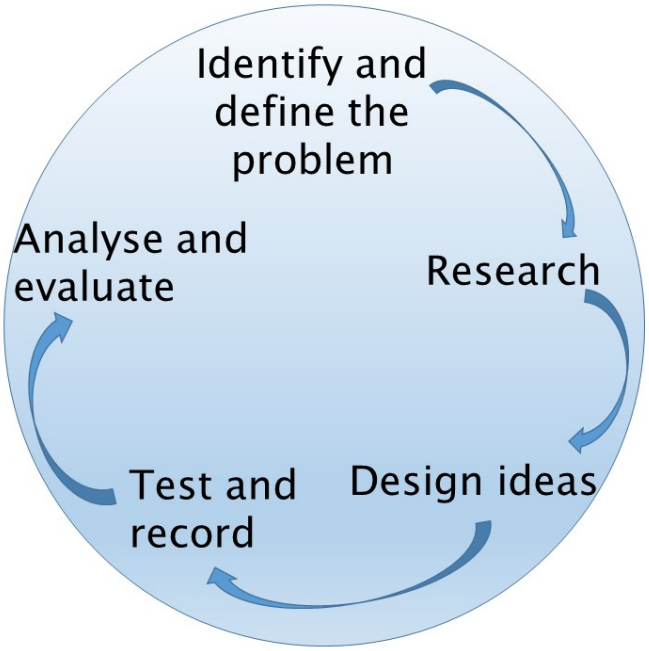
CCUS – Student Booklet

The Challenge

In a world where our understanding of the impacts of carbon dioxide (and other greenhouse gases) on our climate is expanding but our demand for energy is higher than ever, it is vital that energy production becomes more efficient and environmentally friendly. While there are renewable sources of energy, many of these are still expensive and/or inefficient. This means that for the foreseeable future, fossil fuels will play a role in our energy mix.
One of the key ideas to minimise the amount of carbon dioxide, associated with fossil fuels, being released to the atmosphere is through using carbon capture utilisation and storage (CCUS) methods.
Your job is to investigate the advantages and difficulties of CCUS and try to come up with a solution to minimise carbon release into the atmosphere.



Background Information

Carbon dioxide is a greenhouse gas in our atmosphere. There are many ways in which carbon dioxide can enter the atmosphere including; respiration of living things, volcanic eruptions, and in the production and burning of fossil fuels. Since the industrial revolution, the amount of carbon dioxide released into the atmosphere has increased (Figure 1), and climate scientists attribute much of this increase to the burning of fossil fuels to produce energy.

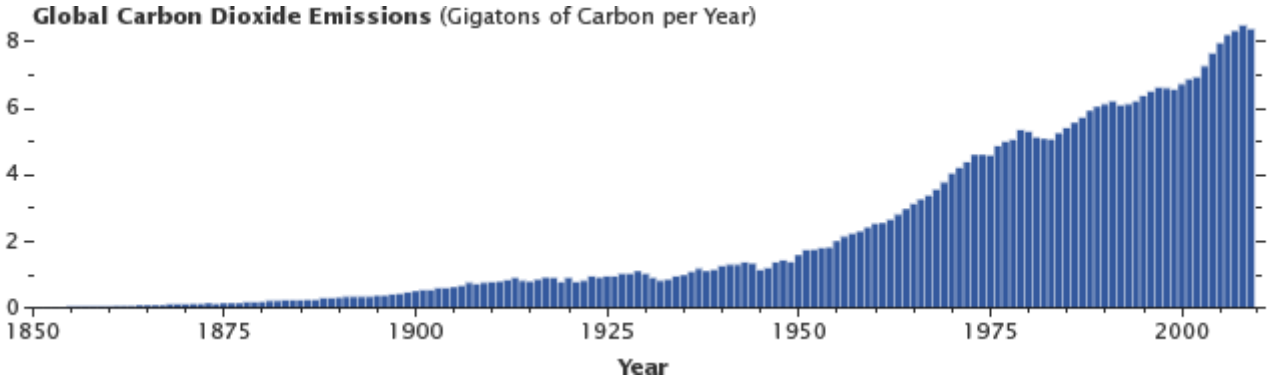


Figure 1. Global carbon dioxide emissions (gigatons of carbon per year) (Earth Observatory, 2011).

Carbon dioxide plays a vital part in the greenhouse effect, as illustrated in Figure 2. Without the greenhouse effect the Earth would be too cold to support life as we know it (like Mars) but higher levels of greenhouse gases can make a planet too warm (like Venus). Having the right amount of greenhouse gases in the atmosphere is vital to the survival of life on Earth. The increase in the amount of carbon dioxide in the atmosphere has been linked to an increase in global temperatures, which is causing polar ice to melt and sea levels to rise, among other problems.

