School ID

2024 AUSTRALIAN SCIENCE OLYMPIAD EXAM
EARTH & ENVIRONMENTAL SCIENCE

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

Student Name: ……………………………………………………………………………………..

Home Address: ……………………………………………………………………………………

……………………………………………………………… **Post Code:** ………………

Telephone: (……….) ……………………………… **Mobile:** ………………………………..

E-Mail: ………………………………………………………… **Date of Birth:** ……/……/……

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

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

Students must be Australian citizens at the time they are offered a place to attend the Australian Science Olympiad Summer School.

The Australian Olympiad teams in Biology, Chemistry, Earth and Environmental Sciences and Physics will be selected from students participating in the respective summer schools.

Please note - students in Year 12 in 2024 are not eligible to attend the 2025 Australian Science Olympiad Summer School.

Data is collected for the sole purpose of offering eligible students a place at summer school.
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☐ **I am an Australian public high school student and would like to be considered for the Australian Science Olympiad Summer School Scholarship.**

Examiners Use Only:

2024 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 – 10.
- 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).

True/False questions are each worth a quarter (0.25) mark.

Total marks for the paper: 65 marks

DATA & DEFINITIONS

Material supplied:

Location and Character name disclaimer

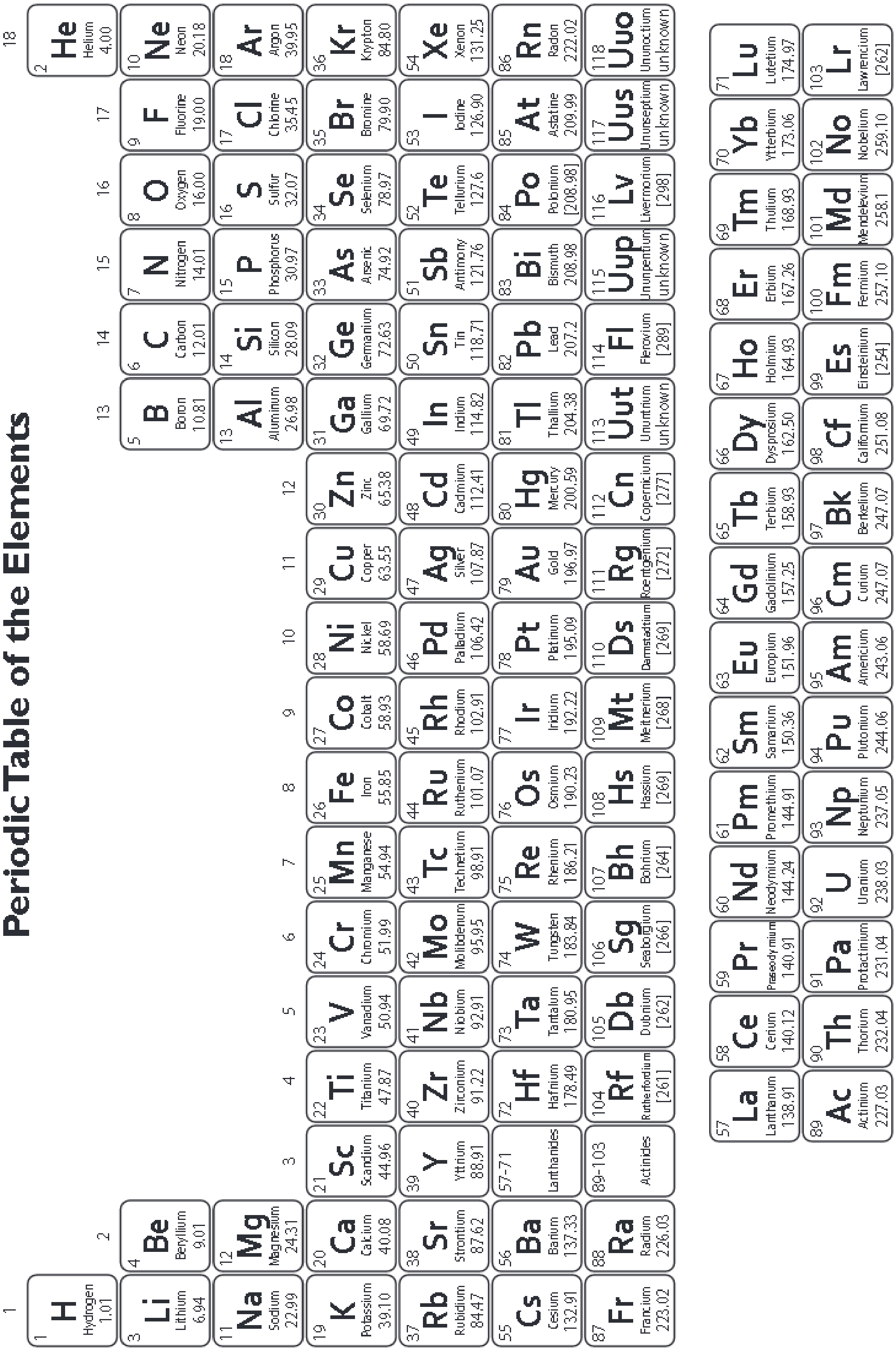
The characters and events portrayed in this paper are fictitious (but fun). Enjoy!

Locations on Earth, and the features they possess, are fictional unless otherwise stated (including those based on actual geography). Locations on other planets are real.

Physical constants and other useful information

Unit or constant	Symbol	Value
Astronomical unit	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

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

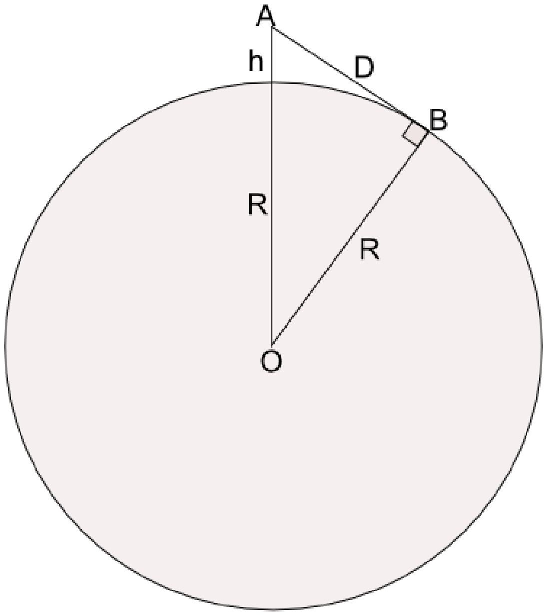


Periodic Table of the Elements

courtesy of http://sciencenotes.org/category/chemistry/periodic-table-chemistry/

Distance to the horizon calculation

-assuming the Earth is a sphere and there is no atmospheric refraction



Observer at A

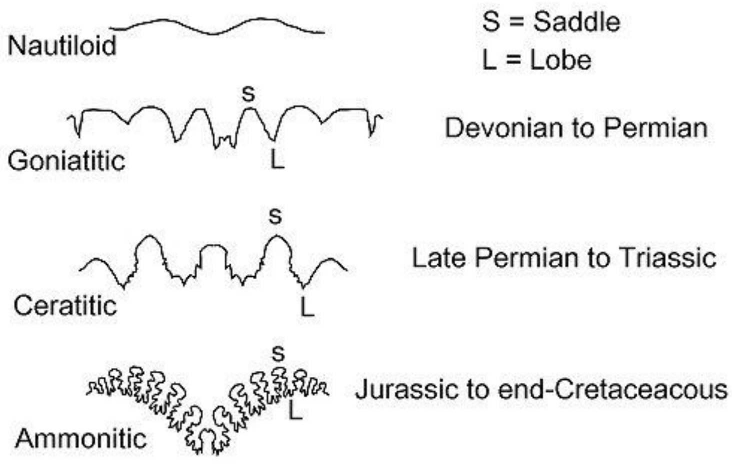
Horizon at B

h is observers height above sea level

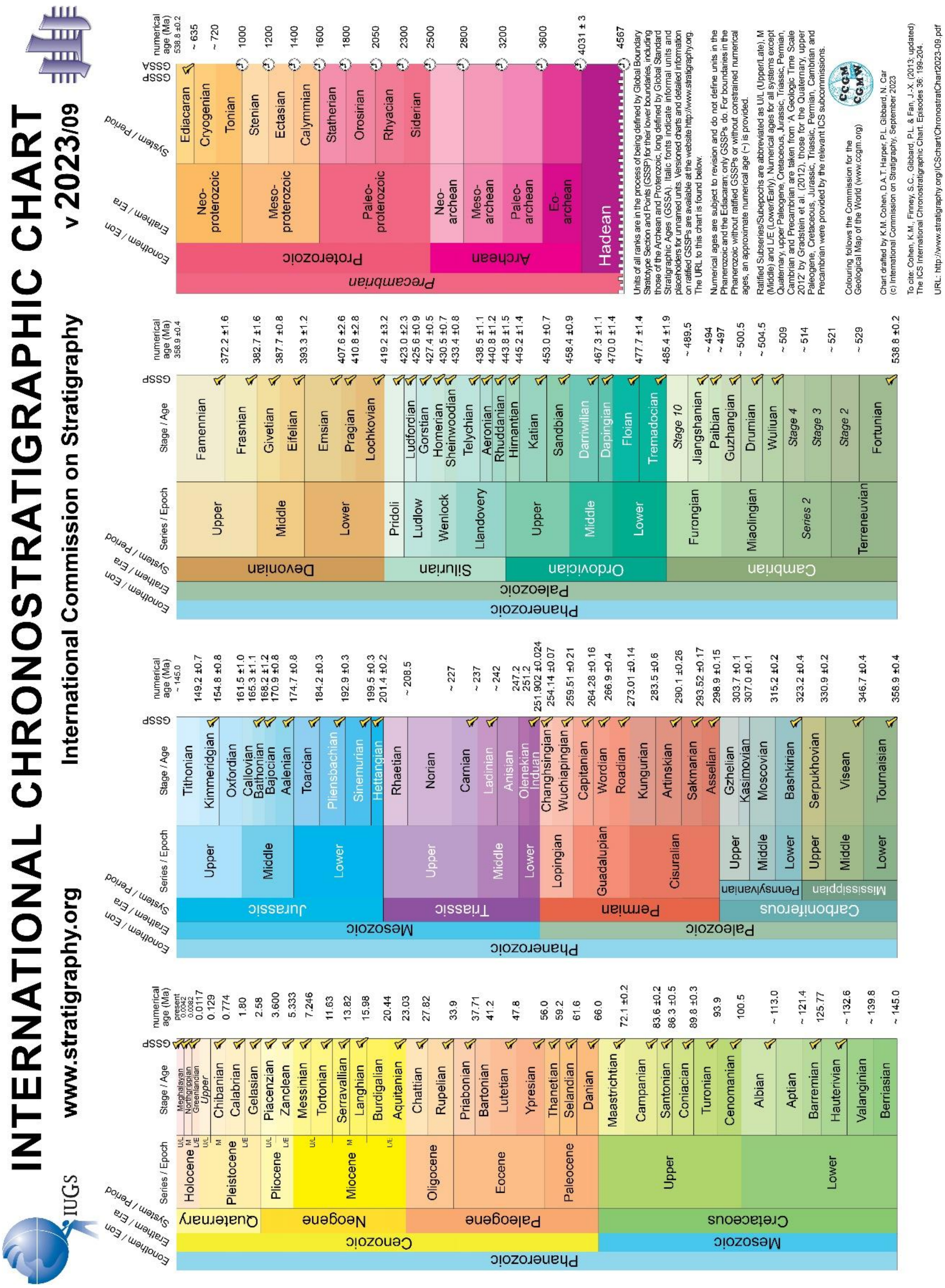
R is the radius of the sphere - for Earth this is 6371 km

D is distance A to B

Identifying different types of ammonites by their sutures



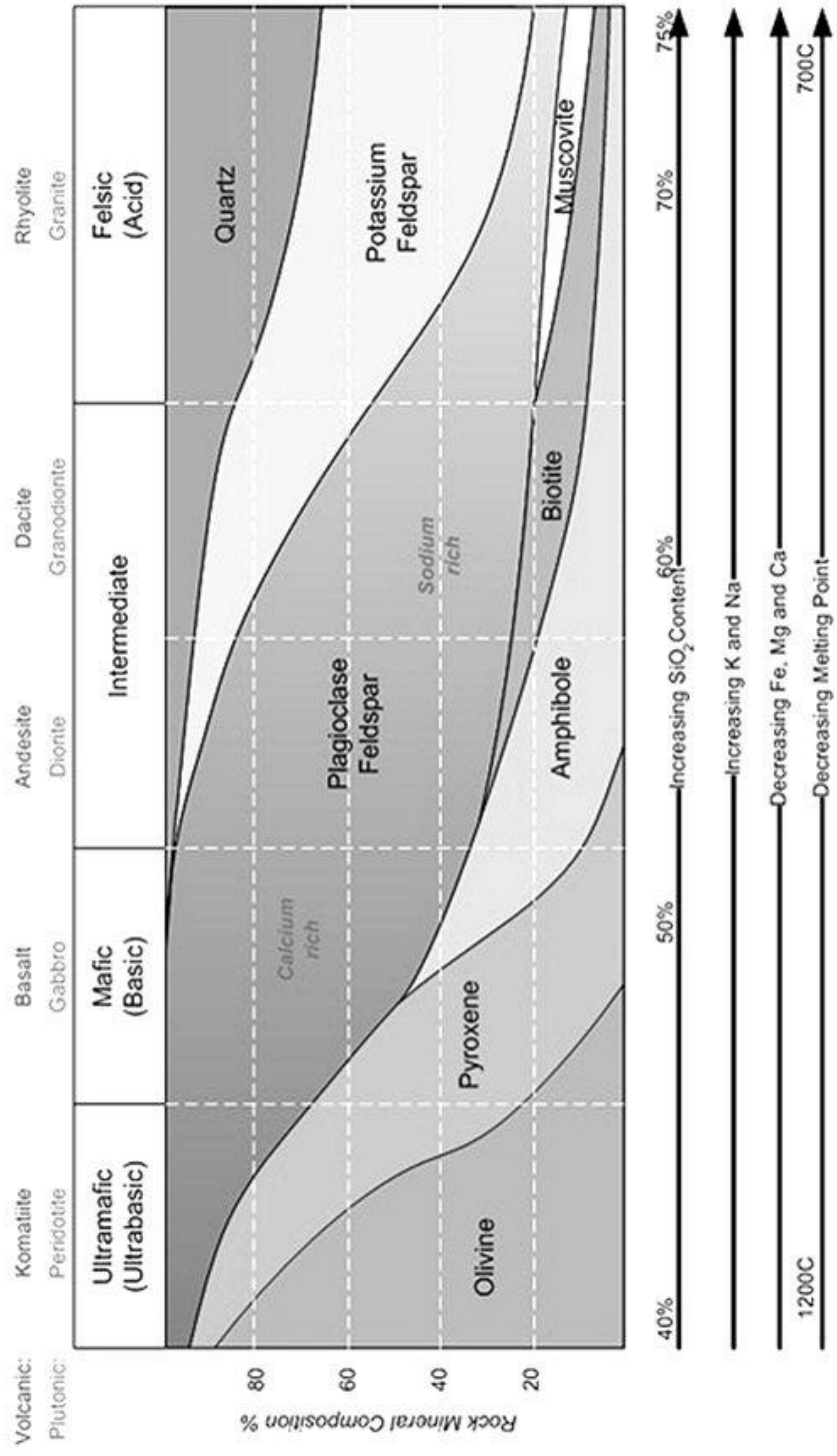
Nautiloids and Ammonites are cephalopod molluscs. Their shells vary from straight to tightly coiled and are divided into chambers by thin dividing walls (septa). Septa vary from very simple curved structures to extremely complex convoluted structures. Suture lines are formed by the intersection of the septa with the outer shell wall. These lines are only visible on external surfaces that have had most of the outer layers worn away to reveal the intersections between the shell wall and the septa.



International Chronostratigraphic Chart 2023/04 courtesy of

https://stratigraphy.org/chart

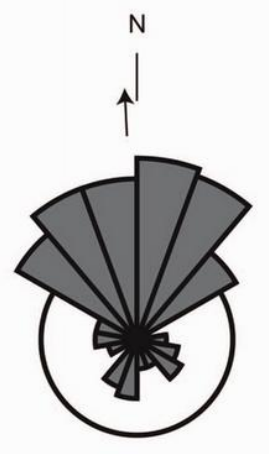
Note: Numerical age (Ma) means the age in millions of years



Igneous rock classification chart

Palaeocurrent patterns

The direction of flow of fluids depositing sediments can be determined from characteristic sedimentary structures constructed as the deposits are laid down. These structures include pebble imbrication, cross-lamination, cross-bedding, flute marks and the profile of ripples.

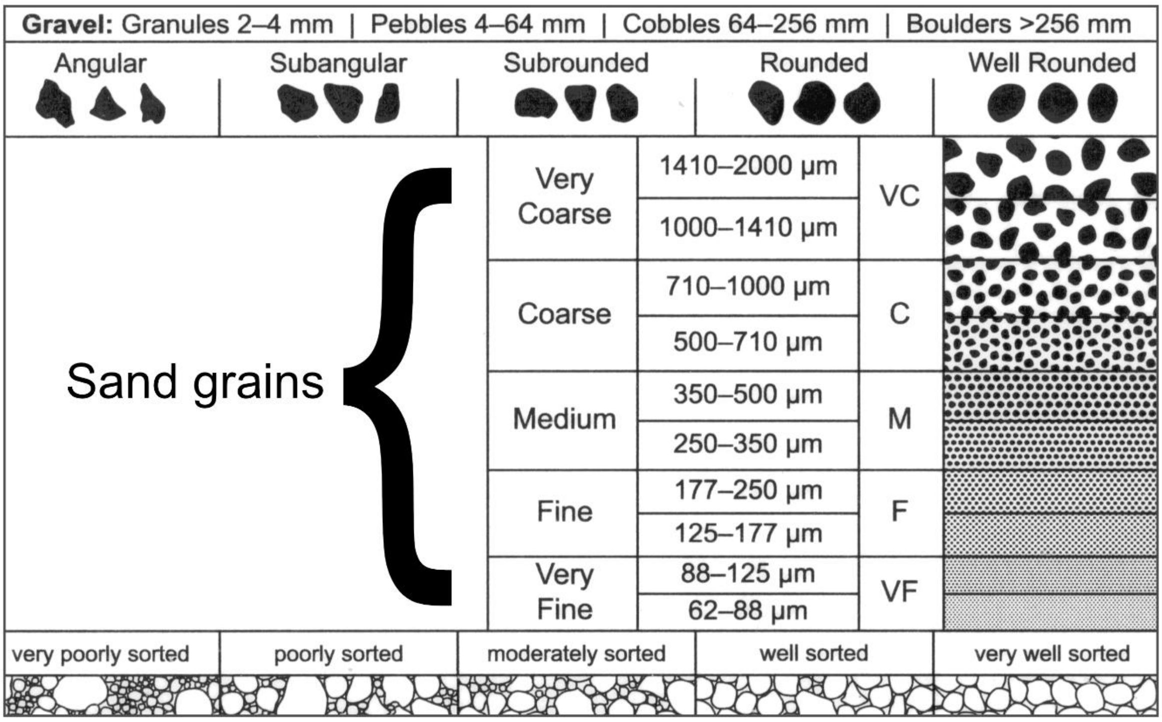


These structures can also be found in ancient sedimentary rocks, enabling the direction of flow at the time, the palaeocurrent, to be measured.

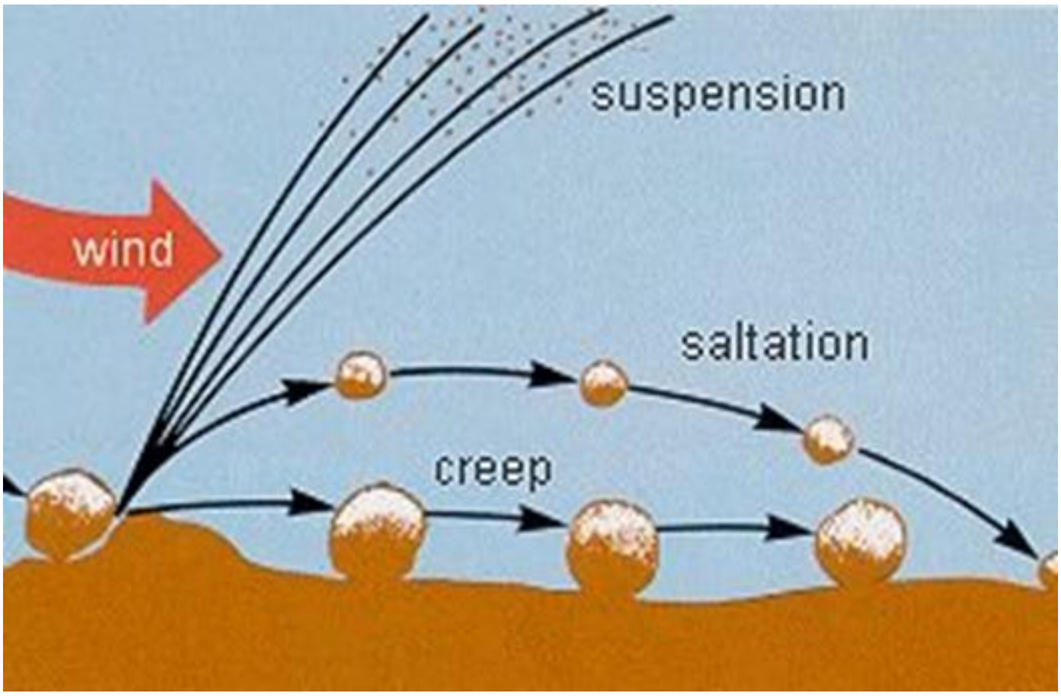
Visual representation of the data using a compass rose enables a quick insight into the nature of the depositional environment for each strata or group of strata. In this type of rose, each wedge represents a 'bin' of data for intervals of 5^{o} to as much as 30^{o}. The radial distance of each wedge is proportional to the frequency of the data in that bin.

