1. Plate tectonics in NZ

Subduction

When plate boundaries push together (converge), one will slide under the other in a process called subduction. The place where this occurs is called a **convergent margin**. Either the oceanic plate can subduct below the continent as below, or it can subduct below another oceanic plate.
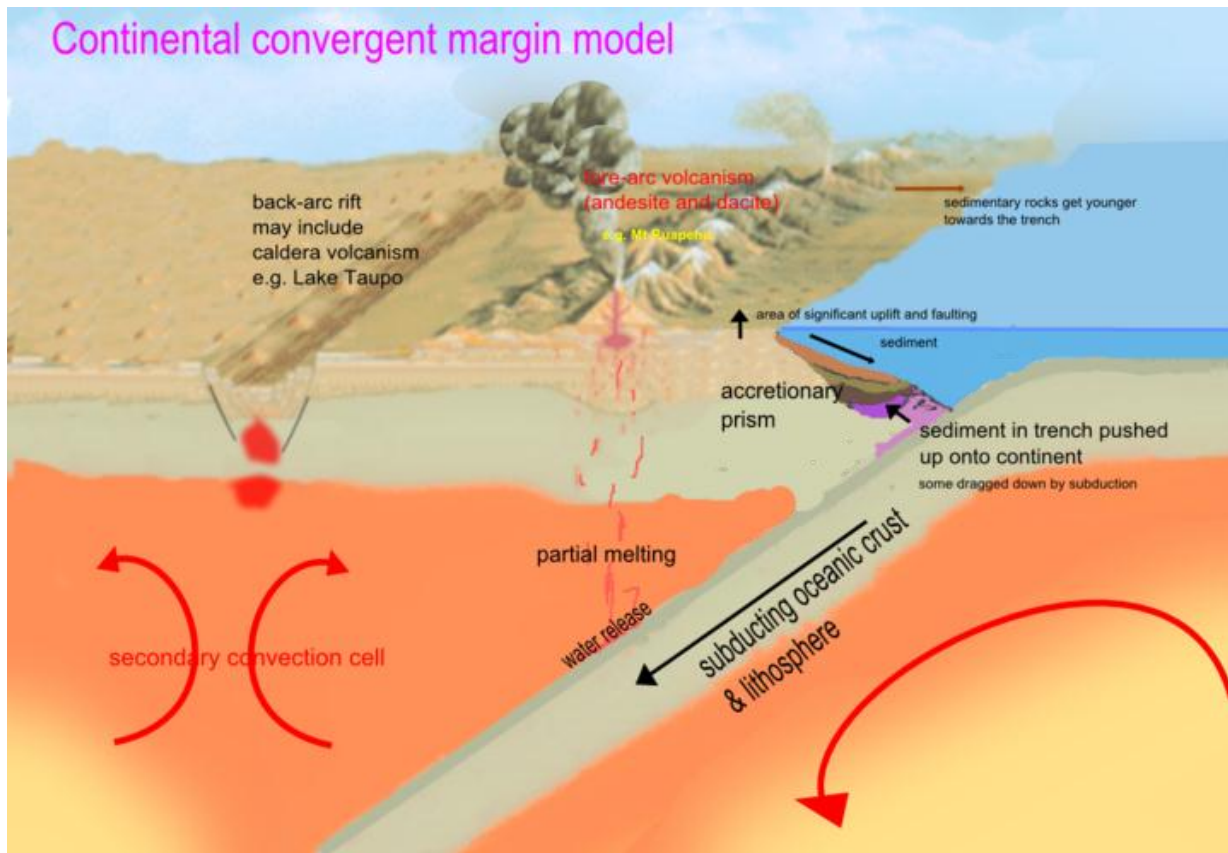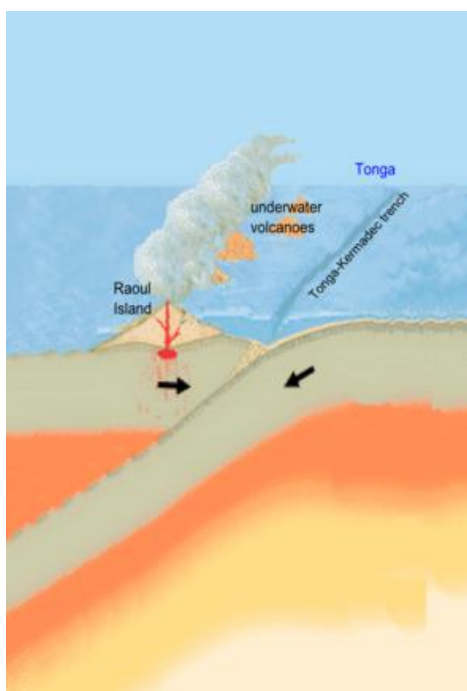

Plate boundary beneath Central North Island

- oceanic crust will always subduct beneath continental crust (because it is denser). This forms a **continental arc.**
- if oceanic crust meets oceanic, one will subduct if it is denser and heaver. This forms an **island arc** left)

In New Zealand, there is a continental arc from Mt Ruapehu to White Island, and an island arc from there to Tonga. There are some transitional effects off the Bay of Plenty.

In a subduction zone

- There is always a trench, where the oceanic lithosphere starts to sink.
- Near land, the trench fills up with sediment e.g. Hikurangi trench off the North Island East Coast.
- Most of the sediment in the trench can't be subducted. It gets pushed back up onto land by plate motion.

This forms an **accretionary prism.** Since more is pushed onto land all the time, sediment is older further inland from the trench.

- Above some particular places where the subducting crust releases water, you get **volcanoes**, which are usually composed of andesite or similar rocks.

In New Zealand, there is evidence of some 'rifting' behind the arc ('back arc rifting') as seen in the first subduction diagram. Out at sea, this has produced the Havre Trough. On land, it has produce the **Taupo Volcanic Zone.** However, most of the rift valley is full up of volcanic material and only in places is it easy to see (e.g. Waikite Valley).

For some reason, this rifting has produced large caldera volcanoes such as Lake Taupo and Lake Rotorua. Yellowstone Park in the USA is another place where this is happening.

Out at sea, you can clearly see the effects of the rifting but there is much less volcanism in the Havre Trough than in the Taupo Volcanic Zone, possibly due to differences in rock type. in the crust

Secondary convection:
Sometimes the subducting lithosphere can set up a small secondary convection cell above it. This can cause rifting, and can trigger melting to form basalt magma. The Taupo Volcanic Zone is thought to be such a rift (back-arc rift), and the rhyolite volcanism there is thought to be the result of huge volumes of hot basalt magma piling up at the bottom of the crust and triggering crustal melting. Not all subduction zones have back-arc rifts, and not all such rifts have associated volcanism.

The diagram above shows the different parts of the plate tectonic model. Plate tectonics are responsible for the formation and growth of continents, for orogenies and marine transgressions.

