School ID

2023 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 2023 are not eligible to attend the 2024 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:

2023 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 – 11.
- All answers should be marked on this paper.
- Circle the correct answer in Multiple Choice and True/False questions.

MARKS

Multiple choice questions are each worth one (1) unless otherwise indicated.

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

Total marks for the paper: 66 marks

DATA & DEFINITIONS

Material supplied:

Location and Character name disclaimer

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

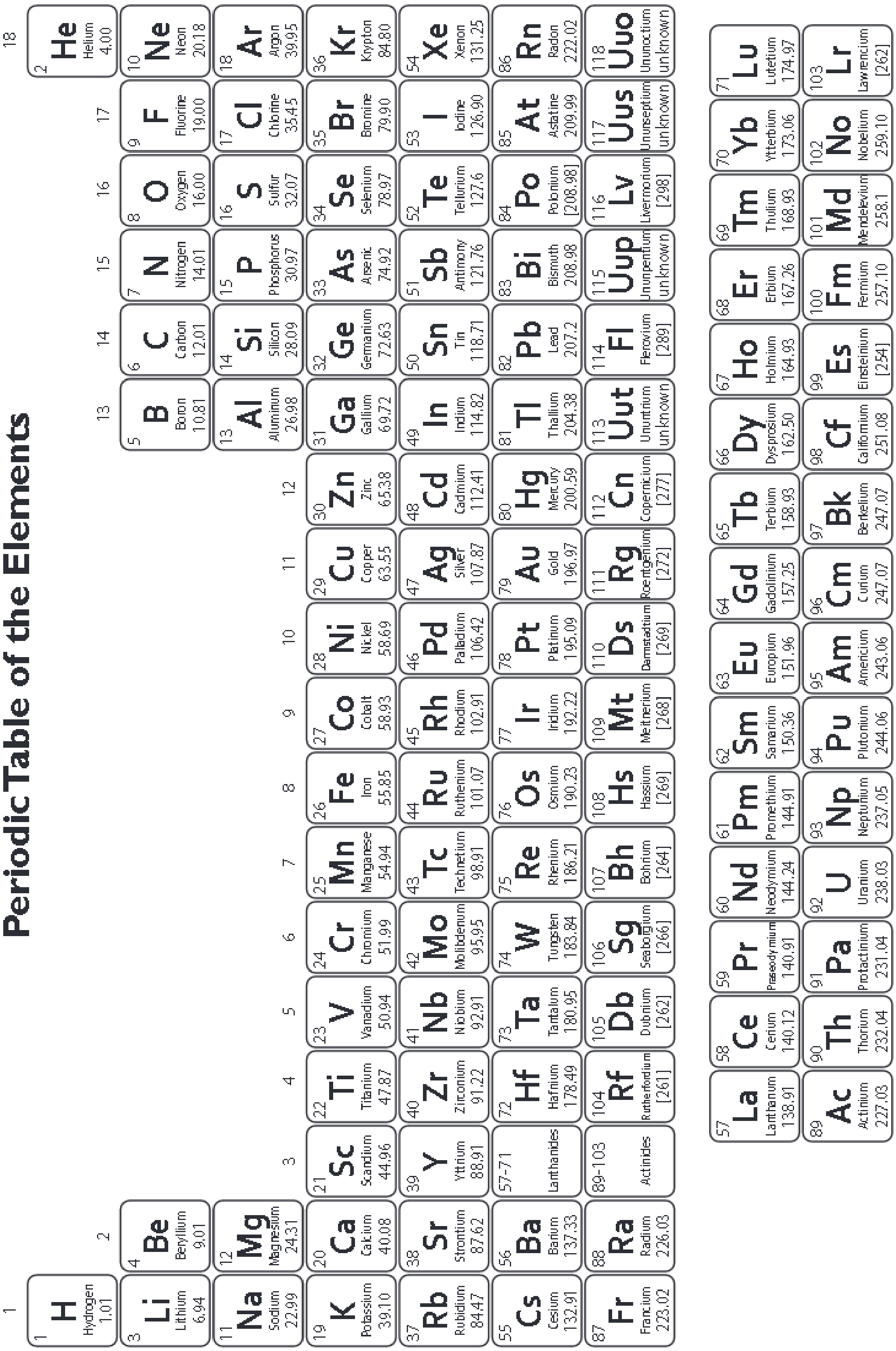
Locations on Earth, and the features they possess, are fictional unless otherwise stated (including those based on actual geography). Locations on other planets are real.

Units and conversions

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

Physical constants

Constant	Symbol	Value
Speed of light	c	299,792,458 m/s effectively 3×10^8 m/s
Lightyear (distance)	ly	1 ly is approx. 9.46×10^{12} km
Parsec (distance)	pc	1 pc is approx. 3.26 lightyears
Universal gravitational constant	G	6.67×10^{-11} Nm^2kg^{-2}
Earth's gravitational acceleration	g	9.8 ms^{-2}
Earth mass	$M_\oplus$	5.98×10^{24} kg
Earth radius	$R_\oplus$	6.37×10^6 m
$g_{planet} = G \times M_{planet} / R^2_{planet}$		

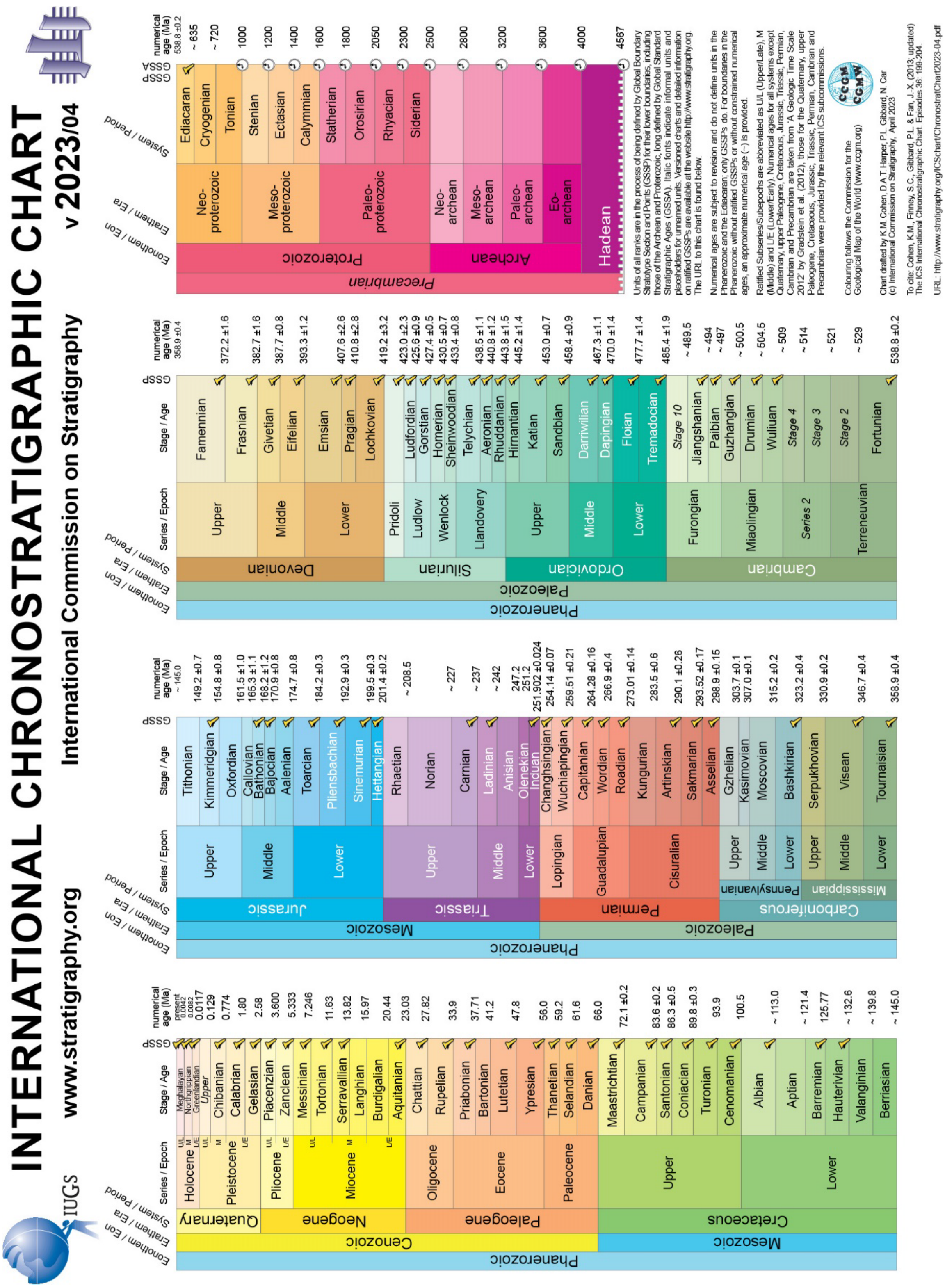


Periodic Table of the Elements

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

	MERCURY	VENUS	EARTH	MARS	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Mass (10^{24}kg)	0.330	4.87	5.97	0.642	1898	568	86.8	102	0.0130
Diameter (km)	4879	12,104	12,756	6792	142,984	120,536	51,118	49,528	2376
Density (kg/m^3)	5429	5243	5514	3934	1326	687	1270	1638	1850
Gravity (m/s^2)	3.7	8.9	9.8	3.7	23.1	9.0	8.7	11.0	0.7
Escape Velocity (km/s)	4.3	10.4	11.2	5.0	59.5	35.5	21.3	23.5	1.3
Rotation Period (hours)	1407.6	-5832.5	23.9	24.6	9.9	10.7	-17.2	16.1	-153.3
Length of Day (hours)	4222.6	2802.0	24.0	24.7	9.9	10.7	17.2	16.1	153.3
Distance from Sun (10^6 km)	57.9	108.2	149.6	228.0	778.5	1432.0	2867.0	4515.0	5906.4
Perihelion (10^6 km)	46.0	107.5	147.1	206.7	740.6	1357.6	2732.7	4471.1	4436.8
Aphelion (10^6 km)	69.8	108.9	152.1	249.3	816.4	1506.5	3001.4	4558.9	7375.9
Orbital Period (days)	88.0	224.7	365.2	687.0	4331	10,747	30,589	59,800	90,560
Orbital Velocity (km/s)	47.4	35.0	29.8	24.1	13.1	9.7	6.8	5.4	4.7
Orbital Inclination (degrees)	7.0	3.4	0.0 the ecliptic	1.8	1.3	2.5	0.8	1.8	17.2
Orbital Eccentricity	0.206	0.007	0.017	0.094	0.049	0.052	0.047	0.010	0.244
Obliquity to Orbit (degrees)	0.034	177.4	23.4	25.2	3.1	26.7	97.8	28.3	122.5
Mean Temperature (C)	167	464	15	-65	-110	-140	-195	-200	-225
Surface Pressure (bars)	0	92	1	0.01	?	?	?	?	0.00001
Number of Moons	0	0	1	2	92	83	27	14	5
Ring System?	No	No	No	No	Yes	Yes	Yes	Yes	No
Global Magnetic Field?	Yes	No	Yes	No	Yes	Yes	Yes	Yes	?

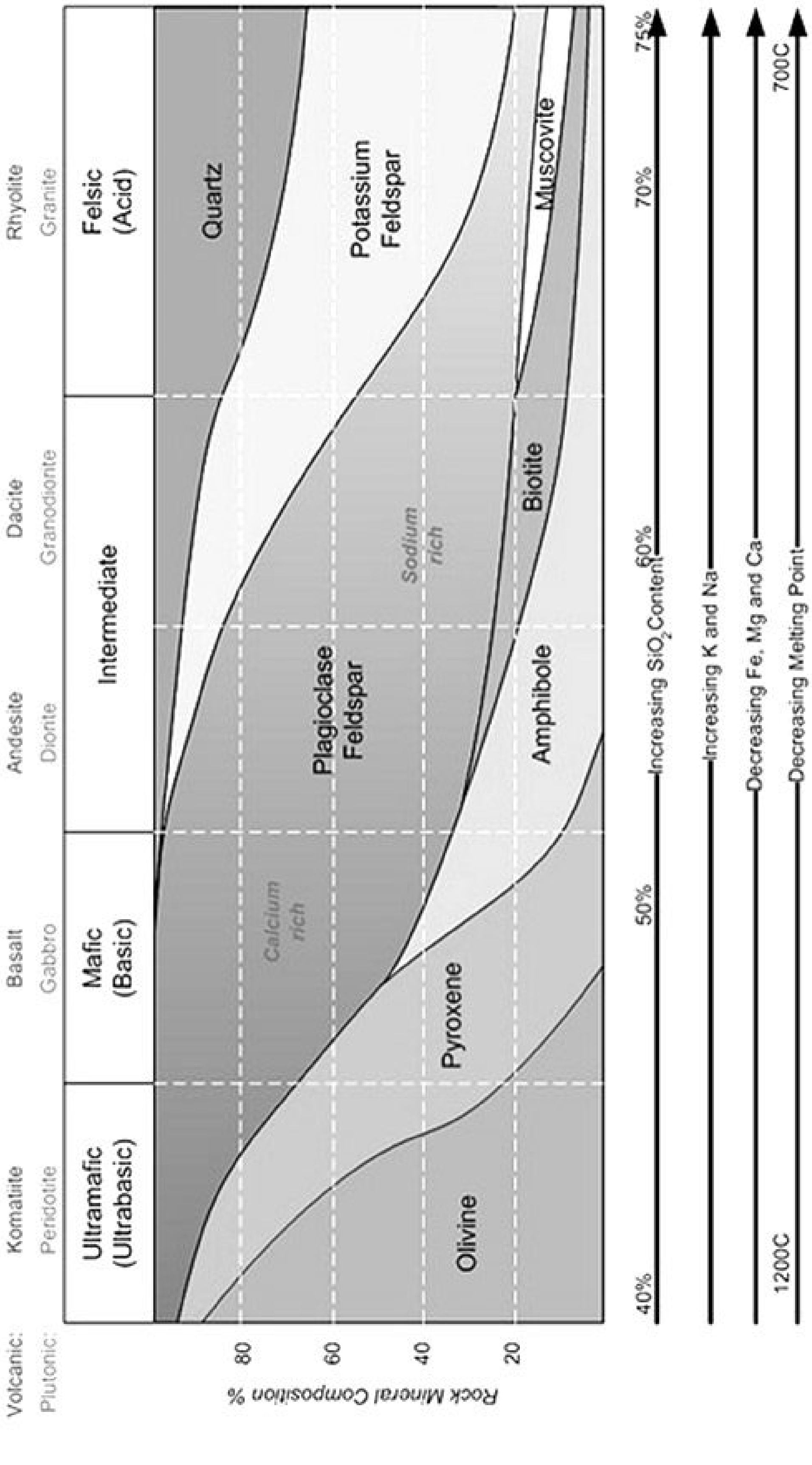
Useful planetary data



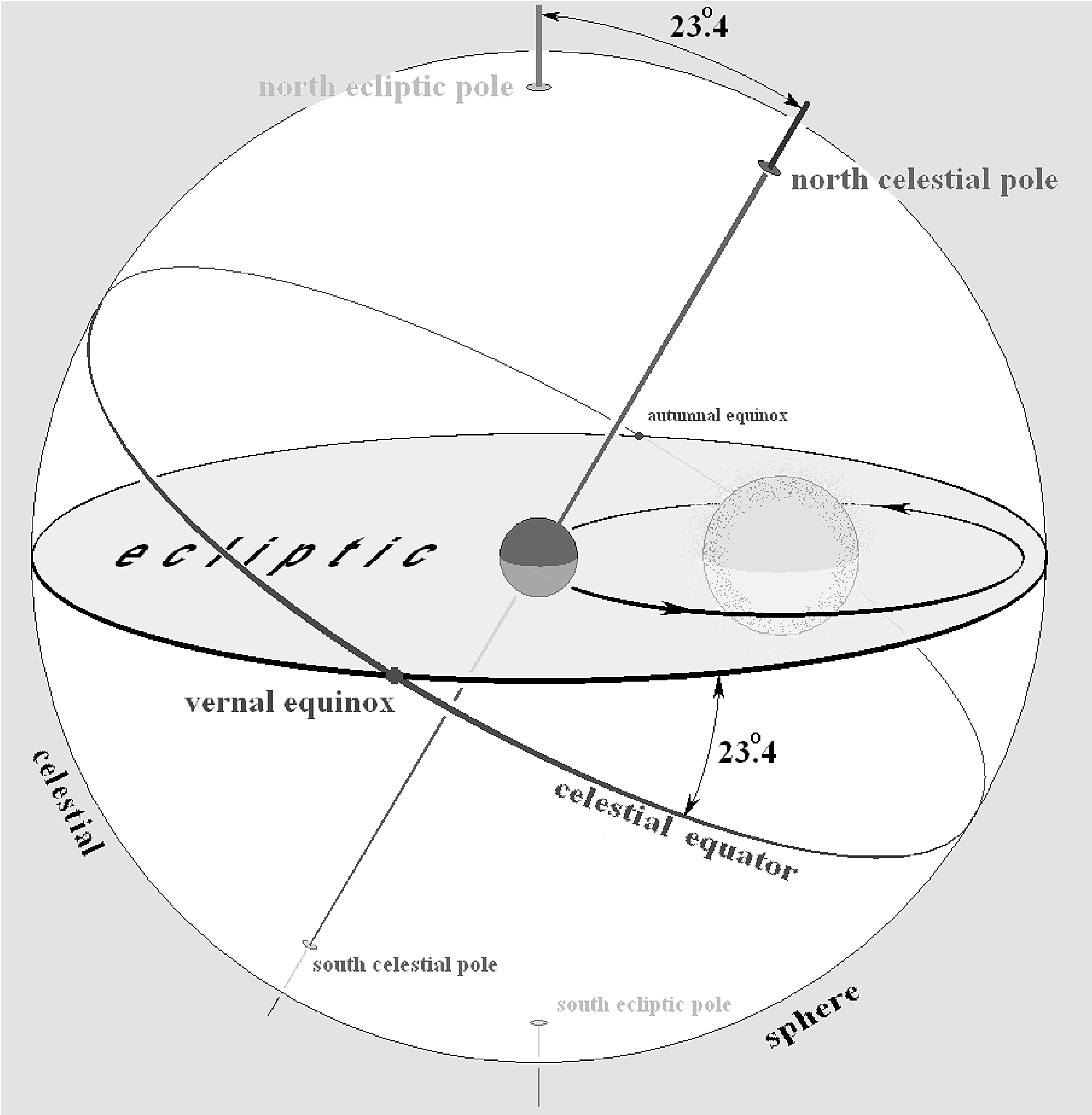
International Chronostratigraphic Chart 2023/04 courtesy of

http://www.stratigraphy.org/index.php/ics-chart-timescale

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

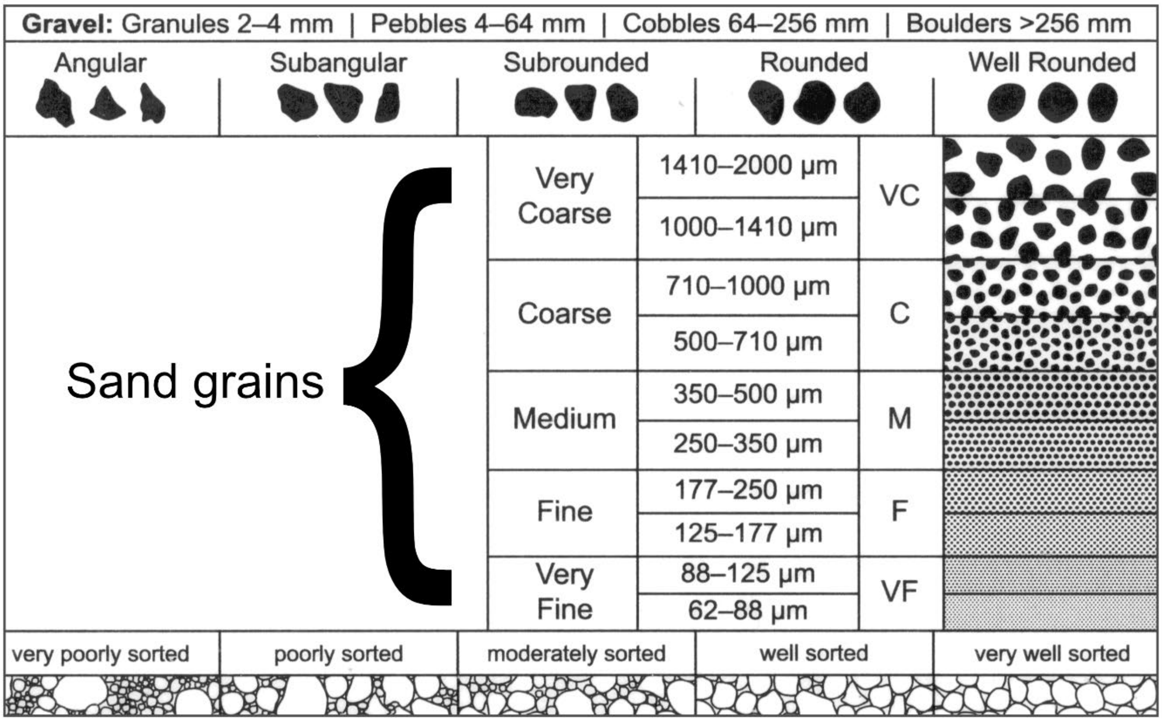


Igneous rock classification chart

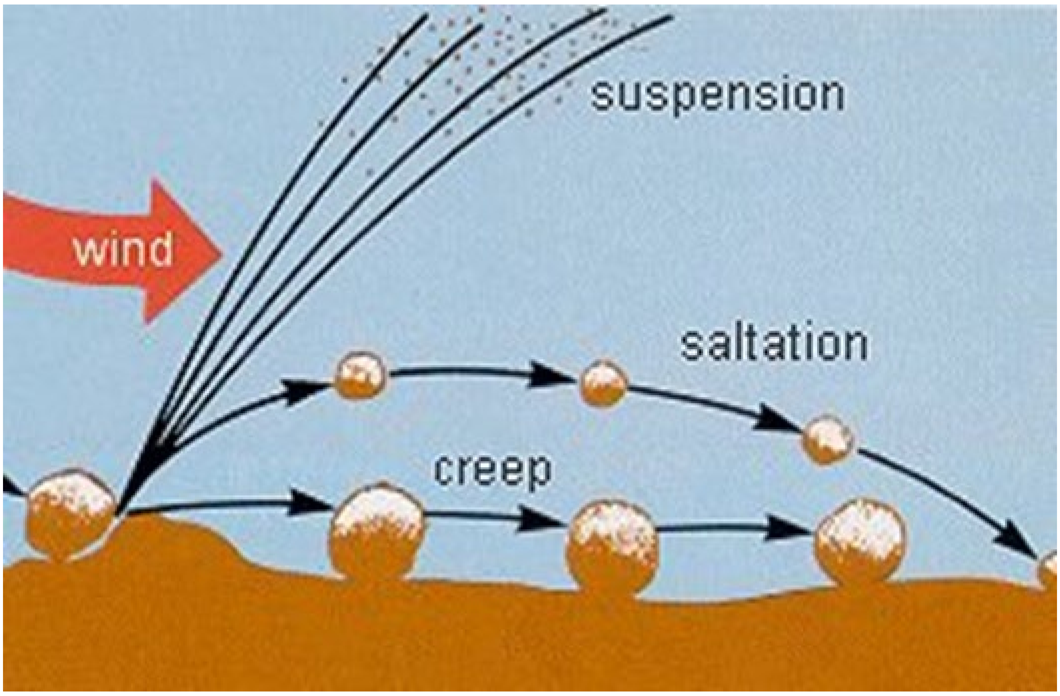


Schematic representation of Earth's ecliptic plane.

Image sourced from https://commons.wikimedia.org/wiki/File:Earths_orbit_and_ecliptic.PNG



Grainsize chart, courtesy of the Geological Survey of NSW

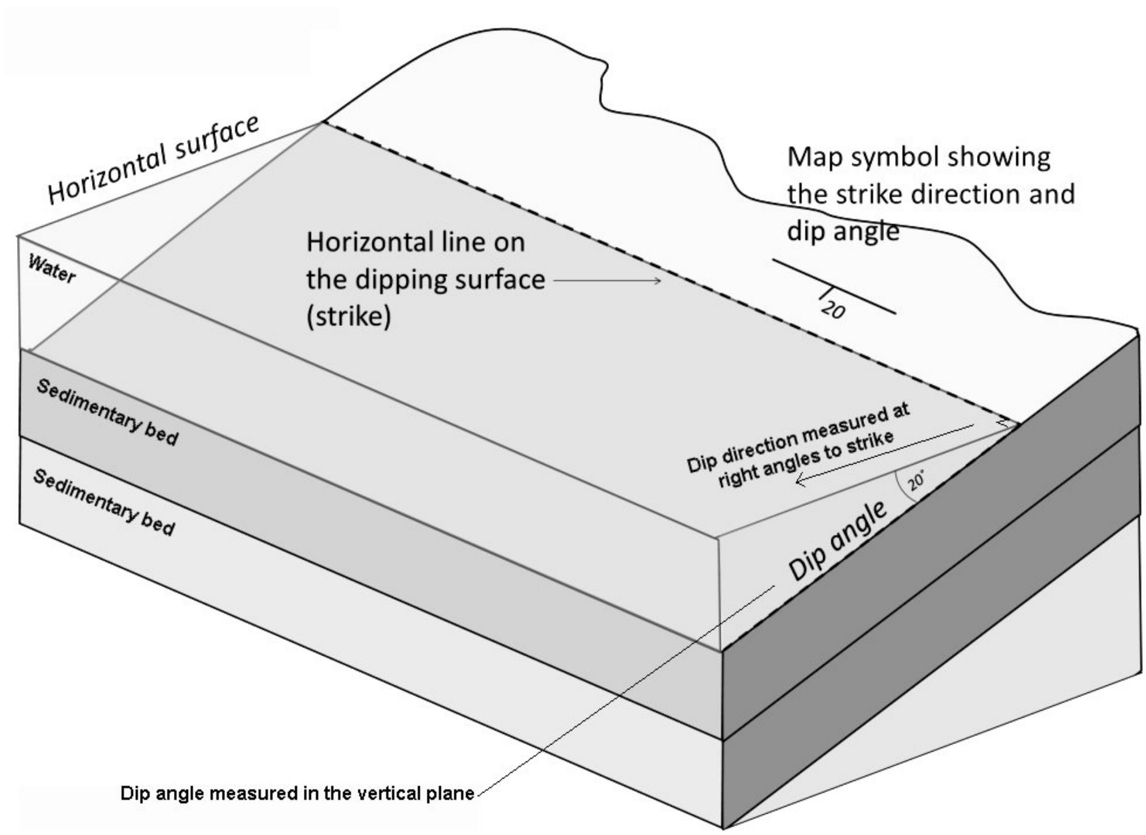


Movement of sand by fluids. Sediments move, driven by fluid motion, by being pushed along or by rolling along the ground (creep), bouncing from one spot on the ground to the next (saltation) or by suspension in the fluid without touching the ground. The transport mode for any given grainsize will vary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

Definition of Dip and Strike

Strike – the trend of a horizontal line contained in the surface of a planar structure such as a sedimentary bed, fault plane or planar intrusive body.

