School ID

2022 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 2022 are not eligible to attend the 2023 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:										

2022 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.
- Ensure that any diagrams you draw are clear and labelled.
- Ensure any written answers are legible.
- All numerical answers must have correct units.
- Marks will not be deducted for incorrect answers.
- Rough working must be done only on page 76 of this booklet.
- Data that may be required for a question will be found on pages 3 - 9
- All answers should be marked on this paper. Circle the correct answer in Multiple Choice and True/False questions. Other questions require you to write in the space provided or draw on the diagram provided.

MARKS

Multiple choice questions are each worth one (1).

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

Total marks for the paper: 65 marks

DATA & DEFINITIONS

Material supplied:

Characters

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

Units and conversions

Degrees Celsius (°C) 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
$g_{planet} = G \times M_{planet} / R^2_{planet}$		

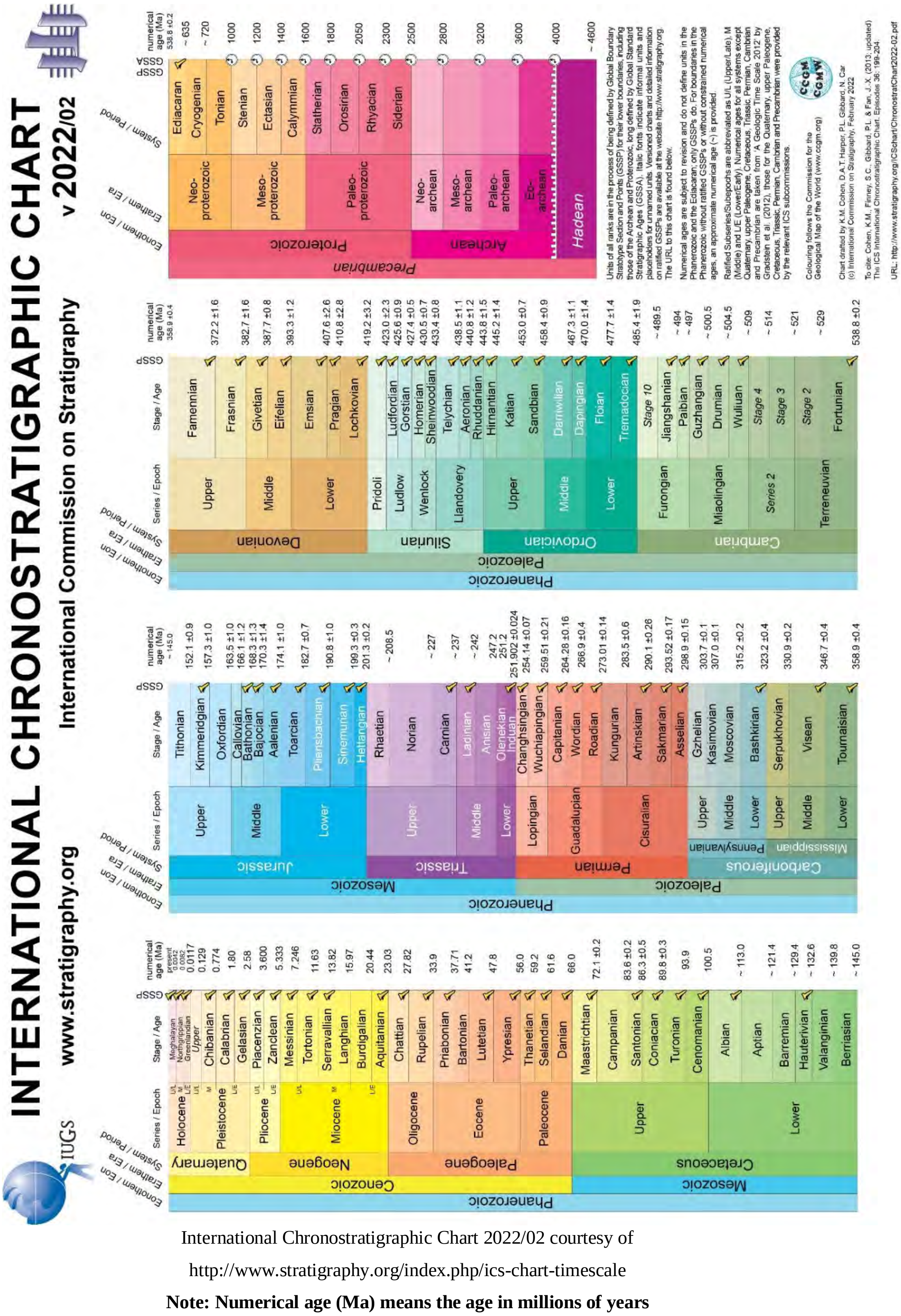
Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 84.80
37 Rb Rubidium 84.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molibdenum 95.95	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.25
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.09	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium [208.98]	85 At Astatine 209.99	86 Rn Radon 222.02
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.06	71 Lu Lutetium 174.97
89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.1	102 No Nobelium 259.10	103 Lr Lawrencium [262]

Periodic Table of the Elements courtesy of

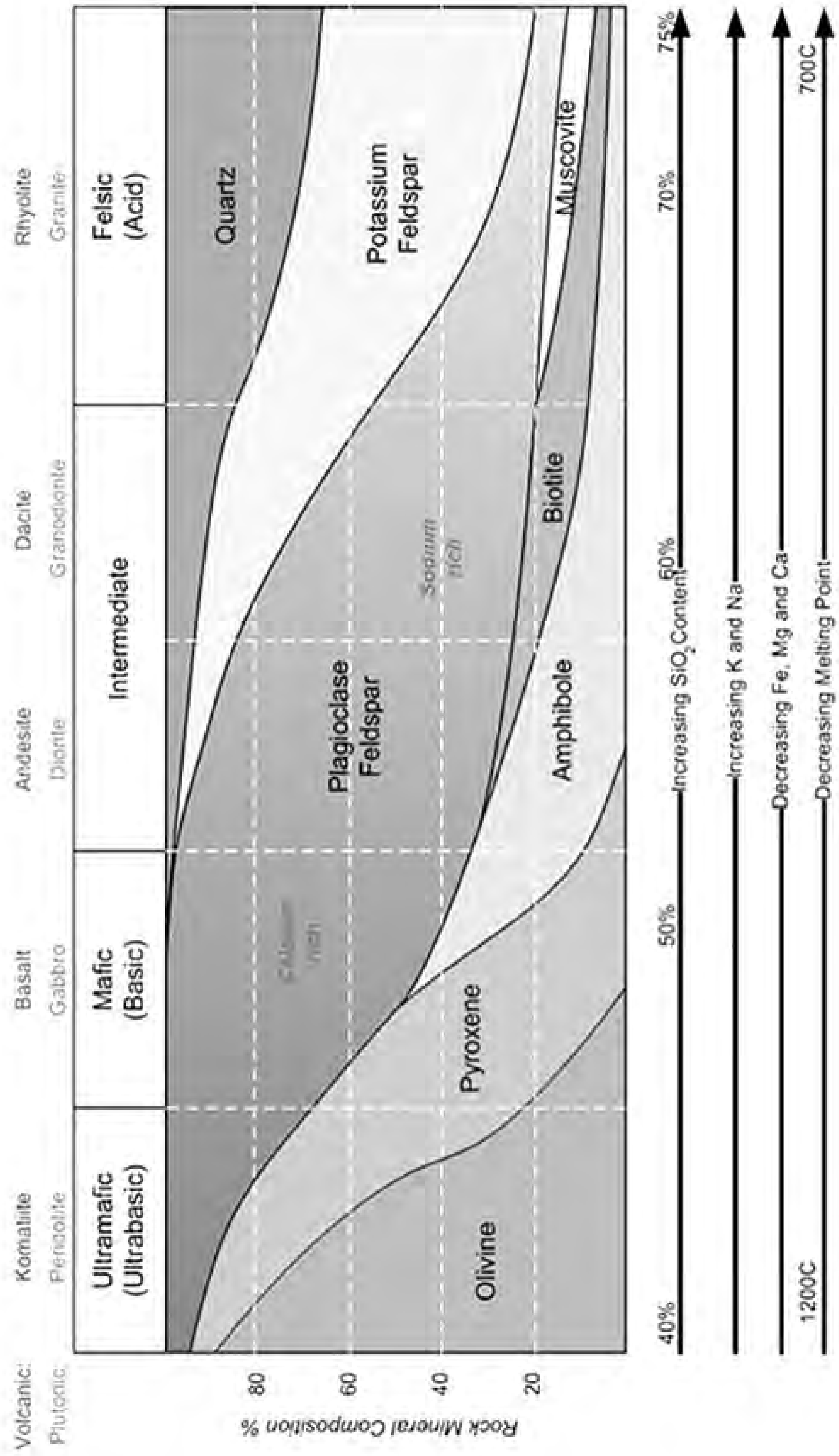
http://sciencenotes.org/category/chemistry/periodic-table-chemistry/



