurements provided for BAR must be incorrect because the average of $W_{BAR\text{-}FOL}$ for those values does not match $V_{BAR\text{-}FOL}$.

In further discussions about the event's impact on the northern hemisphere, Jean Luc shared Figure 23 on the next page, commenting that the data demonstrates the truly global impact this event had.

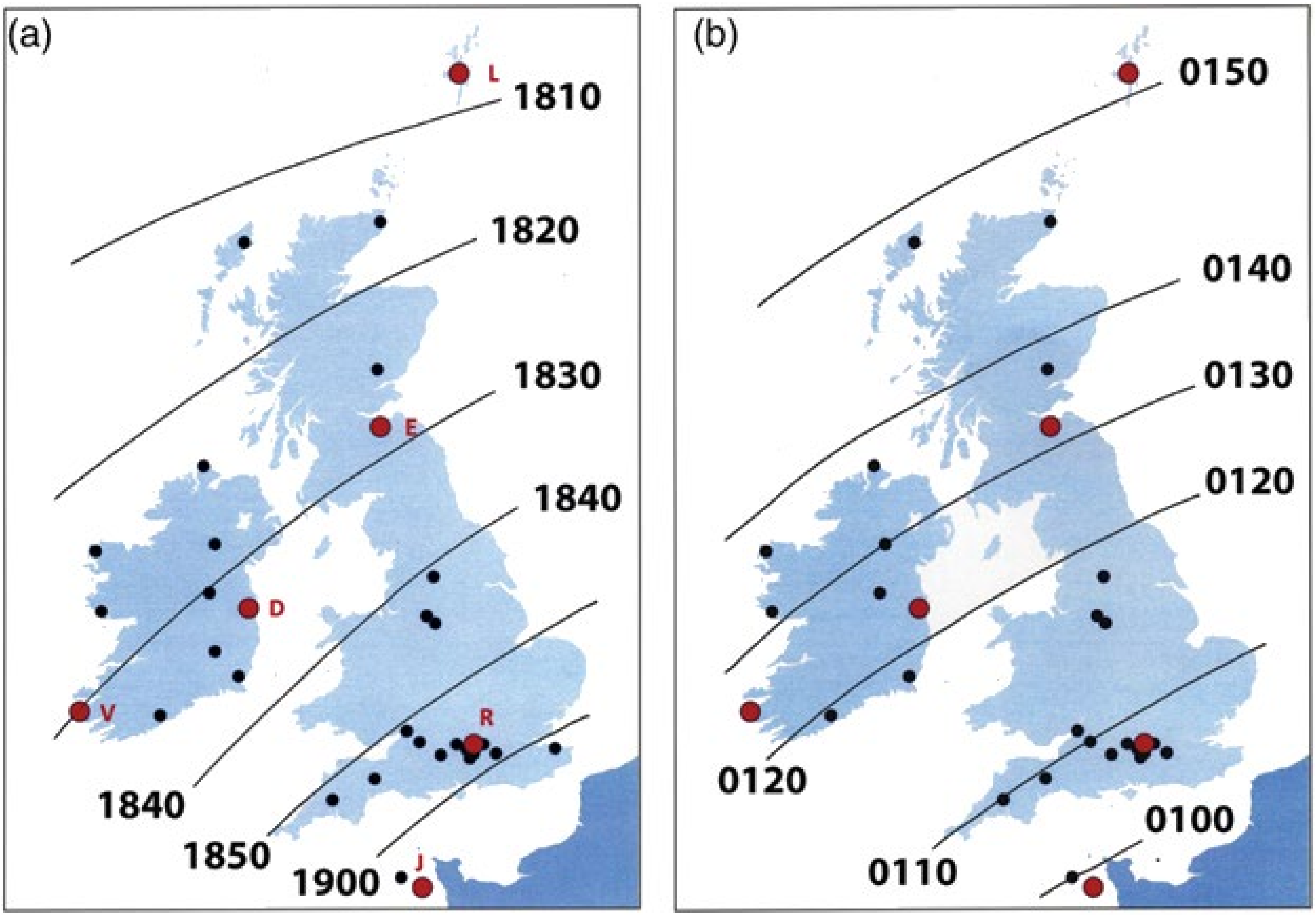


Figure 23:. Panel (a): Time of passage (in UTC) of an air pressure wave across the British and Irish Isles associated with eruption in the southern hemisphere. Panel (b): Time of passage (in UTC) of another wave across the same area the following day. The red circles labelled L, E, D, V, R & J and the black dots are all recording stations. The black lines indicate times (in UTC) where the waves were in 10 minute intervals, as interpolated from the data. North is to the top of the maps.
Arrival times at V: (a) 18.30 UTC, (b) 01:23 UTC
Arrival times at D: (a) 18:34 UTC, (b) 01:21 UTC
Arrival times at R: (a) 18:52 UTC, (b) 01:05 UTC
Arrival times at J: (a) 19:03 UTC, (b) 00:57UTC
Modified image courtesy of the Royal Meteorological Society.

38. Jean Luc noted that the event's air pressure wave was recorded much further north than his home in southern France.

Q: **What directions did Jean Luc say the waves were travelling when they arrived at site V at 18:30 UTC and later the next day at 01:23 UTC and why the (a) wave arrived first?**

The wave travelled ...

a. … first from the Northeast to the Southwest and then from the Southeast to Northwest because the distance via the North Pole to the eruption site in the Pacific is the longest and most obstructed by continental mass.
b. …first from the South to North and then from the North to South because the distance via the North Pole to the eruption site in the Pacific is the shortest and least obstructed by continental mass.
c. … first from the West to East and then from the East to West because there is more continental mass in the western hemisphere than the eastern hemisphere.
d. … first from the East to West and then from the West to East because there is more continental mass in the western hemisphere than the eastern hemisphere.
e. … first from the North to South and then from the South to North because the distance via the North Pole to the eruption site in the Pacific is the longest and least obstructed by continental mass.