When viewed this way patterns do emerge and these patterns are summarised below:

Environment of deposition	**Palaeocurrent vector pattern**	**Regional pattern**
River – braided	Unimodal – low variability	Often fan-shaped
River – meandering	Unimodal – high variability	
Wind blown dunes	Unimodal, bimodal or polymodal	Large variations over vast distances
Deltas	Unimodal	Radiating
Shorelines	Mostly bimodal	Mostly on-shore / off-shore
Marine turbidites	Mostly unimodal	Often fan-shaped



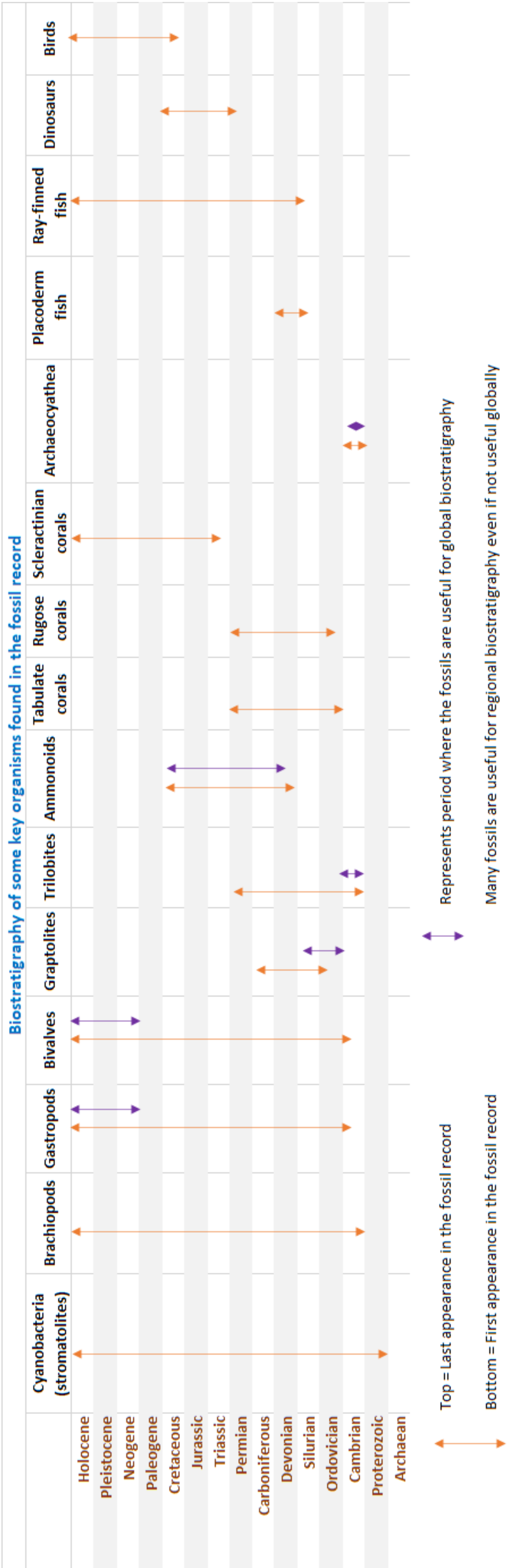
Grainsize chart, courtesy of the Geological Survey of NSW



Movement of sand by fluids. Sediments move, driven by fluid motion, by being pushed along or by rolling along the ground (creep), bouncing from one spot on the ground to the next (saltation) or by suspension in the fluid without touching the ground. The transport mode for any given grainsize will vary as the fluid velocity changes. Image source: https://en.wikipedia.org/wiki/Saltation_(geology)

Hardness	Example Minerals/materials
1	Talc
2	Gypsum
2.5	Fingernail, pure gold, silver, aluminium
3	Calcite, copper coin
4	Fluorite
4.5	Platinum, iron
5	Apatite, Pyroxene group (5 to 6)
6	Orthoclase feldspar, titanium, spectrolite, Pyroxene group (5 to 6)
6.5	Plagioclase feldspar, steel file, iron pyrite, glass, vitreous pure silica
7	Quartz, amethyst, citrine, agate, olivine, tridymite (high temp quartz)
7.5	Garnet, coesite (high pressure quartz)
8	Hardened steel, topaz, beryl, emerald, aquamarine
9	Corundum, ruby, sapphire
9.5	Carborundum
10	Diamond

Mohs Hardness Scale



Biostratigraphy of some key fossils

MULTIPLE CHOICE QUESTIONS – 1 MARK EACH
TRUE/FALSE QUESTIONS – 0.25 MARK EACH

Imagine it is sometime in the future, and humans are colonising the solar system and even other star systems thanks to major improvements in space faring and habitation technology.

The development of the Epstein Drive is almost ancient history but thanks to it and the Stanaway Drive, a 2299 improvement that enables a Martian Congressional Republic Navy (MCRN) corvette-class frigate to accelerate to 10% of light speed in 48 hours, exploration and colonisation of the solar system is now easier than ever before.

The Interplanetary Museum of Human Endeavour (IMHE) operates a small fleet of repurposed MCRN corvette-class frigates using the Stanaway Drive to safely and quickly deploy staff to locations of interest.

The players:

Roxanne Stone, well known areologist* and geologist, previously led Expedition Jezero to physically explore Jezero crater on Mars. Her team ground-truthed the discoveries made way back in the 2020s by the Perseverance Rover. After the success of that mission, her colleagues (including many friends from school days) have continued with the ground-truthing on Mars as well as elsewhere in the solar system. Roxanne's sister Gemma is a climatologist, planetary geologist and mountaineer and was the first person to walk on the surface of Venus.

Under the banner of the IMHE the pan-solar exploration team continues to document and explore the solar system and beyond. Along with Roxanne and Gemma, the team includes specialists in the fields of astronomy, astrobiology, climatology, geochemistry, geochronology, igneous, metamorphic & sedimentary geology, geophysics, hydrology, mineralogy, palaeontology, planetary systems, seismology, and volcanology. Their many friends also bring lots of other skills and interests to the table (mostly via social media discussions).

*Areology: the study of Mars, its planetary geology plus everything else that makes Mars what it is: a rocky planet with some Earth-like and some not so Earth-like characteristics.

Start the exam here:

The IMHE has funded a new series of ground-truthing expeditions. The first-hand observations made along the way will verify or augment findings from robotic missions throughout the solar system during the 20th and 21st centuries.

Roxanne and Gemma are taking a sabbatical on Earth, while the rest of the team are preparing to visit various destinations elsewhere in the solar system.

1. It is a big program and there is room on the team.

Q: Are you ready to join them? (1 mark – both answers are correct)

a. Yes – am I ever. Let's do it!

b. No, but let's do it anyway!

Roxanne and Gemma decided to enjoy their Earth-bound adventures with a visit to the Arrakis Peninsula, given the great reports from team members who travelled there recently. This region of Specerijland (Figure 1) is famous for its arid landforms, fossil-rich Devonian and Permian sedimentary rocks, the ancient rocks exposed in Franklin Fields and Herbert River Gorge, and the amazing coastal and marine environments associated with the Specerij Ocean. The newly opened aero-spaceport, Mos Woestijn (Location 1, Figure 1) is a tourist attraction in its own right and is where Roxanne and Gemma touched down on the flight from their hometown.

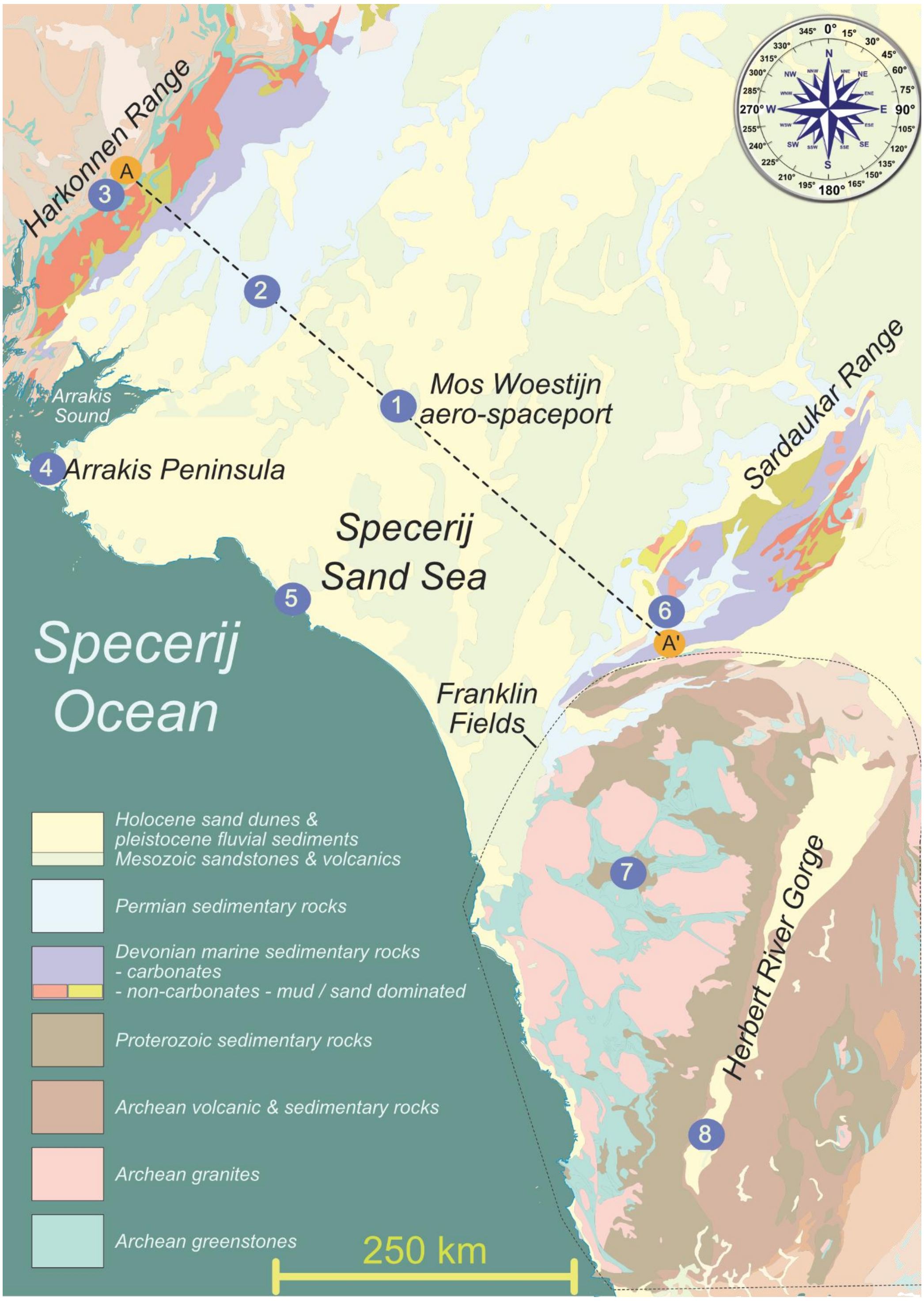


Figure 1: Simplified geological map of Specerijland. The dashed line from A to A' marks the location of a cross-section on display in the Mos Woestijn food hall. Franklin Fields is the area enclosed by the fine dotted line. Locations 2 to 8 are underground and surface places linked to Mos Woestijn by a tunnel network of maglev superfast trains and walking paths.

The pilot apologised for the rough landing, noting that a last-minute wind change was to blame - the light winds from the North had unexpectedly been replaced by 30 km/h Northwesterly winds gusting to 45 km/h, requiring a last minute realignment of their approach. Over a refreshing drink in the cantina, Gemma pulled up the wind data for the aero-spaceport site (Figure 2).

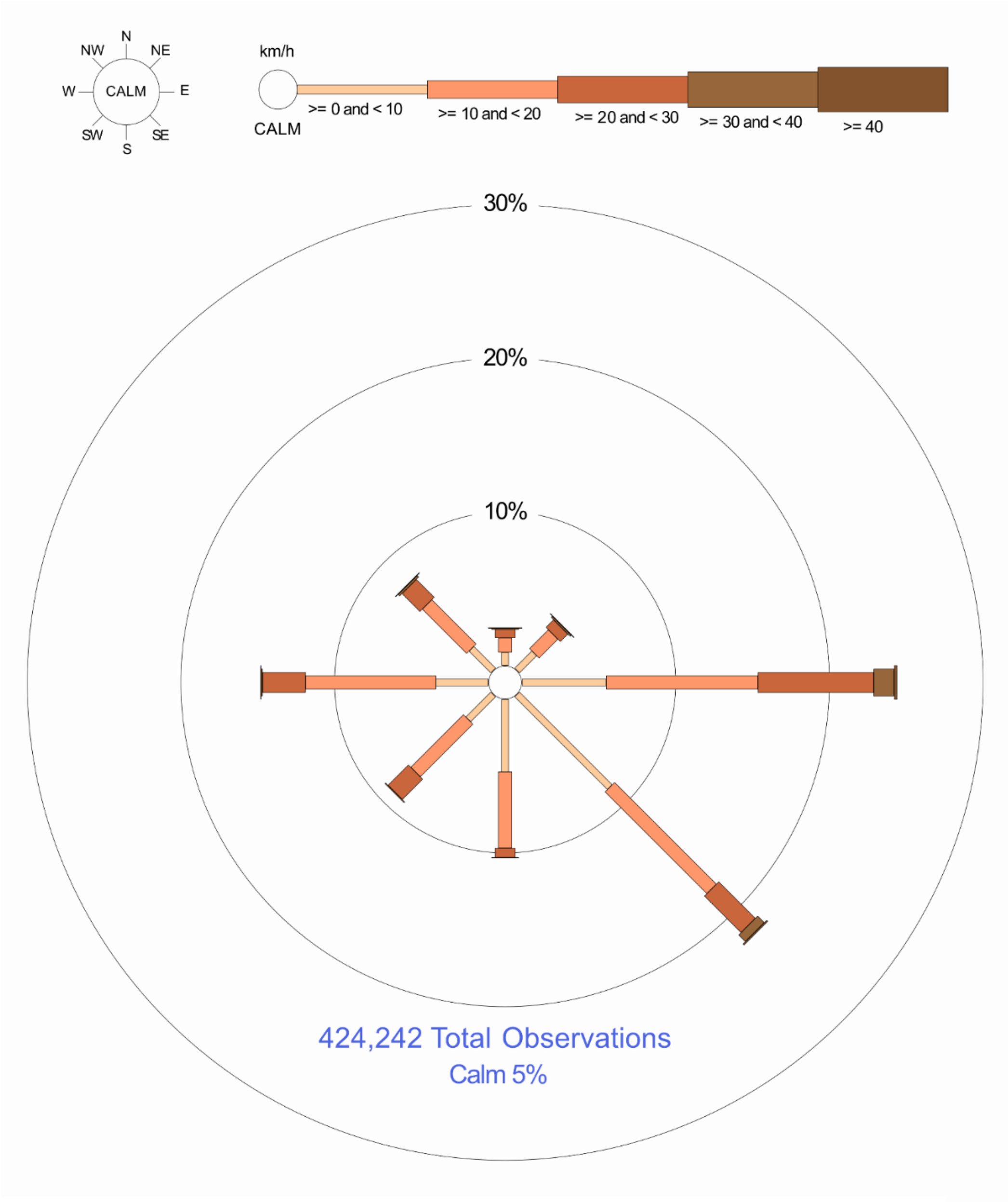


Figure 2: Wind speed and direction rose for Mos Woestijn. Wind directions are divided into eight compass directions. The circles around the image represent the various percentages of occurrence of the winds. For example, if the branch to the west just reaches the 10% ring it means a frequency of 10% blowing from that direction. Calm has no direction.

Modified from data and graphing sourced from https://tinyurl.com/bdfdwkwh

Gemma documented the landing experience on her social media channel. She has roughly 42 million followers spread over planets, a dwarf planet, 10 moons and many orbital stations! She wrote:

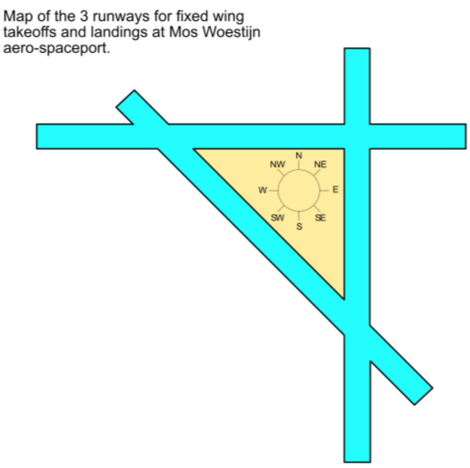
As you know, for fixed-wing aircraft, it is advantageous to perform takeoffs and landings into the wind. Some airports have several runways in different directions, so that one can be selected that is most nearly aligned with the wind. Three runways is usually enough to cover the most common contingencies if orientated appropriately.

2. Gemma also shared the generic map of the Mos Woestijn airport runways, adding:

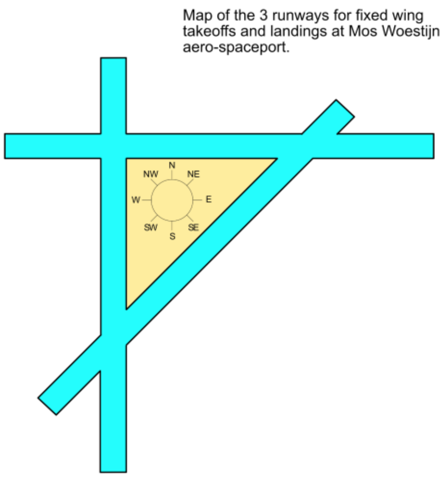
The sudden wind change during our landing approach forced the pilot to abandon ….

Q: What image <u>and</u> wording did Gemma correctly include in this post? (1 mark)

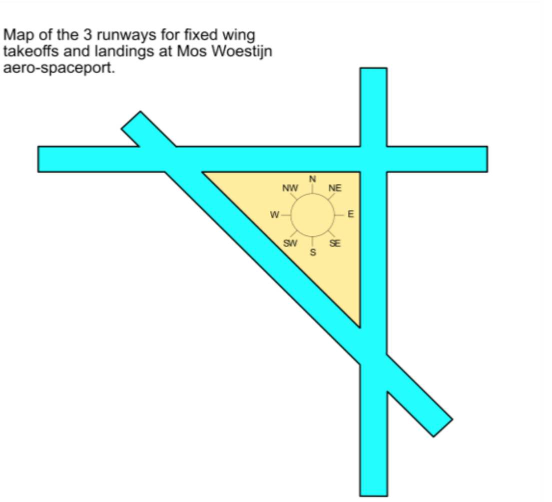
a … the approach from the South and make the approach from the Southeast.



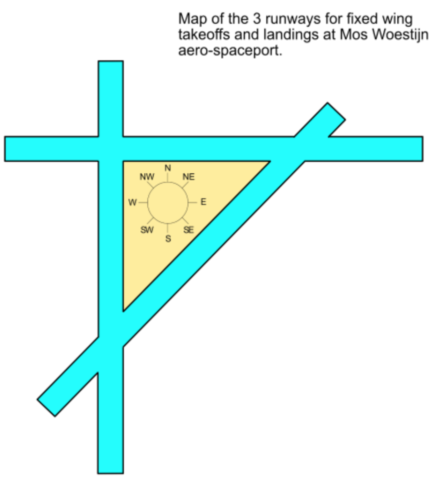
b … the approach from the South and make the approach from the Southeast.



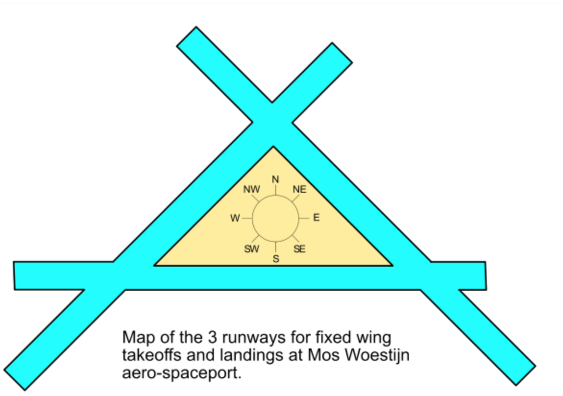
c … the approach from the North and make the approach from the Northwest.



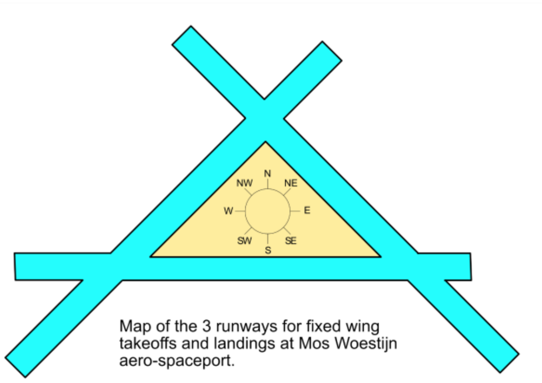
d … the approach from the North and make the approach from the Northwest.



e … the approach from the Southwest and make the approach from the West.



f … the approach from the Southwest and make the approach from the East.



In the late evening, Gemma and Roxanne relaxed on the terrace outside their room in the cool breeze called the *Arrakis Doctor*.

Being so far inland the breeze rarely arrives before midnight and only then because nothing in the sand sea is more than 200 metres above sea level. The amazing afternoon views of the hot dry sand sea and the setting Sun were replaced by a stunningly starry night. They ended up star and planet gazing all night because, apart from those astronomical gems, the sky remained extremely dark until dawn.

3. Gemma shared images of the landscape, the sunset and night sky. Her friend Ariel Windlass, stationed on Mars to study sand dune formations, wanted to know why the sky had been so dark all night.

Q: What was Gemma's reply? (1 mark)

a. There was a lunar eclipse.
b. It was a New Moon.
c. The sand dunes have a low albedo, reflecting only a small amount of the incident light from the stars.
d. The Arrakis Doctor brings in very clear air from the Specerij Ocean.
e. Heat radiating from the warm desert sands changes the refractive index of the air, refracting light away from the surface.
f. The night sky viewed in the desert is always dark.

As avid stargazers, both Gemma and Ariel brought their telescopes for the night of stargazing on Earth and Mars, respectively.

They both pointed their identical Lovell 200 Super-Chromatics (an optical reflecting telescope) at Jupiter to observe its mesmerising vortices and used the onboard computer to capture an image of the viewfinder.

4. Upon conferring, they noticed that Jupiter appeared smaller on Gemma's telescope than Ariel's.

Q: Ariel correctly suggested that: (1 mark)

a. Earth is always further from Jupiter than Mars is, hence Jupiter will always appear smaller for Gemma.
b. Mars is always further from Jupiter than Earth is, hence Jupiter always appears smaller for Gemma.
c. Earth is only sometimes further from Jupiter than Mars. Jupiter appears smaller for Gemma when this is the case.
d. Earth is only sometimes further from Jupiter than Mars. Jupiter appears larger for Gemma when this is the case.
e. This can never be the case, the two must be using different telescope configurations.
f. It is not possible to compare the size of planets in telescope viewfinders as this is dependent on diffraction and refraction from atmospheric effects.

5. As luck would have it, Gemma managed to observe the transit of one of Jupiter's Galilean moons, Europa, that evening. However, she also noticed a dark spot on the surface of Jupiter, near Europa's position (Figure 3).

Figure 3: The view through Gemma's viewfinder. Jupiter's North pole is in the direction of the top left of the image. Jupiter's famous anticyclonic storm, the Great Red Spot, is shown on the right. One of Jupiter's moons, Europa, is shown on the left, along with the dark spot on Jupiter's surface. Image, modified for clarity, courtesy of NASA.

Q: What does Gemma tell Ariel the dark spot is most likely to be? (1 mark)

a. A cyclonic storm on the planet's surface
b. A recent impact crater
c. The shadow cast by Europa on Jupiter's surface
d. The shadow cast by Earth on Jupiter's surface
e. The shadow cast by Mars on Jupiter's surface
f. The shadow cast by another one of Jupiter's moons on its surface

Team member Philip Light, also on Mars but studying soil (regolith) mineralogy, wanted to know if Gemma captured a picture of the green flash as the sun set over the ocean's horizon. For the benefit of some friends who might not be familiar with this term, she explained that a green flash is an optical phenomenon visible shortly after sunset or just before sunrise. It happens when the sun is almost entirely below the horizon, with the upper edge visible. For a second or two, that upper rim of the sun will appear to flash green in colour (or sometimes blue). She included a nice graphic (Figure 4) to help the explanation.

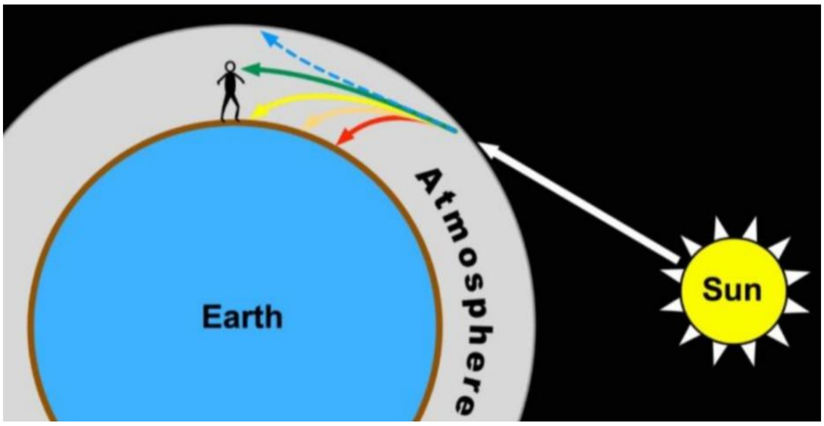


Figure 4: During a green flash, the atmosphere distorts light from the sun and the green rays are what reaches our eyes.
Modified image courtesy of https://earthsky.org/earth/can-i-see-a-green-flash/

6. Gemma was happy to report that this was one of the best places in the world to see the green flash. However, she noted that despite the terrace of the apartment being about 200 metres above sea level (asl), she was sure she could not photograph a green flash over the ocean's horizon from where she was standing.

