School ID

2025 AUSTRALIAN SCIENCE OLYMPIAD EXAM

EARTH AND ENVIRONMENTAL SCIENCE

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

First Name: ……………….…..………… **Last Name**………………………………….
Date of Birth: ….../….../..….

☐ **Male** ☐ **Female** ☐ **Unspecified** **Year 10** ☐ **Year 11** ☐ **Other:** …….

Name of School: …………………………………………….……………….**State:** ……...

Examiners Use Only:										

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2025 AUSTRALIAN SCIENCE OLYMPIAD EXAM
EARTH & ENVIRONMENTAL SCIENCE

Time Allowed
Reading Time: 15 minutes
Exam Time: 120 minutes

INSTRUCTIONS

- Attempt ALL questions of this paper.
- Permitted materials:
  - Non-programmable, non-graphical calculator,
  - Pens, pencils, erasers and a ruler.
- Marks will not be deducted for incorrect answers.
- Rough working must be done only on blank pages provided in this booklet.
- Data that may be required for a question will be found on pages 3 – 16.
- All answers should be marked on this paper.
- Circle the correct answer in Multiple Choice and True/False questions.

MARKS

Multiple choice questions are each worth one (1) unless otherwise indicated. Question 32-25 are worth (0.5 marks)

Question 39 is worth 3 marks.

Questions 47,62 and 63 is worth 2 marks each.

Total marks for the paper: 99 marks

2025 Exam Resources

Materials

You will need a scientific calculator, writing utensil, and scratch paper for working out.

Universal constants, equations & units

Unit or constant	Symbol	Value
Astronomical unit, the average distance between the Sun and Earth	AU	1.496×10^{11} m
Light year	Ly	9.461×10^{15} m
Parsec	pc	3.261 light years = 3.085×10^{16} m
Speed of light	c	299,792,458 m/s ≈ 3×10^{8} m/s
Universal gravitational constant	G	6.67×10^{-11} Nm^2 kg^2
Universal gas constant	R*	8.3144598 J/(mol·K)
Molar mass of Earth's air	M	0.0289644 kg/mol
Earth's equatorial circumference		40,075 km
Earth's longitudinal circumference		40,008 km
Earth's orbital velocity		107,000 km/hr
Mars' mass		6.417×10^{23} kg
Mars' radius		3389.5 km
Anum (year)	a	8,760 hr = 3.1536×10^{7} s
Years before present	a BP	(M)ega = 10^{6}; (G)iga = 10^{9}
Thousands of years BP	ka	
Millions of years BP	Ma	
Billions of years BP	Ga	

Physics

Gravitational Potential Energy

$$U = \frac{-GMm}{r}$$

Where *U* is the gravitational potential energy of an object with mass *m,* at a point *r* from a central mass *M*, and *G* is the universal gravitational constant.

Hydrostatic or Lithostatic Pressure

$$P = \rho g h$$

Where *P* is the pressure at the base of a column of water/rock; where ρ is water/rock density, *g* is acceleration due to gravity, and *h* is the column depth.

Inverse Square Law for Radiation Intensity

$$I \propto \frac{1}{r^2}$$

Where *I* is radiation intensity, and *r* is the distance between the radiation source and the observer

Kinetic Energy

$$K = \frac{1}{2}mv^2$$

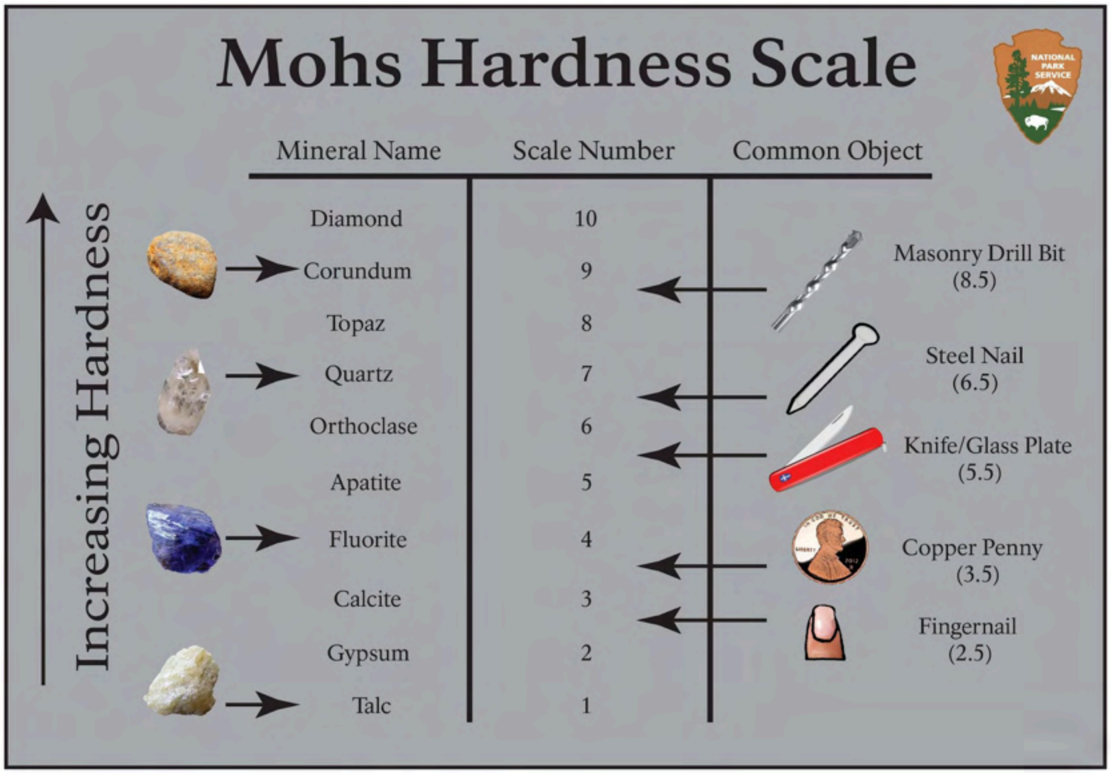
Where *K* is the kinetic energy of an object with mass *m,* moving at a velocity *v*

Conversions

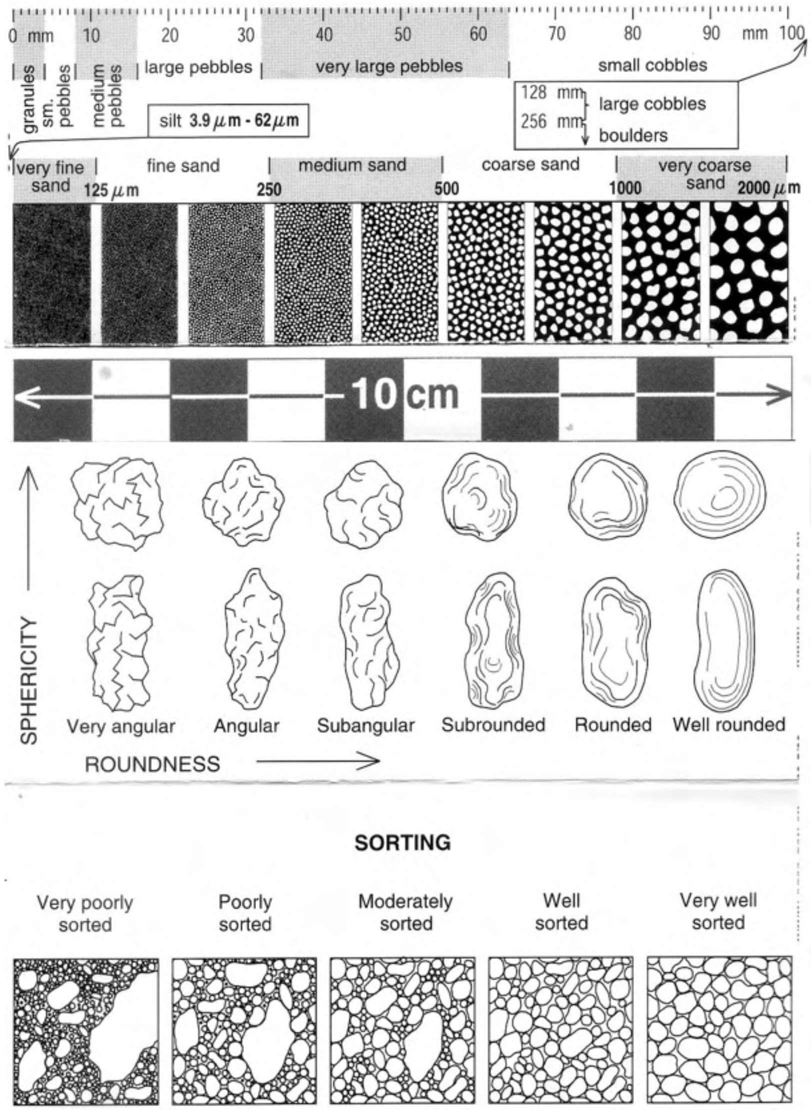
Degrees Celsius (^oC) to Degrees Kelvin (K): $T_{(°C)} = T_{(K)} - 273.15$

Geology

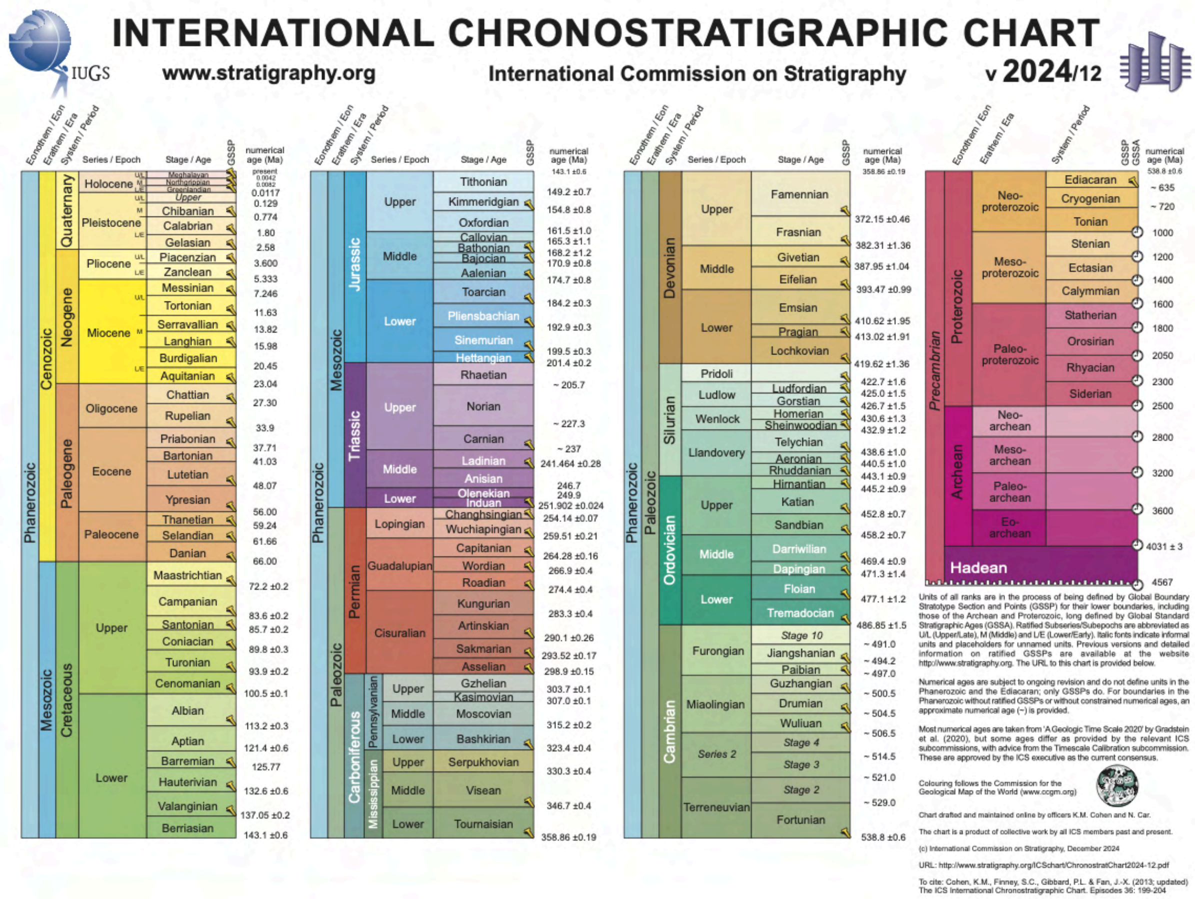
Moh’s Hardness Scale



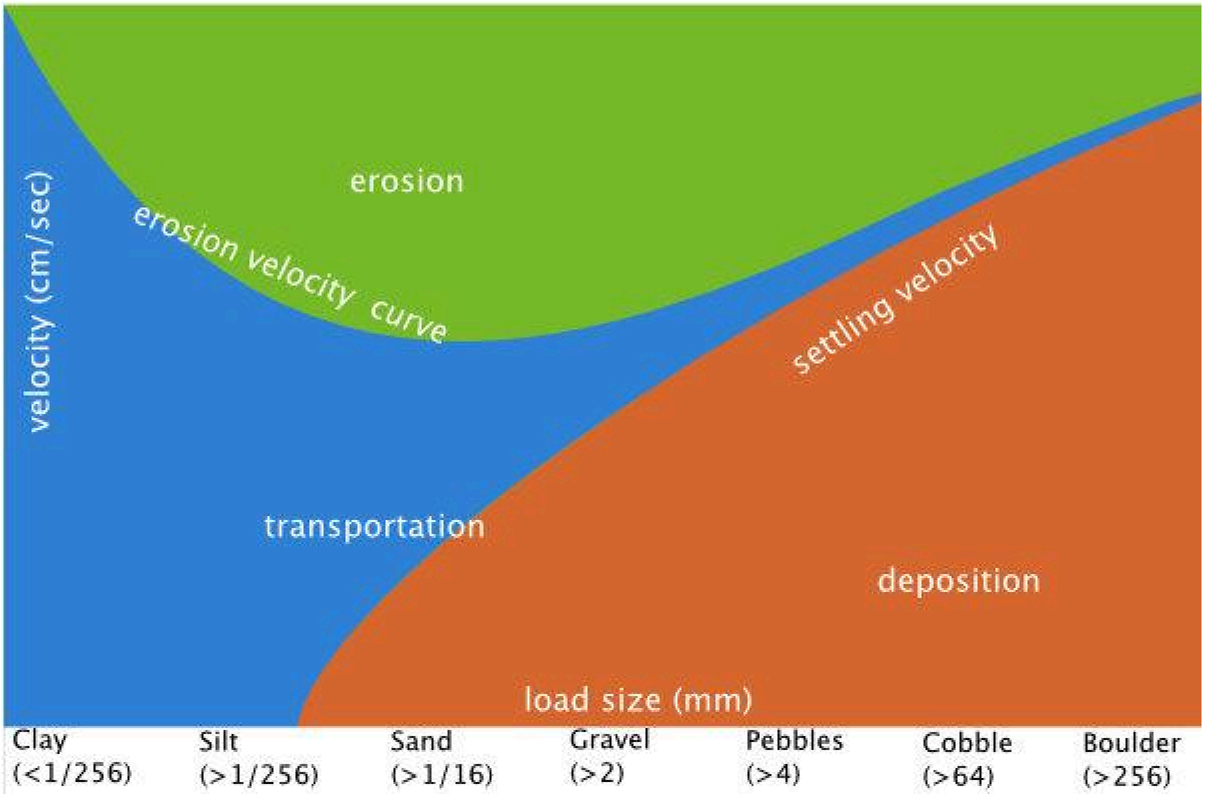
Sand Card


0 mm 10 20 30 40 50 60 70 80 90 mm 100
granules
sm. pebbles
medium pebbles
large pebbles
very large pebbles
small cobbles
128 mm large cobbles
256 mm boulders
silt 3.9 µm - 62 µm
very fine sand
125 µm
fine sand
250
medium sand
500
coarse sand
1000
very coarse sand
2000 µm
10 cm
SPHERICITY
Very angular
Angular
Subangular
Subrounded
Rounded
Well rounded
ROUNDNESS
SORTING
Very poorly sorted
Poorly sorted
Moderately sorted
Well sorted
Very well sorted

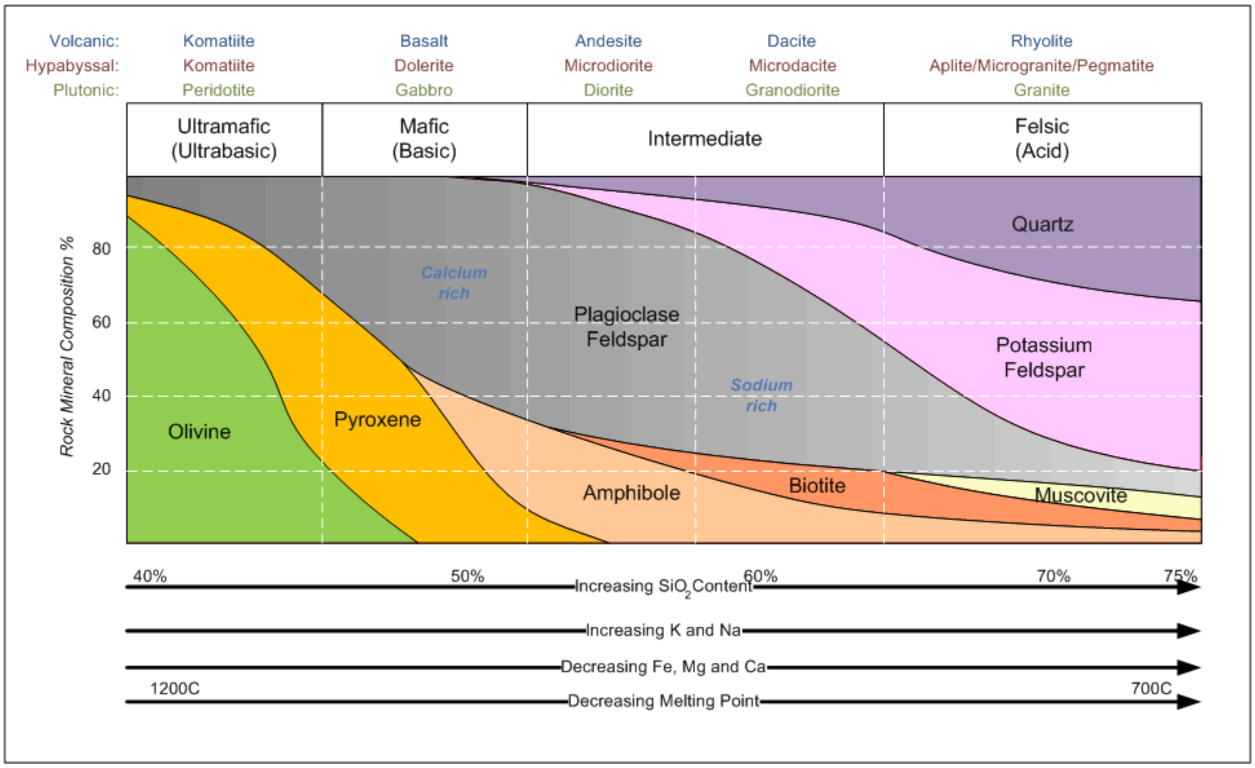
Geologic Time Scale



Hjulström diagram

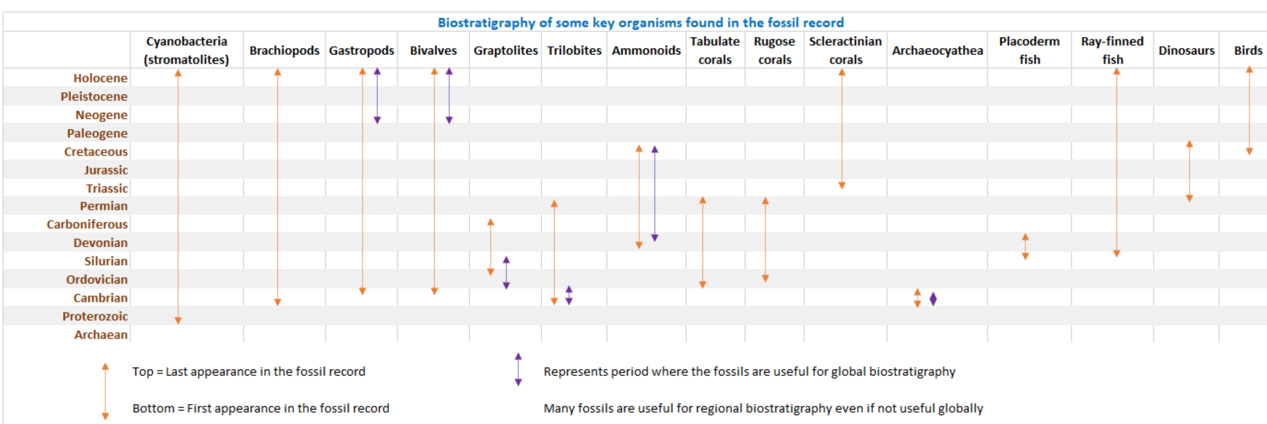


Igneous classification chart



Biology

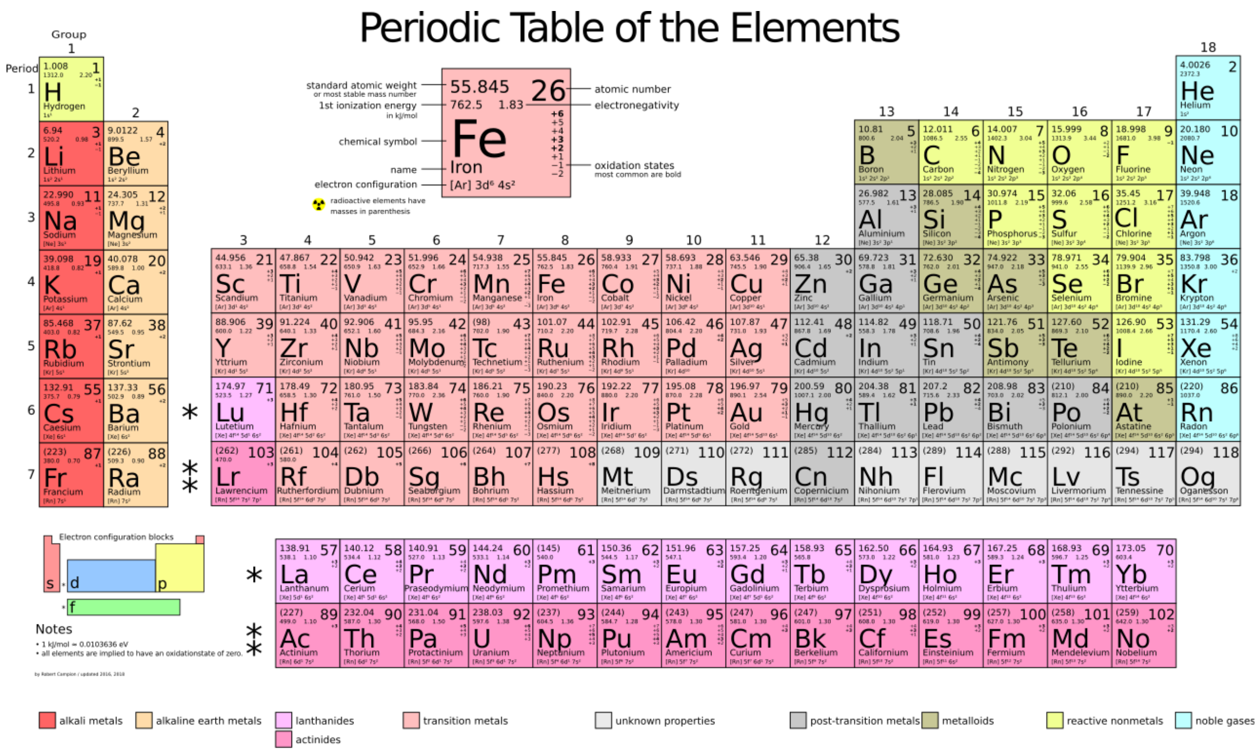
Biostratigraphy table



*Brachiopods, gastropods and bivalves are all members of the mollusca phylum.

Chemistry

Periodic Table



Geochemically useful elements

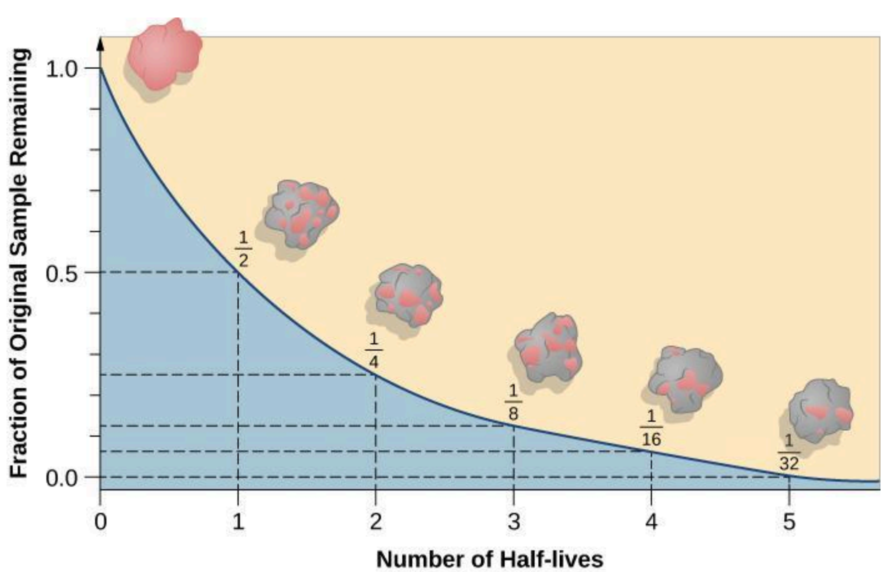
Half-life of radioactive isotopes

Half-life ($t_{1/2}$) is the time in which half of the original number of nuclei decay. This is a statistical process, therefore each nucleus has a 50% chance of surviving for a time equal to one half-life, $t_{1/2}$. Thus, the number of radioactive nuclei decreases from N to N/2 in one half-life.
This decay is exponential, as illustrated by the graph (left).

The half-lives of radioactive isotopes vary from as short as 10^{-23} s for the most unstable, to more than 10^{16} y for the most stable. Irrespective of the isotope, after 10 half-lives, less than 0.1% of the parent material remains. Given small initial sample sizes, the ability to measure the tiny remnants of the parent isotope after 10 or more half-lives is exceeded even if some does remain. Some useful geoscience isotopes are listed below.

Parent Isotope	Daughter Decay product	Half-Life
Tritium (^{3}H)	Helium (^{2}He)	12.43 years*
Carbon-14 (^{14}C)	Nitrogen-14 (^{14}N)	5730 years
Potassium-40 (^{40}K)	Argon-40 (^{40}Ar)	1.25 billion years
Argon-40 (^{40}Ar)**	Argon-39 (^{39}Ar)	1.25 billion years
Rubidium-87 (^{87}Rb)	Strontium-87 (^{87}Sr)	48.8 billion years
Uranium-235 (^{235}U)	Lead-207 (^{207}Pb)	704 million years

*Mid-1960s peak due to atmospheric nuclear testing
**More accurate than K/Ar



Commonly used dating methods

Name of Method	Age Range of Application	Material Dated	Methodology
Radiocarbon	1 - 70,000 years	Organic material such as bones, wood, charcoal, shells	Radioactive decay of ^{14}C in organic matter after removal from biosphere
K-Ar dating	1,000 - billions of years	Potassium-bearing minerals and glasses	Radioactive decay of ^{40}K in rocks and minerals
Uranium-Lead	10,000 - billions of years	Uranium-bearing minerals	Radioactive decay of uranium to lead via two separate decay chains
Uranium series	1,000 - 500,000 years	Uranium-bearing minerals, corals, shells, teeth, $CaCO_3$	Radioactive decay of ^{234}U to ^{230}Th
Fission track	1,000 - billions of years	Uranium-bearing minerals and glasses	Measurement of damage tracks in glass and minerals from the radioactive decay of ^{238}U
Luminescence (optically or thermally stimulated)	1,000 - 1,000,000 years	Quartz, feldspar, stone tools, pottery	Burial or heating age based on the accumulation of radiation-induced damage to electron sitting in mineral lattices
Electron Spin Resonance (ESR)	1,000 - 3,000,000 years	Uranium-bearing materials in which uranium has been absorbed from outside sources	Burial age based on abundance of radiation-induced paramagnetic centers in mineral lattices
Cosmogenic Nuclides	1,000 - 5,000,000 years	Typically quartz or olivine from volcanic or sedimentary rocks	Radioactive decay of cosmic-ray generated nuclides in surficial environments
Magnetostratigraphy	20,000 - billion of years	Sedimentary and volcanic rocks	Measurement of ancient polarity of the earth's magnetic field recorded in a stratigraphic succession
Tephrochronology	100 - billions of years	Volcanic ejecta	Uses chemical fingerprints and age of volcanic deposits to establish links between distant stratigraphic successions

Stable isotopes

Stable isotopes of light elements like hydrogen, carbon, nitrogen, oxygen, and sulfur, are commonly used in geochemistry to understand Earth's processes. The ratios of naturally occurring chemical isotopes are analysed to explain a wide range of geological processes, including paleoclimate, hydrology, biogeochemistry, and ore deposit formation. There are two key terms to understand:

Fractionation:
Stable isotopes of an element can separate during physical and chemical processes, leading to variations in isotope ratios.

Delta Values (δ):
Stable isotope ratios are often expressed as delta values (δ), which are relative to a standard.

