River Channels

We have examined the water cycle on a global and drainage basin scale and we have already looked at how rivers form and how rivers flood. Next we consider the river channel itself: the properties of flow within it and the landforms (due to erosion and deposition) that river channels form.

The Importance of erosion

We have already seen how water flowing overland can erode the soil on slopes to form rills, gullies and eventually permanent channels. Clearly the water carves out channels for itself in the soil and bedrock. Water does this because flow in a channel is more efficient and enables the water to flow downhill more easily. This erosional process does not end here, however, but continues both along the course of a channel from river source to mouth, and over time as rivers and drainage basins evolve. A river may cut down into the river bedrock (vertical erosion) and may also cut sideways into the banks (lateral erosion).

Rivers Contain Lots of Energy!

Rivers have lots of energy! Consider a fast-flowing river, flowing at 10 m/s. Each cubic meter of water weighs one tonne (1000 kg or about 2200 lb). This water contains energy by virtue of the fact it is moving! Such energy, due to movement of mass, is called kinetic energy. This means that every cubic meter of water in this river will contain enough kinetic energy to keep 50 one kilowatt electric heaters working! This is the same kinetic energy as 10 Olympic sprinters running at full speed!

 (You don't need to know this but kinetic energy = $\frac{1}{2}mv^2$, where m is mass (1000 kg) and v is velocity (10 m/s) so v^2 = v x v =100 m^2/s^2, so $\frac{1}{2}mv^2$ = ½ x 1000 kg x 100 m^2/s^2 = 50 000 kgm^2s^{-2} or 50 000 J. An energy expenditure of 1 J/s is the same as one watt (1W) of work, since 1 W = 1 J/s, so if all the energy could be made to do work (unlikely!) then this energy would provide 50 000 W of work).

Another way to look at this is to say that the energy flowing through one square meter (of channel cross-section containing water each second) is 50 000 watts! Now if the river is 10 m wide and 3 m deep, say, that means it has a channel cross-sectional area containing water of 10 m x 3 m = 30 m^2 (30 square meters), so the total kinetic energy flowing past each point is 30 x 50 000 = 1 500 000 W, that's equivalent to 15 000 hundred watt light bulbs or ten elephants charging along every second! Imagine then what this energy can do to obstacles that stand in the way of a fast-flowing river!

This energy can do work for the river! It can be used to carry rock fragments for example! The faster and larger the river, the more power it has and the more material it can carry.

Transport of bed-material load
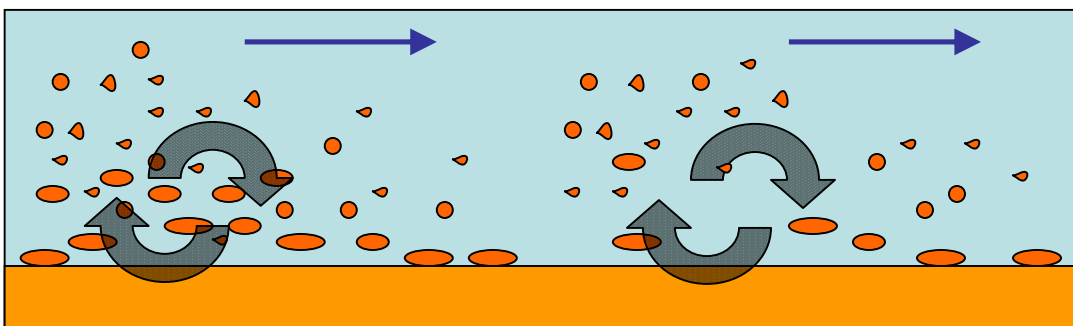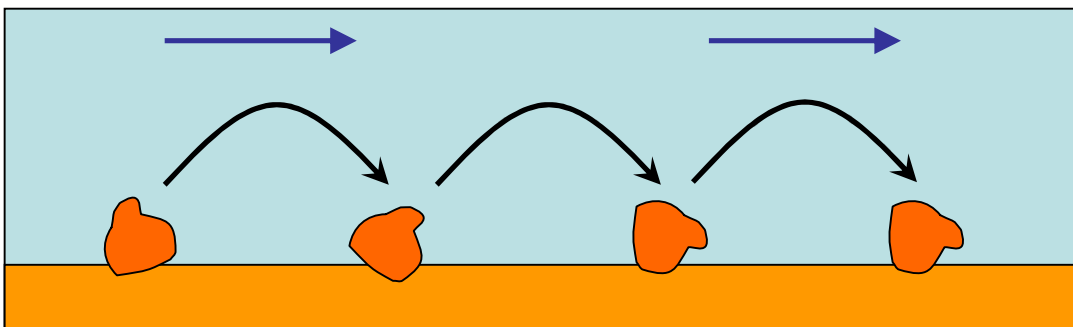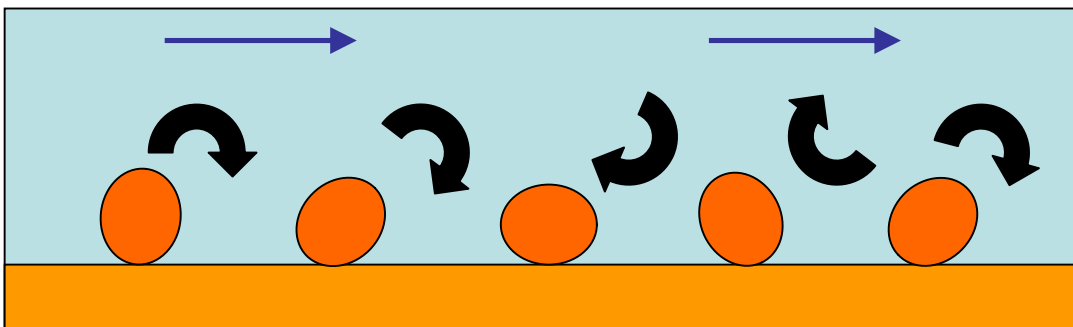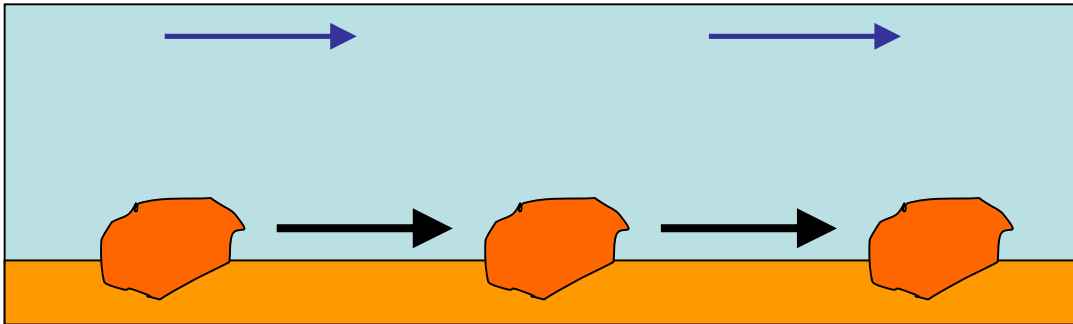
Transport by Rivers