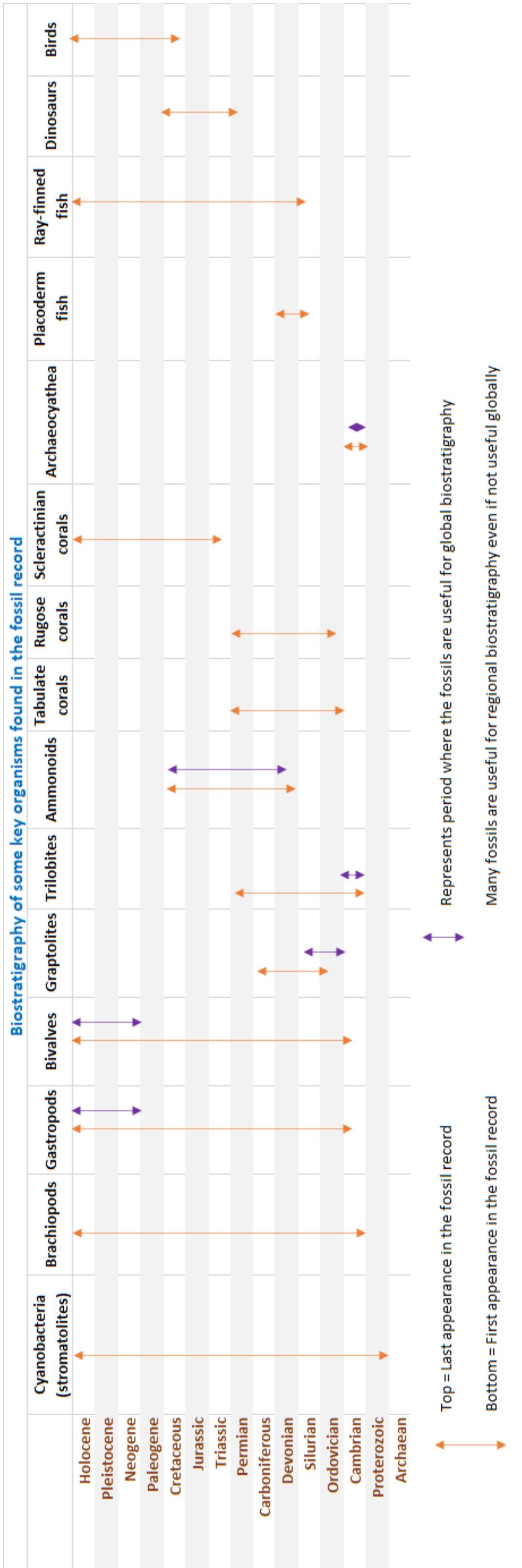
Dip – the angle between the horizontal and a planar structure such as a sedimentary bed, fault plane or planar intrusive body measured in the vertical plane perpendicular to strike.



A depiction of the strike and dip of some tilted sedimentary beds partially covered with water. The notation for expressing strike and dip on a map is shown. Modified from Figure 12.8, https://opentextbc.ca/geology/chapter/12-4-measuring-geological-structures/

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 this technological breakthrough and the 2299 improvement, the Stanaway Drive, the Interplanetary Museum of Human Endeavour (IMHE) is able to safely and quickly deploy staff to interesting locations across the solar system. Stanaway Nestor is credited with improving the original drive's efficiency to the point where it can safely accelerate a Martian Congressional Republic Navy (MCRN) corvette-class frigate to 10% light speed in 48 hours. The Encyclopedia Galactica's entry on Nestor notes:

> *Nestor was an enigmatic character who disappeared in his highly modified Sunflare-class racing pinnace shortly after gifting the patent for his invention to the solar system on the sole proviso it be called the Stanaway Drive.*

The other, more popular, guide to the galaxy ignores his famous invention but notes:

> *Stanaway had a passion for sweets containing chocolate, nuts, coconut and marshmallow. He is thought to have planned to return from wherever he has gone given his patent ended with the words: "I'll be back in time for dessert."*

Suffice to say, the 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. Each ship's pantry is also appropriately stocked in Stanaway's honour.

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.

*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.

Under the banner of 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).

Start the exam here:

The Interplanetary Museum of Human Endeavour (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 Stone and her sister Gemma are exploring the inner planets, while the rest of the team is 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 is set to examine surface features on Mercury and test for the possibility of water existing near the surface in crater-rim shadows.

Roxanne's astronomer friend, Vincent Knight, posted an image (Figure 1) on her social media. Having briefed Roxanne for the mission on this topic he jokingly asked: *You know where to look for water, right?*

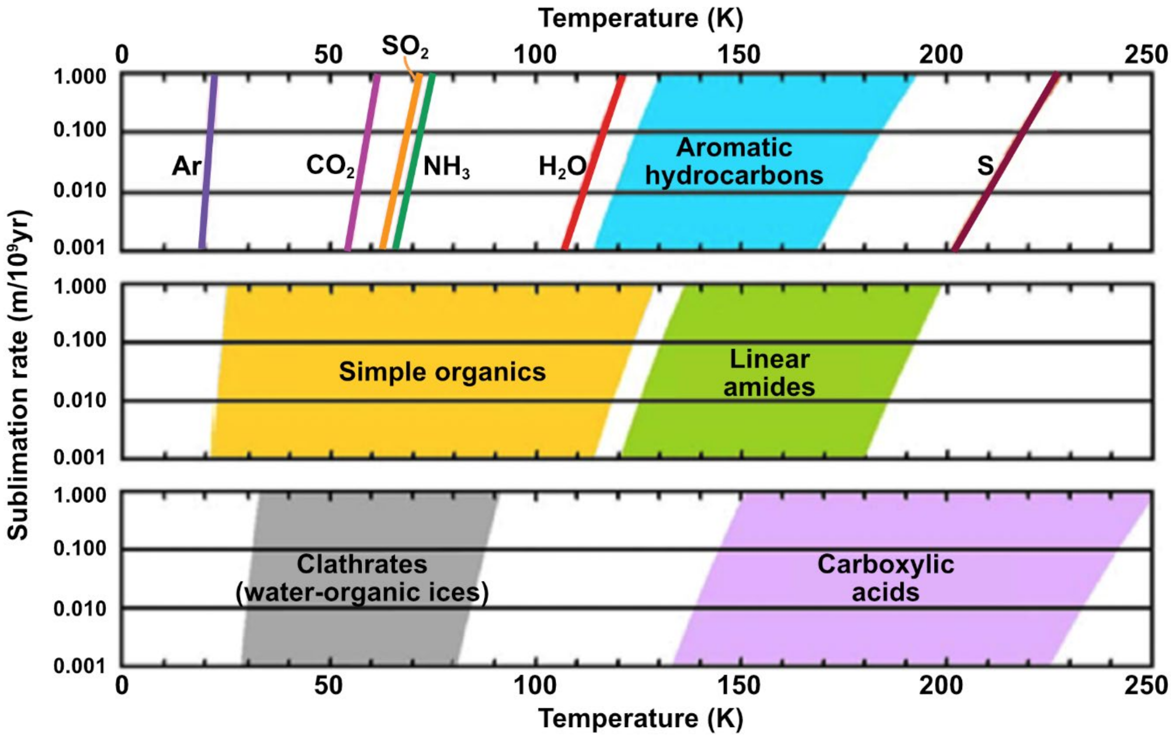


Figure 1: Sublimation rates as a function of temperature for various organic and inorganic compounds. Image modified from Zhang & Page 2009

2. Roxanne, for the benefit of her other friends, replied: *Sunlit surfaces on Mercury are too warm for water ice to be stable. In the vacuum of space it will transition from a solid to a gas (sublimate) if it is warmed above 110K. If present to begin with, water ice will only be found with certainty where the surface temperature has consistently remained below 110K. Additionally, …*

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

a. … Ar, CO_2, SO_2 and NH_3 must also be present for water-ice to be there.
b. … clathrates must also be present for water ice to be there.
c. … Ar, CO_2, SO_2 and NH_3 might also be present if water-ice is found.
d. … organic and water-organic-ice compounds might also be present if water-ice is found.
e. … both a & b.
f. … both c & d.

Gemma shared polar images of Mercury (Figure 2) on her social media, pointing out several locations (circled and labelled W, X, Y, Z) where Roxanne will be putting down on the surface to test for the presence of water at or near the surface.

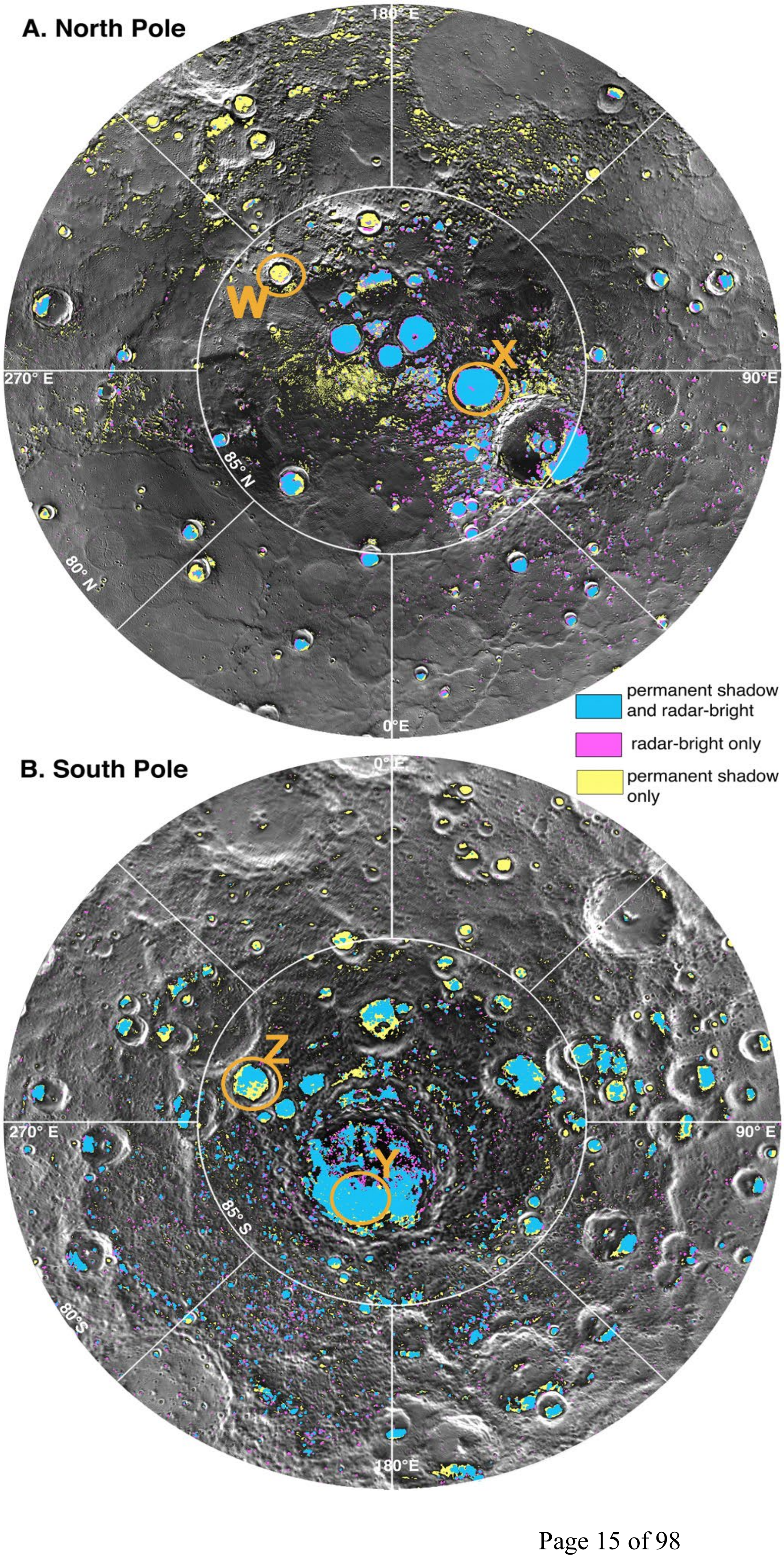


Figure 2: Distribution of permanently shadowed and radar-bright regions within 10º of Mercury's poles. Given what is known of water ice's radar reflectivity, radar-bright sites most probably host water ice. Image modified from Chabot et al, 2018.

Gemma's friend, Rose Kortz, was puzzled. She asked: *Why only those locations near the poles? Why not other craters at lower latitudes?*

3. Gemma replied: *Sunlit surfaces on Mercury are too warm for water ice to be stable. Water ice will only be found where …*

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

a. … the topographic relief of craters is sufficient to keep the location in permanent shadow. On Mercury this is most likely near the poles because orbital inclination is only 7 degrees.
b. … Mercury's Plate Tectonics has constructed mountain ranges that cast long shadows in all directions. The craters in these shadows just provide the landscape for water to pool in.
c. … the topographic relief of craters is sufficient to keep the location in permanent shadow. On Mercury this is most likely near the poles because it has a high (near 90°) obliquity to orbit.
d. … Mercury's Plate Tectonics has constructed subduction zones perpendicular to the orbital plane, forming deep trenches that are in permanent shadow. The craters in these shadows just provide the landscape for water to pool in.
e. … the topographic relief of craters is sufficient to keep the location in permanent shadow. On Mercury, this is most likely near the poles because the magnetic field lines are nearly vertical and perpendicular to the orbital plane.
f. … the topographic relief of craters is sufficient to keep the location in permanent shadow. On Mercury this is most likely near the poles because it has small (near zero) obliquity to orbit.

4. Rose also asked: *Why might site W host water, given that it is not radar-bright (Figure 2)?* Gemma replied: *Sites X, Y & Z are all in permanent shadow and have radar-bright reflections suggesting water is present. However, water might be present at site W because it is in permanent shadow and …*

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

a. … it has a very circular shape, suggesting it was formed by an icy asteroid, not a rocky one.
b. … it's the only crater in the northern polar region without much of a bright-radar response.
c. … it is smaller than the other craters (X, Y & Z) so it is likely to have less water than them and so not look radar-bright.
d. … the unbroken crater wall would confine any water vapour to the crater, creating a fog radar can't penetrate.
e. … if water is present as a liquid it won't be radar-bright like ice.
f. … any water present might be hidden from radar below a thin layer of dust, as suggested by the radar-bright patches in crater Z.

Their mutual friend Luciana Day has been reading the social posts with interest. A retired geography teacher, she loves maps and sent the team an image she'd prepared from a satellite map of Mercury's equatorial region (Figure 3). She was excited to have found a thrust fault feature - the Beagle Rupes - on Mercury and happily joked about the irony of Sveinsdóttir crater having an Icelandic name in such a hot place. She also challenged them to tell her what the age relationships of the unnamed craters she labelled Σ, Δ and Φ are to the Sveinsdóttir crater and the Beagle Rupes.

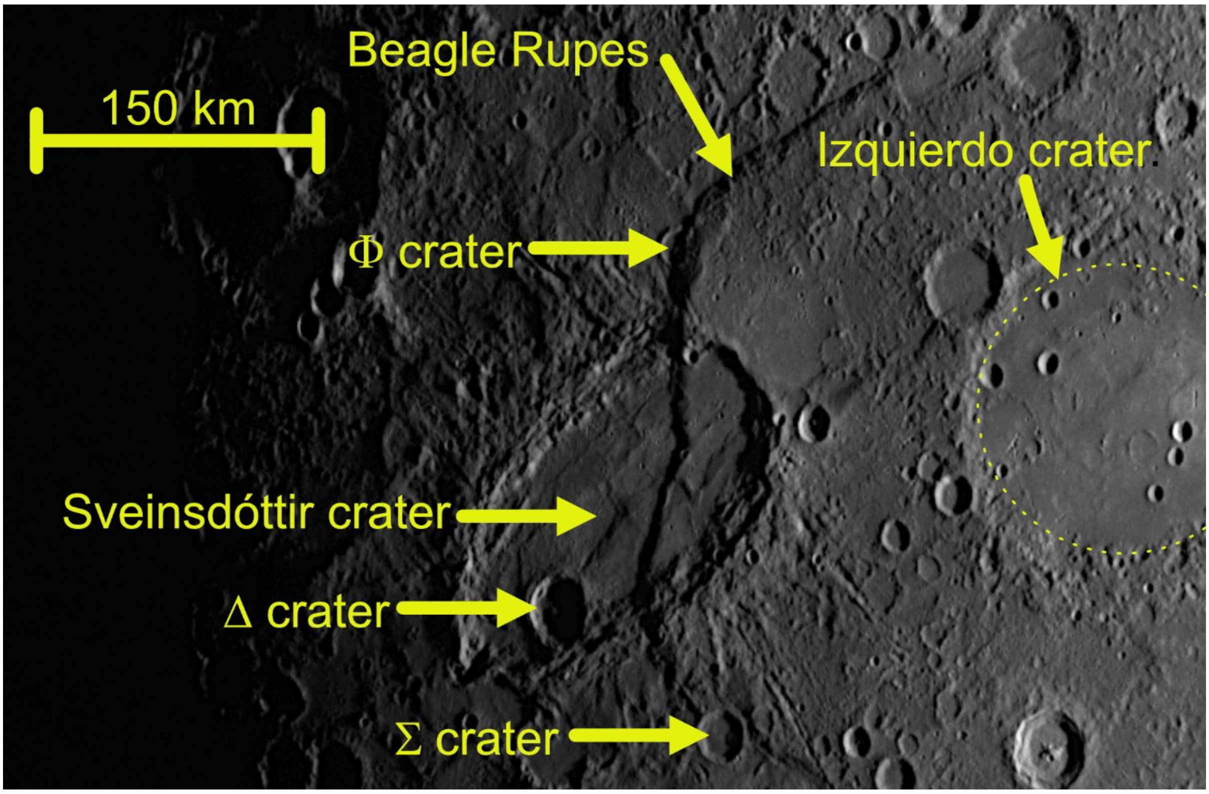


Figure 3: The scarp named Beagle Rupes is a 630 km long linear feature; the surface manifestation of a thrust fault, which formed when Mercury contracted as its interior cooled. For clarity, the rim of Izquierdo crater has been marked by a dashed line.

5. Roxanne was amused by this happy diversion en route to Mercury and replied: *There are obviously many craters in this region that don't intersect with the fault, but we can definitely say ...*

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

a. … Sveinsdóttir crater is the oldest feature of those labelled.
b. … Δ crater is younger than Sveinsdóttir crater.
c. … Σ crater is older than Beagle Rupes.
d. … Φ crater is younger than Beagle Rupes.
e. … Sveinsdóttir crater is the youngest feature of the five.
f. …Beagle Rupes is younger than Izquierdo crater.

6. Sedimentologist and team member Sandra Shore also asked a question. She was intrigued by the very flat looking landscape within Izquierdo crater and wanted to know why it looked that way. Zoe Guāng, astronomer and also a team member, shared an image (Figure 4) and suggested an answer:

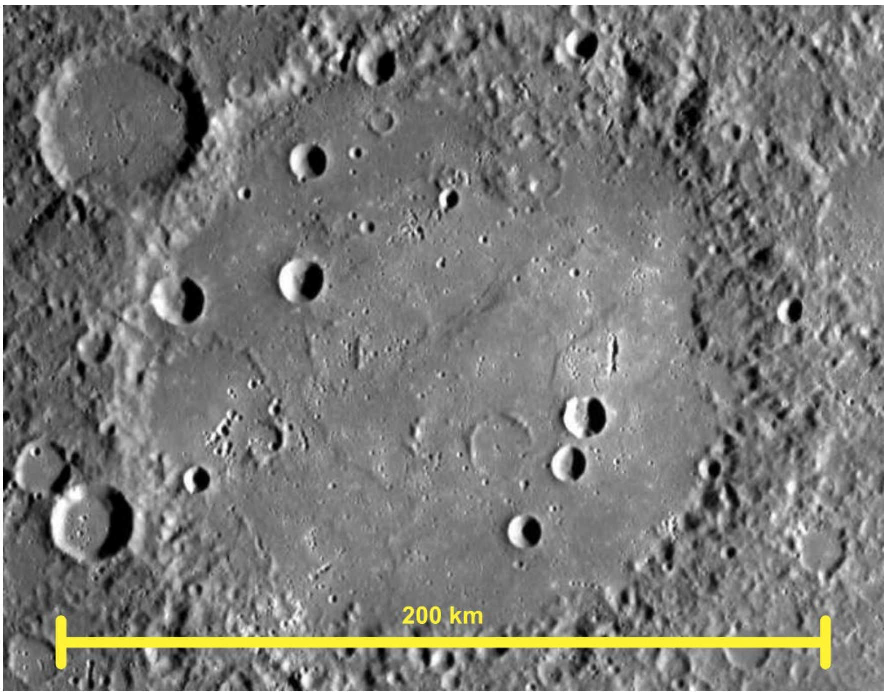


Figure 4: Enlarged image to show Izquierdo crater in detail. This crater is approximately 175 km in diameter. Modified from image supplied by NASA.

You can see from the image that Izquierdo crater does not have a distinct rim and within the crater there are also some faint 'ghost' craters without distinct rims. Together with your correct assessment that the crater floor is very flat this suggests the crater has been infilled by ....

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

a. … plasma from the Sun.

b. … fine sediments (dust) settling on the surface from a massive meteorite bombardment that pre-dates the sharply defined craters within Izquierdo crater.

c. … sediments being washed in from the eroding rim of Izquierdo crater. The sharply defined craters within Izquierdo crater were formed by later impacts.

d. … a lava flow that filled Izquierdo crater and buried or partially buried smaller craters in the process. The sharply defined craters within Izquierdo crater were formed by gasses escaping as the lava cooled.

e. … a lava flow that filled Izquierdo crater and buried or partially buried smaller craters in the process. The sharply defined craters within Izquierdo crater were too tall to be flooded by the lava.

f. … a lava flow that filled Izquierdo crater and buried or partially buried smaller craters in the process. The sharply defined craters within Izquierdo crater were formed by impacts after the lava flow cooled.

Roxanne and Gemma’s brother, Orson, also entered the conversation. He wanted to know why Sveinsdóttir crater (Figure 3) was such a weird shape when all the other craters were quite circular.

7. Roxanne’s astronomer friend Vincent was quick to reply, saying:
   Unusually elliptical in shape, the crater was produced by the impact of an object …

Q: What did Vincent say to complete his reply? (1 mark)

a. … that was actually 3 objects travelling side by side.
b. … that hit Mercury's surface at a low angle.
c. … that hit Mercury’s surface at a very low velocity.
d. … when the planet was rotating faster than it is now.
e. … when the planet was orbiting faster than it is now.
f. … shaped like an egg.

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While en route to the inner solar system, sisters Roxanne and Gemma Stone, had time to conduct observations on some stars before engaging with their research targets on Mercury and Venus. They were particularly interested in nearby G-type main sequence stars (Figure 5) because of their similarity with the Sun and the fact that recent developments had put solar systems around those stars within range of robotic probes capable of reaching, observing and reporting findings back to Earth in less than 200 years.

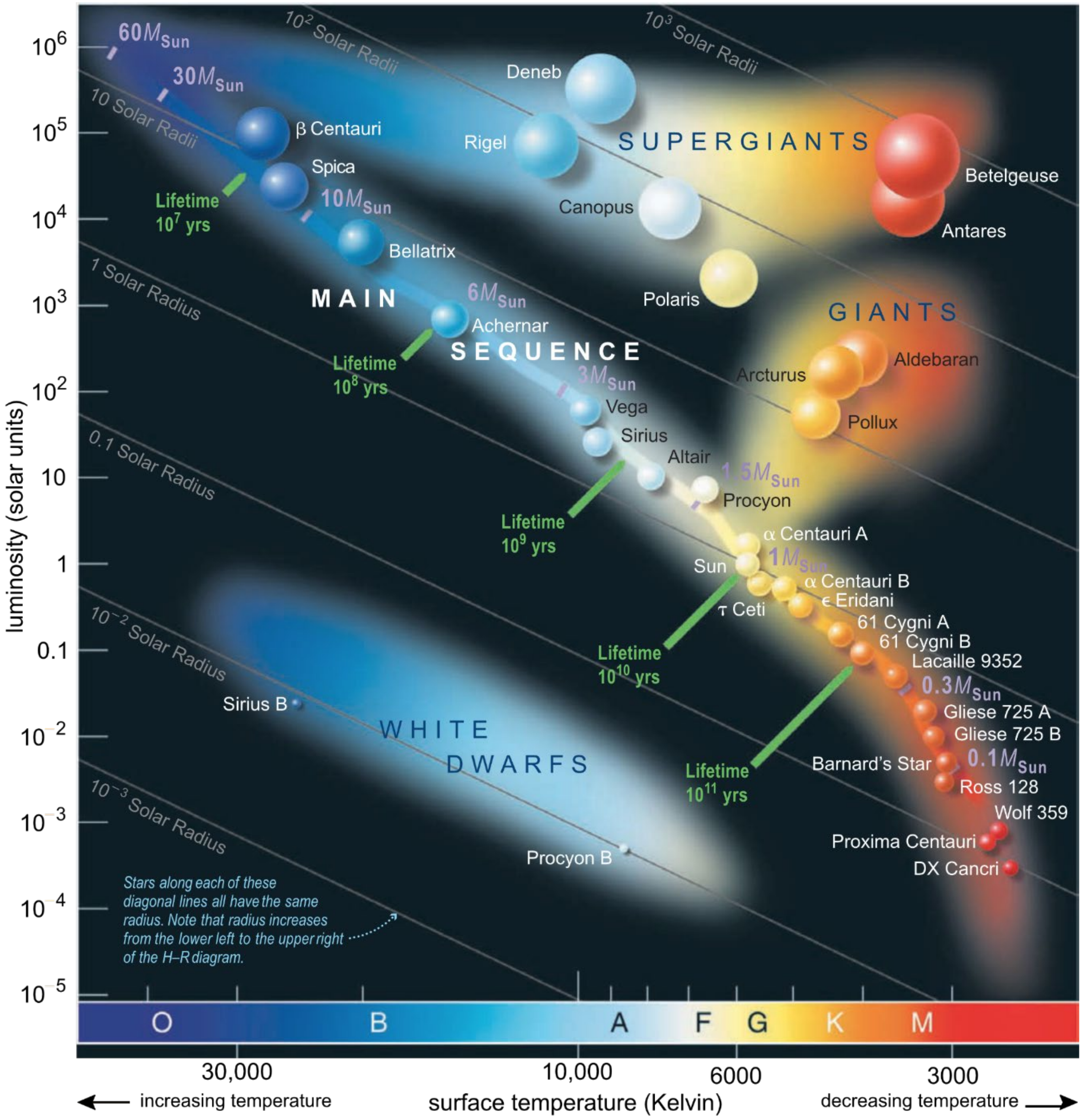


Figure 5: A Hertzsprung-Russel diagram.

Modified from Cosmic Perspectives; Bennett, Donahue, Scneider and Voit 7th Ed.

They were interested in Tau Ceti (τ Ceti) because it is our closest solitary G-class main sequence star – a mere 3.7 parsecs from Earth. They were also interested in alpha Centauri stars A & B because they are our closest binary system at a distance of only 1.3319 parsecs (Figure 5). Each star is known to host a number of planets, although those in the alpha Centauri A & B systems were not confirmed until 2198. Each star has a habitable zone (HZ) defined as the orbital zone within which water could exist on a planet's surface as a liquid (Figure 6).

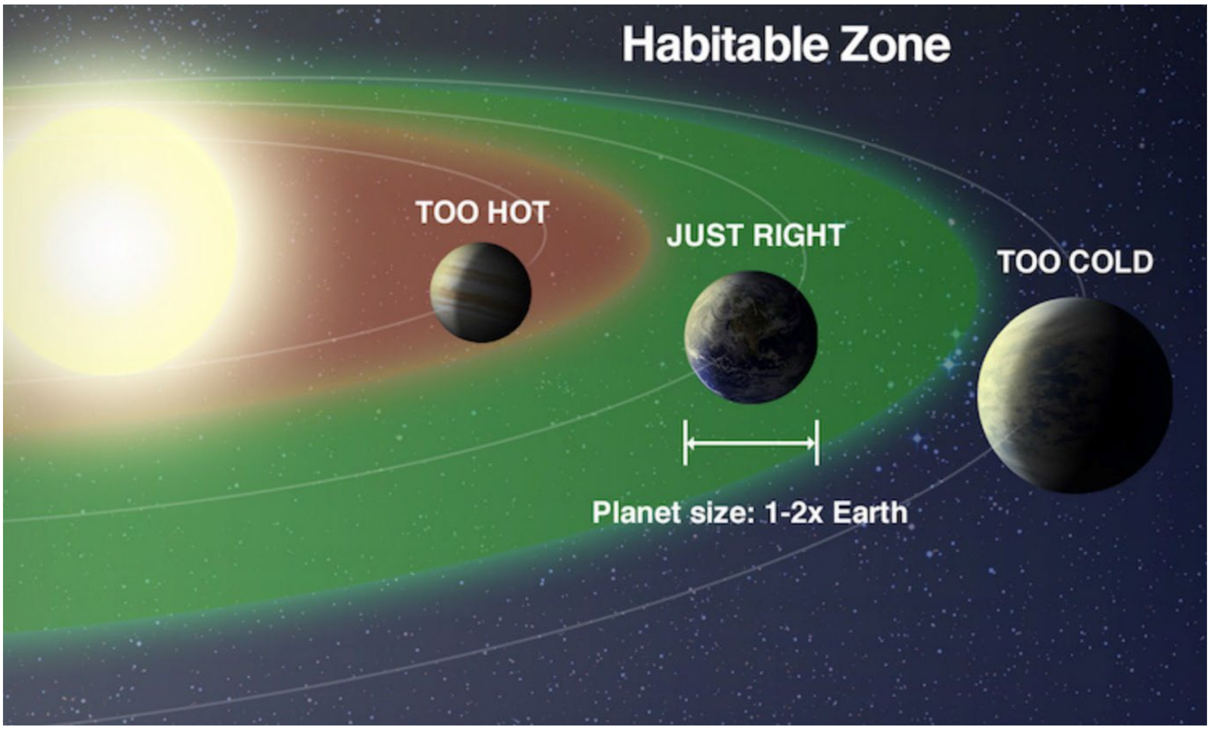


Figure 6: Graphic representation of a star's habitable zone (green zone). Closer to the star than the inner edge it is too hot for liquid water but further from the star than the outer edge it is too cold for liquid water. Modified from image supplied by NASA

8. Probes have been sent to each of these three G-class stars.

Q: Assuming each probe will enter an orbit approximately at the outer edge of the habitable zone, which probe will be furthest from its star? (1 mark)

a. The Alpha Centauri A probe because that star is the biggest and most luminous.
b. Both of the Alpha Centauri probes because they are closest to Earth.
c. The Tau Ceti probe because that star is the smallest and least luminous.
d. The Alpha Centauri B probe because that star is the smallest but most luminous.
e. The Alpha Centauri A probe because that star is the smallest but most luminous.
f. The Alpha Centauri B probe because that star is the biggest and most luminous.