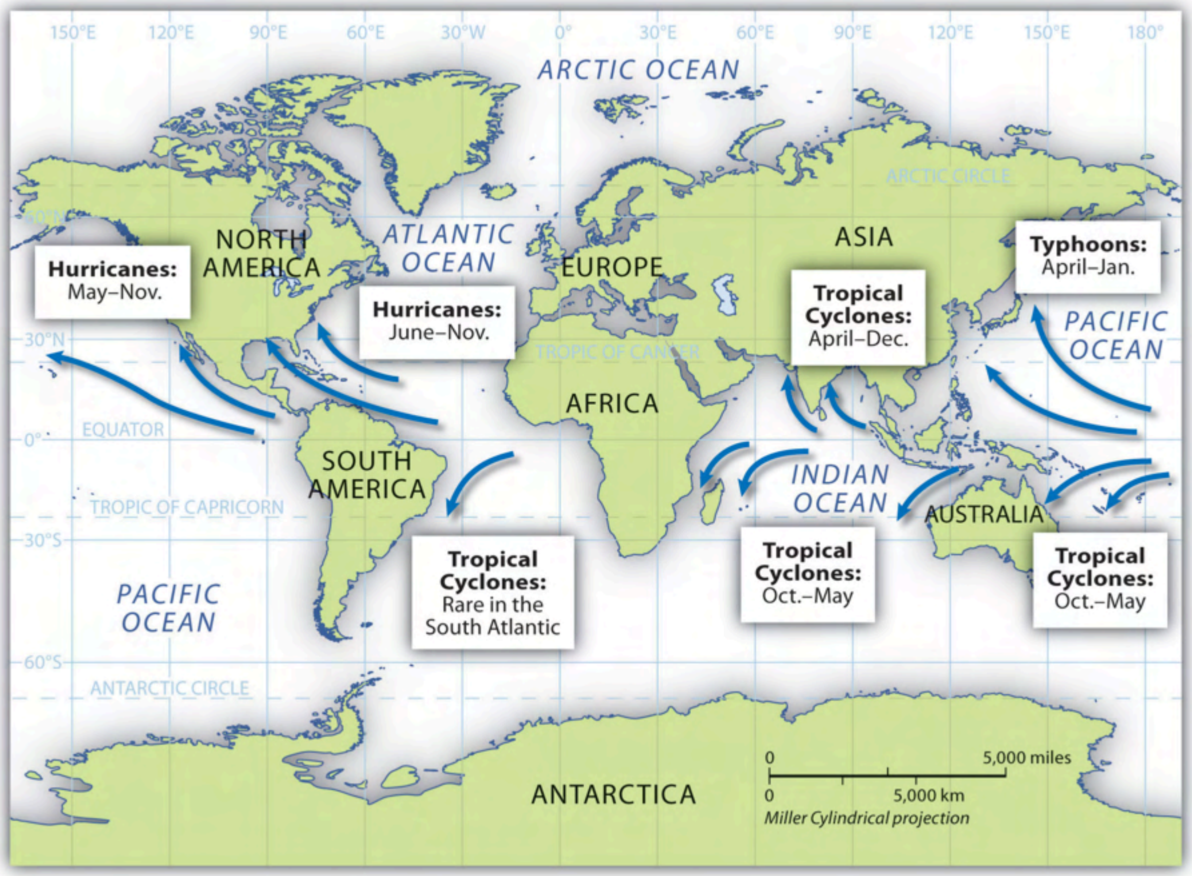
Element	**Stable Isotopes**	**Applications in Geochemistry**
Hydrogen (H)	^{1}H (Protium), ^{2}H (Deuterium)	Temperature indicators in water and ice, paleoclimate studies, groundwater hydrology
Carbon (C)	^{12}C, ^{13}C	Paleoclimate studies, organic matter tracing, carbon cycle research
Nitrogen (N)	^{14}N, ^{15}N	Tracing nitrogen sources and cycling in ecosystems, environmental studies
Oxygen (O)	^{16}O, ^{17}O, ^{18}O	Temperature indicators in water and ice, oxygen isotope fractionation in rocks and minerals, atmospheric studies
Sulfur (S)	^{32}S, ^{34}S	Tracing sulfur sources and cycling in ecosystems, hydrothermal vent studies
Strontium (Sr)	^{86}Sr, ^{87}Sr, ^{88}Sr	Tracing ore sources and mineral deposits, geochronology, paleoceanography
Lead (Pb)	^{206}Pb, ^{207}Pb, ^{208}Pb	Tracing ore sources and mineral deposits, environmental pollution studies, geochronology

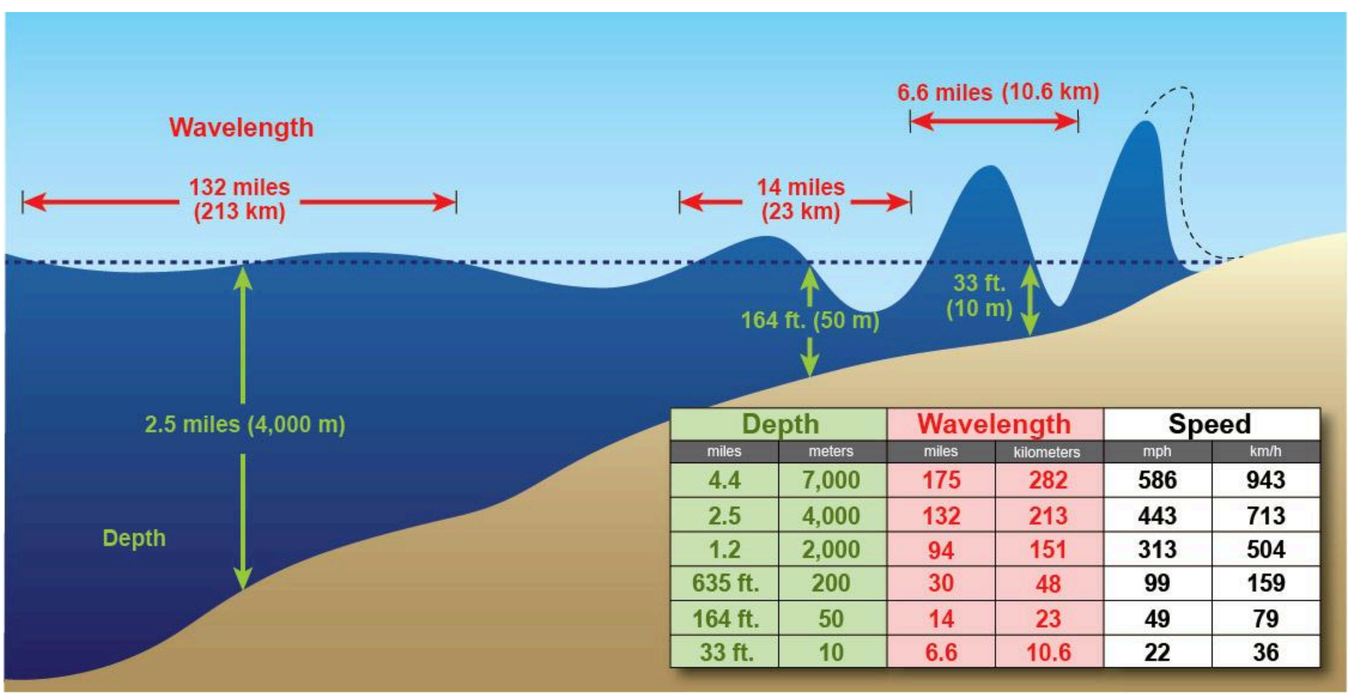
Atmospheric Gases

Gas	Atmospheric Concentration	Residence time	GWP*/ 20 a
Water vapor	Highly variable - other values estimated assuming dry atmosphere	~10 days	
Nitrogen (N_2)	78%	1.6 10e7 a	
Oxygen (O_2)	21%	3,000-10,000 a	
Argon (Ar)	1%		
Helium (He)	5.24 ppm	10e6 a	
Carbon dioxide (CO_2)	0.04%	3-4 a	1
Nitrous oxide (N_2O)		121 a	273
Methane (CH_4)	1.92 ppm	12 a	80
CFCs		Weeks to 1000s a	10s-1000s
Hydrogen (H_2)		4-8 a	
Carbonyl sulfide (COS)		~2a	
Ozone (O_3)	0.07 ppm	100 days	
Carbon disulfide (CS_2)		40 days	
Carbon monoxide (CO)	0.10 ppm	~60 days	
Formaldehyde (CH_2O)		5-10 days	
Sulfur dioxide (SO_2)		days to weeks	
Ammonia/ium (NH_3 + NH_4^+)	trace	2-10 days	
Nitrogen dioxide (NO_2)		0.5-2 days	
Nitrogen oxide (NO)		0.5-2 days	
Hydrogen sulfide (H_2S)		1-5 days	
Dimethyl sulfide (CH_3SCH_3)		0.7 days	

*GWP = Global Warming Potential relative to CO_2

Hydrology / Meteorology

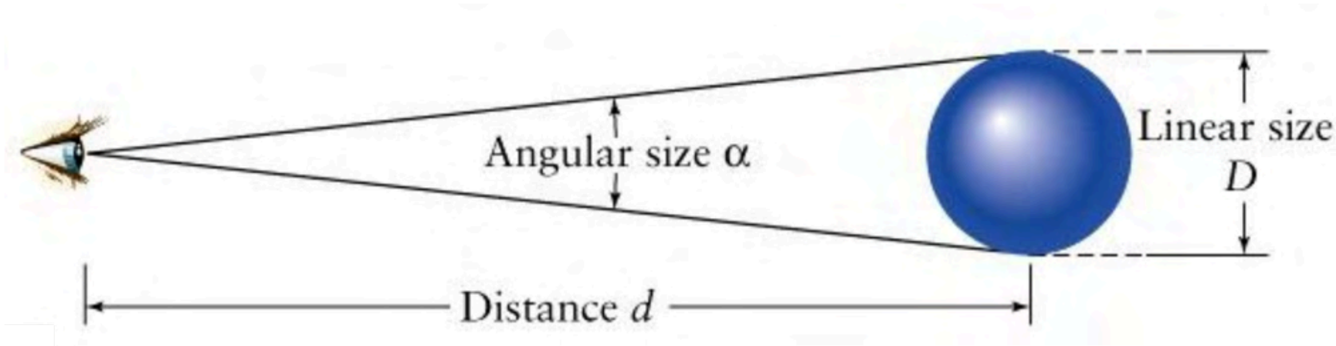




Depth		Wavelength		Speed	
miles	meters	miles	kilometers	mph	km/h
4.4	7,000	175	282	586	943
2.5	4,000	132	213	443	713
1.2	2,000	94	151	313	504
635 ft.	200	30	48	99	159
164 ft.	50	14	23	49	79
33 ft.	10	6.6	10.6	22	36

Astronomy

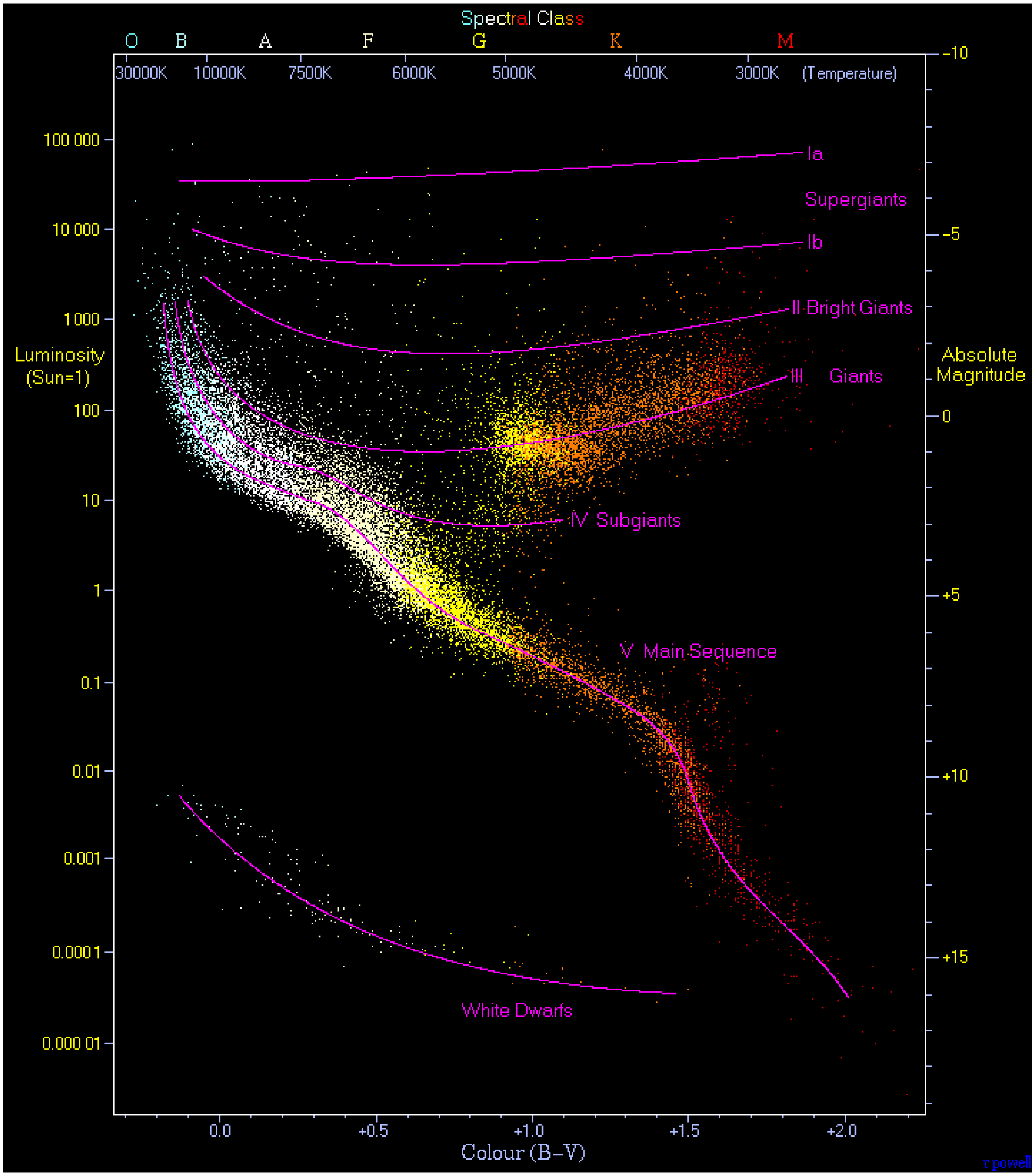
Angular Size



$\alpha = \frac{D}{d}$

Where α is measured in radians.

Hertzsprung-Russell Diagram



Stellar Lifetimes

Spectral Type	O5	B0	A0	F0	G0	K0	M0
Mass (solar)	40	15	3.5	1.7	1.1	0.8	0.5
B–V	**–1.2**	**–0.3**	**0.0**	**0.3**	**0.6**	**0.8**	**1.4**
MS Lifetime	1.0×10^{6}	1.1×10^{7}	4.4×10^{8}	3.0×10^{9}	8.0×10^{9}	1.7×10^{10}	5.6×10^{10}

MS = main sequence

Geologist Roxanne Stone and her brother Orson go for a walk one lovely autumn day in the hills east of Perth, WA. She tells him that while they're not walking on *the* oldest rocks on Earth, they are on the same chunk of continental crust (called a 'craton') as the oldest mineral grains ever discovered. She shows him a map of the major Australian geologic regions, pointing out Jack Hills (site of the famously old 4.463 Ga, zircon crystals) and Perth are both located on the Yilgarn Craton.

1. According to the International Geochronological Chart, in which Era did these minerals crystallise?
    a. Hadean
    b. Proterozoic
    c. Archaean
    d. Paleozoic
    e. Mesozoic
    f. Phanerozoic

2. What dating method could NOT be used to determine the age of rocks or minerals this old?
    a. ^{14}C
    b. U-Pb
    c. K-Ar
    d. Rb-Sr
    e. Fission track
    f. Ar-Ar

Rocks that have been around for several billion years have pretty complex histories. Roxanne tells her brother that the coolest thing about being a geologist is learning how to read the stories the rocks have to tell and unraveling mysteries like a forensic scientist. Orson says this is why he loves walking with her, discovering clues, finding fingerprints, and puzzling out 'who done it.'

3. What types of adventures does Orson correctly presume these rocks have had?
    a. Weathering and erosion
    b. Metamorphism at high temperatures and pressures
    c. Compression and uplift in mountain-building mashups
    d. Subduction into the deep mantle
    e. All of the above
    f. A, B & C but not D

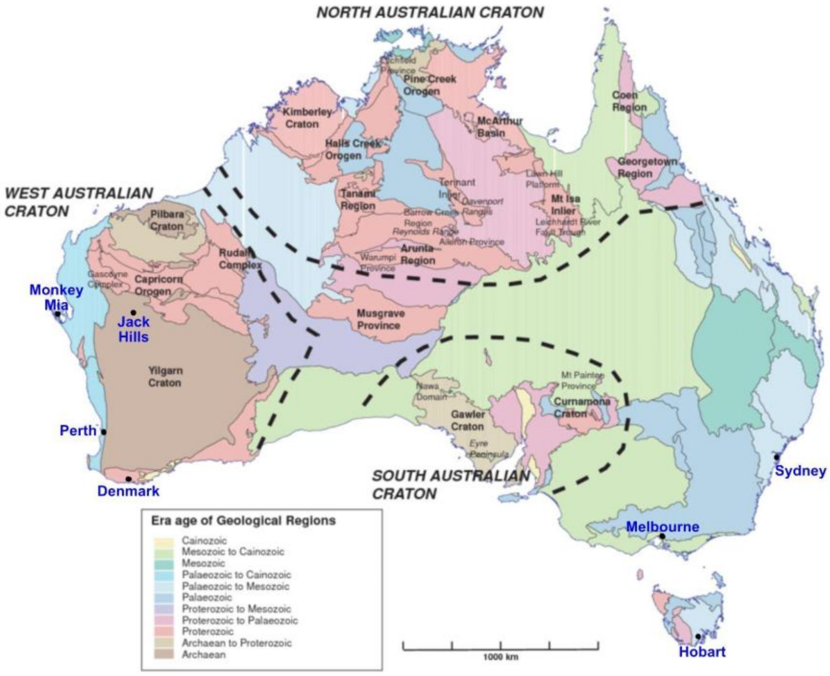


Figure 1: Map of Australia's broad geologic subdivisions and ages. Key locations are marked in blue. Image modified from: Geoscience Australia.

She tells him that zircon is pretty nifty mineral that can show up in all kinds of rocks, can be a huge range of colours and sizes, and although it has a rather simple mineral formula [$Zr(SiO_4)$], it can contain traces of radiogenic or Rare Earth Elements (REEs), particularly uranium (300-600 ppm). It has high Mohs hardness (7.5), high melting temperature (2550 °C), diamond-like or glassy lustre, and a conchoidal fracture but no good cleavage. Then she challenges him to reason out which of these characteristics make zircon useful for the following purposes:

4. *Radiometric dating of igneous rocks*
    a. Simple chemical formula + fracture pattern
    b. Uranium/REE content + high melting temperature
    c. High hardness + fracture pattern
    d. High melting temperature + simple chemical formula
    e. Lustre + Uranium/REE content
    f. Fracture pattern + high melting temperature

5. *Resilience during transport and deposition in sedimentary rocks*
    a. Simple chemical formula + fracture pattern
    b. Uranium/REE content + high melting temperature
    c. High hardness + fracture pattern
    d. High melting temperature + simple chemical formula
    e. Lustre + Uranium/REE content
    f. Fracture pattern + high melting temperature

6. *Use as a gemstone*
    a. Simple chemical formula + fracture pattern + lustre

   b. Uranium/REE content + high melting temperature + fracture pattern
   c. High hardness + lustre + fracture pattern
   d. High melting temperature + simple chemical formula + lustre
   e. Lustre + Uranium/REE content + high melting temperature
   f. Fracture pattern + high melting temperature + high hardness

7. Orson is more into math than his sister, so he challenges her with a question of his own. Assuming the Jack Hills zircons contained 600 ppm U when they formed, approximately how much would they contain today?
   a. Between 5-10 ppm
   b. About 19 ppm
   c. About 38 ppm
   d. Between 38-75 ppm
   e. At least 150 ppm
   f. At least 200 ppm

Roxanne points out a strange cleft in the cliff face and challenges Orson to a quick round of logic puzzles after pointing out a few clear observations:

- The rocks on either side of the cleft are the same colour, have the same texture and crystal size (5-30 mm).
- The rocks within the cleft are darker with barely visible crystals, requiring a hand lens to notice at all (1-3 mm).
- Both rock types are completely crystalline, with a randomly oriented interlocking texture.

Figure 2: Roxanne (~1.5 m) points out the unusual cleft in the cliff face.

8. First, she asks him to explain how these rocks formed and what evidence he has to support his conclusion. What does Orson correctly say?

a. They are both intrusive igneous rocks, having cooled slowly from magma (although at two distinct rates) beneath the Earth's surface because this would give the crystals time to grow without being squashed or stretched into alignment.
b. The lighter coloured, coarser rocks are intrusive igneous, while the darker rocks are extrusive igneous. Both cooled from magma, but the smaller crystals reveal more rapid cooling above ground.
c. The lighter coloured, coarser rocks are intrusive igneous, having cooled slowly beneath the Earth's surface, while the darker rocks are sedimentary, as only deposition of mud and silt in still water can produce such fine-grained rocks.
d. They are two distinctly different types of sedimentary rocks. The coarser grained, lighter coloured rocks must have formed in a high energy environment like a river, whereas the darker fine grained rocks formed in a low energy environment like the bottom of a large lake.
e. They are both the same type of sedimentary rock but differential weathering has darkened the rocks in the cleft while reducing the crystal size.
f. The lighter coloured coarse rocks must be intrusive igneous, having cooled slowly from magma, whereas the darker finer rocks must be metamorphic, having been squeezed between the two sides.

9. Then she challenges him to determine the order formation and to explain his reasoning. How does Orson correctly respond?
    a. The surrounding must have formed first for the darker rock to cut across.
    b. The darker rock must have formed first for the lighter surrounding rocks to form around.
    c. The two different rocks must have formed at the same time because they are found at the same place.
    d. The lighter rock on the left side must have formed first, followed by the darker rocks in the centre, then the lighter rocks on the right, with the lighter rocks forming a kind of dark-rock sandwich that has then been tipped up on its side.
    e. The lighter rocks must have formed first followed by the darker rocks because Bowen's reaction series indicates this progression for magma evolution.
    f. The darker rocks must have formed first in order to be subsequently squeezed by the lighter rocks.

10. Next she challenges him to explain why the cleft formed in the cliff. What is his most logical reply?
    a. The darker rocks must be more susceptible to weathering and erosion, therefore the cliff face recedes more quickly where they were.
    b. The lighter rocks must be more susceptible to weathering and erosion, therefore the cliff face recedes more quickly where they were.
    c. The darker rocks absorb more incoming sunlight, therefore they heat up then cool down more during the day than the surrounding rocks and weaken more rapidly.
    d. The lighter rocks absorb more incoming sunlight, therefore they heat up then cool down more during the day than the rocks within the cleft and weaken more rapidly.

e. The sediments within the cleft are clearly more organic rich, therefore they are more attractive to worms and other burrowing critters that live in sediments.
f. The rocks within the cleft are clearly more deformed and therefore mechanically weaker than the surrounding rocks.

11. Using nothing more than the shadows cast on the rocks at the time of day (roughly 11 a.m. and 1:30 p.m.) and their latitude (~32°S), Roxanne challenges Orson to determine what direction he's facing whilst looking at her pointing at the cliff face. What direction does he correctly work out?
    a. N
    b. S
    c. E
    d. W
    e. SE
    f. NW

Figure 3: Photo 1 (left; same as Figure 2) taken at 10:30 a.m. and photo 2 (right) taken at 1:30 p.m. from slightly different vantage points.

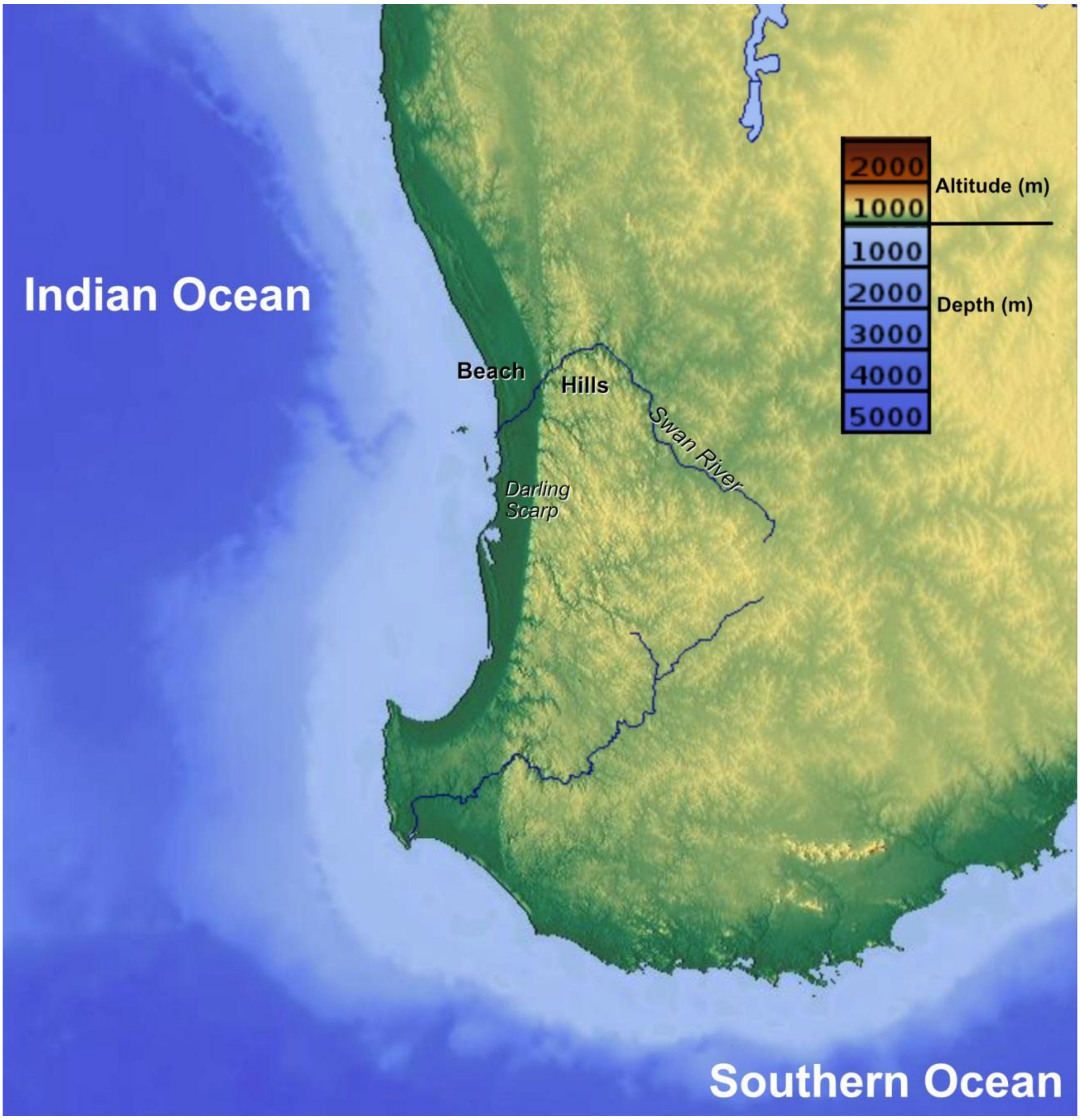


Figure 4: Southwestern Australia's topography and key geographic locations. Image modified from: maps-for-free.com.

Their cousin Gemma calls them from one of Perth's fantastic beaches about 30 km west (Fig. 4) while they're out walking. As they chat, they compare the similarities and differences they can see in the sediment at each location.

Gemma notes that the sand grains on the beach are smaller, more rounded and each grain is a single colour, although the handful she picks up reveals a mix of colours similar to what Roxanne and Orson observe. They find coarse sand to gravel size sediments, which look very much like the surrounding rocks.

Figure 5: Gemma's beach sand (left); Roxanne & Orson's gravelly sediments that are nearly indistinguishable from the parent rock (right).

12. What does Gemma suggest to explain these observations?
    a. Their sediments started from the same or similar rock type, but those at the beach have been transported further, being winnowed and separated by water and wind as they went.
    b. Their sediments started from the same or similar rock type, but those at the beach were from a much finer-grained rock.
    c. Their sediments started from very different rocks, but only the same types of minerals remain due to chemical separation in water.
    d. Their sediments started from very different rocks, but minerals metamorphose into the same low temperature, low pressure polymorphs given enough time at surface conditions.
    e. It's impossible to say where the sediments at the beach came from because all the world's oceans are connected.
    f. There is no possible relationship between the sediments because the two locations are nearly 50 km apart!

Gemma tells her friend Shelly Waters about the conversation with her cousins as the two of them wander along the beach. This causes them to pay closer attention to the changes beneath their feet. They collect four distinct deposits along the length of the same beach (Fig. 6).

13. What can they correctly conclude from their observations?
    a. The four beach deposits were derived from distinct sources and deposited in neighbouring environments by different transport mechanisms.
    b. The four sands are compositionally distinct as the grains have grown to different sizes.

c. The four sands are the same composition, just broken down to different sizes by different weathering processes.
d. Four deposits of such different composition and grain sizes could not naturally form in neighbouring environments, therefore at least one must have been deposited by humans.
e. A handful of shells or gravel mixed with shells is not a ‘sand’, therefore they have only walked across two distinct beach deposits.
f. Neither a handful of shells, a monomineralic collection of uniform grains, nor a gravelly mix of shells and rocks is actually sand, therefore there is only one true sand here.

Figure 6: The four different handfuls of beach deposits scooped up by Gemma and Shelly along their walk.

Shelly asks Gemma if she wants to see something cool. Warily, Gemma agrees as Shelly pulls out a bottle marked “HCl”, squeezes a few drops on the handful of shells and giggles as they turn into a frothy mass of bubbles

14. Which of these equations accurately describes the reaction occurring?
a. $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$
b. $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + 2H_2O$
c. $CaCO_3 + 2HCl \rightarrow CaCl_2 + 2CO_2 + 2H_2O$

d. $2CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$

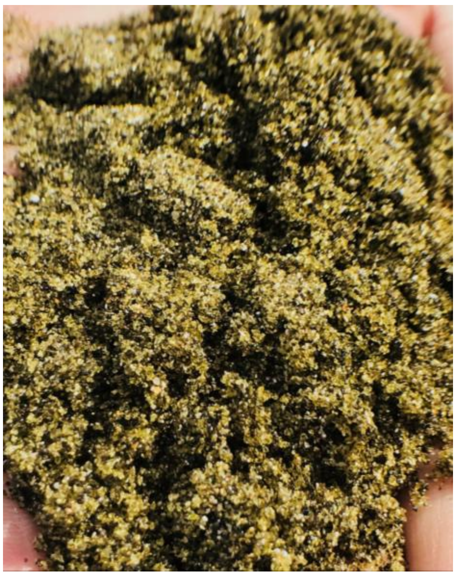
e. $2CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + 2H_2O$

f. $2CaCO_3 + 2HCl \rightarrow CaCl_2 + 2CO_2 + 2H_2O$

15. Shelly is a bit surprised by her friend's stony reaction to such a cool little experiment. Gemma explains she doesn't think it's "*cool to contribute to climate change.*" How has Shelly contributed to climate change with this experiment?
    a. She released CO_2, a greenhouse gas
    b. She released water vapour, the most powerful greenhouse gas
    c. She released $CaCl_2$, a chlorofluorocarbon, one of the most powerful greenhouse gases
    d. She used up a bit of HCl, a powerful atmospheric cooling agent
    e. She released two potent greenhouse gases, CO_2 and $CaCl_2$
    f. She released three potent greenhouse gases, CO_2, water vapour and $CaCl_2$

Giving Gemma a moment to blow off steam, Shelly posts their sand photos and quickly receives an enthusiastic reply from her friend Sandra Shore, who is on holiday in Hawai'i. *"Check out the wild varieties of sand I've spotted on the Big Island!"* she replies. "*It's amazing how much you can figure out about the local geology just from a toe-full of sand! And I love how the third one makes my feet look like poppyseed bagels* 😆 *"*

16. What can Sandra determine just by looking at the sand beneath her feet?
    a. They must have formed from the breakdown of three different rock units because they are very different colours.
    b. They must be different ages because the grains are different sizes.
    c. They must have been transported different distances because the grains are different sizes.
    d. They must have come from rocks of significantly different ages because they are very different colours.
    e. They must be composed of carbonates because they're on a beach.
    f. They must be composed of carbonates because they're sticky.



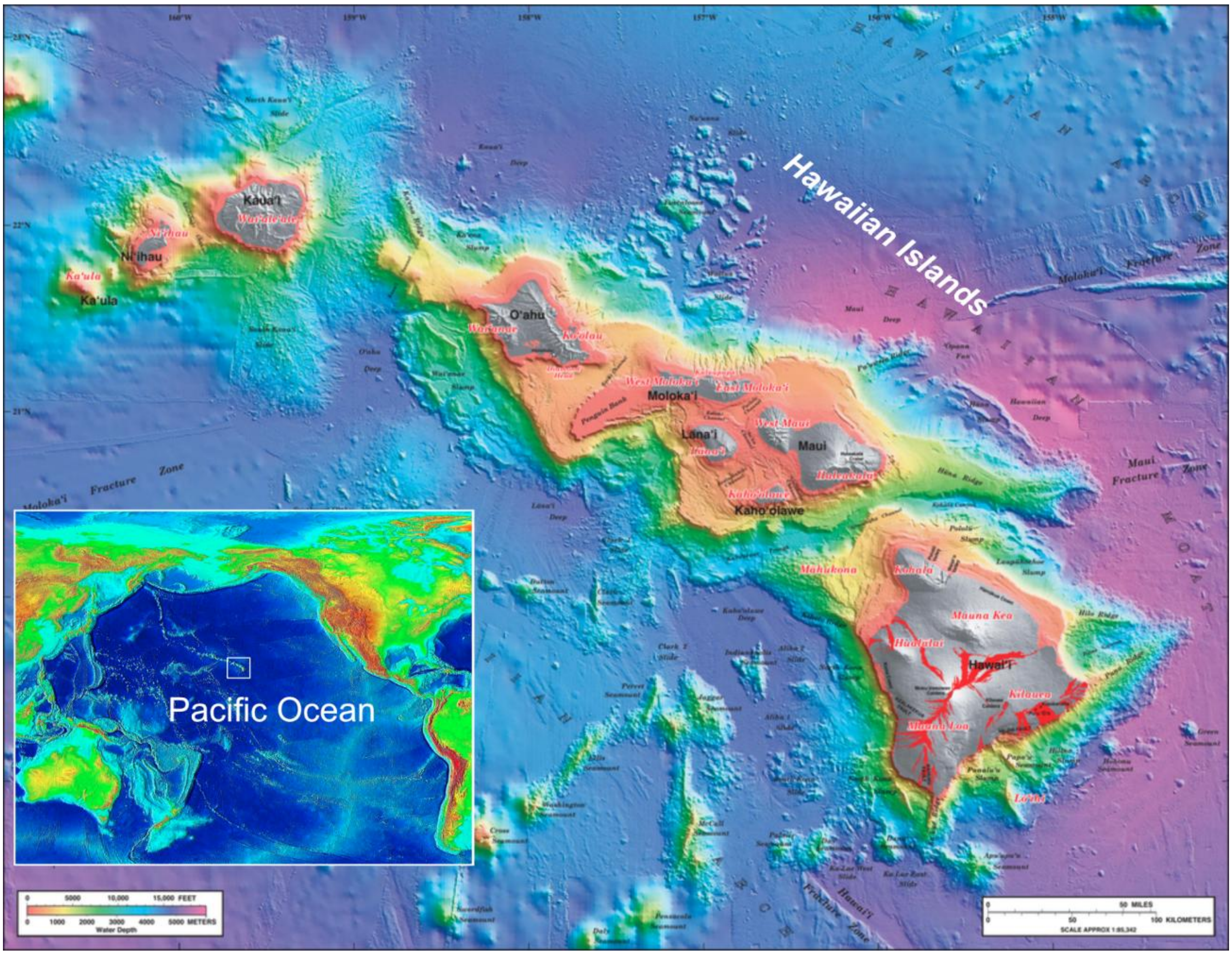


Figure 7: Sandra Shore's holiday photos from the Big Island of Hawai'i and digital postcard.

Gemma and Shelly run into their friends and avid surfers Wade Beachly and Ariel Windlass. They've found a message in a bottle with, "*Help! I've been captured by pirates!"* translated into Spanish, Arabic, Mandarin, Dutch and Hindi. Their initial thought is it must have come from some poor soul near Somalia, where modern-day pirates continue to trawl shipping lanes. Ever the skeptic, Gemma pulls out her phone to share an ocean circulation tool to help visualise the possible route such a bottle could have followed (Fig. 8). She challenges her friends to think critically about where the bottle could have come from.

17. Who comes up with the most logical conclusion?
    a. Shelly is convinced it must have crossed the Indian Ocean from Somalia based on the clear message involving modern piracy and most common languages spoken along the trade routes it would have crossed.
    b. Wade is convinced it must have travelled from somewhere around Madagascar (possibly sent out by mischievous penguins) based on the prevailing wind direction in the southern Indian Ocean.
    c. Ariel is convinced it must have travelled from Antarctica (possibly sent out by tariff-dodging emperor penguins) based on the prevailing southerlies blowing from the Southern Ocean.
    d. Shelly is convinced it must have come from Denmark (the town near the southernmost point of W.A., not the country; possibly sent out by cheeky little Aussie penguins) based on the prevailing ocean surface currents.
    e. Wade is convinced it must have come from Monkey Mia (the westernmost point of W.A.; possibly sent by super advanced stromatolites) based on prevailing ocean surface currents.
    f. Ariel is convinced it must have travelled from Indonesia based on the prevailing northerlies blowing down the coast of W.A.