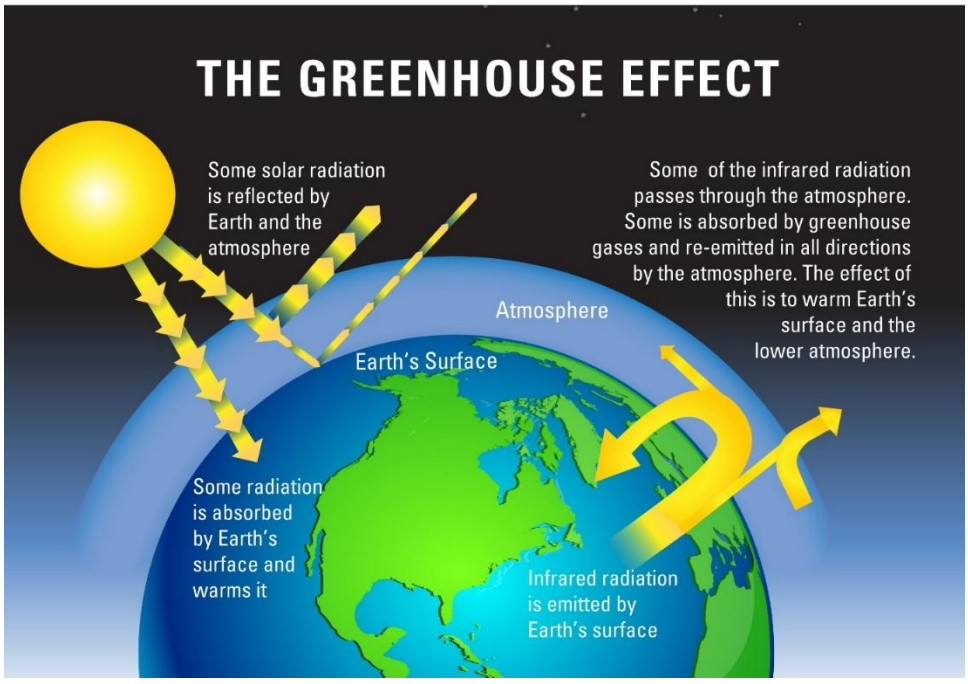


Figure 2. The greenhouse effect helps to keep the planet warm, but higher levels of greenhouse gases can lead to too much heat energy being trapped, causing an increase in global temperatures (The Royal Society, 2019).

The carbon cycle is a natural, global cycle which, when in balance, allows life on Earth as we know it to thrive. One of the largest carbon sinks is the ocean, which removes carbon dioxide from the atmosphere. It currently absorbs about one third of the carbon dioxide released by the burning of fossil fuels (NOAA, 2017). When carbon dioxide absorbs into the ocean its pH levels decrease, this is known as acidification. Acidification of the oceans has been linked to coral bleaching and thinning of shells of marine organisms, which in turn has destroyed some marine ecosystems.

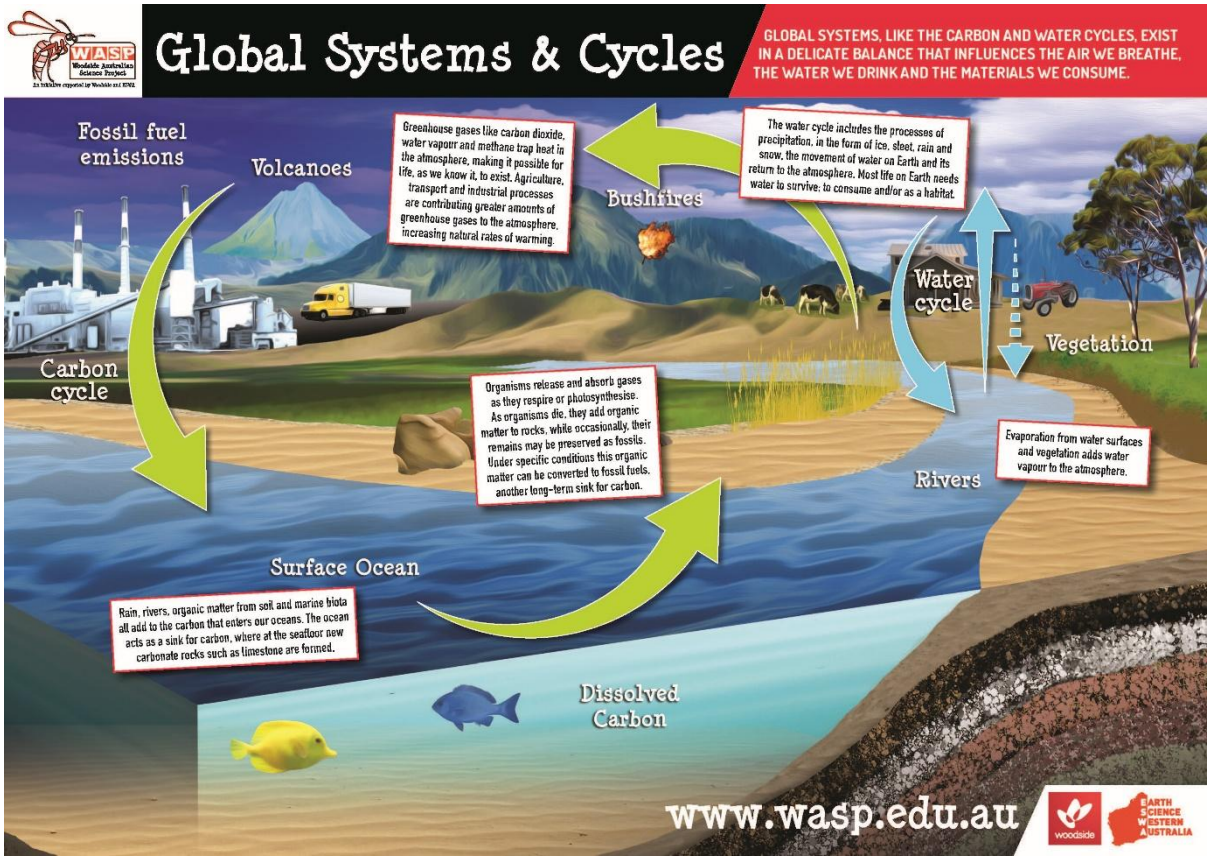


Figure 3. The carbon cycle has natural and manmade inputs. The ocean is a major sink for carbon.

As a global priority, industry and government are investigating how to minimise the amount of carbon dioxide which is released into the atmosphere through human activities. There are some companies using carbon capture and storage methods, however, at present this is very costly. Companies who aim to be both more environmentally friendly and economically competitive are investing in research to look at means of using the carbon dioxide, these processes are known as Carbon Capture, Utilisation and Storage (CCUS).

