11. Gemma was curious to know why there might be sink holes on Titan.

Q: How did Roxanne accurately explain this?

Hi Gemstone,
It is postulated organic-molecule-rich sedimentary deposits on Titan might be soluble in methane or ethane rain run-off and cavitate through dissolution in these organic solvents. On Earth …

a. … many caves are formed in limestone through the dissolution of the $CaCO_3$-rich rock by slightly acidic rain water (formed by rain water reacting with atmospheric CO_2 to form carbonic acid). In both scenarios, caves close to the surface could collapse, forming sink holes.

b. … many caves are formed in granite through the dissolution of the feldspar rich rock by slightly acidic rain water (formed by rain water reacting with atmospheric CO_2 to form carbonic acid). In both scenarios, caves close to the surface could collapse forming sink holes.

c. … many caves are formed in gyprock through the dissolution of the $CaSO_4$-rich rock by slightly acidic rain water (formed by rain water reacting with atmospheric SO_2 to form sulphuric acid). In both scenarios, caves close to the surface could collapse forming sink holes.

d. … caves are formed in most rock types through the dissolution of the silicate minerals by slightly acidic rain water (formed by rain water reacting with atmospheric CO_2 to form carbonic acid). In both scenarios, caves close to the surface could collapse forming sink holes.

e. … many caves are formed in sandstone through the dissolution of the SiO_4-rich rock by slightly acidic rain water (formed by rain water reacting with atmospheric SiO_2 to form sialic acid). In both scenarios, caves close to the surface could collapse forming sink holes.

f. … many caves are formed nicely in gneiss through the dissolution of the mica-rich rock by slightly acidic rain water (formed by rain water reacting with atmospheric CO_2 to form carbonic acid. In both scenarios, caves close to the surface could collapse forming sink holes.

12. Gemma and Roxanne are familiar with caves called lava tubes because they have both stayed in underground habitats constructed inside such structures off Earth. Gemma recently stayed in one on the Moon and Roxanne has stayed in those built during the early years of the Martian Congressional Republic, which are now converted into quality apartments for visiting scientists. When they caught up with friends and their brother Orson a few days after Roxanne's return, they found themselves comparing notes. Gemma was clearly impressed with the quality of the Martian condominiums, but her marine biologist friend, Amber Gris, was aghast, exclaiming:

Wow! You stay in hotels made of lava? How is that even a thing?

Gemma decided to flick pass this question to her brother Orson, a mining engineer. He explained that the lava tubes form naturally in lava flows as part of the eruption process. They are not tunnels excavated through old lava flows, as some people think. However, he was quick to add that a lot of clever engineering is needed to make a lava tube safe and habitable.

Q: How did Orson answer Amber when she asked:

Engineers construct domes on the surface now, like Luna's Tycho City and Pavonis City on Mars, so why did early colonies on Mars and the Moon use lava tubes?

a. Orson included both d & e in his answer.
b. Orson included both e & f in his answer.
c. Orson included d, e & f in his answer.
d. The surface of both Mars and the Moon experience massive temperature fluctuations. Rock is a great insulator so underground environments like caves have relatively stable temperatures, reducing that engineering challenge to manageable levels.
e. Mars has a very thin atmosphere which does not protect the surface from meteors and the Moon has virtually no atmosphere. The layer of thick rock making up the roof of the lava tube provides instant protection from all but the biggest meteorites.
f. Mars and the Moon lack a magnetic field so they are not protected from ionizing radiation the way the Earth is. The layer of thick rock making up the roof of the lava tube provides instant protection, making a great base from which to start.

13. Amber immediately wanted to know what kind of lava, found on both Mars and the Moon, makes lava tubes. She thought it might be all kinds but Roxanne explained, saying:

Lava tubes only form in lava that flows really easily.

Gemma, chimed in saying:

Lava that flows really easily usually has an SiO_2 content between 45% and 55% of the whole rock because the viscosity of lava is proportional to the SiO_2 content.

Orson completed the conversation by saying:

So free flowing, low viscosity lava cools to form a common igneous rock found on Earth, the Moon and Mars called …

a. Basalt
b. Gabbro
c. Andesite
d. Diorite
e. Rhyolite
f. Granite

14. Amber looked puzzled.

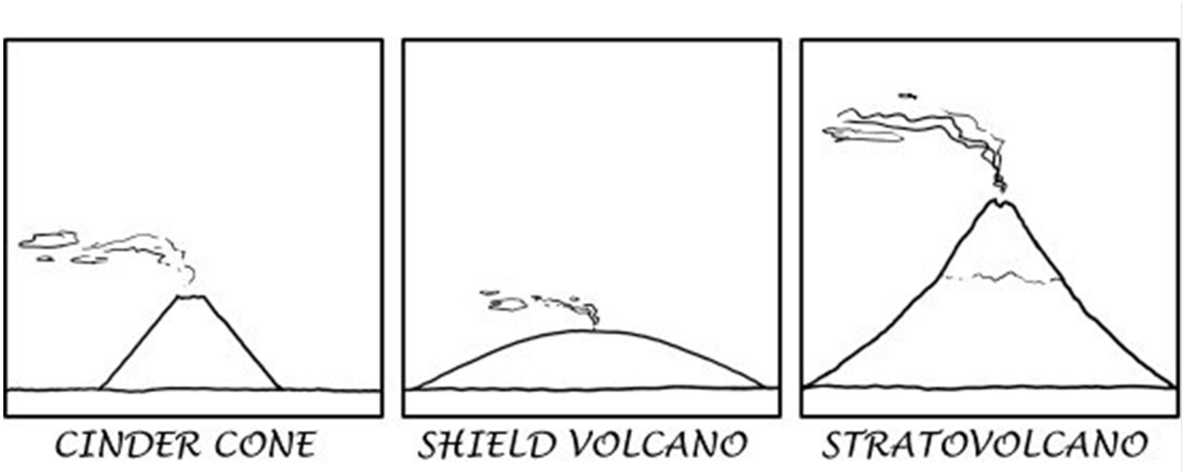
There are lava tubes on Earth too?