Q: What did Gemma add to explain her inability to get the photograph Philip asked about?
(1 mark)

As it happens, yesterday was also the spring equinox and the Sun set exactly due West of us. Unfortunately I could not get a photograph of the green flash over the ocean. The aero-spaceport is ~250 km east of Arrakis Sound and, assuming the air is crystal clear and there is no refraction, to see the horizon with water in the foreground I would need to be standing approximately …

a. … 0.5 km asl.
b. … 1 km asl.
c. … 2 km asl.
d. … 3 km asl.
e. … 4 km asl.
f. … 5 km asl.

7. Roxanne asked Philip how he was enjoying the sunsets on Mars. He replied that the Martian sky is hard to get used to. He said Martian dust is dominated by feldspar and/or zeolite with lesser amounts of olivine, pyroxene, amorphous material, hematite, and magnetite. He noted that during the daytime the sky is a yellowish-brown, even though the thin atmosphere is mostly colourless carbon dioxide. Gemma knew this colour was mostly due to the fine-grained red hematite (with a particle radius of less than 2.5 – 5 μm), which is suspended in the Martian atmosphere during seasonal dust storms. It gives Mars its reddish colour when viewed from space. Philip explained that the sky's colour changed a bit depending upon the dust load but at sunset things got stranger, noting that the sky immediately adjacent to the Sun appeared blue. Both Gemma and Roxanne have seen this for themselves but Roxanne was curious to know just why it happens.

In answer to this, Philip shared an image (Figure 5) and a graph (Figure 6).

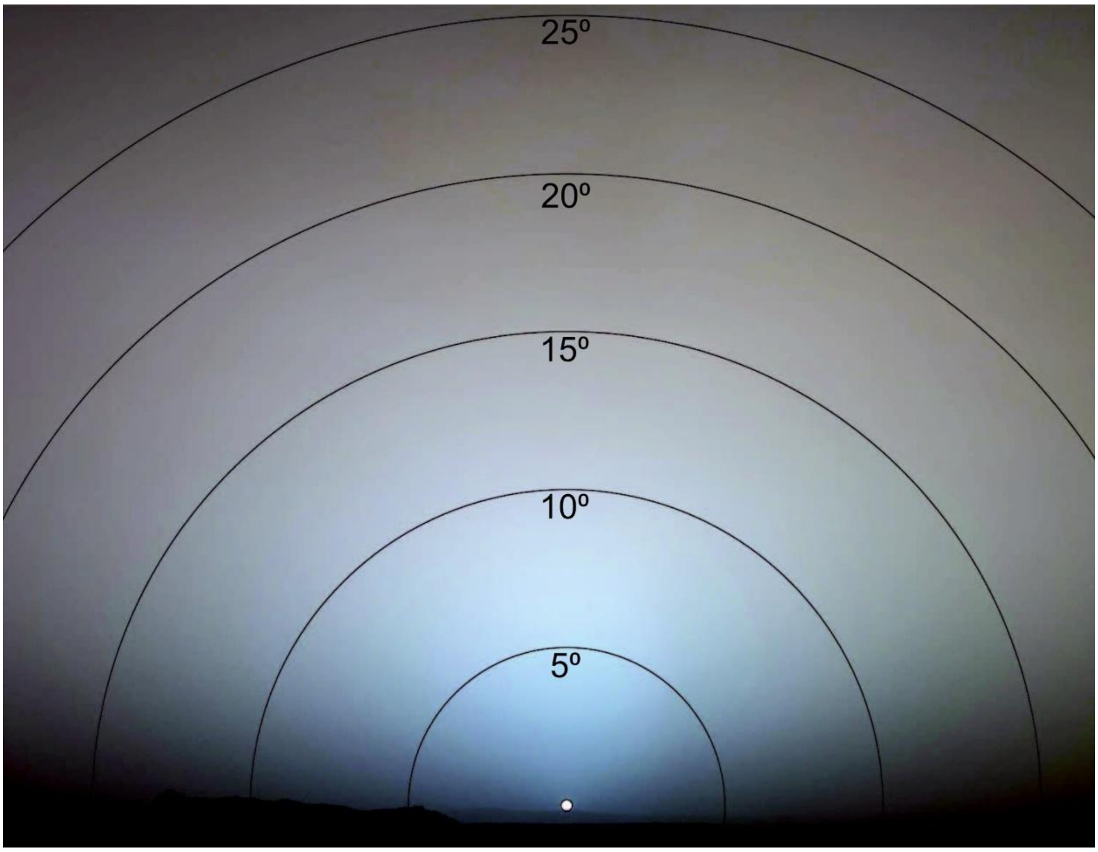


Figure 5: A Martian sunset image with scattering angles overlaid. Modified image courtesy of NASA/JPL/Texas A&M/Cornell.

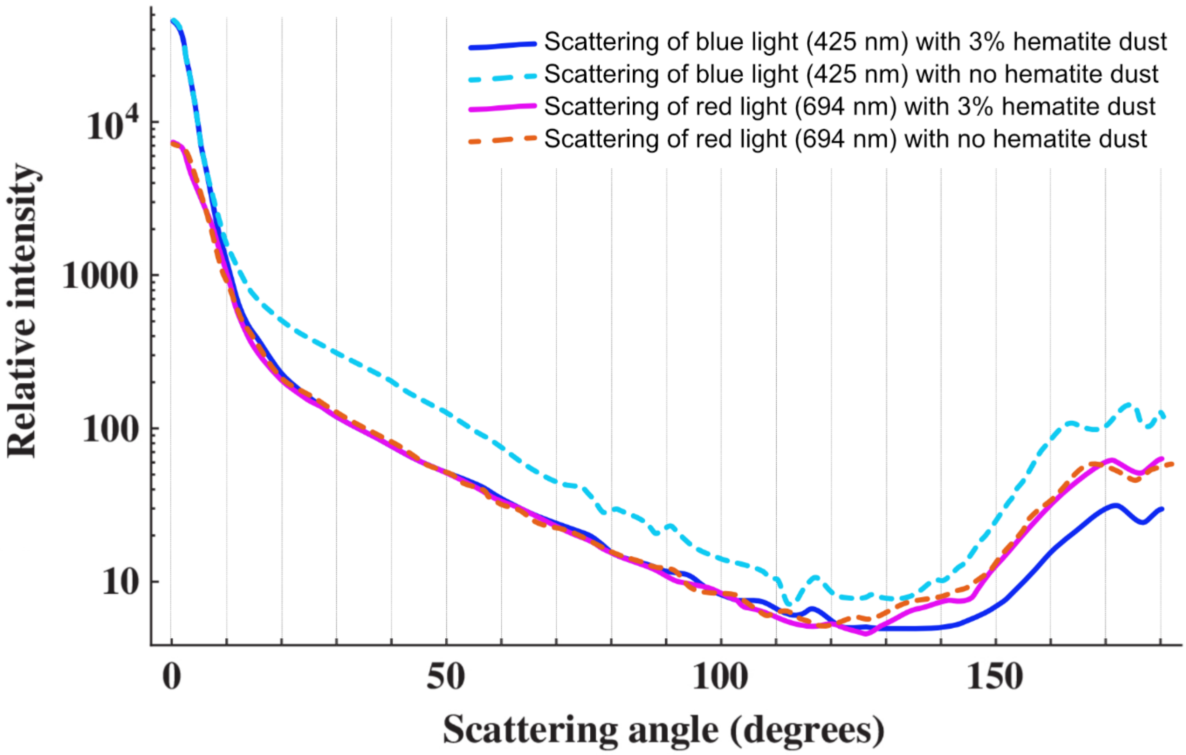


Figure 6: Relative intensity of scattered blue and red light versus scattering angle for 3% hematite dust and dust with no hematite. Modified image courtesy of Ehlers et al (2013).

Q: What did Philip correctly say to accompany the graph? (1 mark)

Unlike Earth, the atmosphere of Mars is dominated by micron-size dust aerosols. It is clear from the graph that …

a. …at angles less than 10°, hematite dust is the sole reason blue light dominates over red around the setting Sun view.

b. …at angles of less than 10°, hematite dust is not the sole reason blue light dominates over red around the setting Sun view.

c. …at angles greater than 10°, hematite dust is the sole reason blue light dominates over red around the setting Sun view.

d. …at angles greater than 10°, hematite dust is not the sole reason blue light dominates over red around the setting Sun view.

e. …sunsets on Earth are only red when there is hematite dust in the atmosphere.

f. …sunsets on Earth are bluer when there is hematite dust in the atmosphere.

8. Gemma also wanted to know what would happen to the Martian sky colour at times other than sunrise or sunset if there is dust in the atmosphere.

Q: What did Philip correctly say in reply? (1 mark)

For scatter angles approaching 180° the presence of hematite enables …

a. … the intensity of red light scattering to dominate, hence why Mars is known as the red planet.
b. … the intensity of blue light scattering to dominate, hence why Mars is known as the red planet.
c. … the intensities of red and blue light scattering to negate each other, hence why Mars is known as the red planet.
d. … the intensity of light scattering to vary, but it is more dependent upon grain size than mineralogy.
e. … the Martian landscape to appear red even though hematite is black in hand specimen.
f. … the Martian landscape to appear red even though hematite is only red when scratched on a white plate to make a powder (streak).

Ariel continued her stargazing effort that evening, moving to admire the constellations. While her favourite constellation is Aries (of course) she was happy to turn her attention to Cetus, a constellation in the southern sky and home to the star Tau Ceti, as she engaged in conversation with the team's good friend Zoe.

Astrobiologist and astronomer Zoe Guāng, is stationed in orbit around Saturn's largest moon, Titan. In between observing Titan's surface for bio-signatures she also spends time analysing the data stream from the most distant probe ever sent into space. The G-class Extraterrestrial Intelligence Search (GETIS) probe, launched many years ago, is now in orbit around the planet Tau Ceti f, part of a large planetary system with an elliptical orbit around the Sun-like star Tau Ceti. Tau Ceti is 3.7 parsecs from Earth and our nearest solitary G-class star. The planet Tau Ceti f is thought to be within the habitable zone of this system given the star's luminosity. It is a super-sized rocky planet with a mass 3.93 Earth masses and a radius of 1.81 that of Earth.

9. Ariel knows constellations appear to rotate relative to the horizon based on latitude and time of night, but she wondered if the overall arrangement of the stars in Cetus appears differently to hers (on Mars), from Gemma (on Earth), Zoe (stationed at Titan) and the GETIS probe at Tau Ceti.

She consulted with Zoe, who responded saying:

"That's a great question! The majority of the easily visible stars (apparent magnitudes of less than 4.0) in the Cetus constellation are between 82 and 418 light years from Earth. Hence, the Cetus constellation…"

Q: What did Zoe say to complete her reply? (1 mark)

a. …looks different for all three observers and GETIS.
b. …looks the same for all three observers and GETIS.
c. …looks the same for Ariel and Zoe, but different for Gemma and GETIS
d. …looks the same for Ariel, Gemma and Zoe, but different for GETIS
e. …looks the same for Gemma and GETIS, but different for Ariel and Zoe.
f. …only exists for Gemma, as the unique alignment of its stars does not exist for Ariel, Zoe or GETIS.

While overhearing the discussions of the others, Roxanne wanted to confirm the claim of Tau Ceti f's potential habitability. She applied a model that considers the planet and its host star as a set of ideal spherical blackbodies (idealized physical objects that absorb all incident electromagnetic radiation, regardless of frequency or angle of incidence), and derived an equation for the equilibrium temperature of the planet, Figure 7.

$$T_{\text{eq}} = \left(\frac{(1-\alpha)(R_*)^2}{4\beta \mathrm{a}^2} \right)^{1/4} T_{\text{eff}}$$

Figure 7: Estimated equilibrium temperature of a planet in Kelvin, T_{eq}, dependent on:
α, the planet's bond albedo (the fraction of total electromagnetic radiation incident on an astronomical body that is scattered back out into space)
R_*, the radius of the host star (in metres)
β, the emissivity of the planet, assumed to be 1.0 for a rapidly rotating body with a strongly advecting atmosphere
a, the planet's orbital semimajor axis (in metres)
T_{eff}, the effective temperature of the host star (in Kelvin)

10. To apply this model, Roxanne relies on the following data obtained from her copy of IMHE's Guide to the Galaxy. The bond albedo of Tau Ceti f remains unknown and, until Zoe's research using the GETIS data establishes it, Roxanne decided to use Earth's bond albedo as a proxy to arrive at an estimate for Tau Ceti-f's temperature.

Radius of Tau Ceti	5.54×10^8 m
Tau Ceti effective temperature	~5320 K
Tau Ceti spectral type	G8V

Table 1: Data relating to the star Tau Ceti, in the constellation Cetus.

Radius of Tau Ceti f	1.154×10^7 m
Semimajor axis of Tau Ceti f's orbit	1.334 AU, where 1 AU is the average distance between the Earth and Sun
Earth's bond albedo as a proxy for Tau Ceti f's albedo	0.29

Table 2: Data relating to the planet Tau Ceti f, orbiting the star Tau Ceti.

Q: What is the equilibrium temperature of Kepler-22b, according to Roxanne's model?
(1 mark)

a. 26 K
b. 70 K
c. 73 K
d. 101 K
e. 145 K
f. 182 K

11. Roxanne is surprised that the equilibrium temperature she has calculated for Tau Ceti f is significantly below the freezing point of water on Earth, which is 273.15 K. She shared her method and findings with the group, concerned that it means the planet may not have liquid water and thus Zoe might be wasting her time. Gemma was quick to point out:

Don't worry, your calculations are appropriate! But remember that what you have found is the equilibrium temperature of the planet. Even though the planet is on the outer edge of the habitable zone (Figure 8), the actual temperature experienced at any given location on the planet is dependent on many other factors, which could all still allow for the possibility of liquid water on the planet at least some of the time.

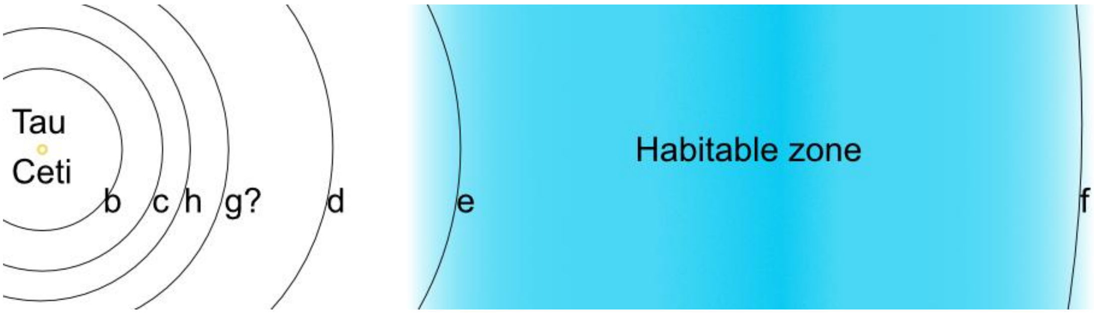


Figure 8: A schematic representation of the Tau Ceti solar system. Planets e, f, g and h are super-sized Earth-like rocky planets but only planets e and f are close to or within the calculated habitable zone (shown in blue). The exact orbit of planet g is yet to be determined.

Q: Gemma was optimistic it would host liquid water because…. (1 mark)

a. … the temperature of the planet's surface varies across latitudes and topography.

b. … the temperature on the planet's surface could vary seasonally, due to the planet's elliptical orbit..

c. … the temperature on the planet's surface could vary seasonally, due to the planet's axial tilt.

d. … the equilibrium temperature of the planet could be greater than calculated, due to the presence of greenhouse gases in the atmosphere.

e. … of conditions mentioned in answers a, b and d.

f. … of the conditions mentioned in answers a, b, c and d.

12. Images streaming back to Zoe from the GETIS probe orbiting Tau Ceti f reveal some very Earth-like vistas, prompting Zoe to exclaim:

This planet is so beautiful, the view from above reminds me so much of Earth because of all the clouds!

Q: Based on Zoe's observations of the GETIS images, which of the following processes can the team conclude must be present on the planet? (1 mark)

a. A hydrological cycle with evaporation, condensation, and precipitation.
b. Weathering, erosion, and deposition of clastic sediments.
c. Plate tectonics with crustal growth and subduction.
d. Hydrothermal activity releasing gases into the atmosphere.
e. An extensive system of groundwater reservoirs in a crust with a high geothermal gradient.
f. Volcanoes exsolving gases including SO_2, H_2O and CO_2.

13. Other members of the team were curious about the data streaming in from GETIS. Palaeontologist, Traci Menandai, was especially interested in the age of the data and the history of the project. In a group chat she said:

The images and the other data are amazing, even if they are ~12 years old when they arrive. Even so, the very fact that we have a probe orbiting a planet in a solar system 3.7 parsecs from Earth is a testimony to the technical skills and planning ability of our forebears. We really do stand on the shoulders of giants! I know that our best drives are able to send vehicles into deep space at ~10% of light speed. Wow! All this wonderful data is being *generated by a project that was started a long time ago.*

Zoe was quick to respond with:

Trust Traci to ask about the age! The data was only 12 years old when it arrived but it took much longer to actually get the data if you include the history of the probe. In fact, the planet wanderer's guide to the solar system tells us it took 27 years to design and build the GETIS probe. Given the first data arrived 10 years ago, the first images in that data stream are the results of the probe's inception …

Q: What did Zoe say to complete her reply? (1 mark)

a. … 51 years ago.
b. …147 years ago.
c. …159 years ago.
d. …169 years ago.
e. … 267 years ago.
f. …307 years ago.

14. Despite all the interest in Tau Ceti and the Cetus constellation, Ariel was still keen on talking about the constellation Aries (obviously her fav) and the amazing data about the solar system orbiting Kepler 22 being remotely sourced by observation platforms in orbits in our solar system. She disrupted the chat by saying:

The Tau Ceti data is amazing but star Kepler 22, in the constellation Aries, is 640 LY from Earth and yet we also have some amazing data about it! For example, did you know there is an Earth-like planet in orbit (Kepler 22 b) and we can model its habitability too, even though we can never send a probe there?

To make the point, Ariel shared a set of graphs (Figure 9) that model the surface temperature of Kepler 22 b as a function of surface albedo, under Earth-like or Venus-like atmospheric conditions.

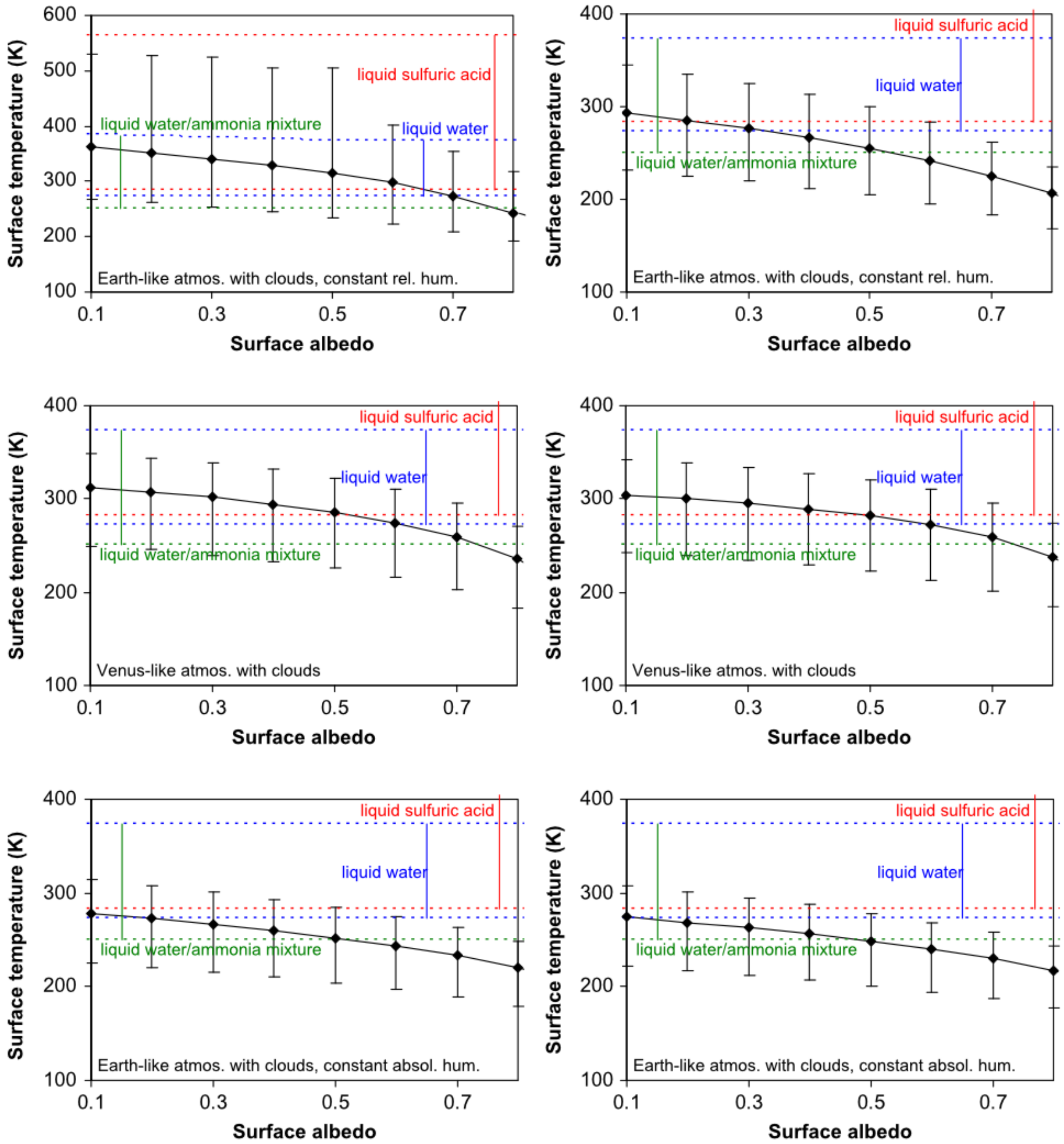


Figure 9: The predicted surface temperature of Kepler-22b (modelled as a terrestrial planet) is shown as a function of surface albedo. The error bars indicate the range of predicted surface temperatures due to the variation of stellar flux, and the dotted lines indicate the range of the liquid phases of the relevant solvents (the inner border of the sulfuric acid liquid phase is not shown). "atmos." = atmosphere, "rel." = relative, "absol." = absolute, "hum." = humidity. (Image courtesy of Neubauer et al., 2012)

Q: Which of the following conclusions can Roxanne correctly draw? (1 mark)

a. If the planet has an Earth-like atmosphere, then liquid water will certainly be present only if the planet has a surface albedo of 0.3 or less.
b. If the planet has an Earth-like atmosphere, then liquid water will certainly be present only if the planet has a surface albedo of 0.4 or less.
c. If the planet has an Earth-like atmosphere, then liquid water will certainly be present only if the planet has a surface albedo of 0.6 or less.
d. If the planet has a Venus-like atmosphere, then liquid water will certainly be present only if the planet has a surface albedo of 0.5 or less.
e. If the planet has an Earth-like atmosphere, then liquid sulfuric acid cannot be present
f. Liquid water/ammonia mixture can be present for all surface albedos.