1. Convergent boundary: At a convergent plate boundary, material is erupted (to form volcanic rocks), intruded (to form plutonic rocks) or deformed by faults and folds, and buried. Such material is too low in density to be subducted again, and so tends to accumulate at these plate boundaries and is later uplifted. You can see in both of the trenches shown above that sediment accumulates. .If the convergent boundary is along the edge of a continent material eroded and carried into the sea gets pushed up onto land, forming successively younger zones as one approaches the plate boundary. This is termed **accretion,** and the place where it happens is an **accretionary prism**. The East Coast of the North Island is an example.
2. Continental Rift Zone: On the far right of the diagram above is a continental rift zone. This is how the split between NZ and Gondwana would have begun (about 80 my ago). The great East Aftrican Rift Valley is a modern example. Sometimes, as when we split from Gondwana, they widen to become an **ocean spreading ridge,** shown in the middle of the diagram. Some of the volcanic activity between Rotorua and Taupo is probably due to rifting, but this rift is unlikely to develop further (see Level 3 notes for more detail on this).
3. Continental passive margin: this is not shown on the picture. This is where a continent gives way to an ocean, with no convergent margin. These are often slowly wearing away and subsiding, and are characterized by extensive river deltas, plains, swamps and coral reefs. The south-east coast of the USA and much of the coast of Australia good examples. Later in the tectonic cycle, these will form siltstones, coal measures and limestones (this sequence is characteristic of a marine transgression). Such deposits are found in NZ from 40-22 million years ago, so we can infer that the tectonic environment was like this. For example, on the Gold Coast of Australia, the rivers and swamps will form siltstones and coals, and the Barrier Reef will someday become limestone. As the area sinks beneath the sea, the reef will move landward therefore the limestone will overly the silt and coal.
4. Island arc: this is another type of convergent boundary. Island arcs can eventually be caught up by plate movement and pushed against a continent. There are old volcanic rocks in Southland and Nelson which are island arc volcanics, and the Dun Mountain belt shown in the map below was probably caused when this collided with the developing continent. This is why these volcanics and intrusives lie between the eastern and western blocks of the Rangitata depositional phase. The Aleutian Islands off Alaska represent a modern example of an island arc that lies between a continent and some of its depositional area.
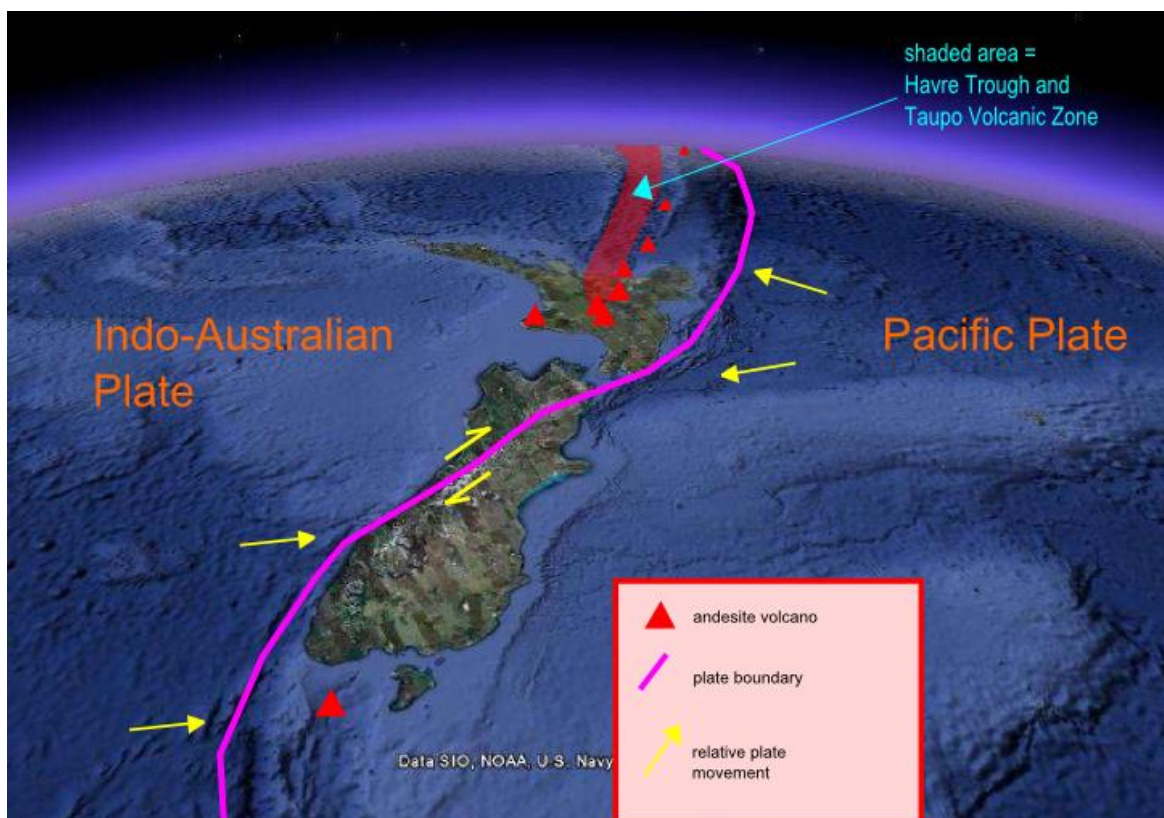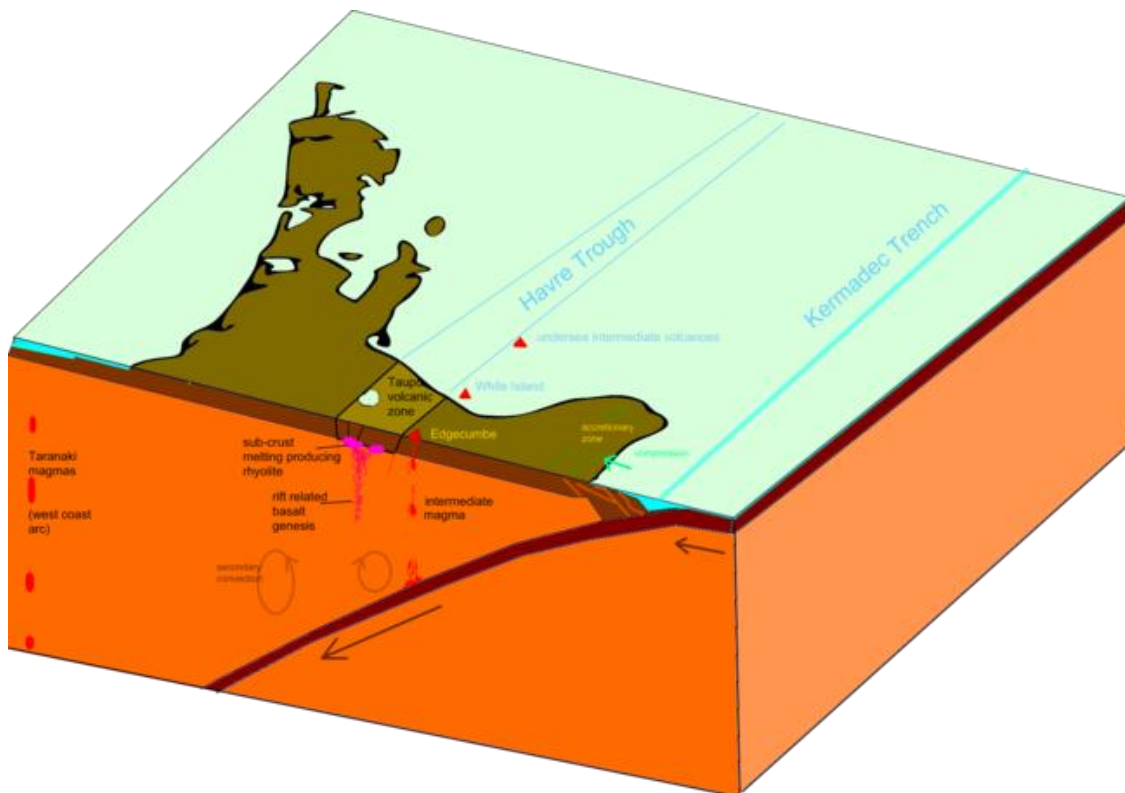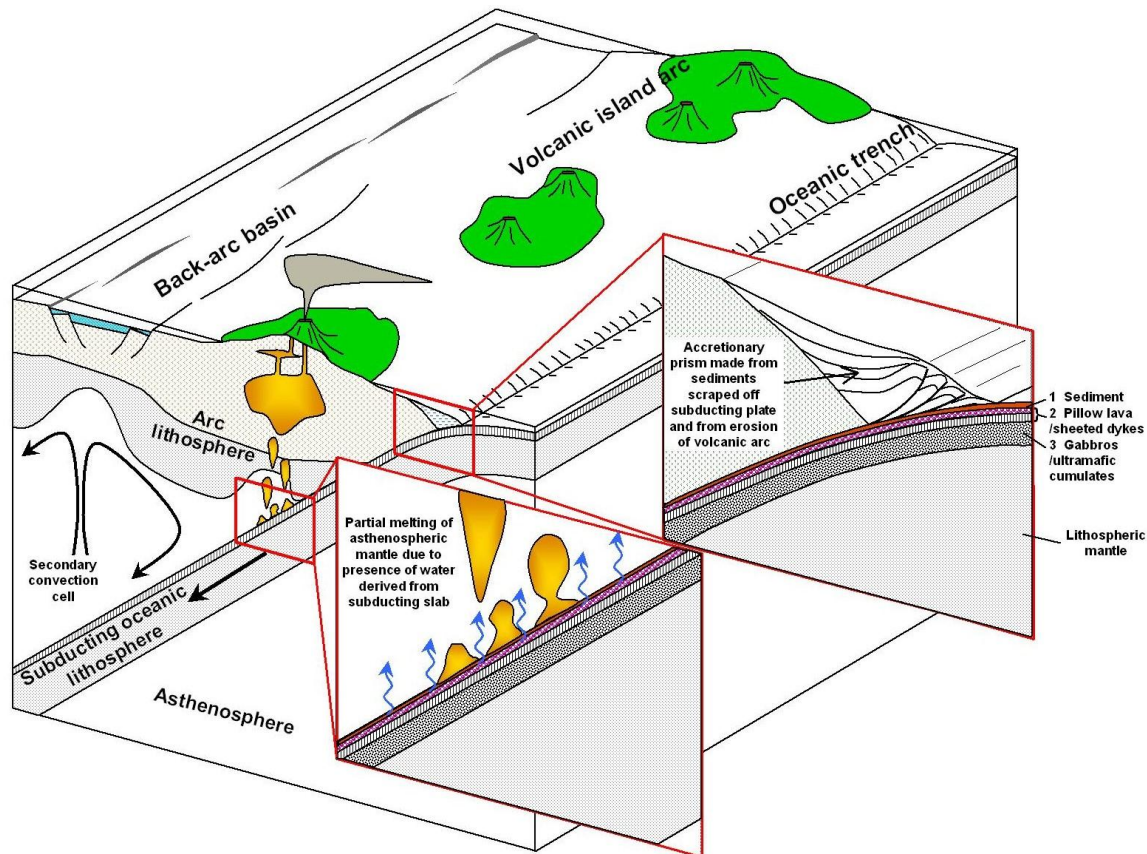
Plate Boundary through NZ (from Google Earth)

Diagram showing present day subduction beneath the North Island.. Click to enlarge.