She exclaimed, adding:

I only go scuba diving for my marine biology work, around really big volcanos that explode. What other types of volcanoes are there?

Roxanne quickly wrote some blocks of text and drew some diagrams on the back of the table napkin (shown below).

Q: Which drawing did she associate with each block of text (draw lines between the text box and the image to indicate your choices)?



• Cover a huge area • Mostly lava flows • Forms over hot spots • Explosive eruptions rare	• Covers a small area • Mostly ash and small pyroclastic fragments • Lots of gas escaping • Lava fountains	• Alternating layers of pyroclastic flows, ash fall and lava flows • Steep sides • Slow moving lava • Form over subduction zones

15. Gemma added that there are lots of other ‘types’ of volcanoes and volcanic landforms including the ‘seas’ on the Moon. Ancient astronomers thought they might actually be seas or oceans and the name has stuck although we now know these rocks are lava flows. She also proudly showed off her green earrings that she purchased in Tycho City. She said they were mined on the Moon, not from the lava flows but from the even lower silicate mantle material (less than 45% SiO_2) brought to the surface by meteorite impacts. What minerals did she say are found in this mantle rock?

a. Olivine, Pyroxene and Plagioclase feldspar
b. Olivine, Pyroxene and Amphibole
c. Olivine, Pyroxene and Biotite
d. Olivine, Pyroxene and Potassium feldspar
e. Pyroxene, Amphibole and Plagioclase feldspar
f. Pyroxene, Amphibole, Plagioclase feldspar and Potassium feldspar

16. Rose was interested to know where abouts on the Moon the green gems in the earrings came from. Gemma said they were certified as coming from Picard crater in Mare Crisium, not far from the Apollo 17 landing site, and also noted the same mineral is found in similar rocks on Earth. Rose, remembering that the Earth’s mantle was between 25 km and 75 km beneath continental crust and about 10 km beneath oceanic crust, asked Gemma if the mantle minerals found on Earth’s surface were also brought up by meteorite impacts. What did Gemma say in reply?

a. Mantle material found at Earth’s surface is fake news. It is physically impossible for it to get to the surface.
b. Mantle material found at Earth’s surface is actually only lunar mantle ejected Earthwards by big meteorite impacts on the Moon.
c. Mantle material found at Earth’s surface is only excavated by explosive volcanic eruptions over subduction zones.
d. Mantle material found at Earth’s surface is mostly exhumed by hot spot volcanoes bringing it up with erupting magma derived from the partial melting of the mantle.
e. Mantle material found at Earth’s surface is mostly exhumed by hot spot volcanoes bringing it up with erupting magma derived from the partial melting of the core.
f. Mantle material found at Earth’s surface is mostly excavated by hot spot volcanoes bringing it up with erupting magma derived from the partial melting of subducting slabs.

17. Knowing Rose preferred fossils to minerals, Gemma noted that the green mineral in her earrings is never found in fossils. She added that the skeletons of animals do contain minerals, with different lineages of animals using various minerals to build skeletons. Their friends, Brady O'Larian and Jeff Gnathostomes, were also present. Brady studies plankton and confirmed that his favourite planktonic critters build skeletons out of silica (SiO_2). Jeff is a world expert in fossil fish and loves fish flavoured ice-cream. He added that humans build their bony skeletons out of calcium hydroxyapatite, a type of phosphate mineral. Gemma asked Jeff why humans evolved a phosphatic skeleton? What was Jeff's answer?

   a. Due to their really big brains, humans have unique energy demands, compared with other vertebrates, leading to the evolution of a skeletal mineral with just the right healing properties needed by big brains.
   b. Human's didn't evolve a phosphatic skeleton. The hominid ancestors of humans did because of their exposure to phosphatic rocks as they made more use of stone tools.
   c. Human's didn't evolve a phosphatic skeleton. Frogs did, and humans are just frogs that have learned to live away from water.
   d. Human's didn't evolve a phosphatic skeleton. The common ancestor of all vertebrates evolved some form of calcium carbonate-mineralised tooth-like dermal armour that was subsequently utilised in mammal evolution to build a phosphatic skeleton.
   e. Why humans are unique in having a bony spine composed of calcium hydroxyapatite is one of the big unanswered questions in evolution.
   f. Human's didn't evolve a phosphatic skeleton. The common ancestor of all vertebrates evolved some form of calcium phosphate-mineralised tooth-like dermal armour that was subsequently utilised in fish evolution to build skeletons.

18. Rose asked Brady: Do your favourite critters ever end up as fossils? Yes! he said, explaining that his favourite critters were tiny protozoa with a diameter of 0.3 mm – 2.0 mm that usually grow an elaborate mineral skeleton made of amorphous opaline silica (hydrated silica - $SiO_2 \cdot nH_2O$) with no crystal structure. He added that radiolarians, as they are called, make excellent index fossils because they rapidly evolve different shapes over time, have lots of species diversity and, being planktonic, have a wide geographic distribution. This means they can be used to accurately identify the age of many sedimentary deposits they are found in. Pleased to be able to talk about his critters, he showed Rose some documents on his phone's holographic whiteboard and challenged her to some questions. He first showed her this graph (figure 3 below) and asked:

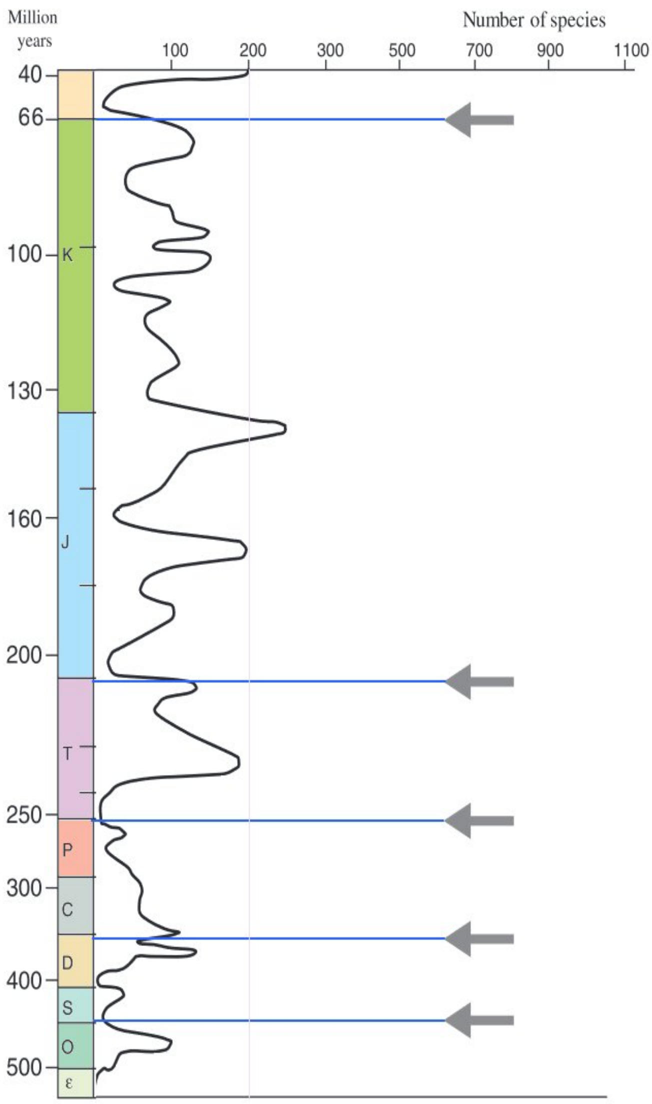


Figure 3: Radiolarians species diversity through time. The continuous line shows the number of species through time. The age scale is logarithmic. The large arrows and blue lines indicate the five main marine extinctions throughout the Phanerozoic. Modified from Vishnevskaya and Kostyuchenko [2000]: The evolution of radiolarian biodiversity. Journal of Paleontology, 34, 124-130.

Assuming index species abundance is proportional to species diversity, with 200 species guaranteed to indicate a useful number of index species, what geological period would radiolarians be of most use to petroleum geologists in determining the age relationships of oil and gas bearing marine sediments?

Q: Which correct answer did Rose reply with?

a. Late/Upper Cenozoic
b. Late/Upper Cretaceous
c. Late/Upper Jurassic
d. Mid Jurassic
e. Mid Triassic
f. All of the Mesozoic

19. Rose turned the tables and asked Brady about the same graph:

Using this graph, and assuming the events causing extinctions spanned no more than a few million years either side of the blue lines, can we say that each of the 5 marine extinction events caused a decline in radiolarian species diversity?

Q: What was Brady's accurate reply?

a. Yes, the graph clearly shows radiolarian diversity declined sharply in response to the events causing extinctions at all the times indicated on the graph.
b. No, the graph shows radiolarian diversity was in decline for more than just a few million years leading up to and after the events causing extinctions at all the times indicated on the graph.
c. No, the graph shows radiolarian diversity did not decline leading up to and after the events causing extinctions at all the times indicated on the graph.
d. No, the graph shows radiolarian diversity was in decline for more than just a few million years leading up to the events causing extinctions at the end of the Ordovician, the late Devonian and the end of the Permian but not decreasing after those events.
e. No, the graph shows radiolarian diversity was in decline for more than just a few million years leading up to the events causing extinctions at the end of the Triassic and the end of the Cretaceous but increasing immediately after these events.
f. No, there is no correlation between the extinction events and radiolarian species diversity.

20. Brady was keen to explain more about his critters. He showed Rose another graph (figure 4 below), explaining that each vertical black line was the known age range of a family of radiolarians. He wondered if Rose could identify which group of radiolarian families, of the 10 he highlighted with numbers, would be most useful for identifying sedimentary layers in drill cores that mark the transition from the Early Cretaceous to the Late Cretaceous?