9. The probes sent to each of these three G-class stars were programmed to orbit and collect data from around their target star for one year before commencing data transmission back to Earth.

Q: Assuming the probes reached a maximum speed of 10% light speed within 48 hours (and ignoring any minor tweaks relativity might suggest), how many years from launch before Earth receives their first signals? (1 mark)

a. 25.1 years for Tau Ceti and 9.7 for Alpha Centauri A & B.
b. 12.1 years for Tau Ceti and 4.3 for Alpha Centauri A & B.
c. 13.1 years for Tau Ceti and 5.3 for Alpha Centauri A & B.
d. 133.7 years for Tau Ceti and 48.8 years for Alpha Centauri A & B.
e. 132.7 years for Tau Ceti and 47.8 years for Alpha Centauri A & B.
f. 134.7 years for Tau Ceti and 49.8 for Alpha Centauri A & B.

Luciana asked another question on socials to clear up a misunderstanding. She wanted to know how Mercury's surface could be completely mapped when its rotation is tidally locked, forcing one side to always face the Sun, while the other remains in darkness.

Astronomer Vincent Knight was quick to reply that Mercury is not tidally locked 1:1, but is in a 3:2 resonance. This means that in one orbit of the Sun (88 Earth days), Mercury rotates only 1.5 times on its axis. Therefore, one Mercury solar day is 176 Earth days long.

10. Luciana then said: *Wow! That means Mercury's terminator (the line between night and day) moves across the planet really slowly compared with Earth. If an astronaut were marooned on the equator, how fast would they have to walk to remain in twilight (between day and night) to avoid the full heat of the day (about 430°C), assuming their space suit could keep them safe from the cold of the night (about -180°C)?* Vincent replied: *At the equator, Earth's terminator travels at about 1667 km/hour but Mercury's terminator speed is only about …*

Q: What did Vincent say to correctly complete the statement? (1 mark)

a. … 3.6 km/hour.
b. … 7.3 km/hour.
c. … 10.8 km/hour.
d. … 1.8 km/hour.
e. … 2.2 km/hour.
f. … 1.1 km/hour.

Meanwhile, as they travel towards Mercury via Venus, Gemma and Roxanne are busy preparing for Gemma's stint aboard the Multidisciplinary Interplanetary Landscape Observatory (MILO), the research platform orbiting Venus, and her history-making descent to the surface. Gemma is keen to observe the surface geomorphology of Venus to determine if there is any active volcanism while she updates atmospheric observations from MILO.

The surface atmospheric pressure is about 90 times higher than Earth's and the average temperature is around 735 K. Landing a human on the hostile surface for the first time was only made possible by recent advances in materials science and engineering, utilising conventional materials in combination with a range of biopolymers found naturally in pollen walls and tardigrade cuticles. These new hybrid materials are incredibly strong and resist degradation in the high-pressure, hot and potentially corrosive conditions found at the surface.

On MILO, Gemma will observe the Venusian atmosphere and send probes to collect samples. Spectrographic analysis has revealed the atmosphere contains a variety of gases (Figure 7).

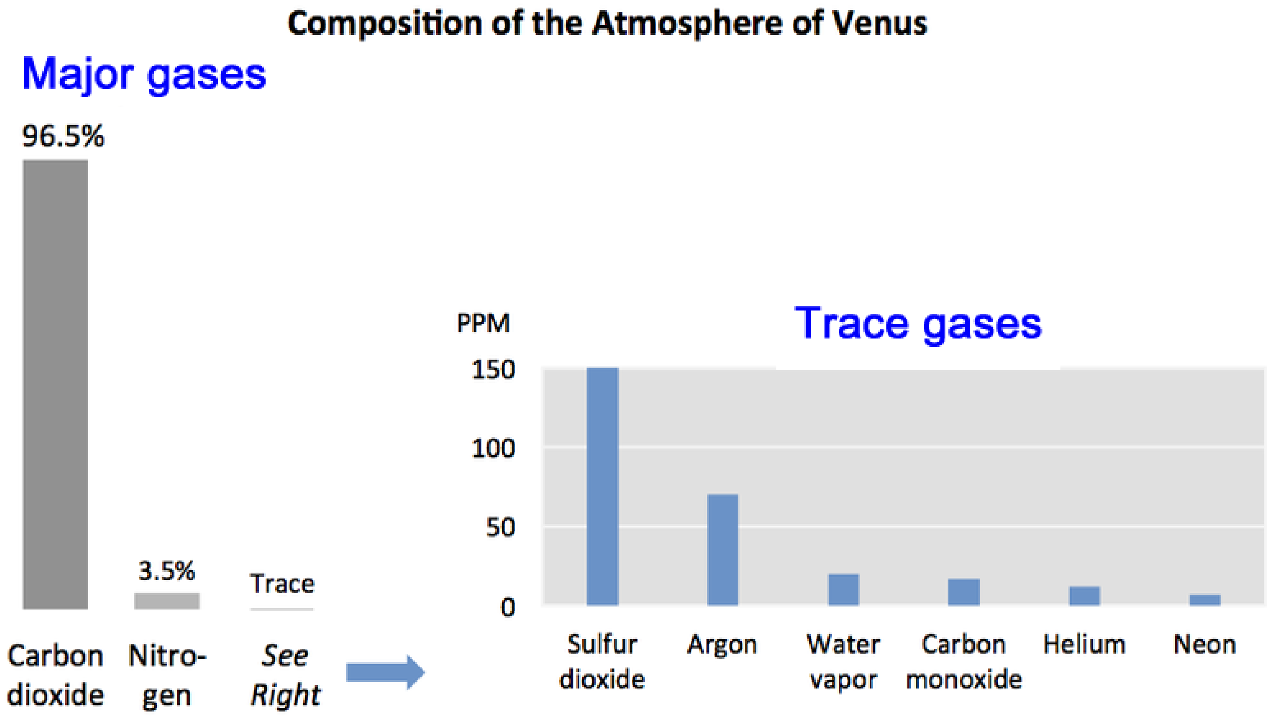


Figure 7: Composition of Venus's atmosphere.
Not shown on the graph are extremely small traces of hydrogen chloride (HCl) present at 0.1–0.6 ppm and hydrogen fluoride (HF) present at 0.001–0.005 ppm. Modified from https://tinyurl.com/bns5fsfs

Gemma shared this information on her socials to illustrate how hostile the atmosphere is to her equipment. To explain further, she added: *Ultraviolet light from the Sun causes photodissociation of CO_2, producing free oxygen that is very reactive ($CO_2 \rightarrow CO + O$). This leads to sulfur trioxide generation ($SO_2 + O \rightarrow SO_3$) which in turn forms sulfuric acid ($2SO_3 + 4H_2O \rightarrow 2H_2SO_4 \cdot H_2O$). The acid will form liquid droplets if the temperature drops below 580 K and the pressure drops below 10^3 bar. Aggregates of these droplets constitute the bulk of Venus's thick, opaque and highly reflective clouds.*

She also shared another image (Figure 8) to help illustrate where the clouds are found within the atmosphere.

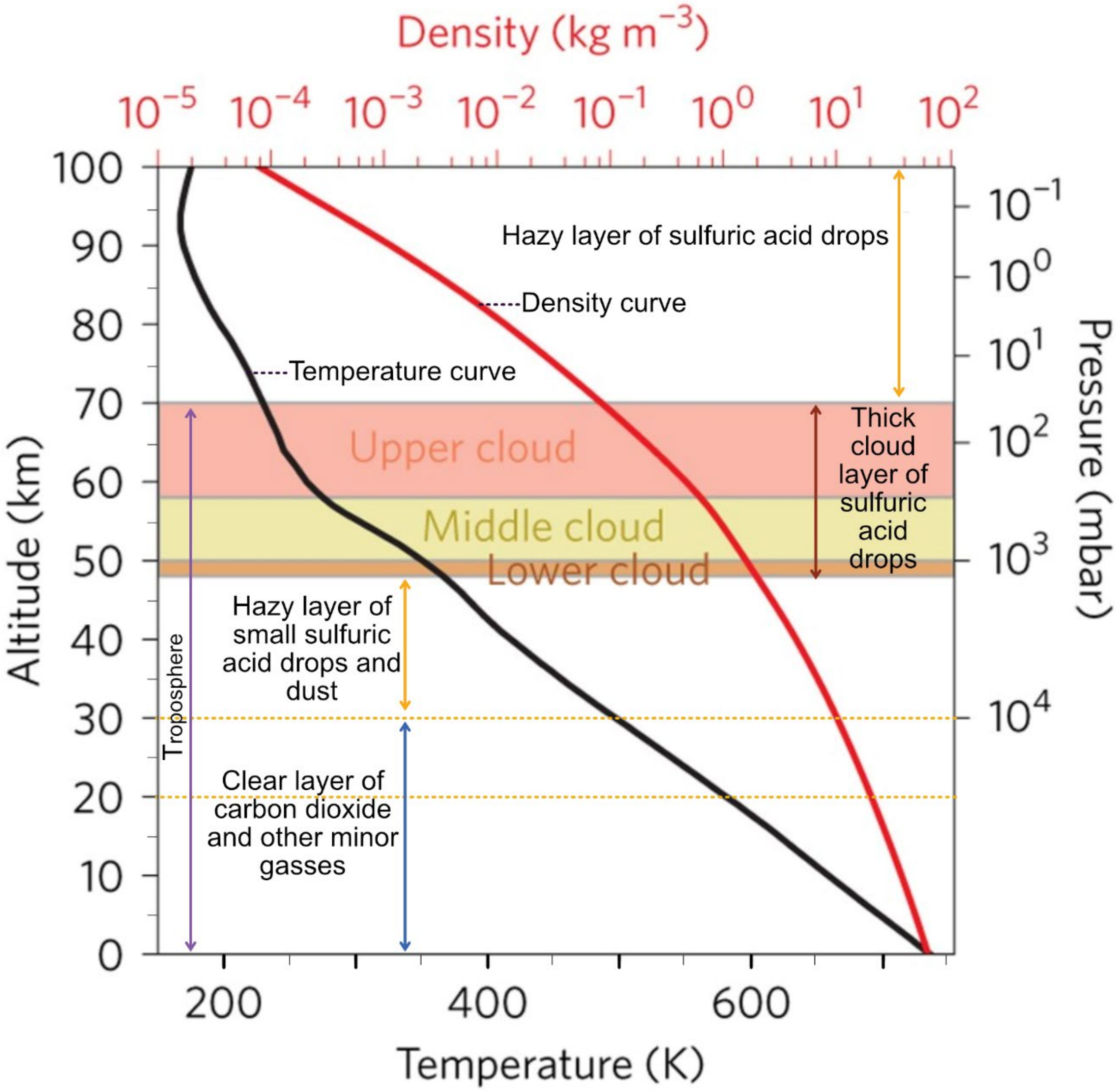


Figure 8: Vertical structure of the atmospheric density, pressure and temperature for Venus. The atmosphere is mostly carbon dioxide with about 3.5% nitrogen. It also carries haze and clouds composed of sulfuric acid droplets. Ground-level pressure is 9.2 x 10^4 mbar. Maxwell Montes, the highest mountain on Venus, rises 11 km above the mean planetary surface. Modified from https://tinyurl.com/5xnhfhkn

11. Rose was stunned that the clouds of Venus are sulfuric acid, not just water. She was curious to know why there is sulfuric acid present in the thick clouds when the atmosphere below an altitude of 30 km is just carbon dioxide and some nitrogen with very small amounts of water, sulfur dioxide and other minor gasses.

Q: What did Gemma say in reply to Rose? (1 mark)

Venus is volcanically active. Volcanoes and lava flows emit SO_2 and H_2O but the photochemically produced sulfuric acid limits SO_2 and H_2O concentrations because sulfuric acid …

a. … cannot condense at such high surface temperatures and pressures. Condensation occurs at higher altitudes, allowing clouds to form.
b. … immediately reacts with the traces of helium present which, because helium is lighter than air, transports the acid to form clouds at higher altitudes.
c. … immediately reacts with the traces of argon present to form a solid precipitate that accumulates on the surface as sand. The acid in the clouds only comes from sulfur in meteors as they burn up in the atmosphere.
d. … precipitates out within one metre of the surface and falls onto the hot rocks where it evaporates thanks to the surface winds. Atmospheric turbulence then transports the acid vapour to an altitude where it can condense and form clouds.
e. … is much less dense carbon dioxide so it will migrate to a high altitude where it condenses to form clouds.
f. … is about the same density of the carbon dioxide-nitrogen-dominated atmosphere but migrates to higher altitudes where it condenses to form clouds because it is a polar molecule responding to Venus's magnetic field.

12. Gemma noted 99% of the atmosphere by mass is found within the troposphere and that 90% of the atmosphere of Venus is within 28 km of the surface (Figure 8). She also noted the probes are designed to take samples from within and below the cloud and haze layers so must be able to survive descending and ascending through the acid-rich zones as well as dipping into the clearer but windy atmosphere within 25-30 km of the surface. However, for weight-fuel reasons, they are not engineered for conditions any closer to the surface.

Q: What else did Gemma say about the probe's specifications? (1 mark)

The probes are programmed to return to MILO once they reach ~25 km above the surface to ensure the probes' safety because they are only capable of withstanding …

a. … category 4 cyclonic winds.
b. … pressures up to 1 x 10^4 mbar and temperatures of no more than 500 K.
c. … pressures up to 5 x 10^4 mbar and temperatures of no more than 675 K.
d. … pressures up to 7 x 10^4 mbar and temperatures of no more than 575 K.
e. … pressures up to 3 x 10^4 mbar and temperatures of no more than 550 K.
f. … pressures up to 9 x 10^4 mbar and temperatures greater than 700 K.

Referring to the same image (Figure 8), their hydrology colleague Darcy Law made this observation: *Wow! The pressure (and density) of the CO_2 atmosphere at ground level is incredibly high. I hope Gemma's equipment is good enough to deal with that hostile environment when she is down there.*

Darcy also shared another image (Figure 9) to help explain the nature of the Venusian atmosphere at ground level.

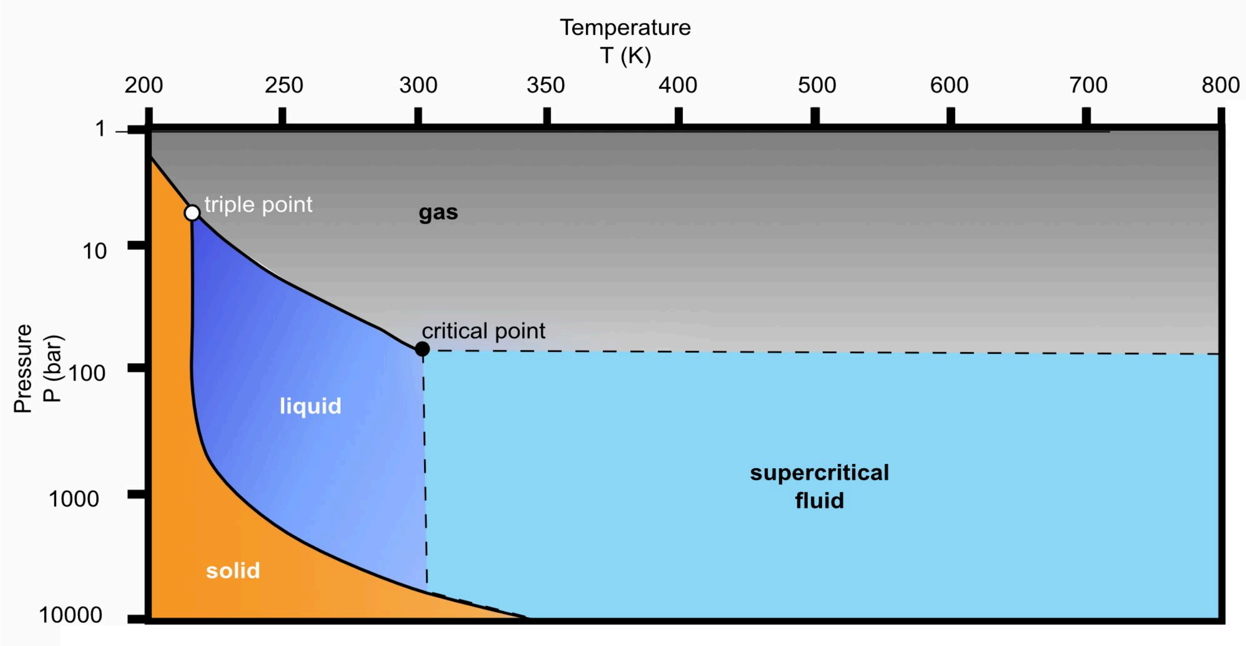


Figure 9: Temperature–Pressure phase diagram for CO_2. The critical point (304.1 K and 73.8 bar) is the point beyond which the liquid and gas phases undergo phase change to become a single supercritical phase. Modified from https://tinyurl.com/3vchv9ua

13. Referring to this diagram (Figure 9), Darcy noted that Venus has a surface temperature of 735 K and pressure of 9.2 x 10^4 mbar (92 bar) and added: *This means …*

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

a. … Gemma will be walking on the surface in liquid CO_2.
b. … Gemma will be walking on the surface in superheated CO_2 gas.
c. … Gemma will need to be careful not to walk into shadows where she might get frozen into the landscape.
d. … Gemma will be constantly walking between a gas, a liquid and a supercritical fluid.
e. … Gemma will be walking on the surface in a CO_2 supercritical fluid.
f. … Gemma cannot reach the rocky surface because it is covered in CO_2 ice.

Astrobiologist Zoe Guāng and palaeontologist Traci Menandai are part of the multidisciplinary team examining the Venusian atmosphere. In their original research proposal they explained that Earth has an aerial biosphere. The bacteria, archaea, eukaryotes and viruses mostly reside in water droplets, but some are free-floating. This is a temporary environment that provides long distance transport for organisms that return to ground level in rain about 3 to 7 days after being swept up from the surface in weather events.

Given this, Venus could host a similar environment. However, any Venusian microbes would need to live their entire life cycle within the atmosphere because they would not survive the surface conditions. A complete life cycle could occur if the organisms form spores as the acidic rain evaporates before reaching the ground. The spores could then return to a livable position through convection processes.

Using the information presented in Table 1 and the image shared earlier (Figure 8), they proposed that some of the probes Gemma launches should take samples at altitudes in the Venusian atmosphere where we know certain Earth extremophiles could survive.

Lowest temperature (K)	Highest temperature (K)	Lowest pressure (mbar)	Highest pressure (mbar)	Lowest pH	Highest pH
~250	~400	50	1.2×10^6	Less than 0.1	Greater than 11
Some permafrost bacteria	A black smoker archaea	A common soil bacteria	A black smoker archaea	A volcanic vent archaea	A soda lake bacteria

Table 1: Temperature, pressure and pH extremes life has colonised on Earth.
Zoe and Traci suggest aerial extremophiles on Venus would need to have evolved mechanisms to survive extremes of temperature, pressure and pH, not just a single extreme.

14. The research proposal was successful once Zoe and Traci were able to demonstrate to the funding body that the pH of sulfuric acid droplets throughout the atmosphere is always less than 1.0. Several probes will be deployed to collect samples aimed at identifying any life forms present.

Q: At what altitudes are the probes most likely to encounter actively growing organisms (if they exist at all) and at what altitude would the spores of such organisms most likely first form? (1 mark)

Assuming life found on Venus has limits similar to the limits shown by Earth's extremophiles, living organisms …

a. … could be encountered at altitudes between 43 km and 75 km. Spores would form below 43 km but above 30 km (below which all acid rain has evaporated).
b. … could be encountered at altitudes between 30 km and 63 km. Spores would form below 30 km but above 20 km (below which all acid rain has evaporated).
c. … could be encountered at altitudes between 43 km and 63 km. Spores would form below 43 km but above 30 km (below which all acid rain has evaporated).
d. … could be encountered at altitudes between 83 km and 95 km. Spores would form below the lower cloud (~48km) but above 20 km (below which all acid rain has evaporated).
e. … could be encountered at altitudes between 20 km and 30 km. Spores would form below 20 km but above 10 km (below which all acid rain has evaporated).
f. … and spores could be encountered at all altitudes.

According to the mission program, Gemma is scheduled to explore the surface of Venus in the vicinity of Maxwell Montes, the highest point on Venus, and another area close to Barrymore crater. It is hoped she will be able to document numerous landforms too small for the remote sensing instruments on MILO to resolve. On the feed, Darcy speculated: *The pressure (and density) of the CO_2 atmosphere might have a significant impact on the behaviour of wind-blown particles even though wind speeds one metre above the surface are typically only 0.5-1 m/s. We know that Earth, Mars and Titan all have sand dunes. Why couldn't Venus?*

Sandra Shore, the mission's sedimentologist, responded with an image of an area between 50º and 55º south of the Venusian equator (Figure 10) adding: *The linear features are probably related to winds moving granular materials. It would be nice if Gemma could groundtruth the area.*

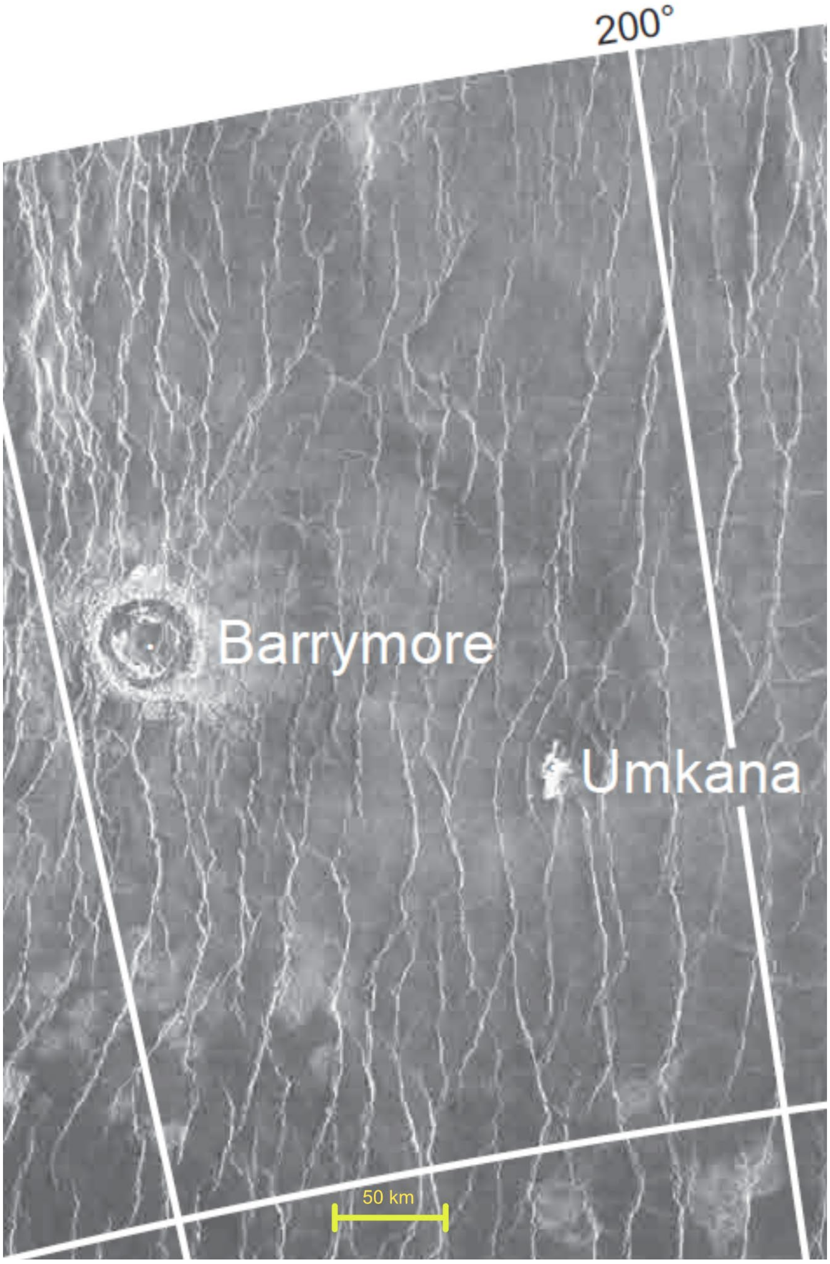


Figure 10: A radar image of the surface of Venus in the vicinity of Barrymore and Umkana impact craters. Barrymore crater is 56.6 km in diameter and located in the southern hemisphere between longitudes 195º and 200º. The top of the image marks the -50º latitude, the white line towards the bottom marks the -55º latitude.

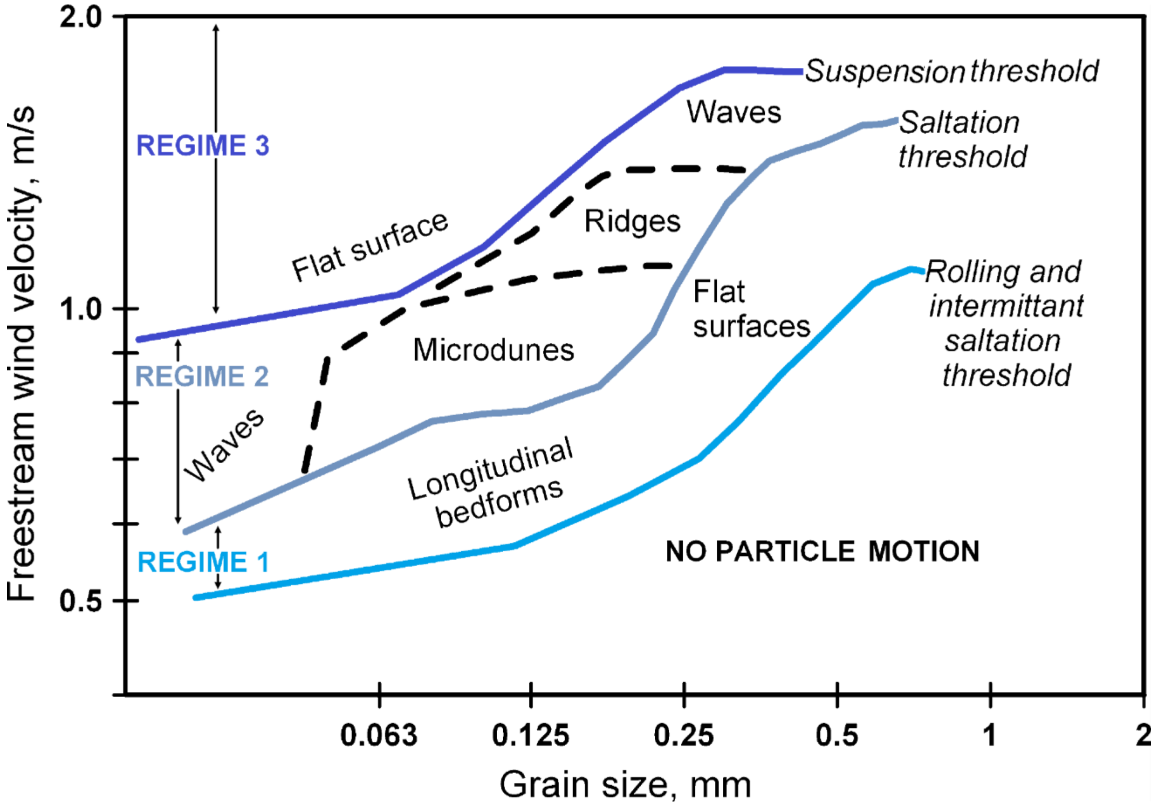


Figure 11: Bedforms formed in wind-tunnel experiments under Venusian conditions as a function of grain size and flow velocity. Longitudinal bedforms, such as ribbons and other linear features, have crests parallel to flow direction. Ripples, ridges, waves and dunes form crests perpendicular to flow direction. Modified from Kreslavsly and Bondarenko 2016.