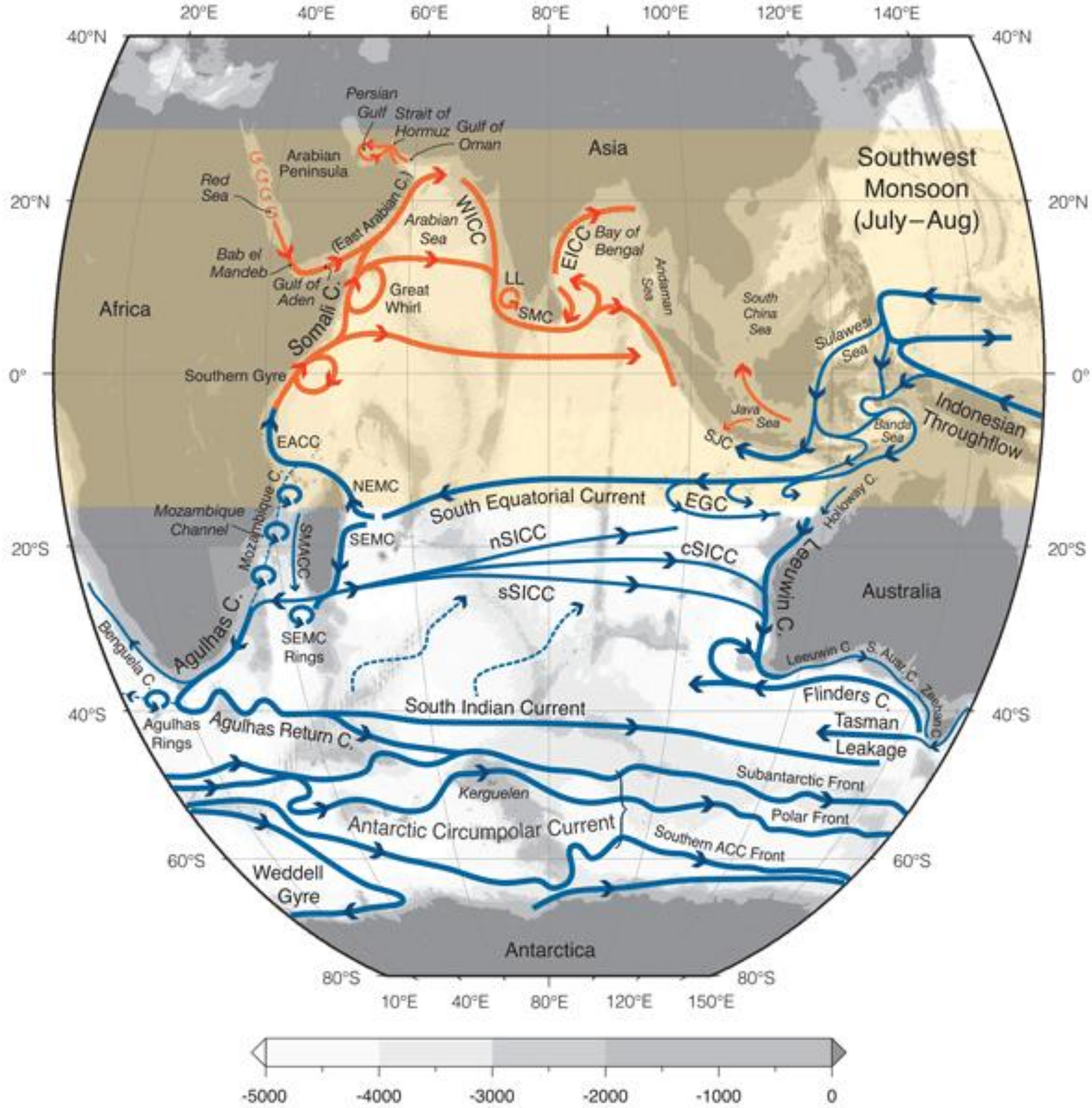


Figure 8. Currents of the Indian Ocean and adjoining water bodies. Image from: Phillips, H.E., et al (2021) https://doi.org/10.5194/os-17-1677-2021

Speaking of winds and waves, Gemma and Shelly wonder what makes for good surf conditions. Ariel informs them that wind direction and speed have a major effect on the type of waves that set up. She loves smooth, clean barrelling waves for long rides and explains that light (ideally under 20 kph) offshore winds, blowing from land towards the ocean, provide the ideal ride.

18. Based on the wind records for Perth (Fig. 9), which month provides Ariel and Wade the best surfing conditions?
    a. February
    b. April
    c. June
    d. August
    e. October
    f. December

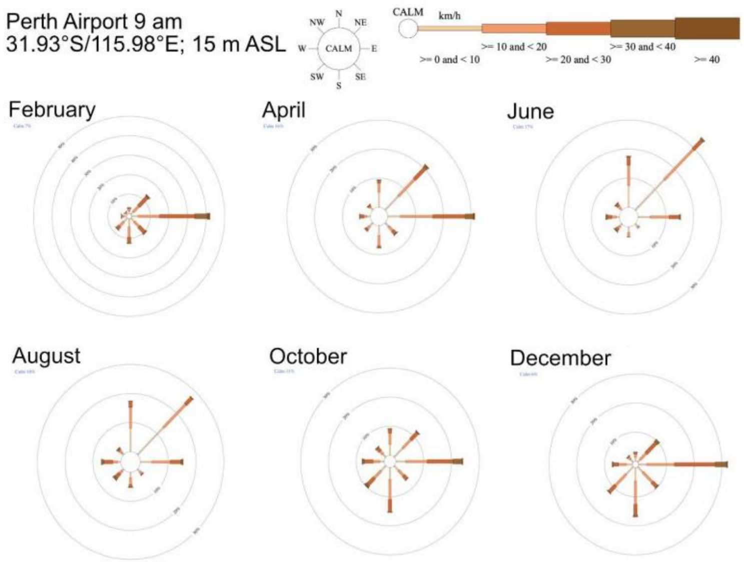


Figure 9: Seasonal variations in measured wind vector frequency for Perth, W.A. The rose diagram limbs extend in the direction from which the wind blows. Data from Australian Bureau of Meteorology.

Watching the surf rolling in and thinking about what they've noticed along the beach, Wade ponders the wave-like structures of dunes. He wonders whether they fit Orson's definition of a wave: *a disturbance that transfers energy from one place to another in an organised way*; *having amplitude, frequency, time period, speed, and wavelength.*

19. Who poses the most correct argument(s) for or against the definition of dunes as waves?
    a. Wade says 'no, not waves' because dunes are composed of discrete sand grains, not a continuous medium for transferring energy.
    b. Ariel says 'no, not waves' because dunes don't have a time period or speed.
    c. Shelly says 'yes, waves' because dunes have amplitude and wavelength.
    d. Gemma says 'yes, waves' because wind-blown sand acts as a medium to transfer energy from one place to another in an organised way.
    e. Wade and Ariel are correct.
    f. Shelly and Gemma are correct.

20. Considering the abundant sand supply locally, which dune type (Fig. 10) should the group observe around them?
    a. Barchan
    b. Reversing
    c. Star
    d. Transverse
    e. Linear
    f. Barchanoid ridge

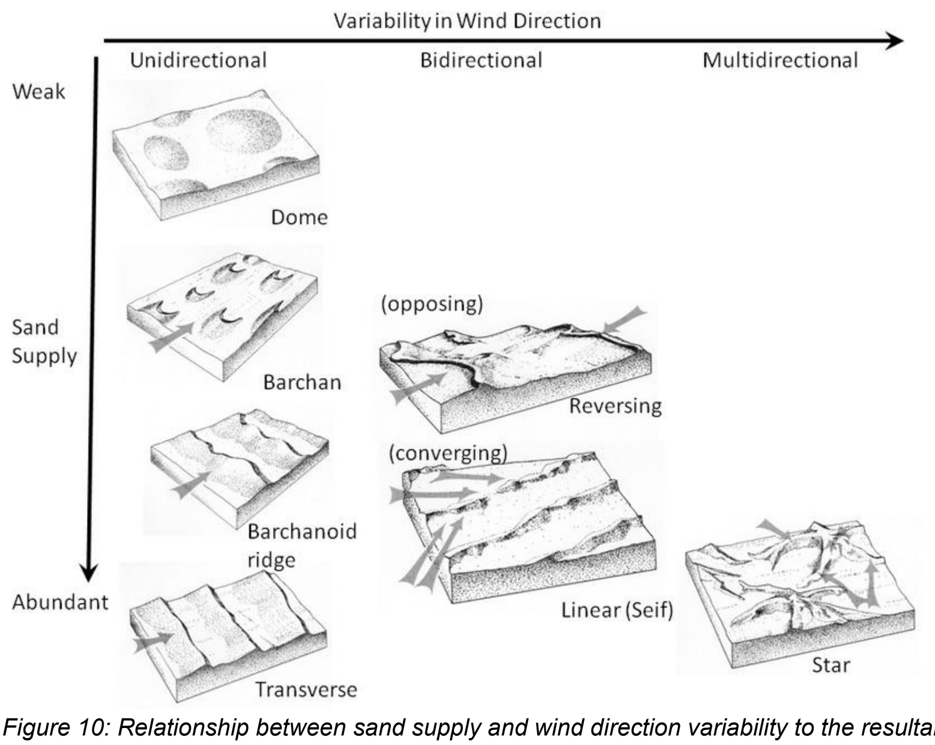


Figure 10: Relationship between sand supply and wind direction variability to the resultant dune forms. Image: McKee 1979 USGS.

Ariel happens to have a 10x magnification hand lens and shows the others pitting on white sand grains (Fig. 11). She explains this only occurs when minerals of the same hardness bash into each other without a liquid layer to buffer the blows.

21. What do the others correctly conclude?
    a. Wade says these grains must have been transported by wind to cause the pitting.
    b. Shelly says the grains are not calcite because they didn't fizz when she put HCl on them.
    c. Gemma says they must all be the same mineral because they are all pitted equally.
    d. Wade says these grains must have been transported by wind because they are all approximately the same size.
    e. None of their conclusions are correct.
    f. All of their conclusions are correct.

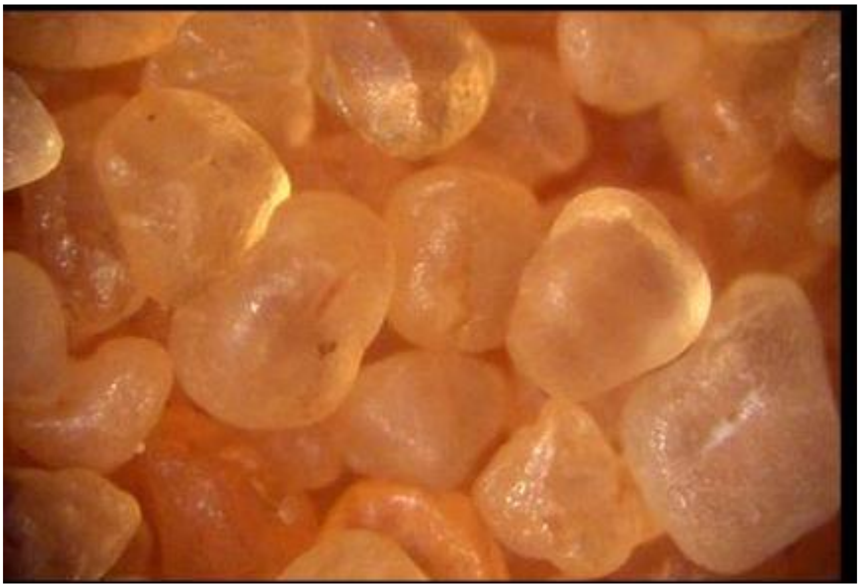


Figure 11: Ariel's magnified frosted sand grains.

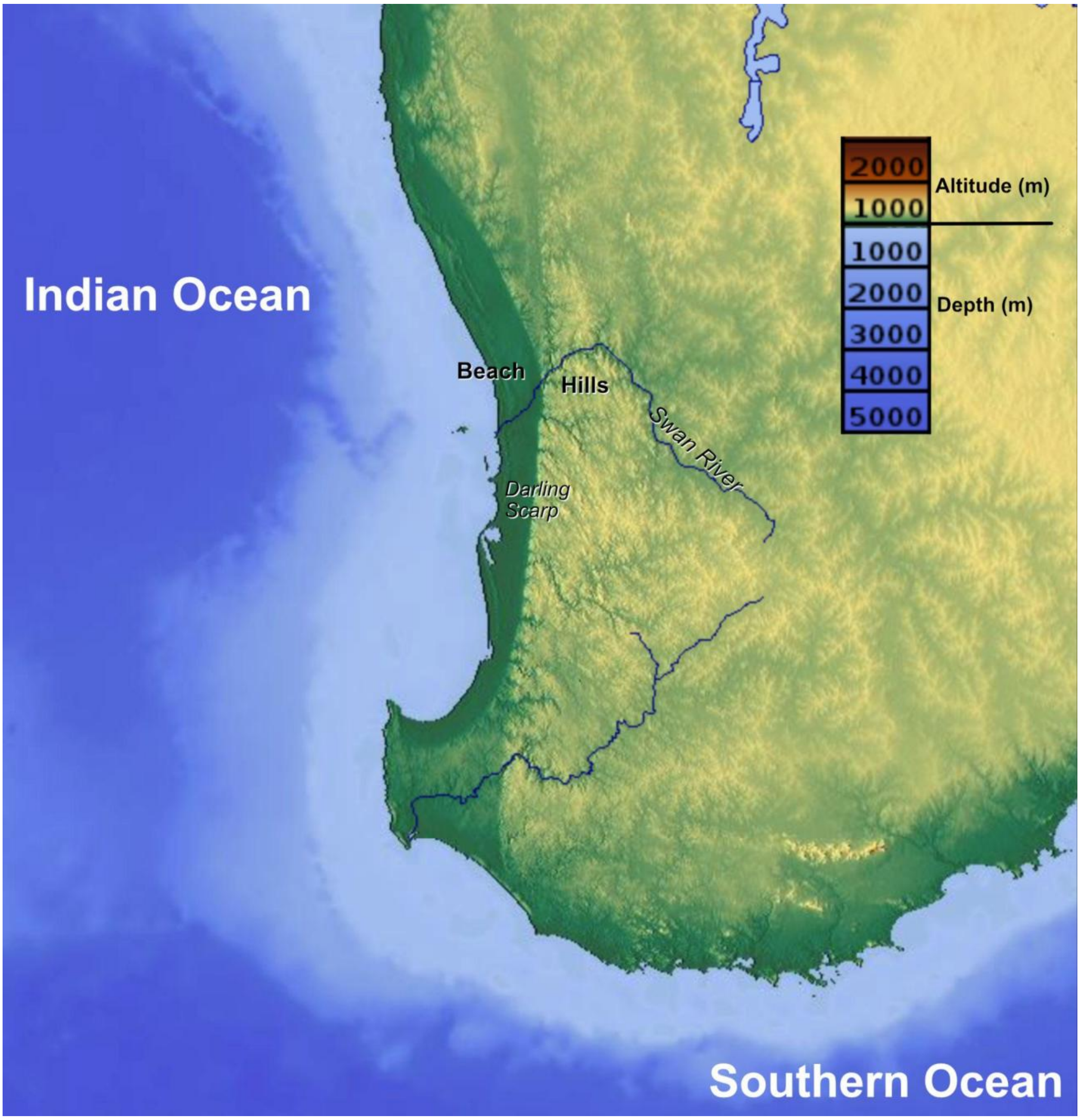


Figure 4: Southwestern Australia's topography and key geographic locations. Image modified from: maps-for-free.com.

The four friends catch up with Orson and Roxanne for a picnic dinner along the Swan River to chat about their day's adventures. Orson jokes about "coming back down after being at altitude all day," having been about 375 m above sea level on their walk in the hills.

22. At sea level, what will Orson experience relative to the air pressure on his walk?
    a. He will be a bit light headed.
    b. He will be under a little more pressure.
    c. He will be experiencing exactly the same air pressure as before.
    d. Impossible to determine, because the effect of air pressure is specific to latitude /longitude, not just elevation.
    e. Impossible to determine, because the effect of air pressure varies more due to humidity than elevation.
    f. Impossible to determine, because the effect of air pressure varies more due to proximity to the ocean than elevation.

Ariel shares that the mean atmospheric pressure at sea level is 101.325 kPa, and that at low altitudes above sea level, the air pressure changes by approximately 1.2 kPa (12 hPa) per 100 metres of elevation change. This prompts Gemma to share the graph in Figure 12.

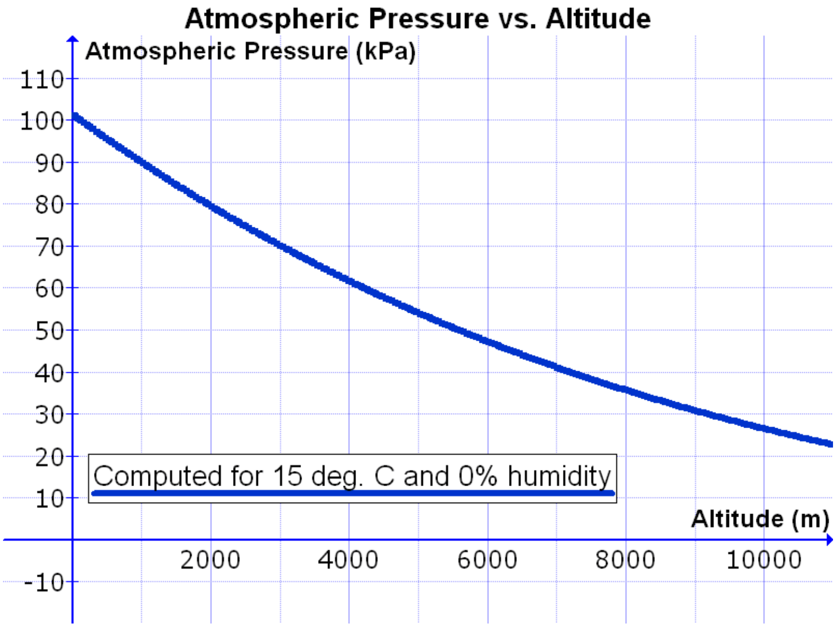


Figure 12: Gemma's altitude-dependent air pressure variation graph.

23. What do they conclude was the approximate air pressure experienced by Orson during his walk?
    a. 64 kPa
    b. 91 kPa
    c. 97 kPa
    d. 100 kPa
    e. 101 kPa
    f. 102 kPa
    g. 105 kPa

Ariel continues, sharing that the water-carrying capacity of air depends on its temperature (Fig. 13). This is why meteorologists often discuss the *relative humidity* of air: a ratio of the suspended water vapour divided by the maximum water vapour that could be suspended at that temperature. *Dew Point* is the temperature to which a particular air packet must be cooled to become saturated with water vapour (Fig. 14).

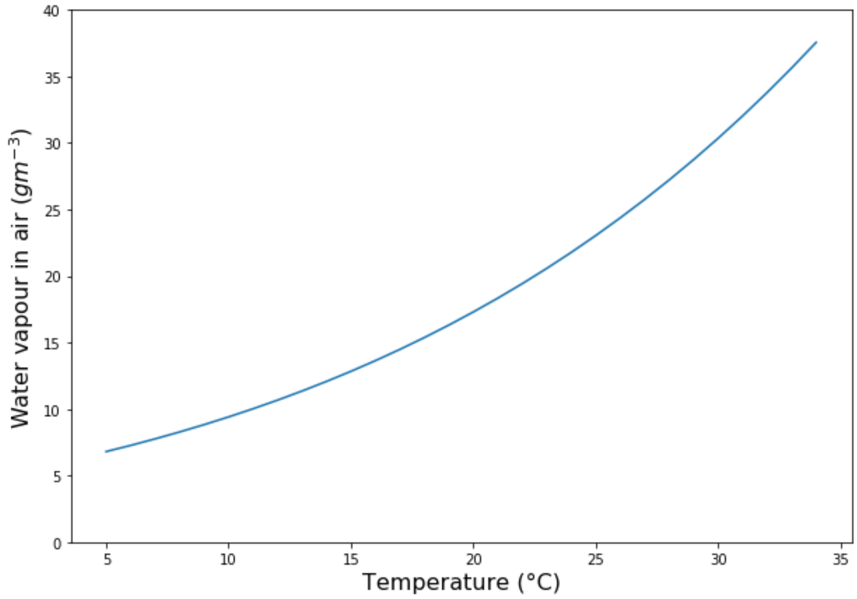


Figure 13: Moisture-carrying capacity of air.

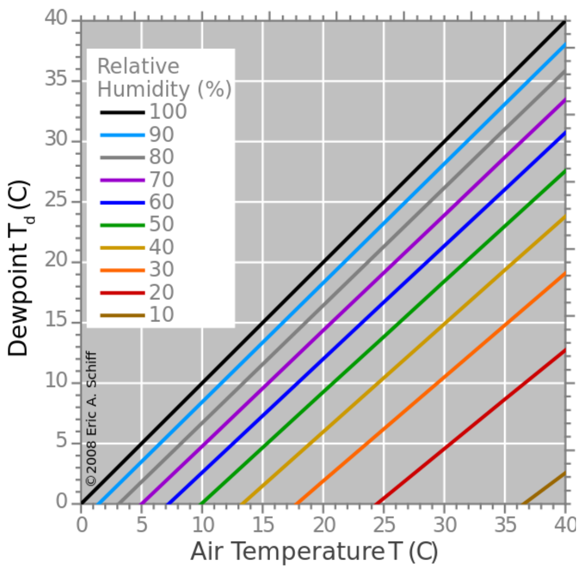


Figure 14: Dew Point temperature.

To help the team better understand, Ariel challenges them to consider a packet of air at sea level with 10 grams of water vapour suspended per cubic metre. The maximum temperature over the course of the day is 25°C, dropping to a minimum of 14°C overnight. She states they should consider the air packet as a closed system (nothing entering or leaving) to determine the maximum relative humidity of the air packet.

24. What is the correct value they calculate?

a. 0%
b. 10%
c. 14%
d. 45%
e. 54%
f. 83%
g. 100%
h. 110%

Ariel then asks them to consider how their model would change if they treat the air packet as an open system (allowing for exchange with the surrounding atmosphere). During the day, evaporation from ocean water increases the amount of water vapour suspended in the air packet.

25. Assuming a constant temperature, how will this affect the relative humidity and dewpoint of the air packet?
    a. Relative humidity increases, dew point increases
    b. Relative humidity increases, dew point decreases
    c. Relative humidity increases, dew point stays the same
    d. Relative humidity decreases, dew point increases
    e. Relative humidity decreases, dew point decreases
    f. Relative humidity decreases, dew point stays the same

Roxanne and Shelly compare samples of the rocks they collected. Rocks from the plateau are all crystalline (Fig.15 top row), rocks from the coast are full of fossils and react with HCl or are made up of small particles (Fig. 15 bottom row).

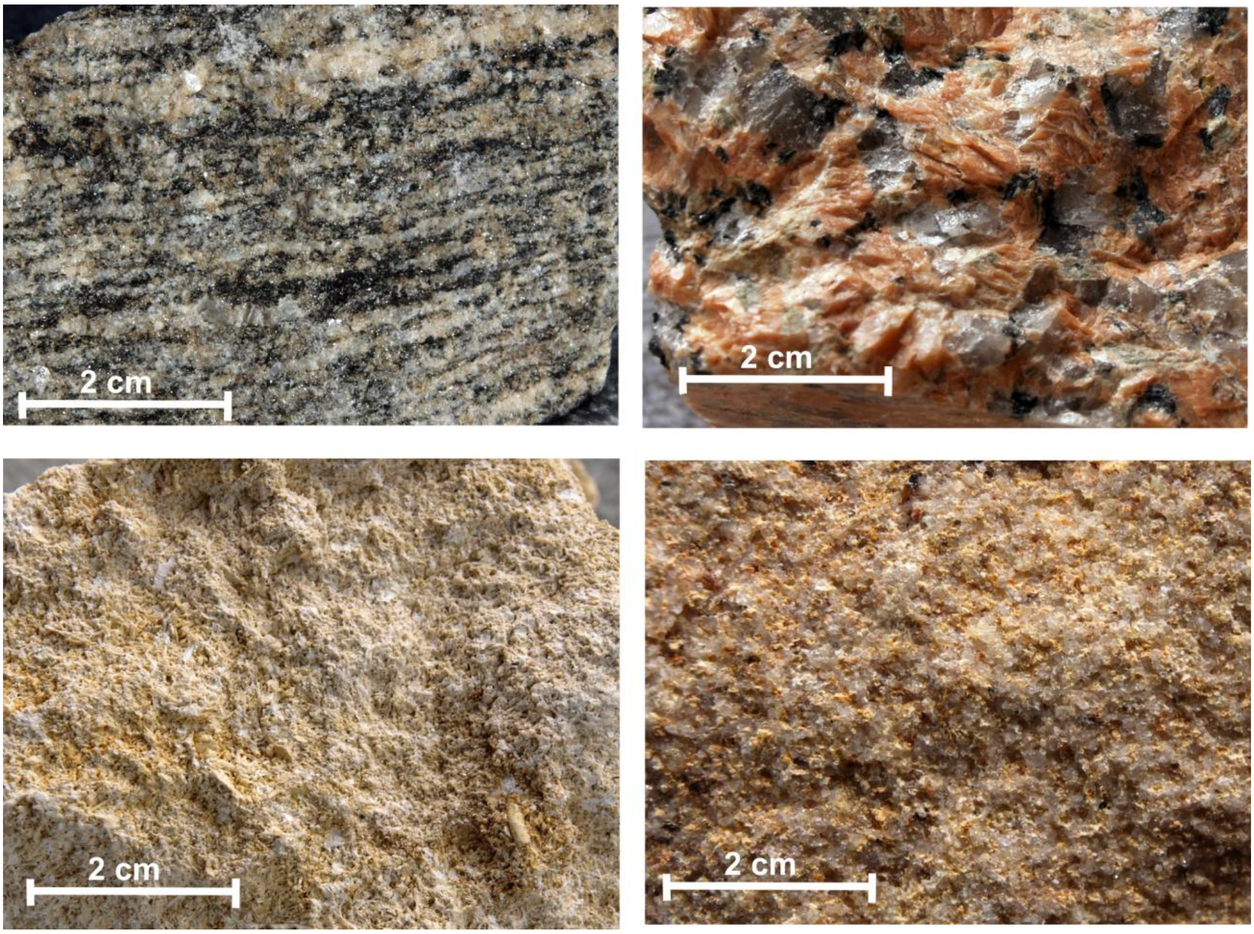


Figure 15: Rocks collected from the Perth hills (top row) and beaches (bottom row). Scales are approximate. Images modified from: TESEP.

Shelly identifies a collection of fossils in the limestone from the beach as molluscs, but she's not certain of their species.

26. What can she definitively determine about the age of these rocks?
    a. They are significantly younger than the crystalline rocks where Roxanne and Orson went hiking because molluscs first developed in the Cambrian.
    b. They are the same age as the crystalline rocks where Roxanne and Orson went hiking because they are on the same craton.
    c. They are older than the crystalline rocks where Roxanne and Orson went hiking because they are at lower elevation.
    d. They must have formed in the Neogene or more recently because that is the period over which molluscs are useful for biostratigraphy.
    e. They must have formed during the Pleistocene or earlier because more modern molluscs are easily identifiable.
    f. They are younger than the crystalline rocks where Roxanne and Orson went hiking because they are not recrystallised.

Wade drops some HCl on the limestone and it fizzes vigorously, however there are some bits that don't react at all. He notes that they range in size from about 0.5-2 mm, are very well rounded, have high sphericity, are transparent, and are not scratched by his pen knife.

27. What does he correctly determine these grains are composed of?
    a. Biotite
    b. Feldspar
    c. Olivine
    d. Quartz
    e. Zircon
    f. Diamond
    g. Topaz

Orson takes a look at Wade's photos and notices the rocks near the beach have regularly-spaced, 20-50 cm thick, horizontal layers and finer, centimeter-scale layers at variable angles to the horizontal surfaces. He didn't see anything like up in the hills. He wonders what could cause such regularly repeating structures to form.

Figure 16: Layered rocks Wade admired near the beach. Note: scale card in image centre is 7 cm.

28. What does Roxanne tell him that correctly explains this observation? “This mix of features is formed from…”
    a. …daily rainfall variations

b. …fluctuations in transport medium and flow direction
c. …fluctuations in ice sheet extent maxima and minima
d. …remnants of giant fish skeletons
e. …mammoth hair
f. …periodic volcanic eruptions

Orson's rather blown away by this spatial juxtaposition of such different rock types on either side of the steep slope separating the beach areas to the west and the hills to the east. Roxanne explains that the Darling Scarp is a fault running nearly due N-S. She draws some simple diagrams in the dirt (Fig. 17) to test her friends' problem solving skills. She explains that her arrows indicate the possible relative motion between the bedrock on either side of the fault.

29. Which diagram do they correctly determine represents the relationship between the crystalline rocks from the hills and the sedimentary rocks from the coastal region?

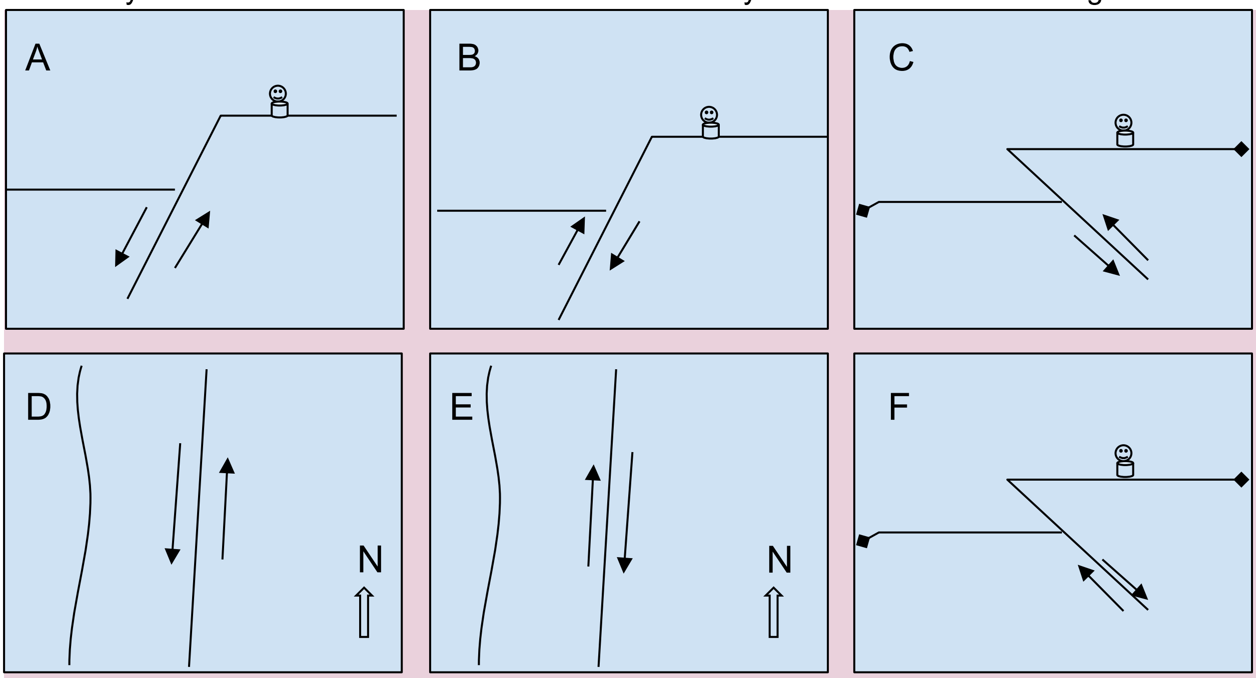


Figure 17: Roxanne's simplified sketches of relative plate motion along the Darling Scarp.

Changes in Latitudes, Changes in Attitudes

Inspired to see more of the world, Ariel decides to join a crew to sail to the Gulf of Mexico. Under the command of Captain Seymour Wistas, the all-star crew is composed of marine biologist Amber Gris, sedimentologist Brady O'Larian, brother and sister 'Carbo-Loading' Nate and 'Silly-Goose' Cate Stone, oceanographer Haly Te, and diving instructor Pearl 'Bubbles' Cousteau.

Worried by the prospect of pirates in the Indian Ocean, the crew decides on a highlight hopping voyage across the Pacific, stopping in Sydney, Vanuatu, Fiji, Tonga, Bora Bora, Tahiti, Marquesas, and the Galapagos before making use of the Panama Canal to reach Jamaica (black dots, Fig. 18).