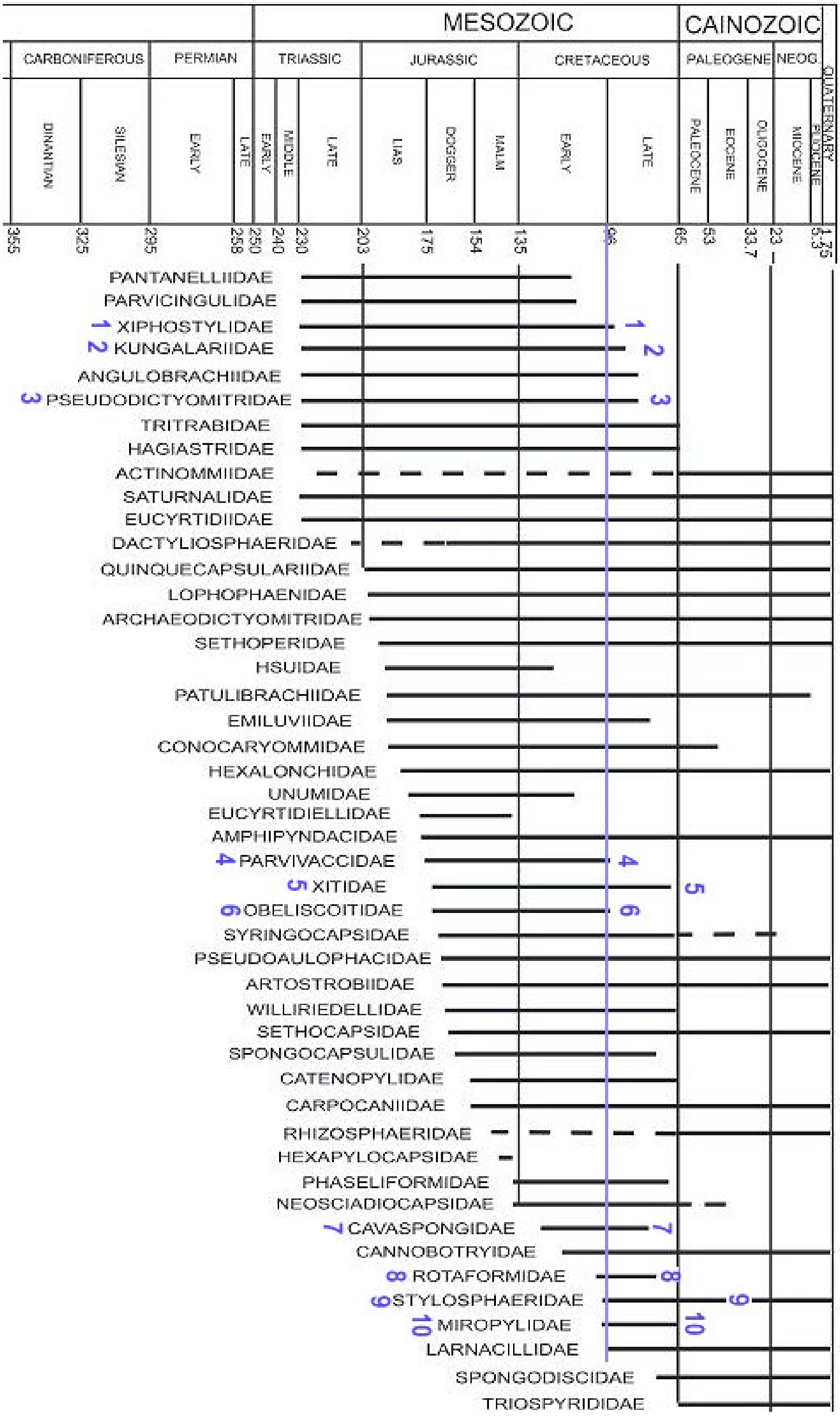


Figure 4: Some radiolarian families through time.

21. **Q: What did Rose accurately reply?**

a. Family 8 is the only one that is useful.
b. Families 8, 9 and 10 together are of the most use.
c. Family 7 is all that is needed.
d. Families 4 and 6 are all that is needed.
e. Families 1, 2, 3 and 5 together are of the most use.
f. Families 4, 6, 9 and 10 together are of the most use.

22. Brady made the observation that radiolarian skeletons form a siliceous ooze on the seafloor that can ultimately be lithified into the silica-rich sedimentary rock ***chert***. Rose remembered that plankton not only contains radiolarians but also plants and other creatures, some of which have skeletons made from calcium carbonate. She showed everyone this table:

Organism	Skeleton composition	Ooze	Rock
Radiolarian – a protozoan	Opaline silica	Radiolarian ooze if more than 30% composed of radiolarian skeletons plus clays.	Chert
Diatom – algae	Opaline silica	Diatom ooze as above	Chert, diatomite
Foraminifera – a protozoan	Calcium carbonate as calcite	Foram ooze if more than 30% composed of foram skeletons plus clays and other materials	Limestone, chalk
Coccolith - algae	Calcium carbonate as calcite	Coccolith ooze	Limestone, chalk
Pteropod – a gastropod	Calcium carbonate as aragonite	Pteropod ooze	Limestone, chalk

Brady's friend Jasper Rossa was present too and, like Brady, he is a plankton specialist but his expertise is in Foraminifera – forams for short. He added that forams are very common planktonic animals but there are many benthic species too, not just planktonic ones. However, he noted that benthic species living below ~4,500 metres don't make carbonate skeletons but live in spaces created by organically gluing sediment grains together. Gemma was confused by this conversation. She asked:

If there are both siliceous and calcareous skeletons raining down on the sea floor from the surface plankton plus benthic foraminifera living in the sediments, why is it that parts of the seafloor have a siliceous ooze forming the silica-rich rock chert? Shouldn't it all be a mixture of calcareous and siliceous material?

Jasper came to the rescue with a holographic image showing Figure 5 (below) and authoritatively replied, saying:

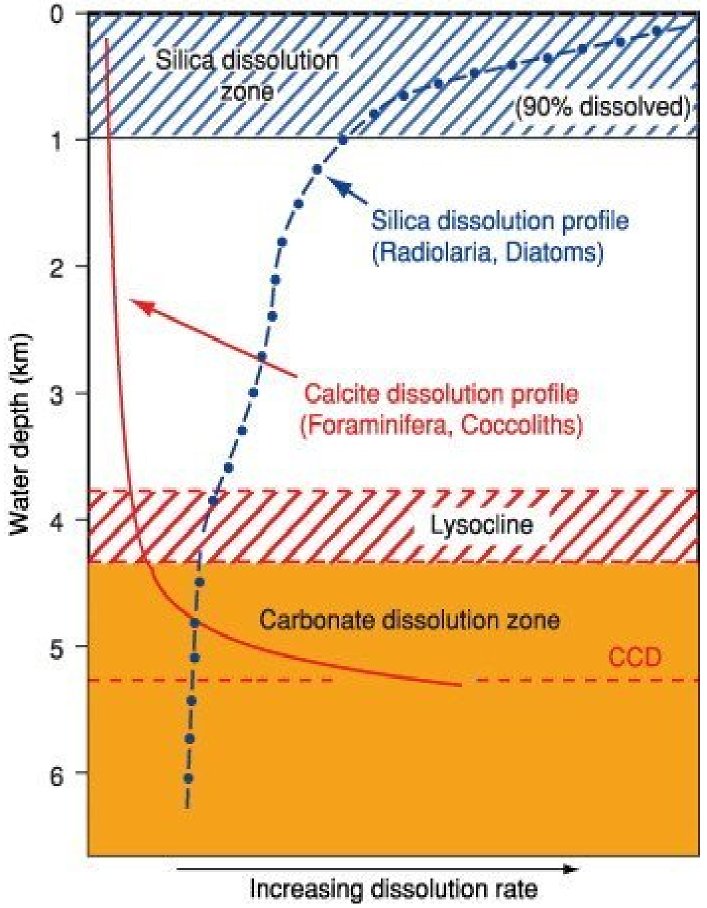


Figure 5: Generalized dissolution profiles of silica and calcite. The lysocline is taken as the level below which there is rapid increase in calcite dissolution, and the calcite compensation depth (CCD), which is the depth at which the rate of supply of biogenic calcite equals its rate of dissolution. Douglas RG (2003) Oceanic sediments (Figure 5) In: Sedimentology. Encyclopedia of Earth Science.