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Background Research

1. What are some of the industrial uses for carbon dioxide?
2. Why aren't all of the carbon dioxide emissions from power plants used for industrial purposes?
3. Explain, with the aid of diagrams, the three different ways of capturing carbon at power plants and describe the pros and cons of each process.
4. Give three example locations of where carbon capture is being conducted.
5. Draw and label an ideal location to store carbon dioxide, include the key words: porous, and permeable and name any geological structures, such as fault or folds.
6. Without considering cost, what are some of the reasons that carbon capture utilisation and storage (CCUS) methods are not used at all power stations?
7. What is enhanced oil recovery? Draw and label diagrams to aid your explanation.
8. What are some of the effects of climate change, and possible outcomes in the future?
9. Other than the geological issues, why is CCUS not carried out at every power station instead of releasing carbon dioxide into the atmosphere?
10. How could use of CCUS be encouraged?

Enhanced Oil Recovery

Objective

To model the process of enhanced oil recovery (EOR) and relate this to its suitability for carbon utilisation and storage.

Method

If you have not already done so, research EOR and explain the principles behind it.
Brainstorm some ideas about how you could model this process, using equipment available to you in the science classroom or household.
Create a labelled diagram of the equipment set up and show this to your teacher. Ensure you have their approval before setting up the model.
Take photos of the model or make a video to show how it works.

Results and Analysis

1. Describe what happened in the experiment.
2. Explain what each stage in the model represented in relation to EOR.
3. What were the strengths and weaknesses of your method?
4. Instead of using the dilute acid to react with the calcium carbonate a student suggested they lit an oil burner under a funnel and collected the gas from the burning of the oil.
   a) What are the strengths of this suggestion in relation to demonstrating enhanced oil recovery?
   b) What are the weakness of this suggestion in relation to classroom safety?
5. What suggestions can you make to improve the model so that is more realistic, but also safe?

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Investigating the Effect of Carbon Dioxide on the pH of Water

Objective

To determine the relationship between the amount of dissolved carbon dioxide in water and the pH of the water. Then use this information to highlight any challenges in designing carbon capture utilisation and storage (CCUS) systems.

Hypothesis

As the amount of dissolved carbon dioxide increases, the pH of the water will_____.

This is because _____.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them. Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a table to capture your results.
2. Plot a graph to show the relationship between the mass of carbon dioxide produced and the pH of the water. If your line of best fit is a straight line, find the gradient of the line.
3. Describe the relationship between the amount of dissolved carbon dioxide and the pH of the water.
4. Does an increasing amount of dissolved carbon dioxide make water more acidic or alkaline?
5. What effects might adding carbon dioxide to liquids have on the equipment and the rocks used for carbon capture and storage, and why does this cause design challenges for CCUS systems?

Evaluation

1. Were there any potential sources of error in your investigation?
2. Were there any outliers or anomalous results? If so, what do you think might have caused them?
3. How could you improve this investigation?
4. Outline any ideas you have to investigate the relationship between concentration of dissolved carbon dioxide and pH of water further.

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Investigating the Effects of Acid on Materials

Objective

To investigate how different metals and rocks react to acid. Then relate your findings to the design of suitable methods for transporting and storing carbon dioxide.

Background Information

Adding carbon dioxide to water increases its acidity (see ocean acidification). To assist with appropriate design, it is vital that engineers designing carbon capture utilisation and storage (CCUS) models are aware of how different materials will react to acidic water. Using pipeline materials which are easily corroded will result in ongoing need for replacement, making them costly. Storing carbon dioxide underground, within and around the wrong type of rock, could lead to it migrating upwards, entering freshwater aquifers or even the atmosphere. This defeats the point of burial. Therefore, it is vital that the scientists and engineers designing the CCUS processes understand the properties of materials involved.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them.
Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a table to capture your results.
2. Were any of the materials unaffected by the acid, if so which ones? Use data to support your answer.
3. Which materials were the most affected? Use data to support your answer.
4. Calculate the percentage of mass lost for each sample during this experiment.
5. Why is finding the percentage mass lost more useful than just looking at change in mass?
6. Did any of the samples lose mass, if so, which ones and what does that suggest?
7. Did any of the samples gain mass, if so, which ones and what could that suggest?
8. Would there be any issues with using the least reactive materials in the process of transporting and storing carbon dioxide (cost, weight etc.)?

Evaluation

1. Were there any potential sources of error in your investigation?
2. How could you improve this investigation?
3. Outline any ideas you have to investigate the reactivity of materials that might be involved in CCUS further.

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Investigating the Effect of Temperature on Solubility of Carbon Dioxide

Objective

To investigate the relationship between the temperature of a liquid and solubility of carbon dioxide gas. Then relate this to storing carbon dioxide at depth in saline aquifers.

Background Information

A method currently under investigation for trapping carbon dioxide is by injecting carbon dioxide gas into saline aquifers deep below ground. It will then dissolve into the brine (salty water) and eventually react to form precipitates, such as calcium carbonate. Injection needs to occur at a depth of 800-2000 metres to ensure that the carbon dioxide does not contaminate any freshwater aquifers. As you move deeper underground temperature increases, this is known as the geothermal gradient. The average geothermal gradient is 25^0C per kilometre, which means for every kilometre you go below ground the temperature increases by 25^0C. It is important to know how temperature affects the solubility of carbon dioxide as the deeper the aquifer the higher the temperature will be.
Plot a graph using information from the above text to show changing temperatures with depth up to 2 km, assuming a surface temperature of 10°C.

Hypothesis

As the temperature of the water increases the amount of dissolved carbon dioxide will

_____. This is because _____.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them.
Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a results table to capture your own data and that of your class. Use this information to work out average results.
2. Use the averages to plot a scatter graph with temperature on the x- axis and displaced water on the y- axis. Disregard any anomalies to create a line of best fit.
3. If your line of best fit is a straight line, find the gradient of the line.
4. What is the relationship between the temperature of the water and the amount of gas dissolved?
5. Considering the geothermal gradient, could more or less gas be dissolved in a deeper aquifer? Use your data to justify your answer.

For consideration:

6. If global temperatures continue to increase, will that make it easier or harder for oceans to trap the carbon dioxide from the atmosphere and what does that mean in terms of the rate of global warming?