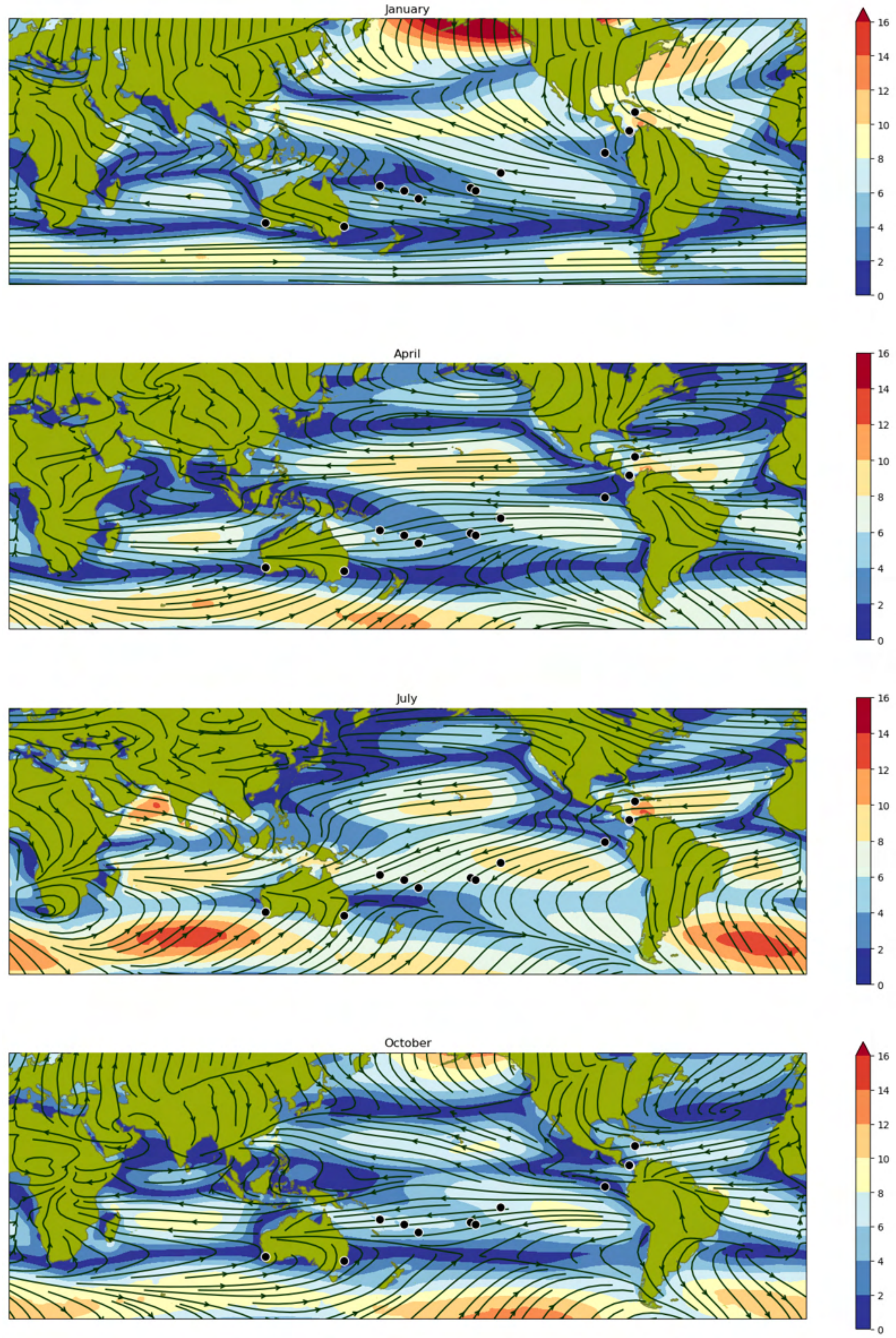


Figure 18: Global monthly mean wind speed (m/s) and direction with voyage route marked by black dots.

Using a map of mean wind speed and direction during each season (Fig.18), they plan the best time to set sail.

30. Keeping in mind that sailboats cannot sail directly into the wind, when do they prudently choose to make their adventure?
    a. January
    b. April
    c. July
    d. October
    e. January or July are similarly suitable, but to avoid cyclone season in the southern hemisphere, they should sail in July
    f. January or July are similarly suitable, but to avoid cyclone season in the southern hemisphere, they should sail in January

Having just read Eric Newby's 'The Last Grain Race', and feeling very swashbuckling about his traditional sailing knowledge, Ariel comments that this was known as sailing "the wrong way around the world", when tall ships were the primary means of transport.

31. In her extensive explanation, she specifies that tall ships could sail no closer than 60 degrees to the wind, and…

    A. Trade winds in the historical trading centers blow from east to west, making it far more efficient to sail east to west.

    B. Trade winds in the historical trading centers blow from west to east making it far more efficient to sail west to east.

    C. Prevailing winds in the Southern Ocean are west to east, and freezing temperatures and extreme swell states made the Southern Ocean dangerous to sail

    D. Prevailing winds in the Southern Ocean are east to west, and tropical waters in the Southern Ocean made it a preferred place to sail

    - A and C
    - B and D
    - A and D
    - B and C

On their long journey from Perth to Sydney, the crew gets to discussing the coral reefs and islands they will see along the way. Amber describes a relationship between the shape of these islands, their reefs and their age, famously discovered by Charles Darwin on his voyage on the HMS Beagle. She manages to dig up the following diagram (Fig. 19) illustrating the stages of island and reef formation.

Brady gets excited about this notion, and pulls up satellite images of the reefs they expect to visit.

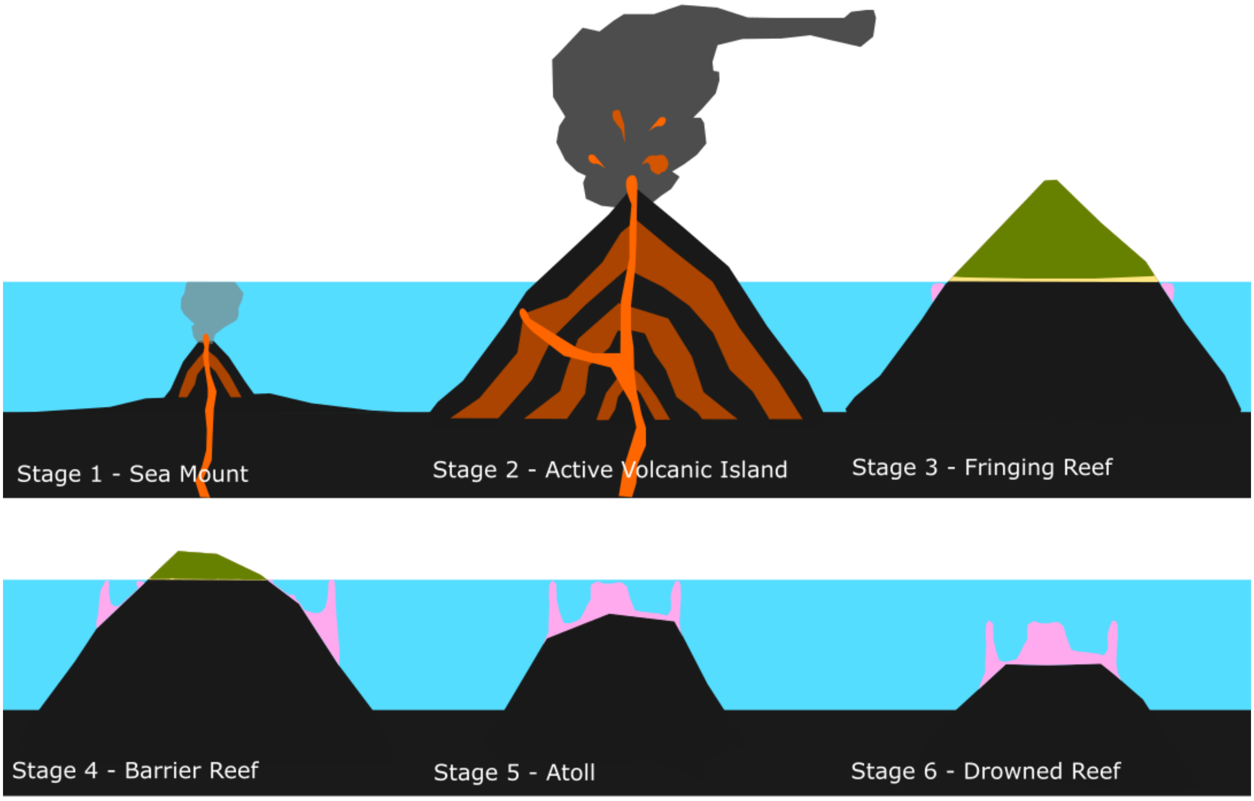


Figure 19: Simplified volcanic and coral island formation stages diagram. Coral is indicated in pink. Atolls can be entirely submerged, or have relatively small islands formed from an accretion of sand, coral rubble, and other debris.

Figure 20: Satellite image of Bora Bora (composite of several images, with deeper ocean approximated from lower resolution techniques). Map data: Google, SIO, NOAA, U.S. Navy, NGA, GEBCO.

32. What formation stage does the crew determine Bora Bora is presently in (Fig. 20)? (0.5 points)
    a. Stage 1
    b. Stage 2
    c. Stage 3
    d. Stage 4
    e. Stage 5
    f. Stage 6

Figure 21: Satellite image of Tofua, Tonga. No clouds are present in this image. All smoke or other visible vapors are emerging from the structure of the island, not the vegetation. Map data: Google, CNES / Airbus.

33. What formation stage does the crew determine Tofua is presently in (Fig. 21)? (0.5 points)
    a. Stage 1
    b. Stage 2
    c. Stage 3
    d. Stage 4
    e. Stage 5
    f. Stage 6

Figure 22: Emao Island, Vanuatu. Composite of several satellite images, some of which had cloud cover. Map data: Google, SIO, NOAA, U.S. Navy, NGA, GEBCO.

34. What formation stage does the crew determine Emano Island is presently in (Fig. 22)? (0.5 points)
    a. Stage 1
    b. Stage 2
    c. Stage 3
    d. Stage 4
    e. Stage 5
    f. Stage 6

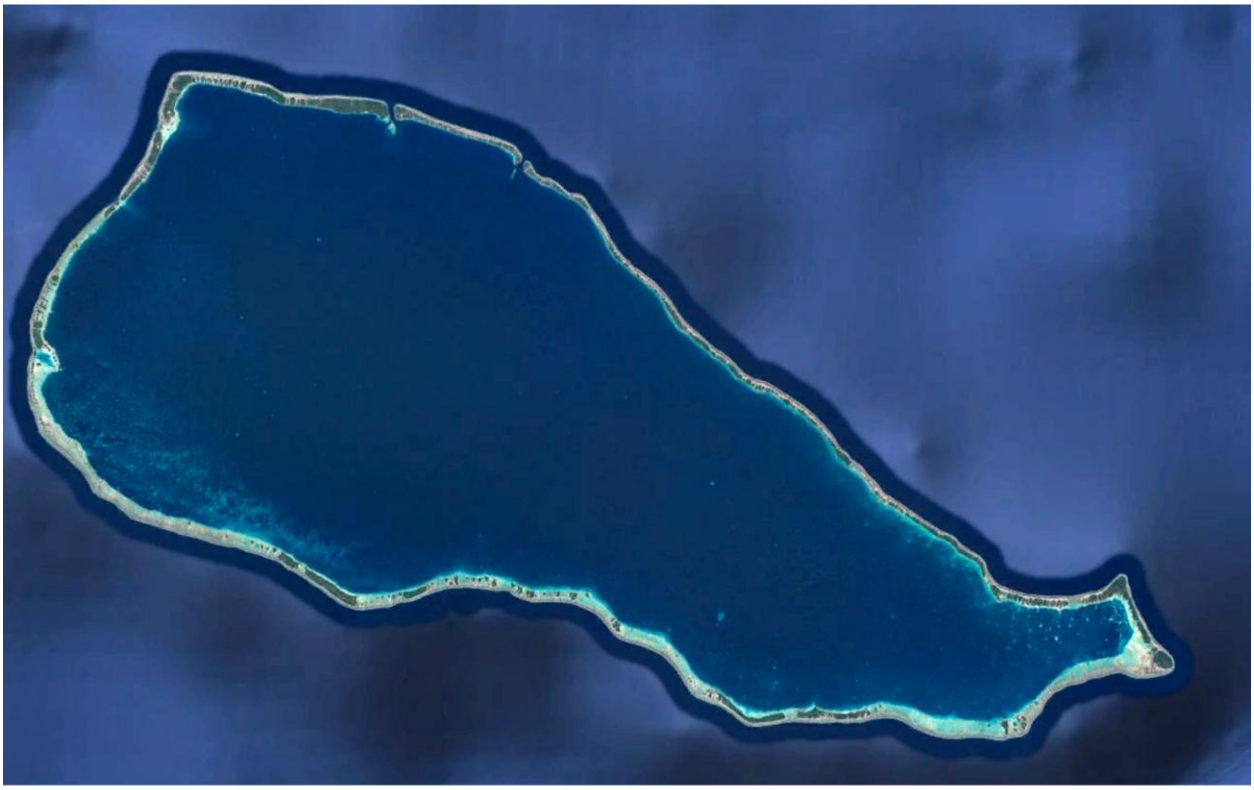


Figure 23: Rangiroa, French Polynesia. Composite of several images, with deeper ocean approximated from lower resolution techniques. Map data: Google, SIO, NOAA, U.S. Navy, NGA, GEBCO.

35. What formation stage does the crew determine Rangiroa is presently in (Fig. 23)? (0.5 points)
    a. Stage 1
    b. Stage 2
    c. Stage 3
    d. Stage 4
    e. Stage 5
    f. Stage 6

36. Amber ponders whether the relative ages of each of the islands they've visited can be confidently determined based only on what is visible in the images. Who provides her the correct answer?
    a. Cate – Yes, they represent different stages of island formation and thus must be able to be placed in age order from Tofua as the oldest, to Emao then Bora Bora, and finally Rangiroa as the oldest.
    b. Nate – Yes, they represent different stages of island formation and thus must be able to be placed in age order from Emao as the oldest, to Tofua then Rangiroa, and finally Bora Bora as the oldest.
    c. Haly – You can confidently identify Emao as the youngest island, but you cannot place the rest in order without knowing the scale of the islands, as erosion rates are approximately consistent but final island size can differ.
    d. Brady – You can confidently identify Tofua as the youngest island, but you cannot place the rest in order without knowing the scale of the islands, as erosion rates are approximately consistent but final island size can differ.
    e. Pearl – No, you would need to radiocarbon date the volcanic rocks.

f. Captain Wistas – No, you would need to radiocarbon date the coral growing in their reefs.

Surfing in a Hurricane

The Curse of the Black Pearl

As the crew draws closer to the Panama Canal, they receive communications from their connections in the Caribbean. Exploration geologist, Tex Thyte, and his geochemist partner, Ellie Ments, send through images of the regional bathymetry, topography, and active volcanic centres (Fig. 24) and the underlying tectonic plates (Fig. 25) to give the team a geophysical overview.

Cate is struck by the odd ridge and strip of newly formed oceanic plate stretching from the eastern tip of Cuba to the crook of the Yucatan Peninsula. She exclaims, “The age pattern is just like that of the Atlantic Ocean floor!”

37. How does Brady correctly explain this observation?
    a. New ocean floor forms at mid-ocean ridges and spreads away from the divergent boundary – therefore, the Caribbean spreading ridge must have opened up less than 60 Ma.
    b. The transverse-fault bounded swathe of ocean floor clearly slid westward from the Mid-Atlantic ridge until it was stopped in its track by the continental plate.
    c. The ages represent the youngest marine critters that have deposited their skeletal remains at that point. As they only live around the shallowest ocean floor, the youngest deposits are always around the ridges.
    d. The ocean floor age pattern is always the same as this until it is buried by the sediments washed from the continents to form the continental shelves. The ocean floor hasn’t been buried here due to the continental shelf gap between southeastern Mexico and northern Nicaragua.
    e. Wherever the ocean floor hasn’t been subducted, it has this age pattern. Since there is no subduction occurring on the eastern side of Central America, this is expected.
    f. The transverse-fault bounded swathe of ocean floor clearly slid westward from the Mid-Atlantic ridge until it was subducted beneath the Cocos plate.

Thinking back to what their Western Australian friends told them before they departed, Captain Wistas is perplexed by the maximum age of oceanic crust on this side of the world. “How come the oldest stuff is only 180 *million* years old here, when Western Australia is like four *billion* years old?!”

38. Who provides the correct explanation?
    a. Haly: oceanic crust gets recycled back into the mantle once it reaches a critical density and begins to sink, forming a subduction zone. This transition occurs ~170 million years after it forms. Continental crust is too buoyant to sink into the mantle.
    b. Brady: oceanic crust gets recycled back into the mantle once it’s covered with enough deep ocean sediments. This takes about ~170 million years because accumulation rates are so slow on the ocean floor. The continental crust is always being eroded, so it sticks around longer.

c. Pearl: oceanic crust gets increasingly water-logged the older it gets. Eventually, it's super saturated and sinks into the mantle. There isn't a process to cause this to happen to continental crust.
d. Amber: all continental crust formed billions of years ago and just gets moved around and reconfigured as oceanic crust convects, bringing up new material, to get out of the way of the drifting continents.
e. Nate: all continental crust formed billions of years ago and is rafted around the globe by subducting oceanic plates. As these pull apart, they form new, young oceanic crust.
f. Cate: all continental crust formed billions of years ago as oceanic crust that gradually dried out, becoming more buoyant. Oceanic crust is younger crust that hasn't had time to drive out the water.

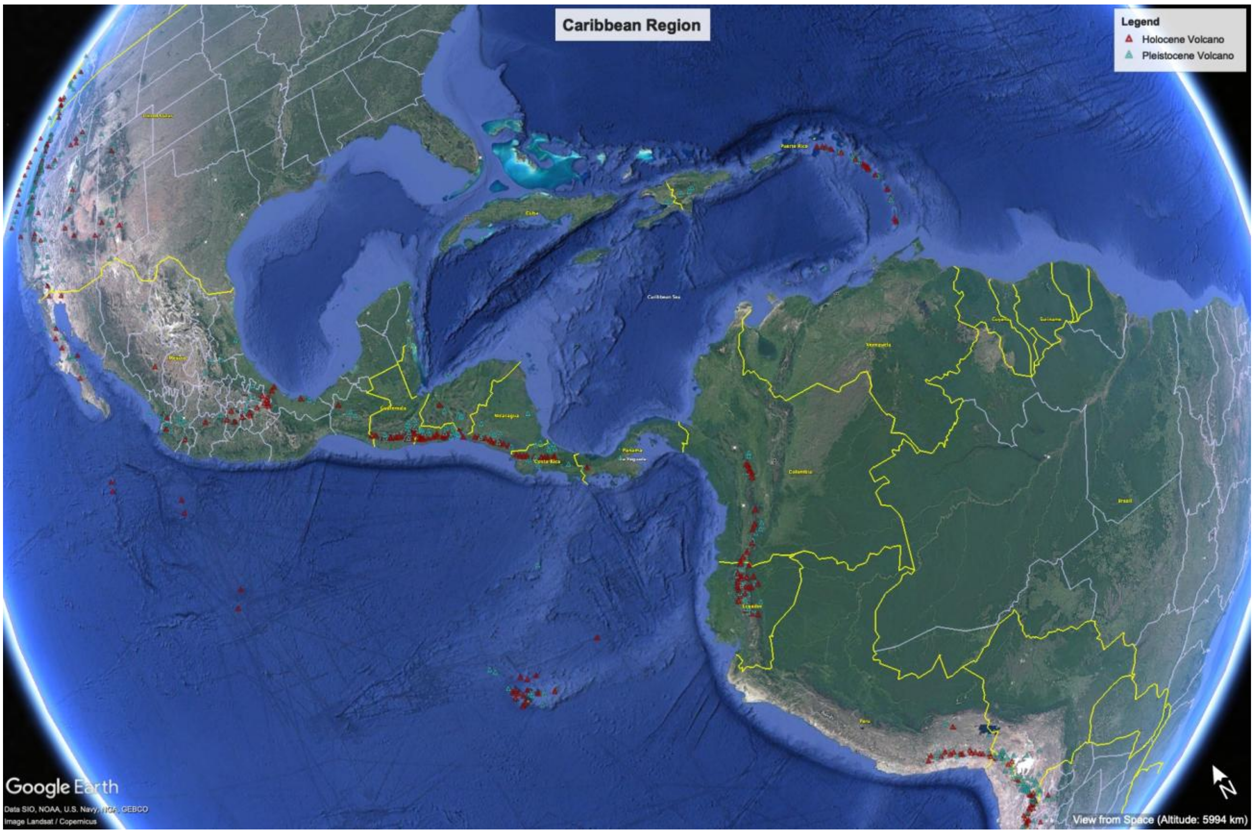


Figure 24: Google Earth view of the modern Caribbean Region. Bathymetry and topography indicated by colours off and on-shore, respectively. Red and blue triangles denote locations of volcanic activity in the recent geologic past.

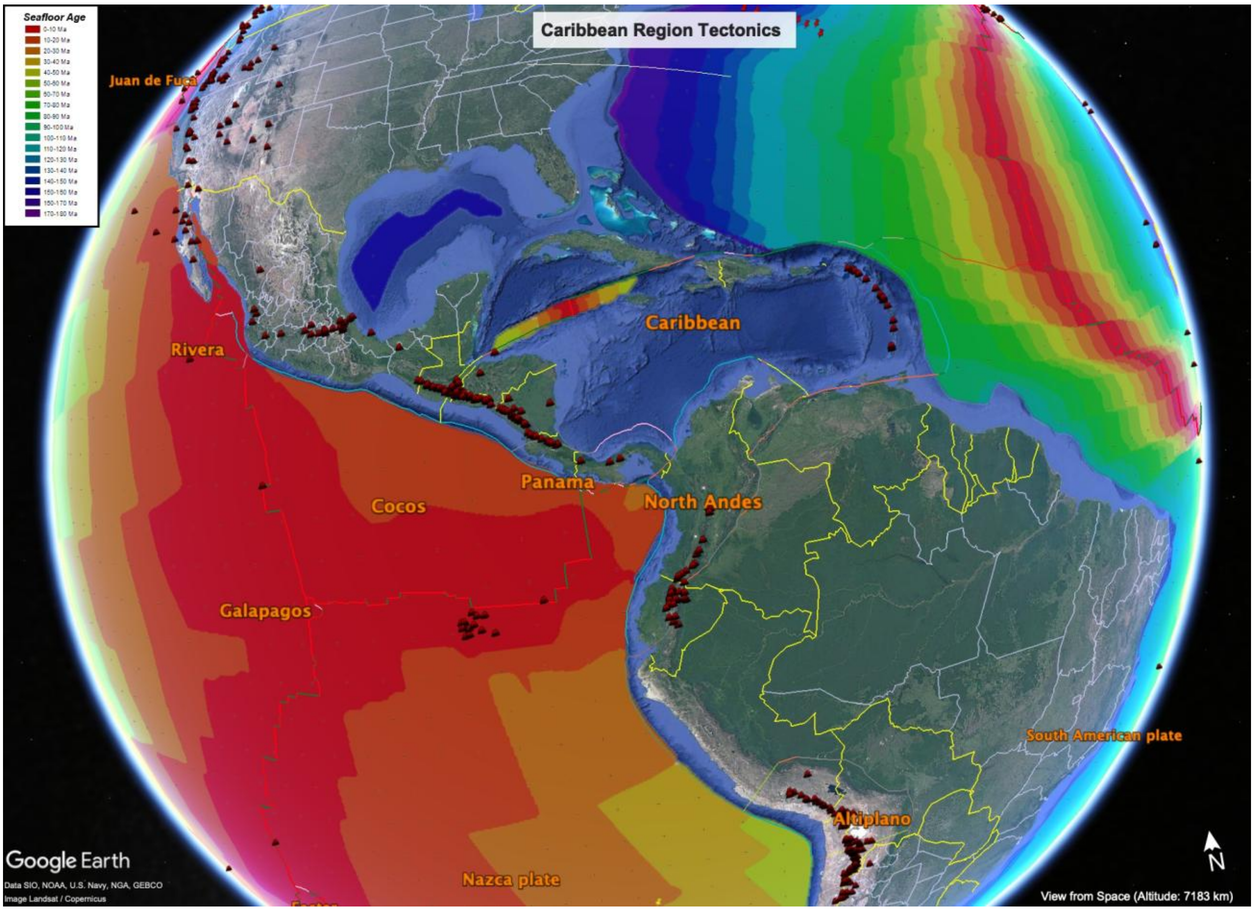


Figure 25: Google Earth view of seafloor ages (broad colour bands correlate with key) and tectonic plate names and boundaries (blue = convergent; red = divergent; green = transverse). Red and black triangles are Holocene volcanoes.

Ariel is curious about the lines of volcanoes that seem to run parallel to the deep ocean trenches (darkest blue) west of South and Central America and east of the Caribbean Plate. No one on the crew is certain if there is a causal relationship for this correlation, so they send their question to another contact in the region, volcanologist Andy Syght, who will be meeting them with his daughter and geology student, Innis.

Innis excitedly replies, “Great question! My dad is busy now, but I just learned all about this! You can find these deep trench-volcanic chain pairs all around the globe, not just here! The active volcanoes are generally about 150 km away from the trench! Hydrous minerals in the subducted slab become unstable around 4,500 MPa, releasing their bound water into the overriding mantle wedge and causing it to partially melt. Just knowing this, you can calculate the depth at which dewatering occurs, and from that, the angle of dip of the subducting plate! Cool, huh?!”

The crew is quite perplexed, but Haly, being a visual-spatial thinker, made a quick sketch to see what Innis was saying (Fig. 26)

Pearl recalls from diving that the pressure at a point at the base of a column is given by the height and density above it, in accordance with the lithostatic pressure equation. Brady chimes in that the average density of basalt is roughly 3.0 g/cm^3.

39. Using these simplifications, what is the depth of dewatering and subduction dip angle they calculate? (3 pts)
    a. 0.100 km / 4°
    b. 0.150 km / 6°
    c. 100 km / 34°
    d. 150 km / 45°
    e. 100,000 km / 60°
    f. 150,000 km / 90°

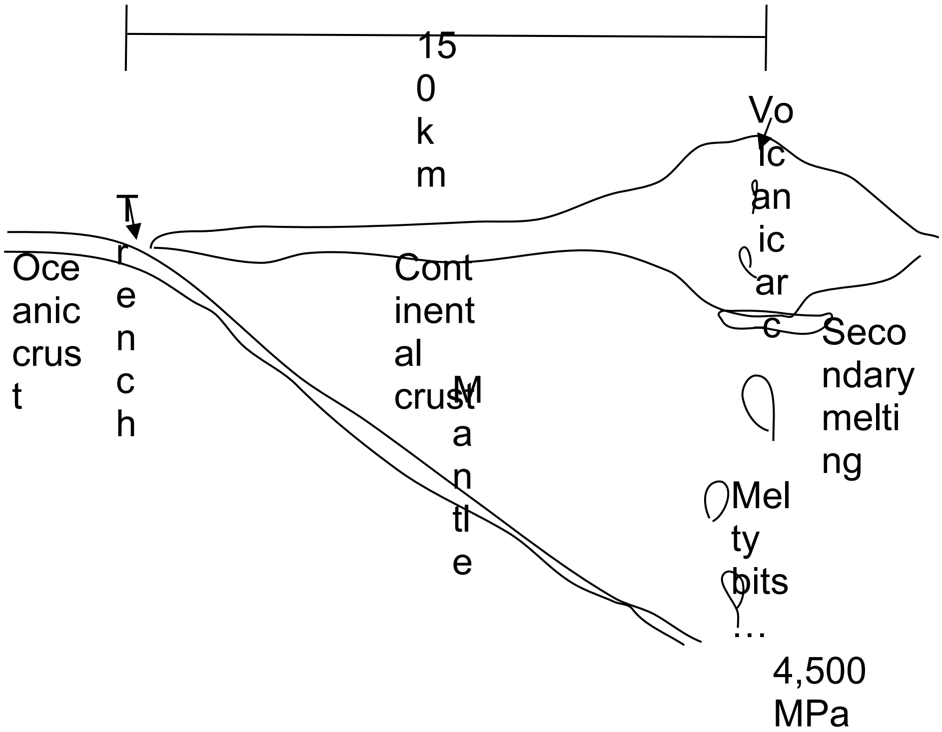


Figure 26: Haly's quick sketch of Innis' explanation.

The other cool factoid Innis shared was that partial melting causes rocks/magma/lava to "evolve". "What on earth does she mean by that!?" exclaimed Captain Wistas. Andy chimed into the chat and clarified that 'magma evolution' refers to the stepwise process of increasing the ratio of SiO_2 to Fe/Mg in igneous rocks. He challenged them with these questions:

40. If the upper mantle is composed of *ultramafic* peridotite and undergoes two steps of partial melting within a continental arc setting, what type of lava would erupt here?
    a. Komatiite
    b. Basalt
    c. Gabbro
    d. Andesite
    e. Rhyolite
    f. Granite

41. What mineral would you *not* expect to find in that lava?
    a. Olivine
    b. Quartz
    c. Plagioclase

d. Alkali feldspar
e. Biotite
f. Amphibole

Curious to augment their ideas about subduction zones, the team engages their seismologist friend, Jean Luc Bringuebaler. Jean Luc explains that seismic tomography is like a CT scan of the planet – a powerful technique to image the Earth's interior using the travel times (specifically, the difference in arrival times) of seismic waves that have passed through the planet from a wide variety of angles. The velocity of shear waves varies as a function of the materials they pass through, generally moving slower through hotter material. He shares the following imaging results with the team.

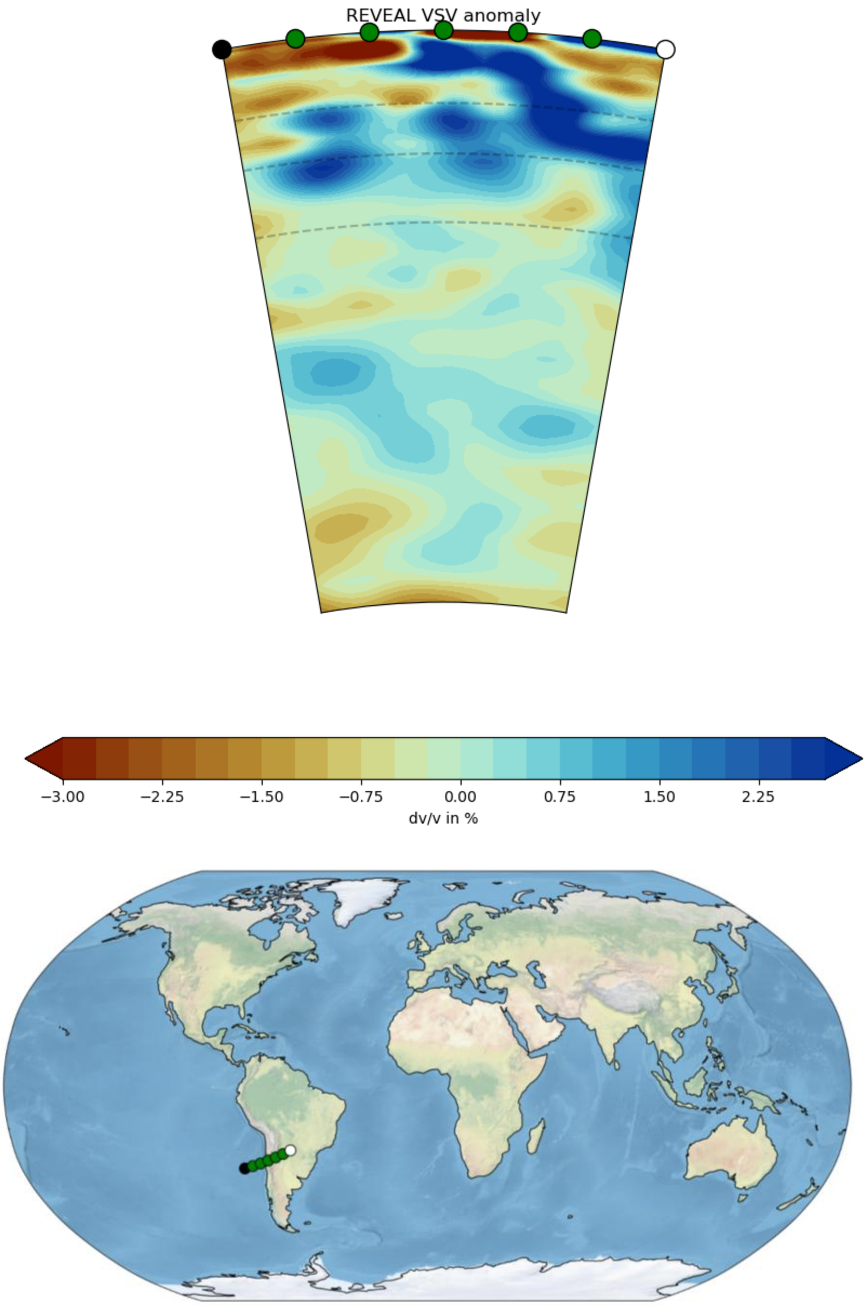


Figure 27: Seismic tomography slice through the Andes subduction zone through the crust and mantle to the core-mantle boundary [2,900 km] with dotted lines indicating mantle discontinuities at 410, 670, and 1000 km depths (top). Red indicates anomalies where seismic shear waves travel slower than the surrounding mantle. Blue indicates anomalously faster moving shear waves. Global map indicating location of tomography cross section (bottom) taken at 70 degree azimuth (angle to North) across the plate tectonic boundary.

42. What does the team correctly conclude from this data?
    a. Their model is completely correct! The subducting Nazca plate descends at a constant dip angle to the core-mantle boundary.
    b. Their model is not entirely correct. The subducting Nazca plate initially slips beneath South America horizontally before descending to ~700 km at approximately the angle they predicted before flattening out again.
    c. Their model is not entirely correct. The subducting Nazca plate partially descends into the mantle but breaks apart before it can reach the depth required for dewatering.
    d. Their model is not entirely correct. The subducting Nazca plate initially slips beneath South America horizontally before descending to ~1,000 km at approximately the angle they predicted before flattening out again.
    e. Their model is entirely incorrect. The subducting Nazca plate melts upon contact with the hot mantle.
    f. Their model is entirely incorrect. It fails to account for a mantle plume that extends upwards from the core-mantle boundary to the surface of the subduction zone.

As they make their way up the Panama Canal, the intrepid sailors have a lot of time to stare at the rock walls lining the canal. Curious about what they're seeing, Brady digs up a field guide to the area, which tells him that the rocks in the region all formed in the Pleistocene. The next page opens to a handy dandy stratigraphic column listing different rock units from youngest to oldest, but he isn't sure where they presently are within this geologic sequence.