Chert forms from the lithification of radiolarian ooze that only accumulates below the CCD …

a. … because there are no foram or coccolith skeletons available to contribute to an ooze below the CCD.
b. … because there are no radiolarian skeletons available to form a silica-rich ooze above the CCD.
c. … but only within the silica dissolution zone because there are no silica skeletons available to form a silica-rich ooze between the CCD and the silica dissolution zone.
d. … because silica crystallises as carbonate dissolves.
e. … or within the Lysocline because there are lots of both types of skeletons present in both these zones.
f. … because there is not enough oxygen at that depth for benthic foraminifera to survive.

23. Rose wondered whether there was a Silica Compensation Depth (SCD) given that she knew that some areas of the deep sea, well below the CCD, do not have a silica ooze accumulating on the seafloor. How did Brady explain this?

a. There is no SDC as such but silica can only accumulate on the sea floor under areas where biological productivity is high and produces lots of planktonic radiolarians and/or diatoms.
b. In some areas the rate of silica reaching the sea floor does not exceed the rate of dissolution so no silica can accumulate.
c. There is no SDC as such but silica can only accumulate on the sea floor under areas where carbonate forming biological productivity is low, allowing for silica forming productivity to occur.
d. There is no SDC as such but silica can only form deposits once all carbonate has been dissolved into the water column.
e. He said both a & b.
f. He said all of a, b & c.

24. Rose also found an interesting diagram (Figure 6 below). She noted that aragonite and calcite are polymorphs of calcium carbonate – that is they have the same chemical formula of $CaCO_3$ but very different crystal structures and different chemical behaviours.

Q: What helpful comment did Jasper make about this diagram?

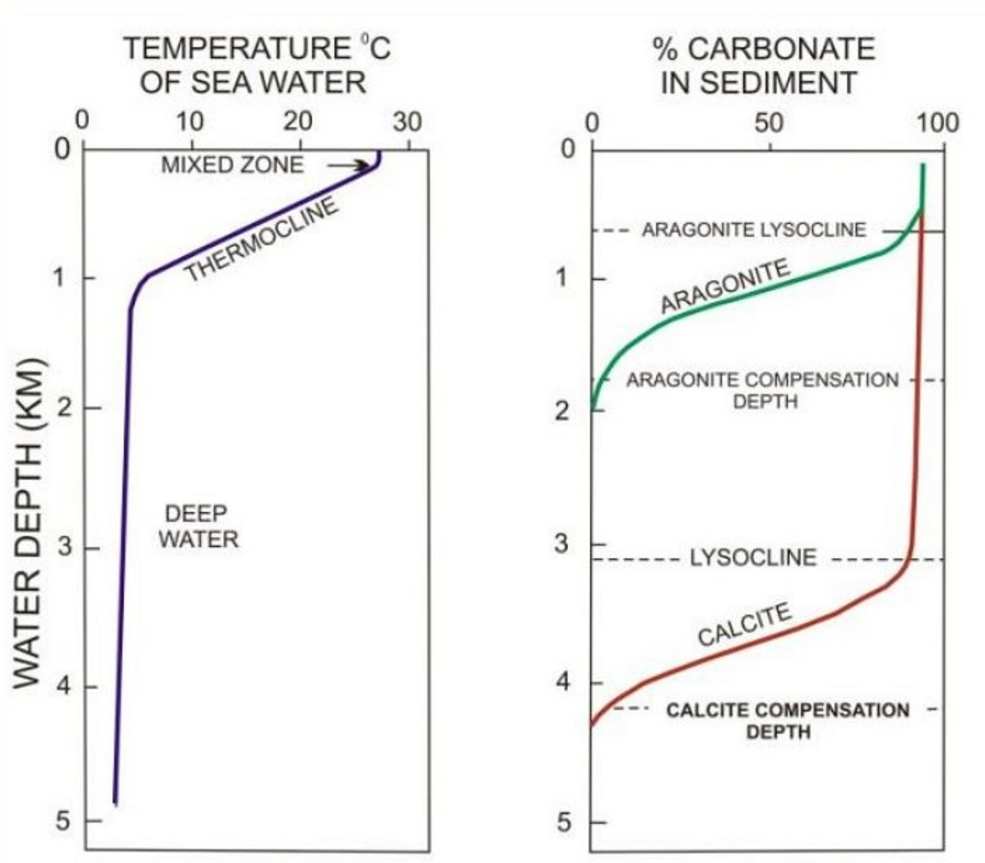


Figure 6:

a. This explains why we see a pteropod ooze layer on top of a foraminfera ooze layer in some carbonate oozes.
b. This explains why we see a foraminifera ooze layer on top of a pteropod ooze layer in some carbonate oozes.
c. This explains why we see a pteropod ooze layer on top of a radiolarian ooze layer in some layers deposited at the calcite lysocline depth.
d. This explains why we see a pteropod ooze layer on top of a radiolarian ooze layer in some layers deposited at the aragonite lysocline depth.
e. This explains why we never see an aragonite limestone in the rock record except when the average global temperature has been much higher than it is today.
f. This explains why we never see aragonite deposited with calcite in the marine environment.