As part of the aero-spaceport development, a massive underground city was built to house inhabitants and visitors. A network of tunnels for foot traffic and trains connects Mos Woestijn to Arrakis Peninsula, the Harkonnen Range, the Sardaukar Range and the coastline with Specerij Ocean (Figure 1) to facilitate safe, comfortable and quick access to places of interest.

An information panel in the massive food hall situated about 100 metres below Roxanne and Gemma's room on the surface displays a cross-section (Figure 10) along with the map (Figure 1).

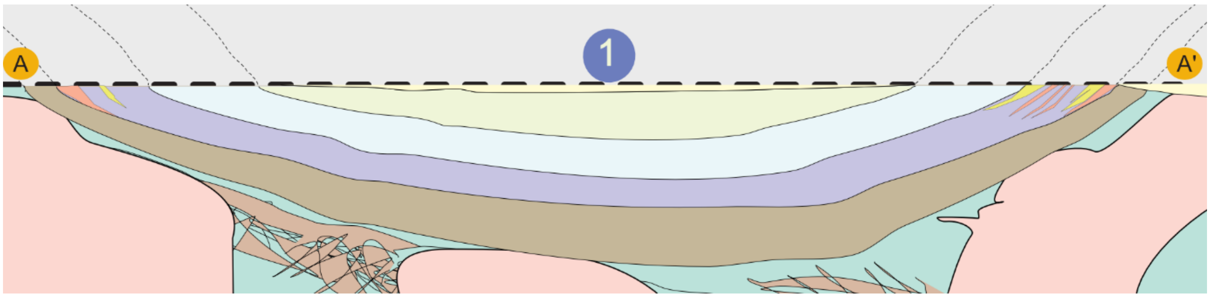


Figure 10: A very simplified cross-section through the landscape looking northeast. Thickness of stratigraphic units is not to scale. The points labelled A, 1 and A' correspond to the same points on the map (Figure 1).

A helpful stratigraphic column also accompanied the cross-section (Figure 11). It shows the average thickness of the main geological units directly beneath Mos Woestijn.

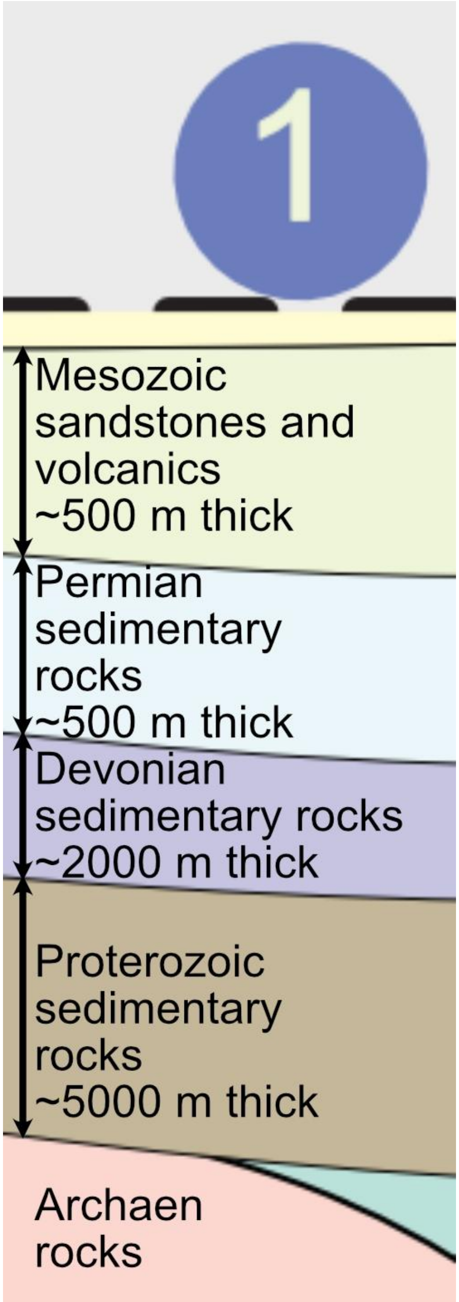


Figure 11: The stratigraphic thickness of major units beneath Mos Woestijn. The unconsolidated Holocene and Pleistocene units at the top of the sequence are less than 50m thick. The thickness of the other units is variable across the basin.

15. The floor of the food hall is paved with sandstone tiles quarried during the excavation and many of them display exquisite fossils. Roxanne and Gemma ignored their meal to examine the fossils beneath their table! Gemma shared her picture of the best one on her socials. It is set within a fine-medium grained quartz sandstone tile (Figure 12).

Figure 12: A really nice fossil in a fine-medium grained quartz sandstone tile.

Q: What did Roxanne say to correctly educate diners nearby when asked what she was doing?
(1 mark)

I am looking at these amazing …

a. … Pleistocene ammonitic ammonite fossils!
b. … Mesozoic ammonitic ammonite fossils!
c. … Triassic goniatitic ammonite fossils!
d. … Permian goniatitic ammonite fossils!
e. … Devonian ceratitic ammonite fossils!
f. … Proterozoic ceratitic ammonite fossils!

16. Well known fossil fish expert, Jeff Ganathostones, had just arrived in Mos Woestijn on his first visit to Specerij and arranged to meet Roxanne and Gemma for lunch. He was also amazed by the fossil-rich tiles, but after ordering some anchovy ice-cream he studied the floor some more. It wasn't long before the ice-cream was gone and he excitedly announced he'd found something 'fishy' while pointing at a tile under some chairs (Figure 13).

Figure 13: Another really nice fossil in a 'fishy' rock.

Q: What did Jeff correctly observe and explain about this tile? (1 mark)

This tile is really 'fishy'. The fossil is real but the rock-plus-fossil is an impossible composite put together by a very skilled artisan because the rock is actually a …

a. … feldspathic sandstone!
b. … schist!
c. … basalt!
d. … rhyolite!
e. … granite!
f. … gneiss!

After three days enjoying all the wonders of Mos Woestijn's underground built environment, the trio set out to explore the natural world hosting the amazing city. Access to the geoscape is provided by the many tunnels linking Mos Woestijn to other underground locations in the region and the shafts that link these places to the surface landscapes (Figure 1).

A helpful information panel at the train station entrance explained from whence the city and its satellite towns source their water and energy. It noted that despite being a desert region, the subsurface rocks host a lot of water and other resources including hydrogen. The next sentence: *The available water, hydrogen and other useful resources within the local geoscape means the region has a secure future* is now prefixed by some beautiful and elaborate street art with the words DON'T PANIC at its core. Jeff commented his planet wanderer's guide to the solar system said the art was apparently by somebody called BNKSE12.0.

17. An FAQ link to the questions visitors ask proved most informative and the trio spent time digesting what was provided before proceeding.

    Q: What did the FAQ correctly state about the origin of the region's potable groundwater?
    (1 mark)

    It rarely rains in Specerij, especially over the sand sea between the Harkonnen Range and Sardaukar Range, but when rain does fall on the ranges it ...

    a. … fills all the surface caves within the rock strata. Luckily, they act as a giant reservoir because all the other rocks in the region are hydrophobic.
    b. … infiltrates low porosity, high permeability archean granites. Fortunately, they are easily accessible close to the surface throughout the region.
    c. … infiltrates some mesozoic, permian and other strata that have high porosity and high permeability. These units slowly distribute and store water throughout the basin beneath the sand sea.
    d. … infiltrates some archean greenstones that have high porosity and low permeability. Helpfully, these metamorphosed mafic and ultramafic rocks contain the green mineral chlorite that purifies water and has healing properties.
    e. … enters sand worm tunnels. From there it seeps into all high porosity strata and is slowly distributed across the basin.
    f. … evaporates during surface runoff. This creates a hydraulic pressure gradient that draws 'fossil' metamorphic mineral dehydration-water up from deep within the basin.

18. An FAQ link to the questions visitors ask proved most informative and the trio spent time digesting what was provided before proceeding.

Q: The FAQ also noted something else about the region's potable groundwater. What important information did it impart? (1 mark)

Some of the water that has accumulated in the aquifers beneath the sand sea is extremely old. In some cases, due to tectonic movements and/or changes in surface topography the infiltration pathways to some aquifers are now greatly restricted or no longer open, except during one-in-one-thousand-year rain events. This means …

a. … some of the groundwater is ancient 'fossil water', which is now past its use-by date and should not be consumed.
b. … some aquifers have very slow recharge rates but can still be accessed because their use is sustainable if the aquifer is also connected to recharge sites in the ocean.
c. … all aquifers need careful management to ensure all usage rates never exceed their recharge rates.
d. … all residents and visitors to Specerij must wear stillsuits, garments designed to prevent moisture loss to the environment.
e. … some aquifers need careful management to ensure all usage rates never exceed their recharge rates but others can be used continuously because there is no limit to the amount of recharge they receive.
f. … some of the groundwater is ancient 'fossil water', meaning it contains ancient microscopic living fossils that are endangered species, protected by law. Some are thought to be dangerous to consume but there is no direct evidence this is so.

The trio were also captivated by the massive energy wealth of the region. The helpful graphic on display (Figure 14) really made it clear to them why this region was not concerned about its energy security. The sign proudly boasted that the entire region is powered by renewable energy derived from gold* hydrogen formed naturally within the geosphere under the Specerij Sand Sea (Figure 1).

Jeff also shared the helpful QR code information associated with the sign with the others:

Where does Specerij's hydrogen come from?

⌘ - It all starts with rain water

Rain water, rare in this dry area, infiltrates into the subsurface via lithological boundaries, faults and porous outcrops. This usually occurs in the elevated areas of the Harkonnen Range (Figure 14) and Sardaukar Range (Figure 1) where rainfall is more frequent and infiltration sites are numerous.

⌘ - Banded Iron Formation weathering

The many layers of Banded Iron Formation found within the Archaean sedimentary sequences interact with rain water, with several chemical pathways producing hydrogen gas (H_2).

⌘ - Archean Greenstone weathering

In deeply buried iron-rich (mafic) rocks, the so-called greenstones that form some of the basement rocks in this region, water and elevated temperatures combine with iron-rich minerals, olivine for example, to liberate hydrogen. This is a relatively fast process, known as serpentisation, that continues as long as the supply of raw materials lasts.

⌘ - Mafic rock weathering

Serpentisation can and does occur wherever water encounters other, younger, mafic rocks in deep, warm situations.

⌘ - Mantle emanations

Serpentisation or similar processes are also responsible for hydrogen generated from mantle rocks, found below the crustal layers of the lithosphere. Deep crustal faults provide conduits for this gas to escape upwards.

⌘ - Archean rocks

Radioactive elements in rocks emit radiation that can split water, a process known as radiolysis. The process is slow, so only ancient rocks are likely to have generated significant hydrogen resources. Many archean rocks in this region contain minerals that host radioactive elements such as uranium (^{238}U, ^{235}U), thorium (^{232}Th) and potassium (^{40}K).

⌘ - Thermogenesis of organic matter

In deeply buried sedimentary rocks organic matter can be heated to the point where the hydrocarbons are broken up to liberate H_2.

* Gold hydrogen is naturally generated, whereas green hydrogen requires water to be split by electrolysis using electricity from renewable sources.

Where does Specerij's hydrogen go once it forms?

⌘ - Some of it escapes!

Some hydrogen gas will escape (seep) to the surface through faults and other fractures in the rocks (Figure 14). Some of it can even diffuse to the surface through highly porous lithologies.

⌘ - Some of it gets eaten!

Inside the near-surface geosphere, and sometimes a little deeper, microbe communities within the rocks and soil consume hydrogen for energy, often producing methane as a byproduct.

⌘ - Some of it gets destroyed. Chemistry happens!

Just as chemical reactions within rocks can produce hydrogen, some reactions within the geosphere can abiotically consume hydrogen, making water, methane and mineral compounds in the process.

⌘ - Some of it gets trapped!

Just like methane gas, oil and water, hydrogen gas can migrate upwards along fractures or through permeable rocks but if it encounters some kind of barrier it might end up being trapped in the rocks below this barrier (Figure 14).

19. Amazed at how the entire Specerij economy is powered by this renewable, zero emissions resource, the trio shared many comments with their friends online.

    Q: What did Jeff correctly state, given the region's hydrogen production sources? (1 mark)

    a. The H_2 extraction rate is no greater than the rate of losses due to seeps, biotic and abiotic processes.
    b. The rate of H_2 generation must have exceeded the loss rate most of the time.
    c. Salt layers must be permeable.
    d. There must be a lot of hydrogen in the core and mantle.
    e. The evolution of hydrogen consuming microbes must be a recent phenomenon.
    f. The basement rocks must be highly radioactive.

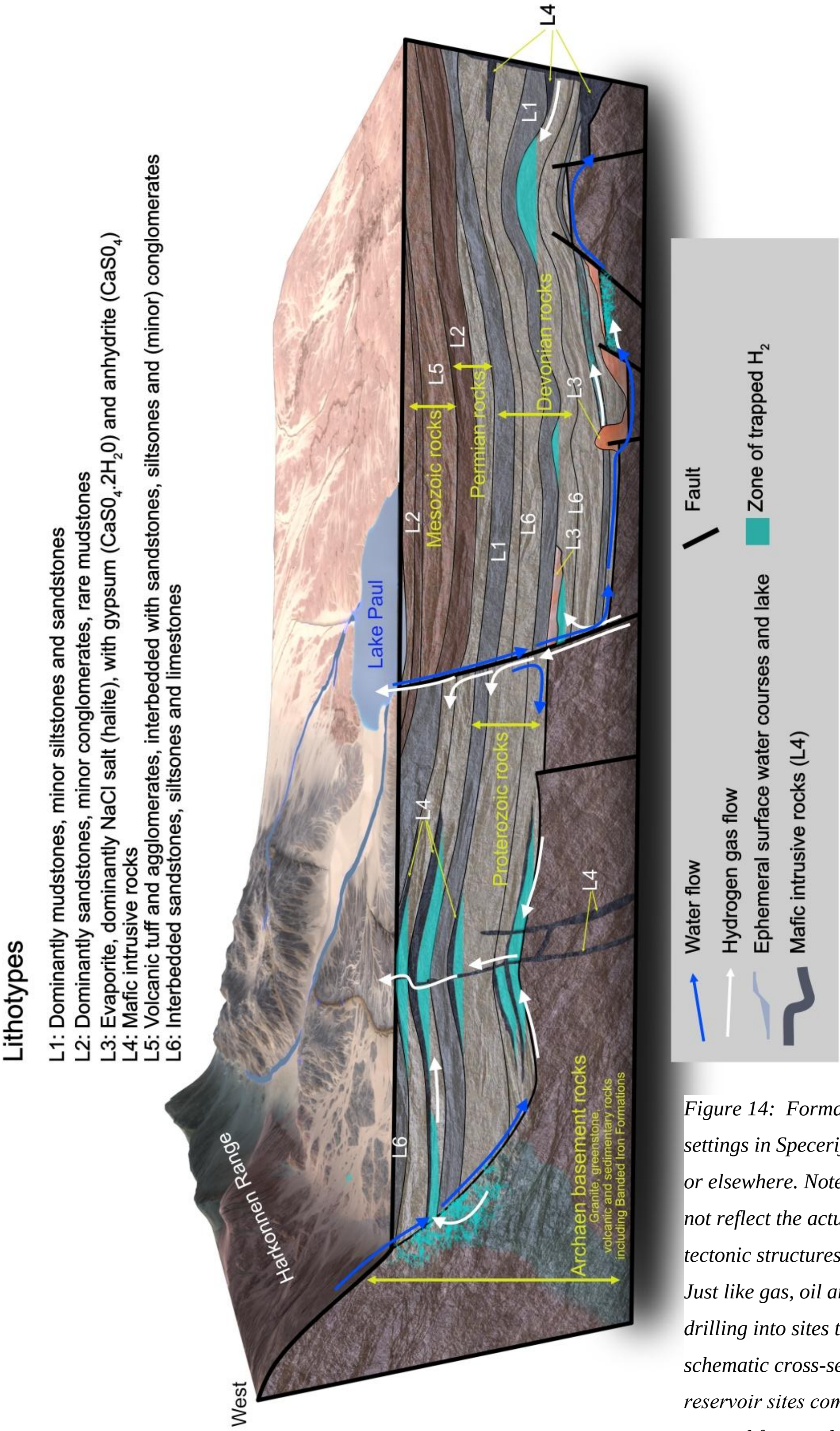


Figure 14: Formation of hydrogen resources in natural settings in Specerij plus likely sites of loss to the atmosphere or elsewhere. Note this is a schematic image only and does not reflect the actual scale of the sub-sand sea basin, its tectonic structures or the exact stratigraphy of the region. Just like gas, oil and water, hydrogen can be harvested by drilling into sites that trap fluids (reservoirs). This schematic cross-section, looking north eastwards, shows reservoir sites common in Specerij's geosphere. Image sourced from and modified with permission from Hydrogenesis.

20. The trio spent so much time looking at the infographics Jeff needed to get another snack. While he was searching for the best anchovy flavoured dessert in Specerij the others kept answering questions from their friends.

Q: Ashleigh Hammer chimed in to question the ultimate hydrogen generation process beneath the Specerij. What did the team accurately identify as the source in this setting? (1 mark)

a. They said it is impossible to determine based on the available information.
b. They said it must be generated by radiolysis within the Mesozoic volcanics, as these are the only rocks in the sequence that contain radioactive elements.
c. They said it must be generated by serpentinisation of Archean mafic rocks, as these are the only rocks in the sequence that contain sufficient quantities of iron-rich minerals.
d. They said it must be generated by radiolysis within the Archean granitic rocks, as these are the only sufficiently old rocks in the sequence that contain radioactive elements.
e. They said it must be derived from the mantle as this area is shaped by deep, tectonic-boundary faults.
f. They said it is most likely generated by a combination of all processes but with weathering, radiolysis and serpentinisation of the Archean basement rocks the major contributors.

21. Some team members wondered what geophysical/geographical/geological evidence the Specerij Energy managers should look for to determine a site's suitability for hydrogen exploration.

Q: What did seismologist Jean Luc Bringuebaler correctly suggest? (1 mark)

a. Suitable locations will yield plenty of clean drinking water from the springs associated with hydrogen seeps.
b. Suitable locations will have significant surface and/or near-surface faults connected to the mantle but no seeps.
c. Suitable locations will have significant surface and/or near-surface faults, seeps, low porosity lithologies,, and reveal no evidence of deep Archean cratonic rocks.
d. Unsuitable locations will contain significant surface and/or near-surface faults, seeps, display high porosity lithologies, and no evidence of deep Archean cratonic rocks.
e. Unsuitable locations will display highly permeable lithologies capped by impermeable layers over a deep Archean basement.
f. Unsuitable locations lack seeps and fresh drinking water from the springs associated with hydrogen seeps.

22. Roxanne was quick to mention to her online followers how many different geological settings provided traps for hydrogen in this region but her friend Haly Te wondered how it was that salt could form a trap given it is so loose in her salt shaker in the kitchen and dissolves in water so easily.

Q: What was Roxanne's expert explanation for this observation? (1 mark)

Evaporite deposits in this region are mostly halite and other salts. They are compacted by burial and …

a. … are highly impermeable because the grains of salt are easily deformed to remove any porosity. In some places the hydrogen can then be trapped under the salt.

b. … are highly permeable because the grains of salt are hard to deform, thus keeping lots of porosity within the salt to host gases like hydrogen.

c. … host lots of bacteria that eat the hydrogen and excrete methane, which is then trapped in the salt.

d. … this enables radiolysis of the water trapped between the radioactive salt grains. The resultant hydrogen is then trapped in the deposit.

e. … yet remain highly porous, allowing hydrogen generated by serpentinisation elsewhere to infiltrate between the salt grains in areas where the evaporite permeability is low.

f. … become impermeable when water or other fluids fill the pore spaces. In some places the hydrogen can then be trapped under the salt.

Image courtesy of https://tinyurl.com/8c4bb3jw

Haly was happy with Jeff's answer but was also curious about the ephemeral lake shown in the diagram (Figure 14). She said she was aware that the dry lake beds of Specerij, especially Lake Paul, were famous for hosting 'land yacht' racing (see adjacent image) because the dry salt pans are both very flat and very windy places. However, she wasn't sure where all the salts came from.

Jeff quickly explained that most evaporites not only contain salt (NaCl) but also gypsum ($CaSO_4 \cdot 2H_2O$), the alunite group of sulphur bearing minerals. $AB_3(SO_4)_2(OH)_6$ where A and B represent a variety of cations such as potassium (K) and aluminium (Al) as well as a range of less common salt compounds. To cut a long geochemical story short, he also explained that the stable sulphur isotope composition in gypsum and alunites, specifically the ^{34}S:^{32}S ratio, can be used as a strong indicator for the sulphur's source. He added a table to his comments to demonstrate this point (Table 3).

Mineral	**$\delta^{34}S$ value (‰)**	**Location**
Alunite and Gypsum	+15.1 to +21.0	Dry lake beds in western Australia
Alunite	+8.4 to +12.3	Permian sandstone
Igneous rock sulphides	-8.0 to +8.0 but mostly -2.0 to +3.0	Weathering at or near the surface. Western Australian mines.
Sulphates in marine waters	+20.6 average	Coastal Australia
Sulphides in metamorphosed sedimentary rocks	-8.0 to +8.0 but mostly -2.0 to +3.0	Weathering at or near the surface. Western Australian mines.
Sulphides in organic rich lake sediments	-17.5 to -6.1	Miocene lake sediments extracted by drill core. Eastern Australian sites.

Table 3: The $\delta^{34}S$ value is a standardized method for reporting measurements of the ratio of ^{34}S and ^{32}S. The method of calculation is not important here but is provided below for completeness. Data in this table is consolidated from a variety of published sources.

$$\delta^{34}S = \left(\frac{\left(\frac{^{34}S}{^{32}S}\right)_{sample}}{\left(\frac{^{34}S}{^{32}S}\right)_{standard}} - 1 \right) \times 1000\ ‰$$

23. Jeff also noted that the sand dunes of Specerij are famous for the amount of wind-blown gypsum found in them, adding that $\delta^{34}S$ ‰ for the Lake Paul deposits and associated dunes is about +16.

Q: What did Haly correctly conclude and write in reply to Jeff? (1 mark)

Assuming the data you have supplied can be reasonably used to interpret the origins of some evaporite minerals in Specerij, I think it is fair to say that, given there are no known organic sulphur-rich lake or river deposits in the post-Mesozoic sequences of the region, …

a. … the Lake Paul evaporites contain sulphur mostly derived from aerosols blown in from the ocean over time but with some dilution from Palaeozoic rocks weathering in the Harkonnen Range.
b. … the Lake Paul evaporites contain sulphur solely derived from sulphides weathering out of Mesozoic rocks exposed in the Harkonnen Range.
c. … the Lake Paul evaporites contain sulphur solely derived from marine aerosols diluted by rainfall on the Harkonnen Range.
d. … the origin of the Lake Paul evaporites remains a mystery.
e. … the Lake Paul evaporites contain sulphur mostly derived from aerosols blown in from the ocean over time but with some dilution from Miocene lake sediments weathering in the Harkonnen Range.
f. … the Lake Paul evaporites contain sulphur derived from sulphides weathering out of Palaeozoic and Mesozoic rocks exposed in the Harkonnen Range with some input from other rocks in the same area.

24. Haly continued chatting with Jeff, asking why there was no hydrogen associated with Lake Paul's salt pan when there was hydrogen associated with evaporites elsewhere in the stratigraphy (Figure 14).