15. Darcy responded with another image (Figure 11) and said: Ground truthing is essential. A robot lander positioned near Umkana crater has recorded, over the period of 4 Earth years, an occasional peak wind velocity of 0.72 m/s and an overage velocity of 0.58 m/s, with steady winds from the SSW. No particulate matter was found suspended in the atmosphere.

Q: What landforms and grain sizes did Darcy predict would be found on the ground between Umkana and Barrymore craters? (1 mark)

a. All regime 1 and 2 bedforms, with grains from 0.031 mm to 0.5 mm diameter.
b. Microdunes composed of sand grains up to ~0.18 mm diameter.
c. Ribbons composed of sand grains up to ~0.18 mm diameter.
d. Ribbons composed of sand grains up to ~0.3mm diameter.
e. Microdunes composed of sand grains up to ~0.3mm diameter.
f. Waves perpendicular to wind flow composed of grains below 0.063mm diameter.

16. Gemma has set her sights on summiting Maxwell Montes (elevation 11 km above the mean planetary surface) not only because she is an avid extraplanetary mountaineer, but also because she considers her equipment* will fare better under the summit conditions than on the plains.

Q: Why would Gemma think this, given the equipment is rated for surface conditions? (1 mark)

a. Temperature and pressure increase with altitude, placing less strain on the equipment at the summit.
b. Temperature and pressure decrease with altitude, placing less strain on the equipment at the summit.
c. Temperature increases while pressure decreases with altitude, placing less strain on the equipment at the summit.
d. Temperature decreases while pressure increases with altitude, placing less strain on the equipment at the summit.
e. At 10 km high she will cross the phase boundary into solid CO_2 where conditions will place less strain on the equipment up to and at the summit.
f. At 10 km high she will cross the phase boundary into liquid CO_2 where conditions will place less strain on the equipment up to and at the summit.

*The equipment built for personal mobility on Venus is designed into an exoskeleton capable of resisting the crushing pressures, the extremely high temperatures and low pH conditions. This is currently fiction but wouldn't it be cool if it wasn't!

Studying the whole of planet atmospheric temperature data (Figure 12), Zoe messaged Gemma noting: *There is no strong correlation between atmospheric temperature and altitudes below 2 km. Weird!*

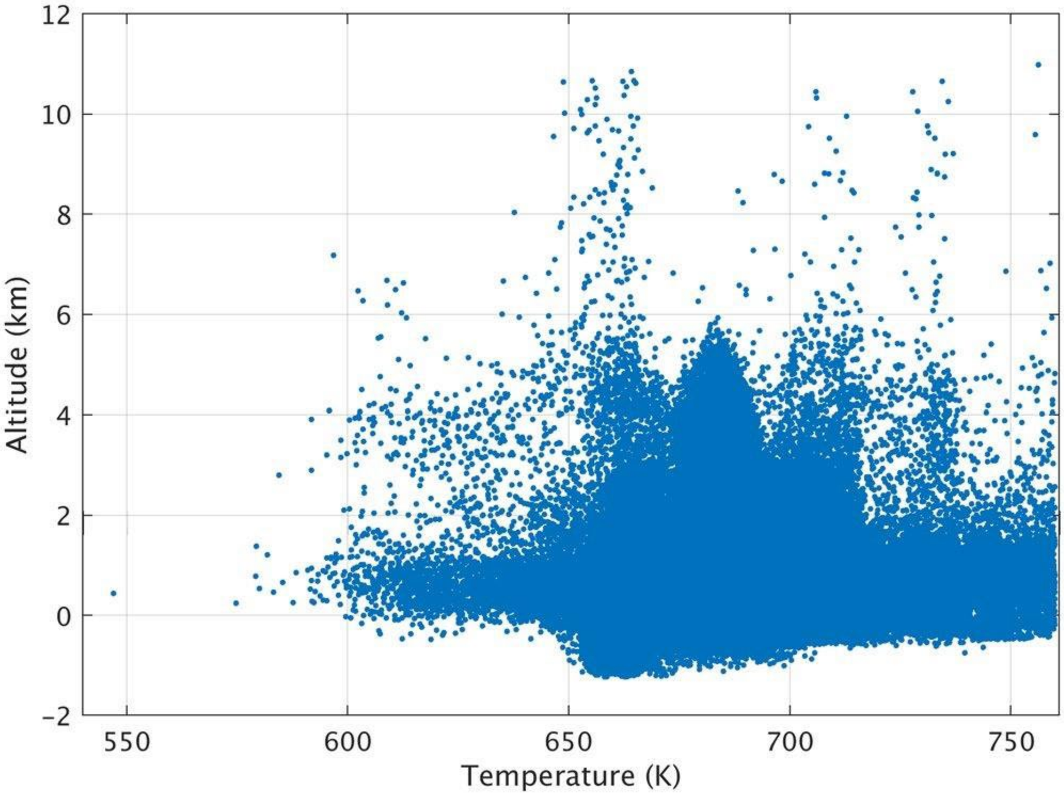


Figure 12: Scatter plot of surface temperature versus altitude in the lowermost 12 km of the atmosphere. Modified from Singh 2019.

17. Gemma agreed and went on to say that most of Venus is covered by flat low-elevation volcanic plains. Adding: *I might encounter the entire range of temperatures. When I'm not climbing Maxwell Montes, I will be mostly exploring the surface with altitudes no more than 2 km above the planetary mean surface.*

Q: What did Gemma suggest might contribute to the wide range of surface temperatures given the thick clouds prevent most solar energy from reaching the surface? (1 mark)

a. Lithospheric heat from volcanism.
b. A large greenhouse effect given a CO_2 concentration of 96.5%.
c. Heat transfer by winds.
d. Lithospheric heat from massive magmatic resurfacing events.
e. Solar energy reaching the surface, despite most of it being reflected.
f. All of the above.

Part of Gemma's planned trek up Maxwell Montes, starting on Lakshmi Planum, is a survey of the circular feature known as Cleopatra (Figure 13).

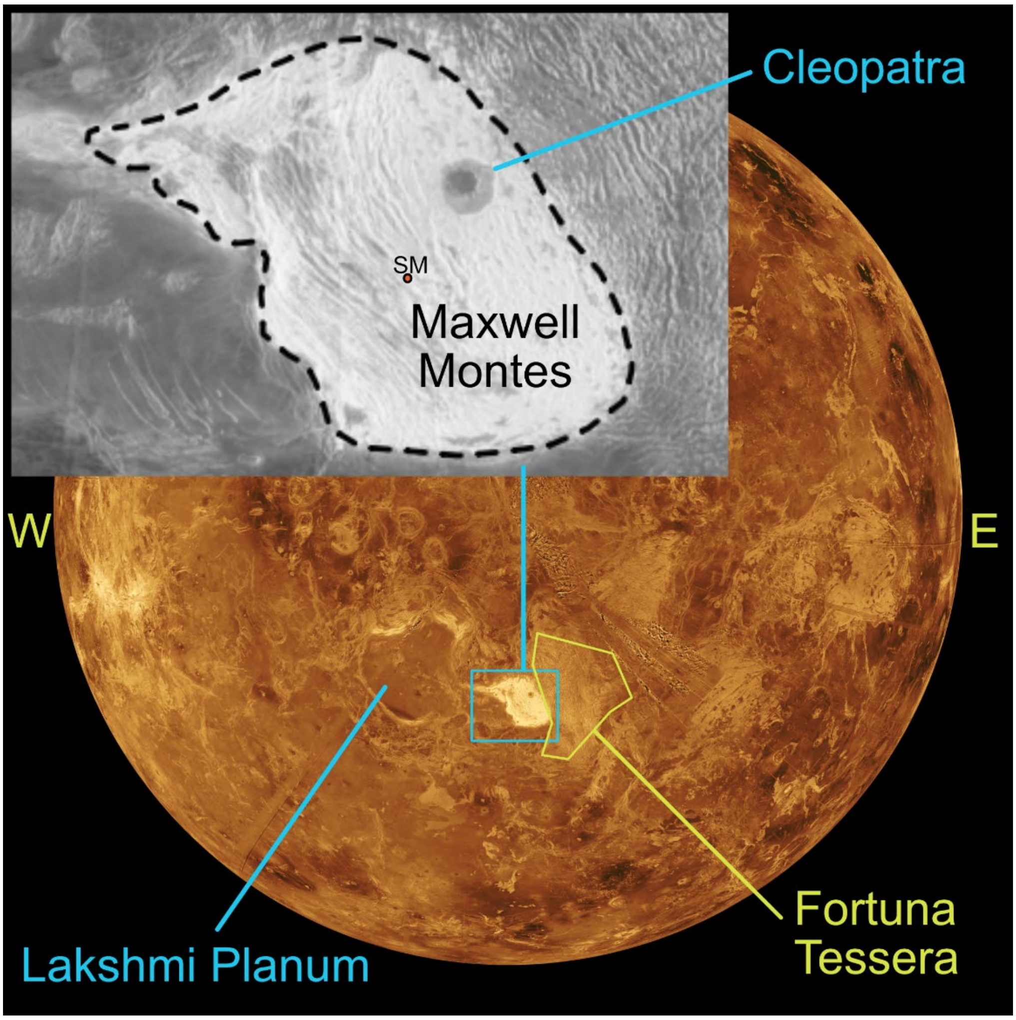


Figure 13: Radar image of Venus: North polar view with the outline of Maxwell Montes inset. The spot labelled SM is the approximate location of Skadi Mons, the highest peak on Maxwell Montes. Cleopatra is a large circular structure 100 km in diameter located on the mountain. Lakshmi Planum is a large elevated plateau ringed by rugged mountains, sitting 3.5 to 5 km above the mean planetary surface. Fortuna Tessera is an elevated region of strongly deformed terrains consisting of densely packed systems of ridges and grooves that criss-cross one another and form a disorderly pattern of polygonal blocks. Images courtesy of NASA.

18. Gemma's brother Orson relayed that Cleopatra is a double-ring impact basin about 100 kilometres in diameter and 2.5 kilometres deep. A steep-walled, winding channel extends through the rough terrain surrounding the crater rim (Figure 14). Darcy asked what could have formed such a crater, which looks a lot like some he has seen on Mars.

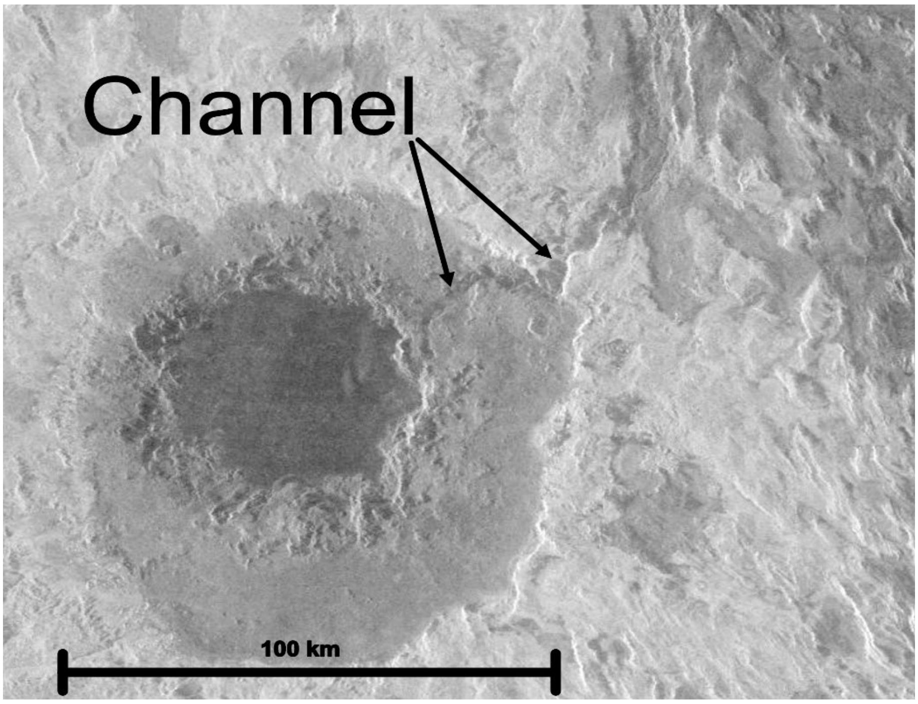


Figure 14: Image of the Cleopatra structure on Maxwell Montes.

Q: What did their colleague Andy Syght write in reply to Darcy? (1 mark)

a. The meteorite impact that formed Cleopatra crater generated a huge volume of lava via decompression melting, which then carved this channel as it flowed down the mountain.
b. The meteorite impact that formed Cleopatra crater generated a huge volume of lava due to the shock wave ahead of the impact, which then flowed through this channel on its way down the mountain.
c. The meteorite impact that formed Cleopatra crater generated a huge volume of liquid CO_2 due to the shock wave ahead of the meteor, which then incised this channel as it flowed down the mountain.
d. The meteorite impact that formed Cleopatra crater generated a huge volume of liquid CO_2 due to decompression in the meteor's wake, which then cut this channel as it flowed down the mountain.
e. The impact that formed Cleopatra crater generated a shock wave ahead of the meteorite, forming a huge volume of liquid water, which then flowed through this channel on its way down the mountain.
f. The impact that formed Cleopatra crater generated a huge volume of liquid water via decompression melting, which then flowed through this channel on its way down the mountain.

19. In her blog Gemma wrote: *It is amazing what the radar images of the surface reveal about Venus. For example: in the Maxwell Montes area above an elevation of 4.75 km it is very radar-bright compared with other features in the surrounding landscape (Figure 13), except for some of the very highest ridges and peaks (over 7 km) that are less bright than areas slightly lower (Figure 13 inset). It is thought this bright zone is due to the highly radar-reflective mineral pyrite in abundance on the surface. My expedition will establish the facts, but there is a problem given the graph in Figure 15.*

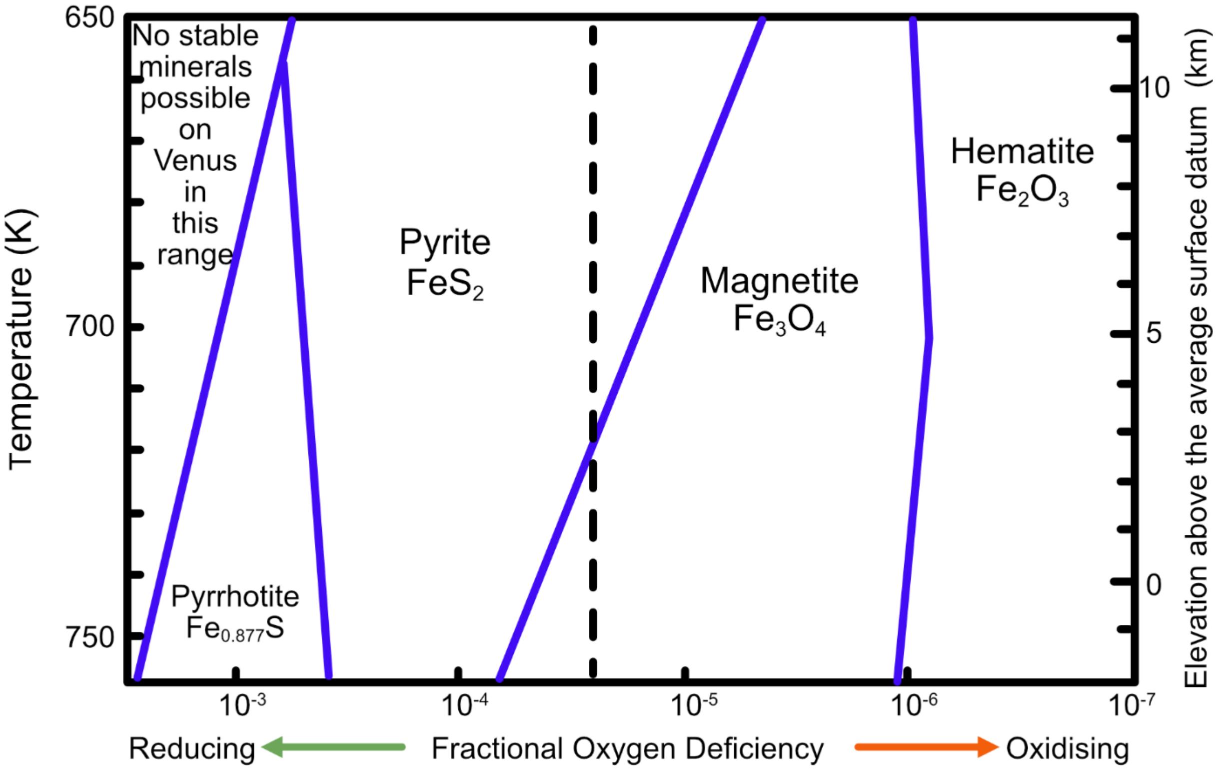


Figure 15: Minerals possibly formed from basalt weathering processes on Venus as a function of temperature and elevation with respect to a range of oxidising conditions represented by the Fractional Oxygen Deficiency (FOD). An FOD of 2.6 x 10^{-5} is calculated to be a good fit for Venus (shown as the dashed black line). The solid blue lines are phase boundaries between one mineral species and another. Modified from Klsoe et al 1992.

Q: What is the problem Gemma identified? (1 mark)

a. For the given FOD, the elevation of the phase change from magnetite to pyrite does not correspond with the elevation of the onset of radar-bright materials as measured on the topography. This suggests the FOD is locally more oxidising or surface temperatures are locally higher than predicted by the nominal temperature gradient given on the y-axis of the graph (Figure 15).
b. For the given FOD, the elevation of the phase change from magnetite to pyrite does not correspond with the elevation of the onset of radar-bright materials as measured on the topography. This suggests the FOD is locally more reducing or surface temperatures are locally higher than predicted by the nominal temperature gradient given on the y-axis of the graph (Figure 15).
c. For the given FOD, the elevation of the phase change from magnetite to pyrite does not correspond with the elevation of the onset of radar-bright materials as measured on the topography. This suggests the FOD is locally more oxidising or surface temperatures are locally lower than predicted by the nominal temperature gradient given on the y-axis of the graph (Figure 15).
d. For the given FOD, the elevation of the phase change from magnetite to pyrite does not correspond with the elevation of the onset of radar-bright materials as measured on the topography. This suggests the FOD is locally more reducing or surface temperatures are locally lower than predicted by the nominal temperature gradient given on the y-axis of the graph (Figure 15).
e. Pyrite oxidises readily on Earth's surface and is therefore never stable in surface soils, whereas magnetite and hematite are very stable. This suggests pyrite is not the radar-bright mineral at all and another model needs to be developed.
f. There is no oxygen in the atmosphere of Venus so the FOD cannot control the mineral phase changes at all.

20. Rose joined the chat about pyrite by saying: *Actually, there are two problems as far as I can see. Gemma has explained the first one, but what's with the highest peaks having less reflectivity than a bit lower? How does your graph explain that?*

Gemma replied: *Well spotted! The graph doesn't explain it at all and is yet more reason for ground truthing. The most likely explanation is ....*

Q: What did Gemma's correct response conclude? (1 mark)

a. …the highest peaks are where the stratigraphically youngest sediments are found according to the Law of Superposition. Given lower weathering rates at the cooler altitudes, the highest rocks will have far less pyrite on their surface as they have not been weathering as long as the lower parts of the mountain.

b. … landslides at the highest elevations, where slopes are very steep, have exposed unweathered rock with a relatively low radar reflectivity. Given lower weathering rates at the cooler altitudes, the highest peaks are shedding reflective pyrite-rich weathering materials faster than it forms.

c. … seasonal CO_2-ice glaciers at the highest elevations, where slopes are very steep, have exposed unweathered rock with a relatively low radar reflectivity. Given lower weathering rates at the cooler altitudes, the highest peaks are being stripped of pyrite-rich weathering materials faster than it forms.

d. … CO_2-ice glaciers form at the highest elevations. The ice has a much lower radar-reflectivity than pyrite.

e. … landslides caused by seismic activity generated by giant sand worms migrating through lava tubes at the highest elevations, where slopes are very steep, has caused localised lava flows that form fresh basalt rock with a relatively low radar reflectivity. Given lower weathering rates at the cooler altitudes, the highest peaks are forming new unweathered rock faster than weathering can produce reflective pyrite-rich materials.

f. … adiabatic cooling of the atmosphere around the mountain tops generates sulphuric acid rain above 7 km. This rain dissolves the pyrite and reprecipitates it in the zone between 4.75 km and 7 km where it adds to the radar-bright surface already there.

Philip Light, team geologist currently exploring ancient outcrops on Earth, was fascinated by the surface features revealed in the radar images. He wrote on socials: *Maxwell Montes and Fortuna Tessera are wrinkled and criss-crossed with tightly packed ridges and valleys (Figure 13 & Figure 16). Lakshmi Planum is surrounded by large mountain ranges with similar ridge-like patterns but has no obvious wrinkles, just some calderas (Figure 16).*

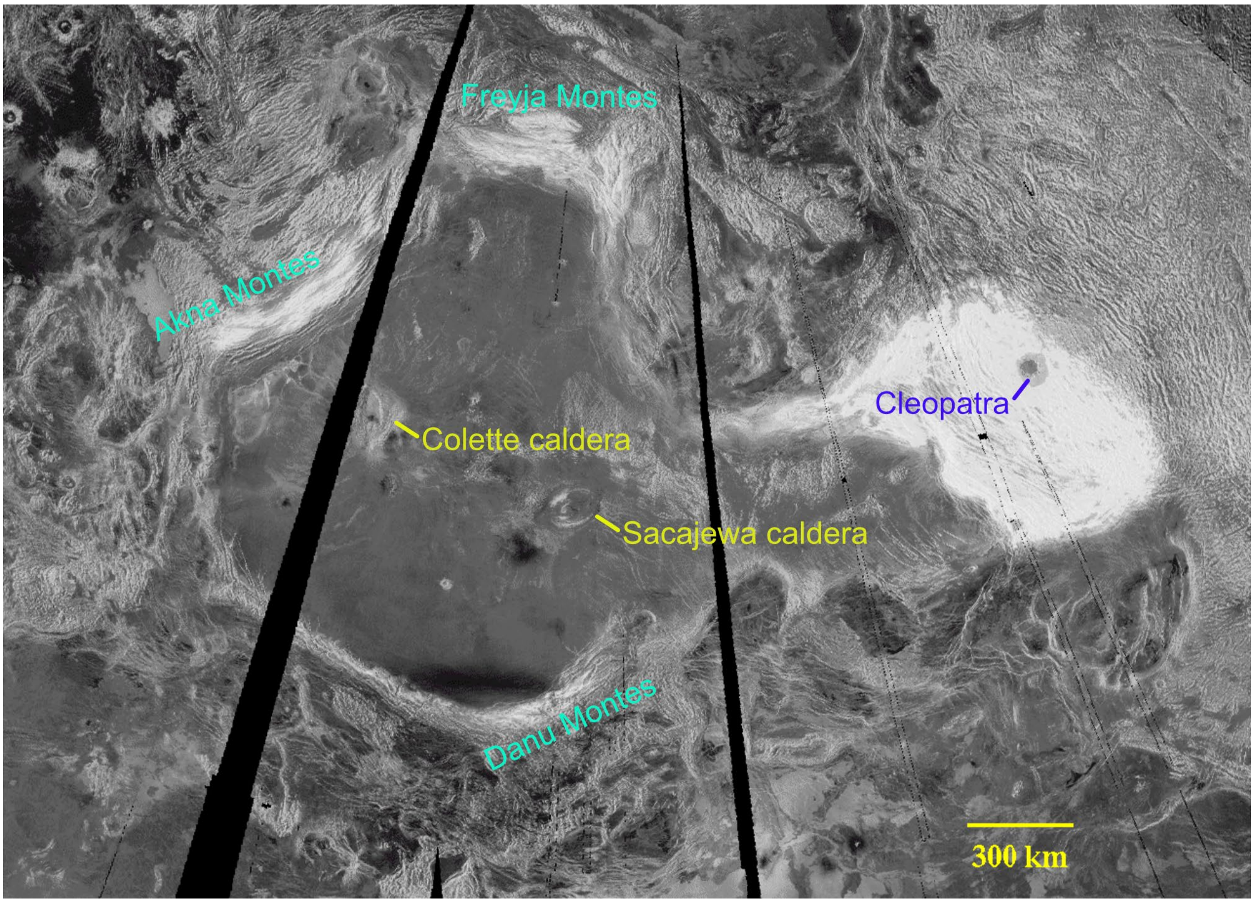


Figure 16: Radar image covering Lakshmi Planum and the surrounding mountain ranges. The straight black lines are missing data. The radar-bright elevated areas of the mountain ranges strongly contrast with the lower areas.

21. Rose replied that she thought all the surface features on Venus were of similar ages thanks to continuous volcanic activity, but this image suggests otherwise. Philip agreed, noting: *Venus is very volcanically active and that is why we don't see many old impact craters. The events represented in these images (Figures 13, 14 & 16) involve:*

IM: Impact of the meteorite forming Cleopatra crater	VHS: Volcanic hot spot calderas
OL: Outpourings of lava	MU: Magmatic upwellings
CC: Compression of the crust	EC: Extension of the crust
MB: Mountain building	BF: Basin formation

From <u>oldest to youngest</u> events, the best model to explain the landscape we see now would be…

Q: Which model accurately reflects Philp's closing comments?

a. Model Va
    i. IM is definitely the oldest, but we can't tell anything about the younger events without Gemma's ground truthing.
b. Model Vb
    i. MB and BF due to subduction under Akna Montes
    ii. IM
    iii. MU, leading to VHS and OL
    iv. MU, leading to EC and CC resulting in ridges and wrinkles
c. Model Vc
    i. MB and BF due to subduction under Akna Montes
    ii. MU, leading to VHS and OL
    iii. MU, leading to EC and CC resulting in ridges and wrinkles
    iv. IM
d. Model Vd
    i. IM
    ii. MU, leading to VHS and OL
    iii. MU, leading to EC and CC resulting in ridges and wrinkles
    iv. MB and BF
e. Model Ve
    i. MU, leading to EC and CC resulting in ridges and wrinkles
    ii. MB and BF
    iii. MU, leading to VHS and OL
    iv. IM
f. Model Vf
    i. IM is definitely the youngest, but we can't tell anything about older events without Gemma's ground truthing.

Back on Earth, geologist Philip Light was following his IMHE colleagues' and friends' adventures whilst enjoying the desert landscapes of the Arrakis Peninsula**.** This region of Specerijland (Figure 17) is famous for its arid landforms adjacent to the fossil-rich Devonian rocks of the Harkonnen Range and the ancient rocks exposed in Franklin Fields and Herbert River Gorge.

He posted that some of the rocks beneath his camp site (Location 1, Figure 17) in the northeast reaches of Harkonnen Range, some older than 3.8 billion years, were formed when Earth and Venus were much more alike. He wrote: *we now know Venus and Earth probably had similar overall chemistry when they first formed from the solar nebula, each with an atmosphere of steam above a magma ocean. Settling of denser materials formed iron-rich cores surrounded by ultramafic mantles on both planets*.