Formation	**Primary Lithology**	**Description**
Gatun Formation	Sandstone	Massive medium- to very fine-grained sandstone, with numerous black and green grains. Extremely fossiliferous, with a particular abundance of molluscs. Key species include *Psammacoma Gatunesis* and *Forthrocorbula Gatunesis*
La Boca Formation	Mudstone	Silty or sandy mudstone, with coraliferous limestone at its base. All strata are carbonaceous, with most showing significant abundance of small foraminifera, notably multiple species of *Siphogenerina*
Cucaracha Formation	Clay Shale	Greyish yellow-green clay rich shale, with some strata showing substantial amounts of volcanic ash. Minimal fossils present, mostly plant debris. Base of

		unit shows some bivalves associated with estuarine water, including species of *Anadara*
Culebra Formation	Coraliferous Limestone	Relatively pure coraliferous limestone, with base of formation grading into carbonate rich sandstone and shale. Many species of scleractinian coral present, along with an abundance of poorly preserved molluscs, including *Turritella altilera*
Caimito Formation	Siltstone, Limestone	Calcareous siltstone with some volcanic material, including pumice. Foraminifera rich limestone unit near base, notably including *Lepidocyclina canellei*. Other fossils present in lower numbers include molluscs, scleractinian coral, and echinoids.
Bohio Formation	Conglomerate	Poorly sorted conglomerate, with clasts generally composed of basalt. No marine fossils present except for thin layers of algal mats in the top of the formation, but fossilised wood is present throughout.

Amber ponders how fossils are able to be used to determine the age of rocks. Brady explains that the time range when certain species lived is a useful concept known as 'biostratigraphy'. "*Aha*," says Amber, "so when rocks contain fossils, we know they're from that time range, and when they don't have the fossils they can't be from that range"
"Not quite," Brady replies.

43. What does Brady add to correct Amber's explanation?
    A. "Not all rocks have fossils – igneous may still have been deposited in that time"
    B. "Not all rocks have all fossils. For example, marine fossils won't be preserved in terrestrial environments, nor will terrestrial fossils be preserved in marine environments."
    C. "Fossilisation is quite rare – even when an organism is present in the formation environment, it doesn't always get preserved as a fossil."
    D. "Fossilisation is so common that all organisms of a time get preserved, which can conceal the fossils you're looking for."
    a. A only
    b. A and B
    c. A, B, and C
    d. A, B, and D
    e. A, B, C and D
    f. B and C

Satisfied with this explanation, Amber decides biostratigraphy is pretty neat, but isn't sure how it's useful.

44. Cate explains that because new sediments are always laid down on top of older sediments, knowing the age for a section of rocks in the middle of a sequence gives you…
    a. … a maximum age for the rocks on top of this section.

b. … a minimum age for the rocks on top of this section.
c. … a maximum age for the rocks below this section.
d. … a minimum age for the rocks below this section.
e. A and D are both correct
f. B and C are both correct

While listening in on this conversation, Haly was counting the bivalve fossils as they passed through the canal. They suddenly realise they haven't seen any for a fair while, and can only see imprints of leaves and bark. They mark this point on their chart of the Panama Canal as location A.

45. Which formation do they correctly conclude they are presently viewing?
    a. Gatun Formation
    b. La Boca Formation
    c. Cucaracha Formation
    d. Culebra Formation
    e. Caimito Formation
    f. Bohio Formation

Not yet knowing whether they're travelling up or down the stratigraphic column (i.e. forward or backward in time), Haly heads down to their bunk. After a nice nap, they come back on deck to hear Nate exclaiming about the forams he saw when he jumped ashore for a run. After squinting through his binocular microscope at a piece of rock he collected (from site B), he quite confidently identifies a few species of *Siphogenerina*.

"Aha!" exclaims Haly, now able to work out which way they are moving through the stratigraphic column.

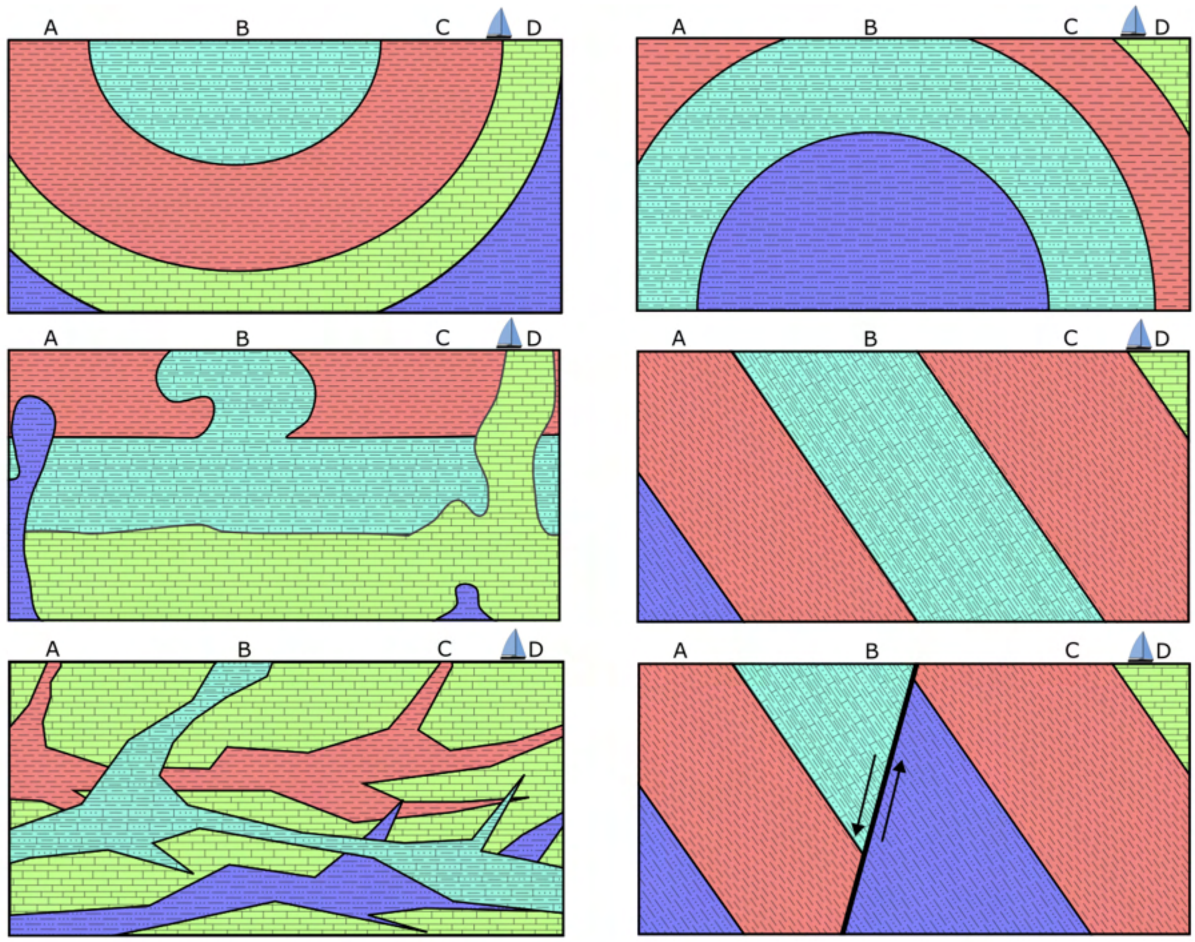
46. What do they predict the crew will encounter next based on the sequence they've passed through?
    a. Lots of well preserved molluscs, including *Psammacoma gatunesis*
    b. Foraminifera rich limestone with *Lepidocyclina*
    c. Coraliferous limestone
    d. No fossils at all
    e. Algal mats
    f. Lots of poorly preserved molluscs, including *Turritella altilera*

A few hours later, Haly notices that their (well founded) prediction of the next rock type was wrong, noting imprints of leaves and bark are once again present in the canal walls. Sensing something fishy is underfoot, they note this observation on their chart as Location C.

A few more hours later, Haly notices they are passing yet another rock type that appears to contain fossilised corals. Nate takes the opportunity to go for another run, and reports that there are fossilised molluscs in the rocks he thinks might be from the *Turritella* genus, but that they're not very well preserved.

After getting over their disappointment of an incorrect prediction, Haly sketches a projection of the rock layers beneath their feet.

47. Which sketch is a reasonable cross section to explain their observations? (**2 points**)



Top left

While Haly was sketching, Cate was thinking about the environment that existed when the rock-forming sediments were laid down. She suggests to Nate, Brady, and Haly that the variation between marine and terrestrial fossils could be the result of huge global changes in sea level from ice ages.

48. Who correctly explains the situation?
   a. Nate, who counters that as they are now 200 m above sea level (due to the incredible technology of canal locks!), the ocean could never get high enough to deposit marine sediments here, even if all glaciers melted.
   b. Brady, who suggests this area was submerged in the ocean while all sediments were deposited, and formations with lots of terrestrial fossils occurred when there was lots of outflow from nearby rivers, washing lots of bark and sticks out to sea.
   c. Haly, who reminds them all that the region was tectonically active at the time, and suggests the sea level changed locally as the complex local plate boundaries caused the land itself to rise and fall relative to the ocean.
   d. Brady and Nate
   e. Haley and Brady

f. Haly and Nate and Brady
g. Cate and Haly
h. Cate and Haly and Nate

Somewhat further upstream, Nate returns from yet another run with a piece of rock that fizzes with acid and looks like it has coral in it. He says he found it in the shallows on the edge of the canal, and is convinced it means they're now in the Culebra Formation. Cate isn't so sure.

49. Which correct explanation does she use to convince him he doesn't have it quite right?
    a. There are other local and regional formations that have coraliferous limestone.
    b. The hulls of passing boats can scrape pieces of rock off the canal walls and carry them significant distances upstream.
    c. The rock could have been transported downstream by the flow of water in the canal, and may not even be from the local unit.
    d. Answers a and b
    e. Answers a and c
    f. Answers b and c
    g. Answers a, b and c

Dead Man's Chest

Once the crew makes their way into the Caribbean, they make contact with Andy Syght's son, Outah, and his partner Lucinia Day who are studying solar flares and sunspots. Lucinia introduces them to the concept of *insolation*, which is the intensity of radiation reaching Earth's surface. It is a function of Earth's distance from the Sun and the angle at which the Sun's rays strike Earth's surface. Most importantly for our day-to-day lives, insolation is a large-scale driver of our seasons.
She shows them a schematic of the 2025 key parameters of Earth's orbit around the Sun (Fig. 28) and provides a list of the geo-orbital values:

- Eccentricity of Earth's orbit: 0.0167086
- Earth axial tilt: 23.44 degrees
- Date of Perihelion: 5th January 2025
- Sun-Earth distance at Perihelion: 147,100,000 km
- Date of Aphelion: 4th July 2025
- Sun-Earth distance at Aphelion: 152,100,000 km

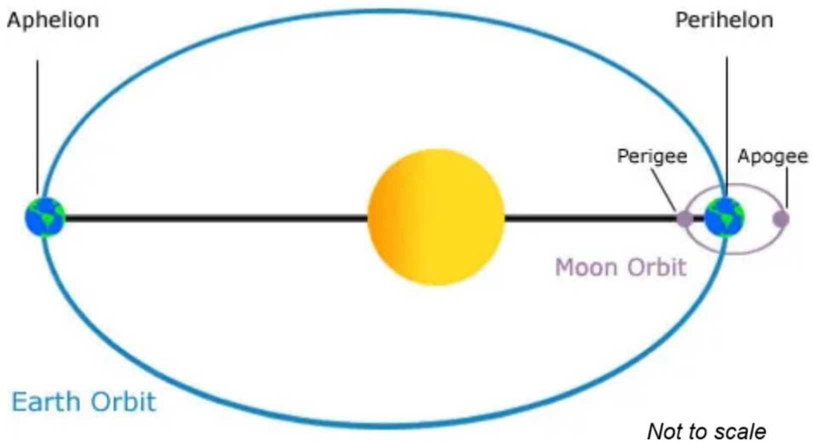


Figure 28: Schematic diagram of Earth's orbital path around the Sun.

50. Outah challenges the crew to use what Lucinia's showed them to determine which of the following conclusions is correct:
    a. The Earth is in Summer in January and Winter in July.
    b. The Earth is in Winter in January and Summer in July.
    c. The Southern hemisphere is in Summer in January, and experiences the same insolation as Northern hemisphere Summer in July.
    d. The Southern hemisphere is in Summer in January, and experiences 7% greater insolation than the Northern hemisphere Summer in July.
    e. The Southern hemisphere is in Summer in January, and experiences 23% greater insolation than the Northern hemisphere Summer in July.
    f. The Southern hemisphere is in Summer in July, and experiences the same insolation as Northern hemisphere Summer in January.
    g. The Southern hemisphere is in Summer in July, and experiences 7% greater insolation than the Northern hemisphere Summer in January.

h. The Southern hemisphere is in Summer in July, and experiences 23% greater insolation than the Northern hemisphere Summer in January.

Lucinia further explains that insolation varies temporally and spatially. These systematic changes lead to long-term climatic variations. She provides another diagram illustrating the three most prominent factors, collectively known as the Milankovitch cycles, which refer to:

- *Eccentricity*: variations in the shape of the Earth's elliptical orbit. It is represented with a number between 0 and 1, with 0 indicating a perfectly circular orbit, and higher numbers indicating a more elliptical orbit.
- *Obliquity*: variations in the axial tilt of the Earth against the orbital plane.
- *Precession*: variation in the orientation of the Earth's axial tilt.

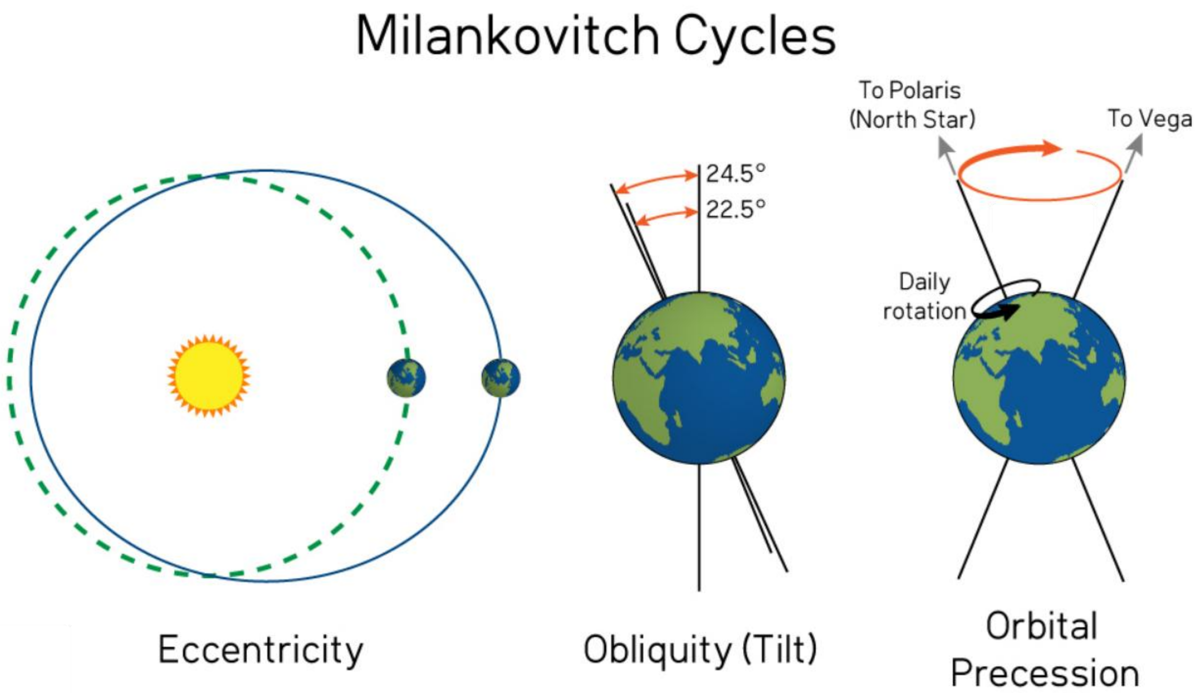


Figure 29: Illustration of Milankovitch Cycles. Image modified from skepticalscience.com.

Lucinia's friend, geochronologist Jiki Nakamura, messages to catch up and is excited to hear what they're chatting about, having just produced a cool graph to explore the correlation between Milankovitch Cycles and global ice volumes (Fig. 30). They challenge the group to interrogate their graph to draw a supported conclusion.

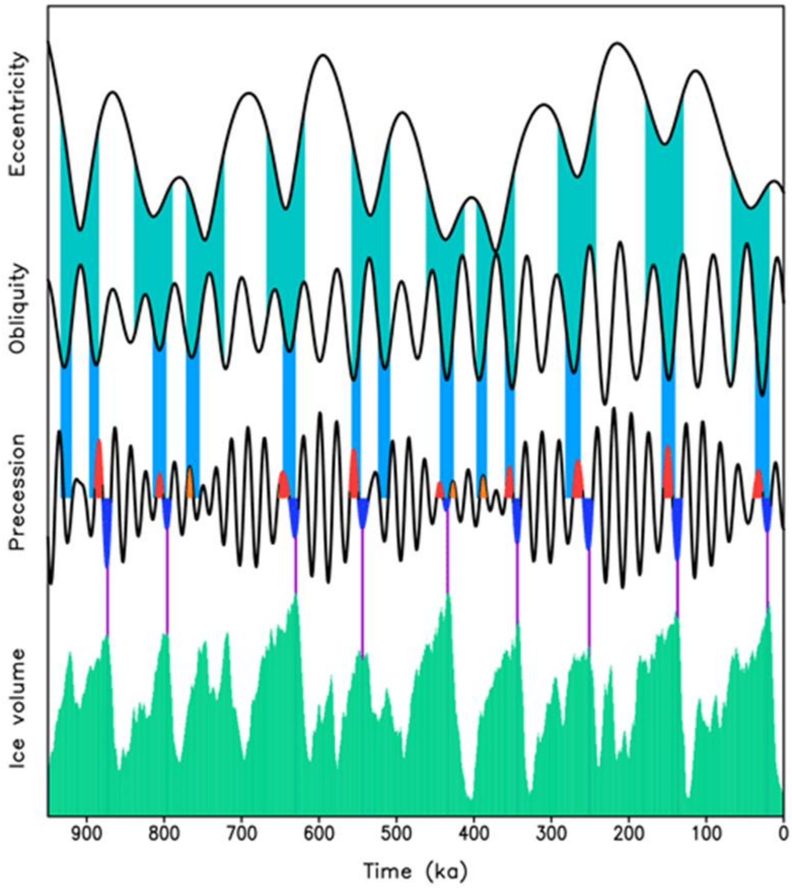


Figure 30: Graph illustrating the total ice volume on the Earth (bottom) and the impact of each Milankovitch cycle on the net solar insolation received by the Earth (orbital forcings; upper three). Image from A. Ganopolski doi.org/10.5194/cp-20-151-2024.

51. Which of the following conclusions does the crew correctly make?

    a. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~100ky, which correlates best with eccentricity variation.
    b. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~100ky, which correlates best with obliquity variation.
    c. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~100ky, which correlates best with precession.
    d. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~40ky, which correlates best with eccentricity variation.
    e. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~40ky, which correlates best with obliquity variation.
    f. The Earth's total ice volume over the last million years predominantly fluctuates over a cycle of ~40ky, which correlates best with precession.

Their paleontologist friends, Traci Menandi and Jeff Gnathostomes also chime into the group chat with a graph they've been arguing over. Traci says, *"Speaking of correlations, how well do Milankovitch Cycles line up with major biodiversity fluctuations since the Cambrian?"*

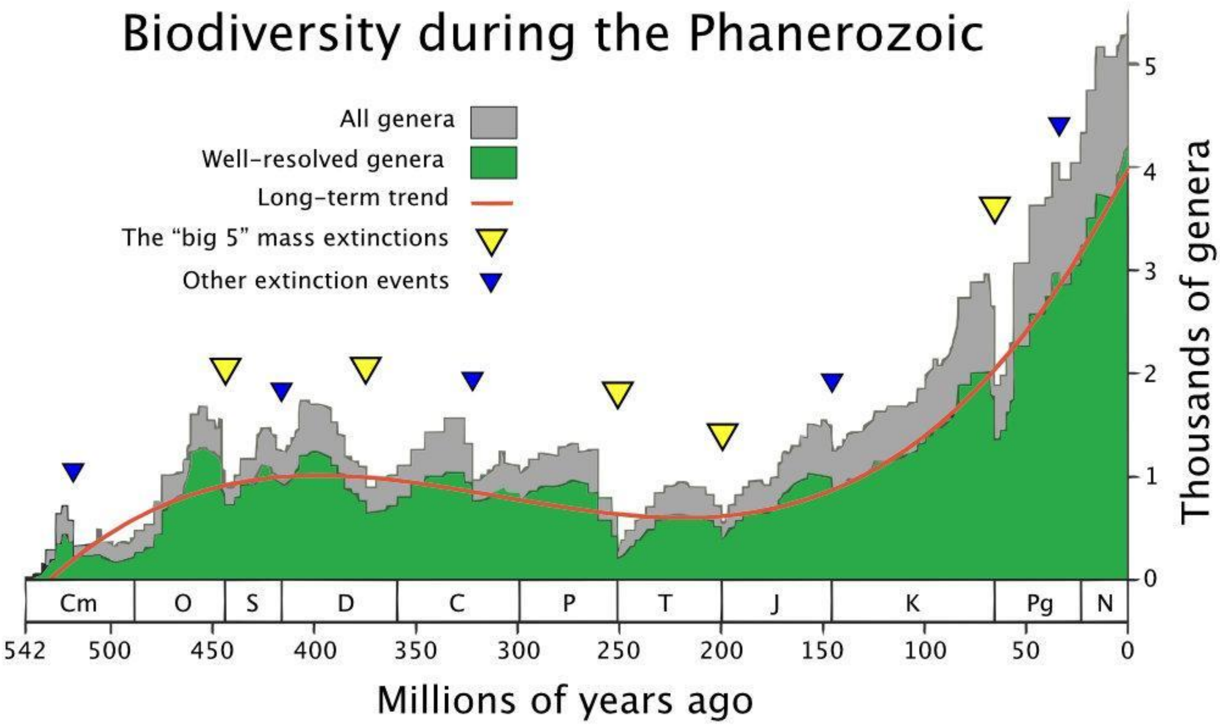


Figure 31: Histogram of the number of thousands of genera (aka genuses) over geologic time. Image from Albert Mestre.

52. What does the crew correctly conclude?

   a. Mass extinctions are strongly correlated with ice extent maxima.
   b. Extinction events are strongly correlated with axial precession.
   c. Extinction events are strongly correlated with axial obliquity variations.
   d. Mass extinctions are strongly correlated with periods of high orbital obliquity.
   e. Mass extinctions are strongly correlated with periods of low orbital obliquity.
   f. Extinction events are not strongly correlated with Milankovitch cycles.

Traci and Jeff launch back into their ongoing debate about the relative merits and downsides of extinctions. Traci asserts that extinctions open up ecological niches for new species to proliferate and exciting leaps of evolution to occur. Jeff grumbles that some of the best critters get lost in the crossfire…

53. What key feature of Figure 31 does Traci use to support her argument?

    a. The number of genera increases dramatically immediately after each of the ‘Big 5’ mass extinction.
    b. The number of genera increases dramatically immediately after all mass extinctions.
    c. The number of genera has increased exponentially since the P-T mass extinction.
    d. The number of genera has fluctuated following an inverse relationship with extinction events.
    e. The number of well resolved genera has increased linearly since the Cambrian as a function of rock record preservation.
    f. The biggest extinctions by proportion of genera lost promote the greatest proliferation proportional to genera gained.

54. Which of the following points does Jeff make to poke a hole in her argument?

    a. Ecological rebound time (time to recover to the same number of genera) is longer than the period between extinction events until the end of the Jurassic, after which genera proliferation exceeds genera loss.
    b. Mass extinction is never a good thing.
    c. Mass extinctions wipe out the critters closest to the top of the food chain, which goes against the notion of survival of the fittest.
    d. The rock record is progressively less well preserved the further back in time you look, therefore most genera wouldn’t be known prior to the Triassic.
    e. Most critters lived in the oceans prior to the Triassic, therefore most of their remains would have been recycled back into the mantle, leaving no record of their existence.

Outah's little sister Innis jumps into the chat to proclaim that, *“Volcanoes make climate trends messy!! Check it out, there’s this volcano in Peru, Huaynaputina that had a massive eruption in February 1600, killing at least a thousand people locally and burying the surrounding area under 2 metres of volcanic rock and ash! It caused a volcanic winter, possibly contributing to the Little Ice Age and maybe altering world history by causing famines across Eastern Europe and Russia for several years!!”*

She uploads the climate records for the past 2,000 years with the timing of major eruptions demarcated for everyone to see (Fig. 32).

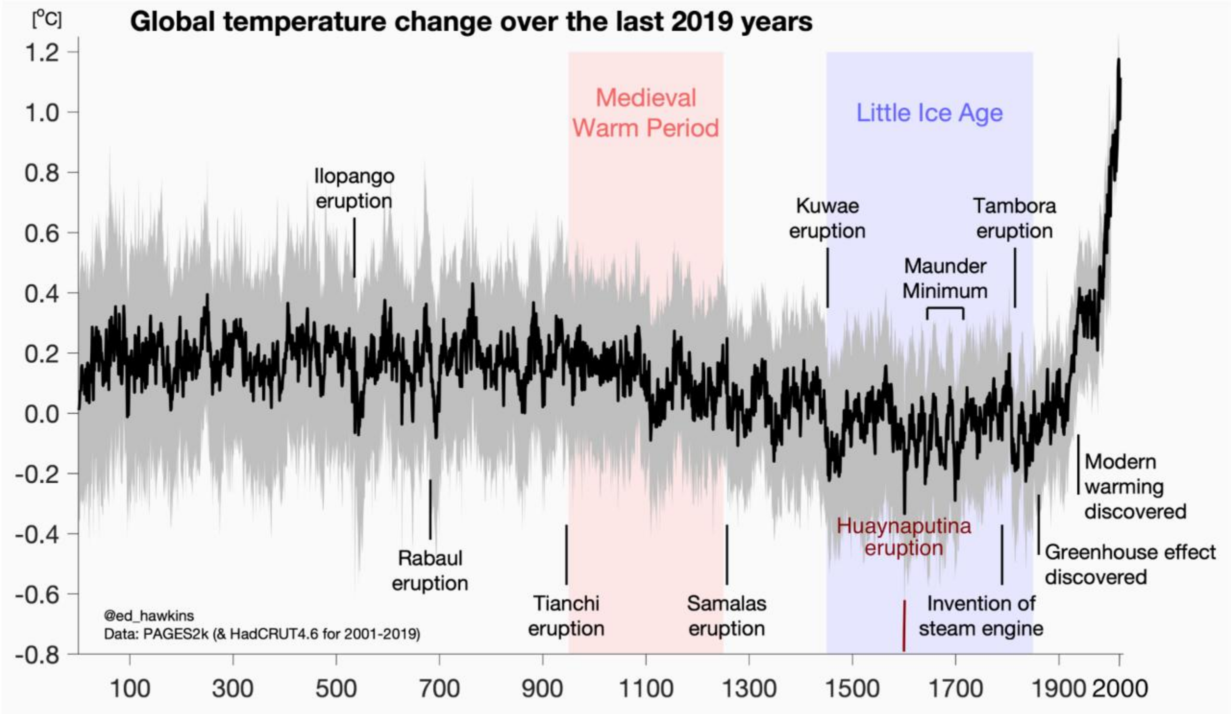


Figure 32: Fluctuations in global temperatures over the past 2,000 years. Black line indicates the mean, with grey bars delineating the max/min temperatures. The Medieval Warm Period and Little Ice Age were locally significant climatic events. Significant eruptions and key anthropoic events during this period are indicated.

Nate is perplexed, *"Wait, I thought volcanoes produced a lot of CO_2, shouldn't they contribute to global warming, not cooling?"*

Lucinia reminds him that global temperature is strongly affected by the amount of insolation and quizzes everyone on how a volcanic eruption might alter this variable.

55. Who correctly solves Lucinia's little puzzle?
    a. Ariel says the blast from a volcano will increase wind velocities, thereby cooling the planet for a few months.
    b. Brady says the extra particles falling into the ocean will increase plankton productivity, thereby consuming more CO_2 and cooling the planet for a few years.
    c. Cate says a highly explosive eruption will eject significant volumes of ash and aerosols into the stratosphere, thereby reflecting sunlight above the lower atmosphere and causing cooling for months to years.
    d. Jeff says the acoustic wave underwater eruptions will upset global fish populations, causing a decrease in their respiration and total CO_2 output, leading to decadal cooling.
    e. Haly says the water vapour released into the atmosphere should contribute to significant warming because of its high heat capacity, therefore the correlations between eruptions and cooling events must be purely coincidental.
    f. Captain Wistas says they're all a bit cooked and that clearly volcanic eruptions make things hotter because they produce lava, which can be as hot as 1,200°C.

56. What is the approximate global temperature deviation attributed to the Huaynaputina eruption?
    a. +1.2°C
    b. +0.4°C
    c. +0.2°C
    d. No associated change
    e. -0.2°C
    f. -0.4°C
    g. -1.2°C

57. Based on the magnitude of global climate change induced by large magnitude eruptions over the past 2,000 years, what would be the expected effect of a highly explosive, SO_2-rich eruption on the current climate trajectory?
    a. It would significantly accelerate the rate of atmospheric warming for decades.
    b. It would make a small contribution to the rate of atmospheric warming for a year or two.
    c. It would have no net effect on the atmospheric temperature over any time period after the eruption.
    d. It would slightly reduce the rate of atmospheric warming for a year or two.
    e. It would significantly reduce the rate of atmospheric warming for decades.
    f. It would reverse the atmospheric warming trend and send the planet into a nuclear winter.

At World's End

After such a riveting discussion, the crew is finding it impossible to get to sleep, so they decide to turn their focus to the worlds beyond ours. With the full Moon visible, they are inspired to contact their astronomer friend, Zoe Guāng, who spends every night peering through her telescope. She sends them an image of the Moon's surface and asks them what they notice.

Pearl exclaims, *"It looks like bubbles rising up from my regulator!"*

Outah says, *"It looks so awfully far away…"*

Amber notices the craters all appear to have a similar, roughly circular shape.

Captain Wistas thinks it looks like the sea surface when rain drops begin to hit it.

Figure 33. Image of Moon through Zoe's telescope.

Brady claims that while asteroids falling directly downward can create circular craters, any asteroid impacting the surface at an angle would create an oblique (elliptical) crater instead. This leads Nate to speculate that all craters on the Moon must be the result of asteroids falling directly downwards, impacting perpendicularly to the surface.

Cate is not so sure, and suggests two different analogues they could consider to improve their conclusion: the profile of craters produced by bomb explosions (Fig. 34) and those of "craters" produced by shot put landing on sand (Fig. 35).

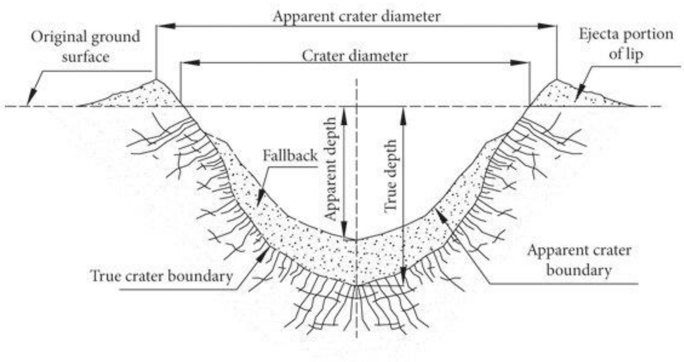


Figure 34: Typical cross sectional profile of the circular crater produced from a bomb explosion. From: Kenkmann, T, et al 2005 GSA doi.org/10.1130/SPE384.

Figure 35: Image of a shot put landing on sand.

https://www.shutterstock.com/image-photo/sphere-landing-sand-shot-put-competition-1505973605?dd_referrer=https%3A%2F%2Fwww.google.com%2F

58. Taking Cate's input on board, Brady correctly concludes:
    a. Due to the proximity of the Moon to the Earth, asteroids travelling on an angle will be pulled away by the Earth's strong gravity, and will not impact the Moon. Thus, all lunar craters are due to asteroids impacting directly vertically.
    b. Due to The Moon's large mass, any asteroid that gets close enough to impact the surface is pulled by the Moon's gravity and redirected to fall directly down onto the surface. Thus, all lunar craters are due to asteroids impacting directly vertically.
    c. Asteroid impacts are very rare. Most asteroids near The Moon miss the planetary body if they fall at an angle. Only asteroids falling directly down onto the planet actually hit the surface. Thus, all lunar craters are due to asteroids impacting directly vertically.
    d. All the craters are in fact volcanic vents, created by extensive volcanism on the surface. This is supported by the small peak present in many of the craters, which is a remnant of the volcano's conduit, where the lava travelled from the interior up to the surface. Thus, all lunar craters are due to volcanic activity, not asteroid impacts.
    e. Impact craters are not created by the asteroid's collision with the surface, but rather the circular explosion that occurs after the asteroid transfers its high kinetic energy to the ground during impact. Thus, lunar craters arise from asteroids impacting at a variety of angles.
    f. Impact craters are not created by the asteroid's collision with the surface, but rather the circular atmospheric shock wave travelling in front of the asteroid, pushing the dust on the surface out of the way. Thus, lunar craters arise from asteroids impacting at a variety of angles.
    g. Impact craters are not created by the asteroid's collision with the surface, but rather the approximately circular shape of most asteroids, which are

gravitationally rounded due to their mass. Thus, lunar craters arise from asteroids impacting at a variety of angles.

59. After settling that debate, Haly ponders the last time they saw a total solar eclipse. They suggest that the group may be able to determine the Moon's angular size. Lucinia chimes in that the Sun's diameter is approximately 1.4 million kilometres.

    What does the group correctly determine?
    a. The Moon's angular size is 0.01 degrees.
    b. The Moon's angular size is 0.04 degrees.
    c. The Moon's angular size is 0.2 degrees.
    d. The Moon's angular size is 0.5 degrees.
    e. The Moon's angular size is 1.0 degree.
    f. They cannot determine the Moon's angular size without further information.
    g. They cannot determine a single value for the Moon's angular size because it changes predictably and significantly over the lunar phases.
    h. They can determine the Moon's angular size, but it is not any of the options given.