Evaluation

1. Were there any potential sources of error in your investigation?
2. How could you improve this investigation?
3. Outline any ideas you have to investigate how the geothermal gradient may impact CCUS methods further.

Investigating the Effect of Pressure on the Solubility of Carbon Dioxide

Objective

To investigate the relationship between pressure and the solubility of carbon dioxide. Then relate this to carbon storage at depth.

Background Information

A method currently under investigation for trapping carbon dioxide is by injecting carbon dioxide gas into saline aquifers deep below ground. It will then dissolve into the brine (salty water) and eventually react to form precipitates, such as calcium carbonate. Injection needs to occur at a depth of 800-2000 metres to ensure that the carbon dioxide does not contaminate any freshwater aquifers. As pressure increases with depth, it is important that engineers are aware of the effect of pressure on dissolved gas and can model how much gas can be dissolved at certain depths below Earth's surface.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them. Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a table for your results and observations.
2. Considering your results, will carbon dioxide dissolve better in an aquifer that is 1,000 m underground or 2,000 m underground? Use your data to support your answer.
3. If you were a project manager working to a budget, which depth would be preferable?

Evaluation

1. Were there any potential sources of error in your investigation?
2. How could you improve this investigation?
3. Outline any ideas you have to investigate the impact of pressure on the solubility of carbon dioxide.

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Investigating the Effect of Salinity on the Solubility of Carbon Dioxide

Objective

To determine the relationship between the salinity of a solution and the amount of carbon dioxide it can dissolve. Then relate this to proposed carbon capture utilisation and storage (CCUS) methods.

Background Information

A method currently under investigation for trapping carbon dioxide is by injecting carbon dioxide gas into saline aquifers deep below ground. It will then dissolve into the brine (salty water) and eventually react to form precipitates, such as calcium carbonate.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them. Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a table for the results and observations of your group and of your class (to calculate averages).
2. Plot average results as a scatter graph, with amount of salt added on the x-axis and the volume of solution displaced on the y-axis.
3. If your line of best fit is a straight line, calculate the gradient of the line.
4. Do your results indicate that it is a good idea to store carbon dioxide in saline aquifers? Explain your answer using your data to justify your conclusions.

Evaluation

1. Were there any potential sources of error in your investigation?
2. How could you improve this investigation?
3. Outline any ideas you have to investigate the impact of salinity on the solubility of carbon dioxide.

Selecting Rocks

Objective

Investigate the properties of different rocks to determine their suitability for carbon storage.

Background Information

Common sites for carbon storage are depleted oil and gas reservoirs and deep, un-mineable coal seams.
This is because they often have the two main geological characteristics which are desirable for a carbon storage site:

- Rocks which are porous and permeable allowing the carbon dioxide to be injected into them and to spread throughout the formation so that it can be filled.
- A cap rock which is not permeable and will prevent carbon dioxide migration upwards.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them.
Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. Create a table for the results and observations of your group.
2. Which rocks would make good host rocks (for storage)?
3. Which rocks would make good cap rocks?
4. Long periods of time are required for injected carbon dioxide to dissolve into brine in saline aquifers. Due to density differences the carbon dioxide will float on top of the brine and push up against the caprock – this causes an uplift pressure on the caprock. It is therefore vital that the rocks will not fracture with this increased pressure. *Were any of the rocks impermeable, but had the potential to split or fracture easily if there was a lot of pressure on them – thus making them unsuitable as a cap rock?*

Evaluation

1. Were there any potential sources of error in your investigation?
2. How could you improve this investigation?
3. Outline any ideas you have to investigate the porosity and permeability of rocks to determine their suitability for carbon storage further.

Mineral Trapping

Part 1 - Research

Objective

Research how minerals might play a role in the storage of carbon and discuss the difficulties of the processes involved. Then investigate the formation of calcium carbonate through experimentation.

Background Information

One of the main advantages of carbon capture utilisation and storage (CCUS) is that the carbon dioxide gas dissolves into brine or reacts with the surrounding rock, forming carbonate minerals. Therefore, it is trapped as a solid which reduces the risk of carbon dioxide leaking and entering the atmosphere.

Research Questions

1. Provide three examples of carbonate rocks.
2. Recent studies in Iceland on the CarbFix project, have shown that the carbonation process can be accelerated when carbon dioxide is injected into basalts. Why are interactions with basalts to form carbonates more effective than with sedimentary
3. What are some of the weaknesses of the CarbFix method, and why might it be difficult to do in Australia?

Part 2 - Investigation

Objective

To investigate the formation of calcium carbonate through experimentation.

Method

Write a method for your investigation ensuring you have made it clear how it will be conducted safely, what measurements you will be taking and how you will take them.
Include a diagram to show how you will set up the experiment.
Show this to your teacher and gain their approval of the method before you conduct the experiment.

Results and Analysis

1. What did you observe during the experiment?

Extension

Filter the calcium carbonate that precipitated from the limewater using a funnel and filter paper over a conical flask. Allow the calcium carbonate residue on the filter paper to dry out and then weigh the calcium carbonate you collected.
Using your results and considering the quantities of materials you used in this investigation determine how much of each reactant you should use to give you 5g of calcium carbonate.
Repeat the investigation using these quantities to test your calculations.

3D Models for Structural Trapping

Objective

To interpret seismic data to determine the best geological location to store carbon dioxide and to create a 3D model of that site.

Background Information

Choosing an area to store carbon dioxide can be complicated. Firstly, there must be two very different rock types on top of each other with the lower being porous and permeable (enabling it to hold the carbon dioxide gas) and the upper rock type impermeable (to prevent the carbon dioxide from migrating upwards). The deeper the site the less likely it is that carbon dioxide will leak and reach fresh groundwater aquifers or the atmosphere.