25. Gemma chimed in, asking:

You have been talking about the sea floor sediments as if the biological stuff is the only material accumulating there. Isn't there clay floating around that has been washed in from the land? If so, where does it go?

Q: What did Jasper say that was confirmed by the other geoscientists in the conversation?

a. Clay washed into the sea by rivers never gets deposited beyond the shallow waters of the continental shelf because salt water makes it all clump together and it fall out of suspension quickly.
b. Some of the clay washed into the sea by rivers, is easily suspended in the water by wave action and can slowly settle out to be deposited in deeper waters along with planktonic debris. The percentage of clay in the deposit is only dependent upon how close to a river mouth the site of deposition is.
c. Some of the clay washed into the sea by rivers, is easily suspended in the water by wave action and can slowly settle out to be deposited in deeper waters along with planktonic debris. The percentage of clay in the deposit is partially dependent upon the depth of the deposit on the sea floor.
d. Some of the clay washed into the sea by rivers, is easily suspended in the water by wave action and can slowly settle out to be deposited in deeper waters along with planktonic debris. The percentage of clay is only dependent upon the depth of the deposit on the sea floor.
e. Clays get deposited at the river mouth delta but all silt and sand washes out to sea where it floats like plankton and slowly settles with the planktonic debris onto the deep-sea floor.
f. Clay is not washed into the sea from the land. It is actually the solid but oil-rich organic material liberated from the skeletons of dead plankton. It all rains down onto the seabed and is the source of oil and gas in sedimentary rocks. Only silt, sand and gravel are washed into the sea by rivers.

26. Now it was Orson's turn to be confused. He recently spent some time looking at deep ocean sediment cores for background on an engineering project laying submarine cables. He recalled some cores that seemed to contradict the information Brady and Jasper were providing about the CCD. He showed them these cores and their locations (Figure 7a,b &c):

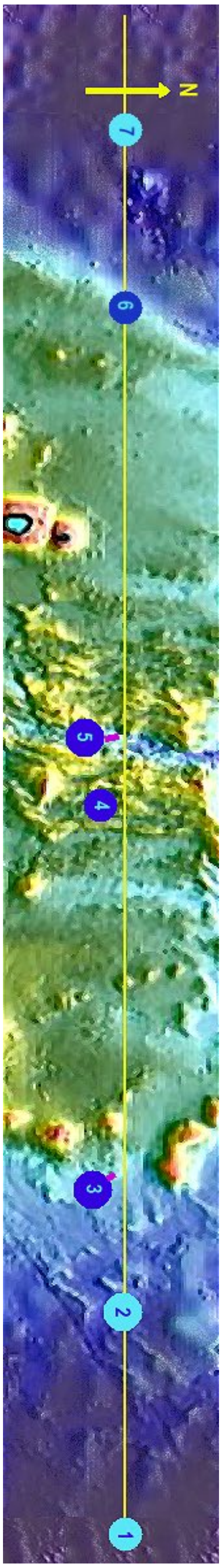


Figure 7c: Sailing East to West 5 cores were taken on the Yellow Transect Line at the locations 1-5 indicated. Bad weather prevented further coring to the west at proposed sites 6 and 7.

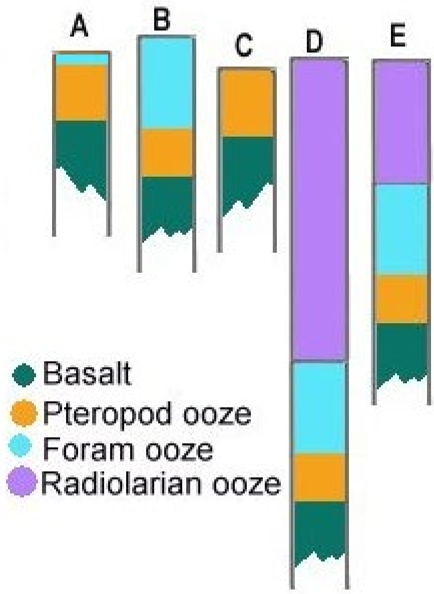


Figure 7a: Five cores retrieved from the transect revealed as many as four major lithologies, as shown here.

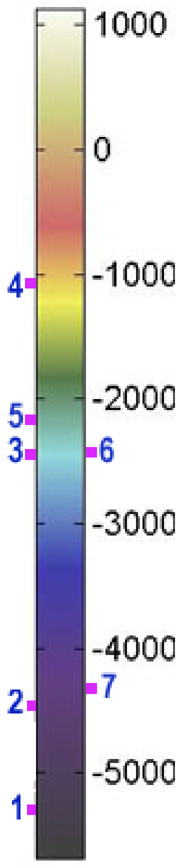


Figure 7b: Bathymetry of the Yellow Transect Line area. Sea level marked as Zero. Depths below sea level colour coded as shown, with starting depth of each core indicated, including sites 6 and 7, which were not drilled due to bad weather.

Unfortunately, Orson misplaced the file that indicated which core (A, B, C, D, E) corresponded with which drill site location (1, 2, 3, 4, 5). They figured it out together, despite the apparently contradictory vertical positions of the oozes in some cores.

Q: What did they conclude?

a. The cores correspondence is - 1:D, 2:E, 3:B, 4:C, 5:A
with cores B, D and E appearing to indicate a progressive deepening of the ocean towards the east in this area over time.
b. The cores correspondence is - 1:D, 2:E, 3:B, 4:C, 5:A
with cores B, D and E appearing to indicate a progressive shallowing of the ocean towards the east in this area over time.
c. The cores correspondence is - 1:D, 2:E, 3:B, 4:A, 5:C
with cores B, D and E appearing to indicate a progressive shallowing of the ocean towards the west in this area over time.
d. The cores correspondence is - 1:D, 2:E, 3:B, 4:C, 5:A
with cores B, D and E appearing to indicate a progressive deepening of the ocean towards the west in this area over time.
e. The cores correspondence is - 1:C, 2:A, 3:B, 4:E, 5:D
with cores B, D and E appearing to indicate a progressive shallowing of the ocean in this area over time.
f. The cores correspondence is - 1:C, 2:A, 3:B, 4:E, 5:D
with cores B, D and E appearing to indicate a progressive shallowing of the ocean in this area over time.