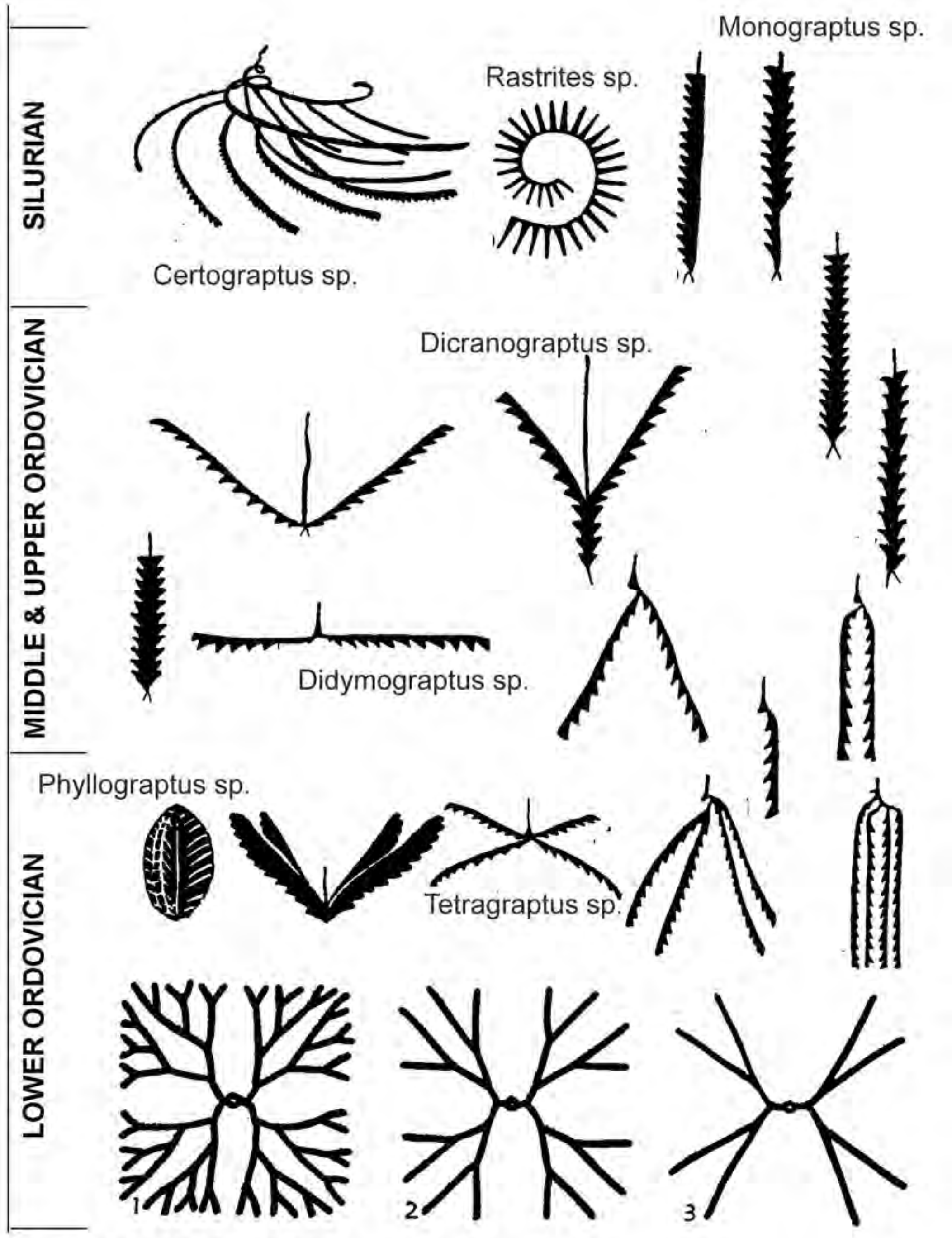
International Chronostratigraphic Chart 2022/02 courtesy of

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

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



Igneous rock classification chart



Graptolite shapes through time
Modified from Moore, Lalicker & Fischer (1952), Figure 22-7

Graptolites through time

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

Hardness scale

Location	Surface Temperature	Surface Pressure	Crustal material/s	Atmospheric composition
Earth Surface Gravity (g) 9.81 m/s²	+70°C (most extreme ever recorded) to -89°C (most extreme ever recorded) (normal global average ~14°C)	1 atm	Dominantly silicates, carbonates, water and ice. Many other mineral classes in minor amounts.	Nitrogen, oxygen, carbon dioxide, water vapour, methane and traces of other natural and anthropogenic gasses.
Europa Surface Gravity 0.134g	-160°C (equator) to -220°C (poles)	~1 x 10^{-12} atm	Water ice	Extremely thin oxygen atmosphere with some water vapour.
Io Surface Gravity 0.183g	-183°C to -143°C (mean is -130°C)	4.93×10^{-9} to 3.95×10^{-8} atm	Silicate rock (basaltic), sulphur and sulphur frost.	Extremely thin sulphur dioxide atmosphere with traces of sulphur monoxide, sulphur, sodium chloride and oxygen.
Titan Surface Gravity 0.138g	-179°C on average	1.5 atm	Water ice bedrock plus sand-sized grains of organic molecules forming a surface regolith.	Thick dense atmosphere of methane (95%), ethane (5%) and small amounts of other carbon-rich compounds. Clouds form and it rains liquid methane and ethane that runs off in rivers to lakes.

Useful planetary data

Geologically active moons of the solar system

Jupiter's moons Io and Europa, and Saturn's moons Enceladus and Titan. They show remarkable geological activity for their small size, with features ranging from volcanoes and water plumes to possible subsurface oceans. Image courtesy of NASA (2019). https://tinyurl.com/47cu9jfp

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 technology including the invention of the [1]Epstein Drive and the [2]WaterPIPE™ catalytic assembly for the rapid separation of water into hydrogen and oxygen.

You should first be familiar with the development of the Epstein Drive, which went into production in 2222. Thanks to this technological breakthrough, the Interplanetary Museum of Human Endeavour (IMHE) is able to safely and quickly deploy staff to interesting locations across the solar system. Suffice to say, the IMHE operates a small fleet of repurposed Martian Congressional Republic Navy corvette-class frigates using the Epstein Drive to safely and quickly deploy staff to locations of interest. According to legend, the trial drive and its inventor were lost in 2221 when it accelerated the ship unexpectedly in the direction of Pluto and could not be shut down because the 10g of acceleration physically prevented him from reaching the emergency shutdown button. Such is physics.

In this imagined future, people take cheap and readily available hydrogen for granted. Every household, transport device and life support system has one or more of the [1]Water Pumped-In Power-Exported (WaterPIPE™) catalytic assemblies for the rapid separation of water into hydrogen and oxygen. This in turn provides instant non-polluting energy through direct combustion and indirectly through fuel cells. It also provides the energy and oxygen needed to build and maintain habitats in space, on asteroids, moons and planets. However, if history taught you anything, it is that this was not always the case. Electrolysis of water to form hydrogen and oxygen gasses was first demonstrated in 1800. However, even in 2022 when hydrogen was first produced on an industrial scale for domestic consumption, the process was relatively inefficient and costly, potentially dangerous, and certainly not suited to miniaturisation. WaterPIPE™ technology, utilising the previously unknown catalytic properties of a metalloid alloy, significantly lowers the amount of energy required to split liquid water into hydrogen and oxygen gases. In fact, as liquid water is pumped through an alloy mesh, only a low-power specific-frequency laser illuminating the mesh is needed to activate the process.

The players:

Roxanne Stone, well known areologist[2] and geologist, previously lead 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 on the moons of Jupiter and Saturn where satellites and robotic surface missions have also generated fascinating observations. Roxanne has recently returned to Earth for a well-earned sabbatical but continues to explore the wonders of the atmosphere, biosphere, geosphere and hydrosphere with her planetary scientist and atmospheric science specialist sister, Gemma.

Under the banner of Interplanetary Museum of Human Endeavour (IMHE) the pan-solar exploration team continues to document and explore the solar system and beyond.

Apart from Roxanne and Gemma the team includes:

Andy Syght (volcanologist),	Philip Light (metamorphic petrologist),
Ellie Mints (geochemist),	Sandra Shore (sedimentologist),
Gabi Roe (igneous petrologist),	Rose Kortz (mineralogist),
Jean Luc Bringuebaler (seismologist),	Traci Menandai (palaeontologist)
Jiki Nakamura (geochronologist),	Zoe Guāng (astronomer & astrobiologist)

[1]WaterPIPE™ is the trademark name, established by the United Nations in 2152. Like the Epstein Drive, this is entirely a fiction but not necessarily a fantasy. Science fiction often inspires future science. Wouldn't it be cool if that was the case for both of these fictions?

[2]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.

Characters

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

A new series of expeditions has been funded by the Interplanetary Museum of Human Endeavour (IMHE). They are aimed at ground truthing observations made by robotic missions sent throughout the solar system in the 20th and 21st centuries. Making other first-hand observations along the way will be a bonus!

Roxanne Stone and her sister Gemma are on Earth, holidaying together, while the rest of the team is preparing to visit various destinations on other planets and moons.

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!

The first Epstein Drive powered ship and its inventor were lost on January 1, 2221. The ship accelerated unexpectedly in the direction of Pluto and could not be shut down. The ship quickly ran out of fuel after achieving 5% of light speed. Astronomers have calculated the trajectory of the ship. Its first encounter with another object in space will be with a planet orbiting the star Epsilon Eridani. Epsilon Eridani is 3.2 parsecs from the Sun.

2. Assuming the navigation AI is still operational, the ship will automatically adopt a stable orbit around the first star system it encounters and confirm its location in a signal directed towards Earth.

   Q: After the ship reaches Epsilon Eridani, when will Earth's scientists receive the message that it arrived safely? (1 mark)

   a. In 2384
   b. In 2395
   c. In 2414
   d. In 2422
   e. In 2429
   f. In 2440

WaterPIPE™ technology went into production in 2053. According to legend, it was invented by tech billionaire Noelene Ambergris who gifted it to the world under the guise of democratising energy ownership and helping solve Earth's greenhouse gas problem. They refused to confirm or deny rumours that their motivation was to produce the final piece in the puzzle to make human colonisation of the solar system possible. However, supporting this conjecture is the fact they were one of the foundation colonists on Mars in 2055.

3. Early opponents of the WaterPIPE™ technology correctly pointed out that water vapour is a greenhouse gas and combustion engines that burn hydrogen produce it. They argued that replacing one greenhouse gas (CO_2) with another one (H_2O vapour) would not solve the problem and might even make it worse. However, we know extra water vapour in the troposphere is rapidly removed as rain whereas extra CO_2 remains for much longer, compounding the problems with atmospheric heating.

   Q: What else did Earth's citizens need to do when adopting the WaterPIPE™ technology to help solve Earth's greenhouse gas problem? (1 mark)

   a. Stop using black coal and only use brown coal to generate electricity.
   b. Increase the capacity for generating renewable energy to power WaterPIPE™.
   c. Burn plastic waste to generate heat and make electricity.
   d. Convert all electric-motor-powered devices to hydrogen-combustion-powered devices.
   e. Replace all solar cells and wind farms with hydrogen-combustion-powered devices.
   f. All of the above.

The WaterPIPE™ and Epstein Drive have facilitated human settlement within or upon artificial satellites, the Moon, Mars, many asteroids, and the moons of other planets, without many of the hardships and long travel times endured by early pioneers. Despite this, water and energy are still critical commodities for humans everywhere.

4. Residents of off-Earth locations often complain that their WaterPIPE™ units require far more energy to operate than those available on Earth even though the liquid-water-to-gas separation components are exactly the same.

   Q: Why would off-Earth locations have an additional energy cost problem? (1 mark)

   a. Off-Earth water (H_2O), at 1 atmosphere pressure and 25°C, has a boiling point than water on Earth under the same conditions. This increases the energy cost required to boil it.
   b. Combustion of hydrogen produces a gas that is not safe to release into confined spaces. Scrubbing the exhaust of dangerous gas adds to the cost.
   c. Most off-Earth water is only available as very cold ice. Melting it adds to the cost.
   d. Most off-Earth water is found as vapour/gas trapped inside ice and needs to be drilled for, just like oil on Earth. Drilling for water vapour/gas adds to the cost.
   e. Off-Earth water contains an extra oxygen atom, which raises the amount of energy needed to dissociate it into gasses and adds to the cost.
   f. Off-Earth water has been exposed to cosmic radiation. The oxygen-16 atoms have all been converted to oxygen-18 and the water is radioactive. Decontaminating the water adds to the cost.