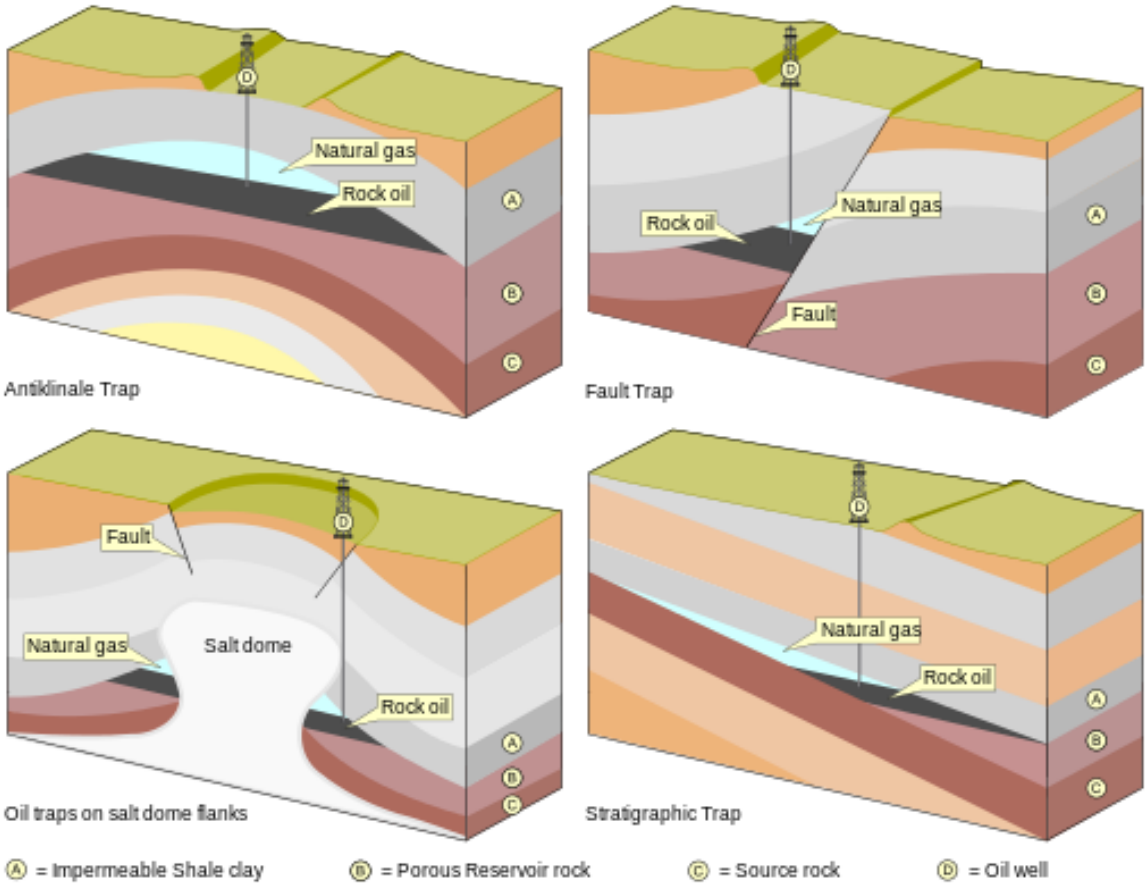


Figure 4. Often oil and gas reservoirs are considered good sites to store carbon dioxide - as they have already trapped oil and gas for millions of years prior to drilling. In these images, rocks types A and C and the salt dome are impermeable and B is permeable and porous, making them ideal geological structures for trapping gas (Wikimedia Commons, 2015).

To determine what is going on below the surface seismic studies are carried out. These result in images which geophysicists interpret to work out the rock types and structures that exist below the surface and ultimately determine the suitability of the area. Folds and faults in rocks occur when there have been compression or tensional forces acting on the rocks squashing them or pulling them apart. An anticline is a fold which bends upwards, these can make excellent traps if they contain the right rock types. Sometimes faults will move rock layers relative to each other (see Figure 4).