27. Despite having solved the correlation problem, there was some debate about the most likely geological setting for this transect and the data it provided. Orson was deeply involved in the planning of the voyage and explained the setting could not be anything other than …

a. … a transect across a subduction zone.
b. … a transect across a mid-ocean ridge.
c. … a transect across a subsiding ocean basin.
d. … a transect across the passive margin of an ocean basin.
e. … a transect across a transform fault.
f. … a transect between a deep-sea trench and a hotspot.

28. Rose asked one last question before everybody left for Orson's house to watch a movie or continue enjoying the clear cloud-free evening on the deck amongst good company.

She made three factual observations:

1) carbonate solubility increases with increasing pressure,

2) carbonate solubility increases with decreasing temperature and

3) carbonates dissolve in carbonic acid at 25°C and 1 atmosphere pressure and, given this equation:

$$CO_2 + H_2O <=> H_2CO_3 <=> H^+ + HCO^{3-} <=> 2H^+ + CO_3^{2-}$$

Rose asked:

What is likely to happen in the oceans as anthropogenic CO_2 levels continue to rise in the atmosphere?

Q: Brady gave an accurate response. What was it?

a. Nothing. CO_2 in seawater is sourced from marine animals, not the atmosphere.

b. For any given pressure and temperature, the solubility of calcite in seawater will decrease and the CCD will rise in the water column.

c. The pH of seawater will drop but the level of the CCD will not change.

d. For any given pressure and temperature, the solubility of carbonate in seawater will increase and the CCD and the Aragonite CD will rise in the water column.

e. For any given pressure and temperature, the solubility of carbonate in seawater will decrease and the CCD and ACD will drop in the water column

f. For any given pressure and temperature, the solubility of calcite in seawater will decrease and the CCD will rise in the water column.

The first thing everybody noticed about Orson's house was his impressive rock and mineral collection but Rose and Amber noticed that his modest fossil collection was also interesting. On the wall Orson had a framed image – a cross section from the first engineering excavation he worked on (figure 8 below). Small dots on the cross section marked places where Orson found the fossils on display.

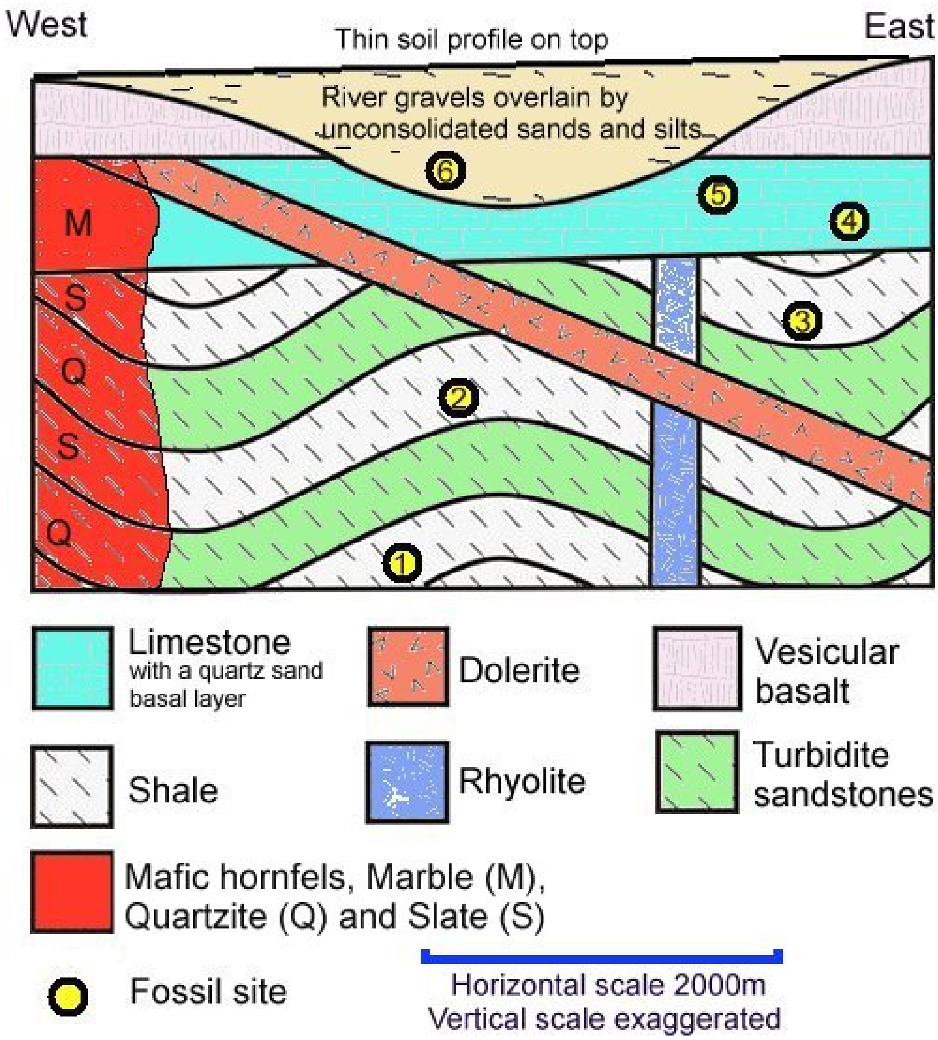


Figure 8: Excavation cutting made during the foundation works for the *Australia to the Moon* space station. The vertical excavation face is viewed looking Northwards. Image courtesy of Orson Stone.