Human off-Earth settlements are nearly always associated with valuable commodities because essential commodity extraction and value-adding form the foundation of most human expansion into new territories. Being essential for life, water is one of the most important commodities in the solar system. Fortunately, we have discovered the solar system has abundant water resources that not only provide drinking water but also vital oxygen and energy when split by WaterPIPE™ technology.

The ice mines of Jupiter's moon, Europa, provide water to asteroid belt settlements that do not have their own water source because Europa's surface ice is cheap to open-cut mine. Small settlements on rockier asteroids prefer to keep any water they find for themselves. The surface crust of Europa is mostly water ice forming a shell about 15-25 km thick. Beneath the shell is a salty ocean 60-150 km deep. It surrounds a rocky interior and metallic iron core (see geologically active moons graphic supplied at the start and Figure 1 on the next page). Water reaching the surface through cracks in the shell, as flows or eruptive plumes, appears to leave reddish-brown stain marks on the surface ice. The massively jumbled areas of broken ice, where there are lots of cracks, are known as Chaos regions.

5. Zoe Guāng (astronomer & astrobiologist) has travelled to Europa for IMHE to ensure that the mining companies are meeting their licence obligations to avoid impacting the Chaos regions of Europa where large amounts of the reddish-brown material is located.

   Q: Why would Zoe and the IMHE be interested in protecting these reddish-brown areas from being disturbed? (1 mark)

   a. Reddish-brown compounds are always the foundation of any good soil and are therefore important to Europa's agricultural industry and should be protected from mining.
   b. The reddish-brown compounds contain lots of iron which reacts with sunlight to form ironic compounds that inhibit plant growth in Europa's soil.
   c. The coloured compounds reaching the surface react with sulphur plumes drifting in from Jupiter's moon, Io, forming sulphuric acid that would badly damage mining and habitat infrastructure if disturbed to form aerosols.
   d. The water reaching the surface contains compounds that would make Europa's Earth-like atmosphere toxic to breathe if disturbed to form aerosols.
   e. The water reaching the surface contains material that could be the only easily researched evidence of life inside Europa's sub-surface ocean. Disturbing any of it could compromise and/or erase vital information.
   f. Reddish-brown compounds are always radioactive.

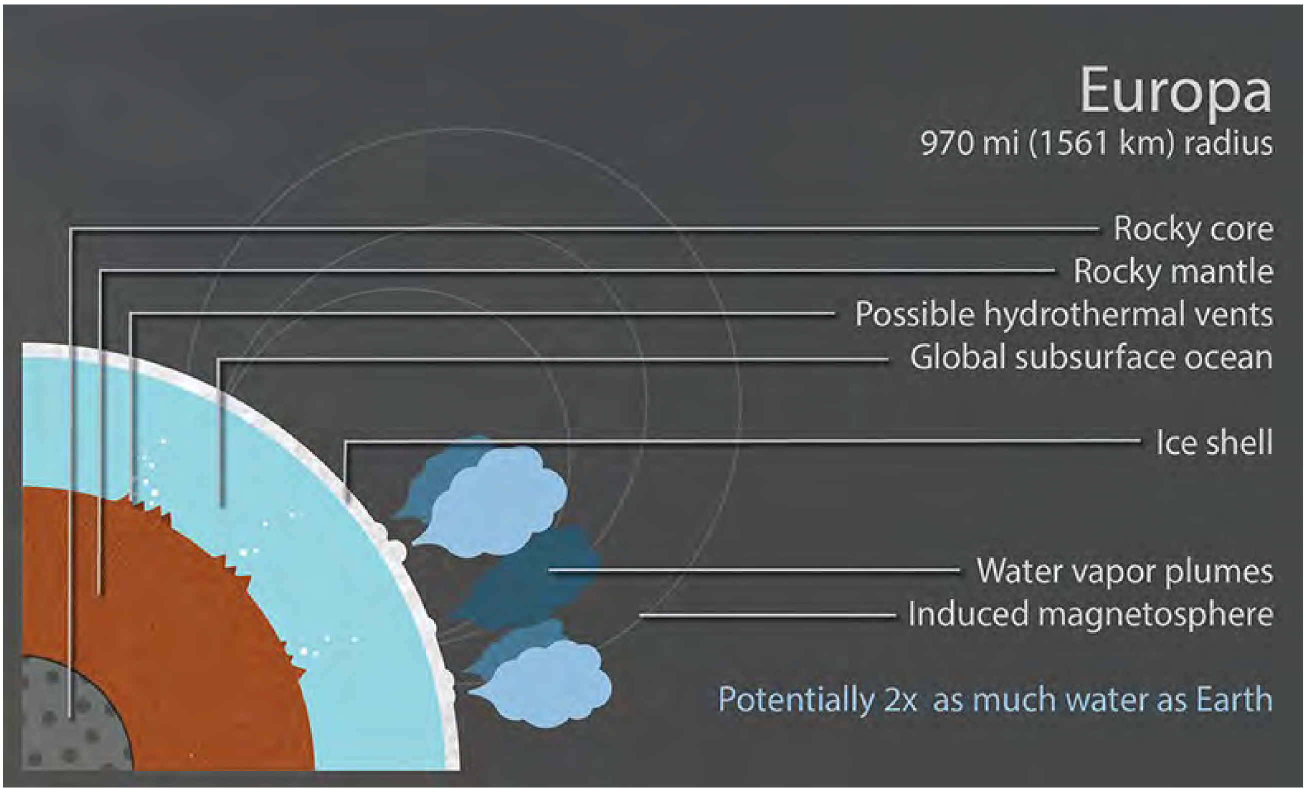


Figure 1: Schematic cross-section through Europa, highlighting the general structure and geologically active features of the moon. Image courtesy of NASA (2019). https://tinyurl.com/47cu9jfp

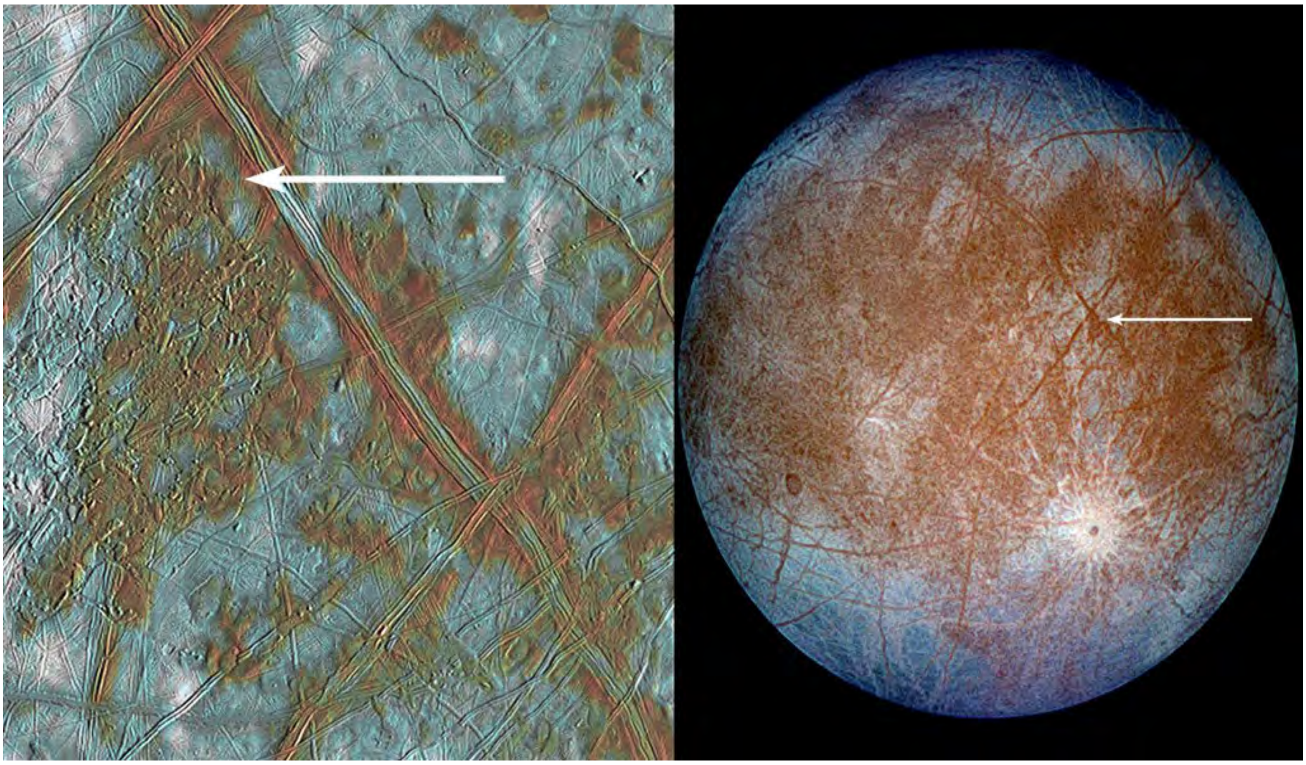


Figure 2: Location of the Conamara Chaos on Europa, indicated with an arrow.
Image courtesy of NASA (https://svs.gsfc.nasa.gov/11176)

After inspecting the ice mines of Europa and certifying their compliance with regulations, Zoe travelled to the region known as the Conamara Chaos (Figure 2 – on the previous page). It is thought that the chaotic appearance is caused by dynamic fracturing of the ice crust plus collapse of ice-block fragments into subsurface lakes within the ice. Over time, floating geometric ice fragments rotate, raft and resettle into all kinds of chaotic configurations.

Flying over Europa, Zoe was able to take high resolution images of the Conamara Chaos region to map the landscape and make inferences about the geological history of this part of the icy crust. She used one image (Figure 3 – on the next page) to illustrate the complexity of the landscape. She identified 5 structures and labelled them A, B, C, D & E:

Structure A is circular and is highlighted by a blue circle.
Structure B is straight and is parallel to numerous smaller, adjacent structures.
Structure C is a slightly curved linear feature.
Structure D is an irregular linear feature.
Structure E is a straight feature

6. In her report she described the landscape and geological history of this part of Europa's icy crust as temporally complex.

Q: What did she write in her report about structure B? (1 mark)

Structure B is straight, parallel to numerous smaller adjacent structures …

a. … and is younger than structures C & D.
b. … and is older than structures C & D.
c. … and is an impact structure made by a non-spherical rock.
d. … and is younger than structures A & D.
e. … and is older than structures A & D.
f. … and formed at the same time as all the other structures.