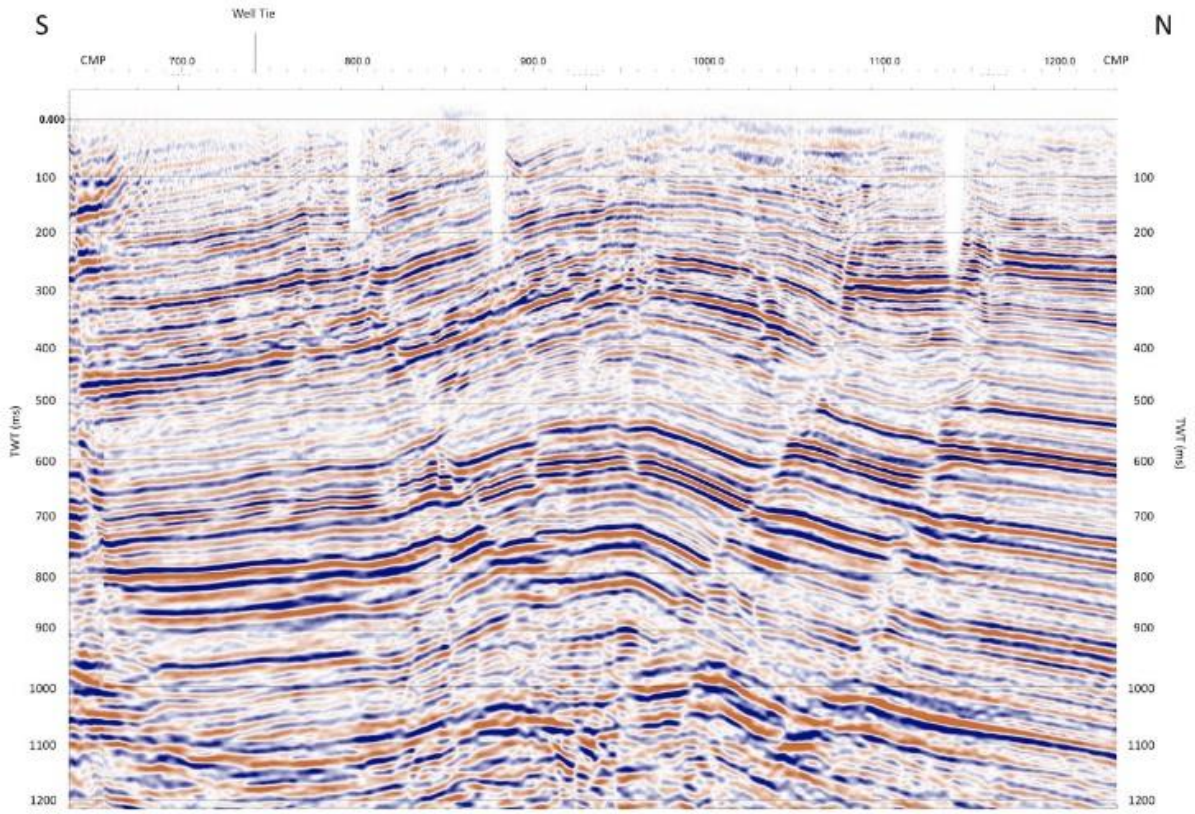
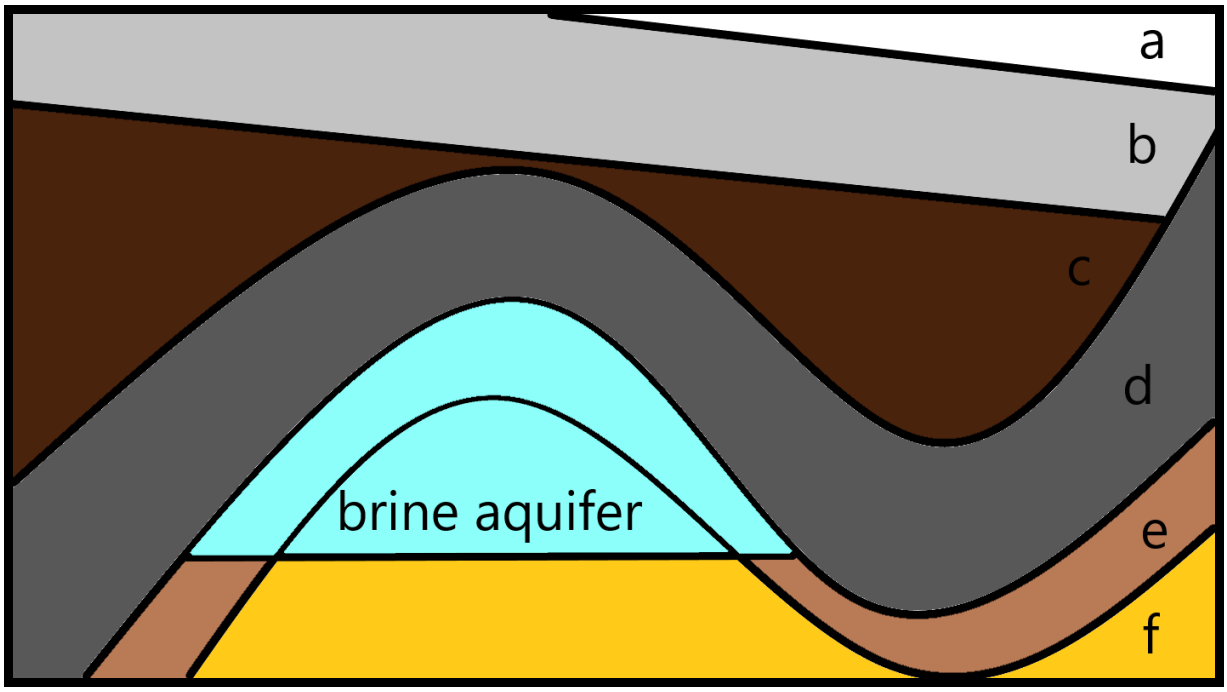


Figure 5. Seismic image - this area contains an anticline (fold) and some faults - can you pick them out? (Sub-Surf Rocks!, 2018)