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Generalised diagram of island arc subduction. Click for original (Mike Norton, Wikipedia)

From Mt Ruapehu to Tonga, the plate boundary forms a **subduction zone.** This subduction zone forms a **continental arc** from Ruapehu to White Island, and an **island arc** from White Island to Tonga.The forward edge of the arcs are marked by a chain of

andesite and dacite volcanoes.

On land, the active or dormant volcanoes include: Ruapehu, Tongariro, Tauhara, Edgcumbe..There are numerous extinct ones, including some now buried beneath younger volcanics.

Offshore, the chain continues with islands - Whale Island, White Island, Raoul Island are all active/dormant. There are numerous submarine volcanoes in NZ territory, including Rumbles 1, II and III and the Brothers volcano.

Between Lake Rotorua and Lake Taupo lie a number of active and extinct **caldera volcanoes**, whose activity is probably related to **back-arc rifting**. The nature of the different types of volcanism will be discussed in more detail in the section on volcanoes.

.Adjacent to the volcanic arc is the **Tonga-Kermadec trench**. As the trench approaches NZ, it becomes shallower. This is mostly because it has filled up with sediment eroded from the North Island; the trench itself continues down to terminate off the coast of Kaikoura. In the area where the trench fills up with sediment, the sediment is pushed up onto land in the process of continental accretion. The East Coast of tne North Island is an example of such an **accretionary prism.**

Towards the Wairarapa coast, the subduction is no longer perpendicular to the plate boundary, and once it passes Mt Ruapehu there is no further volcanism. This is because the 'sideways' component of the subduction is so great that the subducted slab no longer sinks at a rate sufficient to engender the processes that trigger melting. However, as the vector of plate movement is changing with time, it is possible that new volcanoes will eventually appear to the south of Ruapehu.

The subducting slab continues to have an effect on the overlying lithosphere south of the TVZ, producing a large depression south of Taranaki: the Wanganui bight. Here, the basement rocks are dragged down to a depth of nearly 7 km and the depression is filled with huge thicknesses of young sediment. Inland, these young sediments have been upwarped in the vicinity of Taihape, so that very young marine sediments (2-3 million years) are now over 500m above sea level. The rapid burial then exhumation of these sediments has produced rocks with some unusual mechanical properties, which causes considerable land stability problems in the area. Wanganui is also the location of New Zealand's most frequent very deep earthquakes, caused by these processes.

South Island:

Plate movement and subduction in the South Island
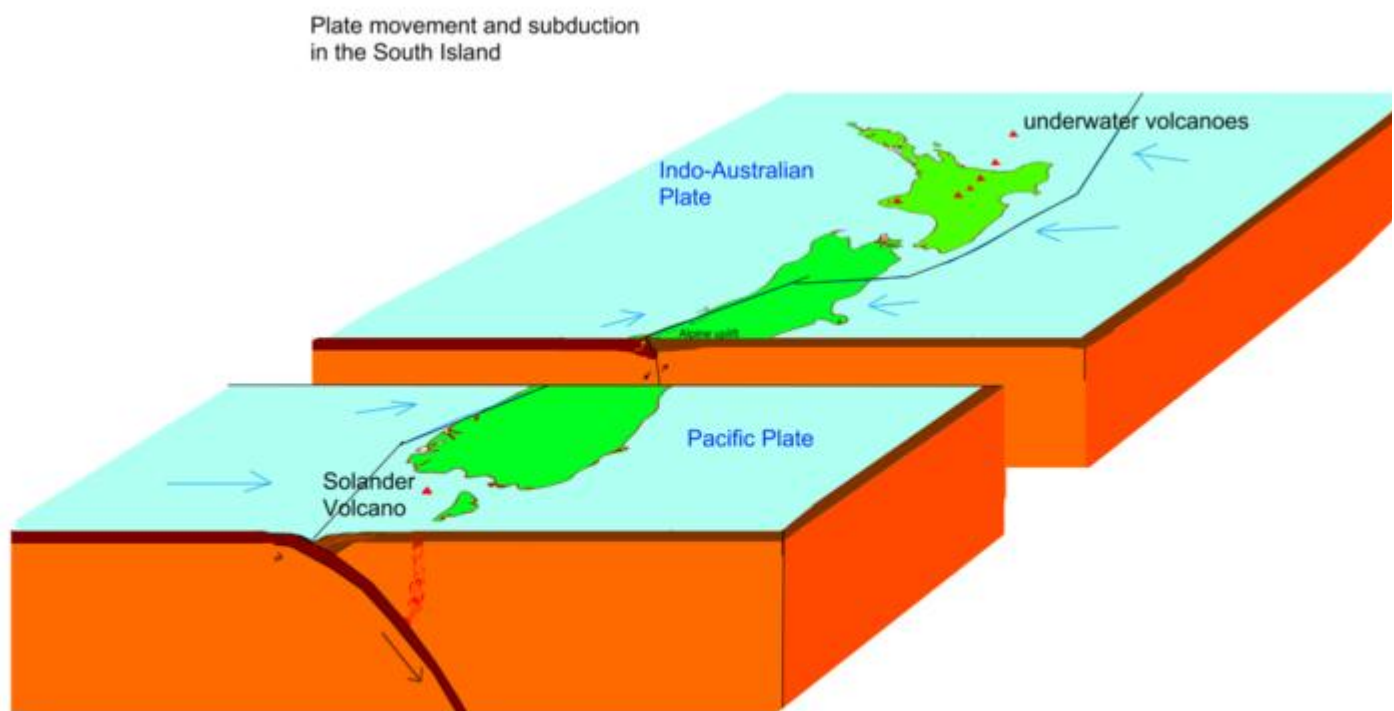
There is no subduction at the Alpine fault (middle slice), and subduction 'changes over' to the south.

Further south, the Pacific plate no longer fully slides under the Australian plate. Instead it thickens the crust, and as a result the mountains grow increasingly large as you move towards the Alpine Fault. By the time the plate boundary reaches the Alpine Fault, there is no subduction, but the remaining compression helps push up the Alps.

Subduction resumes just south of Fiordland. The subduction here is much steeper than in the north, producing high pressure metamorphic rocks called [eclogites](#) at depth. The mineral changes in the descending lithosphere do not produce as much water, resulting in less volcanism. Only one volcano occurs south of the South Island, an andesite volcano at [Solander Island](#). Although

not presently active, this volcano may erupt again at some point in the future. Here, the Indo-Australian plate is subducted beneath the Pacific Plate.

Change-over: New Zealand therefore lies on the zone where the plate motion "changes over" from one direction of subduction to the other. Along about 200 km of the Alpine Fault, the plates slide past each other like this are known as transform plate boundaries.

Intra-plate volcanism: Not all volcanism is associated with a plate boundary. The Auckland and Kaikohe volcanic fields are active intra-plate or 'hot-spot' volcanoes, although not all geologists support hot spots as an explanation for these. Past instances of intra-plate volcanism in NZ include the Banks Peninsula volcanoes, basalts near Timaru, basalts on the Chatham Islands and the Otago Peninsula. Intraplate volcanism is dominated by basalt. This type of volcanism will be discussed in more detail later

Subduction zones:

A subduction zone is where oceanic lithosphere slides under another plate (continental or oceanic) and sinks back into the asthenosphere. This occurs mainly because the lithosphere cools as it moves away from the mid-ocean ridge; as it does so, it becomes denser. Oceanic crust is also denser than continental crust, so will always subduct beneath the continental crust at a convergent boundary. The existence of the convergent boundary itself probably relates mostly to mantle convection.

Subduction can be clearly seen in a pattern of descending earthquakes that follows the descending plate. This is visible in NZ, particularly across the North Island. Each dot in the picture on the right is caused by an earthquake and they are colour coded for depth. It can be clearly seen that they deepen to the west. Geologists call such a descending zone of earthqakes the Benioff Zone. These deep earthquakes cannot be caused by elastic rebound, as shallow earthquakes are, because rocks at this depth are too hot to behave like brittle solids. Instead, the earthquakes are caused by factors such as magma movement and sudden volume changes in rock.

Island arc subduction zones are bounded by a trench where the subduction begins; this is where the subducting plate begins to dip. Near a continent, the trench is often partly filled with sediment and may contribute to the process of continental accretion (see diagram above).