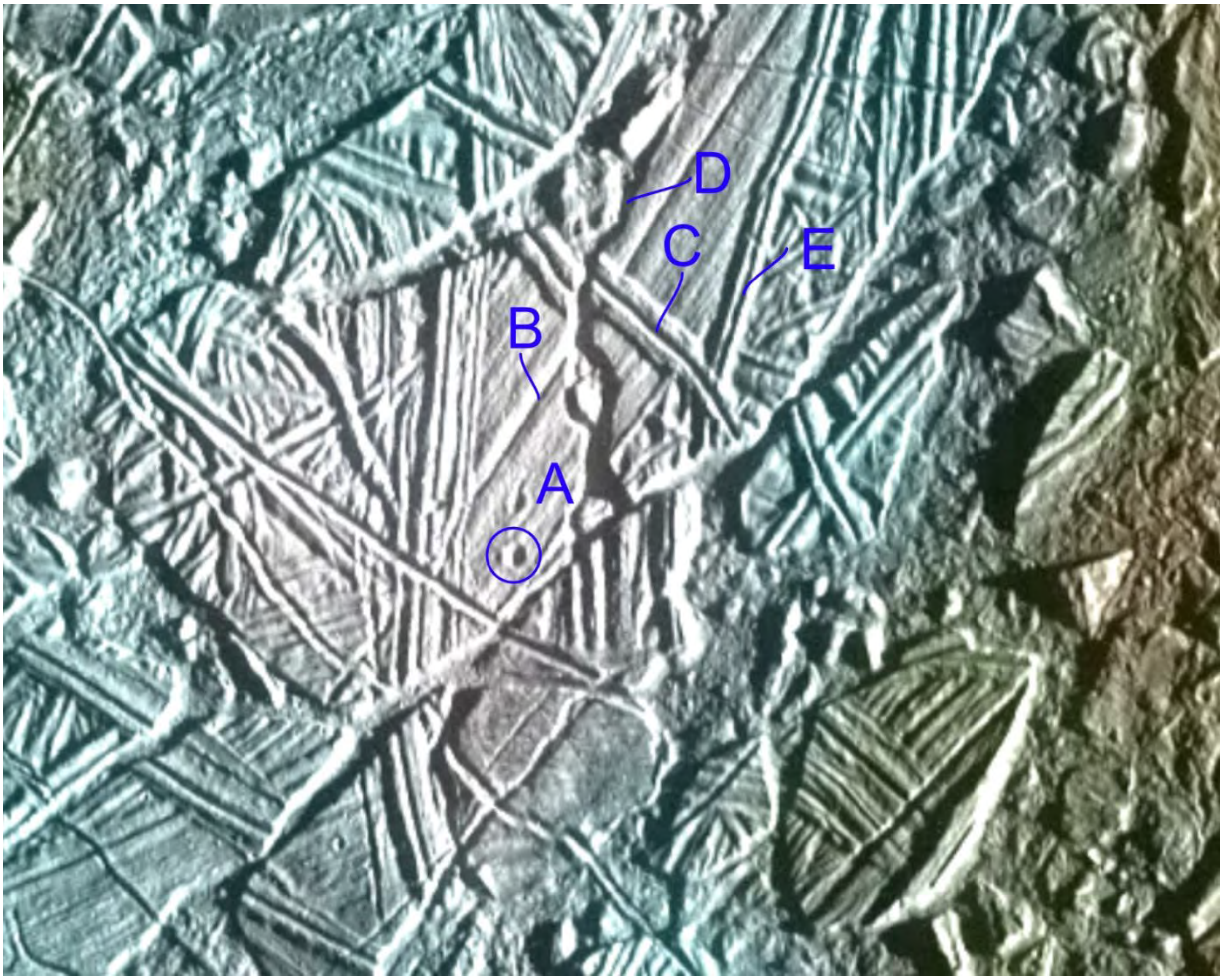


Figure 3: Close up of the Conamara Chao on Europa, highlighting structures A, B, C, D & E. North is to the top of the picture. The image covers an area approximately 25 by 17 kilometres. Modified image courtesy of NASA (https://svs.gsfc.nasa.gov/11176)

7. Zoe also used several other structures to illustrate her point.

Q: What did she write in her report about structure E? (1 mark)

Structure E is straight feature …

a. … and is younger than structure C.
b. … and is older than structure C.
c. … and is the same age as structure D.
d. … and is the same age as structure B.
e. … and is the same age as structure A.
f. … and formed at the same time as all the other structures.

8. In her report, Zoe used the images in Figures 2 & 3 and the image in Figure 4 (below) (taken during an earlier trip to Callisto) to illustrate the changes to the Europan crust over time.

Q: What did she write in her report? (1 mark)

The circular feature A is a small impact crater. There is a much greater density of impact craters visible on Callisto (Figure 4) compared with Europa (Figures 2 and 3). This most likely indicates …

a. … the visible surface of Europa is much older than Callisto's surface.
b. … the visible surface of Europa is the same age as Callisto's surface.
c. … the surface of Europa is too hard for impact craters to form.
d. … Europa is the youngest moon in the solar system.
e. … Callisto has not experienced Europa-like tectonics and chaos-forming activity.
f. … Europa has not experienced the same level of meteorite bombardment as Callisto.

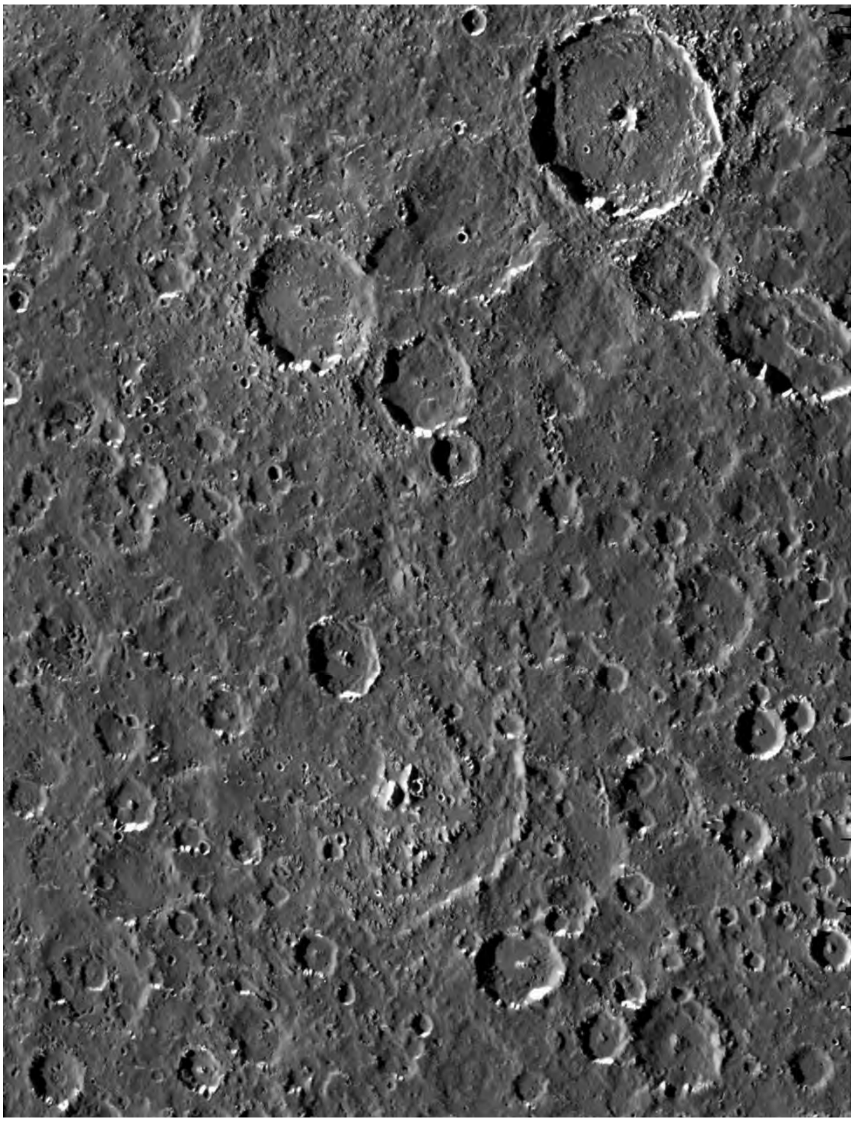


Figure 4: Close up of the surface of Jupiter's moon, Callisto. The image covers an area approximately 222 by 195 kilometres. North is to the top of the image. Modified image courtesy of NASA (https://photojournal.jpl.nasa.gov/catalog/PIA00745)

Zoe shared some of her images with her friends and colleagues. Jiki Nakamura was taken by the view of Callisto's craters (Figure 4).

9. Jiki said that as a geochronologist they were very interested in the timing relationships Zoe noted about the geological and geographical features of Europa. However, they could also see Callisto's craters were telling a story.

   Q: What did they say about Callisto's crater story? (1 mark)

   a. All the craters are the same age.
   b. There were two distinct bombardment events, separated by many millions of years.
   c. Craters of all ages are visible, with the youngest craters having the most distinct rims.
   d. Craters of all ages are visible, with the oldest craters having the most distinct rims.
   e. Craters of all ages are visible, but only the oldest craters have central peaks.
   f. Craters of all ages are visible, but only the youngest craters have central peaks.

10. Jiki also commented about it being a nice clear, sunny day on Callisto when the photograph was taken.

   Q: What did they say in their comment? (1 mark)

   It is so clear and sunny. Standing with your back to the sun you would have no problems seeing all the geographic details …

   a. … on the northern horizon.
   b. …on the eastern horizon.
   c. …on the southern horizon.
   d. …on the western horizon.
   e. …on Saturn's surface.
   f. …beyond the horizon.

While Zoe was inspecting Europa, team members Sandra Shore and Andy Syght took a shuttle to Jupiter's innermost moon – Io. The volcanoes of Io are very active, constantly erupting silicate (basaltic) lava, liquid sulphur and SO_2 gas (Figures 5 and 6 on the next page). The volcanic SO_2 gas entering the atmosphere sometimes forms a snow-like granular frost on the surface if it is cooled enough. Like snow on Earth forming thick icy layers beneath the most recent falls, the SO_2 frost can build up to form a thick layer covering the surface (Figure 6). Where lava encounters the thick SO_2 layer, the resultant SO_2 outgassing (as the SO_2 sublimates from solid to gas) is vigorous enough in some circumstances to physically move fragmented lava and surface granules of SO_2 frost across the ground in a bouncing form of transport (called saltation). The frost granules and lava fragments accumulate downwind in dune structures as the velocity of the transporting gas dissipates.

11. Sandra and Andy are tasked with documenting this lava-frost interaction at the geotourism site on Io known as Prometheus Patera. They have been asked to make recommendations to the IMHE for improving the visitor experience and protecting the site, given the site is both physically dangerous and environmentally sensitive.