Q: What did Roxanne say to help Jeff out with the correct answer? (1 mark)

a. Sand trout live in the lake and use hydrogen as an energy source.
b. The rocks immediately below Lake Paul (L2 & L5) are isolated from hydrogen sources by the flow of water down the fault (exposed on its southwestern shoreline).
c. The rocks immediately below Lake Paul (L2 & L5) are isolated from hydrogen sources by the fault (exposed on its southwestern shoreline).
d. The rocks immediately below Lake Paul (L2 & L5) are isolated from hydrogen sources by impermeable Devonian L1 lithologies.
e. The rocks immediately below Lake Paul (L2 & L5) are mostly permeable. This allows fluids to migrate to the surface anywhere to the west of the fault.
f. The rocks immediately below Lake Paul (L2 & L5) are mostly impermeable, preventing any fluids from approaching Lake Paul from below.

25. Philip's exploration efforts on Mars aims to identify places associated with mafic rocks where hydrogen might also be available. Gemma commented that the formation of the phyllosilicate serpentine from olivine is a metamorphic process (serpentinisation) that typically occurs when olivine-rich rocks interact with warm water. She provided some fun equations to summarise the processes and support the statement:

EQ1: $2Mg_2SiO_4$ (forsterite) + $3H_2O \Rightarrow Mg_3Si_2O_5(OH)_4$ (serpentine) + $Mg(OH)_2$ (brucite)
Subsequent reactions can also produce minerals such as talc. EQ1 also creates conditions conducive for water to oxidise the ferrous ions (Fe^{2+}) in fayalite.

EQ2: $3Fe_2SiO_4$ (fayalite) + $2H_2O \Rightarrow 2Fe_3O_4$ (magnetite) + $3SiO_2$ (quartz) + $2H_2$

She also added the fun fact that olivine (a transparent, bottle green mineral) contains both Mg and Fe in a variable ratio. The end-member containing 100% Mg is called *forsterite* (Fo) whereas *fayalite* (Fa) is the name given to the 100% Fe end-member. The ratio of Fe:Mg within a specific olivine is expressed as a ratio of Fo to Fa (e.g. $Fo_{50}Fa_{50}$, $Fo_{20}Fa_{80}$, etc.)

Q: What else did Gemma tell Philip would be essential to his successful search for hydrogen on Mars? (1 mark)

Mars was volcanically active and capable of circulating warm water through the rocks so, when looking for hydrogen, you first …

a. … need to be sure the mafic rocks are not magnetic.
b. …need to be sure the rocks are no longer mafic and contain lots of quartz.
c. … need to find evidence of flowing water eroding channels across the mafic rocks.
d. … need to be sure the mafic rocks hosted olivine and there is serpentine in them now.
e. … need to be sure the mafic rocks exclusively hosted fayalite and there is serpentine in them now.
f. … need to be sure the mafic rocks exclusively hosted forsterite and there is serpentine in them now.

Meanwhile, their old uni buddies, Andy Syght and Gabi Roe, have been adventuring around Iceland in early Summer.

The landmass is uniquely situated atop a hotspot along the divergent plate boundary of the Mid-Atlantic Ridge, between 63.4°N and 66.5°N latitude (Figure 15). Like other hotspots situated within oceanic plates and mid-ocean ridges, Iceland is formed from basaltic magma.

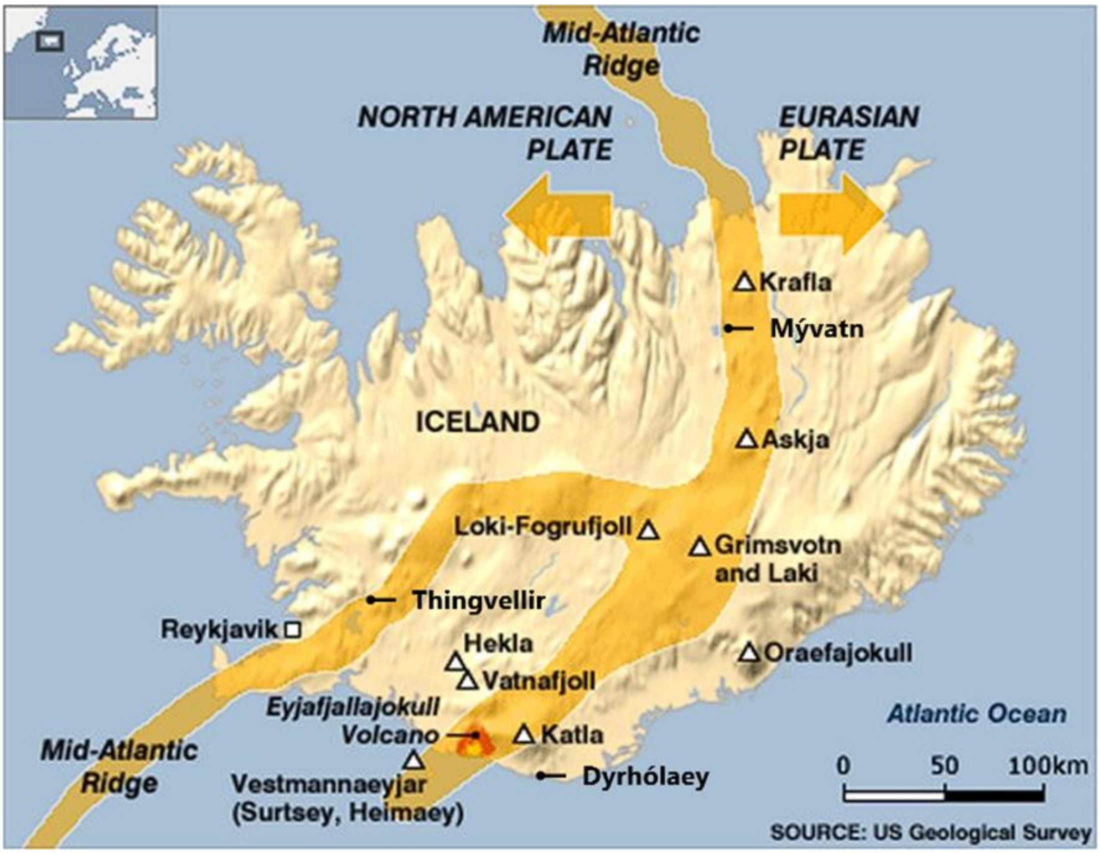


Figure 15: Map of Iceland and its position relative to the Mid-Atlantic Ridge.

Prior to their trip, in anticipation of all the glorious geology awaiting them, Gabi and Andy take a virtual tour of some outcrops they hope to visit. These two (Figure 16 and Figure 17) strike them as quite intriguing:

Figure 16: Outcrop A

Figure 17: Outcrop B

26. Gabi challenges Andy to think about what they can actually determine about these locations based on what they can see in the images (Figure 16 and Figure 17) and what is known about Iceland's tectonic setting.

Q: What does Andy correctly say? (1 mark)

Both these outcrops are dominated by parallel features, some horizontal and some vertical. This means…

a. … they all formed via sedimentary processes, the vertical ones have just been uplifted and folded.
b. … they all formed via metamorphic processes, the parallel features are aligned mineral planes called *foliation*.
c. … they formed from a variety of processes, including successive lava flows, sequential deposition of granular material, and layering of metamorphic rocks.
d. … they followed the Laws of Original Horizontality and Lateral Continuity, so all the layers started out flat and continuous, but at location B they were compressed until vertical.
e. … they are likely related to extrusive mafic igneous processes, but we'd need to have a closer look to say more with certainty.
f. … they formed via tectonic and sedimentary processes, the vertical ones have been rotated by the actions of vertical faults.

27. Andy followed up with a question of his own, asking: *What additional observations do you want to make at these sites when we get there to better understand why each outcrop looks the way it does?*

Q: What wise words does Gabi respond with? (1 mark)

a. We should perform the 'tink!*' test to see if they are shales or their metamorphic equivalent – slates. (*a highly rigorous test that involves striking the rock with a pen to see whether it goes 'thunk' for shale or 'tink!' for slate.)
b. We should grind a bit of each rock between our teeth to see whether they are mudstones or siltstones.
c. We should pour HCl on them to see whether they are limestones or granites.
d. We should examine them with a hand lens to determine their mineralogy and grain sizes.
e. We should bash them with our rock hammers to see how easily they break.
f. We should compare the rocks against a colour chart to determine their chemical composition.

When they arrive in Iceland, their first stop is Thingvellir National Park (Figure 15), where the crust fractures dramatically forming a rift valley, with fissures ranging from metres up to tens of kilometres. Gabi exclaims, *Wow, this is really cool! It looks like we could take our own journey to the centre of the Earth from here.* Andy points to a patch of snow lingering at the end of a narrow fissure (Figures 18, 19 & 20) and laughs, *Well, if you want to see something that's literally cool, check that out.*

Figure 18: View from above a large fissure

Figure 19: View while walking through a large fissure

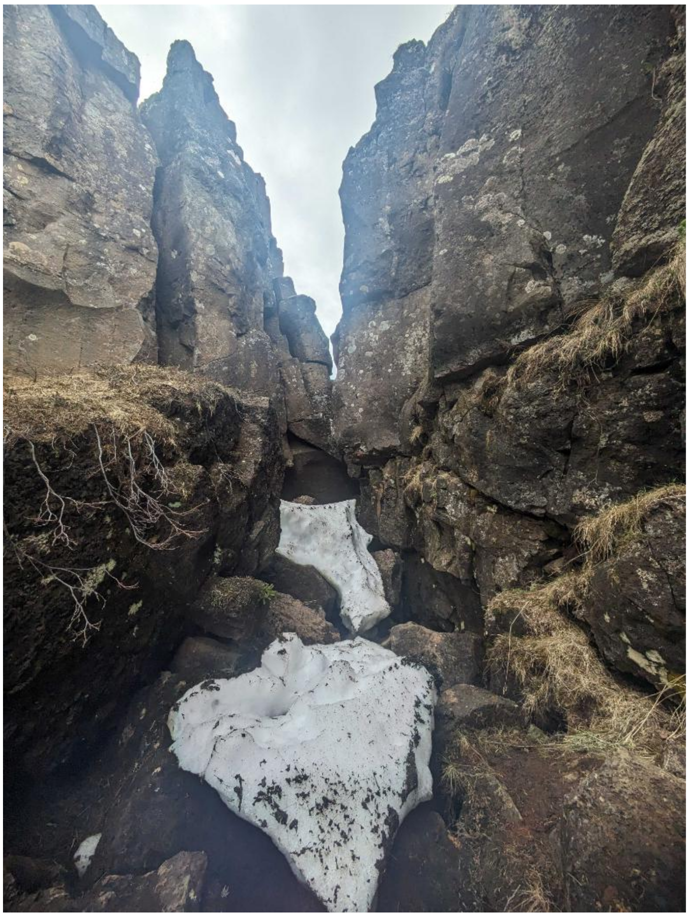


Figure 20: Snow in the end of the fissure, where it narrows.

28. Although the temperature hasn't dropped below zero in weeks and there is no snow anywhere else around, this patch persists (Figure 20). Andy and Gabi are a bit perplexed, so they contact their friend Daytona Light to see if she can illuminate the situation.

Q: How does Daytona correctly explain why the snow has not melted? (1 mark)

a. The Sun stays at low angles in the sky at high latitudes. This, combined with the orientation of the rift, ensures the sun rarely shines on the snow even on cloud free days.
b. The snow does melt during daytime, but freezes again at night.
c. The fissure must tap into a cool seep from the mid-ocean ridge to locally depress the air temperature.
d. The snow does melt at night, but re-freezes during the daytime when it's cloudy.
e. This is clearly a perennial snow field that will become a glacier when it has enough mass to flow.
f. In summer at high latitudes, the 'midnight Sun' actually has a local cooling effect, which results in anomalous snow patches where it shines most intensely.

Gabi notices many rocks covered in thick, continuous carpets of moss heath, which she thinks looks like a cozy place for a quick kip. Andy points out that the soft-looking carpet bit only covers some surfaces, whereas some rock faces have a rougher, splotchy coverings of flatter lichens, not moss heath. They share this photo (Figure 21) from another fissure zone with their botanist friend, Bryan Zoie:

Figure 21: View of another fissure with Thingvallavatn, the largest natural lake in the country, visible in the background.

29. Bryan notes: *This moss heath makes its home on volcanic rocks with some areas famous tourist destinations. Your photo is excellent as it shows they are not evenly distributed across the landscape. Instead they predominate on surfaces where…*

Q: What did Bryan say to complete his message? (1 mark)

a. …they receive the most sunlight and hence stay warm enough to grow while also maximising their photosynthetic opportunities.
b. …water accumulates in depressions, on colonising flatter lichens and on biofilms, enabling moss to colonise, which in turn then trap and hold water thus enabling more of their growth.
c. …where the rough surface of the vesicular rock faces allows for adhesion, irrespective of its orientation.
d. …where the rocks are young enough not to have yet developed sufficient soil covering for vascular plants to take root, allowing the moss monoculture to prevail.
e. He said a combination of statements from a, b and d.
f. He said a combination of statements from a, b and c.

Thinking how awesome it would be to subsist on rocks, water and sunlight alone, Andy and Gabi continue on to their next stop at some cliffs on the south coast near Vik, overlooking the black sand beaches (Figure 15).

They find many dark coloured rocks (X) of variable sizes. Upon closer inspection, they notice some are embedded in a lighter coloured rock type (Y), whereas others sit loose on the surrounding ground. Some, but not all, samples of rock X have visible holes in the rock surface. Andy takes plenty of photos to share with his friends back home (Figures 22 - 26). Unfortunately he forgot to pack his EESO scale card, so uses his sunglasses instead, noting that the frame is ~12 cm wide.
While Andy photo-documents everything, Gabi does a bit of scratching around and notices the lighter material Y is composed of is much softer than the dark chunks of X within it. She does a quick info search and finds a research paper claiming both materials initially had the same composition and formed by the same fundamental process during the same event – shallow emergent *Surtseyen* volcanism (Figure 27). Andy is rather blown away by this revelation!

Figure 22: Triangular sample of rock X (centre left), approx 20 cm diameter, embedded in rock Y.

Figure 23: Loose samples of rock X, ranging from 1 cm to 5 cm in diameter, on top of rock Y.

Figure 24: Loose samples of rock X, ranging from 2 cm to 10 cm in diameter.

Figure 25: Sample of rock X, showing holes on rock surface.

Figure 26: Sample of rock X, 1 m in diameter, embedded in rock Y

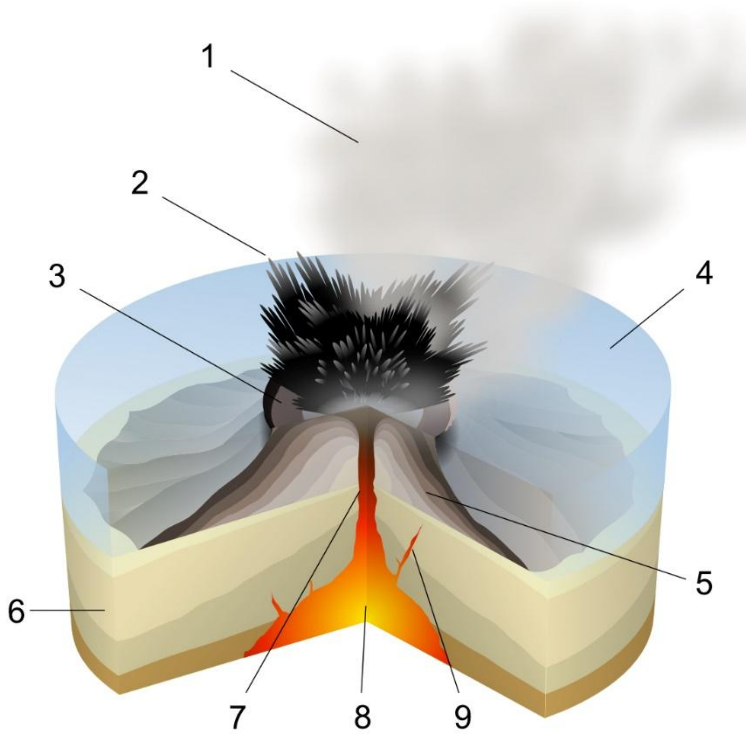


Figure 27: A schematic diagram of a Surtseyan eruption. 1. Water vapor cloud 2. Ballistic ash 3. Crater 4. Water 5. Layers of lava and ash 6. Stratum 7. Magma conduit 8. Magma chamber 9. Dike. Image courtesy of https://tinyurl.com/mpn49p48.

30. After seeing their images on socials, their geochronologist friend, Jiki Nakamura, was curious about the relationships between the two materials.

Q: How did Gabi respond to Jiki? (1 mark)

"*Using the law of …*

a. … superposition we can conclude that rock X formed briefly before being deposited upon rock Y."
b. … superposition we can conclude that rock Y formed briefly before being deposited upon rock X
c. … inclusion we can conclude that rock X formed briefly before inclusion within rock Y.
d. … lateral continuity we can conclude that rock X formed briefly before continuing on from rock Y.
e. … lateral continuity we can conclude that rock Y formed briefly before continuing on from rock X.
f. … inclusion we can conclude that rock Y formed briefly before inclusion within rock X.

31. Gabi draws Andy's attention to the loose samples of rock X in Figure 24.

Q: How does Andy correctly explain their presence to Gabi? (1 mark)

a. The loose samples of rock X have been eroded out of rock Y on site.
b. The loose samples of rock X have been deposited at the site by water transport.
c. The loose samples of rock X have been deposited at the site by wind transport.
d. Rock X material is clearly less resistant to physical weathering than the material of rock Y.
e. Rock X material is clearly less resistant to chemical weathering than the material of rock Y.
f. Rock Y material is clearly less resistant to chemical weathering than the material of rock X.

32. Jiki asks for more information about the rocks.

Q: What did Andy correctly explain to Jiki about the rocks? (1 mark)

a. The different densities of rock X (containing many holes vs. no visible holes) indicate variations in gas content of the erupting lava over short timescales.
b. The presence of the fine grained material of rock Y can only be explained by explosive eruptive action.
c. The blue-grey colour of rock X can only be explained by the presence of the trace mineral glaucophane.
d. The presence of rocks X and Y at the top of the cliff can only be explained by global sea level drop after rock formation.
e. The triangular sample of rock X can be used to reconstruct the shape of the volcanic vent.
f. The 1-m diameter sample of rock X is too large to be formed during the same event as other samples of rock X, therefore it must have been transported to the site via another mechanism, e.g. glacial transport.

33. To further help Jiki they add more.

Q: What additional pieces of evidence, other than the existence of two rock types, do Andy and Gabi point to that support the idea that these rocks represent deposits created by *Surtseyen* volcanism? (1 mark)

a. The holes in some samples of X appear to be frozen gas bubbles (vesicles).
b. The angular nature of some pieces of rock X is consistent with explosive fragmentation.
c. The chaotic mixture of X and Y materials supports a very high energy formation environment.
d. They pointed only to features mentioned in answers a and c.
e. They pointed to features mentioned in answers a, b and c.
f. They can point to no other evidence but claim *Surtseyen* volcanism is the only possible explanation for the generation of the light colour of rock Y.

34. Upon closer inspection of the roughly horizontal ground surface at the cliffs while fulfilling his amateur photographer dreams, Andy discovers a peculiar site, worth sharing with his friend (and once upon a time undergraduate lab partner) Ariel Windlass. Here, a range of subangular pebbles sit upon a fine-grained material that is dusty when dry.

Andy shares the following photo of the ground surface to Ariel, viewed from above (Figures 28 a and b).

Figure 28 a: The ground surface photographed by Andy.

Figure 28 b: A close up of the central portion of the image

Q: What does he caption his photo with? (1 mark)

a. This photo shows that the wind predominantly blows from the right.
b. This photo shows that the wind predominantly blows from the left.
c. This photo shows graded bedding.
d. This photo shows gravitational settling.
e. This photo shows that the sun is very low on the horizon casting long shadows to the south of each pebble.
f. This photo shows a conglomerate rock.

35. Still enjoying mucking about with his camera while Gabi gets down with the rocks, Andy comes up with a brain teaser for his Science friends back home in Australia (Figure 29).

Figure 29:

I took this photo of my camera (with my phone) in Iceland around midday today.

What direction was I facing?

Q: How did his friends correctly respond? (1 mark)

a. You're facing North!
b. You're facing South!
c. You're facing East!
d. You're facing West!
e. Don't be silly, there's not enough information in this image to answer that!
f. Stop messing with us, you can't be in Iceland as the midnight sun shines down vertically 24 hours a day in summer.

While Andy is busy with his camera, Gabi heads down the cliffs to the black sand beach. She is surprised to see dark coloured "sand" of dramatically different grain sizes as she makes her way from the carpark towards the shoreline. She documents each type in turn (Figures 30, 31, 32, 33)

Fed up, she yells back up the cliff to Andy, *The name is a lie! The so-called 'black sand' is mostly grey, and only becomes black when it is wet.*

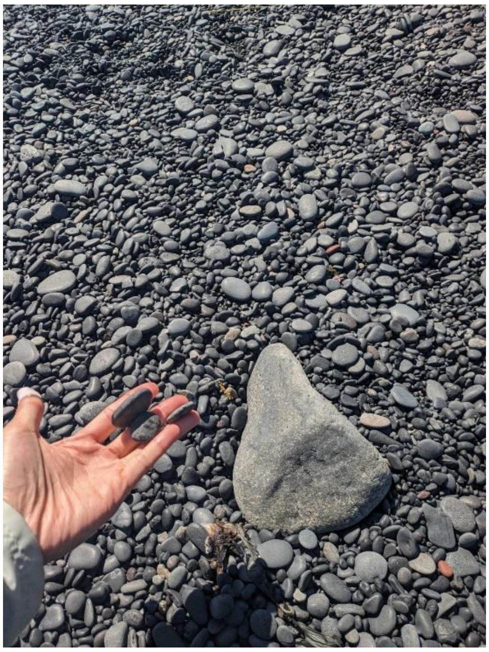


Figure 30

Figure 31

Figure 32

Figure 33

36. Wading in the shallow waters, she contemplates how the varying sizes of "sand" must have made it to the beach.

Q: What does Gabi confidently conclude? (1 mark)

Apart from some of the grains being too large to technically be called sand …

a. … the "sand" grains were initially generated by non-beach processes acting on several different rock types.
b. … the "sand" grains could only have been generated by beach processes acting on several different rock types.
c. … the "sand" grains were initially generated by non-beach processes acting on a single rock type but have been significantly reworked and sorted by wave action.
d. … the "sand" grains were generated at the beach, by several beach processes, and have been significantly reworked and sorted by wave action.
e. … the "sand" grains were generated at the beach, by a single beach process, requiring no reworking or sorting by wave action.
f. … the coarse components of the "sand" must have formed at the beach, but the smaller grains were formed by non-beach processes and transported over long distances before coming to rest here.

37. Andy arrives at the beach in awe, exclaiming: this beach is nothing like my light-coloured beach back home in eastern Australia! It must be due to a lack of marine critters and granitic source rock.