You can see a picture of the seafloor around NZ here; note in particular the 'double line' parallel to the Kermadec Trench, caused by the secondary convection cell shown above. This continues onto land to become the rift zone in which the caldera volcanoes of the Taupo Volcanic Zone sit.

Production of andesite: During the process of subduction, magma is produced when the subducted crust reaches certain depths. Water is thought to be critical in this process; there are several possible sources for this water:

- as the subducted material descends, it is heated and subject to pressure. This causes changes in the minerals, particularly the release of water from hydrated minerals.
- Water may be carried down in ocean sediments (in pore space or similar).

The water released rises into the overlying mantle lithosphere, where it triggers **wet melting,** which produces **andesitic** magma. This magma may be modified into higher or lower silica compositions by processes that happen as it moves or begins to crystallise. Melting is only partial, but the melted material is 'squeezed out' like a damp sponge to rise up as a magma body. The water is not present in liquid or gas form, but rather is combined with the silica in the form of silicic acid, H_4SiO_4
This is formed by chemical reaction between water and silicon dioxide. The reaction is reversible, and it is the reverse reaction which releases water vapour producing the gas which drives much volcanic activity.

Subduction related rhyolite and basalt: The rhyolite and basalts associated with the Taupo Volcanic zone are produced by a different mechanism, probably associated with tensional (pull-apart) forces further back in the subduction zone (see diagram). The tensional forces trigger dry melting of mantle lithosphere, produceing basalt which rises and pools at the bottom of the crust where the heat from it triggers crustal melting, producing granitic/rhyolitic magma. Some andesite and dacite magma gets produced by mixing of the basalt with the rhyolite, e.g. Mt Tauhara and some of the ignimbrites from the Mangakino Volcanic Centre.

Evidence on land for the rifting can be seen in the Google Earth shot below of the Waikite Valley, south of Rotorua:
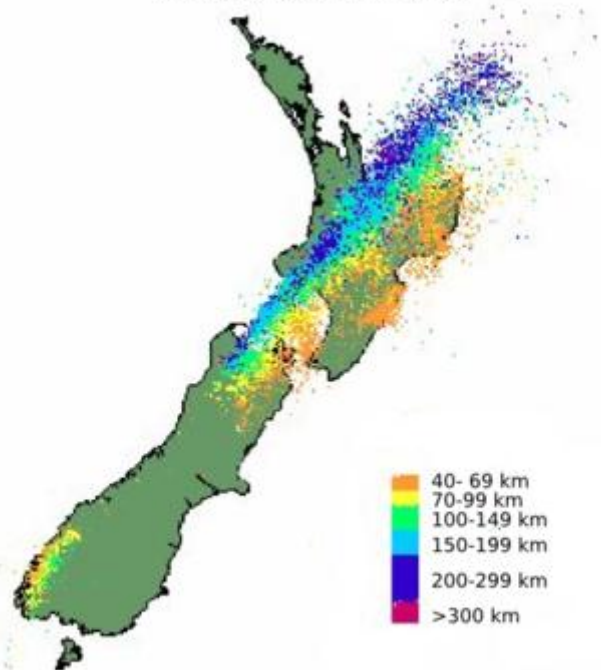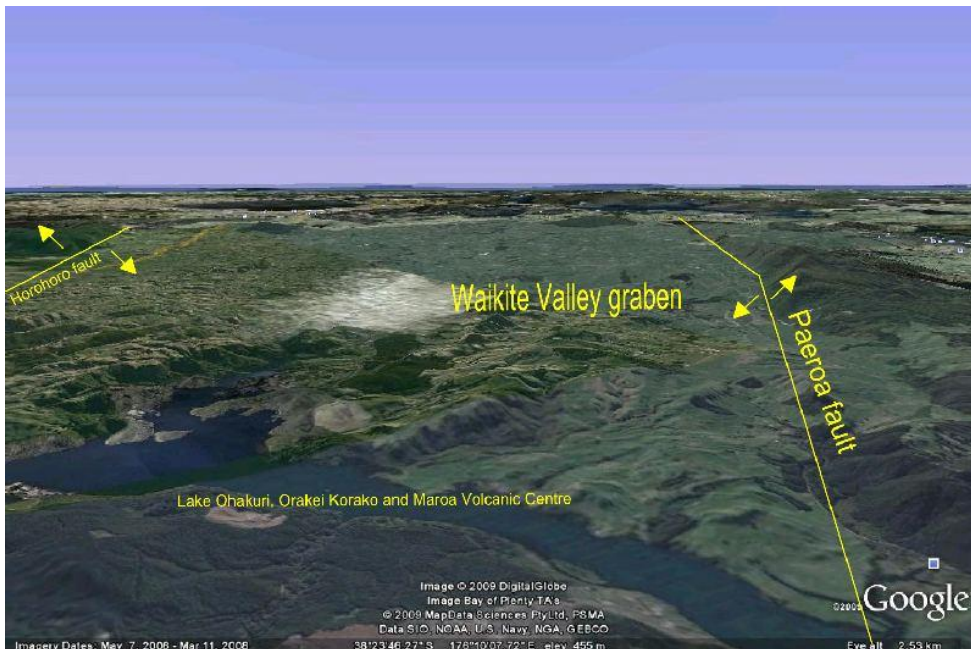
Waikite Valley, looking north towards Rotorua

This graben (rift valley) is a southern extension of the Havre Trough. Elsewhere, the pattern is less clear because the landscape is buried under recent pyroclastic flow deposits (ignimbrites).

Other sources of volcanism:
Melting can be associated with other processes, such as pressure released when plates are pulled apart. This may be what is happening beneath Auckland and other areas of 'intra-plate' volcanism. It may also contribute to the large scale plutonic activity and associated caldera volcanism in the Taupo Volcanic Zone through back-arc rifting as shown in the diagram. This is an area of current research.

Other types of convergent boundary:
Subduction is one variety of convergent plate boundary. Other convergent boundaries include **transform boundaries**, such as the Alpine Fault in NZ, and the well known San Andreas Fault in California. **Continental collision zones** occure where two continents collide. The Himalayas (collision between India and Asia) and the European Alpine zone (Africa/Europe collision, complicated by the geology of the Mediterranean) are overseas examples. New Zealand is not, strictly speaking, a continental collision zone, but the northern South Island, where the plate boundary is making a transition between sideways movement on the Alpine Fault and subduction in the eastern North Island, exhibits some of the characteristic features of a continental collision zone. There is a fairly large compressive element in the movement of the Alpine Fault which is responsible for the uplift.

2. Earthquakes and seismic activity

Earthquakes are caused by waves in the solid ground called seismic waves. These can be produced in several ways

- Elastic rebound on faults
- Movement of magma
- Sudden volume changes in rock
- Underground explosions

Elastic rebound is the most common cause of shallow earthquakes.

Faults
Faults are cracks in the crust, along which there has been movement between the two sides (a break without movement is called a joint). Fault movement can be vertical, horizontal or some combination of these. **Most faults are not plate boundaries.** Most faults are small, like the one on the left. Note the folding around the fault, indicating the stress on the rocks. The movement is a result of tectonic forces, but the actual plate boundary can be hundreds of kilometres away.

Horizontal faults are called transcurrent, or strike-slip faults (except those across a spreading ridge, which are called transform faults). The Alpine fault is an example.

Faults and earthquakes: When there is movement either side of a fault, strain builds up on the fault until it fails and the fault moves. The sudden movement on the fault causes the earthquake (seismic waves). This is called **elastic rebound.** Imagine bending a plastic ruler until it snaps. As you bend it, it is like the movement that builds up on either side of a fault. The sudden shock your hands feel when the ruler snaps is the 'elastic rebound', caused by a sudden release of energy.

The amount of movement across an active fault can be measured by accurate surveying fixed points some considerable distance either side of the fault e.g. across the Wellington Harbour for the Hutt Fault (which runs along the Hutt motorway). The more movement builds up, the more strain energy is stored on the fault. Faults tend to have an 'average' amount of movement across them before they fail, and cause an earthquake. Unfortunately, it is only an average, and therefore cannot be used to predict the exact time of an earthquake, only to estimate the probability of an earthquake occurring in a given timeframe. This is still useful - if a fault is in excess of its historic average, the chance of an earthquake is high and the severity of the quake is also likely to be high. Knowledge of this is used for engineering and civil defence planning.

Back to our snapping ruler analogy for a minute: many earthquakes are more like snapping a bunch of dried spaghetti before cooking it - the snap is 'noisy' as individual strands break. This is why quakes can take some time.

Seismic waves:

Fault movement produces two types of waves: P (pressure, or primary) and S (shear, sideways or secondary). The P waves travel faster than S waves, so if you are some distance away, they reach you first.

When seismic waves near the surface some of their energy is translated into disorderly 'surface waves' (L waves) which do much of the damage. It is somewhat similar to the way that ocean swells become surf at the beach.