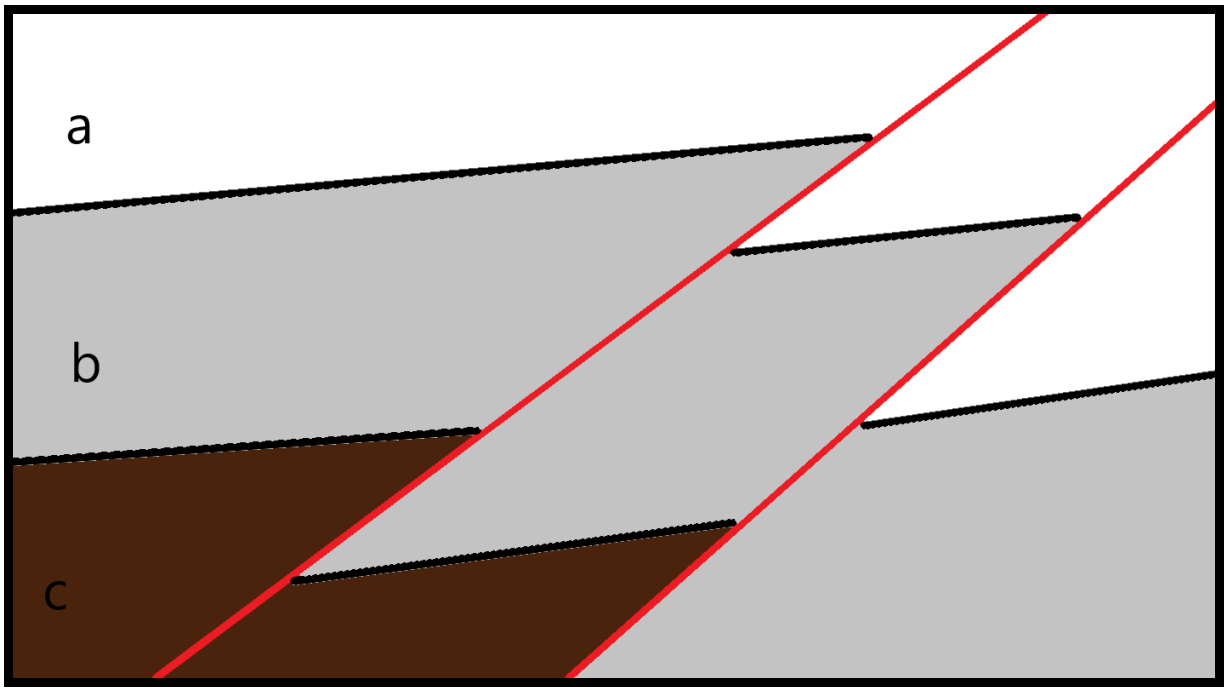
Method

1. Draw and label the following geological structures: anticline, syncline, normal fault, reverse fault.
2. Explain how each trap in Figure 4 prevents gases from leaking and migrating upwards. (Hint: think about the rock types and use the terms impermeable, permeable and porous).
3. Below are some geological structures which have been interpreted from seismic data. The red lines show faults. Some drilling has enabled the rock types to be determined:

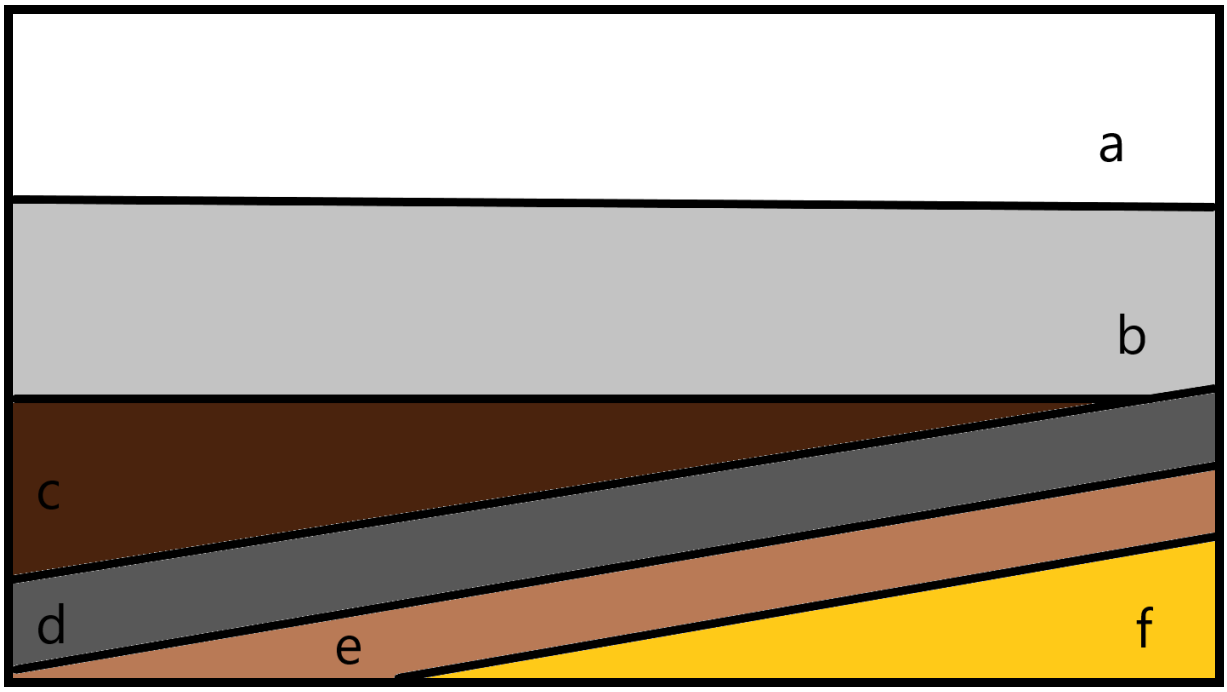
A	Impermeable quartzite	B	Impermeable porous basalt
C	Permeable sandstone	D	Impermeable shale
E	Porous and permeable mudstone	F	Porous and permeable limestone