> Their mutual friend, Tracee LeMents, responded: *We know from robot probes that most rocks on Venus' surface are extrusive basalts. However, generating basalts requires separation of magma derived from partially melted peridotite. There would need to be some type of crust there already to allow partial melting, so what was the primordial crust made of?*

22. Philip had a one-word reply.

Q: What was Philip's answer? (1 mark)

a. Komatiite
b. Gabbro
c. Andesite
d. Diorite
e. Olivine
f. Granite

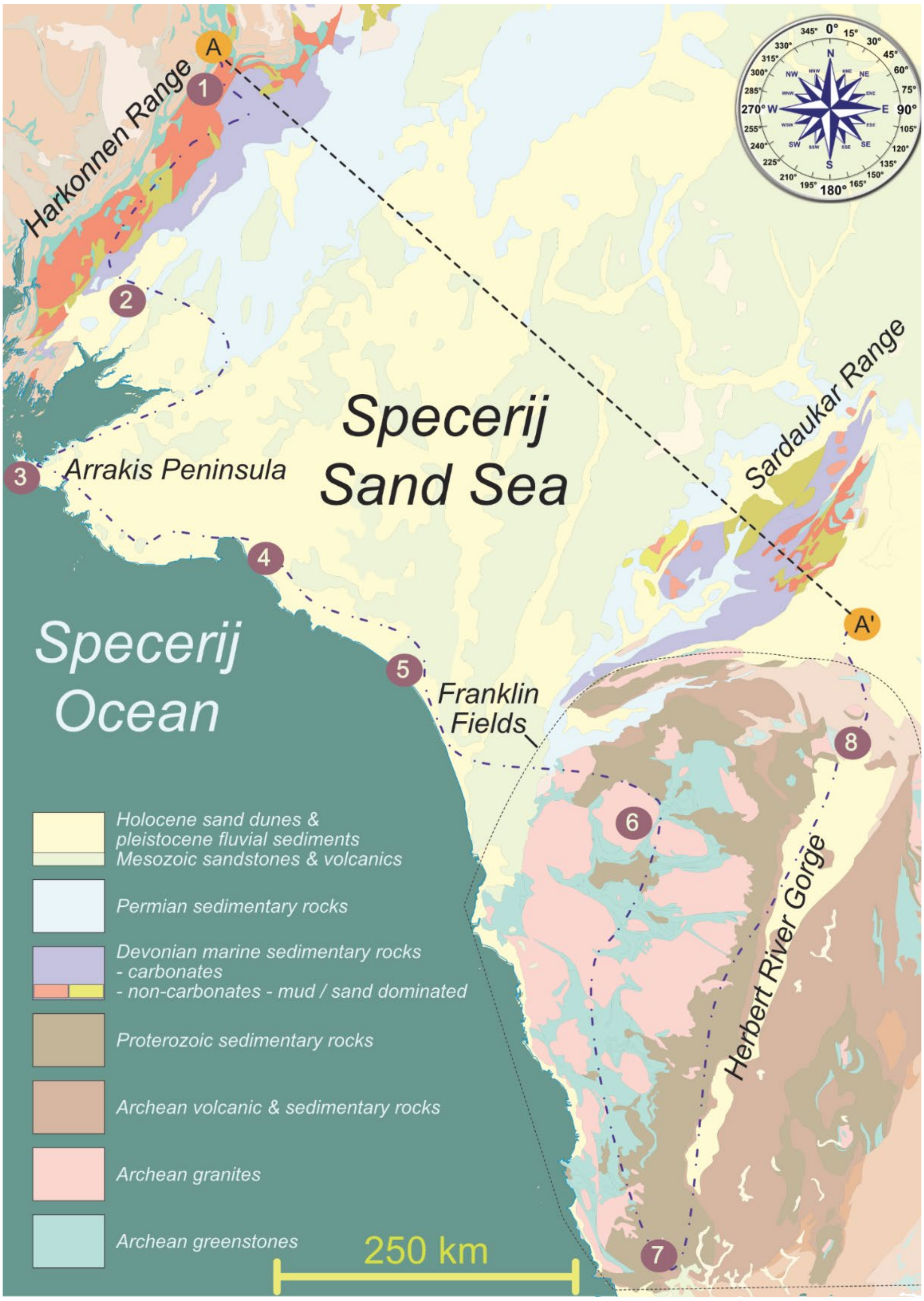


Figure 17: Simplified geological map of Specerijland. The dot-dash line represents Philip's planned route from A to A' via the Arrakis Peninsula, Franklin Fields and Herbert River Gorge. Franklin Fields is the area enclosed by the fine dotted line. Locations 1 to 8 are places Philip Light has stopped at to document interesting phenomena.

Having sought and received all the appropriate cultural, ecological and safety approvals, Philip has plans to travel from A to A’ following the dot-dash line via:

- a trek from the northeast to southwest along the spine of the Harkonnen Range
- coastal cliff outcrops on the Arrakis Peninsula
- coastal outcrops along a trek southeast to Franklin Fields
- landscapes and outcrops of Franklin Fields
- a trek upstream through the Herbert River Gorge

23. Geologist and team member Gabi Roe noted he wasn’t visiting the Sardaukar Range, asking if he could predict whether the orientation of the Palaeozoic rocks there would be the same as those of the Harkonnen Range. Philip replied with a sketch adding: *Attached is a photograph of a nice outcrop I am camped near (Figure 18). These beds have a strike of 45º and are dipping towards the south east. This geometry is typical of all the Palaeozoic and Proterozoic units within the Harkonnen Range. The sketch is a very simplified cross-section for the line A-A’. It illustrates why I know what to expect for the orientation of the rocks in the Sardaukar Range.*

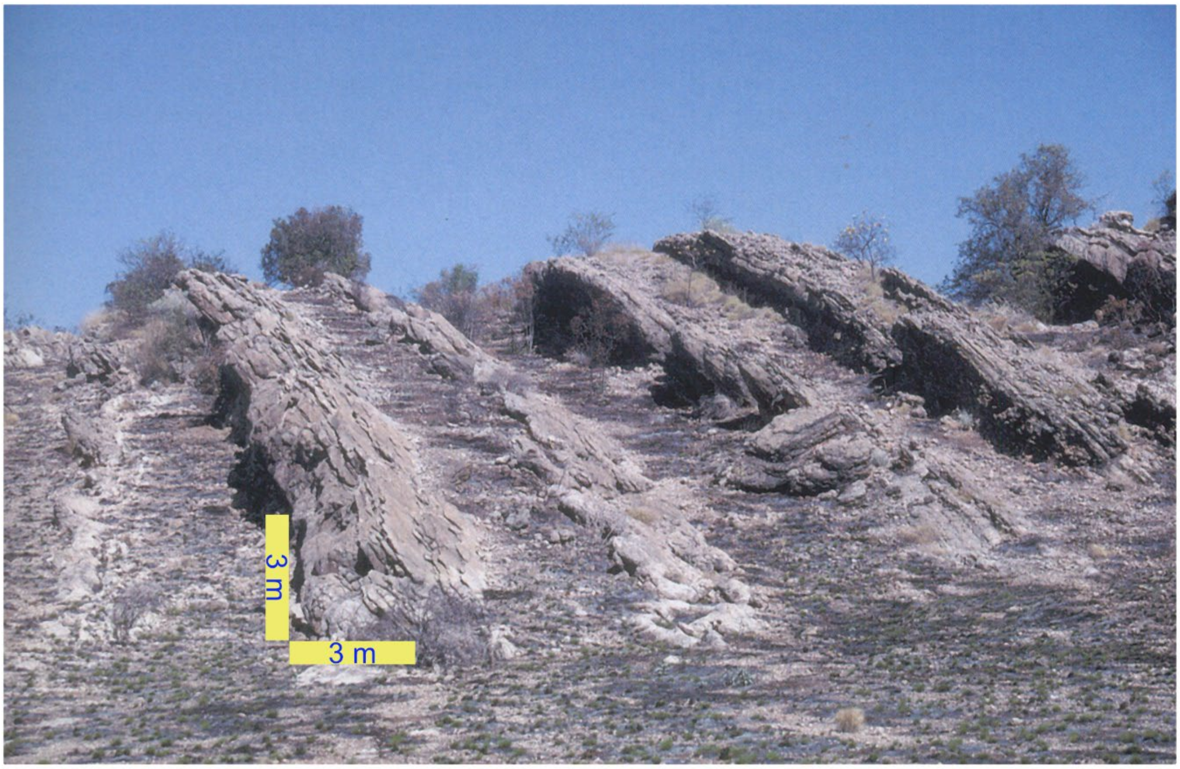
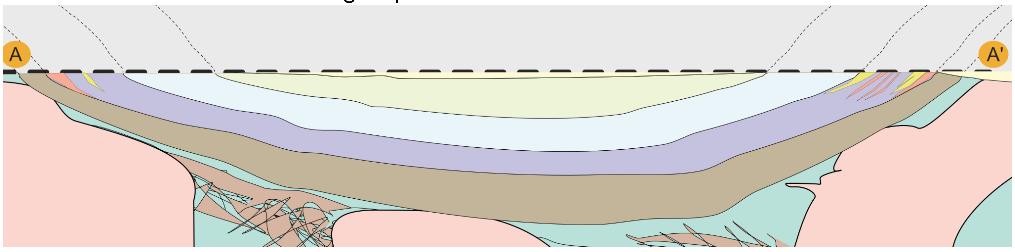


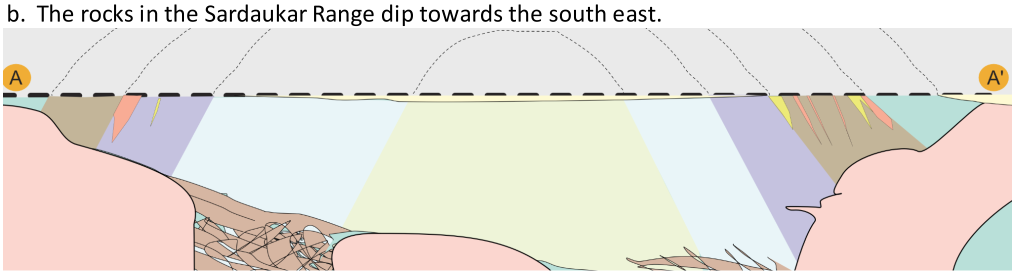
Figure 18: Devonian limestone outcrop in the Sardaukar Range. The beds have a strike of 45º and are dipping towards the south east. The protruding beds are fossil-rich limestones, each bed containing distinctive fossil assemblages. Image modified from Playford et al, 2009.

Q: Which sketch and comment is the one that Philp shared? (1 mark)

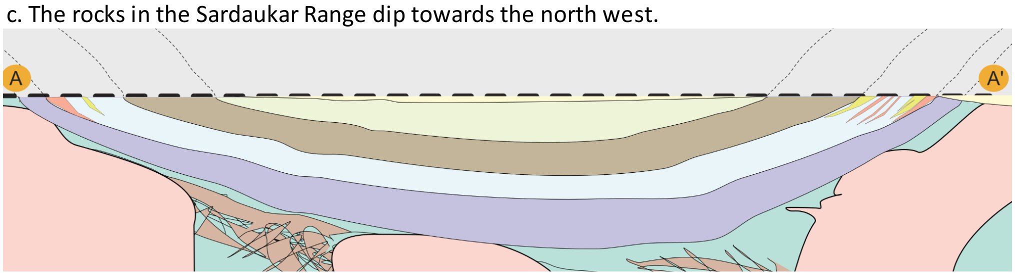
a. The rocks in the Sardaukar Range dip towards the north west.



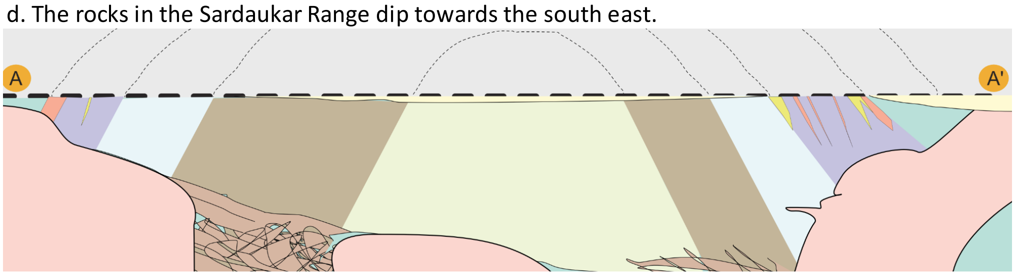
b. The rocks in the Sardaukar Range dip towards the south east.



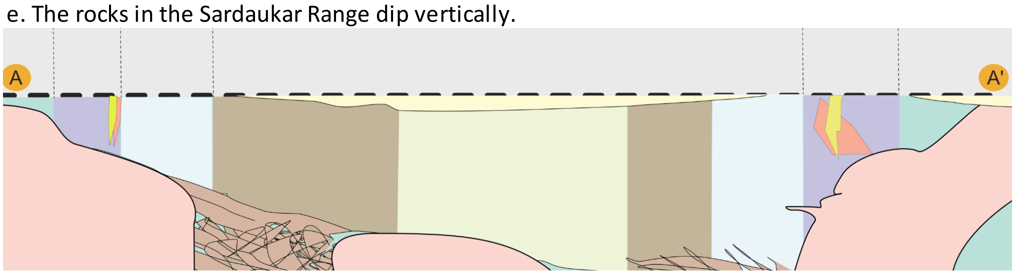
c. The rocks in the Sardaukar Range dip towards the north west.



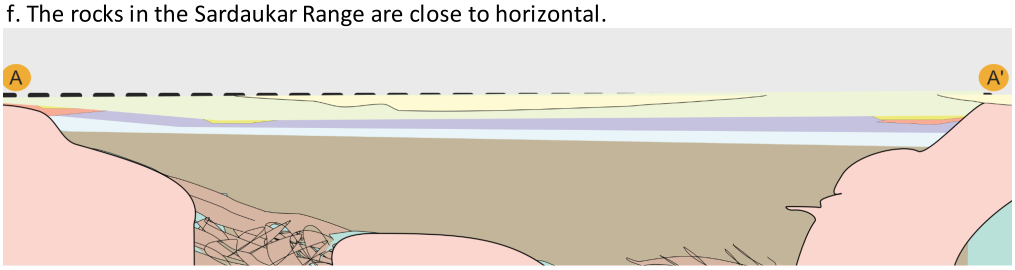
d. The rocks in the Sardaukar Range dip towards the south east.



e. The rocks in the Sardaukar Range dip vertically.



f. The rocks in the Sardaukar Range are close to horizontal.



Philip wasn't sure the search for life on Venus would yield anything but he easily found fossils in the Devonian rocks beneath his camp bed on Earth! He explained to his friends that he was camped somewhere between the Devonian rocks of the Harkonnen Range and the early Proterozoic (Siderian) rocks of the Atreides Group (Figure 17 & Figure 18).

24. Gabi was intrigued by Philip's outcrop photograph (Figure 18). She noted there were 6 protruding sets of beds with sets of hard-to-see recessed beds in between them. She asked Philip to explain why the outcrops were like this.

Q: What was Philip's answer? (1 mark)

The recessed beds contain some fossils but …

a. … they also contain a lot of easily weathered quartz grains and are therefore more prone to crumble and be washed away by rain as they weather.
b. … they are also metamorphosed and are therefore more prone to crumble and be washed away by rain as they weather.
c. … they also contain a lot of mud and silt and are therefore more prone to crumble and be washed away by rain as they weather.
d. … they also contain a lot of pillow lavas and are therefore more prone to crumble and be washed away by rain as they weather.
e. … they also contain a lot of siliceous binding minerals and are therefore more prone to crumble and be washed away by rain as they weather.
f. … they also host igneous dykes and are therefore more prone to crumble and be washed away by rain as they weather.

25. Gabi was even more intrigued by the outcrop in the photograph (Figure 18). She understood the outcrop's appearance was weathering related but wasn't sure why the rocks would vary in such a cyclical manner.

Q: What explanation did Philip's provide? (1 mark)

a. Each 'cycle' from protruding to recessed rock types represents changes in sea level from deeper water metamorphic environments to shallow water where reef-building communities form limestone.
b. Each 'cycle' from recessed to protruding rock types represents changes in sea level from shallow water to deeper water where reef-building communities form limestone.
c. Each 'cycle' from recessed to protruding rock types represents changes in sea level from deeper water to shallow water where reef-building communities form limestone.
d. Each 'cycle' from recessed to protruding rock types represents changes in sea level from deep water rift zones to shallow water where reef-building communities form limestone.
e. Each 'cycle' from protruding to recessed rock types represents changes in sea level from the continental shelf to the abyssal plain where reef-building communities form limestone.
f. Each 'cycle' from recessed to protruding rock types represents changes in sea level from dry desert sand dunes to shallow water where reef-building communities form limestone.

26. Philip had a great time fossicking for fossils at locality 1 (Figure 18), finding a lot of easily identifiable fossils. The 5 most easily identified are shown in Figure 19 (a-e – on the next page). He was joined for this part of his adventure by Jeff Gnathostomes, famous fossil fish palaeontologist. Jeff was keen to find lots of fossils, whether they be placoderm fish or fish food (invertebrates), in the Devonian rocks. Philip thought he found an archaeocyathid – an extinct sponge-like organism (Figure 19f & Figure 20) common as reef-builders in some Palaeozoic limestones.

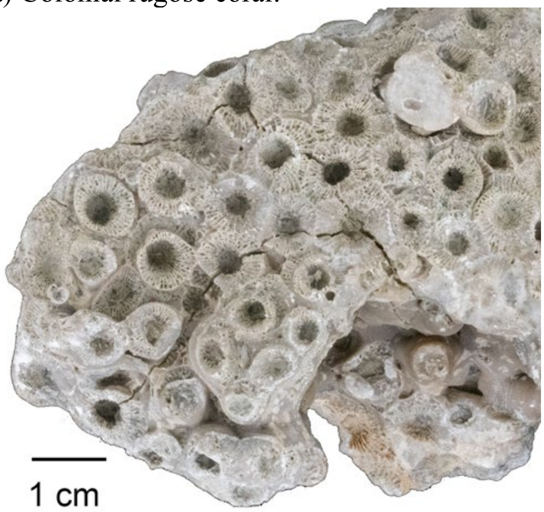
Figure 20: An archaeocyathid limestone, typical of marine bioherms (reef-like mounds) found in some Cambrian deposits.

Q: What explanation did Jeff give Philip to convince him his mystery fossil (Figure 19f, bottom right?) was <u>not</u> an archaeocyathid? (1 mark)

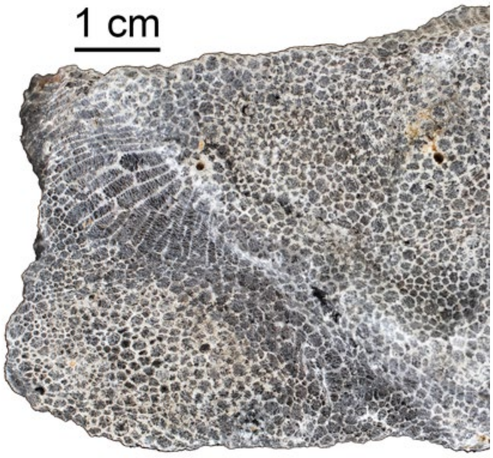
Some archaeocyathids superficially resemble some corals, but a close examination reveals there are clear differences between the skeletons of these sponge-like organisms (Figure 20) and the skeletons of rugose or tabulate corals. Additionally, …

a. … your 'fossil' is obviously a back filled sand trout burrow.
b. … Archaeocyathid skeletons dissolve in rainwater.
c. … Archaeocyathid biostratigraphy only overlaps with trilobites.
d. … Archaeocyathids lived on land. The fossils you found are all remains of marine animals.
e. … Archaeocyathids did not evolve until after the organisms you found as fossils were completely extinct.
f. … Archaeocyathids were completely extinct before the organisms you found as fossils evolved.

a) Colonial rugose coral:

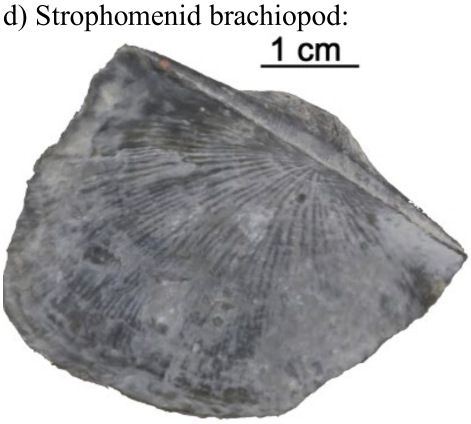


b) Colonial tabulate coral:



c) Colonial branching tabulate coral:

d) Strophomenid brachiopod:



e) Phacopid trilobite:

f) Philip's unknown fossil find:

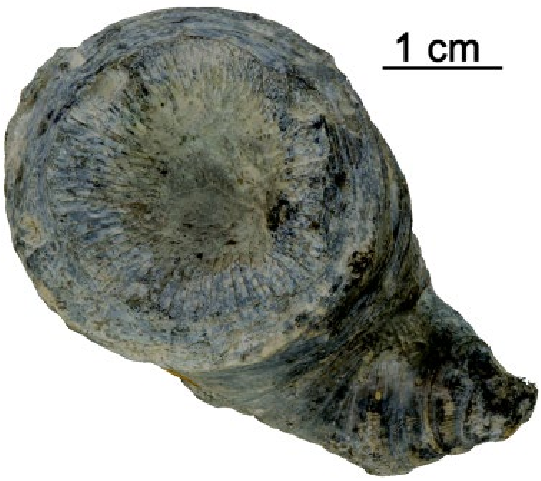


Figure 19: The suite of fossils found at site 1 (Figure 18).

Philip's unknown fossil is shown bottom right. It has a distorted conical shape.

27. Philip accepted Jeff's explanation, and upon further examination concluded his mystery fossil was actually a solitary rugose coral. However, he was still unsure why the fossils, and hence the rocks they are in, are described as Devonian in age.

Q: What did Jeff say to Philip in response to his Devonian puzzle? (1 mark)

In the absence of a radiometric date on the rocks, fossils are our only clue to the age of the rock. However, to be sure the rocks are of Devonian age we must either accurately identify one of your fossil finds as an index fossil for the Devonian or …

a. … find a placoderm fish fossil in these rocks.
b. … find both a placoderm fish fossil and an ammonoid fossil in these rocks.
c. … find both a placoderm fish fossil and a graptolite fossil in these rocks.
d. … find both a graptolite fossil and an ammonoid fossil in these rocks.
e. … find both ray-finned fish fossil and a graptolite fossil in these rocks.
f. … find sand worm fossils in these rocks.

28. As they trekked south west along the spine of the Harkonnen Range (Figure 18), Jeff and Philip encountered some interesting scenery (Figure 21). When they stopped for lunch in the shade, Philip noticed a breeze emanating from a large fissure in the rock face. He exclaimed: *Excellent. I knew we would find caves in this area!*

Q: What made Philip certain they would find caves in this area? (1 mark)

a. $CO_2 + H_2O \Leftrightarrow H^+ + (HCO_3)^-$
b. $2H^+ + CaCO_3 \Leftrightarrow Ca^{2+} + CO_2 + H_2O$
c. $SO_2 + H_2O \Leftrightarrow H^+ + (HSO_3)$-
d. $2H^+ + MgCO_3 \Leftrightarrow Mg^{2+} + CO_2 + H_2O$
e. Both a & b.
f. Both c & d.

Figure 21: Cycads thriving in a limestone ravine, south western Harkonnen Range. Image modified from Playford et al 2009.

Philip and Jeff are experienced cavers and also have the appropriate permits to enter caves in this area. They simply couldn't resist exploring inside a little since they had the right equipment with them! Inside, after carefully progressing along a narrow passageway, they found a number of large spaces (called chambers by cavers). In one chamber (dubbed Jeff's Chamber) they found some bones protruding from sandy red-brown cave floor sediments. They appeared to be articulated*. In another chamber on a different level (dubbed Philip's Chamber), they found a sandy yellow-brown sediment on the cave floor with broken bits of bone – many with teeth marks – everywhere. They took photographs, complete with scale cards, and made sketches to document exactly what they found on the surface of the sediments in each chamber. Once back outside they sent all this information, complete with the cave mouth coordinates, to team members Jiki Nakamura (geochronologist) and Traci Menandai (palaeontologist).

**Articulated* means the bones of the skeleton are in the same relative position to each other as they were in life.

29. Traci replied immediately, informing them that this cave (known as Paul's Cave) is not new to science, but has never been excavated. Extracting and documenting the vertebrate fossils in cave deposits is an exacting and time consuming process but the images do show identifiable remains. She added: *Finding articulated remains is exciting. They help us understand what the animals might have looked like, especially if they are previously unknown species!*

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

a. The remains in Jeff's Chamber indicate the animals died in the cave, perhaps after falling down a sinkhole, and were not fed upon by scavengers after dying from the fall.
b. The remains in Philip's Chamber suggest the animals possibly died outside the cave and their disarticulated remains were washed into the cave, perhaps down a sinkhole.
c. The remains in Philip's Chamber suggest the animals possibly died in the cave, perhaps after falling down a sinkhole, then subsequently fed on by scavengers.
d. The remains in Philip's Chamber suggest the animals were possibly captured by predators and taken into the cave for consumption.
e. Both a & b.
f. All of a, b, c & d.

30. Jiki Nakamura was also excited by the find. She told them about a well-documented cave, Jessica's Cave, in the same area. They said 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 2; Figure 22).

Unit #	**Dated material**	**Dating method**	**Level within the cave**	**Numeric al 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 $^{40}Ar/^{39}Ar$.				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 2: 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.

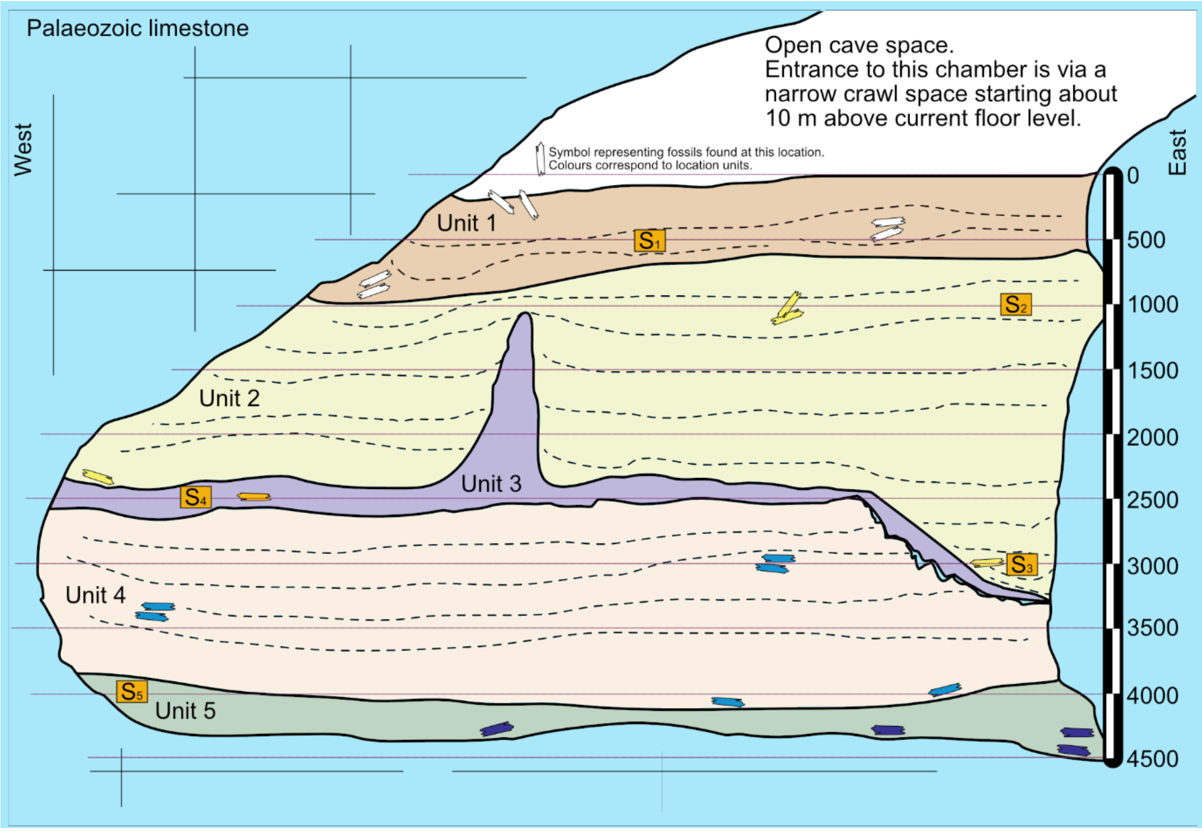


Figure 22: Cross section of cave deposits in Sordkreek's Chamber within chamber Jessica's Cave, looking towards the North showing five distinct documented lithological units. No datable material was found in Unit 4, however, fossils in Unit 4 correlate with others elsewhere associated with basalt lava flows dated at 2.05 ± 0.2 and 3.25 ± 0.2 Ma.

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

Assuming a cave system takes as much as 5 million years to develop into a large open space and the cave opened to the surface very early in its history, fractures in the Palaeozoic limestone did not start to host groundwater and form caves until sometime in the ....

a. … Holocene.
b. … Pleistocene.
c. … Pliocene.
d. … Miocene.
e. … Oligocene.
f. … Eocene.

31. Philip and Jeff were familiar with this type of cave stratigraphy, but their astronomer friend, Daytona Light, was puzzled by some of the data. She wanted to know how it was possible for fossils between 2–3 million years old to be found at the same depth (3 m) as fossils dated at ~57,500 a.

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

a. Prior to flowstone deposition, increased water flow into and through the cave system eroded some of Unit 4, forming a channel along the eastern wall.
b. After flowstone deposition, increased water flow into and through the cave system eroded some of Unit 4, forming a channel along the eastern wall.
c. Sometime after the deposition of Unit 2, a massive earthquake caused large, heavy fossil bones in Unit 2 to settle down to 3 m via liquefaction.
d. Sometime after flowstone deposition, animal burrows caused a collapse along the eastern wall.
e. The dating performed at S_3 must be faulty, probably because it is too close to the upper limit of AMS C-14 dating.
f. The correlation of Unit 4 fossils with those constrained by basalt flow age dates elsewhere must be incorrect.