- P = **primary** waves; these are 'pressure' waves (like sound). The direction of particle motion is parallel to the direction of wave motion i.e. longitudinal. P waves travel faster than S waves, and can travel through liquids as well as solids. The 'P' stands for primary.
- S = **secondary** waves; these are 'sideways' or 'shear' waves. The direction of particle motion is perpendicular to wave motion i.e. transverse. They cannot travel through liquids. 'S' stands for secondary.

Drum image (c) GNS Science
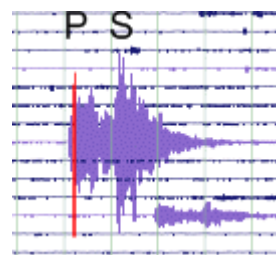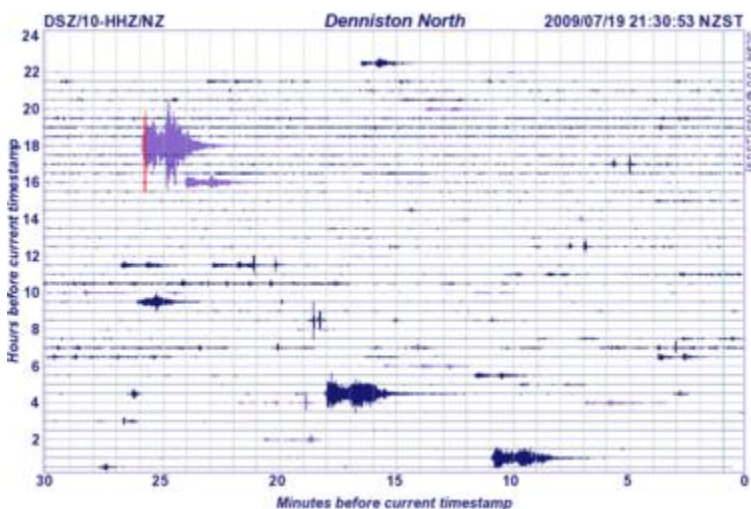
detail of one shock

The time difference between P and S waves can be used to calculate the distance to the point of origin of the earthquake, called the **focus**.

The seismic drum trace shown on the left is from Denniston (near Westport), a few days after the major 7.8 Richter Dusky Sound quake of July 2009. Above left is detail of one shock, with the P and S labelled (the present on the drum is bottom right, top left is the furthest time ago). Vertical lines are 1 minute apart, so you can see the P and S traces were about 60s apart. P waves travel about 10 km per second faster than S waves in the hard rock of the South Island, so the quake is about 600 km away. If we had two more suitably spaced traces we could establish the exact location of the focus (as shown in the example below), but it is the right distance to be an aftershock of the Dusky Quake.

Epicentre:

The epicentre of an earthquake is the point on the surface directly above the focus - the point where the earthquake waves originated. To work out where it is, the distance to the earthquake from 3 different locations is used to draw a circle around each location:
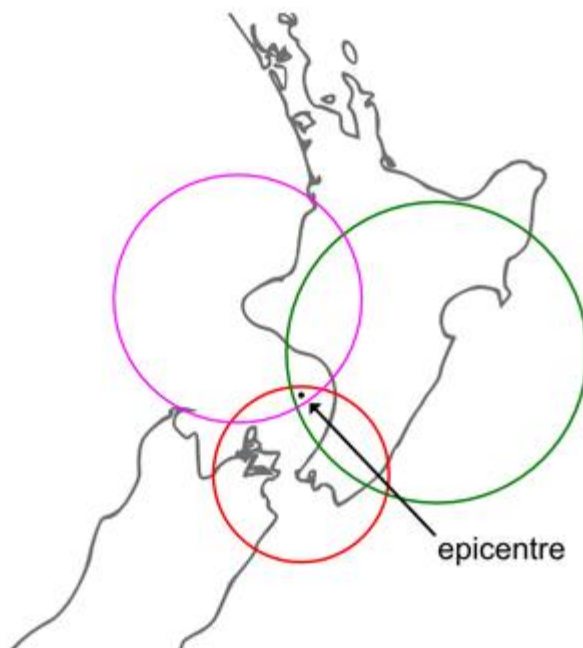
Example: The pink, green and red circles represent the distance of a quake from three seismic stations at New Plymouth, Napier and Wellington respectively as calculated using the different arrival times of P and S waves as shown abive

The three circles intersect to make a small triangle. If they intersected exactly at a point, the earthquake would be on the surface or very shallow. However, earthquakes in this part of the country are deep and the triangle arises from this (because the circles are drawn on the surface of the earth). The point below the epicentre where the earthquake waves actually originated is called the **focus**.

Earthquake intensity

The size of an earthquake is measured on two scales. The **Richter** scale indicates the amount of energy released by the earthquake and is the same wherever you measure it. Each number on the Richter scale is about 40 times bigger than the one below it, so a 5 on the Richter scale is about 160 times bigger than a 3 and about 6400 times bigger than a two. This is termed a **logarithmic** scale. The upper limit for an earthquake on the Richter scale is about 9.5; beyond this, rocks are not strong enough to store that much energy.

Epicentre determination

The **Modified Mercalli Scale** is a measure of the effects of a quake, so it depends on both the size of the quake and where you are.

3. Volcanic Activity

3.1 Magma

Magma is molten rock. It can be produced by melting of the crust or mantle; normally, this melting is **partial** so the magma is not chemically identical to the rock that produced it. Different magmas are produced in different places and in different ways.

Basaltic magmas are produced by the dry melting of mantle material, usually through pressure release or heat from mantle plumes. They are mostly formed at mid-ocean ridges, hot spots and rifts.

Andesitic magmas are produced in subduction zones, and probably are caused by reactions between the water released from the subducted lithosphere and the overlying 'mantle wedge', which is termed 'wet melting'. There are several different sorts of andesites produced in different parts of a subduction zone; for example the andesites of Taranaki are different from those of Tongariro (they overly a deeper part of the subduction zone). The island andesites e.g. Raoul Island are different again. This suggests that the processes that produce magma from subduction are quite complex.

Rhyolitic magmas are produced by the melting of crustal rock, or mixing of crust and basalt to andesite magma, or when andesite magmas are modified by partial crystallization. They are mostly found in continental arcs and back-arc rift zones, although large island arc volcanoes (such as some underwater ones in the Kermadecs) can produce rhyolite. A rock called dacite is in-between rhyolite and andesite. Current thinking weems to be that most rhyolites in the TVZ are produced by crustal melting by and partial mixing with large volumes of basalt magma produced by the back-arc rift process. Most of this basalt does not make its way to the surface (the 1886 Tarawera eruption was produced by some that did).

Magma composition and rock type
(Introduction to igneous rocks here.)
There are many ways in which the composition of magma can vary, but the most important is the amount of **silica** (SiO2, or molten quartz) dissolved in the magma. The way that this shows up in the rock is the proportion of light coloured (white, cream, pink) minerals, which are compounds of silica and aluminium, calcium, sodium and potassium oxides. Dark (black, brown or green) looking minerals are compounds of silica and iron or magnesium oxide, and contain much less silica. So the more light coloured minerals there are in a rock, the more **silica-rich** it is. Rocks with a high proportion of dark minerals are **silica-poor.** Rocks in between are termed **intermediate.** Volcanic and plutonic rocks can be roughly named according to the proportion of silica present in the magma:

Silica content	Volcanic rock name	Plutonic rock name
Low silica (45-55%):	basalt,	gabbro.
Intermediate (55% - 64%)	andesite,	diorite
High silica intermediate (65%-70%)	dacite,	granodiorite

High silica (>70%):   rhyolite,   granite

*Note: the term **dacite** will probably not be used in the NCEA exam, but several well known volcanoes in NZ have this lava type including Mt Maunganui, Mt Edgecumbe and White Island. Dacite volcanoes, as the composition implies, tend to be somewhat between andesite and rhyolite in their appearance and eruptive style.*
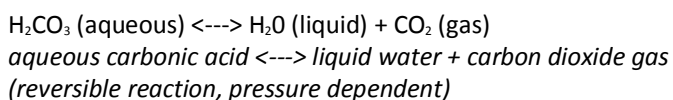
Special volcanic rock types:

Basalt or andesite lavas which are full of bubbles are termed scoria. Dacite or rhyolite lava full of bubbles is termed pumice . Obsidian can be formed from volcanic glass of andesite to rhyolite composition (rhyolitic ones are most common). Pumice is obsidian that is full of bubbles. A mixture of pumice and ash deposited by pyroclastic flow is termed ignimbrite.
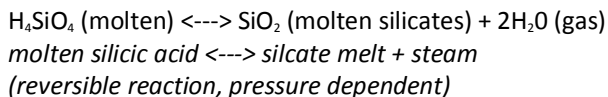
3.2 Types of Volcano

Magma which reaches the surface is erupted to form a volcano. It then cools quite quickly to form fine-grained volcanic rock. The different appearance of different volcanoes depends mostly on four factors: the viscosity (runniness) of the magma, the amount of dissolved gas (mostly H_2O and CO_2), whether or not the magma encountered groundwater on its way up (hot magma tends to explode when it encounters liquid water, particularly if this happens just under the surface), and how much (volume) of magma was erupted.