60. If the team continued to observe the lunar surface, at what time would they no longer be able to, due to the setting of the Moon?
    a. 2 AM
    b. 6 AM
    c. 10 AM
    d. 2 PM
    e. 6 PM
    f. 10 PM

In the early hours of the morning, Zoe sends them an awesome image of a comet labelled with a set of arbitrary coordinate axes (Fig. 36) and a conceptual map of the solar system (Fig. 37).

Outah shares, *"I've read that comets can sometimes show two tails when their path brings them near enough to the Sun. Solar radiation causes volatile gases such as* H_2O *and* CO_2 *to be vaporised, then radiation pressure expels them from the comet as a blue tail of ions. A grey tail of metallic and siliceous dust is also released, although it follows a different path."*

Zoe responds that using Outah's information and the relative temperatures experienced by planetary bodies in the Solar System, they should be able to work out where the comet is relative to other planets and the direction to the Sun in her image.

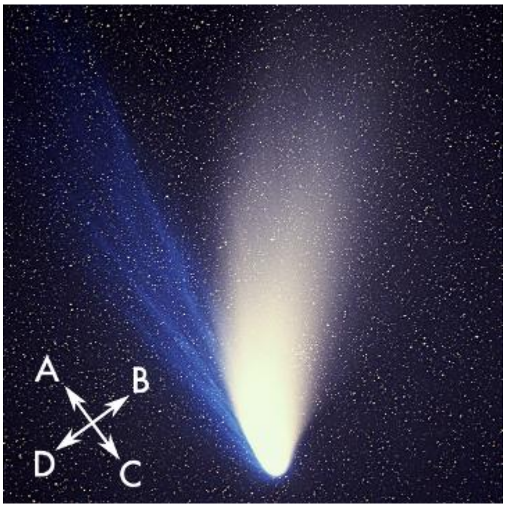


Figure 36: Zoe's comet photo with arbitrary coordinates.

Figure 37: Planets of the Solar System and their largest natural satellites.

61. What does Pearl correctly work out from Zoe's comet image?
    a. The comet is between Jupiter and Pluto, is travelling in direction C, and the sun is located in direction C.
    b. The comet is between Mercury and Mars, is travelling in direction A, and the sun is located in direction B.

c. The comet is between Saturn and Pluto, is travelling in direction C, and the sun is located in direction B
d. The comet is between Mercury and Mars, is travelling in direction D, and the sun is located in direction C.
e. The comet is between Saturn and Pluto, is travelling in direction C, and the sun is located in direction A.
f. The comet is between Jupiter and Pluto, is travelling in direction A, and the sun is located in direction D.

62. (2 marks) Outah challenges the crew to consider a hypothetical Martian asteroid impact at a speed of 17 km per second, causing material to be ejected. At some time after impact, the ejected material's gravitational potential energy has increased by 2.6 $\times 10^{19}$ J, while the material's total kinetic energy is 1.8 $\times 10^{19}$ J. What is the impactor's *minimum* mass?
    a. 2.06 x 10^9 kg
    b. 1.25 x 10^11 kg
    c. 1.80 x 10^11 kg
    d. 3.04 x 10^11 kg
    e. 2.06 x 10^12 kg
    f. 1.25 x 10^17 kg
    g. 1.80 x 10^17 kg
    h. 3.04 x 10^17 kg

Some rocks found on Earth have compositions most similar to rocks found on Mars, which allows them to be inferred as of Martian origin.

Outah explains that these rocks must have been ejected from Mars' gravitational influence and travelled through space before coming to land on Earth. To do so, they would have needed to acquire a total energy equal to the gravitational potential energy they had on the surface of the planet.

63. (2 marks) Using the same impactor speed of 17 km per second and assuming an ejecta mass of 2.5 $\times 10^{13}$ kg, what is the minimum required impactor mass for the ejecta to escape Mars' gravitational influence and potentially reach Earth?
    a. 2.5 x 10^11 kg
    b. 2.2 x 10^12 kg
    c. 2.5 x 10^13 kg
    d. 3.7 x 10^16 kg
    e. 2.2 x 10^21 kg
    f. 3.7 x 10^22 kg

As a final point of interest, Zoe shares a technique to help better understand star clusters. Star clusters are a group of between tens to a few thousand stars all formed from the collapse of a nebula and therefore have roughly the same age. She provides the crew with the following diagram.

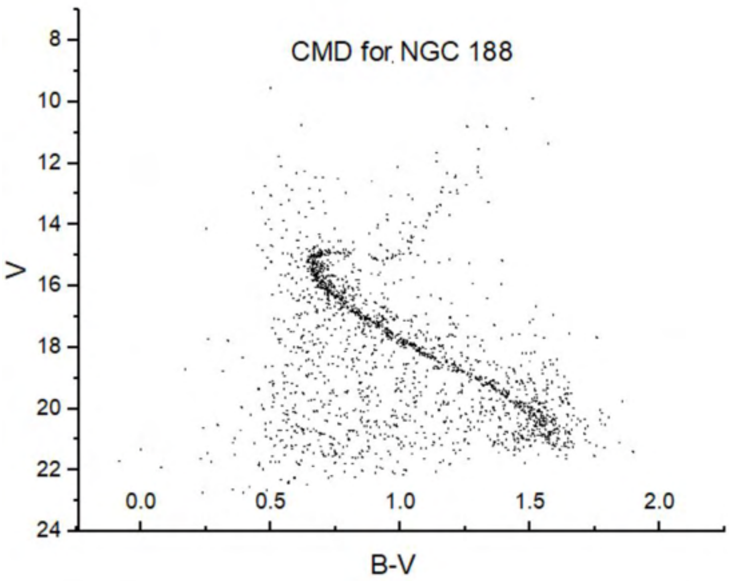


Figure 38: Hertzsprung-Russell diagram for the NGC 188 open cluster. The vertical axis corresponds to luminosity/absolute magnitude. The horizontal axis corresponds to a colour index. From Mondai, A (2002) doi:10.1088/1742-6596/2267/1/012095.

64. What is the approximate age of NGC 188?
    a. It is around 1 million years old.
    b. It is around 10 million years old.
    c. It is around 100 million years old.
    d. It is around 1 billion years old.
    e. It is around 10 billion years old.
    f. It is around 100 billion years old.

Dead Men Tell No Tales

Coming to land on the Yucatan Peninsula, the crew finally meets up with Tex and Ellie at their drilling site in the middle of the buried Chicxulub impact crater (Fig. 39). Everyone is very excited to hear about their findings and the day the dinosaurs died after learning that the impact date coincides with the Cretaceous-Paleogene mass extinction, wherein 75% of all plant and animal species on Earth were wiped out, including all non-avian dinosaurs. Their drilling work has uncovered a fascinating set of geologic features, revealing much about the size and trajectory of the asteroid, the rock types present at the impact site, and the volume of rock vapourised upon impact. These details are determined from the shape and size of the crater, which is approximately 180 km in diameter and 20 km deep

Tex shows them a global map with the paleo-plate reconstructions from 66 Ma overlain on the outlines of the present continent locations (Fig. 39), which reveals significant movements in the intervening time. He explains that scientific drilling programs around the world add significant detail to our understanding of plate movement and geologic events.

Jiki, Zoe, Jeff and Tracy excitedly chime in on the group chat that this is an outstanding example of where their different specialties in geochronology, paleontology and astrophysics overlap.

Jiki, who loves a good thought exercise, challenges everyone to contemplate how the Cretaceous-Paleogene mass extinction event was dictated by the precise impact timing. Zoe remarks that they have to use some simplifying assumptions for this hypothetical scenario, requiring a simple model considering only the Earth's rotation (ignoring Earth's orbit around the Sun) to determine where the asteroid would have landed if it hit at a different time. She adds the constraint of a perfectly vertical descent onto Earth's surface.

Haly notes that tidal interactions between Earth and the Moon result in a transfer of angular momentum, causing the Earth's rotational rate to gradually slow over geologic time. They add that in the Late Cretaceous, a day was approximately 23.5 hours long.

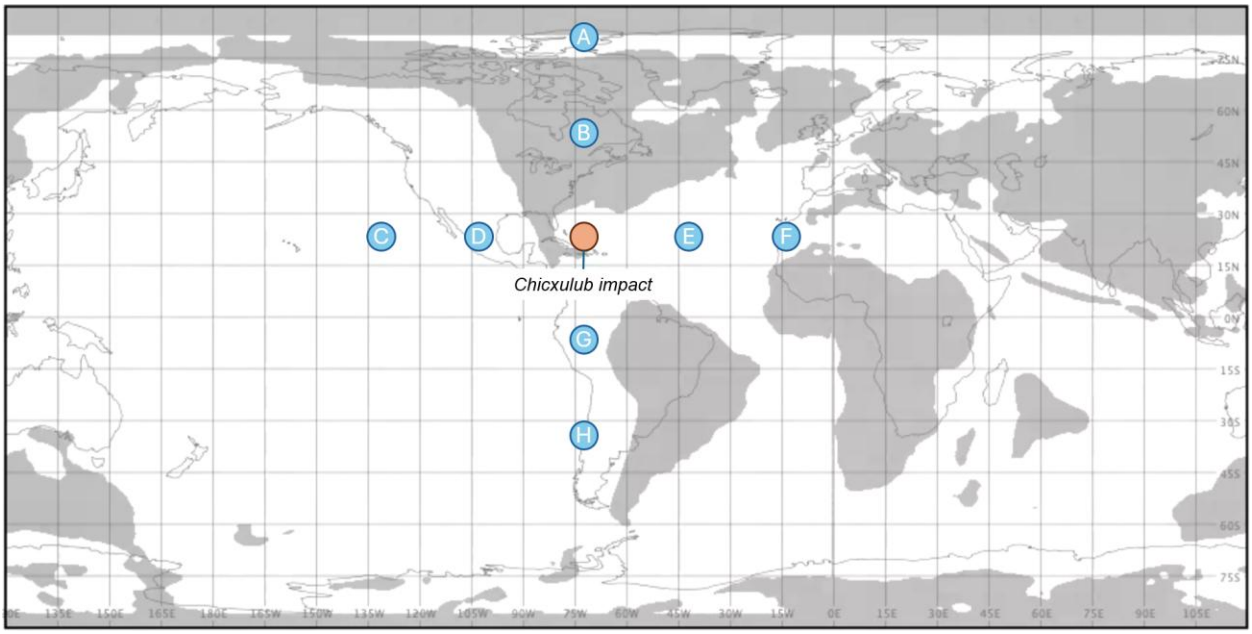


Figure 39: Continental locations 66 Ma are shown in grey superimposed over outlines of modern continental distribution. The Chicxulub impact centre is indicated in orange along with eight hypothetical impact locations.

65. Where would the asteroid have landed if it arrived 2 hours earlier?
    a. A
    b. B
    c. C
    d. D
    e. E
    f. F
    g. G
    h. H

Haly is extremely excited about the wild waves the impact would have generated. They explain the concept of wave shoaling to the others as, "*the change in wave behavior as they move into shallower water, causing waves to slow down, decrease in wavelength, and increase in amplitude*. *The opposite holds when entering deeper water.*"

Captain Wistas finds a NOAA video of a numerical model simulation of wave action triggered by the impact. He's absolutely horrified at the notion of encountering 5+ m high waves travelling so fast through the open ocean.
[video] https://sos.noaa.gov/catalog/datasets/tsunami-asteroid-impact-66-million-years-ago/

Tex says, *"Oh, it would've been way worse than that! We've figured out that a couple minutes after the asteroid struck, the curtain of material ejected from the crater pushed out a 4.5 kilometer high wall of water! Some 10 minutes after impact, a 1.5-km high tsunami started sweeping across the ocean in all directions!"* He shows them a model output of the maximum wave amplitude and current speed, noting that the model is saturated at 1,000 cm, so waves greater than 10 m are not indicated.

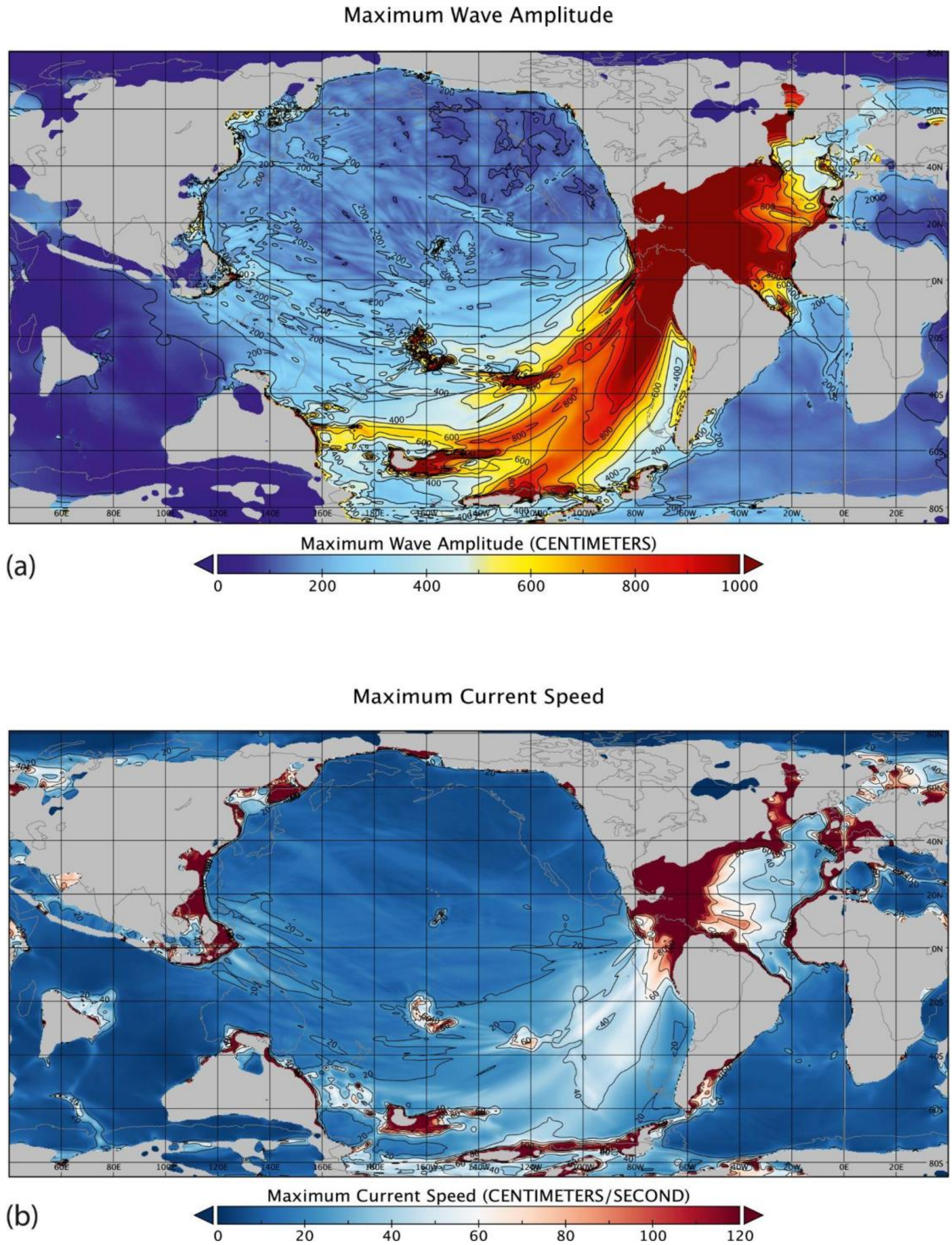


Figure 40: Maximum tsunami sea surface perturbation heights (a) and maximum flow velocity at each grid cell (b). From Range, MM et al (2022) doi.org/10.1029/2021AV000627.

Pearl exclaims, "*OMG, so, like, every place we visited on the way here would have completely drowned in this tsunami?!*"

66. Who correctly replies to her?
    a. Captain Wistas – "Alas, it would seem so."
    b. Cate – "Sydney and Vanuatu would have been fine, but all the little islands would have been submerged."
    c. Haly – "Sea level at the end of the Cretaceous was, on average, 170 m higher than today as there were no ice caps, so all those places were already under water before the tsunami passed."

d. Nate – “The islands that now have fringing or reefs would have been much higher 66 million years ago, so they would have been fine.”
e. Amber – “Sea level must have been much lower during the Mesozoic to allow dinosaurs to proliferate across the globe, so all the locations would have been completely fine.”

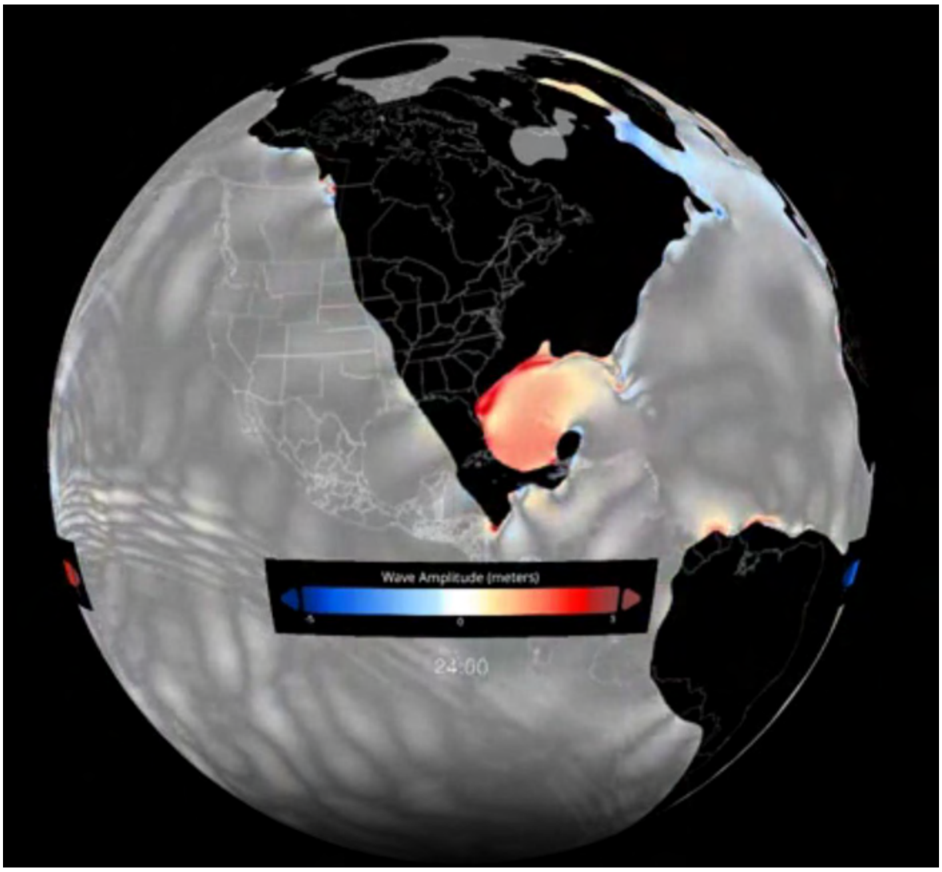


Figure 41: Screenshot of the NOAA simulated wave amplitude video 24 hours after the Chicxulub impact. Colour bar scale for Wave Amplitude ranges from -5 (blue) to 5 (red) meters. Continental reconstruction at the time of impact is indicated in black, superimposed over outlined modern plate configuration. Video source: https://sos.noaa.gov/catalog/datasets/tsunami-asteroid-impact-66-million-years-ago/.

67. Which of the following correctly explains what is observed in the image?
    a. After 24 hours, the energy from the tsunami has sufficiently dissipated such that no areas experience a wave height of greater than 1 m.
    b. After 24 hours, more than 80% of the energy from the initial tsunami wave remains in the water, concentrated in the Gulf of Mexico region.
    c. The Northern coast of paleo-South America experiences high wave heights due to shallow water depths near the shore.
    d. The Northern coast of paleo-South America experiences low wave heights due to deeper water depths near the shore.
    e. The Western coast of paleo-North America experiences high wave heights due to shallow water depths near the shore.
    f. The Western coast of paleo-North America experiences low wave heights due to deeper water depths near the shore.

g. The energy from the tsunami in the Gulf of Mexico is a contributing force to the Westwards plate tectonic motion of the North American plate.
h. The energy from the tsunami in the Gulf of Mexico is a contributing force to the Eastwards plate tectonic motion of the North American plate.

Ellie's feeling a bit impatient with all the wishy-washy talk about water, so she pulls out some drill core and a simplified geologic illustration of what they've uncovered.

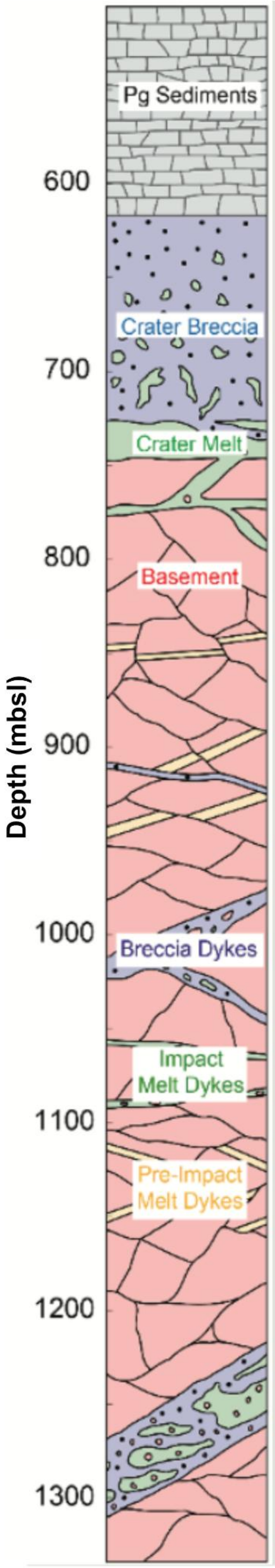


Figure 42: Simplified sequence of geologic units recovered from drilling within Chicxulub crater. Depth is recorded from sea level downward (meters below sea level); the top of the column is the seafloor. (Pg = Paleogene) Modified from IODP.

She provides the shocking explanation that the granitic rocks found beneath the area prior to the impact (basement) show evidence of impact-induced fracturing and injection of impact-generated melts down to about 1,100 meters below sea level. The extreme heat and pressure of the impact would have vapourised the uppermost rock layers before melting and fragmenting subsequent layers. The crater melt about 740 m down is the uppermost remnant of pre-impact material.

For about the first 10 minutes after impact, 30-40 kilometers of lithosphere would have responded like a swimming pool full of jelly having a bowling ball dropped into it, with the rocks surging up and out before re-solidifying.

68. She challenges the crew to explain how she can determine the relative age of the crater breccia, crater melt, basement rocks, breccia dykes, impact melt dykes, and pre-impact melt dykes without using any radiometric analyses. How do they correctly respond?

a. Using the principle of cross-cutting relationships (younger rocks cross cut older units).

b. Using the principle of superposition (younger rocks deposited atop older layers).

c. Using the principle of lateral continuity (continuous deposition across the lateral extent of a basin).

d. Using the principle of inclusion (older fragments are included within more recently formed rocks).

e. They conclude she must combine all of the aforementioned principles to determine the relative age of all these units.

f. They conclude it would be impossible to determine the relative age of all these units without radiometric dating.

She further explains that the top of the crater breccia unit is a 1-m thick tsunami deposit composed of sand-sized impact debris and glass beads known as *tektites*, with the bulk composition of all the vapourised material combined. She challenges them to work out how long it took for the ~100-m crater breccia unit to be deposited, reminding them that typical sedimentation rates range from less than a few millimeters per thousand years in deep sea environments to several meters per thousand years in river deltas.

69. Who correctly estimates the time required to deposit the crater breccia?
    a. Brady – about 10 million years, assuming a fairly slow deposition rate for a shallow marine environment of 10 mm/ka.
    b. Haly – about 1 million years, assuming a moderate deposition rate of 100 mm/ka in a shallow shelf environment.
    c. Pearl – about 100,000 years, assuming a moderately high rate of deposition in a dynamically changing environment of 1 m/ka.
    d. Captain Wistas – about 1,000 years, assuming a very high deposition rate of 100 m/ka because those are some crazy big waves!
    e. Nate – about 100 years, assuming it would take about this long for marine ecosystems to rebound sufficiently to start depositing Paleogene limestones.
    f. Cate – about 10 years, assuming most of the material fell directly back into the hole within a matter of hours and the last of the tsunami sloshed back over within a decade.
    g. Ariel – about 1 day, because that's about the time it would take for the tektites to fall back down through the atmosphere and the last of the tsunami to reflect around the paleo Gulf of Mexico.

Tex shows them the geophysical impact model developed from the results of all the drilling and geologic investigations in the region (Fig. 43). He tells them that drilling outside the impact crater reveals that there were significant deposits of sulfate rich evaporite rocks forming a shallow marine shelf in the proto-Caribbean. As there are no sulfate-rich layers within the impact crater, it is presumed the total volume of sulfates were vapourised by the impact and ejected into the atmosphere, producing an enormous volume of sulfate aerosols (several thousand gigatonnes of asteroidal and target material combined).

He also shares the numerical models developed to illustrate how the ejecta curtain and impact plume would interact with the atmosphere to be dispersed globally (Fig. 44). This shows that some ejecta likely reached escape velocity (>11 km/s) and that the front of the dust-laden cloud travelled at least 8,000 km in the first hour after impact, shrouding the earth in dust, soot, sulfate aerosols and other ejecta within 4-5 hours.

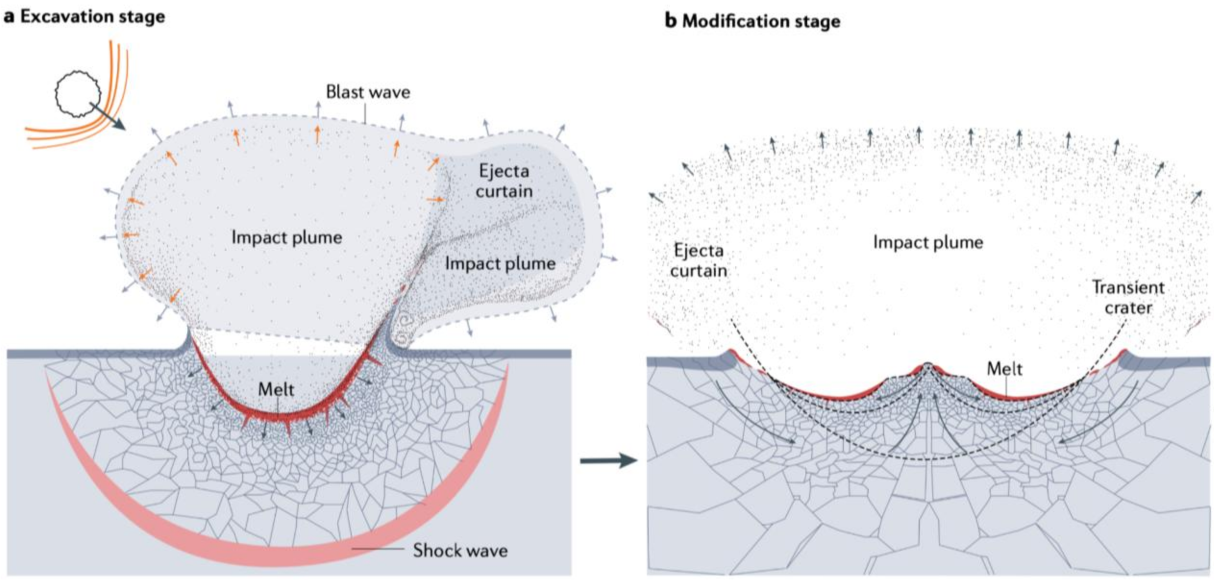


Figure 43: Evidence-based impact model for a meteor the size of the Chicxulub impactor. When an asteroid penetrates the target, it generates shock waves (a) with initial pressures of several hundreds GPa. The extreme heat and pressure cause melting and vaporization of both the impactor and impacted target rocks. Shortly thereafter, the cavity rim collapses downwards and inwards while the central area initially collapses inwards and upwards, then downwards and outwards (b). From Morgan, J.V., Bralower, T.J., Brugger, J. et al (2022) doi.org/10.1038/s43017-022-00283-y.

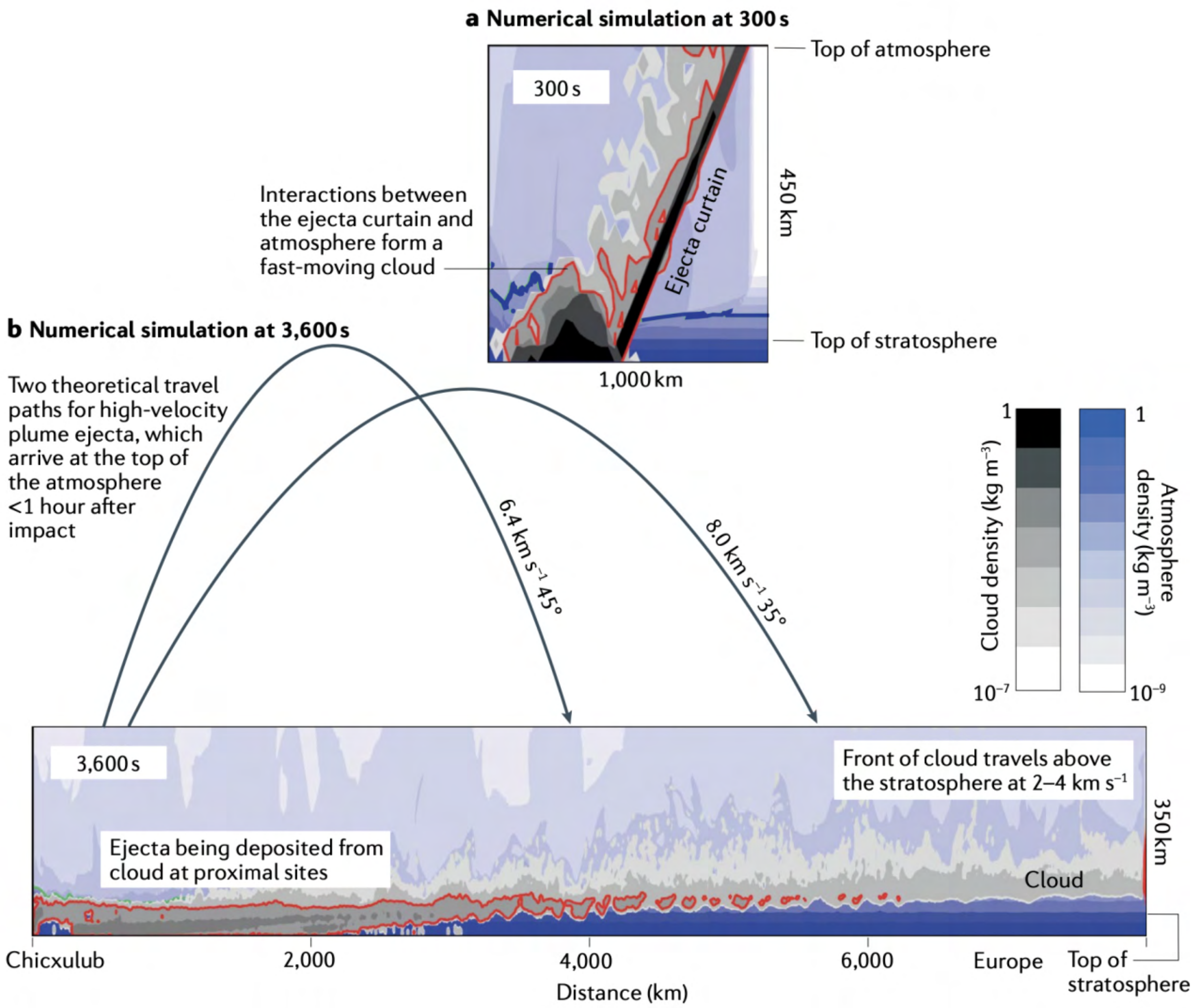


Figure 44: Numerical model of ejecta cloud front at: a) 5 minutes after impact; b) 1 hour after impact. From Morgan, J.V., Bralower, T.J., Brugger, J. et al (2022) doi.org/10.1038/s43017-022-00283-y.

Thinking back to what they learned about how explosive volcanic eruptions affect the climate when they suddenly inject large volumes of sulfate aerosols into the stratosphere, the crew makes some predictions about how the impact would have affected the global temperature effect.

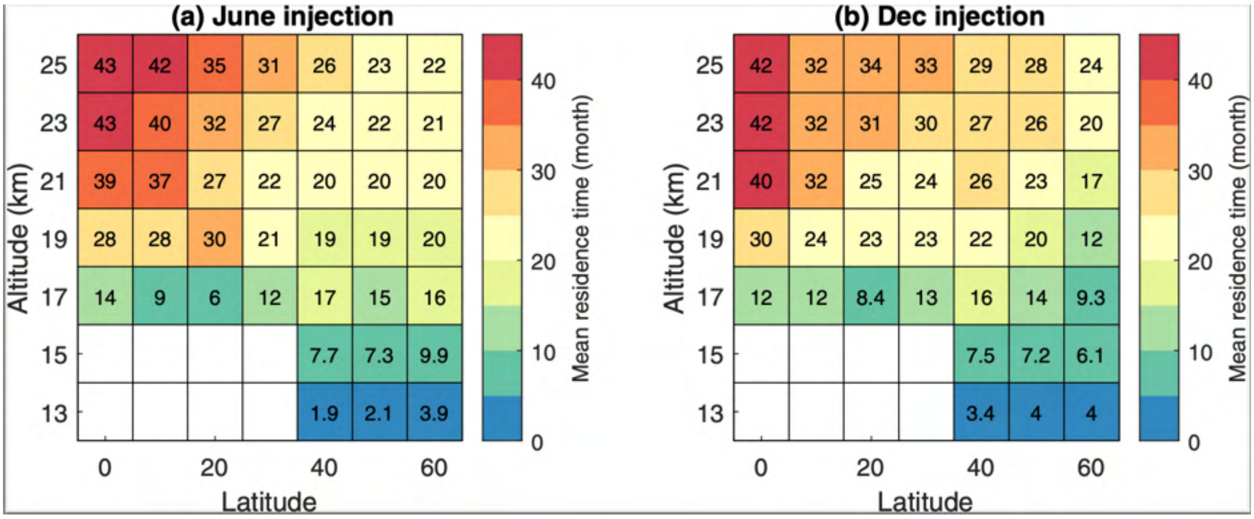


Figure 45: Mean residence times (in number of months) of sulfate aerosols in the stratosphere spanning various altitude and latitude combinations. Results are shown for injections in the Northern hemisphere Summer (a) and Winter (b). From Toohey, M et al (2025) doi.org/10.5194/acp-25-3821-2025.