32. Daytona was happy with Jeff's explanation about the mis-matched ages at the 3 m level but remained puzzled by how Unit 5 came to contain volcanic ash.

Q: Jiki was quick to answer by saying … (1 mark)

a. When lava enters a wet cave it creates a steam explosion, forming ash that is then plastered onto the cave floor, walls and ceiling.
b. When caves are open to the surface, wind-blown sediments (including ash from volcanic eruptions) can settle into the cave and form deposits on the cave floor.
c. When streams erode granites exposed on the surface and then run underground into caves, they carry with them the weathering products of those igneous rocks which are in turn deposited on the cave floor.
d. Volcanic ash is a soft fluffy material, used by many cave dwelling animals for bedding.
e. Volcanic ash is a euphemistic term for the waste products left behind by sand worms as they mine the cave sediment for the organics found in bones.
f. The palaeontologists call it ash but it is actually intrusive magma forming a sill. You can tell this because it has so many gas bubbles trapped in it.

33. Daytona was pleased with her new found knowledge of cave deposits but wanted to know more about the flowstone speleothem, especially the weird pointy bit sticking up through Unit 2 in the cross section. Jiki shared another image (Figure 23), stating this was from an as yet unpublished research paper and adding: *The pointy thing is a stalagmite. The flowstone and stalagmite were formed by the same chemical precipitation process but a drip point from the ceiling supplied the water for the stalagmite. That water, and water from other places in the cave, will have contributed to the growth of the flowstone. In this new paper, we show:*

a) the average growth rate for the upper 1 m of the stalagmite is ~1.8 mm / 100 years.

b) differential growth rates of the stalagmite, for several intervals in the upper 1 m, are …

Figure 23: The upper 1,000 mm of the stalagmite excavated in Sordkreek's Chamber, Jessica's Cave (Figure 22). Four dates were successfully measured from samples taken from the stalagmite 1,050 mm, 1,104 mm 1,404 mm and 2,050 mm below the surface.

Q: What growth rates for intervals GR1, GR2 and GR3, expressed as mm/100 years, did Jiki quote from their paper? (1 mark)

a. GR3 = ~1.2
   GR2 = ~0.3
   GR1 = ~5.1
   suggesting the drip rate dramatically decreased during GR2.
b. GR3 = ~0.51
   GR2 = ~1.2
   GR1 = ~0.3
   suggesting the drip rate was highest during GR2.
c. GR3 = ~0.3
   GR2 = ~1.2
   GR1 = ~5.1
   suggesting the drip rate decreased over time.
d. GR3 = ~0.03
   GR2 = ~0.12
   GR1 = ~0.51
   suggesting the drip rate progressively decreased over time.
e. GR3 = ~2.12
   GR2 = ~2.2
   GR1 = ~51
   suggesting the drip was highest during GR3.
f. GR3 = ~2.3
   GR2 = ~51
   GR1 = ~2.1
   suggesting the drip rate was highest during GR2.

34. Jeff was quick to add that stalagmite growth rates don't necessarily correspond with changes in climate. Jiki concurred saying: *Drip rates in caves can vary because of factors other than rainfall change due to climate change. Such factors include changes in ground temperature and cave humidity plus ...*

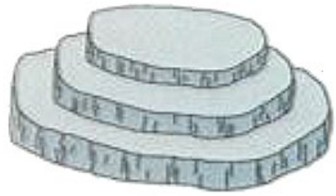
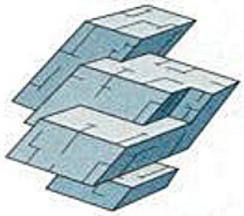
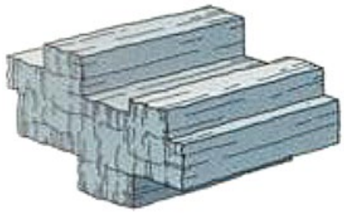
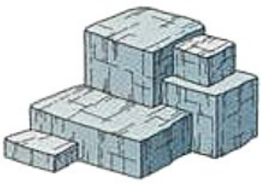
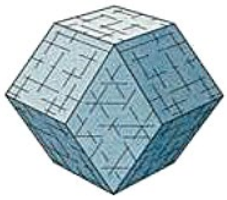
Q: What did Jiki conclude their remarks with? (1 mark)

a. … local ground movements opening or closing fractures.
b. … large scale tectonic events reorganising surface drainage.
c. … the growth of crystalline materials blocking conduits for water.
d. … the formation of sinkholes, blocking and/or reorganising surface and/or subsurface drainage.
e. … the lateral migration of meandering surface streams.
f. All of the above.

35. Rose noted that the recrystallised interior of the stalagmite is transparent and vitreous like quartz (Figure 24), but also has parallel sets of internal fractures, which quartz does not. She challenged her non-mineral-obsessed friends to determine the cleavage pattern based on observations from the image. She was pleased to see she had educated all her friends well!

Figure 24: Close up view of the lower section through the stalagmite shown in Figure 23.

Q: Which image was selected as correct by all her friends? (1 mark)

a		d	
b		e	
c		f	

36. Rose further challenged them to figure out what items they have on their person or in their field kit they could use to confirm the mineral's identity.

Q: Which object(s) was/were selected as correct by all her mineral obsessed friends (and some of the others)? (1 mark)

a. Gypsum crystals from water filter.
b. Talcum powder from personal hygiene kit.
c. Silica glass window on rover.
d. Hardened steel blade or thermos canister.
e. Fingernail, aluminium food box and vinegar from meal kits, plus copper wire from electronics.
f. Carborundum plates on the base of sand dune skis and diamond ring.

37. Their friend and team member Ellie Mints joined the chat saying: *Stable oxygen isotope ratios tell us about changes in climate and seawater properties over time because the shells of marine organisms are built of calcium carbonate ($CaCO_3$) using materials, including oxygen, extracted from seawater.* She also shared this statement from a *virtual textbook she co-authored:

> The two main stable oxygen isotopes are ^{16}O and ^{18}O. They both occur in water (H_2O) and in the calcium carbonate ($CaCO_3$) shells of marine animals. The most abundant and lighter isotope is ^{16}O. Since $H_2{}^{16}O$ is slightly lighter than $H_2{}^{18}O$, it evaporates more readily from the ocean's surface. Evaporation increases as sea water warms and so too does rainfall. However, since $H_2{}^{18}O$ is slightly heavier than $H_2{}^{16}O$ it is more likely to rain out nearer the evaporation point. From this we can draw several conclusions.

Q: What did Ellie conclude her remarks with? (1 mark)

a. The further rainfall is from the evaporation source, the more relatively enriched in ^{16}O it is likely to be.
b. The further rainfall is from the evaporation source, the more relatively enriched in ^{18}O it is likely to be.
c. A higher amount of ^{16}O in a shell probably indicates higher sea surface temperatures at the time the shell formed.
d. A higher amount of ^{18}O in a shell probably indicates higher sea surface temperatures at the time the shell formed.
e. Both a & d
f. Both c & b

*Holographic text books with embedded 3D and 4D models, graphs and diagrams are a cool idea! Maybe you can make them a reality someday ☺

38. Roxanne's brother Orson chimed in saying: *Stable oxygen isotope ratios are very cool but what do they have to do with caves?*

Q: Ellie's reply was very helpful. She said … (1 mark)

Most caves are formed through the actions of rain water on limestone. Water saturated with calcium cations and carbonate anions also re-precipitates calcium carbonate inside caves to form speleothems like flowstone and stalagmites.

a. Speleothems record climatic conditions via the $^{16}O/^{18}O$ ratio of rainwater incorporated into their component minerals.
b. The water that dissolved the space to make the cave contains oxygen from the skeletons of ancient marine organisms in the limestone. It records a climate signature via their $^{16}O/^{18}O$ ratio.
c. The speleothem's minerals contain oxygen dissolved out of the skeletons of the creatures that built the limestone. They carry a climate signature thanks to its $^{16}O/^{18}O$ ratio in the rock.
d. The cave's atmosphere incorporates some of the oxygen from the limestone, which records a climate signature in its $^{16}O/^{18}O$ ratio.
e. The cave's atmosphere incorporates some of the oxygen from the rainwater, which records a climate signature in its $^{16}O/^{18}O$ ratio.
f. Caves are awesome but they don't record any climate data.

After a long day's caving, Jeff and Philip sat around a campfire at location 2 (Figure 17) talking about life, the universe and everything. Staring up at the sky, they spotted (and counted) 41 meteors burning up but another one appeared to continue on and make landfall. They quickly reported this potential meteorite via the *Fireballs* app, still going after all these years, and plotted its trajectory, heading south-southwest (195°). It turns out it was the time of the annual Southern Taurids meteor shower!

39. After consulting their maps, they decided to explore for it when they reached the right general area (Figure 17). They blogged: *Assuming it didn't burn up completely or land in the sea, our calculations suggest it landed near location …*

Q: Which location did they nominate? (1 mark)

a. 1	b. 2	c. 3
d. 4	e. 5	f. 6

40. After the excitement of the meteorite abated, they had a lovely evening star gazing. From sunset until first light the sky was exceptionally dark . In the morning, Philip asked their astronomer friend Zoe why it had been so dark on such a clear night. She explained it had been a new Moon. This is when the Moon cannot be seen at night because it sets approximately at sunset and rises at about sunrise. Hearing his heartbeat a little louder at the thought of his favourite music, Philip asked jokingly: *So last night, were we looking at the dark side of the Moon?*

Zoe replied: *No, there was no moon to see, it was on the opposite side of the planet to you. Also, the Moon is tidally locked to the Earth so we only ever see the one side, known as the near side. The so-called 'dark side of the Moon', also known as the far side, is …*

Q: What did Zoe complete her sentence by saying? (1 mark)

a. … always dark, even during a new Moon.
b. … only dark when it is a full Moon.
c. … only dark when it is a new Moon.
d. … never dark, no matter the phase of the Moon seen from Earth.
e. … only dark during the winter or summer solstice.
f. … only dark during a solar or lunar eclipse.

41. Jeff and Philip explored their #2 campsite area in the morning. In between the crests of massive longitudinal sand dunes, trending north-south, there were places where bedrock was exposed. In one place a spring-fed stream had cut down into the bedrock to reveal a three-dimensional scene, complete with a wonderful swimming hole (Figure 25 at right). Luckily they knew where their towels were. Jeff, who loves swimming almost as much as anchovy ice cream, was a very hoopy frood.

Figure 25: Swimming hole.

Photographs they shared with their friends include shots of fauna, flora and rocks. Zoe's reaction to seeing one picture (Figure 26a) was: *Wow! What is that?? How on Earth did that weird pile of stuff end up being a rock?*

Philip responded to Zoe with a few more images (Figure 26 b-g)

Figure 26a: Rock outcrop photographed in a gorge upstream of the swimming hole. This cross section view, cut by the flowing stream, shows a bed approximately 2 m thick. The top of the unit can be seen in the top left hand corner of the image.

Figure 26b

Figure 26c

Figure 26d

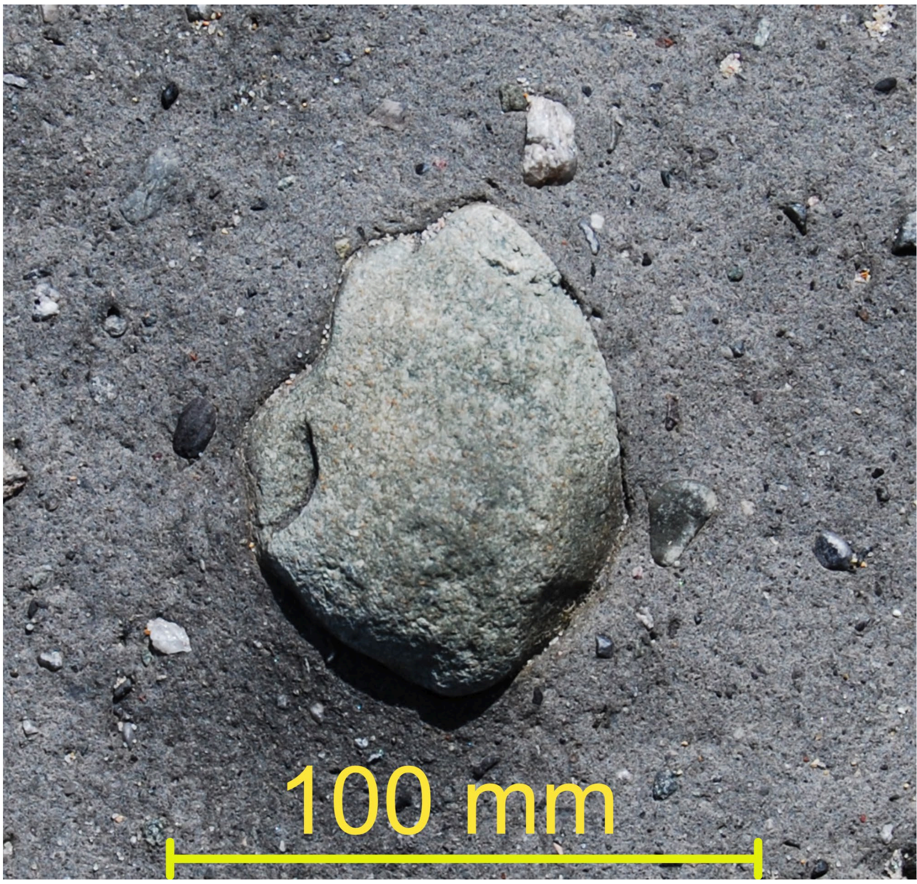


Figure 26e

Figure 26f

Figure 26g

Q: What did Philip say to go with these interesting images? (1 mark)

The grains forming this sediment are …

a. … very well sorted.
b. … very poorly sorted.
c. … well sorted.
d. … moderately sorted.
e. … poorly sorted.
f. … shaken, not stirred.

42. Zoe was impressed by the different kinds, shapes and sizes of pebbles she could see in the photographs but wondered how they all came to be in this one rock.

Q: What was Philip's reply to her query about the diversity of pebbles in the rock? (1 mark)

All the grains, not just the obvious pebbles, are derived from many different source rocks in the landscape. This is probably because this rock was formed …

a. … by an explosive volcanic eruption, blasting apart the cooling magma, the older volcanic rocks and the other near-surface rocks through which the magma had intruded. The fragments lithified through 'heat welding' immediately after the debris landed on the surrounding landscape.
b. … as a result of a massive landslide from a mountain range containing a geologically complex suite of rock types. The fragments lithified through compaction and cementation immediately after the debris landed on the surrounding landscape.
c. … by a meteorite impact on a geologically complex terrain. This formed a large circular deposit of shattered rocks of all grain sizes. Infiltration of groundwater then deposited cementing minerals.
d. … by glacial transport of rocks from a geologically complex terrain. The rocks and sediments of all sizes were transported in ice to the coast where it was rafted out to sea before the icebergs melted. The seafloor sediments then experienced compaction and cementation.
e. … by a volcanic mudflow, known as a *lahar*. Loose rocks and sediments in a steep volcanic terrain are whipped into a violent and fast-flowing slurry when mixed with large volumes of water. This sets like concrete when it loses momentum.
f. … by any of the above processes, based on the observations. Further observations are needed to determine the most likely process.

43. Philip made several observations about this interesting outcrop and the large pebbles sticking out of it. His first comments concerned the first images (Figures 26a, 26b & 26c). He wrote: *In both the cross-section exposure (Figure 26a) and the bedding plane views (Figures 26b & 26c) there are pebbles sticking out of the fine grained grey material. I wonder why this happens?*

Q: Everyone knew Philip knew the answer, but which of his friends gave the most accurate reply? (1 mark)

a. Gabi said: Differential erosion.
b. Sandra said: The grey material is easier to erode than the pebbles.
c. Rose said: The angular white pebble in Figure 26c is probably quartz, it is harder than the grey material.
d. Jeff said: None of the pebbles are fish fossils; erosion happens.
e. Darcy said: The flowing water from the spring has been effective at eroding the grey material.
f. Zoe said: All the comments are correct but complement each other, taking them together makes for the best answer.

44. Next came Philip's comment on the big red clast in the rock in Figure 26d. He wrote: *Believe it or not, this incredibly hard high-silica rock has a deep-sea sedimentary origin. How could I determine that?*

Q: Which of Philip's friends rose to the challenge and answered correctly? (1 mark)

a. Gabi said: A close look shows it is finely laminated, suggesting it originally formed from fine grained material settling on the seabed. It was originally a siliceous ooze formed from the silica-rich skeletons of some types of marine plankton.
b. Sandra said: A close look shows it is finely laminated, suggesting it originally formed from fine grained material settling on the seabed. It was originally a carbonate ooze formed from the carbon-rich skeletons of some types of marine plankton.
c. Rose said: The laminations show it is volcanic in origin. Each layer of ash forms one lamination. The red colour shows it is felsic igneous rock, not sedimentary at all.
d. Jeff said: Laminations indicate layers. The colours indicate it is iron rich. A deep sea origin can only mean it is a fragment of a hydrothermal deposit from a mid ocean ridge eruption centre.
e. Darcy said: The laminated appearance and the fact that it is really hard indicates it was formed from very fine-grained quartz sand raining down onto the seabed after drifting well out to sea, suspended by the natural turbulence of the ocean waters.
f. Zoe said: The colour, a deep red, with fine laminations of slightly different colours but of the same composition, is a give away that it is a banded iron formation.

45. Philip kept up the game with comments about the large clasts in the rock in Figures 26e & 26f. He wrote: *Both these rocks are metamorphic. One is a bit green and one has quartz veins shot through it but what indicates they are metamorphic?*

Q: Which of Philip's friends correctly explained what characteristics can be used to determine the clasts are metamorphic? (1 mark)

a. Gabi said: Both rocks are completely recrystallised, making for larger versions of the original crystals in the rock.
b. Sandra said: The green rock's colour indicates it is a greenschist, a low grade metamorphic rock. The black rock has quartz veins and they are only ever found in metamorphic rocks.
c. Rose said: Both rocks contain phenocrysts, larger crystals that crystallise from a melt at metamorphic temperatures and pressures.
d. Jeff said: Both rocks are composed of mineral assemblages that only form at metamorphic temperatures and pressures.
e. Darcy said: The black rock is obsidian. The quartz veins demonstrate it has been metamorphosed. The green rock is a metamorphosed olivine basalt.
f. Zoe said: The green rock is a copper ore that only forms from hydrothermal fluids at a mid ocean ridge. The black rock is a meteorite with shocked quartz, which forms veins via shock metamorphism.

46. Finally, Philip asked about the big pink-ish clast in the rock in Figure 26g. He wrote: *This rock is very coarse grained. It is fully crystalline with 3 predominant mineral types: quartz, an orangy-pink feldspar, and a white feldspar. The crystals appear to be randomly oriented relative to each other. Where would this rock have originally formed?*

Q: Which of Philip's friends correctly described the formation environment? (1 mark)

a. Gabi said: This rock is a rhyolite that formed as an intrusive felsic magma cooled slowly, at least 4 km beneath the surface.
b. Sandra said: This rock is a rhyolite that formed as an intrusive mafic magma cooled slowly, at least 4 km beneath the surface.
c. Rose said: This rock is a gabbro that formed as an intrusive felsic magma cooled slowly, at least 4 km beneath the surface.
d. Jeff said: This rock is a gabbro that formed as an intrusive felsic magma cooled slowly, at least 4 km beneath the surface.
e. Darcy said: This rock is a granite that formed as an intrusive felsic magma cooled slowly, at least 4 km beneath the surface.
f. Zoe said: This rock is a granite that formed as an intrusive mafic magma cooled slowly, at least 4 km beneath the surface.

47. Philip explored the area some more before moving camp. Beneath the curious rock he photographed, he found some bedding planes of the same Devonian sequence he'd camped on earlier. These bedding planes had many north-south trending parallel grooves scratched into them (Figure 27). Further exploration led him to discover a conglomerate and sandstone outcrop overlying the curious rock (Figure 27). He was very excited to find a dinosaur footprint close to the contact between these beds and the curious rock they overlaid (Figure 27).

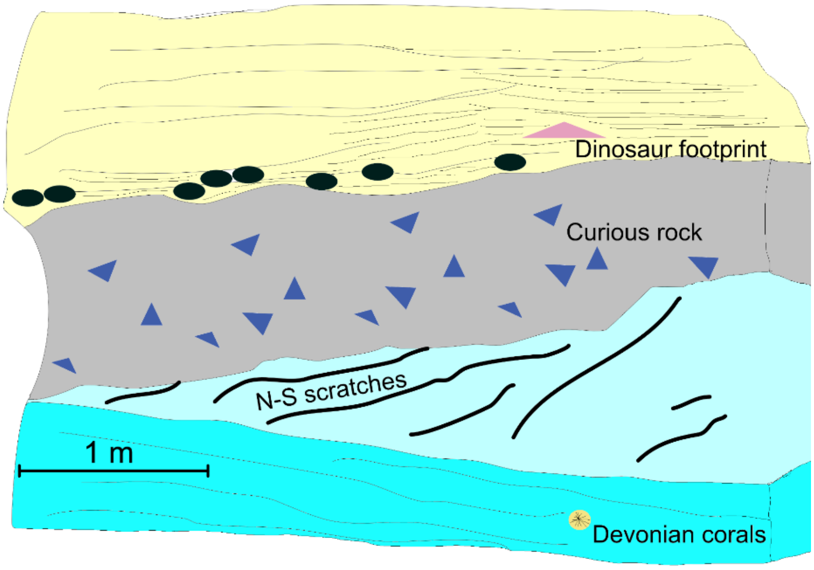


Figure 27: Philips field sketch at the location where the dinosaur footprint was found and all 3 units can be seen in outcrop. Black ellipses represent gravel-rich layers. Dark blue triangles represent the larger clasts in the curious rock (Figure 26). The layer with scratches is a roughly horizontal bedding plane.

He updated his travel blog with: *I just found an amazing dinosaur trace fossil. Using this information and after consulting the Average Global Temperature Curve (Figure 28) I have decided the curious rock must have been deposited during…*

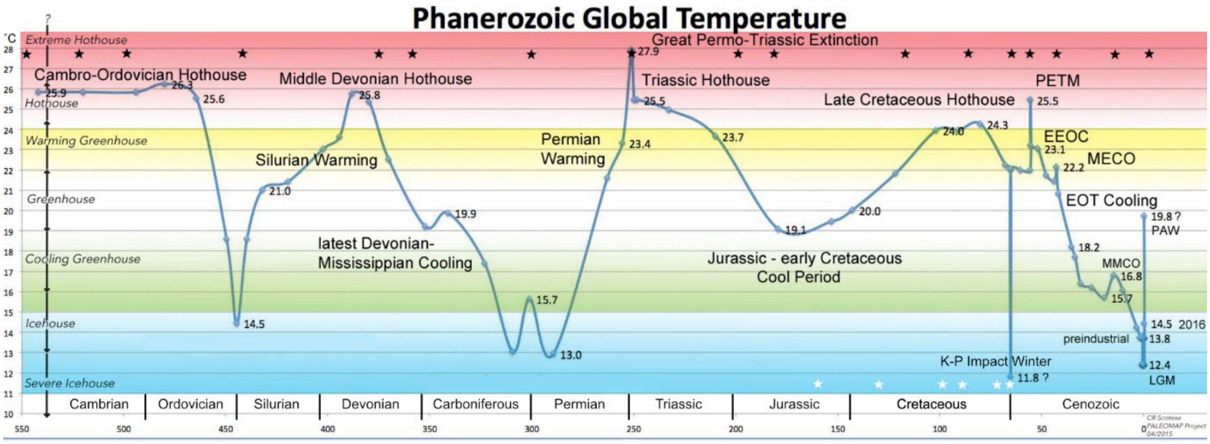


Figure 28: Average Global Temperature Curve for the last 540 Million Years. Surface ice probably did not exist during hothouse conditions. Icehouse conditions allowed large icecaps to develop on each pole, complete with large glaciers outflowing in all directions. White stars indicate rapid cooling episodes. Black stars represent rapid warming episodes. Modified from Scotese 2015.

Q: What words did Philip finish his sentence with? (1 mark)

a. … the Silurian or Devonian.
b. … the Devonian or early Carboniferous.
c. … the late Carboniferous or Permian.
d. … the Permian.
e. … the early Carboniferous.
f. … the Triassic.

48. Rose was excited Philip had found dinosaur evidence, but was puzzled why the asteroid impact that wiped out the dinosaurs 66 million years ago corresponds with a global cooling event.

Q: What explanation did Philip give to help Rose understand why this is so? (1 mark)

a. Asteroids are made of ice, so when this asteroid entered the atmosphere it cooled the entire planet.
b. The asteroid's impact ejected so much debris into the atmosphere that it blocked out the sunlight for a period of time, cooling the Earth significantly.
c. The asteroid's tail grew so large as the asteroid approached the Earth it blocked out the sunlight for an extended period of time, cooling the Earth.
d. The asteroid's impact vapourised the entire Atlantic Ocean, causing a global rain event that cooled the Earth for an extended period.
e. The asteroid's impact punched a hole into the mantle, causing massive volcanic eruptions that cooled the Earth for an extended period by ejecting large volumes of SO_2 and aerosols into the atmosphere.
f. Asteroids are made of supercooled rocks (around 4 K), so when this asteroid entered the atmosphere it cooled the Earth down.

49. Jeff and Philip moved camp to location 3, (Figure 17) but only stayed one night because cyclone Paul (Figure 29) was predicted to make landfall in the area immediately north of the Arrakis Peninsula (location 2 Figure 17) in about 72 hours. Philip blogged that he was going to move further south along the coastline quicker than he had previously planned because of the incoming cyclone. He added: *Since we are in the Southern Hemisphere…*

Q: What did Philip say to complete his post? (1 mark)

a. … cyclone Paul will dump a lot of rain well to the north of us, but the Arrakis Peninsula coast will still get very wet and windy and suffer from a large storm surge. Moving south will keep us away from the worst of the onshore winds.
b. … cyclone Paul will dump a lot of rain well to the south of us, but the coast will still get very windy and suffer from a large storm surge. By the time we move south tomorrow the worst of it will be over.
c. … cyclones never land where predicted, so it doesn't matter where we camp. We'll just have to take our chances.
d. … cyclone Paul will dump a lot of rain immediately over Arrakis Peninsula and turn into a tropical low over the Harkonnen Range. We will get very wet, but the storm surge will be confined to the coastline north of the peninsula and there will be no wind.
e. … cyclone Paul will produce a lot of onshore wind south of the peninsula, so the further south we get the better, especially since the storm surge will only be north of the peninsula.
f. … cyclone Paul's winds will be lofted to high elevations by the location of the Harkonnen Range, so our campsite will be safe from any winds. Moving further south will ensure we are safe from the storm surge.

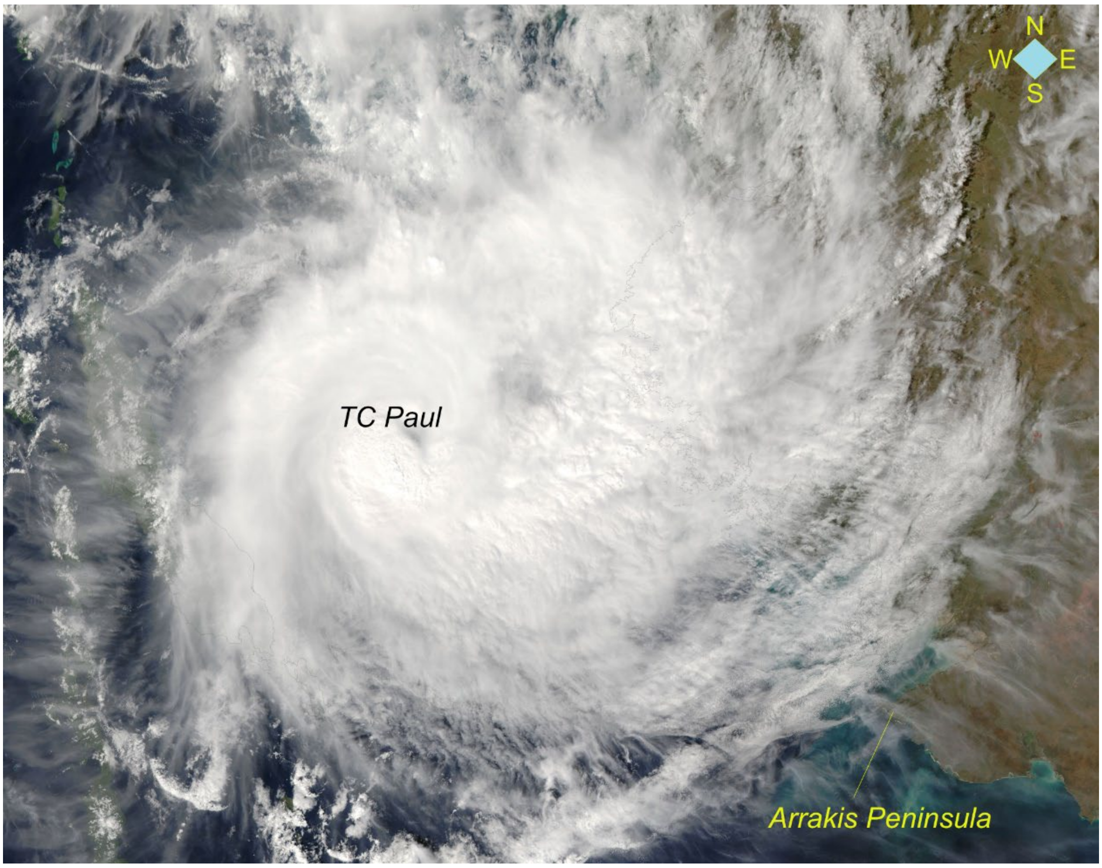


Figure 29: Cyclone Paul, northwest of Arrakis Peninsula and tracking towards the east, approximately 72 hours before the predicted landfall north of Arrakis Peninsula. The label "TC Paul" is just north of the cyclone's eye.