As the magma reaches the surface, gas that is dissolved in it begins to form bubbles due to the pressure release. This is very similar to the way that bubbles form in soft drink when you open the bottle. Before the bottle is opened, the gas is kept dissolved by a combination of pressure and chemical reactions:

H_2CO_3 (aqueous) <---> H_2O (liquid) + CO_2 (gas)
aqueous carbonic acid <---> liquid water + carbon dioxide gas
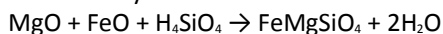*(reversible reaction, pressure dependent)*
When the bottle is opened, the equilibrium moves to the right. If it is vigorous enough, the drink can spray out (in the coke/mentos photo on the right, the reaction has been sped up by a catalytic effect of the mint through a phenomenon called *nucleation*)

When magma approaches the surface, a similar reaction occurs:

H_4SiO_4 (molten) <---> SiO_2 (molten silicates) + $2H_2O$ (gas)
molten silicic acid <---> silcate melt + steam
(reversible reaction, pressure dependent)
Note that other chemical reactions in the magma contribute to the water pressure; in some ways it can be considered an acid-base reaction e.g.
$MgO + FeO + H_4SiO_4 \rightarrow FeMgSiO_4 + 2H_2O$
The compound FeMgSiO

4
is the mineral olivine; it is crystalline so forms as the magma cools. It is denser than

Violent effervescence of diet coke

the melt and settles to the bottom of the magma chamber. This alters the composition of the magma. There are many other similar but more complex reactions, which ones take place depends on the magma composition.
The net effect is that as magma approaches the surface, steam and other bubbles of gas are created.. This can result in vigorous explosions or fountains of lava.
==Remember: The more silica-rich a magma, the less runny (or more viscous) it will be.==
Imagine if in the mentos photo above right, I was able to make the consistency of the coke something like golden syrup while increasing the pressure even more. It couldn't possibly escape fast enough (too viscous) so would explode instead of fountaining out. If it was hot hokey pokey with the bicarb added, and it solidified into blobs as it sprayed out, you would have a model for the formation of pumice.
Other gases besides water are significant in volcanoes, particularly carbon dioxide, hydrogen sulfide and sulfur dioxide. Some of them are also kept in pressure solution.
A large amount of the variation in volcanic activity is due to how much dissolved gas there is in the magma and how easily it can escape.
(note: there is an exception; mamgas very rich in sodium or potassium can be anomalously fluid. Mayor Island is a NZ example of such a lava - it is rhyolite, but unusually fluid and the eruptions are more like basalt).
The most fluid magmas flow a long way over gentle slopes and the gas escapes easily, so they tend not to be very explosive. Very 'sticky' magmas tend to be shattered into little bits as the gas tries to escape; this causes explosive and ash eruptions. Blobs of this lava can actually expand with bubbles as they fly through the air to form pumice. Viscous but gas poor lava flows form steep cones or domes.

Basalt volcanoes

Basalt magmas are quite runny, so the gas can escape quite easily (often producing a fountain of lava) and the lava flows long distances over quite gentle slopes to form a "shield" shaped volcano. Some of the frothy magma sometimes solidifies near the fire fountain before it can flow away, so it builds up a steep but small cone of scoria. Mt Wellington is a good example of such a cone. The scoria tends to float on top of lava like soapsuds on water. These cones are called **scoria cones** (in NZ) or cinder cones (note that they often, but not always, have a central crater; if they don't they can be mistaken for rhyolite domes but they are much smaller than such domes). Some NZ cinder cones sit atop shields e.g. Rangitoto, One Tree Hill. Others form small, discrete volcanoes (which is the more common form overseas).

Explosive activity often occurs at the beginning of the eruption when the hot magma encounters rock and soil wet from groundwater; this is referred to as a phreatic eruption. If the volcano splutters to a halt after this, you will be left with a large, shallow explosion crater surrounded by a shallow ring-cone of the ejected material (called tuff).Otherwise, a scoria cone will build up in the centre, as shown in the photo below of a volcano on the margins of Lake Omapere, Northland.

Tuff ring and scoria cone, at the dege of Lake Omapere. Tuff has been coloured pink for recognition.

Tuff layers, North Head, Auckland
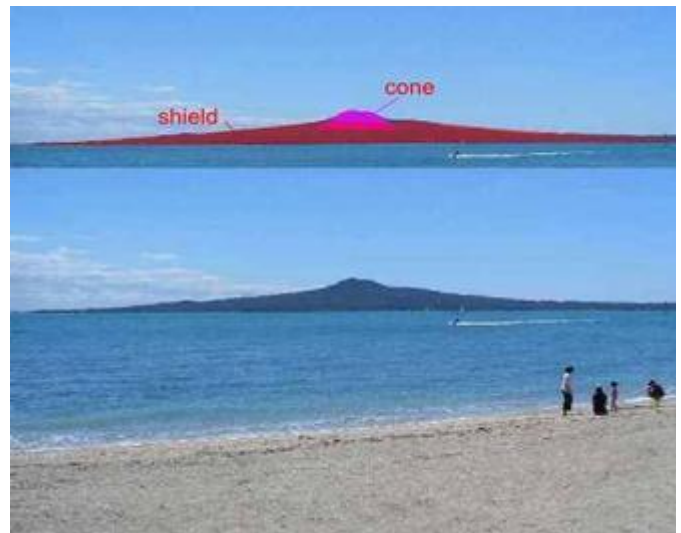
Rangitoto, shield volcano with summit cone

Explosion craters of this sort are called maars; Panmure Basin, Orakei and Onepoto are all examples in the Auckand field and there are numerous others in the Auckland and Franklin fields. They are not well preserved over long periods of time, so tend to be found in young fields. Some literature wrongly labels maars as calderas. One way to tell the difference is that calderas are much larger (explosion craters are rarely more than about 2km

Panmure Basin - a maar (explosion crater)

across). See the picture of Lake Rotorua down the page for an example.

Mt Wellington from Taylor hill, now...

...and as it might have looked 9000 years ago

Many volcanoes then build up some small cones (scoria cone or cinder cone) inside this explosion crater, and some completely overwhelm their explosion crater and bury it in lava, e.g. Mt Wellington (above). These largest of the basalt volcanoes are the ones that build up shield volcanoes. Only Rangitoto and One Tree Hill, in Auckland, show clear shields in NZ. Mt Wellington formed a lava 'lake' which was quarried and the hole left behind is being subdivided into housing.

Aa lava surface, Rangitoto

Pahoehoe lava cliff, Milford

Scoria. Colour can be black, red, yellow

Basalt

Although basalt lava is very fluid, it can form different textures on the surface. The blocky surface at Rangitoto on the left is a texture called aa (pronounced like 'haha' without the h sounds),

or it can form a smoother surface called pahoehoe. The pahoehoe above right has formed a skin of solid rock while still liquid lava drained out underneath, you can see that just below the top of the photo. When this happens more extensively it forms caves called lava tubes or lava caves. I have a video clip on this but have removed it from the page because it was causing it to crash. contact the author if your are wanting to use video resource material.

Intermediate volcanoes - andesite
Intermediate magmas are less runny, and form large, steep lava cones. Mt Egmont/Taranaki and Mt Ngaruahoe are good examples of this; Mt Ruapehu is also an example but consists of several cones grown together.
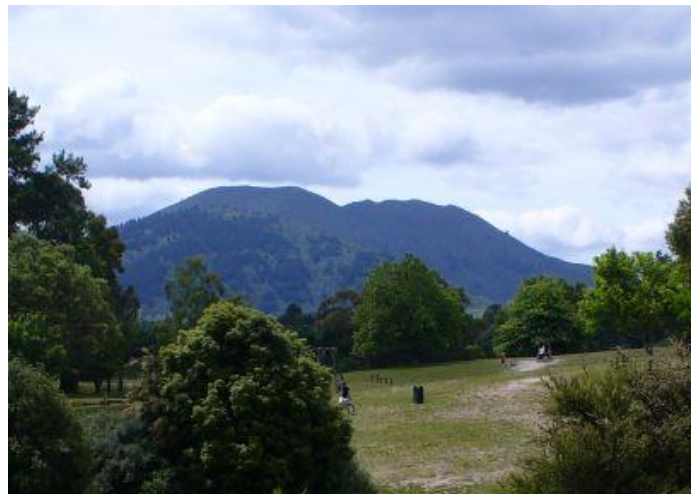

Andesite

Taranaki

Taranaki is an andesite cone, with a small 'parasite' cone (a second but less active vent from the same magma source) inturrupting its otherwise very symmetrical shape. The close up shows andesite similar to that from Taranaki/Mt Egmont. Lower silica intermediate volcanoes have scoria on them, rather like basalt volcanoes. Ngauruhoe is a very low silica andesite. Its slopes are loose scoria.