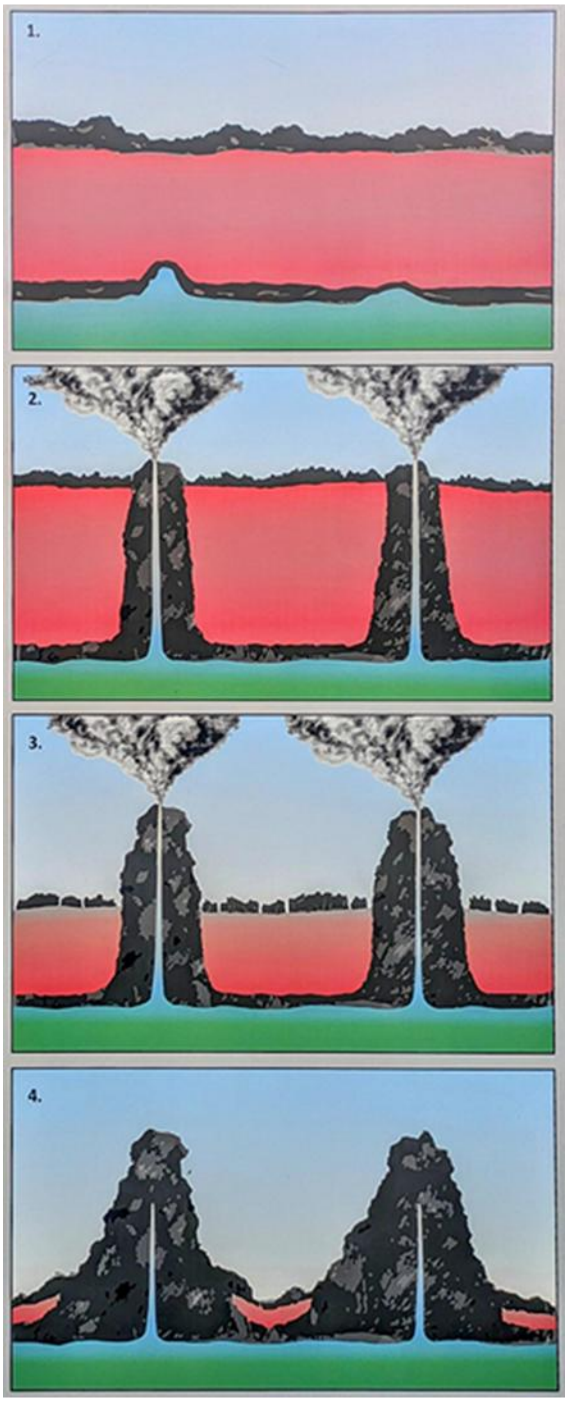
Q: What does Andy expect to find on the beach at home? (1 mark)

a. Shell fragments
b. Feldspar grains
c. Basalt grains
d. Quartz grains
e. A combination of a and d
f. A combination of a, b, and d

38. For their final stop, Gabi and Andy visit Myvatn, a volcanic lake in central Iceland. The region is a geologic wonder, with fissures, lava fields, hot springs, pseudocraters, and of course, volcanoes!

Andy finds himself drawn to the unique formations of Dimmuborgir lava field (Figure 34) and stops to take many photos. Meanwhile, Gabi carefully reads the sign at the trailhead, which offers an excellent explanation of the field's formation (Figure 35).

Figure 34: The alien landscape formed in the Dimmuborgir lava field (image courtesy of https://tinyurl.com/5a4svzms).



1: Lava spills over a water-filled depression or marshland forming a lava lake. The surface layer solidifies quickly and the under-laying layer immediately.

2: The magma heats the water in the sub-surface layer, creating steam at the water's surface below the lava. The steam bursts up through vents while the surrounding magma solidifies.

3: The lake breaches its dam, causing molten lava to flow between the steam vents and out into the lava channel. The surface crust subsides.

4: Left standing are lava pillars, columns and ridges and other remains of the steam vents. Between them are dykes and gaps, where lava flowed during the eruption.

Figure 35: Information panel in the Dimmuborgir lava field

Andy adds that in part 4, the remaining liquid lava can also drain away, leaving behind open tunnels known as lava tubes. Where some of the surface rocks collapse into the tubes, they form openings or 'skylights' into these subterranean caverns which in turn create new habitats for a variety of microscopic and macroscopic organisms.

Q: After learning about the formation of the lava field, what does Gabi correctly conclude about this pillar forming landscape? (1 mark)

a. The height of the pillars is a good rule-of-thumb estimate for the depth of the lava lake before it drained away.
b. The columns are great tourist attractions as the central conduit of each one forms a geyser once the lava has cooled down.
c. The silica content of the rock pillars is greater at the top and less at the bottom due to fractional crystallisation.
d. Lava lakes will always generate these pillar-like features, even without an underlying source of water.
e. Even though the pillars are all formed from the same lava flow, some are much older than others.
f. The heat of the steam escaping from the pillars has metamorphosed the rock, forming amphibolite.

Figure 36: Opening into a cavity of unknown depth. (bottom right)

The signs in the field are very clear to remind tourists to stay on the paths. One reason for this is the risk of falling into underground cavities if one strays even slightly off the path. Openings are common (for example, Figure 36) and are not always easy to see. In addition, the roof rocks of fully covered cavities often become unstable over time, creating the risk of unexpected collapse if walked on.

39. Philip responded to the image they posted on socials, remarking that:

As you know, I am on Mars where living conditions are even harsher than in Iceland! However, here on Mars we actually live in the really big lava tubes because…

Q: What did Philip add to finish his correct statement? (1 mark)

a. … basaltic eruptions produce lots of gases, including oxygen, which is denser than the other gases such as CO_2 and SO_2 so it accumulates in the lava tubes giving us a ready made atmosphere to breathe.
b. … Mars has no global magnetic field to protect us from incoming high energy radiation and charged particles, but they cannot penetrate rocks.
c. … (sadly) the sand worms that lived in them are extinct.
d. … they provide easy access into the mantle where we can harvest diamonds from the surface of the lava lakes found there.
e. … Mars is smaller than the Earth, so there is less land area for habitation on the surface.
f. … Mars is further from the Sun than Earth, but the atmosphere is almost entirely CO_2, a greenhouse gas, making Mars unbearably hot for humans unless we live underground.

Figure 37: Volcanic rock in the lava field.

As he wanders about photographing everything he can get his lens on, Andy stumbles upon a lovely piece of volcanic rock in the lava field (Figure 37).

40. Observing closely, he finds some significantly larger minerals bound by crystal faces within the rock (Figure 38).

Figure 38: Large minerals observed within the rock.

Q: What does he correctly conclude about this pale green crystal? (1 mark)

a. It had more time to cool from a liquid state than the surrounding rock.
b. It had less time to cool than the surrounding rock.
c. It was picked up by the lava as it flowed across the ground surface.
d. It grew in the holes as water flowed through the lava after it cooled.
e. It is mineralogically distinct from the surrounding rock.
f. Its green colour indicates it must be Martian.

41. Gabi shows him a picture she took of another sample she spotted at an earlier pit stop that also seems to have some similarities. She challenges him to determine if the white minerals in her photo (Figure 39 a and b) and the pale green minerals in Andy's photo (Figure 38) have the same sort of formation history relative to the host rock.

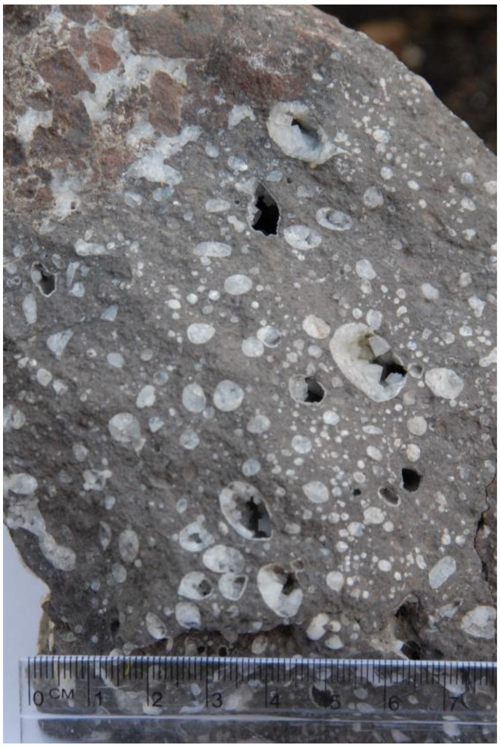


Figure 39a: Rock with white minerals.

Figure 39b: Close-up of one spot with white minerals.

Q. What does Andy cleverly surmise? (1 mark)

In response to whether the green and white minerals have the same sort of formation history relative to the host rock:

a. No, they don't. The white crystals are not bounded by flat crystal faces where they're in contact with the host rock, but they do where they jut into the cavity they fill in.
b. No, they don't. The white crystals are rounded pebbles that have clearly been picked up by the lava as it flowed over the surface.
c. No, they don't. The white crystals are actually fossil crinoids, a type of stalked sea lily.
d. Yes, they do. The white crystals are bound by crystal faces on all sides, indicating they were plucked from the magma chamber before eruption.
e. Yes, they do. The white crystals are larger than the host rock mineralogy, indicating they cooled faster.
f. Yes, they do. The white crystals were precipitated from hot water that flowed through the holes after the lava solidified.

42. An information board nearby describes the the diatomaceous earth present at the bottom of Lake Myvatn:

Diatoms, a type of microalgae ranging in size from 2 to 200 micrometers, are abundant in Lake Myvatn because the inflow of mineral-rich geothermal water from the Krafla geothermal system provides the ideal setting for these photosynthetic planktonic organisms. The biogenic silica ($SiO_2 \cdot nH_2O$) skeletons of dead diatoms have accumulated on the floor of the lake for approximately 2000 years and now form a layer around five metres thick.

Andy was pleased to see the starting point for the formation of diatomite, a soft white rock also known as "diatomaceous earth", as his mentor Greg had told him so much about. In Australia, these deposits, always associated with extinct hotspot volcanoes, are often mined because the material is useful as an abrasive, a filter, an absorbent and an inert filler in paint and plastics.

Q: When Andy shared his photos with Greg, what was Greg's response? (1 mark)

Your images and observations provide the perfect example of how similar Cenozoic volcanoes in eastern Australia created similar environments for these amazing organisms to thrive. What all these deposits have in common with your example are:

a. The associated volcanism is dominated by basaltic lava flows.
b. The white diatomite fizzes when the HCl acid test is applied.
c. The species of planktonic diatoms in these deposits are all extinct.
d. The water involved in the formation of these deposits is marine.
e. The biogenic silica, like opal, is harder than quartz and makes a better abrasive than garnets.
f. The diatomite has no permeability despite having a high porosity.

43. Gabi is curious to explore how the average sedimentation rate in Myvatn over the past two millennia compares to other modern freshwater lakes, and finds a study using radiometric dating to determine the sedimentation rate for the last century in Kodaikanal Lake, South India (Figure 40).

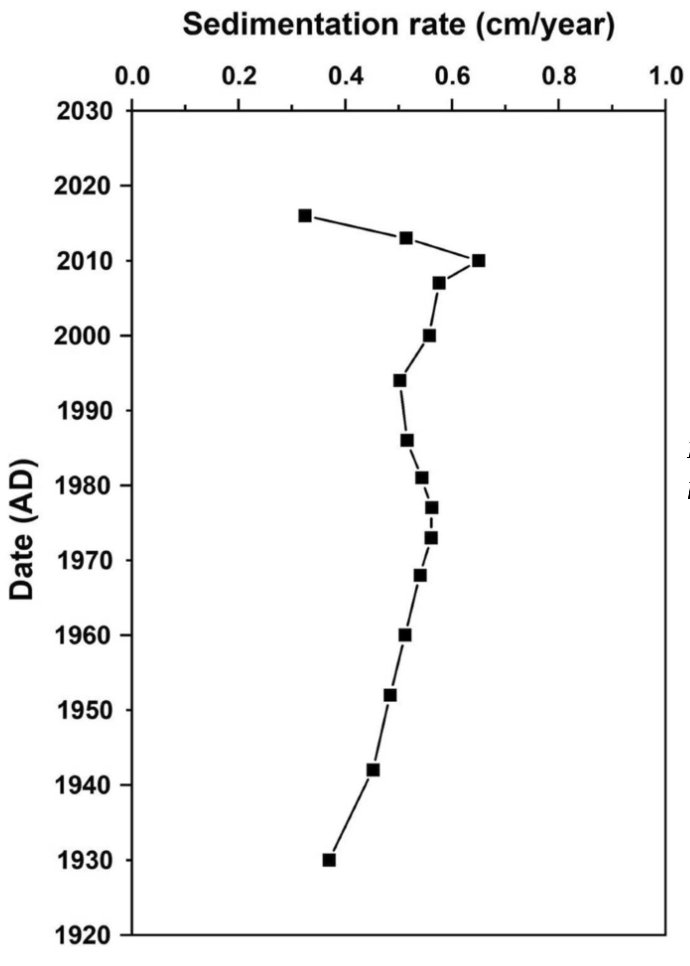


Figure 40: Sedimentation rate in Kodaikanal Lake from 1930 to 2015. https://link.springer.com/article/10.1007/s12665-023-10896-1#Fig7

Q: How does the sedimentation rate in Lake Myvatn compare to Kodaikanal Lake? (1 mark)

a. It is approximately half as fast.
b. It is approximately equal.
c. It is approximately twice as fast.
d. It is approximately 5 times as fast.
e. It is approximately 10 times as fast.
f. It is approximately 50 times as fast.

Roxanne, Gemma and Jeff enjoyed reading about Gabi's and Andy's adventure in Iceland as they trekked from Mos Woestijn (Location 1, Figure 1) along the underground tunnel connecting the aero-spaceport to the Harkonnen Range.

The engineers did an excellent job of highlighting all the rock types exposed during tunneling for foot traffic, ensuring all the best features were on display rather than being totally covered in concrete like the high speed train tunnel walls.

At Location 2 (Figure 1) they spent a pleasant few days exploring the wonders of the geosphere, especially the Permian volcanics on display. The main engineer on the project, Orson Stone, explained to Jeff and his sisters Roxanne and Gemma that he was particularly proud of the palaeo-surface he discovered and preserved (under a very durable ultra-clear glass), that was now part of the trek (Figure 41).

Figure 41: A 200-m section of the trek tunnel is paved with this material. Each hexagon is approximately 500 mm across.
Image courtesy of US National Parks Service.

44. Orson, now on Mars managing another tunnel project, added:

The hexagonal shapes are classic examples of cross-sections through cooling columns that develop in some lava flows. This ancient surface was buried beneath a thin (less than 1 m) fine-grained felsic ashstone, which was in turn buried conformably under an extensive sedimentary sequence, complete with middle Triassic marine fossils.

Q: What else did Orson say about the geological history of this rock? (1 mark)

a. The lava flow developed a horizontal foliation because of the black mica (biotite) that crystallised as it cooled.
b. The fine-grained felsic ashstone is Devonian in age and was deposited after a prolonged period of weathering and erosion that resulted in polishing of the hexagonal shapes in the palaeo-surface.
c. The lava flow was emplaced before a massive glacier scraped off overlying layers, scratching and polishing the remaining palaeo-surface.
d. The lava flow developed a horizontal lineation because of the black amphiboles that crystallised as it cooled.
e. The lava flow developed horizontal laminations as it cooled that easily peel off in thin layers if not protected by the special glass we have used on the path.
f. The lava flow was buried by a pyroclastic flow immediately after it was emplaced, preserving the shiny surface of the ropy lava (*pahoehoe*).

45. Their friend, Rose Kortz, is always excited to hear about fossils. She asked:

What type of fossils did you find in the Triassic sediments?

Q: What did Gemma report she had seen in an information panel set into the wall where some of the fossils were on display? (1 mark)

The display of the fossils is oresome, with lots of beautifully preserved shells and corals shown in association with their host sedimentary layers. They include…

a. … ammonites, brachiopods, rugose corals, tabulate corals, and ray-finned fish.
b. … ammonites, bivalves, rugose corals, tabulate corals, trilobites, and ray-finned fish.
c. … ammonites, brachiopods, gastropods, and scleractinian corals, plus ray-finned fish in life position within an archaeocyathea reef complex.
d. … ammonites, brachiopods, gastropods, and scleractinian corals, plus ray-finned fish and even a small dinosaur.
e. … brachiopods, gastropods, graptolites, and scleractinian corals, plus ray-finned fish and even a trilobite.
f. … brachiopods, rugose corals, and scleractinian corals in life position within an archaeocyathea reef complex.

Gabi and Andy are also enjoying finding out about the landscapes of Specerij. Continuing on their travels from Myvatn through the Dimmuborgir region they pick up a handy-dandy regional map with some geographic info (Figure 42). They're glad they've learned one Icelandic term along the way: *jökull* means glacier. .

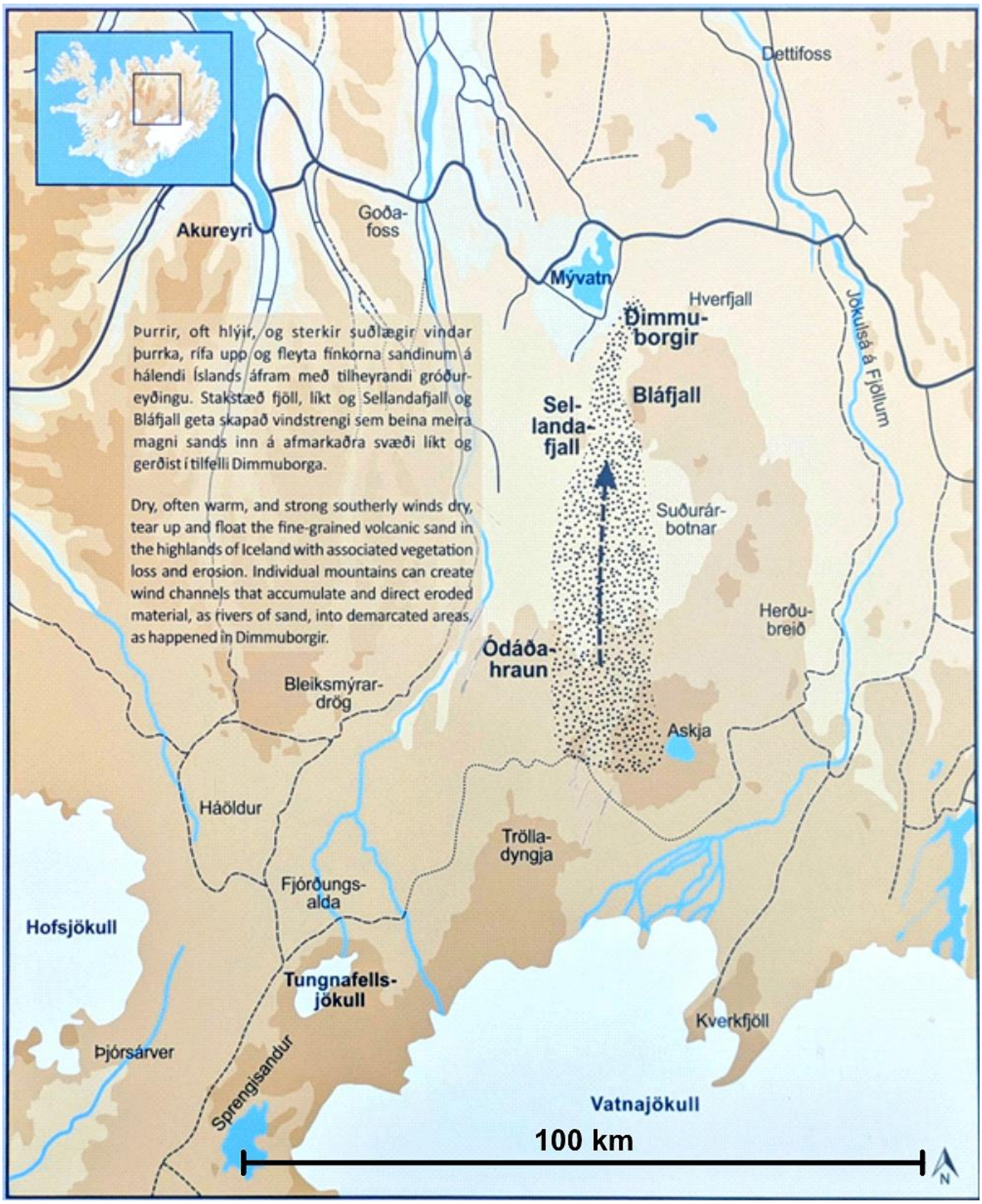


Figure 42: Map of the region between Vatnajökull and Myvatn

46. They’re struck by the small desert to their south in an area with lots of water and decide to read more. They discover that prior to settlement in the ninth century Iceland’s lowlands were forested or covered in shrubs. The delicate ecosystem was soon disturbed in an unfortunate post-settlement cycle of vegetation loss and erosion due to firewood use and grazing. Sparsely vegetated land is far more vulnerable to destruction as volcanic eruptions spread thin layers of volcanic ash across the landscape, suffocating remaining vegetation and further exposing soil to wind and water erosion in a process known as *desertification.*

Andy has heard about this process in other places like the Sahara Desert, but was blown away to discover it could happen somewhere as cold and wet as Iceland. Both he and Gabi are a bit perplexed by the strong southerly winds described in the pamphlet in a region dominated by westerly trade winds. They contact their old friend Gayle Snowdon to ask if she can help them better understand what’s going on.

Q: What process does Gayle suggest will best explain why there would be strong southerly winds through Dimmuborgir? (1 mark)

a. Cold, dense, dry air would form over Vatnajökull and rush continually downslope to the north.
b. Air flows more quickly across broad open planes than through valleys where it is channelled.
c. Air flows more quickly parallel to mid-ocean spreading rifts, which are oriented north-south in this region.
d. Warm, low density, vapour-rich air would be lifted up off Vatnajökull causing dry air from Dimmuborgir to rush continually upslope to the south.
e. It is too cold in Iceland for the atmosphere to contain any liquid water, so the entire island is a desert.
f. Precipitation in Iceland is strictly in the form of snow, therefore the desert region forms every summer.

47. The internationally important RAMSAR wetlands of the Lake Mývatn Region also records the changes in the environment with sediments accumulating in the peat bog lake at different rates while incorporating pollen from the floral assemblages present at the time. A core taken from Viðvík has revealed some important facts about the sedimentation rate (Figure 43).

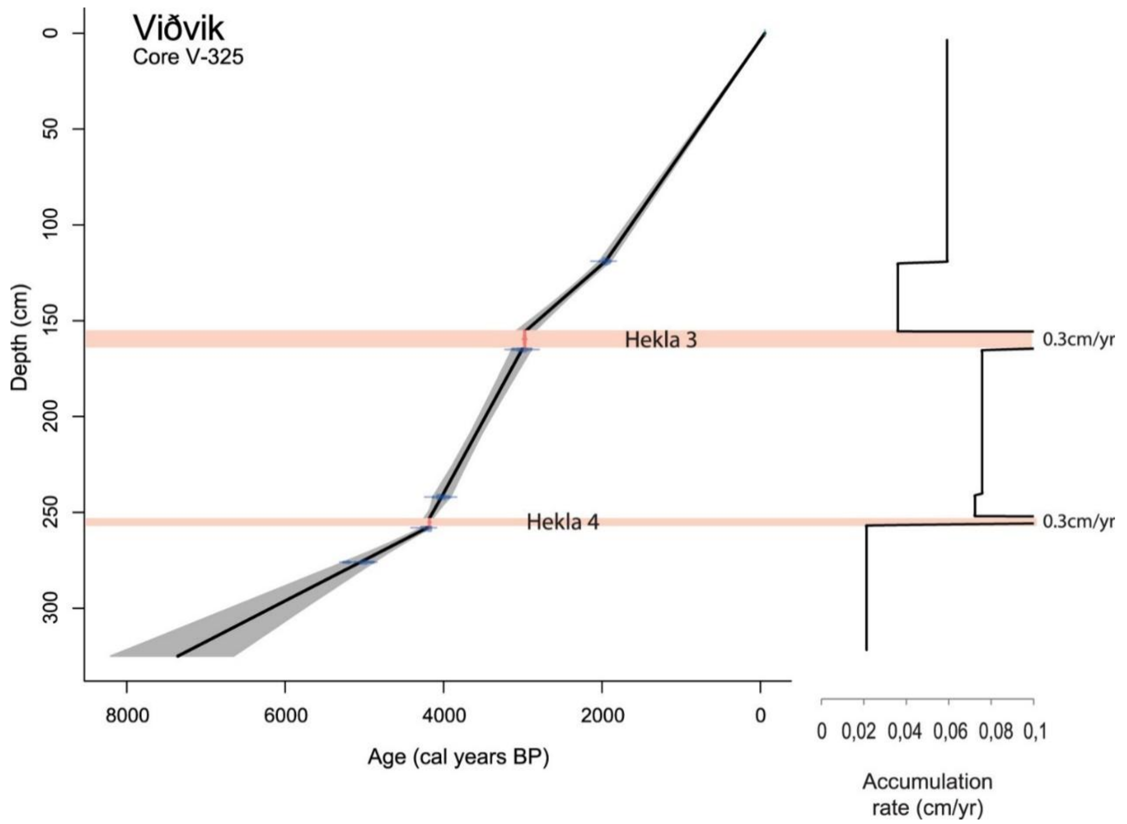


Figure 43: ~8000 year record of sediment accumulation taken from an Icelandic beat bog at Viðvík by coring. Hekla 4 and Hekla 3 are tephra layers deposited by eruptions from the Hekla volcano. These eruptions produced the most distinct tephra layers found in northern Iceland.