50. Jeff and Philip could only get to location 4 via Highway 42 (Figure 30) as they travelled west to east. They both examined the satellite map of the area and each drew an interesting conclusion, inferred from the map.

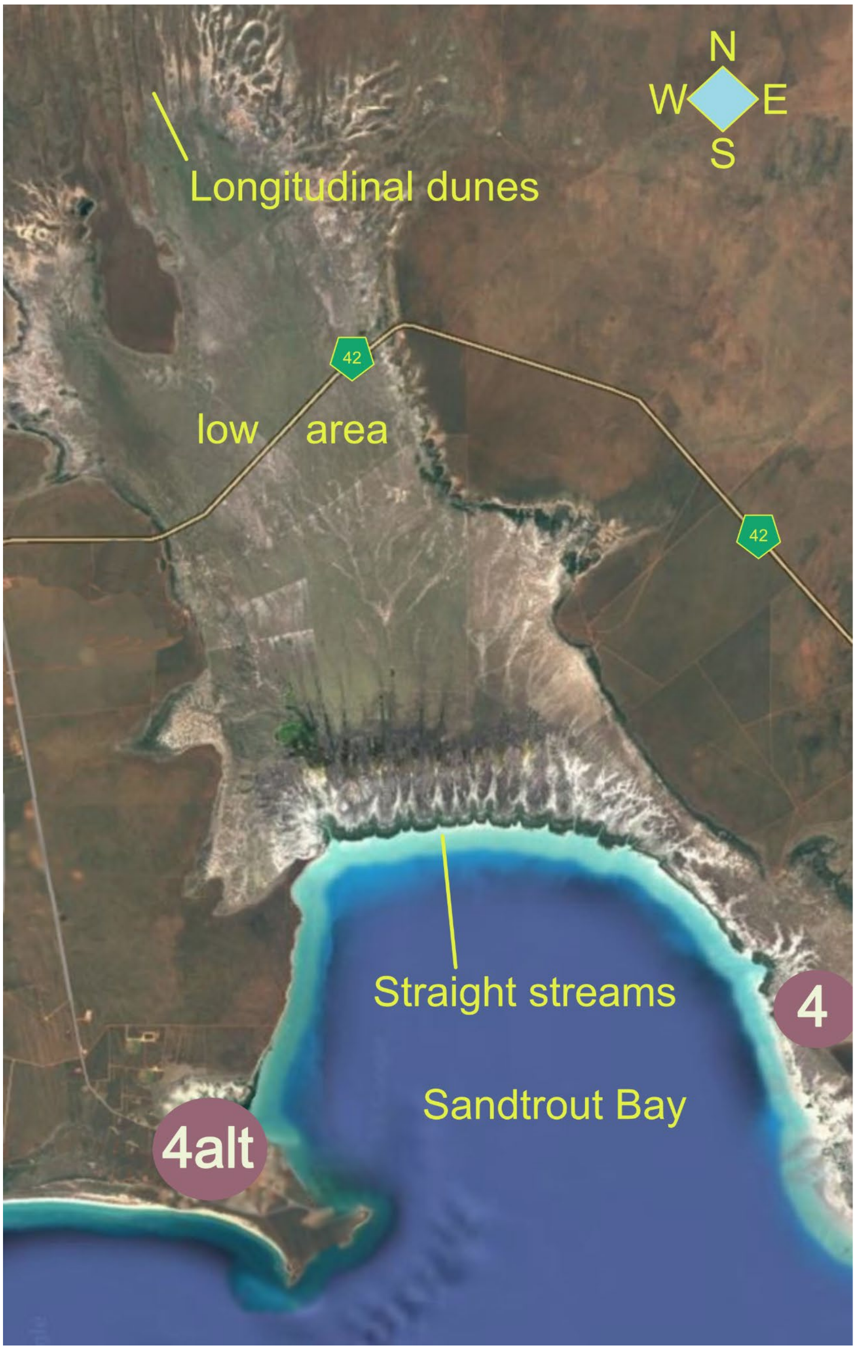


Figure 30: Sandtrout Bay. The longitudinal dunes trend North-South. The straight streams pass through coastal scrub growing on elevated ridges. Highway 42 crosses a low-level area north of Sandtrout Bay and the straight stream ridges. Locations 4 and 4alt are campsites. The satellite image was captured in June, 2.5 years prior to Philip's trip. In the marine zone of this image, dark blue is seawater deeper than 3 m. Pale blue is tidal sea water covering beach sands. White is exposed beach or dune sand.

Q: What logical inferences did they draw based on their observations and knowledge of Earth systems processes? (2 marks)

a. Jeff =1 Philip = 5
b. Jeff =2 Philip = 6
c. Jeff =1 Philip = 6
d. Jeff =3 Philip = 4
e. Jeff =3 Philip = 5
f. Jeff =7 Philip = 8

1: The prevailing wind direction is from the North-South.

2: The prevailing wind direction is from the East-West.

3: The prevailing wind direction is from the Northwest-Southeast.

4: When sea level was lower the Sandtrout Bay area was covered in east-west trending coastal dunes.

5: When sea level was lower the Sandtrout Bay area was covered in north-south trending dunes.

6: When sea level was lower the Sandtrout Bay area was covered in a forest of coastal scrub.

7: The longitudinal dunes are formed by north-south migrations of sandtrout.

8: The location and geometry of Sandtrout Bay proves the low area is a buried 'fossil' deepsea subduction trench, formed by compressional plate tectonics.

9: The location and geometry of Sandtrout Bay proves the low area is down-faulted block (a horst) formed by extensional plate tectonics..

10: The sand in the longitudinal dunes is entirely marine in origin.

11: The sand on the Sandtrout Bay beach is entirely windblown in origin.

12: The sand on the low area has been emplaced by a tsunami.

51. When Jeff and Philip arrived at Sandtrout Bay they were unable to reach their preferred campsite at location 4 (Figure 30) due to flooding from the cyclonic rain dumped on the area over the previous few days (Figure 31a and 31b). They used the alternative campsite 4alt (Figure 30) and waited for the water levels to subside. Figure 32 indicates what the flooding was like in the low area north of Sandtrout Bay on January 10.

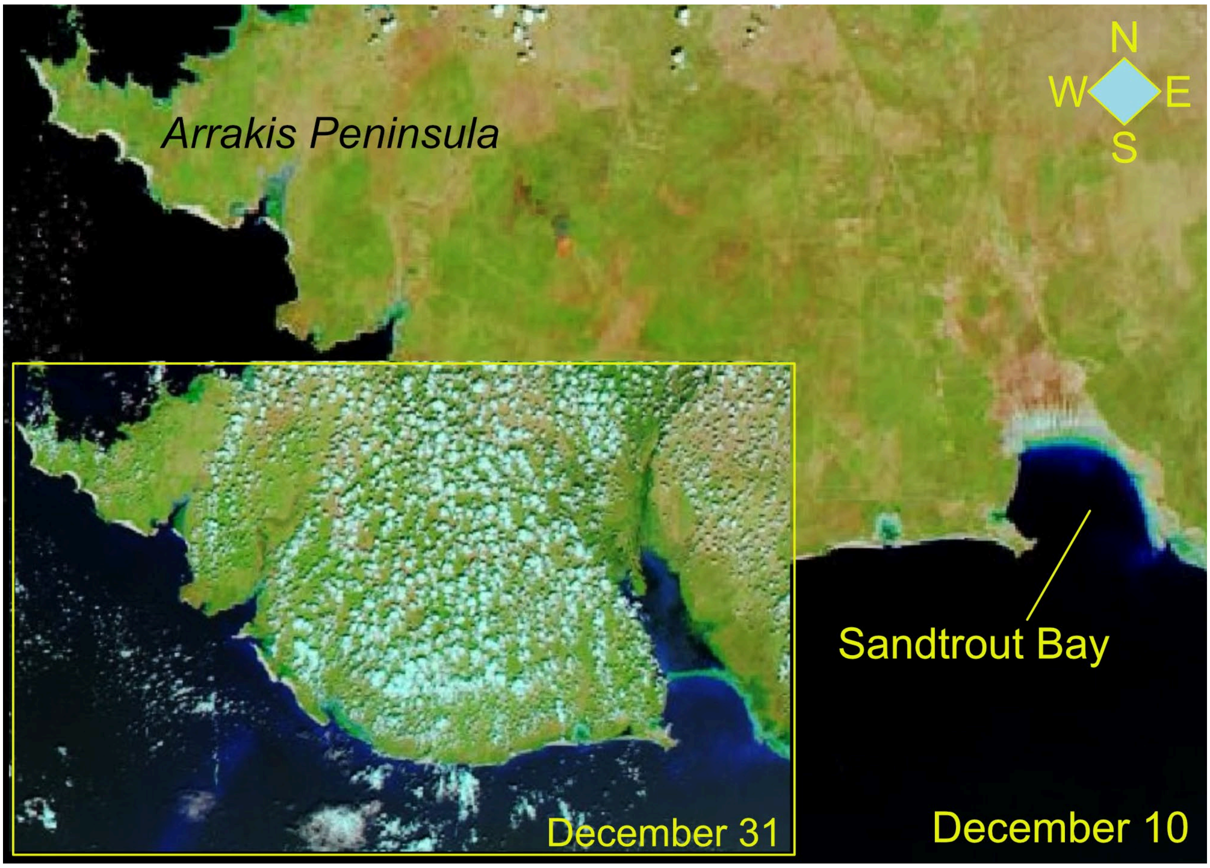


Figure 31a and Figure 31b (inset): Satellite images of the Arrakis Peninsula area 5 days before Cyclone Paul's landfall and 2 days after Cyclone Paul had dissipated into a tropical low over the interior much further to the east.

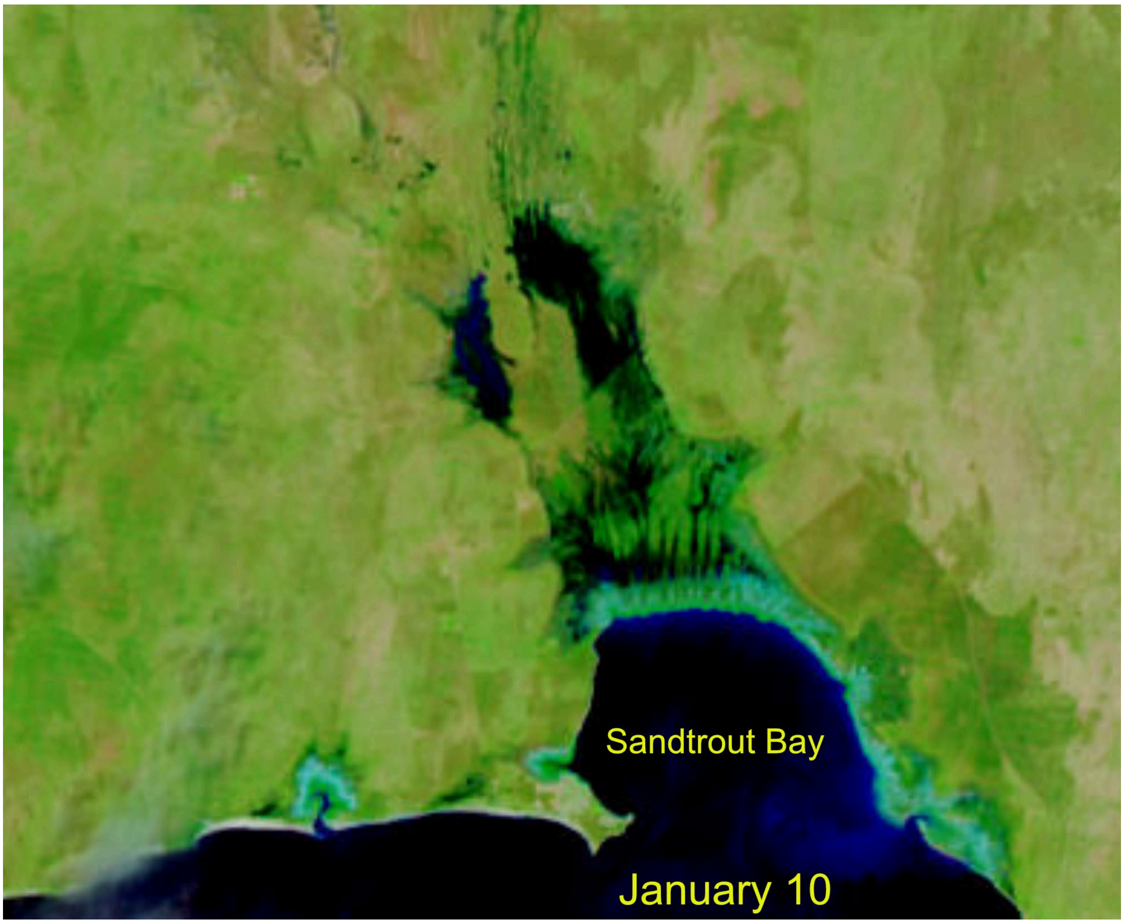


Figure 32: Satellite image of the Sandtrout Bay area 10 days after the flooding peaked.

Philip was enjoying himself, relaxing at their campsite waiting for the water levels to subside. Jeff spent his time discussing the local environment with his followers.

Q: What accurate observations did the group make as part of their discussion? (1 mark)

a. It was a lot wetter 2.5 years ago than it is now.
b. A large seed reserve is stored in the soils of the region.
c. Sand dunes have high porosity but low permeability.
d. Both the sand dunes at the rear of the Sandtrout Bay beach and the adjacent longitudinal dunes are fully exposed in January.
e. If the rate of drainage/evaporation from the low area is constant, the area should be mostly free from standing water by the end of January, assuming no further rainfall events occur in the meantime.
f. At the peak of the rain event, in-flow to the low area exceeded out-flow to Sandtrout Bay.
g. The period December 10 to January 10 had much higher tides than usual.

h. It had been raining on the Arrakis Peninsula landscape for many weeks before the cyclonic rain event.
i. The straight streams flow between elevated ridges, even in the low area.
j. The period December 10 to January 19 had much lower tides than usual.
k. Salinity in Sandtrout Bay would have been much higher than usual in the period December 31 to January 10.
l. The area north of the Sandtrout Bay beach dunes and south of Highway 42 is a depositional trap for suspended sediments once ocean outflow ceases.
m. The low area north of Highway 42 is an excellent location for a sea salt mine.

a) b, e, f, h, i, l
b) b, e, f, h, i, m
c) a, e, f, h, i, l
d) c, i, h, j, m
e) b, f, g
f) g, j, k

52. Highway 42 finally opened and the stranded campers were able to continue onto location 5 (Figure 17). At location 5 Philip was happy to find some rocky shore platforms and coastal cliffs. Jeff was pleased to find some awesome sandy beaches. Prospecting the intertidal zone, finding fossils in the rocks, kept them occupied for several days. Not only did they find some freshwater fish and mussel fossils, they also found a dinosaur trackway (several footsteps in a row).

Philip wrote: *The trackway we found is in a fine-grained rock that fizzes when acid is applied. . The overlying mudstone is weathered away, making it difficult to show the entire trace fossil in a photograph, but I have a good picture of one. I've provided a drawing of it to highlight the key features (Figure 33).* Jeff was very excited by the find and quickly identified it as most probably the footprint of a small bipedal dinosaur of the genus *Megalosuripus*.

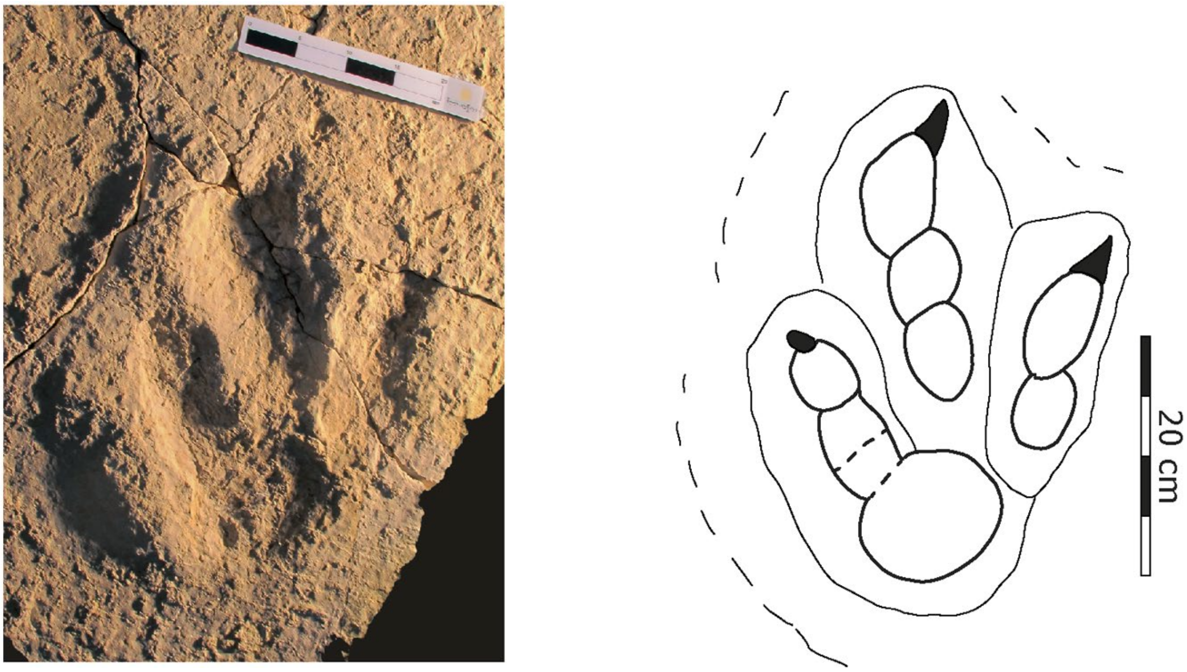


Figure 33: The best footprint Philip could find and his drawing of it to show the animal had 3 clawed toes. Image modified from Razzolini, et al., 2017.

Team member and palaeontologist Traci Menandai was also excited, being an expert on dinosaur locomotion. She sent Philip a diagram of bipedal motion and asked him if his trackway could be measured as per the diagram (Figure 34). Traci also wrote: *It is possible to estimate the animal's speed of motion (v) if we can measure a trackway and know the animal's size and therefore its hip height. We can estimate this creature's hip height (h) based upon the skeletons of known bipedal dinosaurs with a similar foot size. In this case h is roughly 4.9 x length of the pes or foot (PL). All our empirical evidence suggests:*

$v \simeq 0.25g^{0.5} \times S^{1.67} \times h^{-1.17}$ where g is the gravitational constant, S is the stride length and h is the hip height.

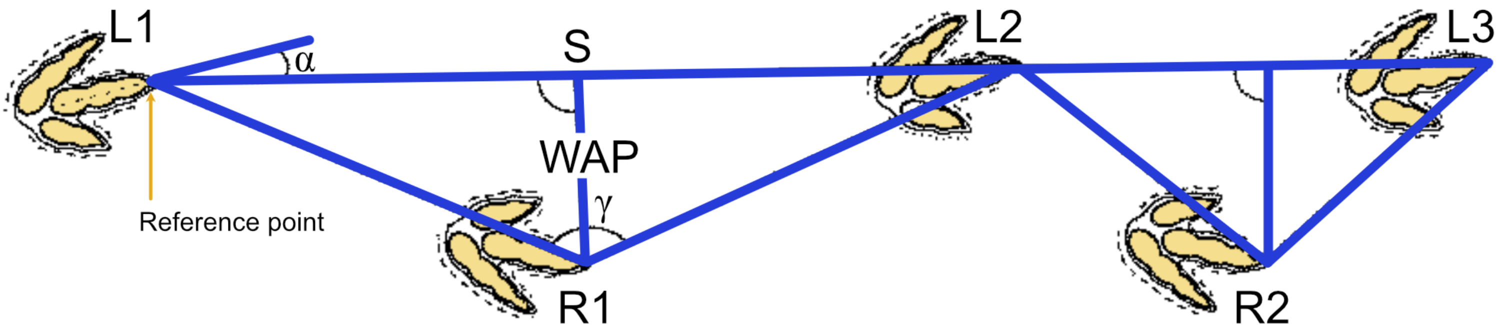


Figure 34: A bipedal dinosaur trackway's measurement parameters. Image modified from Razzolini, et al., 2017.

- *L1, L2 and L3 are prints made by the left foot. R1 and R2 are prints made by the right foot.*
- *LP and RP are left and right pace respectively.*
- *S is the stride length.*
- *WAP is the width of the angulation pattern (perpendicular to stride length)*
- *γ is the pace angulation*
- *α is the rotation of the track with respect to the next stride line*
- *The reference point for the start of the trackway is the tip of the third digit.*

Philip happily made as many measurements as he could and came back with this data based on 9 trackways he found:

Average pes length PL (cm)	Average stride S (cm)
31.6	247.6

Q: What average walking speed (v) did Traci calculate for this dinosaur? (1 mark)

a. ≃ 9.8 km/h
b. ≃ 5.9 km/h
c. ≃ 4.6 km/h
d. ≃ 3.5 km/h
e. ≃ 2.4 km/h
f. ≃ 7.7 km/h

53. Sandra was interested to read that the footprints were in a fine-grained rock that fizzed when acid was applied. She asked Philip for more details and to explore the rocks for other fossils. With the help of local fisherfolk, Philip found many fossils in the beds exposed in the cliff sequence.

He noted the mudstones were actually marls – carbonate rich mudstones. Within the marls he found numerous tiny ammonites plus lesser numbers of bivalves (eg; pippies), echinoderms (eg: sea urchins and starfish) and gastropods (eg snails). Within the other beds he found more bipedal and quadrapedal animal trackways, plus stromatolite-like carbonate-rich laminations and an abundance of invertebrate burrows in some layers. In addition there were signs of desiccation cracking, bidirectional wave ripples and a variety in gastropods common to hypersaline environments.

Q: What palaeoenvironment did Sandra suggest the cliff sequence represented? (1 mark)

a. A wave-dominated delta wherein river sand is reworked into submarine sandbars and wind-blown sand dunes. Waves constantly rework sediment from the deep estuary deposits into the delta foresets.
b. A wave-dominated beach where back-beach wind-blown dunes develop and are stabilised by coastal grasses and scrub.
c. A river-dominated delta that is often exposed to high evaporation rates due to low flow during the dry season.
d. A tidal flat which lies close to or above the mean high-water level for most tides. It is inundated intermittently by high tides or by tides augmented by a storm surge.
e. A tidal flat which lies below the mean high water level for spring tides. It is frequently inundated by ordinary tides and is always wet.
f. A river floodplain which floods frequently due alpine storms and is exposed to hot dry conditions at other times.

54. While Philip was measuring dinosaur tracks, Jeff was observing the sandy beach between the rocky platform and the ocean. Each end of the beach terminates at a rocky headland (Figure 35). He noted one end of the beach had accumulated a lot of flotation devices lost by fisherfolks. Being keen on all things fishy, he wanted to know why they were accumulating in one spot rather than being distributed randomly along the beach.

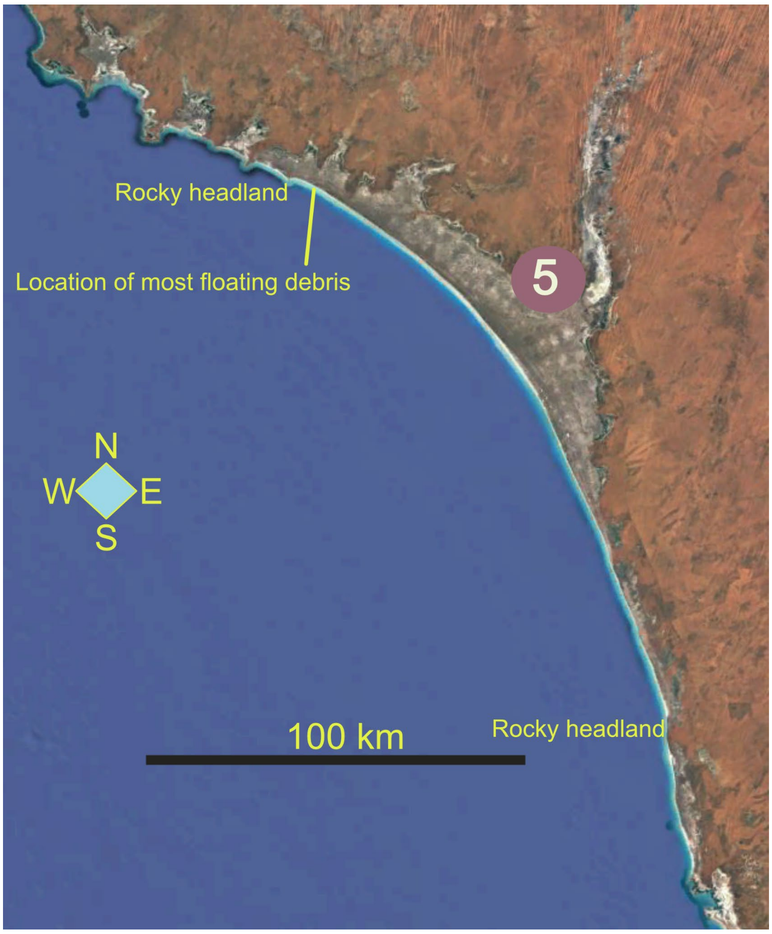


Figure 35: Location 5 showing the beach and the site of floating debris accumulation.

Team member and sedimentologist Sandra Shore came to his aid: *When floating material is washed onto the beach by waves, it travels in the wave's movement direction. However, as the water recedes, it moves down the beach face under the influence of gravity. If the waves are at an angle to the beach front, anything moving up and down the beach with the waves, like flotation devices, will come back to the shoreline further along the beach from the point it first washed up.*

Local fisherfolk had told Jeff all human-sourced debris were removed from the beach (for recycling) after TC Paul passed and that the material he found arrived recently under the influence of the current prevailing wind.

Jeff shared a map of the beach with Sandra, who quickly replied: *Nice map, it clearly demonstrates the prevailing wind behind the waves has recently come from the…*

Q: What direction did Sandra conclude with? (1 mark)

a. … north.
b. … south.
c. … east.
d. … west.
e. … spiralling winds left behind by the cyclone.
f. … jet stream directly above the Spicerji Ocean.

55. After a fun time finding fossils and beach combing, Jeff and Philip headed inland to location 6 (Figure 17) where they were joined by colleagues Gabi Roe and Andy Syght, who happened to be studying the local geology. Gabi explained that the Archean rocks exposed in the area are mostly granites or greenstones. The greenstones are a suite of sedimentary rocks interbedded with mafic, ultramafic and felsic volcanic rocks. Intrusion of granites has greatly deformed and metamorphosed the greenstones, creating a modern erosional landscape of granite domes surrounded by a variety of steeply dipping and deformed metamorphic rocks.

Gabi was excited to show her friends around this amazing landscape and geoscape (Figure 36), but was even more excited about some of the other rocks she showed them, especially the one they couldn't actually see! She started by giving them a copy of Figure 36.