Mt Edgecumbe

Tauhara

High silica intermediate: These volcanoes are a bit steeper than normal andesite volcanoes, in-between cones and domes. Edgecumbe and Tauhara are two examples. The rock type is callled **dacite**, but this name will not be used in the exam. They are intermediate rocks with 65-69% silica. Quite a few of the underwater volcanoes between White Island and Tonga have this composition. One of the main distinguishing characteristics is that when full of bubbles the lava is more like pumice than like scoria.

Rhyolite

Pumice

Rhyolite is made from a very silica-rich type of magma. If it cools underground, it forms **granite.** Silica-rich magmas are normally very viscous, and as a result the gas has great difficulty escaping. Their eruption mode therefore depends on how much gas is present.

Pumice formation: gas-rich rhyolite magma is 'blasted out' as blobs of thick, syrupy lava. As these fly through the air, they rapidly expand (like unexpanded polystyrene dropped in hot water, or when you put the bicarb in while making hokey-pokey). These bubble-filled glassy blobs make pumice. Pumice is volcanic glass with bubbles (mostly formed by water vapour). It is usually rhyolitic in composition, but some pumices are dacite (particularly those from the offshore volcanoes between White Island and the Kermadecs). Pumice may contain some crystals that were in suspension before eruption (called phenocrysts).

Caldera formation: many NZ rhyolitic eruption centres are so large that they form calderas. It is important to understand that this is **not a crater.** It is formed by ground subsidence. So much magma is erupted that the overlying ground subsides, forming a depression called a caldera *(to see a picture of a caldera on the summit of the underwater Brothers volcano, click here)*.

Below right is a Google Earth view of the Rotorua Caldera, looking towards the west from above Lake Okataina. You can contrast the size of Lake Rotorua with the explosion crater in which Lake Rotokawau is located (near Hell's Gate, lower right of picture). Despite this huge size difference, the Rotorua caldera is one of the smaller calderas in the TVZ (and Lake Rotokawau a fairly large explosion crater). Below left is a diagram showing the stages in the formation of a caldera. One of the features to note is the formation of a dome, often over the vent. Mokoia Island is an example of such a dome, as is Mt Ngongataha and Hospital Hill in Rotorua. In the extreme foreground are some of the domes at the edge of the much larger Okataina Volcanic Centre.
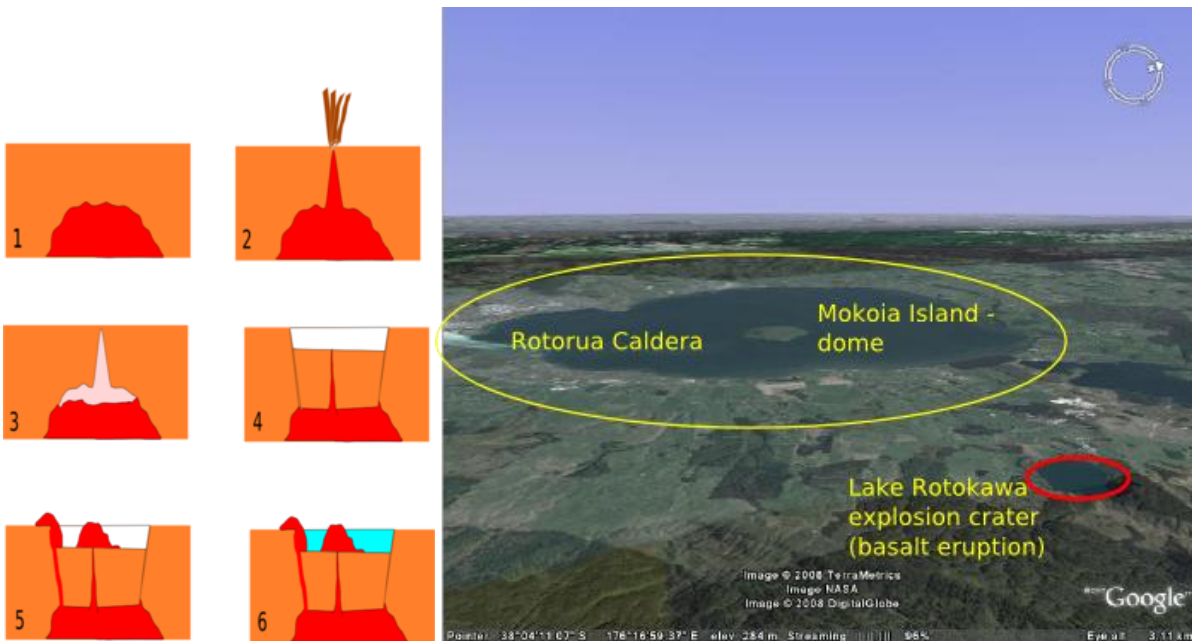
Pyroclastic flow: The hot material can be carried high by the expanding, lighter-than-air superheated gas (mostly water vapour). Eventually, this *eruption column* loses buoyancy and collapses. The resulting materail hits the ground at high speed. It is still very hot - 300 to 600 degrees celsius. The turbulence when it hits the ground sucks in cold air, which rapidly expands, creating more turbulence, which sucks in more air and so on. This creates a turbulent cloud of hot ash which can flow tens of kilometres over the ground at high speeds (100 to 400 kph) in a pyroclastic flow. It will continue until it is no longer fast enough, or hot enough, to create the turbulence that keeps it going (further from the vent, pyroclastic flows often become confined to valleys as the downhill movement helps keep up the speed).

Large pyroclastic flows leave behind a layer of distinctive ash called **ignimbrite.** Some of these ignimbrites are tens of metres thick, extending for hundreds of square kilometres. In quite a few of them, the pumice and glass shards of the ash were so hot when the ignimbrite

formed that they have welded together to form a hard rock very much like the rhyolite you find in a dome (see next section). The photo on the right is of such an ignimbrite outcrop in the Waikato (known locally as Hinuera Stone). Such rocks puzzled geologists in the 19th Century because they knew this lava was too viscous to form the large, flat sheets they found; it was the 1930s before the explanation was forthcoming. The youngest ignimbrite in the North Island is the Taupo Ignimbrite, erupted about 230 AD from a vent near the east side of Lake Taupo. It is a non-welded ignimbrite and is relatively thin because it was moving much faster than average.

Maungaongaonga dome...
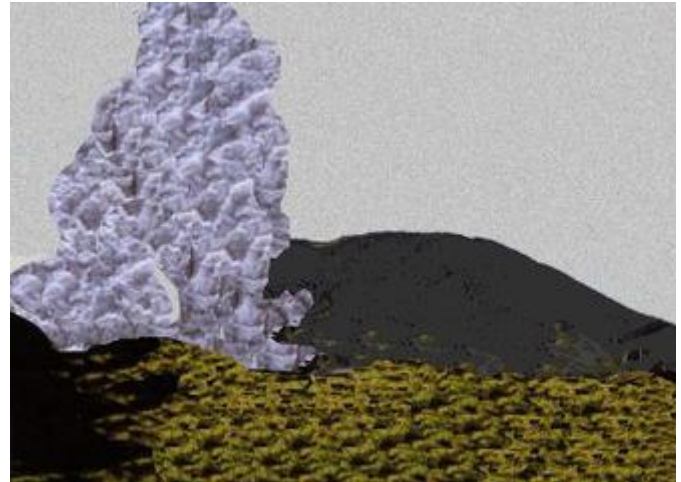
....with a small pyroclastic flow on the east flank

Dome formation: Once the caldera has collapsed into the partly empty magma chamber (3 and 4 in diagram), some magma is usually erupted out the vent and the caldera margin faults to form rhyolite domes (5 on the diagram). This magma has lost most of its gas, so 'oozes' out relatively quetly. Domes can form pyroclastic flows when the hot rock on their steep side collapses and disintegrates, sucking in cold air in a similar manner to the very large events; however, these pyroclastic flows are usually small and only travel a few hundred metres beyond the foot of the dome. There are over a hundred rhyolite domes in the Rotorua-Taupo area. The skin of the dome is sometimes **quenched**, forming obsidian (quenching means very rapid cooling; no crystals form and instead it forms glass), while the inside is made


Small dome, Tokaanu

Obsidian (Wikimedia)

of rhyolite.The rhyolite dome in the photo on the right is on the southside of Lake Taupo, near Tokaanu. The dome shape is clearly visible. It is partly buried in the fan of sediments where the Tongariro River enters the lake, so what we se here is the emerging top of the dome. The dome in the photos above (Maungaongaonga, near the Waikite Valley) is more typical. I have shown a possible recreation of the emplacement of the pyroclastic debris flow that can be seen on the left looking at the hill might have looked like. The present flat area in the foreground is the floor of a former lake.