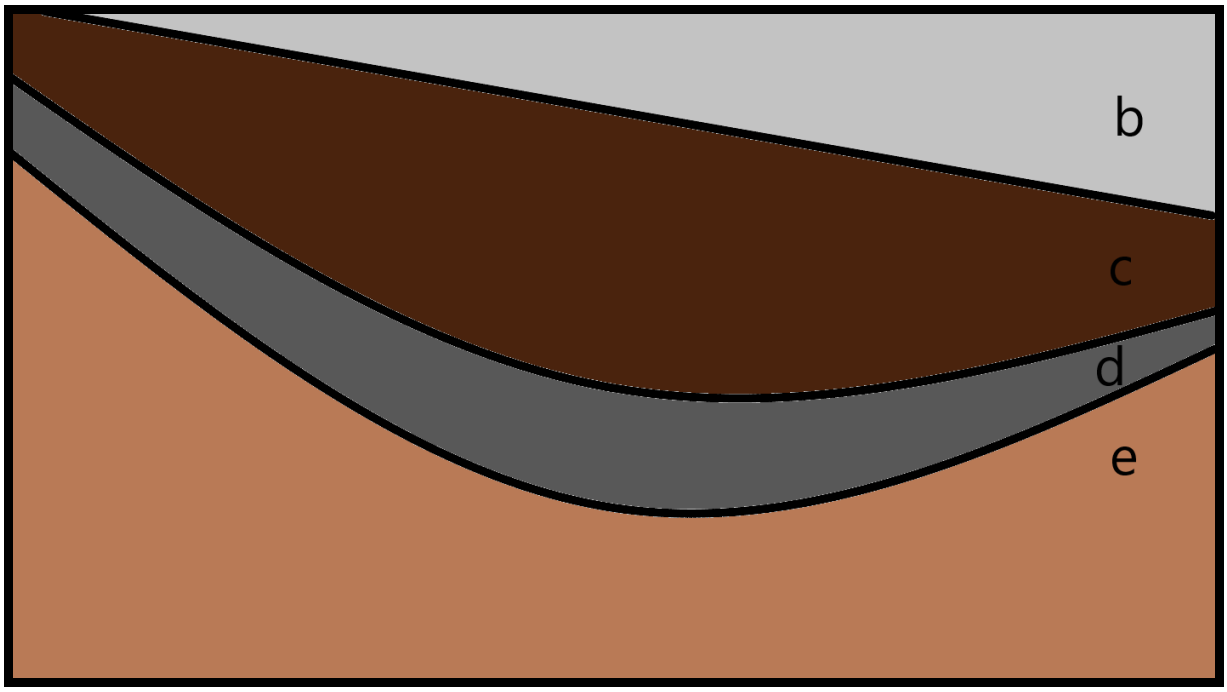
Site 1



Site 2

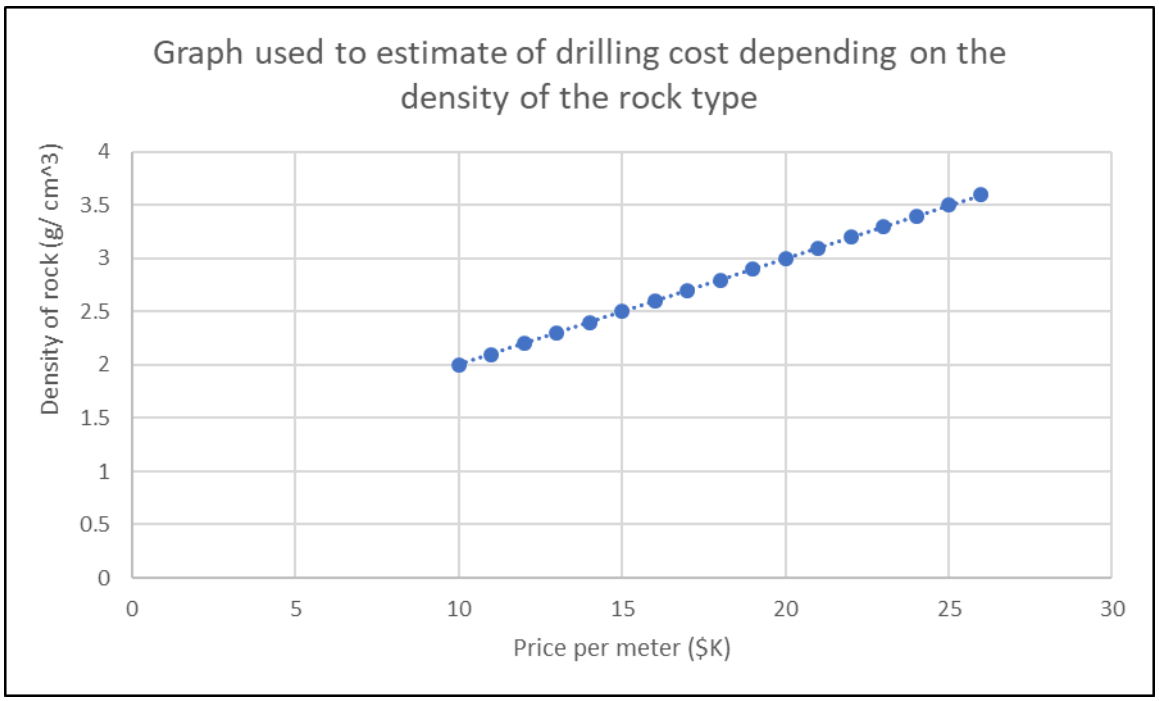


Site 3



Site 4

Using your knowledge and understanding of carbon storage, discuss the pros and cons of each site and suggest if, how and where carbon could be injected.
The first factor to consider is the geology of the area; will any of the sites be able to trap and store the carbon dioxide?
Consider the permeability and reactivity of the different rock types as well as the geological structures. Remember the depth of burial is important to ensure carbon dioxide doesn't reach any freshwater aquifers or even the surface.
The next most important factor to consider is the cost of the project. Drilling through rock is expensive. Below is a graph which gives a rough guide to how the density of rock affects the cost of drilling (it takes much more time, and also wears out drill bits quicker when drilling through very dense rock than it does to drill through soft rock.)



Research the densities of the different rock types featured:

A	Impermeable quartzite		B	Impermeable porous basalt	
C	Permeable sand stone		D	Impermeable shale	
E	Porous and permeable mudstone		F	Porous and permeable limestone	

Drilling does not have to be vertical – you will have to do some mathematical models to determine the cheapest way to drill through the rocks to inject the carbon dioxide into the desired layer. Note: the scale of the site cross sections given is 1 cm = 20 m

Ensure your calculations are clear so you can justify your reason for drilling in a particular way.

Other cost considerations to consider is the area of the storage site. The more carbon dioxide that can be stored the better as this will mean you will not have to find other sites. Determine which site has the largest area to store carbon dioxide (in one dimension – a 3D model would give you more information to work with).

What other social, economic, environmental, and cultural and health and safety factors would have to be considered in the planning of a carbon storage site?

Modelling the Site

Decide which site (from the four shown above) you would use to inject carbon dioxide in to be stored and create a model of the site to show how it could be safely stored.

Explain how you will test your model.

Evaluation of Model

1. Was your model successful in preventing leakage? How do you know?
2. How well do you think your model compared to actual geological structures?
3. After making your model, do you still feel that the site you selected was suitable for storing carbon dioxide?
4. While making your model was there any other information that might have been useful?