29. Orson commented that excavating some of the metamorphic rocks proved challenging because they were so hard, especially the hornfels. Amber said that she didn't know much about rocks despite really liking fossils and asked why some of the rocks were harder than the others.

Q: How did Orson partially explain this?

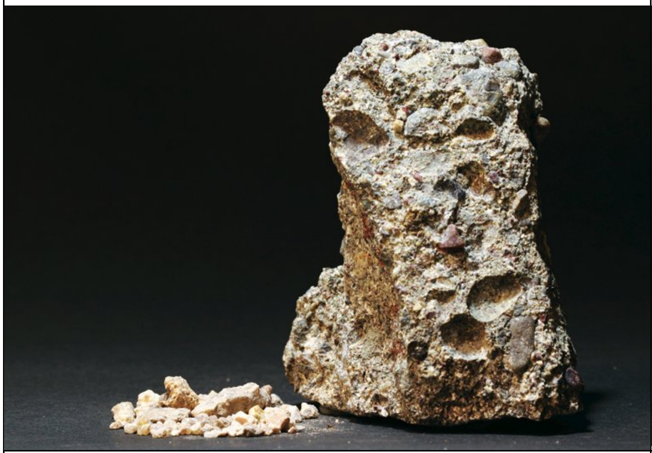
a. Sedimentary rocks are softer than igneous rocks that in turn are softer than metamorphic rocks.
b. Marble is metamorphosed limestone and quartzite is metamorphosed sandstone so the quartzite is a lot harder than the marble
c. Marble is metamorphosed limestone and quartzite is metamorphosed sandstone so the quartzite is a lot softer than the marble
d. Slate is metamorphosed sandstone but the metamorphic fabric it develops – a kind of layering caused by the alignment of mica crystals – make it much softer than the original sandstone.
e. Quartzite is metamorphosed shale but the metamorphic fabric it develops – a kind of layering caused by the alignment of quartz crystals – make it much softer than the original shale.
f. All the other rocks weather much faster than metamorphic rocks, making them much softer and there easier to excavate than the metamorphic rocks.

30. Orson also commented that excavating a second 5000-metre cutting adjacent to and immediately west of the first cutting revealed another hard rock. This rock occupied almost all of the cutting and outcropped as a hill above the cutting covered in boulders with rounded shapes. Amber didn't know what *outcropped* meant but Orson explained that an *outcrop* is a place where rock strata can be seen at the surface. Amber was even more curious to know what this rock was.

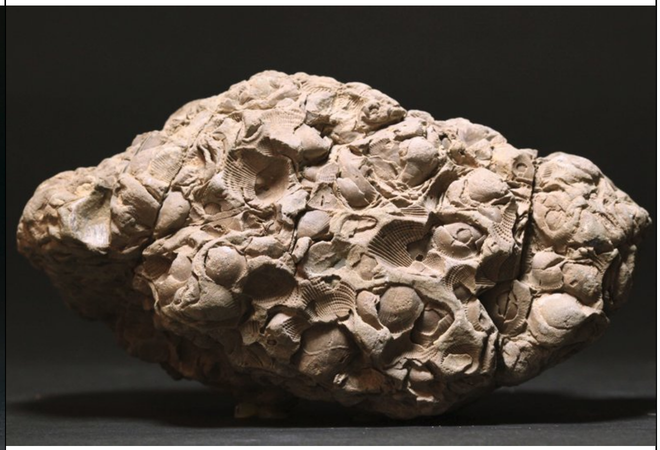
Q: Which rock did Orson point out in his collection.

a. Rock A
b. Rock B
c. Rock C
d. Rock D
e. Rock E

A

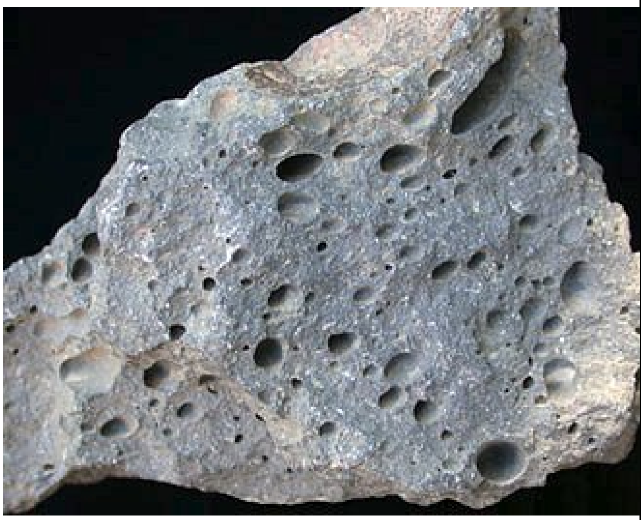


B

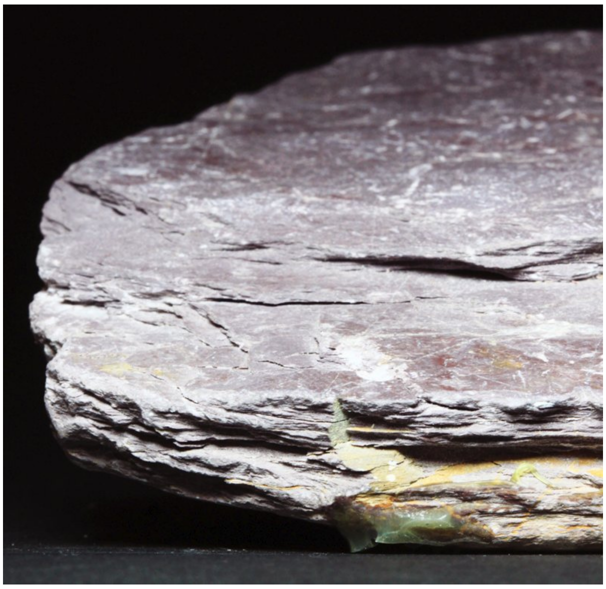


B

C



D



E