Lakes: Calderas often then fills with water, forming a lake (6 on diagram), or several lakes (Lakes Okataina, Tarawera and Okareka all lie within a single caldera/volcanic complex called the Okataina Volcanic Centre).Lake Rotorua is a good example of such a caldera. Mokoia Island is a dome in the caldera centre, and there are quite a few other domes around the caldera including Ngongataha and Hospital Hill.

Summary: The diagram below summarizes the relation ship between viscosity and gas content in forming different sorts of volcanoes. It shows gas content increasing upwards on the vertical axis, and viscosity increasing to the right on the horizontal.

## Volcano type as a function of gas content and viscosity
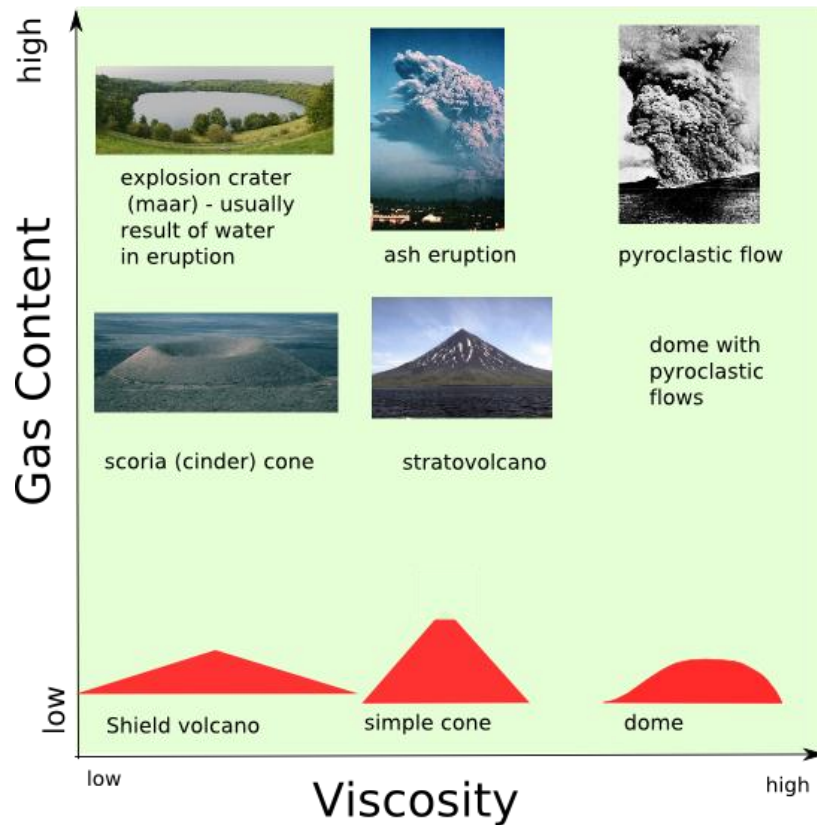
Of course, real volcanoes don't look at this diagram when they erupt, and many volcanoes will have a mix of different eruption types. Neither are the boundaries between the types sharp - different sorts of volcano grade into each other.

3.3 Eruptions

Volcanoes are somewhat more predictable than earthquakes. Magma has to make way from its source, deep underground, to the surface. This produces signs a vulcanologist can interpret. As well, the past history of volcanoes is investigated so that factors such as the average time between eruptions and the time since the last eruption can be considered. Signs of an impending eruption

Ngaruahoe seismic drum. The large quake is the one that caused the Samoa tsunami i.e. is from far away. The micro-quakes are associated with magma movement and heating. Some show P and S traces about 10s apart, indicating depth about 100km
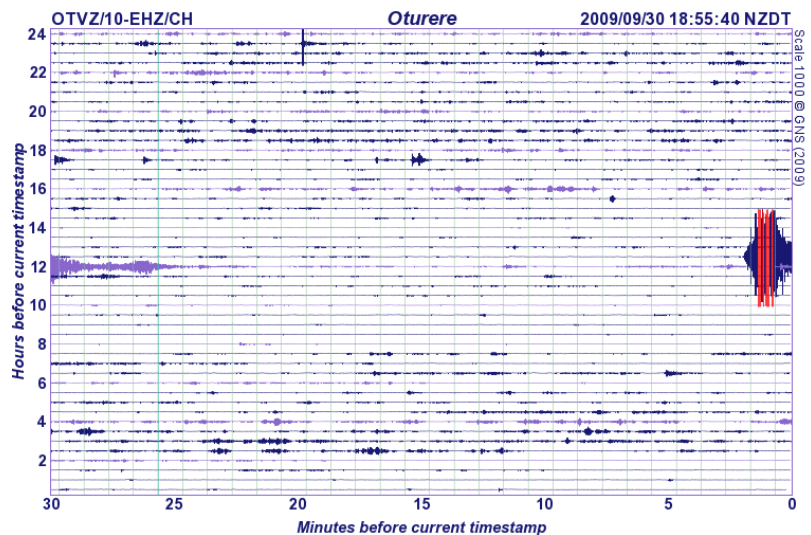
- seismic activity: an ascending magma plume generates an ascending pattern of small earthquakes, which normally become more frequent and more intense as eruption nears. In a place like Auckland, where the magma comes from a few hundred kilometres down, this would give between hours and weeks of warning. Also, volcanoes such as Ngaruahoe produce an increase in seismic 'noise' as new magma is injected beneath them because of the heat expanding the rock around it (this is why Ngaruahoe was stepped up from level 0 to 1 recently, although the noise quietened down and it is back at 0 at the tim I write this). New magma injection into such a frequently active volcano doesn't always mean immanent eruption. The seismic noise from Ngaruahoe can easily be seen on the drum trace above and an increase in it would spark an alert (the large quake on the diagram is the 8.3 Richter quake that caused the tsunami in Samoa on 30th September 2009; the P wave is a good 6 minutes ahead of the S wave, which is rather spread out. Image courtesy of GNS Science). Some of the

stronger microquakes have discernible P and S traces about 12 s apart, indicating a distance of around 120km. This is likely to be straight down.

- ground swelling: as the magma nears the surface and pushes the country rock aside, the surface swells. This can be detected with sensitive tilt-meters, which would be brought in once other signs indicate likely eruption. This can help narrow down where a new volcano might appear (as would be necessary in Auckland)
- Increased gas output from intermittently or low level active volcanoes, such as Ruapehu or White Island. Also, the gas composition can also change prior to an eruption, which is why it is constantly monitored on these volcanoes.
- Ground steam and gases from where a new volcano might appear. This applies particularly to places like Auckland and Kaikohe where any future eruption will be from a new vent rather than an existing volcano; similarly for any new hot-spot volcano in the South Island (although these erupt over a much longer timescale in more widely scattered locations - the last one formed the Banks Peninsula complex 3-10 million years ago)

3.4 Volcanic risk

There are a range of risks from volcanoes in New Zealand. Fortunately, some of the most devastating eruption types are also the least frequent. The likeliest volcanoes to erupt are Ruapehu, Ngaruahoe and White Island. All three have erupted in the last half century with little effect, though ash is likely to disrupt air travel. Ngaruahoe is overdue for an eruption.

Egmont is probably the volcano of most concern, because the time since the last eruption now exceeds the average time between eruptions. Although the next eruption is most likely to be another small, ash forming eruption similar to the last one (in about 1760), the possibility of a devastating cone-collapse episode cannot be discounted and deciding how much of Taranaki to evacuate will be a major headache.

The Auckland field has a probability of about 5% of erupting in the next 50 years, although this figure is based on some very uncertain assumptions about the behaviour of the magma source. An Auckland eruption would cause enormous property damage, but should not cause major loss of life if people are prudent (although, as I write, people are rushing down to the beach to watch a possible tsunami, which doesn't give me much confidence in prudence). This is because there should be a good amount of warning. The Kaikohe field probably has about a quarter the chance of erupting of Auckland over the same time span, but is largely rural.

Another explosive basaltic eruption, like the Tarawera 1886 eruption, is possible in the TVZ. If it doesn't come up in a lake, as it did in 1886, there would be a lot less damage. However, there are quite a few lakes to hit. If the basalt dyke swarm hits a rhyolite magma chamber in Okataina or Taupo, it would probably trigger a major ignimbrite eruption.

Several domes in the TVZ, including Tarawera and Edgecumbe, could produce pyroclastic flows.

Mayor Island could erupt, and ash from this volcano is poisonous because of high fluorine concentrations.

The most devastating eruption would be a large eruption from one of the two active calderas, Taupo and Okataina. An eruption on the scale of the last one from Taupo would have almost unimaginable consequences - there would be few survivors between Auckland and Palmerston North. The chances aren't high, but the TVZ is the world's most active rhyolitic eruption centre.