    Q: At Prometheus Patera, the dunes are only observed adjacent to contacts between lava flows and thick beds of solid SO_2. However, elsewhere on Io there are dunes built of SO_2 frost granules that are not associated with lava flows. What does this suggest to Sandra? (1 mark)

    a. Io's dunes cannot be formed by atmospheric processes.
    b. Io's dunes are reworked by giant spice-producing sand worms.
    c. Io's atmospheric movements sometimes reach a velocity capable of moving frost granules because the moon is so close to Jupiter and its massive storm systems.
    d. Io's atmosphere contains more than just SO_2 gas.
    e. Io's thin atmospheric movements sometimes reach a velocity capable of moving frost granules without the help of outgassing caused by lava flows.
    f. The other dunes must be formed by liquid water-based processes.

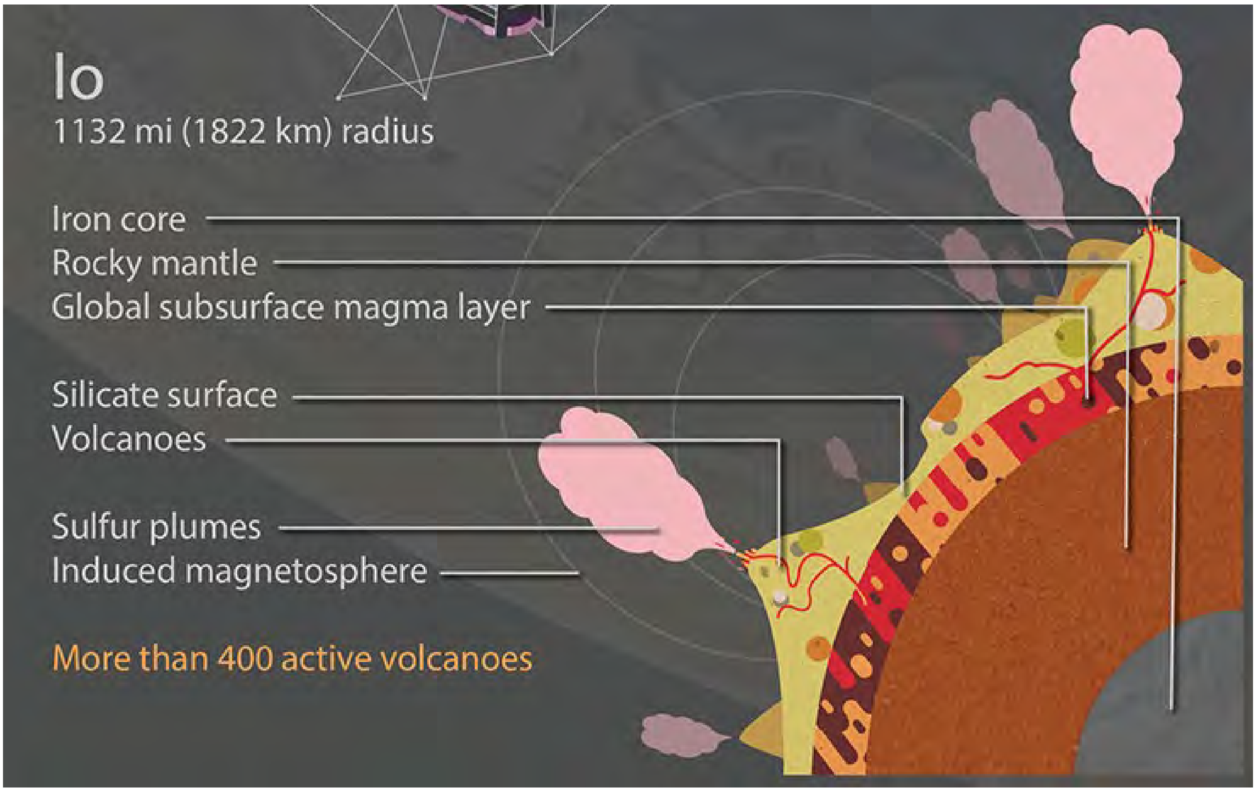


Figure 5: Schematic cross-section through Io, highlighting the general structure and geologically active features of the moon. Image courtesy of NASA (2019). https://tinyurl.com/47cu9jfp

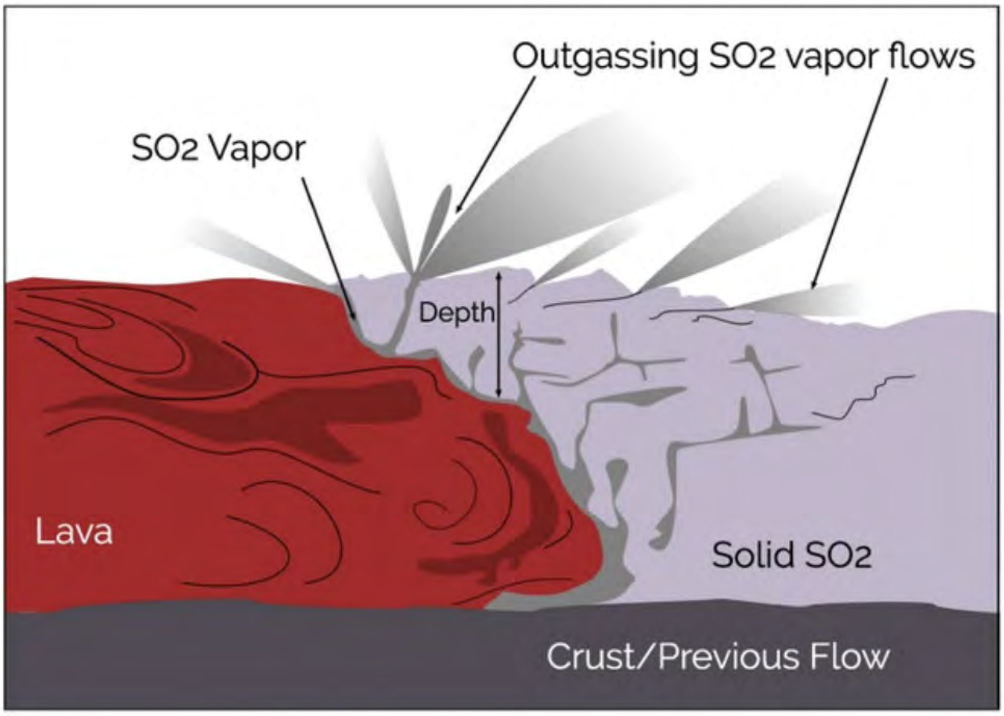


Figure 6: The geometry of the lava-SO_2 frost interaction. The light grey regions all consist of SO_2 vapor, which outgas as vapour flows upon reaching the surface.
Image courtesy of https://tinyurl.com/2ja856sz

Sandra has carefully monitored Io's extremely thin SO_2 gas atmosphere as part of the background data for their report. On average, the daytime atmospheric pressure at Prometheus Patera was ~1 x 10^{-9} bar but varied considerably as Io entered and exited Jupiter's shadow. In the two Earth hours Io is in Jupiter's shadow the atmospheric pressure collapses to less than 1 x 10^{-12} bar because the SO_2 freezes out as frost. When Io emerges from the shadow, most of the recent SO_2 frost sublimates to a gas and the atmospheric pressure returns to previous levels.

While on site, Sandra and Andy witnessed multiple dune-forming outgassing events. They recorded both the atmospheric pressure and temperature of the outgassing SO_2 during each event (Table 1). In addition, using the best safety equipment available, they were able to sample fresh lava and confirm a surface flow temperature of 1100°C.

Event #	Atmospheric Pressure	Outgassing Temperature at ground surface
1	1 x 10^{-9} bar	225 K
2	9 x 10^{-8} bar	185 K
3	1 x 10^{-9} bar	301 K
4	5 x 10^{-9} bar	600 K
5	2 x 10^{-9}bar	445 K
6	1 x 10^{-11} bar	225 K

Table 1: Pressure and temperatures recorded for outgassing events.

Consulting the useful phase diagram for SO_2 (Figure 7 – next page), they were able to confidently say a number of things about Io's atmosphere and the outgassing events in their report.

Q: What correct statements did they make in their report?

12. Assuming the average daytime atmospheric pressure at Prometheus Patera is ~1 x 10^{-9} bar, the average daytime atmosphere's temperature must be at least… (1.0 mark)

   a. 95 K
   b. 112 K
   c. 125 K
   d. 183 K
   e. 197 K
   f. 225 K

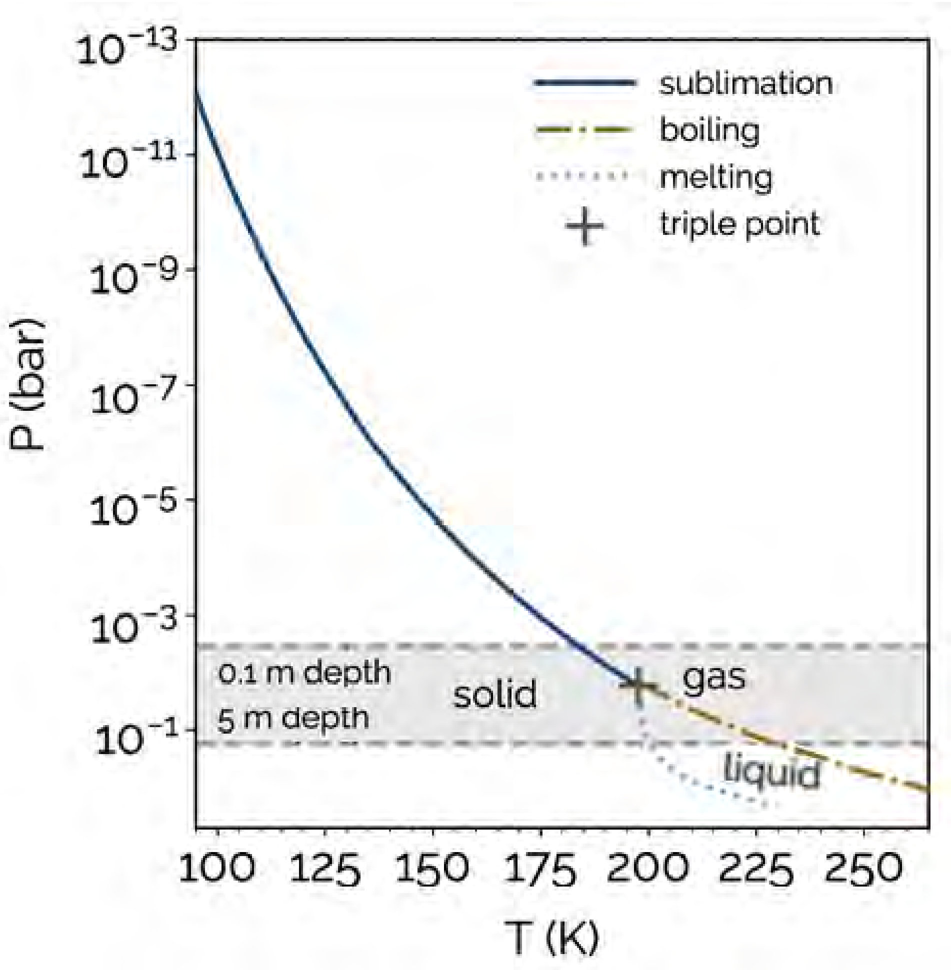


Figure 7: The SO_2 phase diagram, with the phase transitions depicted as lines. The blue line marks Pressure – Temperature points at which sublimation occurs. To the right of the line SO_2 can only exist as a gas. To the left of the line SO_2 can only exist as a solid.
Modified image courtesy of https://tinyurl.com/2p99we36

13. When in shadow… (1.0 mark)

a. …Io's atmospheric temperature must drop below 95 K.
b. …Io's atmospheric temperature must remain above 95 K.
c. …Io's atmospheric temperature must increase to 183 K.
d. …Io's atmospheric temperature remains unchanged.
e. …a blue glow, indicative of burning sulphur, becomes visible.
f. …Io's atmospheric temperature must drop from 150 K to 115 K.