Graph courtesy of https://doi.org/10.1080/04353676.2020.1723984

Q: What did Roxanne note about the graph that Gabi shared in her chat (Figure 43)? (1 mark)

Fascinating graph Gabi, I'm glad you shared it. It clearly shows …

a. … the rate of sedimentation decreased after Hekla 4 and decreased after Hekla 3.
b. … the tephra deposition events took place over thousands of years.
c. … the rate of sedimentation increased after Hekla 4 and decreased after Hekla 3.
d. … the tephra events controlled the rate of sedimentation between 3825 BP and 2880 BP.
e. … heat from Hekla 4 improved vegetation growth.
f. … Hekla stopped erupting after 2880 BP.

48. They also share some pollen record data with Gayle and ask her opinion whether the vegetation change was truly caused by human activity or if larger scale natural environmental changes were to blame: The Viðvík core also revealed some important facts about the flora over time (Figure 44).

Figure 44: Pollen percentage diagram plotted versus depth, according to the applied age-depth model used in Figure 43. The dots in the diagram indicate low percentages of pollen.

Information on each plant family:

Apiaceae - herbs and edible root vegetables	*Poaceae - grasses*
Betula - birch trees	*Potamogeton - pond weeds*
Carex - grass-like plants	*Rumex - herbs in buckwheat family*
Ericaceae - heather and heath-like plants	*Salix - willow trees*
Equisetum - horsetail (primitive vascular plant, living fossil)	*Varia - unknown plants*
Lactucea - includes the Lactuca (lettuce) genus	

Image courtesy of https://doi.org/10.1080/04353676.2020.1723984

Q: What did Gayle say when asked if the paleoenvironment was already changing prior to human settlement in the ninth century? (1 mark)

Was the vegetation change and associated desertification truly caused by human activity? Great question!

a. Yes, this interpretation is supported by a reduction in volcanism after settlement.
b. Yes, this interpretation is supported by a significant change in the flora around 2500 BP.
c. Yes, this interpretation is supported by a significant change in the flora around 600 BP.
d. No, this interpretation is refuted by a significant change in the flora around 3000 BP.
e. No, this interpretation is refuted by a reduction in flora, especially grasses (poaceae) over time.
f. There is nothing within this data set that indicates how the paleoenvironment was changing over time.

49. Gabi wonders if the Arrakis Peninsula where the Stone sisters are vacationing was vegetated prior to human settlement. She asks colleagues, Shelly Waters, Wade Beachly and Sandra Shore for their opinions.

Q: What evidence might they find in the geologic record that would indicate a more humid paleoenvironment on Arrakis Peninsula? (1 mark)

a. Shales containing marine microfossils
b. Conglomerates containing well rounded quartz pebbles
c. Deeply weathered basalt dykes cross cutting sandstones
d. Graded sandstones containing fern-like plant fossils in the finer layers
e. Evaporite deposits
f. Glacial till deposits

50. After a quick visit to the surface at Location 2 to see the amazing dune fields of Specerij (Figure 1) and inspect a hydrogen collection facility the trio trekked on to Location 3 in the Harkonnen Range (Figure 1). The highlight of this part of the trip was a visit to the famous limestone caves of the region, including the cave visited not that long ago by Philip and Jeff on a previous expedition.

Their geochronologist colleague, Jiki, saw the wonderful cave speleothem images they posted and reminded them of the discussions they had previously, saying:

One of the most famous caves, Jessica's Cave, was excavated last century by the wealthy fossil fan and philanthropist, Fons Sordkreek. He not only found the remains of extinct animals, but also various layers within the fossil-rich sediments containing datable materials (Table 3; Figure 45).

Unit #	**Dated material**	**Dating method**	**Level within the cave**	**Numerical age**	**Associations**
Unit 1	Quartz sand grains	Optically Stimulated Luminescence	S_1: 500 mm below top surface	23,000 ± 1655 a	Loose sand. Bones of extant rodents, marsupials, reptiles, bats and birds.
Unit 2	Charcoal	Accelerator Mass Spectrometry C-14	S_2: 1,000 mm below top surface S_3: 3,000 mm below top surface	47,500 ± 150 a 57,500 ± 150 a	Consolidated sand and clay. Remains of extinct and extant marsupials plus extant reptiles, bats and birds.
Unit 3	Flowstone	Uranium/Thorium series	S_4: 2,500 mm below top surface	378,350 ± 500 a	Calcite cemented sands and gravel. Remains of extinct marsupials.
Unit 4	Fossils in this unit correlate with other deposits bracketed by lava flows dated between 2.05 ± 0.2 Ma and 3.25 ± 0.2 Ma using Argon-Argon ($^{40}Ar/^{39}Ar$).				Calcite cemented clays, sands and gravel. Remains of extinct marsupials and reptiles.
Unit 5	Volcanic ash minerals	Argon-Argon ($^{40}Ar/^{39}Ar$)	S_5: 4,000 mm below top surface	6.05 ± 0.2 Ma	Calcite cemented sands and gravel with a layer of volcanic ash. Remains of extinct marsupials and reptiles.

Table 3: Data relating to each unit within the cave deposit. a = years before present; Ma = millions of years before present. Flowstone is a calcium carbonate deposit precipitated from water that has percolated through limestone. It accumulates in caves as water drips, trickles and splashes. Flowstone is one of many speleothems formed by this process. Other common speleothems include stalactites and stalagmites.

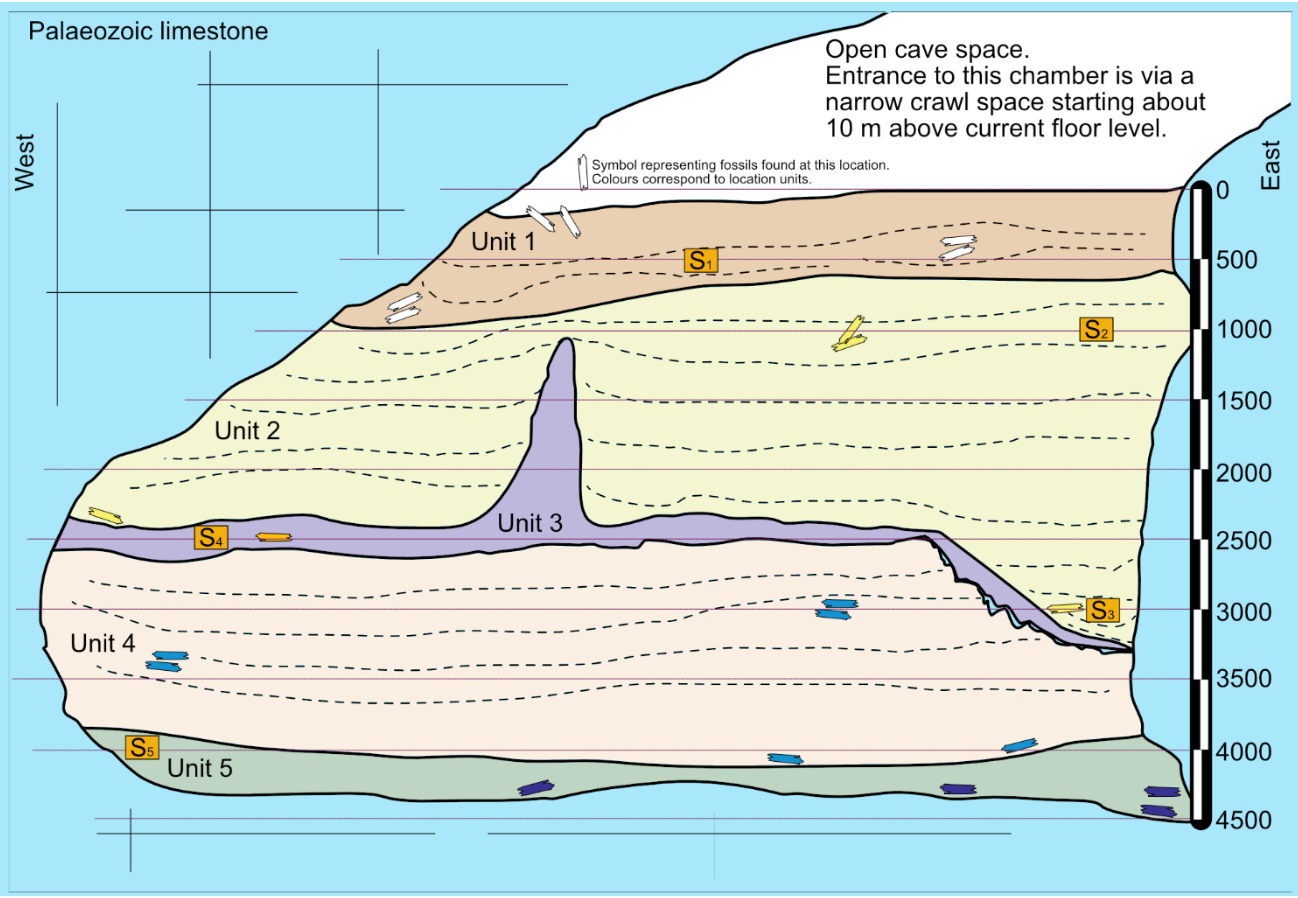


Figure 45: Cross section of cave deposits in Sordkreek's Chamber within Jessica's Cave, looking towards the North showing five distinct documented lithological units. No datable material was found in Unit 4, however, fossils in Unit 4 correlate with others elsewhere associated with basalt lava flows dated at 2.05 ± 0.2 and 3.25 ± 0.2 Ma.

Q: What else did they say? (1 mark)

We know from cave formation rate studies that the limestone caves began forming in the Palaeozoic limestones no later than the early Miocene. However, the cave must have also ....

a. … experienced a very dry period of non-deposition starting around ~380 thousand years ago.
b. … been open to the surface no later than the late Miocene
c. … been open to a surface environment subject to fires during the late Pleistocene
d. … hosted a rich diversity of vertebrates during the late Pleistocene.
e. … been subject to water flowing through it sometime between ~2 million years ago and ~380 thousand years ago.
f. …all of the above.

51. Orson was curious to know why the fossils in Unit 4 were not directly dated using Accelerator Mass Spectrometry (AMS) ^{14}C techniques.

Jiki answered, saying:

For ^{14}C dating to be useful we must have a good quality source of carbon in the deposit which Unit 2 clearly has. While Unit 4 has no charcoal, carbon can be extracted from bone. However, even if carbon could be extracted from the fossils it would be of no use because …

Q: What did Jiki say to explain this? (1 mark)

a. … sand worms only use ^{14}C to build their tissues, including bone, so they give erroneous results.
b. … carbon from Unit 2 would have been dissolved by groundwater and re-precipitated in Unit 4, contaminating any carbon in the bone.
c. … bone contains additional carbon, so the ^{14}C will be diluted by too much ^{12}C.
d. … the bones would have been contaminated with ^{14}N from the calcite cement in the deposit.
e. … the bones would have been contaminated with ^{40}Ar.
f. … the age of the bones is well beyond ten ^{14}C half-lives.

.

52. Jeff is a keen caver but was a bit out of his element (water) exploring the underground landscape within the Devonian limestones. Despite this, he was very happy to visit the caves where he had previously found a nicely preserved placoderm fish. Having mentioned this in the chat, fossil enthusiast Rose replied, saying she found it hard to believe that a fossil like that could be found in a cave.

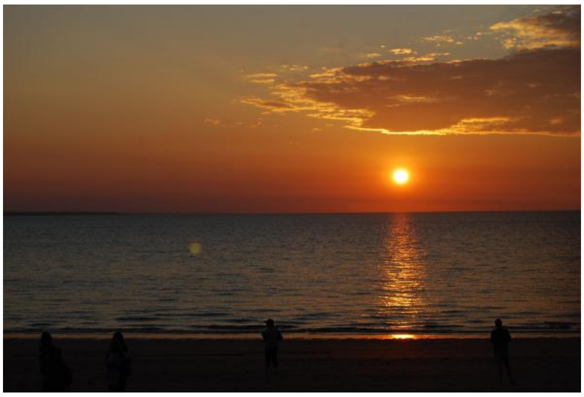
Jeff answered, saying:

I did find it in the cave but…

Q: What did Jeff say in completing his statement? (1 mark)

a. … it could only have found its way into the cave and be buried in the cave sediments after a cyclone pushed a storm surge inland from the Specerij Ocean.
b. … it must have been brought into the cave by a sand trout that was using the cave for shelter after a successful hunt.
c. … it was probably brought into the cave by an unscrupulous tour operator trying to find a new angle to promote their business.
d. … it was preserved in the speleothem of Unit 3 so its bones were easy to spot sticking out of the calcite flowstone.
e. … it was living in a pool on the floor of the cave until the environment started to dry out towards the end of the Pleistocene. When the water ceased flowing into the cave the pool dried out and the fish mummified in the dry mud on the cave floor. That's why it was easy to find.
f. … it was preserved within the wall of the cave, so its bones were easy to spot protruding from the limestone where it had been slowly exposed over time by water dissolving the calcium carbonate.

The trio had a wonderful time caving at Location 3 (Figure 1) but eventually had to move on. They took the high speed train under Arrakis Sound from the Harkonnen Range to Arrakis Peninsula. The landscape of the peninsula did not disappoint in a place where the Specerij Sand Sea meets the Specerij Ocean (Location 4, Figure 1). The sunsets were amazing.



Sunset over the Specerij Ocean, taken from Arrakis Point on Arrakis Peninsula.
Image courtesy of Jeff Gnathostomes.

Jeff was in his element with sand and water everywhere! The local shopping arcade even had fresh fish ice cream.

In the chat he commented that as he beach-combed it was hard to tell where the ocean beach ended and the sand sea began, with the extra complication that the coastal cliffs were comprised mesozoic sandstones, overlain by Pleistocene river sands that sat directly below the Holocene dunes of the sand sea. He shared an image of this location (Figure 46).

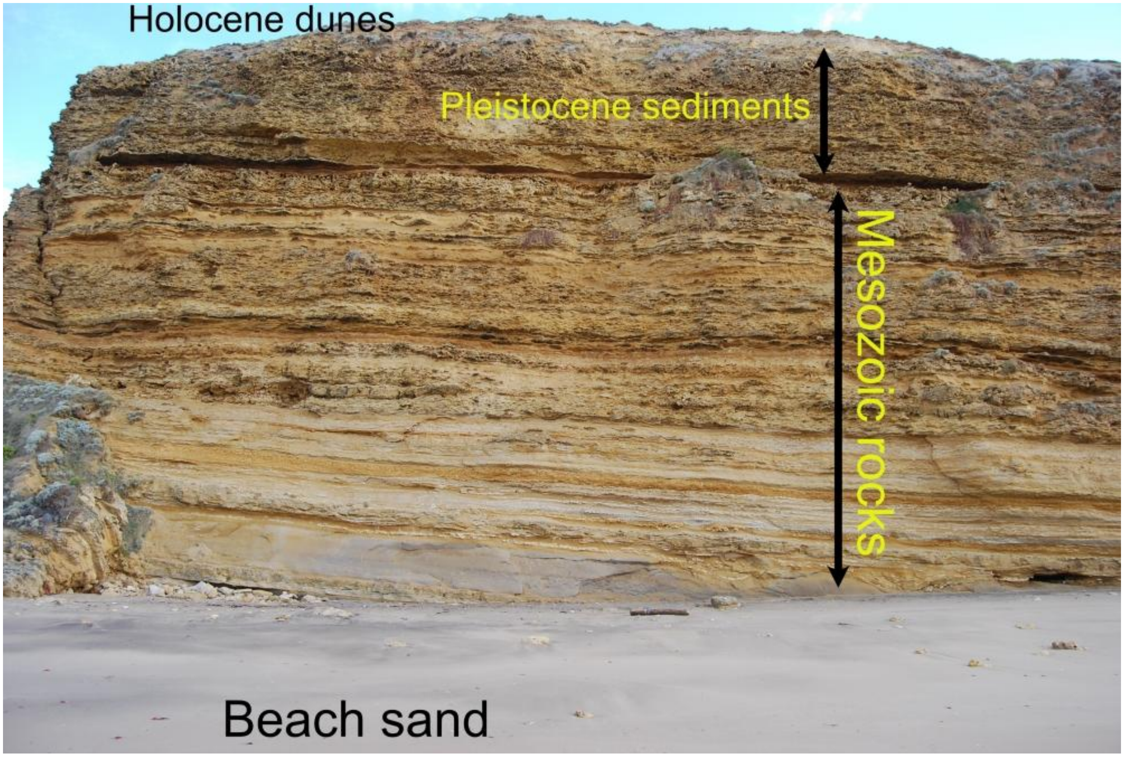


Figure 46: Coastal cliff, Arrakis Peninsula. The beach in the foreground is where Jeff was beach-combing. The material at the very top of the cliff is unconsolidated Holocene dune sands. The cliff face is outcropping Mesozoic sandstones, overlain by consolidated Pleistocene river sands that are almost indistinguishable from the Mesozoic sandstone. The entire cliff face is approximately 15 m high. Image courtesy of Jeff Gnathostomes.

53. Team member Shelly Waters was fascinated with the appearance of the cliff face. She asked Jeff why some layers in the outcrop were sticking out more than others.

Q: What did Jeff say to properly explain this phenomenon? (1 mark)

Some layers are ...

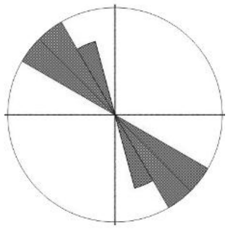
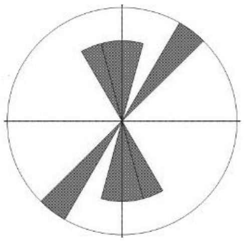
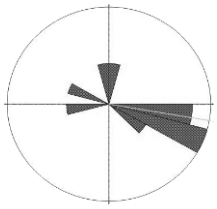
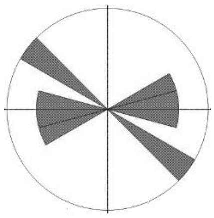
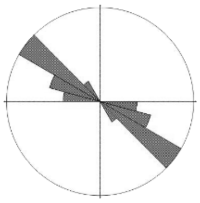
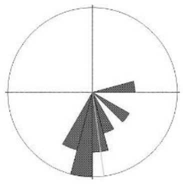
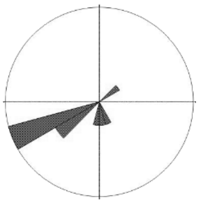
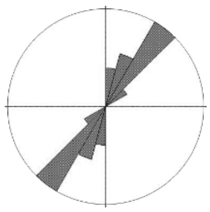
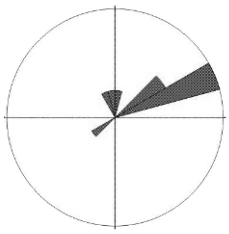
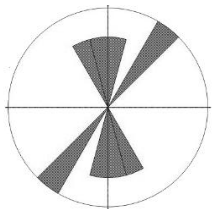
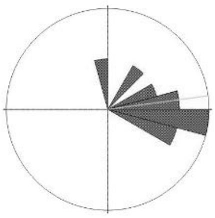
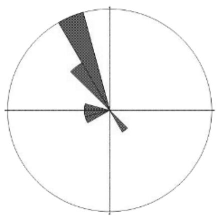
a. …more resistant to erosion than others because they have been cemented together with iron oxides.
b. … less resistant to erosion because they have been cemented together with silica.
c. … more resistant to erosion because they have been stuck together by salt crystals forming as sea spray evaporates.
d. … less resistant to erosion because the sand grains are dominantly quartz.
e. … less resistant to erosion because the sand grains are porous.
f. … more resistant to erosion because they have hosted sand trout larvae.

54. Shelly was also amazed that Jeff could see a difference between the Mesozoic sedimentary rocks and the Pleistocene sediments in the cliff face (Figure 46). She asked Jeff how he could tell them apart.

Before he could answer, team member Sandra Shore posted a comment in the chat:

I led the team that mapped that area back in the day. To be fair they do look the same from the photographer's point of view. However, the difference is in the detail only visible up close. Apart from the fact that the Pleistocene river system reworked the Mesozoic sediments, they are very different. At this location the Mesozoic sediments were deposited in a marine environment dominated by tidal currents, whereas the Pleistocene sands are river deposits. In the absence of marine or non-marine fossils, the best evidence is to be found in palaeocurrent data for each suite of sediments.

Q: Which pair of palaeocurrent rose diagrams did Sandra share online to make her point? (1 mark)

	Mesozoic palaeocurrents	*Pleistocene palaeocurrents*
a.		
b.		
c.		
d.		
e.		
f.		

55. After a wonderful time on the beach at Arrakis Peninsula the trio drove a hydrogen powered vehicle (of course) along the coast to Location 5 (Figure 1).

Camping at this location allowed them to explore more of the coastal cliffs, including where Philip had found dinosaur footprints in the coastal rock platforms during a previous expedition. However, after a day of exploring and finding nothing they decide to head inland the next morning to find out more about the sand sea between their camp site and Mos Woestijn (Location 1, Figure 1).

They had only travelled a bit over a kilometre when they started to encounter some very strange looking landforms: streamlined hills carved from outcrops of the Pleistocene and Mesozoic bedrocks. Jeff's handy drone camera revealed they are at least three times longer than they are wide, often in parallel groups with a gap between each one. Jeff shared a picture on his socials (Figure 47).

Figure 47: Yardangs. Image source: https://tinyurl.com/5n7z48db

Ariel Windlass responded with: *WOW! They are the best yardangs I have seen in a while* 🙃

Yar-what? Queried Jeff.

Ariel responded with: *YARDANGS! Landforms generated by the action of wind. They have a very characteristic shape that many say resembles the hull of a boat.*

Jeff thought they looked more like sand trout. Ariel said that to be fair there are at least 4 general morphologies:

- Mesa-like (flat tops)
- Long-ridges
- Saw-toothed
- Whaleback (so yes, maybe sand trout)

… and numerous sub-types. However, they are all wind-carved ridges. They mostly occur in hyper-arid regions, so it is no surprise they are found in the Specerij Sand Sea.

Q: What did Ariel say regarding what all yardangs have in common? (1 mark)

Apart from occurring in hyper-arid regions, it is thought they can only form if the rocks have pre-existing weaknesses or channels that initiate trough formation between the yardangs. The incipient troughs then focus the wind into the troughs, continuing the process. This is known as …

a. … negative feedback.
b. … positive feedback.
c. … negative erosion.
d. … positive erosion.
e. … negative deposition.
f. … positive deposition.

56. Philip, currently on Mars studying sand dunes, posted a picture to the chat (Figure 48a) noting that he is currently camped in this region.