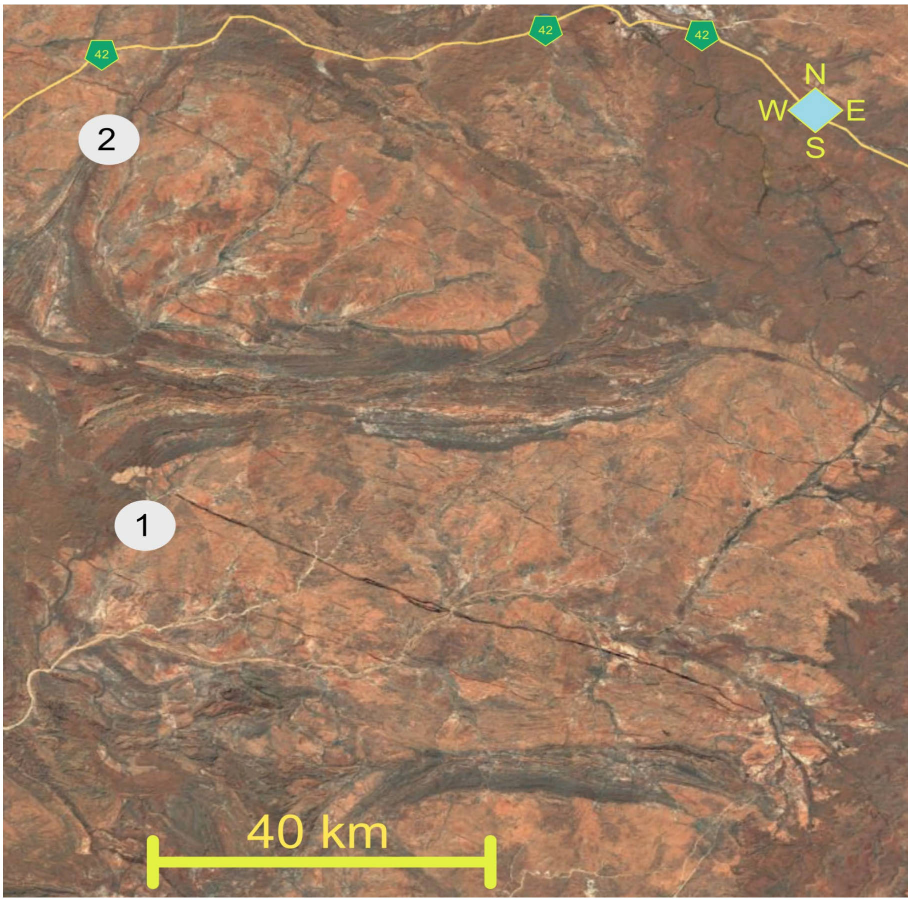


Figure 36: Satellite view of the Franklin fields area, east of location 6 (Figure 17). Sites 1 and 2 are places Gabi took Jeff and Philip to talk about the rocks!

At Site 1, Gabi challenged them to locate themselves and determine the origin of the strange black lines seemingly drawn in crayon across the granite dome they were standing on. Having discovered the black rock in an outcrop, a debate ensued.

Q: What did Philip correctly say about the distinct black line closest to location 1? (1 mark)

a. The black line striking northwest across the granite is a shallow dipping fault, infilled with black chert to form a fault breccia.
b. The black line striking northwest across the granite is a vertically dipping mafic dyke.
c. The black line striking southeast across the granite is a shallow dipping mafic dyke.
d. The black line closest to Site 1 is a vertically dipping felsic sill.
e. The black line striking southeast across the granite is a steeply dipping fault, infilled with black chert to form a fault breccia.
f. None of the above. It is just a weathering fissure common in regularly jointed granites. Shadows in the fissure make it look wider than it really is.

56. After pondering the origins of the black line at Site 1, Andy took them to Site 2, where a finer black line is evident in the image (Figure 36). Walking northwest to highway 42, they noticed a curious pattern (Figure 37).

Figure 37: Closer view of the black linear feature to the northwest of location 2.

Q: What did Jeff correctly say about the NW-SE trending thin black line closest to location 2? (1 mark)

a. It is a dry creek bed. It is visible from land and air due to subtle changes in topography and mineralogy. There is nothing there other than sand and gravel weathering products creating slightly darker soil.
b. It is a steeply dipping dyke completely weathered away at the surface. Nothing can be seen at the surface, but slightly darker soil formed from residual weathering products is visible from the air.
c. It is offset by a series of dextral strike-slip faults (to the right).
d. It is offset by a series of sinistral strike-slip faults (to the left).
e. It is a sidewinding sandworm trace fossil.
f. It is a tornado path scar that weaves right and left.

57. Slipping back across the road to Site 2, things turned even stranger (Figure 36). They found two linear features marked on the geological map that are nearly or completely impossible to see on the ground (Figure 38a).

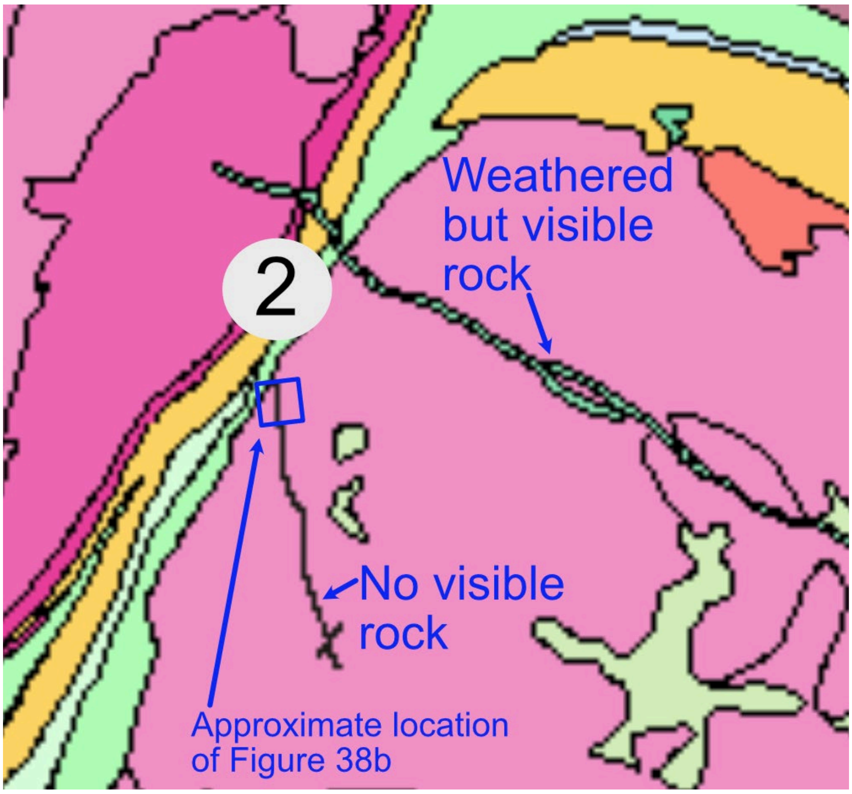
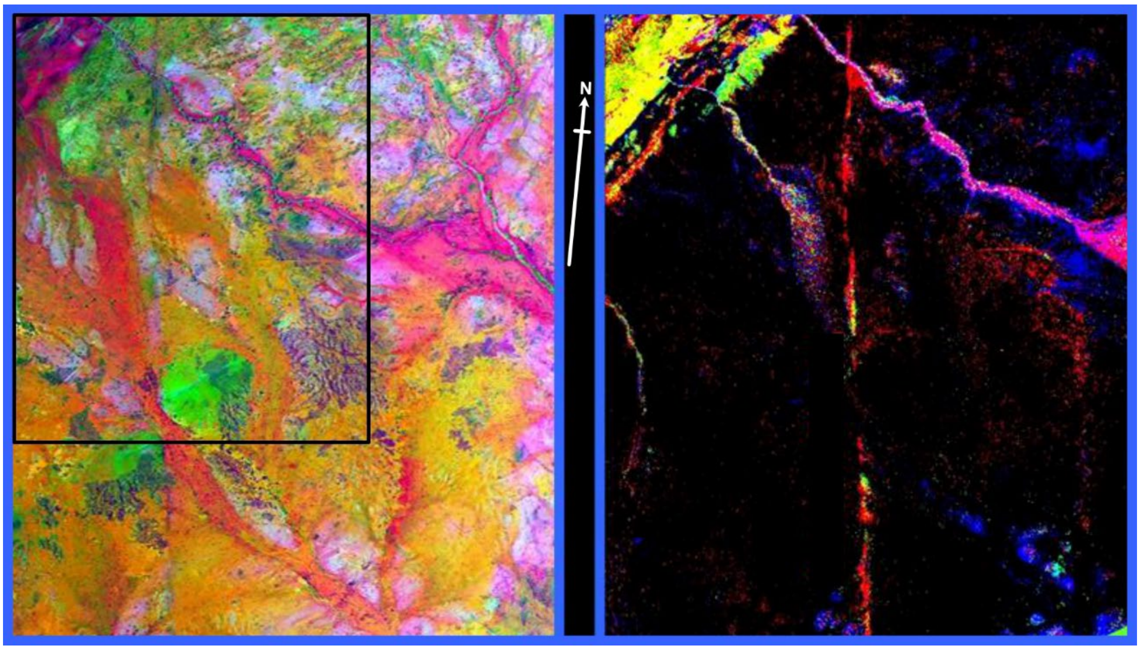


Figure 38a: Simplified geological map of the Site 2 area. Pink colours are granite. Other colours are deformed greenstone lithologies. An invisible 'mystery' rock is marked on the map south of Site 2.

Gabi and Andy challenged them to explain the mystery line on the map that did not appear to correspond with anything on the ground but gave them another map first (Figure 38b & c).

Figure 38b & 38c: False-colour derivative of a Landsat image (left) and a hyperspectral image (right) of a location just south of Site 2 (Figure 37). These images are colour coded to highlight specific bands within the electromagnetic (EM) spectrum beyond the visible light range. The right image is a subset of the left (black box area) tuned to those frequencies reflected by carbonate and chlorite minerals. North for both images is shown. Image courtesy of Geological Survey and Resource Strategy Division, Department of Mines, Industry Regulation and Safety. © State of Western Australia 2023.



Q: What did Philip correctly postulate about the optically invisible but mineralogically distinct linear feature? (1 mark)

a. It is a dry creek bed. It shows up on the map due to subtle changes in topography and mineralogy. There is nothing there other than sand, gravel and carbonate weathering products typical of the region's geology.
b. It is a steeply dipping dyke that has weathered away completely at the surface. Nothing can be seen by the human eye, but the residual weathering products have useful EM spectrum signatures.
c. It is a strike-slip fault with offset to the right (dextral). The fault breccia produces weathering products that have useful EM signatures.
d. It is a strike-slip fault with offset to the left (sinistral). The fault breccia produces weathering products that have useful EM signatures.
e. It is a sandworm trace fossil. The worm's coprolites produce chlorite-rich weathering products that have useful EM signatures.
f. It is a tornado path scar. The violent weather systems stir up carbonate-rich sediments with useful EM signatures.

58. After a fun time at location 6, the group journeyed on to location 7 (Figure 17). This site was adjacent to an amazing cliff exposure of a truly beautiful Banded Iron Formation rock, dated at 2.3 billion years old. It consists of compositionally defined alternating <1-mm thick layers of either a very iron-rich mixture of minerals (e.g. hematite (Fe_2O_3), magnetite ($Fe^{2+}Fe^{3+}{}_2O_4$), ankerite ($Ca(Fe^{2+},Mg)(CO_3)_2$), and/or siderite ($FeCO_3$)) or iron-poor chert. (Figure 39).

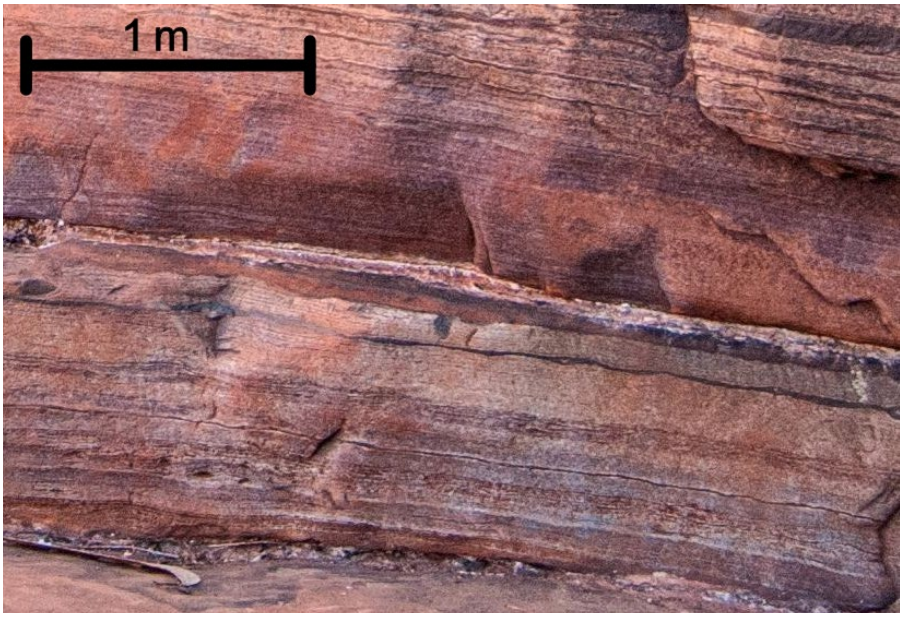


Figure 39: Iron-rich and iron-poor couplets in outcrop.

These iron rich/iron poor couplets are interpreted as cyclical layers deposited in a tidal environment, where each pair represents one day. The team previously established these bands correlate to daily tides, and monthly and yearly tidal cycles, using careful analysis of measurements taken from drill cores. This and other studies have led the team to conclude that 2.3 billion years ago the day length was about 18 hours (Figure 40).

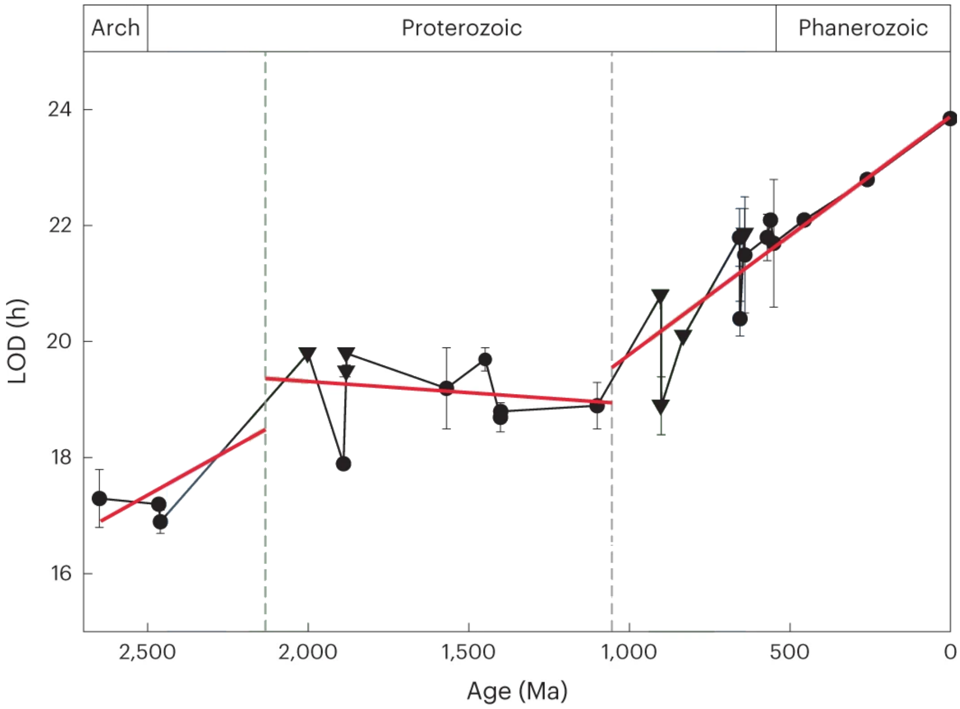


Figure 40: Length of Day in hours (LOD) compilation graph from ~3000 Ma to the present day. Triangles are data from tidal couplets and stromatolites with fine-scale layering. Circles are other data sources. The red lines are the linear regressions. Modified from Mitchell & Kirscher, 2023.

Q: Based on these observations and conclusions, what else did Philip remark? (1 mark)

This suggests …

a. … that at this time there were over 480 days per year.

b. … Banded Iron Formations only formed when the day length stabilised between 2000 Ma and 1000 Ma.

c. … Earth's rotation rate stabilised during the mid Proterozoic.

d. Both a & b

e. Both a & c.

f. All of a, b & c.

59. Exploring the area revealed some interesting laminated structures within the Banded Iron Formations (BIFs). Jeff thought they were fossils but Philip was not so sure. He noted the rocks were dated as ~2.3 billion years old. He posted his best image (Figure 41) in the hope that someone could help him.

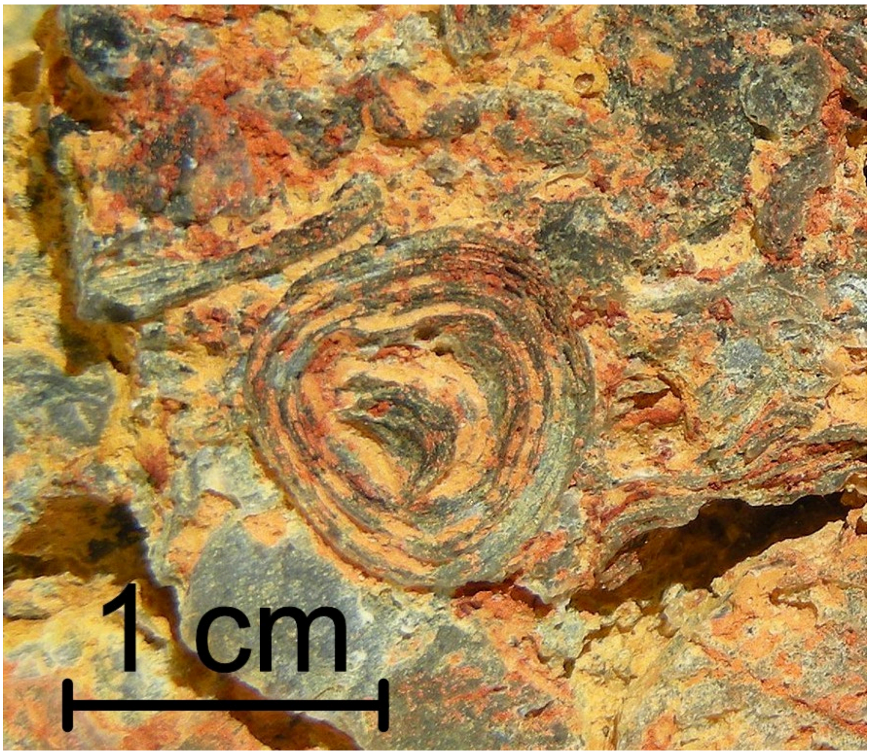


Figure 41: A possible stromatolite found by Jeff and Philip.

Q: What did their palaeontologist friend Traci say to convince them it was probably a stromatolite? (1 mark)

Stromatolites evolved in the early Proterozoic, at least 3 billion years ago, and are still alive today. While this structure looks biological in origin it would be helpful to …

a. … find it in association with other Precambrian fossils such as archaeocyathids which would place it in a truly environmental context.
b. … examine it under a microscope and find preserved cellular structures.
c. … find it in association with skeleton builders such as brachiopods which would make us confident it is a skeletal structure.
d. All of a, b & c.
e. Both a & b.
f. Both b & c.

60. With their journey at an end, the Earth-based members of the teams settled around a campfire at location 8 (Figure 17) to enjoy an evening of stargazing and exchanging messages with team members elsewhere in the solar system. As fate would have it, the evening offered up a rare astronomical phenomenon, a 5-planet-1-Moon "alignment" known as a syzygy. A syzygy occurs when at least three celestial bodies located in the same gravitational field appear in a somewhat straight line.

On this evening every team member was technically present at the campfire! Roxanne was exploring Mercury. Gemma was exploring Venus. Others were on the Moon, Mars and moons of Jupiter and Saturn.

They all agreed to shout (physically and electronically) HELLO! at exactly the same Earth time (dawn).

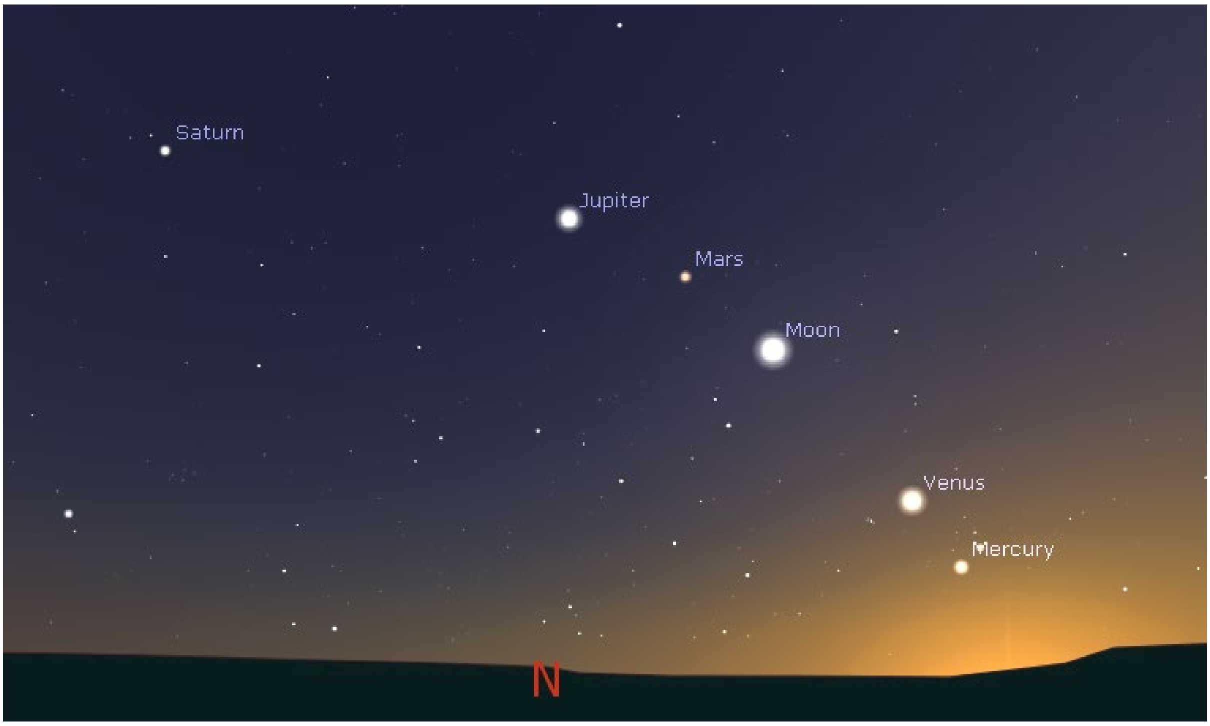


Figure 42: The view from location 8, just before dawn.

While organising this special event, astronomer Zoe shared this image to make the planning a bit easier (Figure 43).

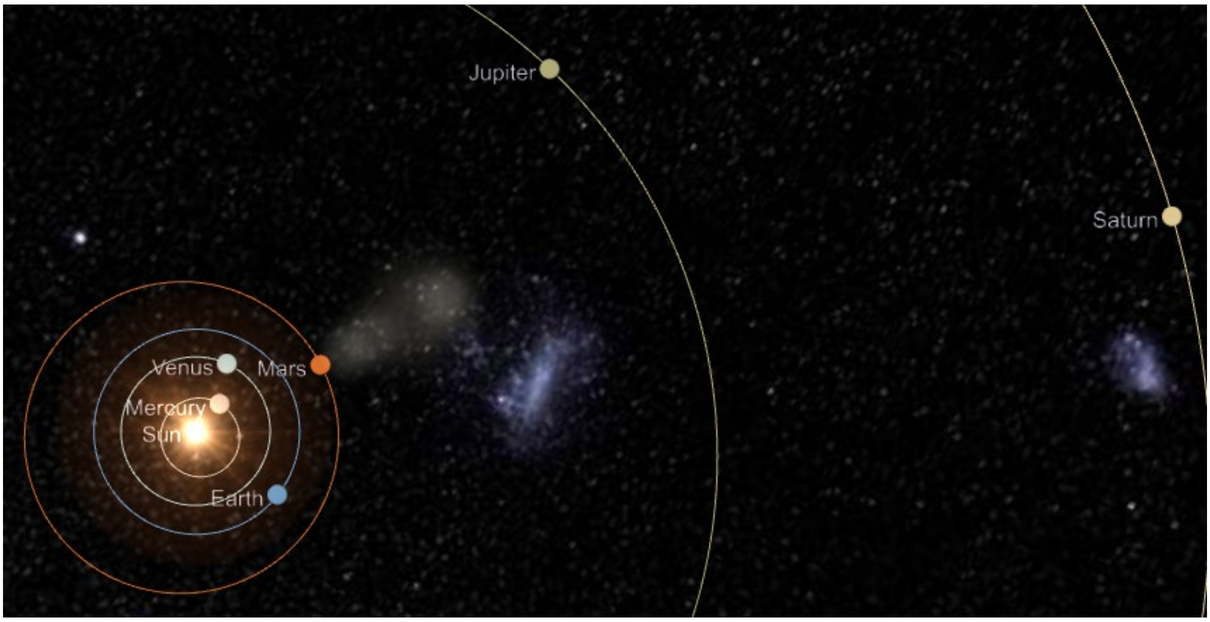


Figure 43: Relative positions of the planets on this special day.

Q: In what order would the messages arrive on Earth from their interplanetary colleagues? (1 mark)

a. The Moon, Mercury, Venus, Mars, Jupiter, Saturn.
   Messages from Saturn would take approximately 3.1 times as long as messages from Jupiter.
b. The Moon, Mercury, Venus, Mars, Jupiter, Saturn.
   Messages from Saturn would take approximately 1.1 times as long as messages from Jupiter.
c. The Moon, Mercury, Venus, Mars, Saturn, Jupiter.
   Messages from Saturn would take approximately as long as messages from Jupiter take plus the time messages from the Moon take.
d. The Moon, Mercury, Mars, Venus, Saturn, Jupiter.
   Messages from Saturn would take approximately 3.1 times as long as messages from Jupiter.
e. The Moon, Mercury, Mars, Venus, Jupiter, Saturn.
   Messages from Saturn would take approximately 1.9 times as long as messages from Jupiter.
f. The Moon, Mercury, Mars, Venus, Saturn, Jupiter.
   Messages from Saturn would take approximately 1.9 times as long as messages from Jupiter.

As tradition demanded, they played their favourite True / False game with each other. 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?

61. **True or False?** Talc is the softest mineral

    True or False (0.25 Mark)

62. **True or False?** Hot spot volcanoes are formed from subduction zone melting processes.

    True or False (0.25 Mark)

63. **True or False?** The beginning of the Cambrian period is marked by the first appearance of fossils in the rock record.

    True or False (0.25 Mark)

64. **True or False?** Partial melting of rocks produces more felsic melt, but complete melting produces the same composition melt as the starting material.

    True or False (0.25 Mark)

65. **True or False?** Io, Europa, Ganymede and Calisto are all moons of Saturn.

    True or False (0.25 Mark)

66. **True or False?** Tasmania is an extension of the Australian mainland, not a separate tectonic (micro) plate.

    True or False (0.25 Mark)

67. **True or False?** Marble and quartzite are two words for the same metamorphic rock.

    True or False (0.25 Mark)

68. **True or False?** There was a subduction zone between India and Eurasia before the two continents collided.

    True or False (0.25 Mark)

69. **True or False?** Mars has a tilted axis, just like Earth, and as a result has distinctive seasons.

True or False (0.25 Mark)

70. **True or False?** Amber is a waxy secretion produced by whales. It traps marine insects as it floats around before settling to the bottom of the ocean, forming a hard, rock-like substance.

True or False (0.25 Mark)

71. **True or False?** If you are trekking over limestone, it is an over karst day no matter how sunny it is.

True or False (0.25 Mark)

72. **True or False?** A hole in a rock in the shape of a fossil that used to be there is called a mould.

True or False (0.25 Mark)

73. **True or False?** Chalcopyrite is an ore mineral for copper.

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?** Hawaii is formed by a hotspot (mantle plume) rising beneath a mid-ocean ridge.

True or False (0.25 Mark)

76. **True or False?** All minerals have at least one cleavage plane.

True or False (0.25 Mark)

77. **True or False?** The Permian mass extinction happened at the start of the Permian period.

True or False (0.25 Mark)

78. **True or False?** Earth's Moon is the largest moon in the solar system.

True or False (0.25 Mark)

79. **True or False?** The largest volcano in the solar system is on Venus.

True or False (0.25 Mark)

80. **True or False?** There is no such thing as fish-flavoured ice cream.

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.

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