14. When an outgassing event occurs from the base of a 5-m thick layer of solid SO_2… (1.0 mark)

   a. …the outflowing material is entirely liquid until the temperature drops to 197.5 K.
   b. …the outflowing material is entirely gas with a minimum temperature of 197.5 K.
   c. …the outflowing material is entirely gas with a minimum temperature of 183 K.
   d. …the outflowing material is entirely liquid with a minimum temperature of 183 K.
   e. …the outflowing material is entirely gas with a minimum temperature of 229.5 K.
   f. …the outflowing material is entirely liquid with a minimum temperature of 229.5 K.

15. When an outgassing event occurs, the outflowing SO_2 gas usually contributes to the SO_2 atmosphere. However, during… (1.0 mark)

   a. … event #1 SO_2 frost was observed forming from the outflowing SO_2 gas.
   b. … event #2 SO_2 frost was observed forming from the outflowing SO_2 gas.
   c. … event #3 SO_2 frost was observed forming from the outflowing SO_2 gas.
   d. … event #4 SO_2 frost was observed forming from the outflowing SO_2 gas.
   e. … event #5 SO_2 frost was observed forming from the outflowing SO_2 gas.
   f. … event #6 SO_2 frost was observed forming from the outflowing SO_2 gas.

16. Noting the nominal pressure within the ground materials, to initiate shallow (~0.1m deep) outgassing… (1.0 mark)

   a. … the lava must have raised the SO_2 ground temperature above 185 K.
   b. … the lava must have raised the SO_2 ground temperature above 230 K.
   c. … the lava must have raised the SO_2 ground temperature above 115 K.
   d. … the lava must have raised the SO_2 ground temperature above 197 K.
   e. … the lava must have flowed over the surface.
   f. … the lava must have melted all deeper layers first.

17. Io's atmosphere collapses to the ground as frost when the moon enters Jupiter's shadow. However, there is always some atmospheric SO_2 because … (1 mark)

a. … Io's gravity is constantly pulling SO_2 gas from Jupiter's clouds.
b. … equatorial winds replace the atmosphere lost to frost with fresh gas from the warm side.
c. … one side of Io is always facing the Sun.
d. … SO_2 frost boils in Jupiter's shadow when the pressure drops below 1 x 10^{-11} bar.
e. … SO_2 gas is constantly erupting from Io's volcanoes.
f. … some SO_2 has a lower freezing point.

Sandra and Andy reviewed published data on the location before they arrived. One graph that Andy found interesting is shown in Figure 8. He noted that the saltation threshold – the point at which grains can be moved in a bouncing motion by outgassing – is both temperature and grain-size dependent for the known outgassing velocity range. The narrow band of outgassing velocities shown in Figure 8 represents the lower and upper limits for this phenomenon on Io. The five outgassing temperature curves, each for two grain types, have been established by laboratory experiment.

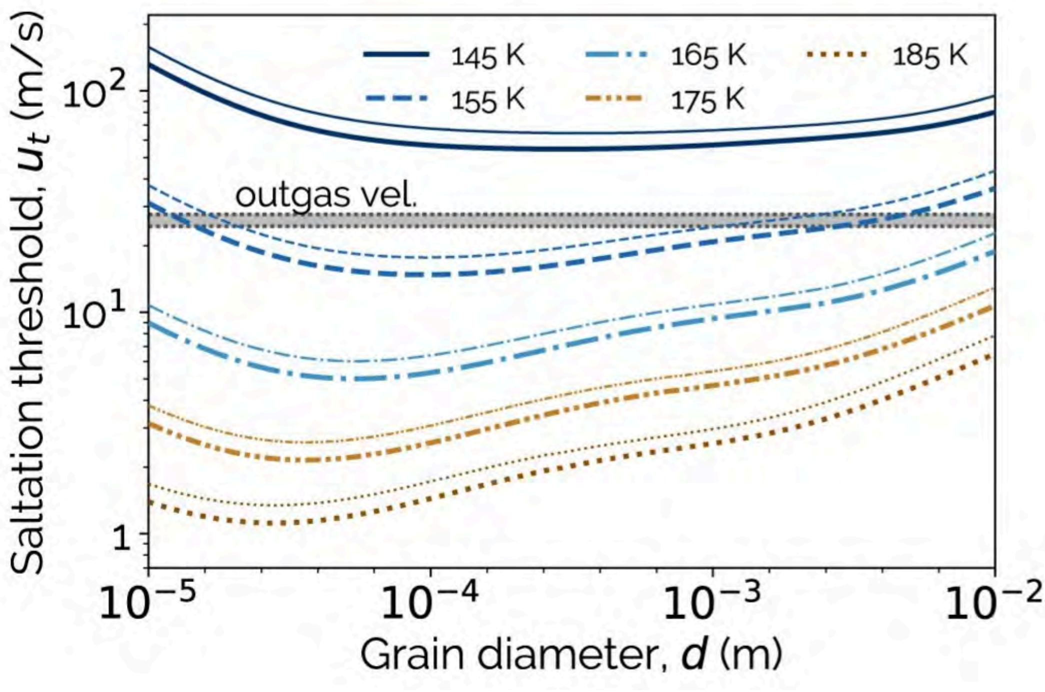


Figure 8: This graph shows the saltation threshold as a function of grain diameter (d) and temperature (K - kelvin). The saltation thresholds are shown for grain compositions of either basalt or SO_2 and are also compared with the calculated initial outgassing velocities at Prometheus Patera shown in the shaded band labelled outgas vel. Thick lines are the threshold for SO_2 grains, while the thinner lines are for basalt grains. When the outgassing velocity is higher than the saltation threshold for a given grain size, saltation may occur. Note: At Prometheus Patera all grainsizes between 10^{-5} and 10^{-2} m diameter are present.
Image courtesy of https://tinyurl.com/2ja856sz

18. Another accurate statement they included in the report was:

Given the … (1 mark)

a. … mean atmospheric temperature on Io and the range of outgassing velocities, frost granules and lava fragments of all sizes always contribute to dune formation.
b. … range of outgassing velocities and temperatures at Prometheus Patera, it is impossible for frost granules to contribute to dune formation.
c. … range of outgassing velocities and temperatures at Prometheus Patera, it is only possible for lava fragments to contribute to dune formation if the outgassing temperature is 165 K or higher.
d. … range of outgassing velocities and temperatures at Prometheus Patera, it is only possible for all fragments to contribute to dune formation if the outgassing temperature is 165 K or higher.
e. … range of outgassing velocities and temperatures at Prometheus Patera, it is only possible for all fragments to contribute to dune formation if the outgassing temperature is 165 K or lower.
f. … range of outgassing velocities and temperatures at Prometheus Patera, it is impossible for lava fragments to contribute to dune formation.

While Sandra and Andy were busy on Io, their friends and IMHE colleagues – Philip Light and Gabi Roe – were on Earth enjoying a visit to Mount Etna to watch the interactions of a new lava flow with the current snowpack. When Sandra shared images of their adventures on Io with the whole team, she knew Gabi would be excited to see a similar process in action on another planetary body. Gabi was indeed excited. She noted that the explosive behaviour of lava interacting with SO_2 frost is very similar to the behaviour she was observing on Mount Etna between lava and snow pack.

19. Gabi wrote back to Sandra, saying:

…Not all interactions between lava and ice are explosive, but when they are, they're very similar to those you've documented between lava and solid SO_2. In both tourist hot spots they even create similar hazard management issues. Another great example of uniformitarianism!

Gabi did go on to note several differences between the settings to be mindful of when thinking about similarities between the resultant explosive activities. She said:

…One of the most important differences to affect the behaviour of materials ejected by explosive activity would be…

Q: Select the correct phrase to complete the sentence. (1 mark)

a. …gravity on Io is only about 0.183 g.
b. … SO_2 gas is poisonous.
c. … Io is tidally locked (one side always faces Jupiter).
d. … Io has an average albedo of 0.62 but Earth only has an average albedo of 0.31.
e. … SO_2 reacts with H_2O to form sulphuric acid.
f. … SO_2 is not a greenhouse gas.

Gabi sent this first-hand account of a recent incident on Mount Etna:

> **…Dozens of tourists arrived early this morning to see a lava flow that had appeared overnight. A giant stream of rock, glowing red, was oozing down the slopes - and we were also there monitoring its progress.*
>
> *However, about 20 minutes after the tourists arrived, a burst of white steam emerged from the lava – it didn't make much of a noise or look especially threatening – but all of us and their guides started asking the tourists to move because we knew what might be coming.*
>
> *Then, moments later, there was an explosion. Red hot rocks, ash and hot mud - flung high into the air - started to rain down in every direction!*
>
> *Luckily no one was injured on this occasion.*

20. Sandra noted she had seen similar things happen on Io. She said this event was a classic example of a type of phreatic eruption (explosive behaviour caused by superheated gasses rapidly expanding and exceeding any confining pressure – similar to the failure of a pressure cooker). In this case, the intense heat of the lava flow flashes ice to steam in a confined space, generating a steam explosion from under the thin lava flow.

    Q: What else did Sandra say in reply to Gabi? (1 mark)

    a. Phreatic eruptions also occur when near-surface magma encounters confined groundwater as happened at Whakaari (White Island) in 2019.
    b. Phreatic eruptions also occur when near-surface magma encounters older lava flows.
    c. Phreatic eruptions also occur when subducting lithosphere encounters the asthenosphere.
    d. Phreatic eruptions also occur when lava flows onto the floor of the deep sea as seen at mid-ocean ridges.
    e. This is the only circumstance under which phreatic eruptions can occur.
    f. Io's eruptions are not phreatic because no steam is involved.

* this fictional quote is a paraphrasing of an actual 2017 quote from a BBC camera crew filming on Mt Etna.