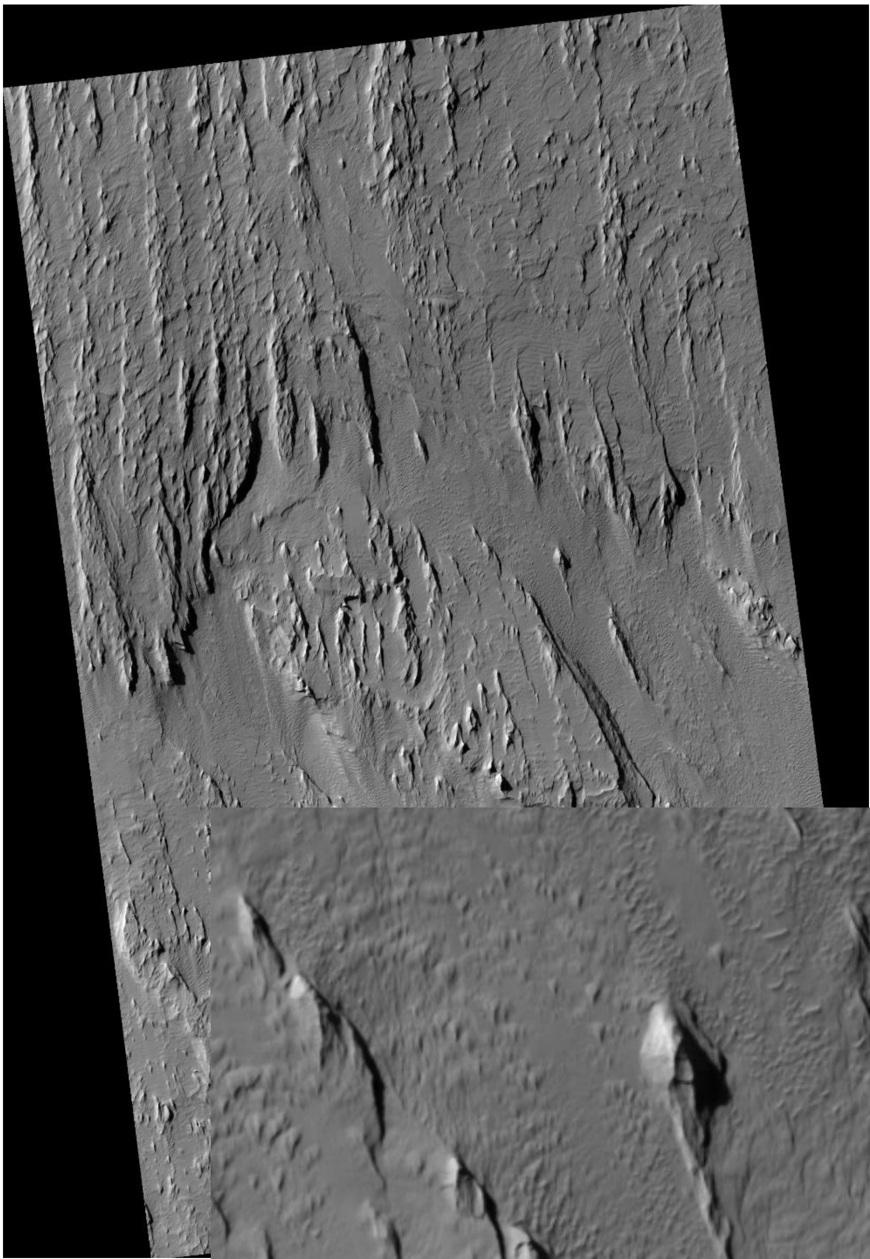


Figure 48a: Yardangs on Mars.The image, taken by satellite at an altitude of 266 km, is ~5 km wide. Martian north is up. Image courtesy of NASA/JPL-Caltech/UArizona

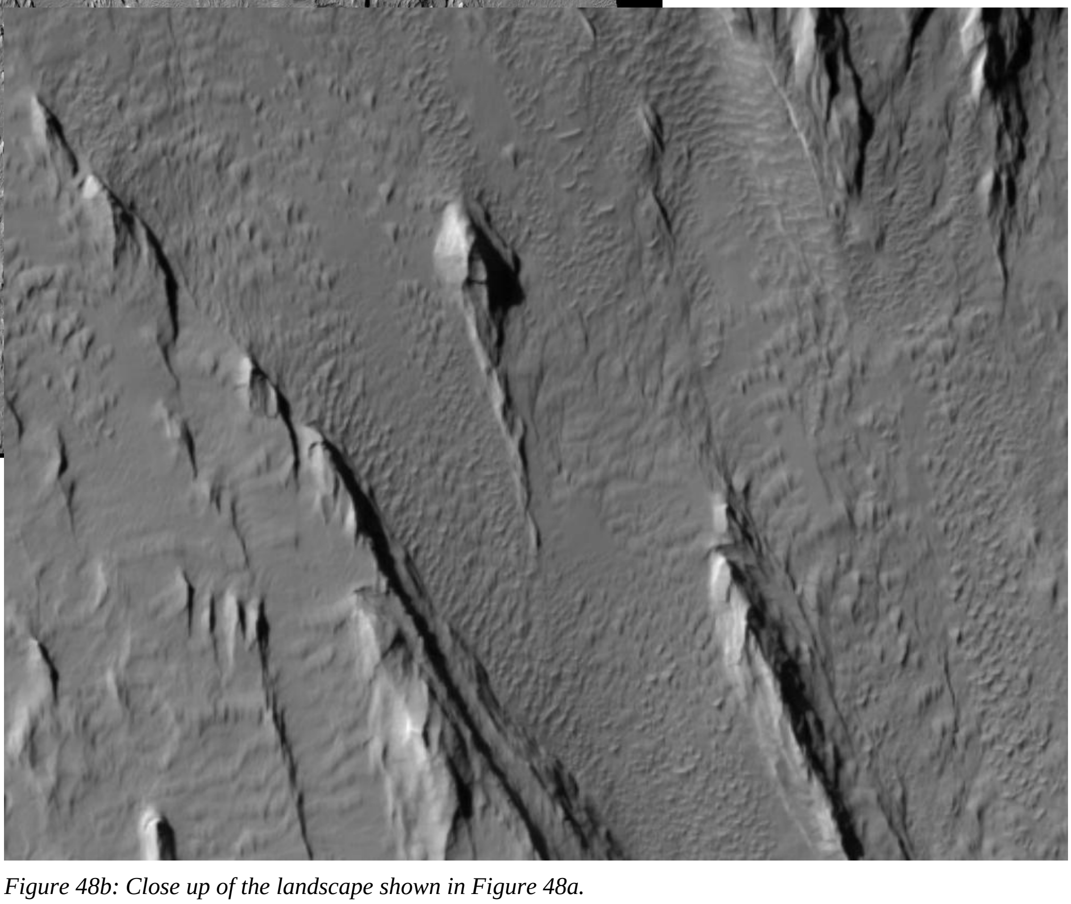


Figure 48b: Close up of the landscape shown in Figure 48a.

Ariel Windlass responded with: *That's impressive!* She also shared an image:

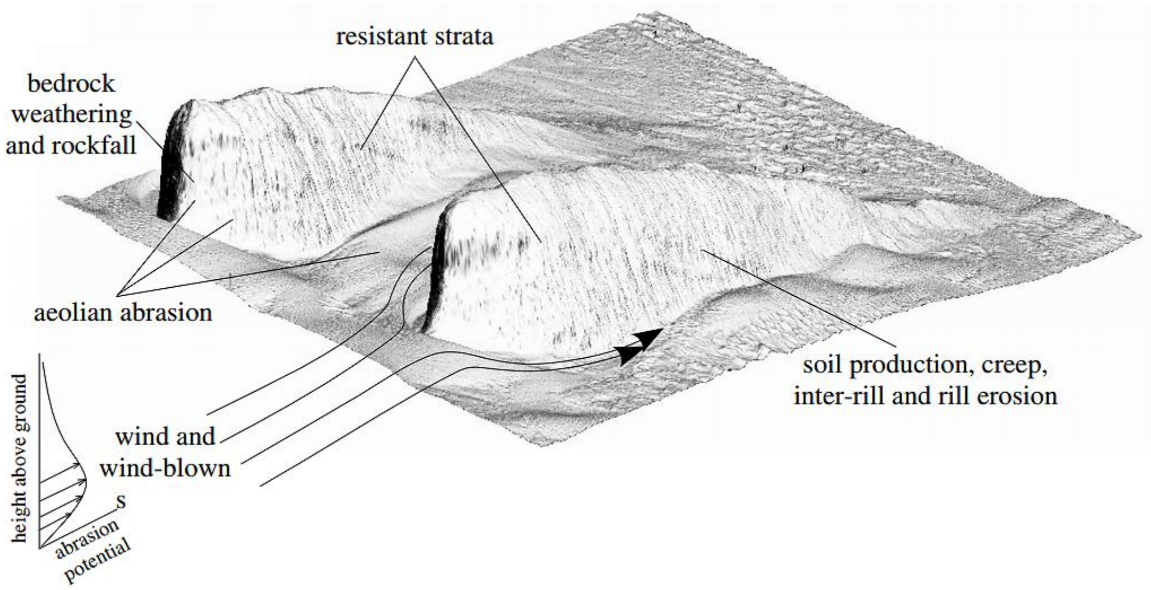


Figure 49: Diagram illustrating the principal processes controlling yardang development.
Courtesy of Jon D. Pelletier et al, 2018

Q: What did Ariel say about Mars, based on the satellite image? (1 mark)

a. The wind in your region of Mars must be very consistently blowing from the south-southwest.
b. The wind in your region of Mars must be very consistently blowing from the north-north east
c. The wind in your region of Mars must be very consistently blowing from the north-northwest.
d. The wind in your region of Mars must be very consistently blowing from the south-southeast.
e. Mars must be a windy place all the time.
f. Mars must have had a lot of flowing water before it dried out and became windy.

57. In addition to her diagram (Figure 49 Ariel also shared her research methodology, studying sediment flux around yardangs. Her collection apparatus consists of plastic containers secured to a post with sample tubes extending into the air flow (Figure 50). She said they are called MWAC towers but the reason for this name is lost in the sands of time!

Figure 50: An MWAC tower. Courtesy of Jon D. Pelletier et al, 2018.

She explained that her team placed the 8 towers around yardangs in two locations with relatively isolated single pairs of yardangs:

- A location where loose sand sheets occur in the troughs between yardangs – called the blue site.
- A location where there is no loose sand between the yardangs, and 100 m upwind of the yardangs - called the brown site.

The 8 locations and the data are portrayed schematically in Figure 51.

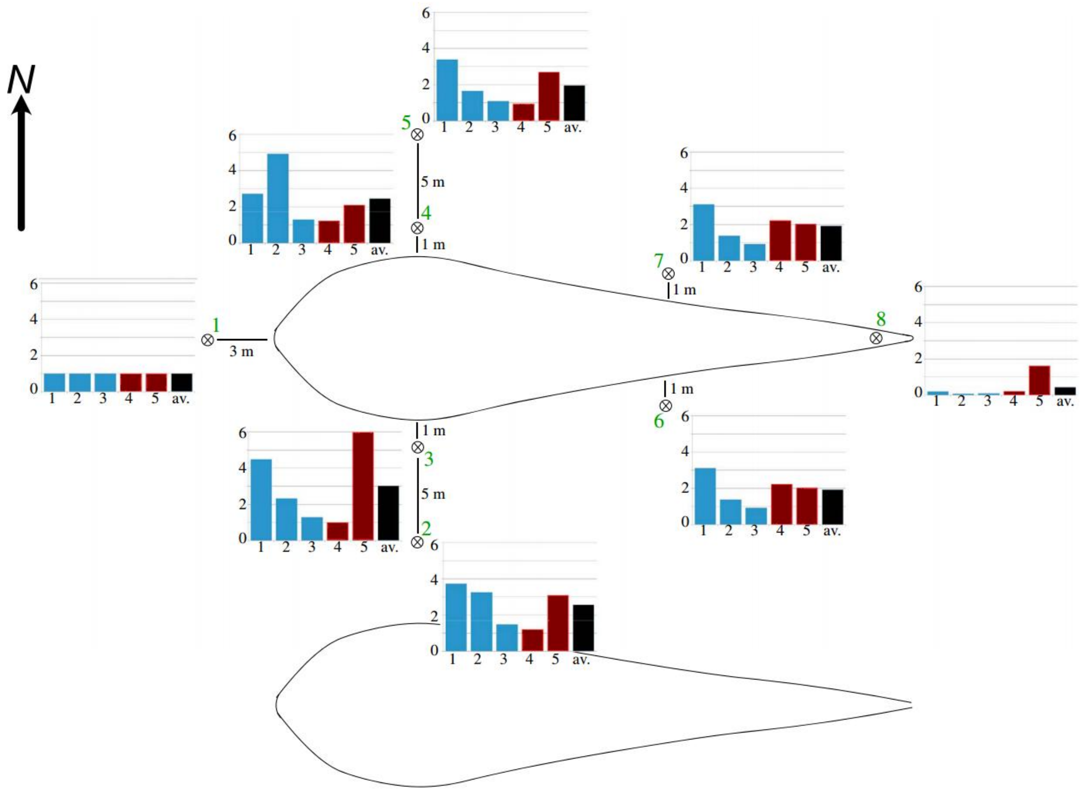


Figure 51: Diagram illustrating the relative eolian sediment flux 21 cm above the ground as a function of time (5 time intervals) and 8 positions around nearby yardangs. Each graph shows the eolian sediment flux (relative to the windward position) at each of five measurement intervals, plus the average of the five time intervals. Blue bars correspond to the blue site. Brown bars correspond to the brown site. Black bars are averages for the 5 time intervals. Data has been normalised to the location-1 trap, hence all intervals show a value of 1 at location 1. The location of each numbered tower is marked by ⊗ Courtesy of Jon D. Pelletier et al, 2018.

Q: What did Philp correctly observe about this data? (1 mark)

a. The average flux at location 8 explains why there is no loose sand upwind of brown site yardangs.
b. The average flux is highest for locations furthest from the yardangs.
c. The fluxes at location 8 indicate erosion of the yardangs has been caused by some agent other than wind-blown sand.
d. The fluxes at locations 3, 4, 6 and 7 indicate yardang erosion occurred during the 5 time intervals of the study.
e. The fluxes at locations 2 and 5 indicate the troughs are being eroded more than the yardangs.
f. The fluxes at location 1 indicate yardang erosion is caused by sand trout migrating along the troughs, not wind-blown sand.

After spending a wonderful night camped under the stars, Roxanne, Gemma and Jeff caught the underground superfast train from Location 5 to Location 6 (Figure 1) to explore the wonders of the Sardaukar Range. Their friend, Lois Underhill, was puzzled. After looking at the map (Figure 1) and cross-section (Figure 10) she wanted to know why they were going to the Sardaukar Range when it just looked like a mirror image of the Harkonnen Range.

Roxanne explained that while the sedimentary sequence was basin wide, the lateral variations of the depositional environment, combined with the structural history of the local area and regional differences in weather and climate, meant that the Sardaukar Range had many unique vistas and geoscapes on offer. She was especially excited to visit the northern margin of Franklin Fields (Figure 1) to explore some Proterozoic rocks after having visited so many Palaeozoic ones so far.

58. When they first headed out into the field, just minutes after they checked into their accommodation, an amazing outcrop greeted them. Roxanne quickly snapped a picture and posted to the chat and @Lois (Figure 52), saying: *Check this out. Nothing like this at location 3 in the Harkonnen Range!*

Figure 52: Amazing cross-bedded sandstone outcropping in the Sardauker Range. Image courtesy of Roxanne Stone.

Lois was amazed at the scale of the outcrop. *Wow. How tall are those trees?* she asked.

Our guidebook says they are a rare local species that are hundreds of years old and are about 20 m tall, replied Roxanne, adding that she estimated the field of view was ~300 m wide.

Ariel Windlass joined the conversation, adding another image to the chat (Figure 53).

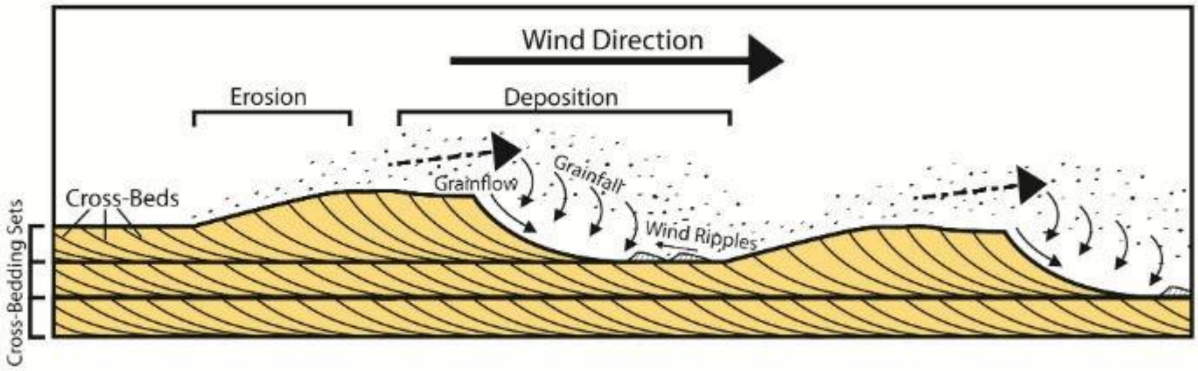


Figure 53: Formation of aeolian cross-bedding.
Image courtesy of US National Parks Service.

Q: What did Ariel accurately add about dunes that formed these cross-beds? (1 mark)

The dunes are huge. They must have had a minimum height of …

a. …5 m
b. …25 m
c. …50 m
d. …75 m
e. …100 m
f. …150 m

59. After spending hours walking through massive sandstone canyons in awe of the Mesozoic outcrops, they emerged into another kind of landscape on the northern margin of Franklin Fields (Figure 1). Here the Atreides Formation, part of the Proterozoic sequence that overlies the Archean basement rocks, outcrops in spectacular fashion. It includes a wide range of sedimentary and volcanic rocks and is up to 3 km thick. The sedimentary rocks include clast and matrix-supported conglomerate, feldspathic quartz sandstone and pebbly sandstone, and slaty shales. The volcanic rocks include felsic and mafic volcaniclastic deposits, basaltic flows and local pillow lava. Dolerite and layered mafic sills locally form a significant part of the stratigraphy.

Roxanne is very excited to see such diverse geology in such a small area. The non-volcanic suite represents alluvial fan systems, braided river systems, lake environments, deltaic environments and shorelines.

Their National Park Guide, Jade Montane, was curious to know which of the commonly outcropping rocks were typical of each of these very distinct environments.

Roxanne and Gemma drew 2 columns on the sandy floor of a dry creek bed next to a deep water hole. In the first column they put the environments of deposition. In the second column they put the names of the common rock types and challenged Jade to connect them with sticks they were gathering for the evening's camp fire.

Q: Use an arrow to connect the deposit name to the description (1 mark)

Lake deposits		Medium to very coarse grained quartz-rich sandstone and siltstone with parallel-stratification and very low angle planar cross-stratification. Shallow scours, and straight-crested symmetrical and asymmetrical ripples with bimodal and some unimodal palaeocurrents.
Delta deposits		Siltstone and mudstones with ripples, horizontal laminations with some beds fine upwards to a muddy top.
Alluvial fan		Fine to medium to coarse-grained quartzo-feldspathic sandstone. Stacked sets of medium-scale trough cross-bedding preserve fan-shaped palaeocurrent rose plus symmetrical and asymmetrical ripples.
Braided river		Pebbly sandstone showing parallel stratification and low-angle scour surfaces. Low variability in palaeocurrent directions..
Shoreline		Lenticular pebble and cobble conglomerate interbedded with scoured and trough cross-stratified sandstone.

60. Jade was happy she understood the sedimentary rocks so well but was more dubious about her knowledge of igneous rocks. Roxanne and Gemma drew another 2 columns. In the first column they put rock types. In the second column they placed descriptions (and real rocks) but also showed her photographs using their holoprojectors.

Q: Use an arrow to connect the rock type to the description (1 mark)

Basalt lava flow		Fine-grained, dark grey to black rock; contains pockets of gas bubbles and polygonal joints
Mafic sill		Stacks of oblate parcels of medium to fine-grained dark grey rock; crystal size increases toward centres; edges are glassy/bubbly
Felsic volcaniclastic		Lapili to bomb-sized fragments (sometimes found welded together) of fine-grained black rocks containing abundant mafic minerals
Mafic volcaniclastic		Welded matrix of fine-grained angular felsic crystals and lithic fragments supporting mixed fragments of other rock types
Pillow basalt		Coarse-grained, dense, black rock, no bubbles; contacts above and below show fine-grained/glassy chilled margins

And just like that, their sojourn in Specerij was over. Locations 7 and 8 will have to wait until next time. At the end of a field trip, as tradition demanded, they played their favourite True / False game with each other around the campfire. See if you can match them as they challenged each other with quirky truths and false facts. Can you do as well as them in picking fact from fiction?

Circle the correct answer

61. **True or False?** Volcanic glass is a crystalline solid.

    True or False (0.25 Mark)

62. **True or False?** If you are trekking over a foliated rock outcrop, composed of alternating light and dark coloured bands of minerals, it is a gneiss day for a walk and not a day slated for a nap.

    True or False (0.25 Mark)

63. **True or False?** During a Full Moon, the Moon rises at sunset and sets at midnight.

    True or False (0.25 Mark)

64. **True or False?** Io is a volcanically active asteroid.

    True or False (0.25 Mark)

65. **True or False?** All marine fossils found in limestone are composed of calcium carbonate.

    True or False (0.25 Mark)

66. **True or False?** The Australian mainland has mountains that were once hotspot volcanoes in the Neogene.

    True or False (0.25 Mark)

67. **True or False?** Shale and slate are two words for the same sedimentary rock.

    True or False (0.25 Mark)

68. **True or False?** There is a mid-ocean ridge between Australia and Antarctica.

    True or False (0.25 Mark)

69. **True or False?** There is an active subduction zone between Australia and the North Island of New Zealand.

    True or False (0.25 Mark)

70. **True or False?** Amphibole minerals can only be found in mafic and felsic igneous rocks.

True or False (0.25 Mark)

71. **True or False?** The end of the Mesozoic era, 66 million years ago, is marked by a mass extinction event caused by a massive solar storm.

True or False (0.25 Mark)

72. **True or False?** Limestone caves are the result of water with a pH slightly greater than 7 dissolving calcium carbonate minerals.

True or False (0.25 Mark)

73. **True or False?** Conglomerate is a sedimentary rock with same range of grain sizes as the sedimentary rock called breccia.

True or False (0.25 Mark)

74. **True or False?** A nonconformity is the name given to the eroded surface of an igneous or metamorphic rock that is overlain by sedimentary rocks.

True or False (0.25 Mark)

75. **True or False?** Iceland is formed by a hotspot (mantle plume) rising beneath a mid-ocean ridge.

True or False (0.25 Mark)

76. **True or False?** A quartz crystal can scratch another quartz crystal.

True or False (0.25 Mark)

77. **True or False?** Coal formation starts with the accumulation of organic matter, mostly plants, in swampy environments.

True or False (0.25 Mark)

78. **True or False?** White mica (muscovite) and black mice (biotite) both have one perfect cleavage.

True or False (0.25 Mark)

79. **True or False?** Titan, the largest moon of Saturn, has lakes of liquid methane on its surface.

True or False (0.25 Mark)

80. **True or False?** Jeff will find fish-flavoured ice cream to enjoy, no matter where he is.

True or False (0.25 Mark)

As the Moon rose on Earth, they decided to call it a night and bid farewell to their far-flung friends until next time.