70. Which of the following statements about the persistence of cooling sulfate aerosols is correct?
    a. Injection altitude has a greater effect than latitude.
    b. Injection latitude is the primary control on residence time.
    c. Residence time has a strong seasonal control.
    d. Aerosols injected at high latitudes always stick around much longer than at low altitudes.
    e. Aerosols injected at high latitudes always stick around much longer than at high altitudes.
    f. Residence time has no seasonal control.

71. What is the longest potential time for sulfate aerosols from the impact to have a cooling effect?
    a. 1.5 year
    b. 2.5 years
    c. 3.5 years
    d. 10 years
    e. 43 years
    f. 400 years

72. Thinking back to their earlier hypothetical scenario of the asteroid landing somewhere else on Earth, Ariel wonders what difference it would make if the impact

site were in the deep ocean or on land instead of a shallow marine shelf. What does the crew correctly surmise?

A. An impact in the deep ocean would have vapourised enormous volumes of sea water, causing short-term global warming and generally leaving the dinosaurs to rule for another age.
B. An impact in the deep ocean would have had no global effect as the water would absorb all the shock, leaving the dinosaurs to rule for another age.
C. An impact in the deep ocean would have vapourised enormous volumes of sea water, causing a smaller but longer term global cooling, affecting the dinosaurs to a lesser extent and leading to their coexistence with mammals.
D. An impact on land would have vapourised and ejected a huge mixed batch of fine rock particulate matter, blocking out the sun for weeks to months, causing short-term cooling on a smaller order of magnitude than what occurred.
E. An impact on land would have vapourised a huge volume of silicate rocks, causing even more extreme cooling and eradicating all life on Earth.
F. An impact on land would have squashed a great many dinosaurs, leading to localised extinctions and potentially unravelling the Mesozoic food web.
    a. A and D
    b. A and E
    c. A and F
    d. B and D
    e. B and E
    f. B and F
    g. C and D
    h. C and E
    i. C and F

Amber ponders how an impact of the same magnitude in a different season and latitude would change the outcome, assuming the asteroid still landed on a shallow marine shelf.

73. How does the crew correctly sum up the seasonal and latitudinal effects?
    a. There isn’t a significant seasonal difference, but an impact at higher latitude would have a longer effect.
    b. There isn’t a significant seasonal difference, but an impact at lower latitude would have a longer effect.
    c. There isn’t a significant difference in an impact during a different season or a different latitude.
    d. An impact in the northern hemisphere summer would have a much more extreme cooling effect than in winter, but the effect of latitude is minimal.
    e. An impact in the northern hemisphere winter would have a much more extreme cooling effect than in summer, but the effect of latitude is minimal.
    f. An impact in the northern hemisphere summer would have a much more extreme cooling effect than in winter, and an impact at higher latitude would be longer.
    g. An impact in the northern hemisphere summer would have a much more extreme cooling effect than in winter, but an impact at higher latitude would be shorter.

Their pal Jeff sends them a message from his field area in Hell Creek, North Dakota, about 3,000 km north-west (Fig. 46).

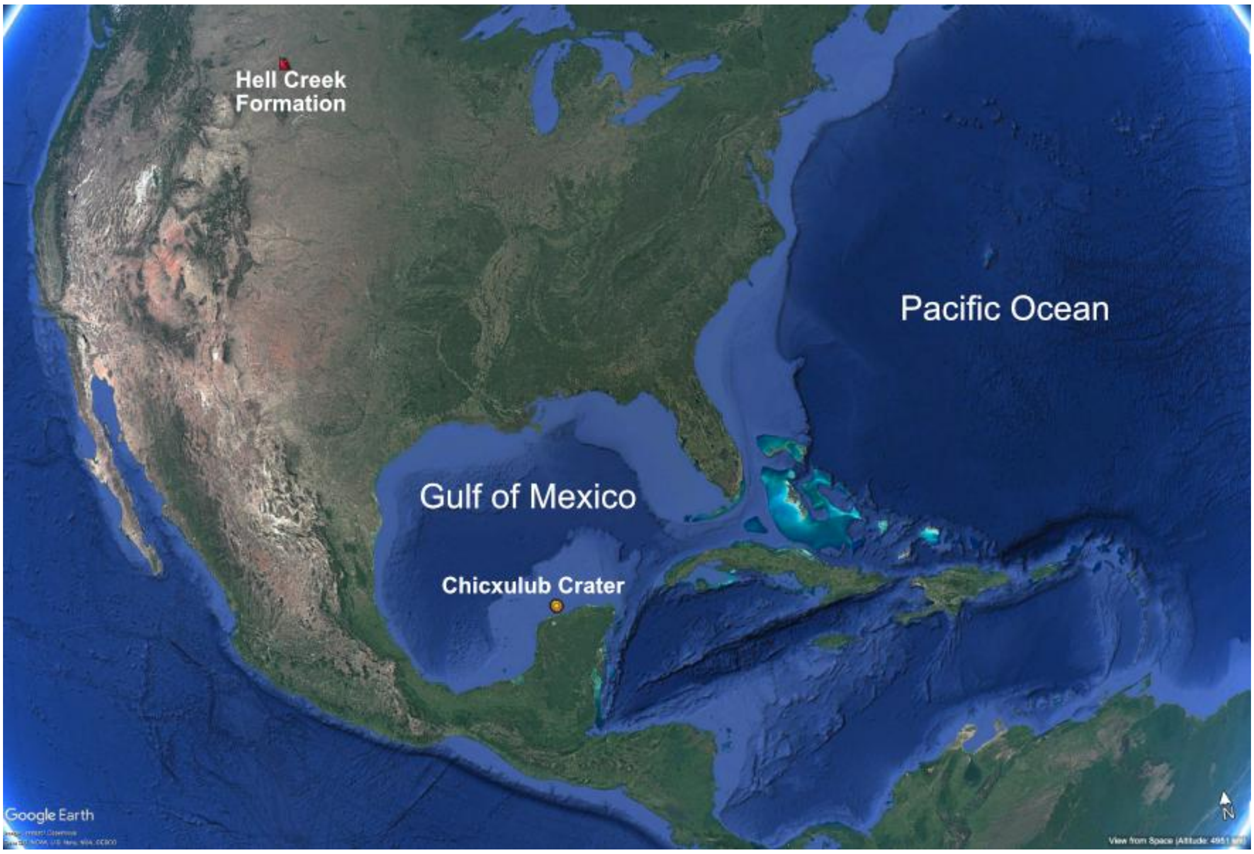


Figure 46: Jeff's virtual postcard to the crew showing his field location relative to theirs.

"Howdy, folks! You would not believe what we found up here today – a 66 million year old fish lodged in a tree!"

Traci chimes in, *"Jeff never lets the truth get in the way of a good tale, but seriously this fish died 66 million years ago after being ejected out of the water fast enough to jam it into a tree. Jeff's postcard is also a little misleading if you want to think about what happened the day these poor fish ate tree. Check out my reconstruction of Late Cretaceous North America instead."* (Fig. 45) *"The truly remarkable thing about this layer of the Hell Creek Formation is not only does it tell us about the day the dinosaurs died, but we can also see that nearly all of the organisms in it died by drowning in mud from the tsunami!"*

Figure 47: Traci's image of the North American landmasses in the Late Cretaceous. The approximate locations of the Hell Creek formation and Chicxulub Crater are marked for reference. Modified after SD Sampson, MA Loewen, AA Farke, EM Roberts, CA Forster, JA Smith, AL Titus, CC BY 4.0.

74. Considering the Western Interior Seaway was quite shallow at the time of impact, approximately how long after impact were the fish hit by the tsunami?
    a. About 2 minutes

b. About 20 minutes
c. About an hour
d. About 20 hours
e. About 2 days
f. About a week
g. About 2 weeks

75. There are spherules of glass in the fish gills, which would suggest the fish were still alive and sucking in ejecta when the tsunami hit. Is this hypothesis confirmed or ruled out by the relative arrival times of the tsunami and ejecta cloud?
    a. Confirmed – the ejecta cloud would have arrived approximately 18 hours before the tsunami.
    b. Confirmed – the ejecta cloud would have arrived approximately 1 hour before the tsunami.
    c. Confirmed – the ejecta cloud would have arrived approximately 1 day before the tsunami.
    d. Ruled out – the tsunami would have arrived approximately 1 hour before the ejecta cloud.
    e. Ruled out – the tsunami would have arrived approximately 18 hours before the ejecta cloud.
    f. Ruled out as they would have arrived simultaneously.

Jeff shows them a nifty little data compilation used to calibrate the season of untimely death in the Hell Creek Formation (Fig. 48). He tells them, *"By correlating ranges of seasonal insect behaviour with sub-yearling fish fossil size ranges, isotopic data, and bone growth patterns, we can work out seasonal ranges for each species at their time of death. Combining a group of different species allows us to work out the most likely timing of the death event. When do you reckon the dinosaurs kacked it?"*

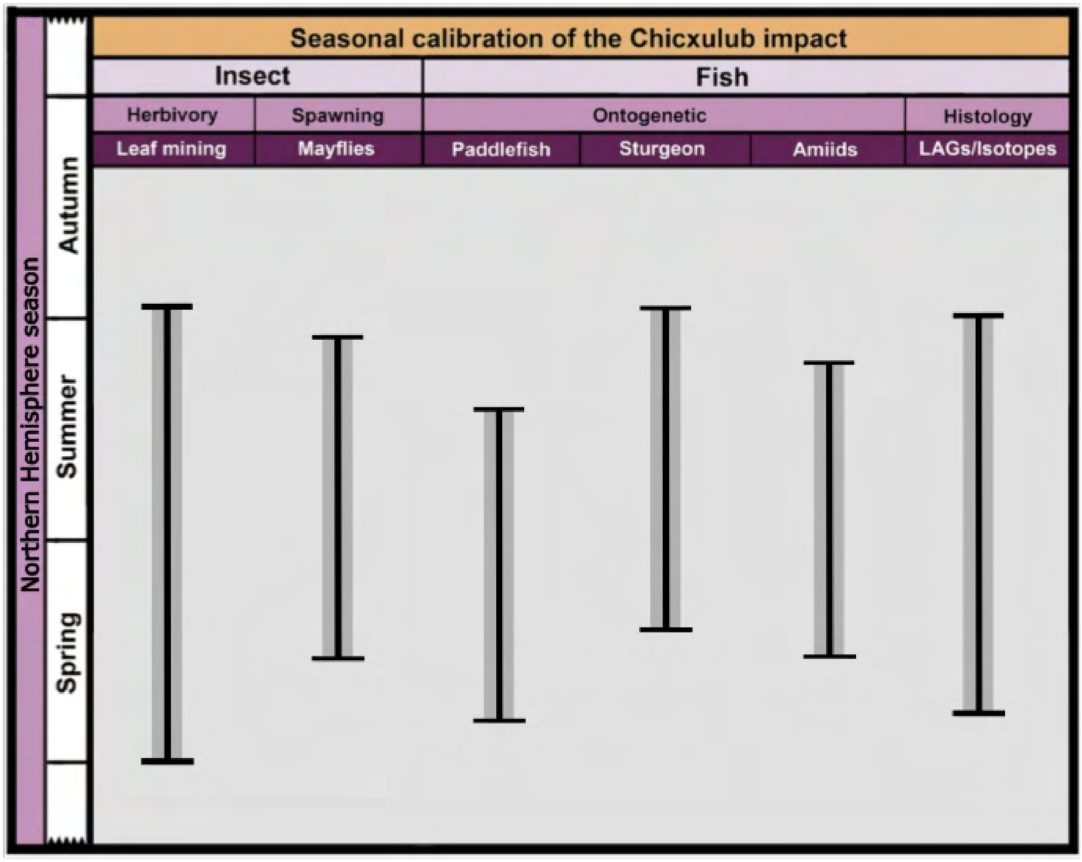


Figure 48: Seasonal calibration of the Chicxulub impact from biological markers. Modified from DePalma, RA et al (2021) doi.org/10.1038/s41598-021-03232-9.

76. What season does the crew work out is the most likely time of death for the Dinosaurs?
    a. early Spring to late Spring
    b. early Summer to late Summer
    c. early Autumn to late Autumn
    d. mid Spring to mid Summer
    e. mid Summer to mid Autumn
    f. mid Winter to mid Spring

Jeff is just getting warmed up on the grizzly details and shows them how they work out the season limitations on paddlefish bone tissues (Fig. 49). *"You see, we slice and dice their little bones then analyse the repeating cycles of growth and repose, just like tree rings, I suppose. This allows us to show how they grow, the fishy age and what they know, tells us when they died through season flows, noting that growth in most species is rapid in spring and tapers off in late summer."*

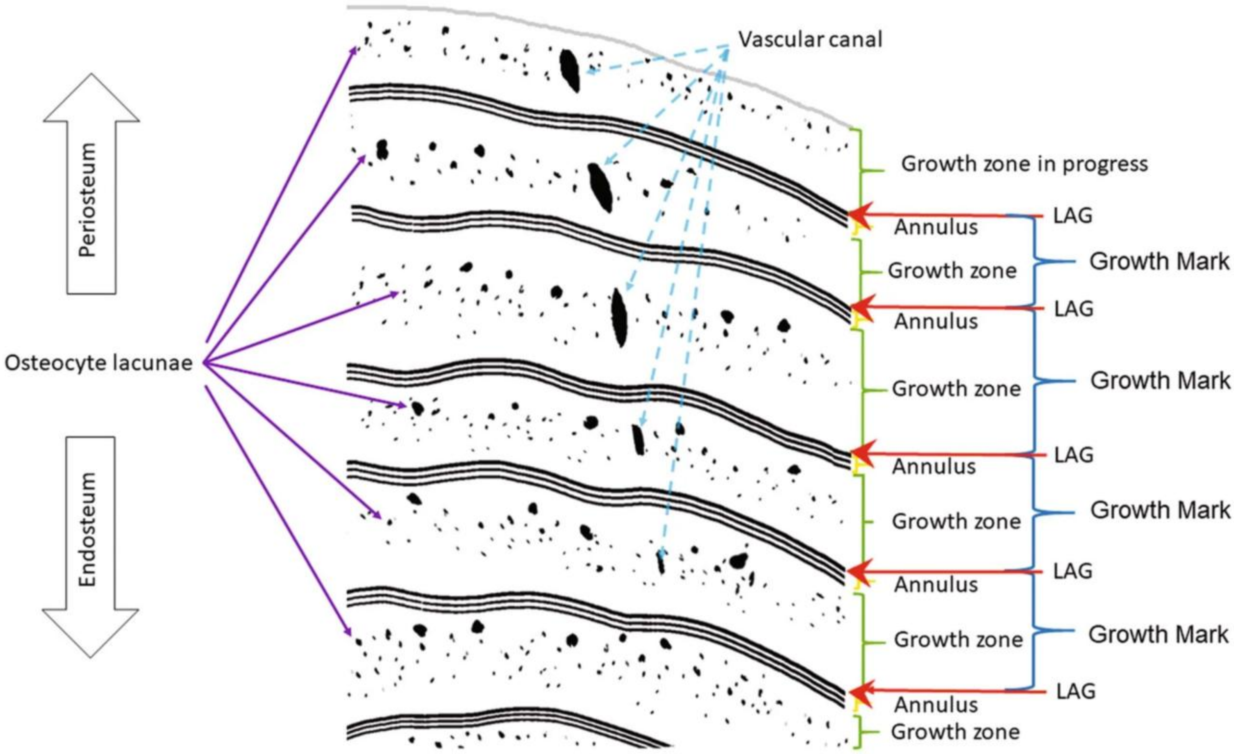


Figure 49: Schematic diagram of the microscopic structures in paddlefish bone tissues indicating key growth features. These bones record annual growth cyclicity. A Growth Mark spans a single annual growth cycle divided into a growth zone (spring/summer), an annulus (autumn), and a LAG (no growth in winter). From During, MAD et al (2022) doi.org/10.1038/s41586-022-04446-1.

77. Based on the evidence from Jeff's fossilised paddlefish inner ear bone and his cryptic bit of poetry, in what season did the impact occur?
    a. Autumn-Winter
    b. Autumn
    c. Winter
    d. Spring-Summer
    e. Spring
    f. Summer

On Stranger Tides

Having had his fill of fishy tales, Nate is keen to learn more about the geologic features around the Chicxulub Crater, so Tex tells him that in addition to thick evaporite layers, there were significant limestone deposits, consistent with shallow, warm marine settings. As he's doing a bit of reading, Nate comes across a cool little diagram (Fig. 50) illustrating how erosional features form in a limestone bounded above and below by siliciclastic rocks. He asks his sister if she can figure out what controls the distribution and orientation of caves and springs in this kind of setting.

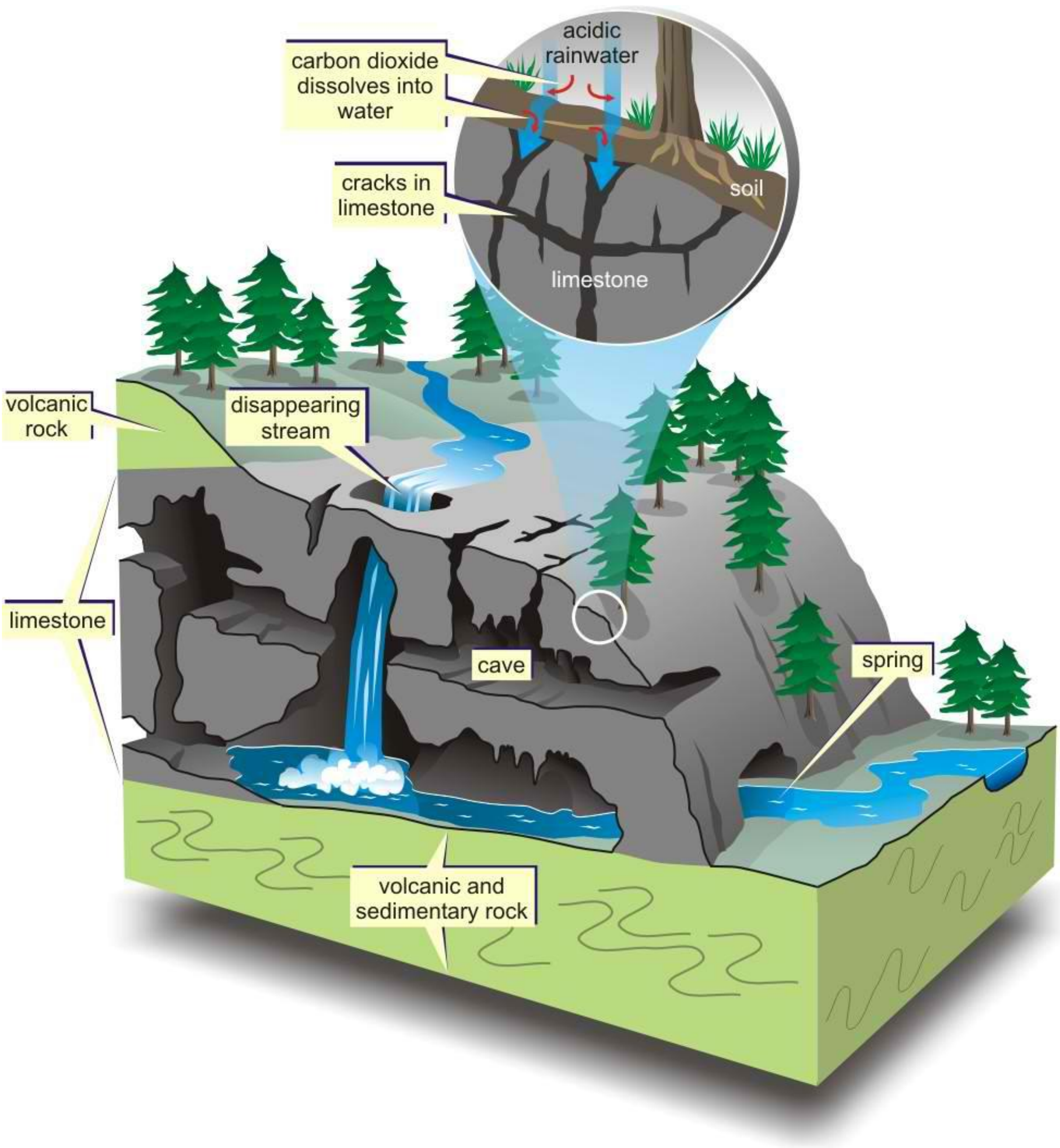


Figure 50: Karstification mechanisms. Source: McColl et al (2005) Geological Survey of Canada.

78. How does Cate correctly answer? *"Too easy, it results from…"*
    a. …the preexisting fracture pattern within the carbonate rocks coupled with much less soluble siliciclastic bounding layers.
    b. …the preexisting fracture pattern of carbonate rocks.

c. …the bounding layers of volcanic and sedimentary rocks.
d. …the root systems of the trees opening cracks in the overlying soil.
e. …the pH of the infiltrating rain water.
f. …the root systems of the trees opening cracks in the overlying soil coupled with the pH of the infiltrating rain water.

"OK, smarty pants," Nate fires back. *"If that was too easy for you, then try explaining why, when limestones tend to fracture along orthogonal joint sets, we find a circular distribution of cenotes around the Yucatan Peninsula?"* He shows her the regional gravity anomaly map with white dots indicating cenote locations (Fig. 51).
"Nate," she replies quietly, *"what on earth is a 'sen-oh-tay'?"*
"Oh," he answers, *"that's the local term for the naturally formed karstic sinkholes that expose the groundwater and sometimes lead to underground cave systems. This region is world famous for their cave diving!"*

79. What does Cate correctly reason out?
    a. There must have been a ring-shaped zone of fractured rocks around the impact site.
    b. The preexisting fracture pattern of carbonate rocks is arbitrary and this semi-circular distribution is purely coincidental.
    c. Bounding layers of volcanic and sedimentary rocks only exist in a ring around the impact crater.
    d. Trees with deep enough root systems to prise open cracks in the soil above the limestone only grow in a semi-circular region around the impact crater.
    e. The infiltrating rain water only reaches the optimal pH to dissolve the limestones at a set distance from the coast.
    f. The limestones must have been deposited in a ring around the crater after the impact.

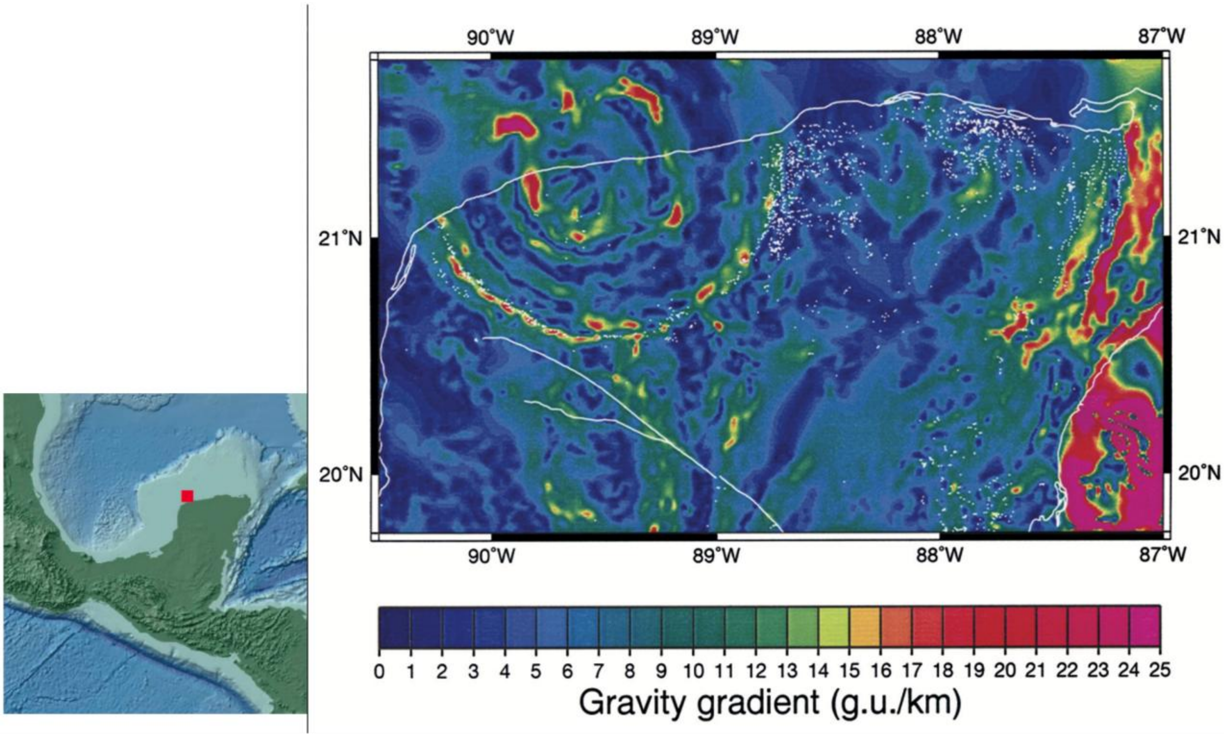


Figure 51: Gravity anomaly map over the Chicxulub crater. White dots indicate the location of cenotes. Location map from: French & Schenk (2004) USGS ; Gravity anomaly from: Connors, M. et al (1996) doi.org/10.1111/j.1365-246X.1996.tb04066.x.

Pearl overhears their conversation and gets psyched up for some cave diving. She has a lot of experience freshwater diving, so naturally packs her weights to help her stay neutrally buoyant as she descends.

80. Nate uses Figure 52 to warn her that she may need to carry more weights than she is used to for dives of a similar depth. How does he correctly explain why she should do this?

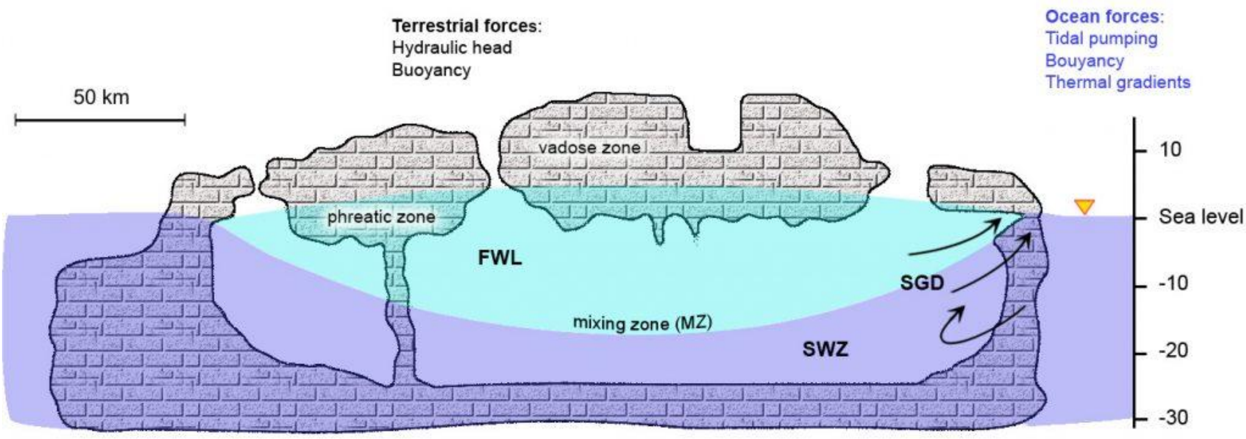


Figure 52: Diagram of the Yucatan Peninsula, where the groundwater is separated into two layers of different salinity and density: the shallow freshwater lens (FWL) and the deep saltwater zone (SWZ) that filters through the rock. The mixing zone between the two layers is called halocline. SGD: Submarine Groundwater Discharge surfaces creating freshwater springs at the adjacent coastal ocean. From https://sites.northwestern.edu/monroyrios/2017/12/26/speleogenesis/.

a. As Pearl descends deeper into the cenote, the increased water pressure will cause her lungs to inflate, making her feel more buoyant.
b. As Pearl descends deeper into the cenote, the increased water pressure will cause her lungs to deflate, making her feel more buoyant.
c. When Pearl hits the mixing zone, the salinity of the water she's in will dramatically increase, making her feel more buoyant.
d. When Pearl hits the mixing zone, the salinity of the water she's in will dramatically decrease, making her feel more buoyant.
e. As Pearl descends through the water column, she will feel no difference in buoyancy as there is not enough salt in the water to change it significantly.
f. As Pearl descends, the increase in pressure will cause her lungs to deflate cancelling out the increase in buoyancy from increased salinity.

Figure 53: Pearl checking out the cenote. Image: Jill Heinerth https://sites.northwestern.edu/monroyrios/sistema-sac-actun-en/.

Deeper into the cave, Pearl comes across exquisite formations that appear to drip down from the ceiling and loom up from the floor (Fig. 53). From previous dives, she knows these are called speleothems, with common formations known as stalagmites and stalactites. These form when fluids carrying dissolved carbonate come into contact with air with low CO_2 concentration, precipitating calcium carbonate and releasing CO_2 via the chemical reaction:

$Ca(HCO_3)_2(aq) \rightleftarrows CaCO_3(s) + CO_2(g) + H_2O(l)$

However, she is confused how the speleothems can form through precipitation of $CaCO_3$ in a cave system that formed by dissolving the surrounding limestone.

81. What is the correct explanation for this relationship does Nate provide when Pearl resurfaces?
    a. The speleothems must form after cave formation from fluids dissolving limestone relatively nearby.
    b. The speleothems must form after cave formation from fluids dissolving limestone hundreds of kilometers away.
    c. The speleothems must form during cave formation from hyper-saturated fluids from local dissolution.
    d. The speleothems must form during cave formation from hyper-saturated fluids from dissolution hundreds of kilometers away.
    e. The speleothems must form prior to cave formation and resist dissolution during cave formation due to a more resistant crystal structure.
    f. The speleothems must form prior to cave formation and resist dissolution during cave formation due to their sheer majesty.

Nate explains that speleothems can form either on damp surfaces that are mostly exposed to the air, such as stalactites and columns, or on surfaces that are submerged under streams of running water, like rimstone dams.

82. Using the diagram in Figure 54, what do they conclude about the type of speleothem and the surrounding sea level when the speleothems were forming?
    a. The speleothems in this part of the cave formed in contact with **outside air**, meaning sea levels must have been **lower** during their formation.
    b. The speleothems in this part of the cave formed in contact with **outside air**, meaning sea levels must have been **higher** during their formation.
    c. The speleothems in this part of the cave formed in contact with small **isolated pockets of air**, meaning sea levels must have been **lower** during their formation.
    d. The speleothems in this part of the cave formed in contact with small **isolated pockets of air**, meaning sea levels must have been **higher** during their formation.
    e. The speleothems in this part of the cave formed under streams **running water** in contact with **outside air**, meaning sea levels must have been **lower** during their formation.
    f. The speleothems in this part of the cave formed under streams of **running water** in contact with **outside air**, meaning sea levels must have been **higher** during their formation.
    g. The speleothems in this part of the cave formed under streams of **running water** in contact with small **isolated pockets** of air, meaning sea levels must have been **lower** during their formation.
    h. The speleothems in this part of the cave formed under streams of **running water** in contact with small **isolated pockets of air**, meaning sea levels must have been **higher** during their formation.

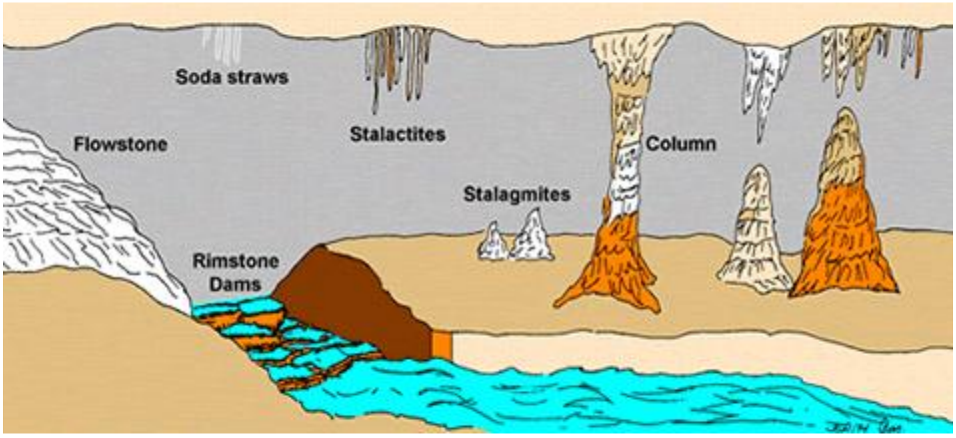


Figure 54: Speleothem morphology diagram. From https://mostateparks.com/page/55118/speleothems.

As she swims past, Pearl knocks off both a stalagmite and a stalactite. Although devastated by the destruction of these features, she collects the pieces for later analytical work. To begin her investigation, she slices both in half.