21. Philip also wrote to Sandra and Andy, asking them to collect a sample of Ionian lava. He told them he was making a collection of all the basalt lavas found throughout the solar system and was keen to add an Ionian sample to it.

Q: What would Sandra and Andy have to check to ensure the sample they picked for Philip really was a basalt? (1 mark)

It should be fine-grained and …

a. …they would need to ensure it had visible quartz phenocrysts.
b. …they would need to check its bulk chemistry was greater than 60% SiO_2.
c. …they would need to check its bulk chemistry was between 45% and 52% SiO_2.
d. …they would need to ensure it was vesicular.
e. …they would need to ensure it is mostly composed of olivine crystals.
f. …since all igneous rocks are types of basalt with different SiO_2 bulk chemistries, it wouldn't really matter which sample they picked.

Meanwhile, back on Earth, Roxanne Stone and her sister Gemma are on holiday. They take great delight in visiting interesting places and challenging each other to explain the phenomena they encounter.

One of their favourite places, and the first location on their itinerary, is the coastal area known as Cape Enterprise. A rocky headland, called Kirk Point, dominates this area (Figure 9 on next page). The rocks at this location are interbedded layers of sandstone and mudstone. The mudstones contain fossil graptolites, the remains of planktonic marine organisms common in Ordovician and Silurian times. The sandstones hardly ever contain fossils. Their friend and colleague, Sandra Shore saw their social media post while at work on Io and commented:

… such a classic outcrop. I love that place! The interbedded mudstones and sandstones are a turbidite sequence. It's amazing how the sandstone beds – called turbidites – are deposited by density flows (highly turbulent liquids which have a suspended load of fine-grained particles forming a slurry) caused by underwater avalanches from shallow water locations into deep water locations. She also attached a picture: Figure 10 (after Figure 9).

Figure 9: A view of Kirk Point at Cape Enterprise, looking directly south.

Locations A, B, C & D are sites where the sisters found fossils.

Photograph courtesy of Gemma Stone.

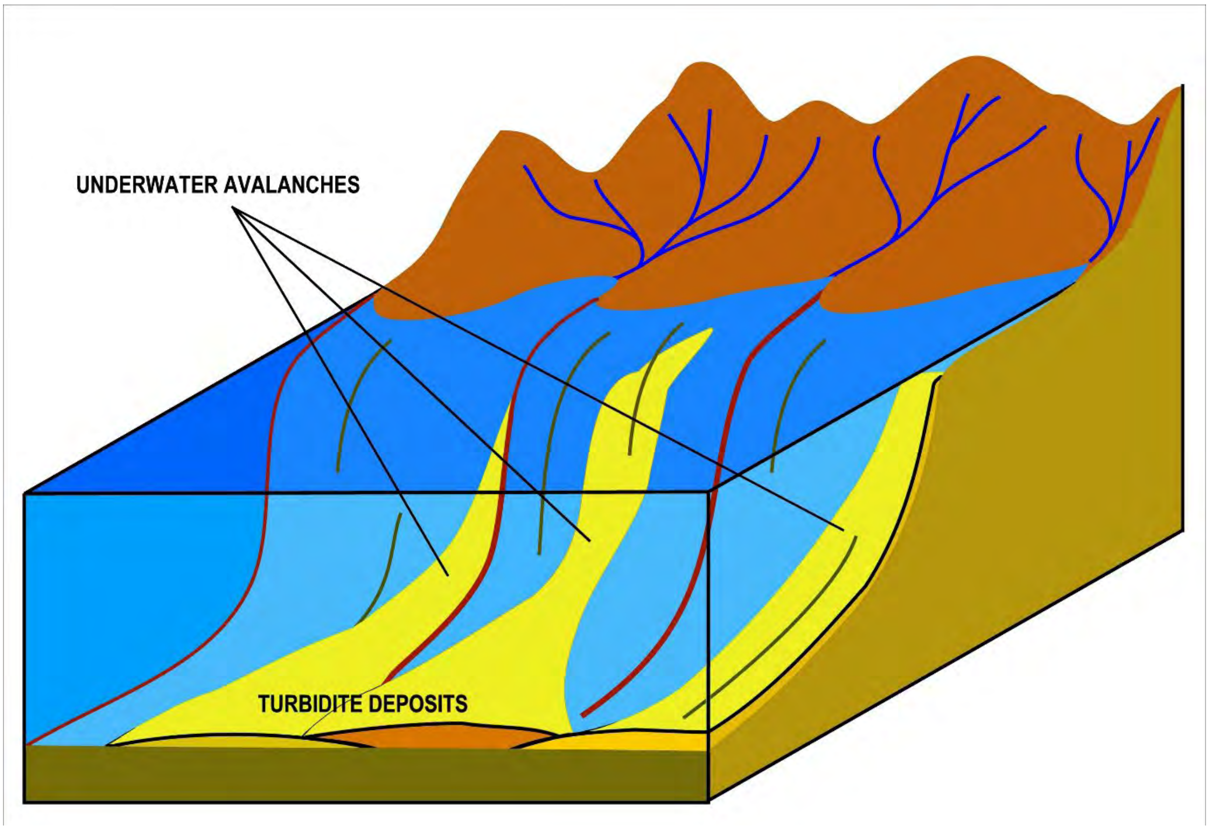


Figure 10: A diagram to demonstrate the process of turbidite deposition by underwater avalanches at the edge of continental shelves. It can also occur in deep lakes with a similar geography.
Modified from https://tinyurl.com/ye25zdkj

22. Gemma wanted to know how the mudstones formed, given the high energy depositional environment of the turbidite sandstones.

Q: What did Sandra say in reply? (1.0 mark)

Mudstone deposits only form in low energy depositional environments. The interbed mudstones …

a. …are slivers of older mud rock forced into the sandstones by thrust faulting typical of a subduction zone.
b. …are deposited by mud settling out of suspension in between turbidite events.
c. …are the result of mid-ocean-ridge sea-floor spreading and exhibit magnetic reversals.
d. …are caused by burial compaction, causing some sandstone layers (usually every second one) to experience dissolution of all the silicate minerals, leaving just clay behind.
e. …are caused by groundwater infiltrating the turbidites (usually every second one) long after lithification and altering the mineralogy to clays.
f. …are the carbon-rich remains of graptolites settling onto the sea floor in between turbidite events.

Another friend and colleague, Philip Light, also commented on their media posts:

> *… it's one of my favourite places too! The fantastic stack of folds is a great example of chevron folding. He also attached two images: Figure 11 & Figure 12 on the next page.*