f. … first from the Northwest to Southeast and then from the Southwest to Northeast because the distance via the North Pole to the eruption site in the Pacific is the shortest and least obstructed by continental mass.

39. Jean Luc continued making correct observations about the behaviour of both wave events.

Q: What did he say about the velocity of the waves?

a. Both waves passed over the British and Irish Isles at the same velocity.
b. The first wave (a) was travelling faster than the second wave (b).
c. The first wave (a) was travelling slower than the second wave (b).
d. The (a) wave doubled its velocity as it passed over site R.
e. The (b) wave doubled its velocity as it passed over site R.
f. Both waves exhibit random velocity variations.

40. Philip commented that he read about a similar multi-wave, from similar and opposite directions, that happened when Krakatoa explosively erupted in 1883.

Q: What did he say when Sandra asked how it is possible to get successive waves coming from opposite directions when the volcano only exploded once?

a. Earth is an oblate spheroid, therefore a wave travelling out in all directions over the surface will cross over itself from opposite directions once the expanding wave front circles overlap.
b. Earth is an oblate spheroid, therefore a wave travelling through the core from one side to the other will cross over itself from opposite directions once the expanding wave fronts overlap
c. Earth is too big for expanding wavefronts to overlap before the energy of the wave is dissipated. Overlapping waves come from other explosions triggered elsewhere by the first one, giving the illusion of multiple waves from the one event.
d. A wave travelling through the Earth's core from one side to the other will trigger mantle convention which in turn will upwell into the recently destroyed volcanic vent and cause a second massive explosion and a subsequent wave.
e. A massive explosion expels rock and gas material in all directions as well as causing an air pressure wave. However, the removal of such a large volume of material causes a reverse wave as the atmosphere rushes in from the opposite direction to fill the void left by the initial expulsion of material.
f. There are enough large volcanic eruptions over time to always coincide with large rocks crashing down on Earth from space. Multi wave events are just coincidences.