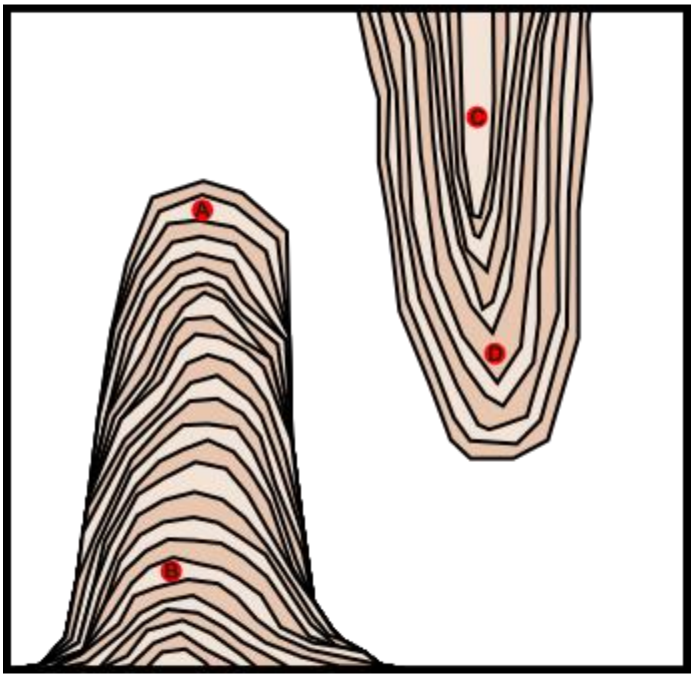


Figure 55: Pearl's cross-sectional sketch of the speleothems she accidentally broke illustrated in their original orientations.

83. What can Pearl correctly conclude about the layers within the speleothems?
    a. A is older than B, D is older than C
    b. A is older than B, C is older than D
    c. B is older than A, D is older than C
    d. B is older than A, C is older than D
    e. A is older than B, but you cannot tell whether C or D are older
    f. B is older than A, but you cannot tell whether C or D are older
    g. C is older than D, but you cannot tell whether A or B are older
    h. D is older than C, but you cannot tell whether A or B are older

84. Pearl also wonders if you can tell whether the stalagmite or stalactite is older. Nate tells her:
    a. Because the stalagmite has more layers than the stalactite, we know it is older.
    b. Because the stalactite has more layers than the stalagmite, we know it is older.
    c. Because the stalagmite has more layers than the stalactite, we can infer that it is older but would need to use a dating technique to be sure.
    d. Because the stalactite has more layers than the stalagmite, we can infer that it is older but would need to use a dating technique to be sure.
    e. We cannot tell the relative age of the stalagmite and stalactite, but a dating technique would resolve the difference.
    f. We cannot tell the relative age of the stalagmite and stalactite, and no dating technique would be able to resolve the difference.

85. Ellie is really enjoying all the engaging discussions and challenges the crew to work out what technique they would need to use to determine absolute ages for their speleothems. What approach do they correctly choose?

a. Stable isotope geochemistry of Hydrogen
b. Stable isotope geochemistry of Carbon
c. Stable isotope geochemistry of Nitrogen
d. Stable isotope geochemistry of Sulfur
e. Radiometric dating of Carbon
f. Radiometric dating of Hydrogen
g. Radiometric dating of Nitrogen
h. Radiometric dating of Uranium

86. She pushes them further to work out how they could determine the *temperature* of the water when each speleothem layer was constructed. Which technique do they correctly choose?
    a. Stable isotope geochemistry of Hydrogen
    b. Stable isotope geochemistry of Carbon
    c. Stable isotope geochemistry of Nitrogen
    d. Stable isotope geochemistry of Sulfur
    e. Radioactive decay of Carbon
    f. Radioactive decay of Hydrogen
    g. Radioactive decay of Nitrogen
    h. Radioactive decay of Uranium

It just so happens that deep holes like cenotes, known as marine blue holes off shore, provide a nifty way of recording changing tropical cyclone frequency patterns across the Gulf of Mexico. Jiki shows the crew a collection of hurricane deposit records from the region, including drill cores from Florida, Mexico, Belize, Puerto Rico, and the Bahamas (Fig. 56). Storms passing nearby produce distinct coarse-grained overwash deposits in these sediment traps.

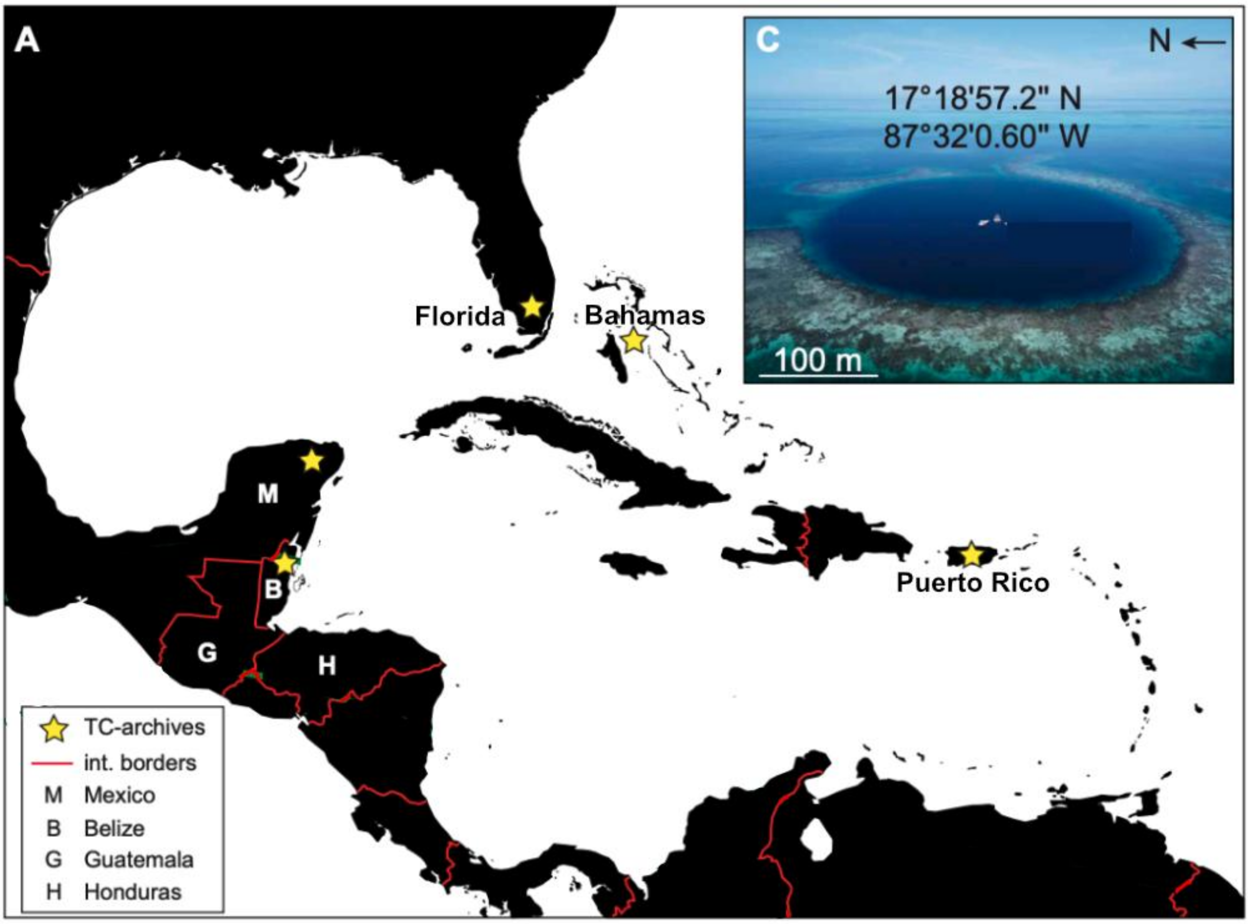


Figure 56: Map of circum--Caribbean region with important tropical cyclone-frequency archives (yellow stars). Drone view of the Great Blue Hole (inset). Modified from Schmitt et al, 2025 CC BY-NC 4.0.

Ariel explains that tropical storms are more likely to form when sea surface temps are high and vertical wind-shear stresses are low in the Atlantic hurricane development region. This means that climate change will most likely increase the potential for tropical storm hazards.

Jiki says, “To understand how climate conditions alter tropical cyclone frequency on centennial to millennial timescales, we have to ‘read’ sufficiently sensitive sedimentary records with very good temporal resolution. Meaning they are constantly recording in such a way that we can tell the difference between business as usual and rapid storm events.”

The Great Blue Hole off the coast of Belize is a world-class scuba diving destination Pearl can’t wait to visit.

87. When would be a VERY BAD time of year to hang around if the crew wishes to avoid getting caught in one of the many tropical cyclones that devastate the region?
    a. December to March
    b. February to May
    c. April to July
    d. May to October
    e. June to November
    f. August to December

Brady finds a nice diagram that neatly illustrates why marine blue holes make excellent tropical storm record keepers (Fig. 57). Jiki supplements this with a drill core record from the Great Blue Hole correlated with depositional variations controlled by relative sea level (Fig. 58).

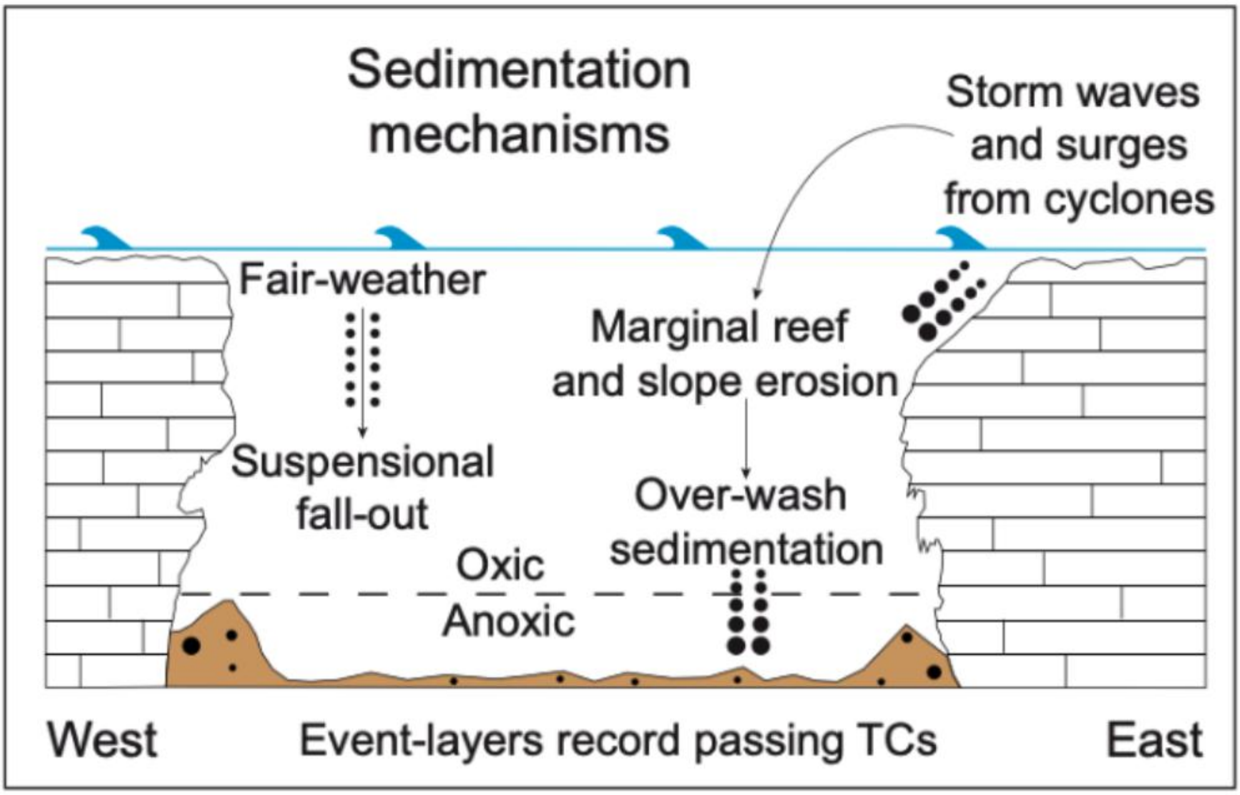


Figure 57: Schematic model of tropical storm sedimentation in marine blue holes. From Schmitt et al, 2025 CC BY-NC 4.0.

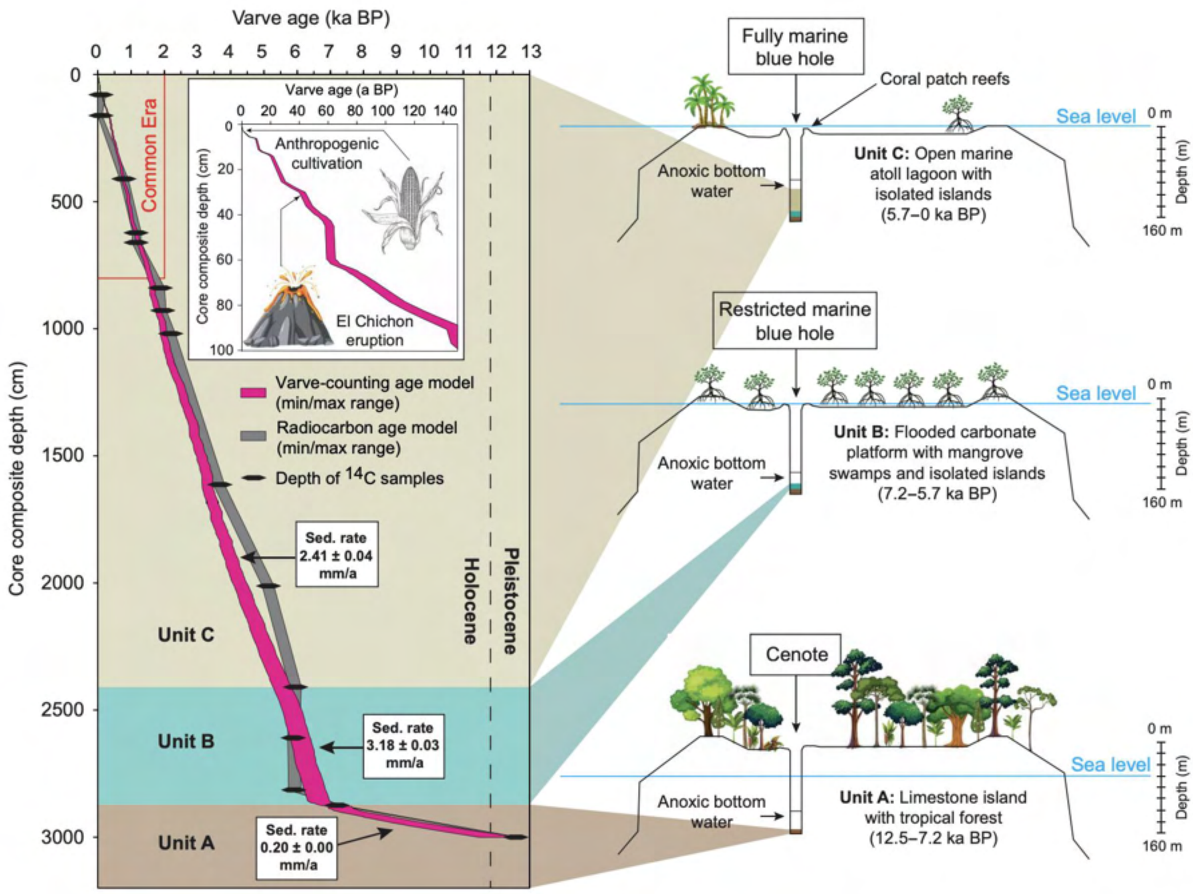


Figure 58: Relationship between measured and inferred age as a function of drill-core depth (left) correlated with paleoenvironment reconstructions (right). The age model is based on varve-counting (fine annual layers), radiocarbon dating (black marks), observation of pollen associated with anthropogenic cultivation (corn, pine and palm) from 2.5-cm depth, and volcanic glass shards from the 1982 CE eruption of El Chichón (Mexico) at 30-cm depth. The Great Blue Hole sediment succession is separated into three major units (A, B, and C), which are characterised by differing composition and sedimentation rates. These reflect three distinct depositional and environmental settings. Additional information indicates unit A extends 1.85 m further down to a Pleistocene bedrock of karst breccia. From Schmitt et al, 2025 CC BY-NC 4.0.

88. Jiki gives the team a tricky question to work out, *"How can you explain the dramatic change in sedimentation rate in this environment about six thousand years after the end of the Pleistocene?"* Who comes up with a satisfactory solution?
    a. Captain Wistas – the waves in the Pleistocene must have still been huge in this area after that meteorite impact!
    b. Jeff – the explosive proliferation of new fish species after the last glacial maximum clearly led to higher deposition rates.
    c. Amber – the explosive proliferation of marine mammals after they returned to the oceans would have led to higher deposition rates.
    d. Brady – the explosive proliferation of unicellular eukaryotic species after the last glacial maximum would have led to higher marine sedimentation rates.
    e. Haly – rising global sea levels after the last glacial maximum would eventually submerge the carbonate platform, facilitating more continuous sedimentation within the sink hole.

f. Pearl – decreasing water pressure at shallower levels within the sink hole would lead to less compaction of the sediments.
g. Ariel – increasing atmospheric temperatures after the last glacial maximum would lead to thermal expansion of the oceans causing sedimentation to proceed faster.

89. Jiki poses another challenge: *"What satisfactory explanation can you give for why the dating errors (min/max range) from varve counting increases further back in time?"* Putting their heads together, what correct conclusion does the crew draw?
    a. Greater compaction of older sediments
    b. Bioturbation (wormy critters digesting sediments and dragging mud around) of sediments causes increasing disturbances over time.
    c. The probability of erosion of some layers is low overall, but more time creates more opportunities for improbable events to occur.
    d. Counting errors
    e. Insufficient seasonal variation to create couplet
    f. A combination of all these factors

90. Cate remarks on the impressively consistent sedimentation rate determined by the varve counting method back to nearly 6,000 years ago. She is, however, perplexed by the one very inconsistent radiocarbon date from the sample around 2000 m down. What reasonable explanation does someone else provide for this single significant outlier?
    a. The material recovered from 2000 m was burned about 500 years before being washed into the cenote and buried.
    b. The material recovered from 2000 m was carried up through the underlying sediment layers by a burrowing critter.
    c. The material recovered from 2000 m was carried down through the overlying sediment layers by a burrowing critter.
    d. Radiocarbon dating is not reliable for geologic materials.
    e. Radiocarbon dating always gives ages older than the actual material age.
    f. Radiocarbon dating always gives ages younger than the actual material age.

91. The eruption of El Chichon volcano in southeastern Mexico produced a significant ash cloud that spread over the Caribbean. The tephra layer from this eruption is clearly preserved 30 cm down in the GBH sediments and used to verify the varve-counting technique. How is the El Chichon ash dated with certainty as being deposited in 1982 CE?
    a. The eruption was reported on the news
    b. The ash layer buried neolithic tools
    c. Radiocarbon dating of glassy shards
    d. U-Th dating of feldspars in the ash
    e. Fission track dating of zircons in the ash
    f. A combination of all the aforementioned techniques
    g. None of these techniques can be used to accurately date a modern eruption

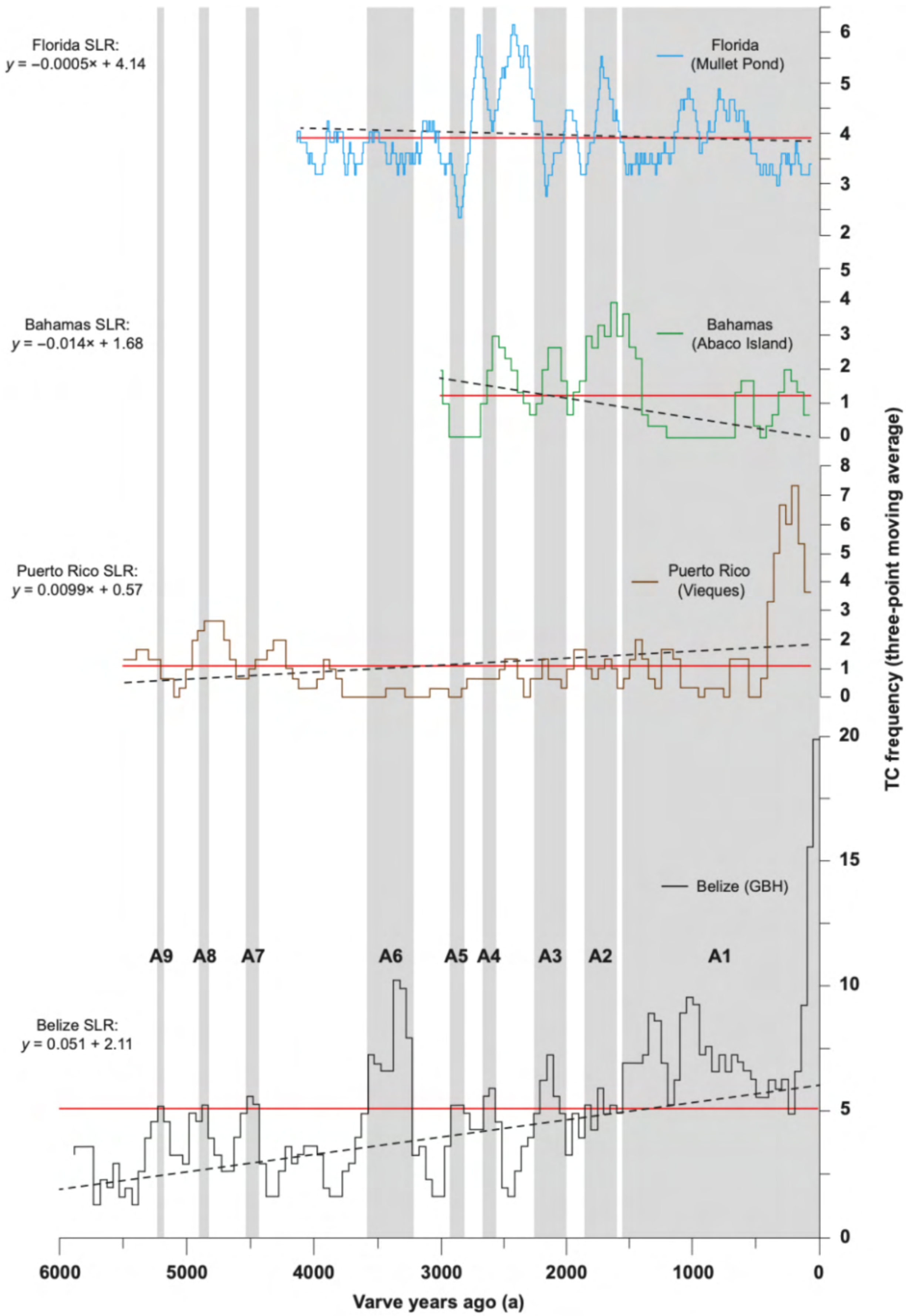

Florida SLR:
y = −0.0005× + 4.14
Florida
(Mullet Pond)
Bahamas SLR:
y = −0.014× + 1.68
Bahamas
(Abaco Island)
Puerto Rico SLR:
y = 0.0099× + 0.57
Puerto Rico
(Vieques)
Belize (GBH)
Belize SLR:
y = 0.051 + 2.11
A9
A8
A7
A6
A5
A4
A3
A2
A1
TC frequency (three-point moving average)
Varve years ago (a)
6000
5000
4000
3000
2000
1000
0

Figure 59: Comparison of multi-millennial tropical cyclone-frequency records around the Gulf of Mexico from the Great Blue Hole (Belize), Puerto Rico, the Bahamas, and Florida, over the past 5,700 years. Site-specific active versus calm tropical cyclone periods are indicated by the red threshold lines. Long-term cyclone event trends are approximated using a linear regression (dashed black line). From Schmitt et al, 2025 CC BY-NC 4.0.

92. Which, if any, site(s) indicate(s) a correlation between anthropogenic climate change and an increase in the frequency of tropical cyclones at low latitudes?
    a. None
    b. Belize
    c. Puerto Rico
    d. Bahamas
    e. Florida
    f. All

93. What could reasonably explain the different trends (black dashed lines) at these neighbouring locations?
    a. Modern climate change is forcing tropical storm tracks towards the equator.
    b. Modern climate change is forcing tropical storm tracks away from the equator.
    c. Eustatic sea level rise
    d. Eustatic sea level fall
    e. Different erosion rates
    f. Different deposition rates

Amber has remained rather quiet for most of the journey but pipes up as they set off for their final destination, *"Wow, I've learned so much about rocks, water, space, extinctions, and the atmosphere on this trip! Now it's my turn to teach you something about how increasing tropical storm frequency has actually driven evolution on islands here in the Caribbean.*

In 2017, two hurricanes hit the same island just two weeks apart, having a detrimental effect on local lizard populations. Researchers found that surviving lizards had demonstrably longer front toe pads, all the better to cling to trees in high winds, and shorter hind legs, causing less drag as their bodies flew out like flags in the gales, than the pre-hurricane-season population. These traits continued to dominate the subsequent generations."

94. What Amber described is an excellent example of…
    a. Darwin's 'survival of the fittest'
    b. Lamark's 'inheritance of acquired traits'
    c. Mendelian inheritance of gene pairs
    d. Predetermined evolutionary trends
    e. A selectively neutral genetic change
    f. Intelligent design

The final stop on this epic journey is a visit to Port Royal, Jamaica (Fig. 60, under the last 'a' in Jamaica). For a crew so determined to go the 'wrong way' around the world to avoid pirates, finishing up at a place that was once frequented by smugglers, feared pirates like

Blackbeard, Calico Jack, and Captain Morgan, and all other unsavoury types is rather ironic. Once considered the wickedest city on earth, Port Royal was the richest, busiest, and most nefarious port in the Americas.

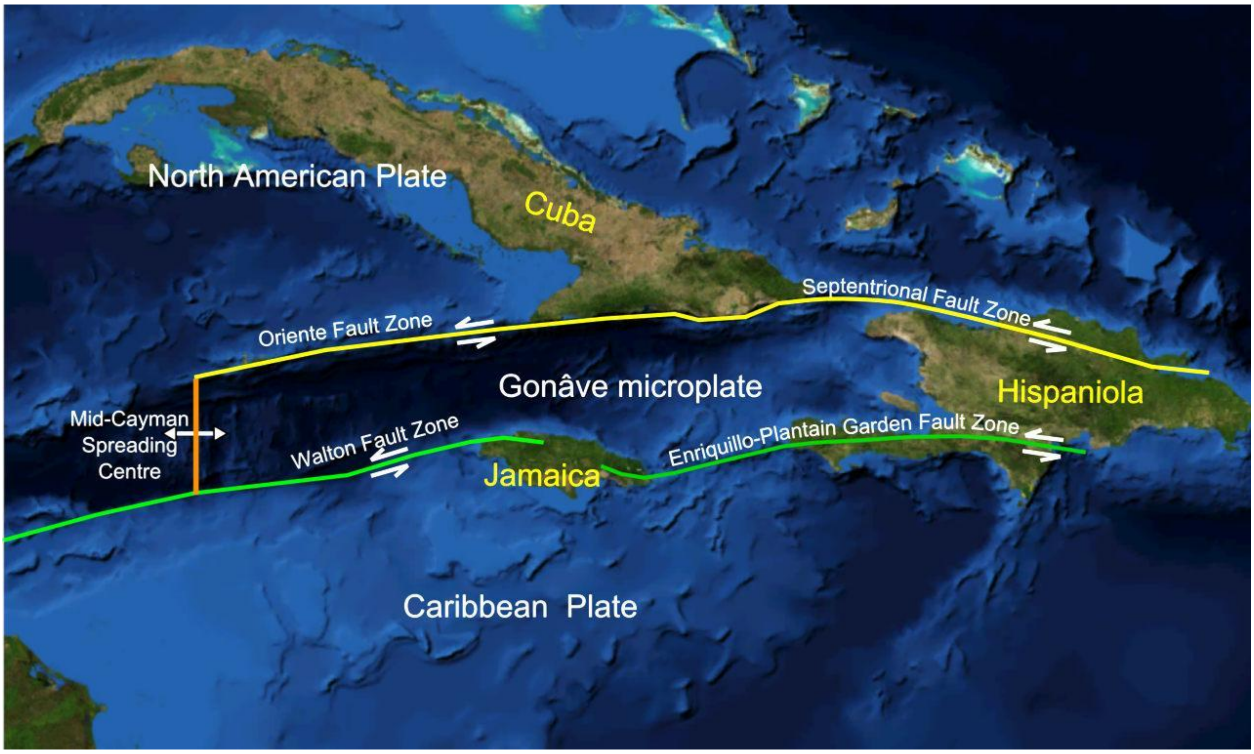


Figure 60: Tectonic setting between Jamaica and Cuba. Modified from Google Earth imagery.

Captain Wistas summarises the tale he finds in an old newspaper clipping (Fig. 61) for them, *"One fateful morning in June 1692, a massive earthquake caused two thirds of the city to sink into the sea. Most of the city was brick buildings built on a triangular spit of sand, not bed rock. In the nearly 15 minutes of shaking, larger houses crumbled almost immediately, followed by smaller ones sliding off into the harbour. When unconsolidated sand is subjected to intense shaking, it undergoes liquefaction, as seemingly solid ground turns to liquid. People in the streets were swallowed up by fissures that opened beneath them and the entire graveyard was exhumed… Shivers, wouldn't have wished to witness that!"*

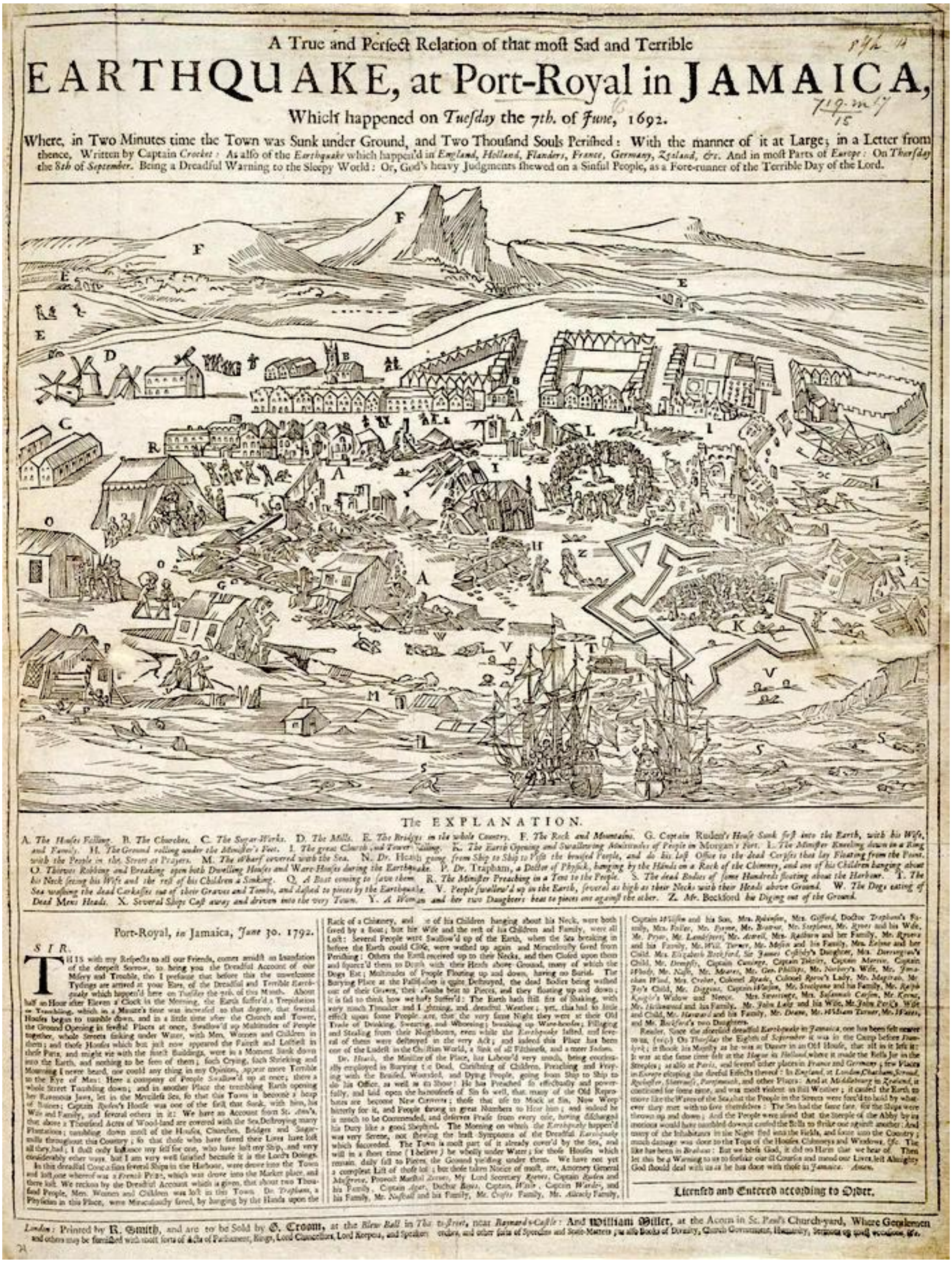


Figure 61: Newspaper account of the Port Royal catastrophe.

The crew messages their friend Jean Luc to tell him about their adventures and ask him how seismologists were able to estimate that the earthquake in 1692 (long before there were modern seismic instruments) was a magnitude 7.5.

95. What does Jean Luc tell them? *“Pre-seismic-instrumentation earthquake magnitudes can be estimated…”*
    a. …by comparing the type and extent of damage, displacement, and duration of shaking to modern events.
    b. …by looking at the type of fault it is on. All left-lateral (sinistral) strike-slip faults produce M7.5 earthquakes.
    c. …by looking at the arrangement of local faults. All left-lateral (sinistral) strike-slip faults bounded by at least one normal fault produce M7.5 earthquakes.
    d. …by looking at the type of fault it is on. All right-lateral (dextral) strike-slip faults produce M7.5 earthquakes.
    e. …by looking at the arrangement of local faults. All right-lateral (dextral) strike-slip faults bounded by at least one reverse fault produce M7.5 earthquakes.
    f. …by analysing the thickness of tsunami deposits generated by the event.

All shaken up from that unsettling history, the crew goes out for ice cream to celebrate their successful voyage before everyone heads home. The delightful dessert selections inspire Cate to pose one final challenge to the chat just for fun – *“If your favourite ice cream were a rock type, what would it be?”*