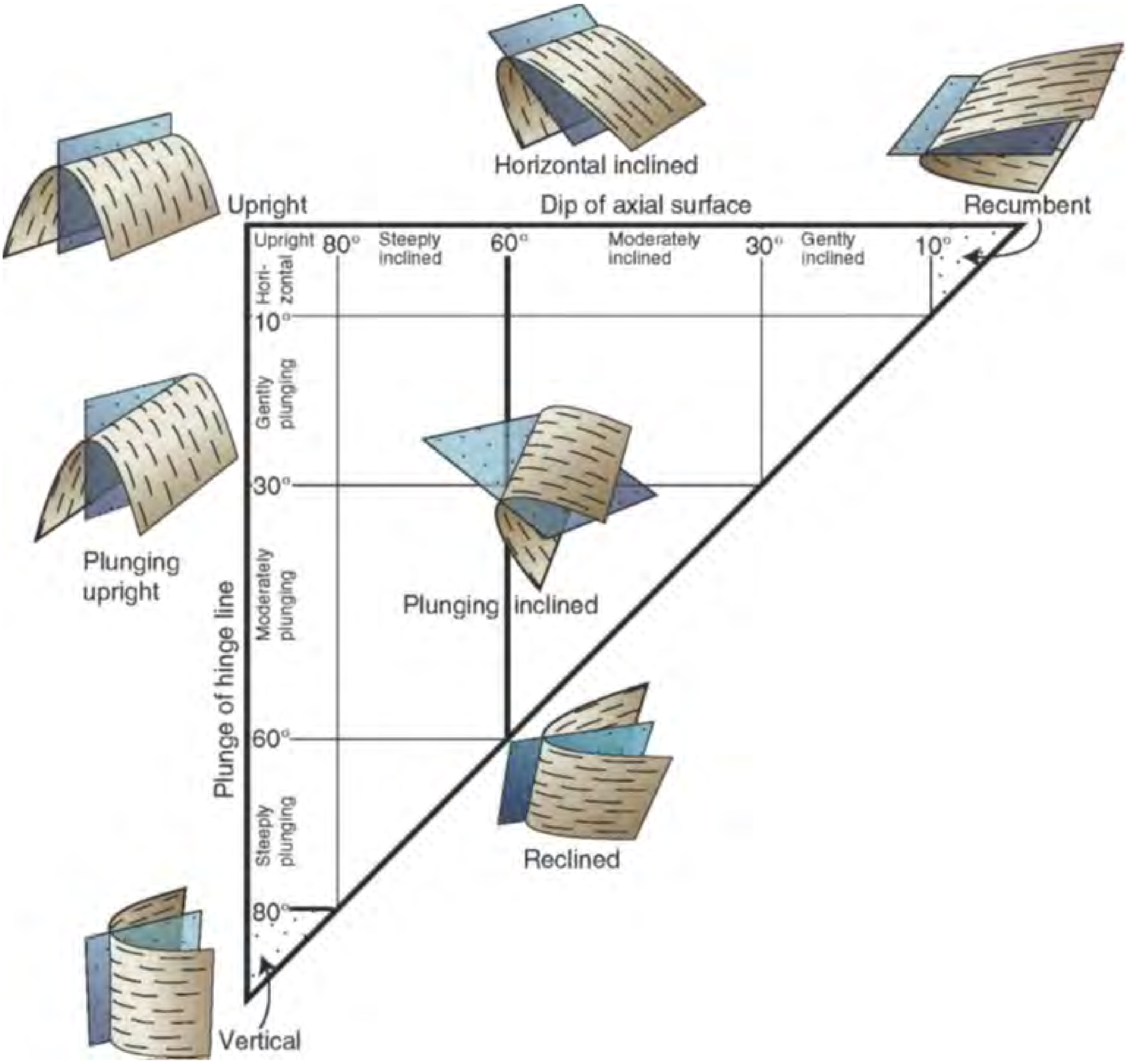


Figure 11: *Fold geometry variations. Modified from Fleuty (1964).*

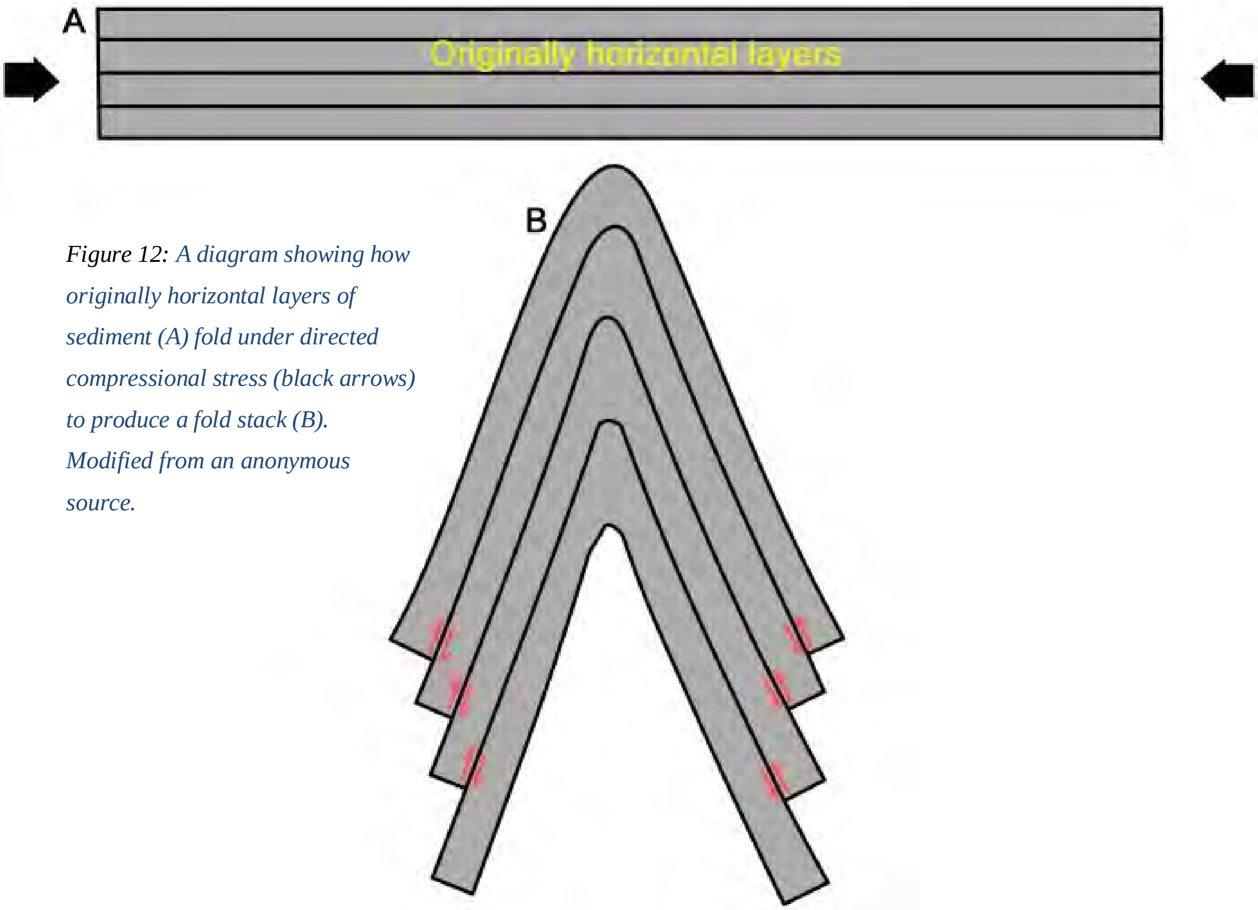


Figure 12: A diagram showing how originally horizontal layers of sediment (A) fold under directed compressional stress (black arrows) to produce a fold stack (B). Modified from an anonymous source.

23. Roxanne asked for more information about the folds.

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

The chevron folds in your photograph …

a. …are recumbent and plunging 10 degrees.
b. …are vertical and plunging 80 degrees.
c. …are inclined and plunging more than 45 degrees.
d. …are horizontal inclined less than 30 degrees.
e. …are reclined and plunging at 60 degrees.
f. …are upright and plunging less than 30 degrees.

24. Roxanne thanked Philip and commented that the geometry of the landscape was really intriguing.

Q: What else did Philip say in addition to his previous reply? (1 mark)

The chevron folds also indicate …

a. …the rocks experienced tectonic compression from the east and west.
b. …the rocks experienced tectonic extension from the east and west.
c. …the rocks experienced tectonic extension from the north and south.
d. …the rocks experienced tectonic compression from the north and south.
e. …the rocks experienced tectonic extension from above and below.
f. …the rocks experienced tectonic compression from above and below.

As Roxanne and Gemma explored the fold stack, some of the mudstone layers at outcrop A in Figure 9 revealed lamination surfaces covered in graptolite fossils. They also found some broken fragments of colonial coral fossils in some of the sandstone beds at location A and location C.

Gemma has always loved fossils and was keen to know more about them, especially the coral fragments. She shared photographs of the fossils on her social media (Figure 13 and Figure 14 on the next page).

Figure 13: Graptolites in outcrop.
Modified from an image in https://tinyurl.com/38t24k9p

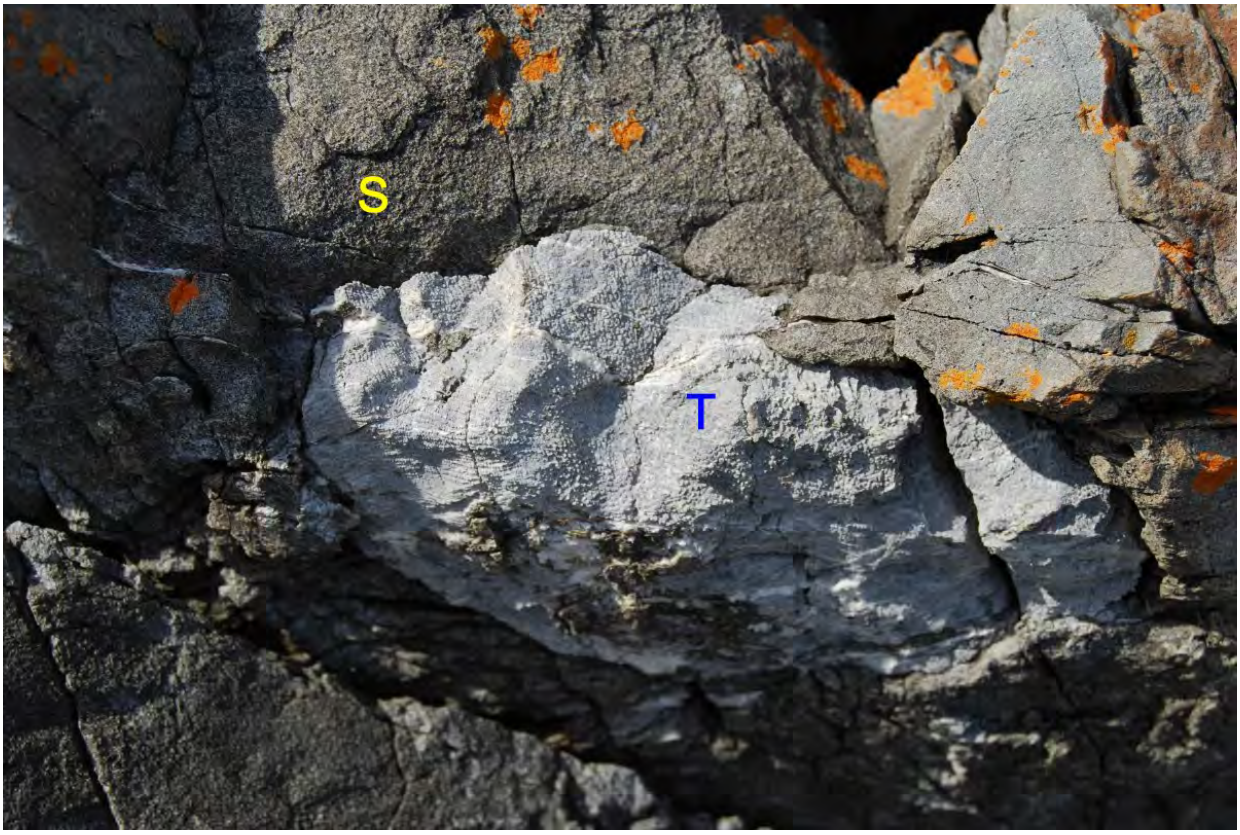


Figure 14: Image showing a broken light-coloured fragment of colonial tabulate coral (T) within the bedding of a darker coloured turbidite sandstone (S). Image 100 mm wide. Image courtesy of Gemma Stone.

25. Gemma was very excited to find the coral fossils in such an unusual setting and asked Roxanne to explain.

Q: What did Roxanne say about the coral fossils? (1 mark)

The coral fossils …

a. …are Ordovician in age and were living on the sand prior to the sand's collapse into a density flow.
b. … are Silurian age and were living on the sand prior to the sand's collapse into a density flow.
c. … are Ordovician in age and were living on the turbidite sand deposit prior to the deposition of the graptolitic mudstone.
d. … are Silurian in age and were living on the turbidite sand deposit prior to the deposition of the graptolitic mudstone.
e. … are Devonian in age and were living inside the turbidite sand deposit prior to the deposition of the graptolitic mudstone.
f. … are Cambrian in age and were living inside the turbidite sand deposit prior to the deposition of the graptolitic mudstone.

26. Everyone loves finding fossils and Gemma shared her discoveries and excitement with her friends.

Q: What else was Gemma able to say in her social media posts about the fossils she found? (1 mark)

I found evidence in some asymmetrical sedimentary structures within the sandstones that the layered sequence has not been overturned: Upwards in my photograph is the same as it was when the sediments were deposited, despite the folding. This means the graptolites …

a. …found in outcrop A are slightly older than those found in outcrop C but the chevron folding prevents working out the age relationship with the graptolites found at B and D.
b. …found in outcrop A are slightly younger than those found in outcrop C but the chevron folding prevents working out the age relationship with the graptolites found at B and D.
c. … found in outcrop A are slightly younger than those found in outcrop C but slightly older than those found in outcrops B and D.
d. … found in outcrop A are slightly older than those found in outcrop C but slightly younger than those found in outcrops B and D.
e. …found in outcrop A are the same age as the folding.
f. …are all exactly the same age.

27. Rose was very keen to hear more about the fossils Gemma was finding but Gemma had a disappointing message for Rose.

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

a. We found no other fossils, probably because the depositional environment for these sediments was not suited to hosting much of the easily fossilised lifeforms of the time.
b. We found no other fossils, probably because the area was not volcanic at the time so there was no volcanic ash to kill and bury the wildlife.
c. We found no other fossils, probably because the rocks have been through low grade metamorphism that would have dissolved all the carbonate skeletons.
d. We found no other fossils because the graptolites were the only planktonic lifeforms at the time and corals the only benthic lifeforms at the time.
e. We found no other fossils, probably because neritc (free swimming) lifeforms stayed out of the zone where turbidites were being deposited as much as possible.
f. We found no other fossils, probably because trilobites liked eating everything other than corals and graptolites.