The materials (other than water) carried by a river are referred to as the river load. All rivers carry three different types of load:

1. The dissolved load. This is material transported in solution. Consider ordinary table salt, which is sodium chloride (NaCl). When you add salt to water it dissolves and enters solution as ions of sodium (Na^+) and chloride (Cl^-). You can not see these ions, since they are very small (about one ten thousand millionth of a meter in diameter or 10^{-10} m (0.1 nanometer)). (Though some substances dissolve to form coloured solutions). Only certain substances dissolve in water, such as soluble salts like nitrates and phosphates. You can think of substances dissolving in water only if they react chemically with the water.

2. The Wash load. This consists of very fine particles (smaller than 0.064 mm) that move readily in suspension. These particles are not normally found on the river bed, they are just so light that they get carried away by the water. These substances are not in solution. Imagine adding talcum powder to a glass of water and stirring it. The powder will not dissolve, but it is still carried in the water as solid particles suspended in the water.

3. The bed-material load. This consists of larger and heavier particles (all particles larger than 0.064 mm) which do occur in appreciable quantities in the river bed. These larger particles, for example sand, shingles and pebbles, are sometimes carried in suspension, when they get lifted into the water by turbulence, or else they slide, roll or jump (saltate) across the river bed at a speed less that that of the flowing water. In fact, each of these particles will sometimes be carried along the river bed and sometimes in suspension, depending on turbulence and speed of the water. (See the diagram below to understand saltation).

The larger particles require more energy to carry. A river may be able to drag large boulders along its river bed when the channel is full and the water flowing fast, but if the speed of the water drops, then these boulders may remain stationary and even finer particles in suspension, like silt or sand, may be dropped onto the river bed if the water loses too much energy and can not carry as much. We shall soon see precisely what causes water to lose or gain energy. A gain in energy may cause water to pick-up more load, eroding the river bed and banks, whilst a decrease in energy will cause it to drop load out of suspension, forming deposits. Various landforms are associated with river erosion and deposition. If the water loses lots of speed (and so energy) even the wash load may be deposited.

It makes sense, you can carry more rocks when you have more energy! The dissolved load, however, is easy for a river to carry and the amount carried depends more on the volume of water available, than on its kinetic energy. You can dissolve more salt in a large glass of water than you can in a small glass of water!

Q. What are the 'particles' that rivers can carry?

A. These particles are rock fragments of various sizes, formed when bedrock gets eroded (broken-up and worn-down). The table below shows the names we give to rock particles of different sizes.

Particle class name	Size range (mm)
Clay	Less than 0.004
Silt	0.004 - 0.064
Sand	0.064 - 2
Gravel	2 – 64
Cobbles	64 – 256
Boulders	More than 256

Computer boffins amongst you may have realised that the size ranges are classified in powers of 2 (don't worry if you do not know what this means!). You are NOT expected to remember these numbers, but you should know the category names and be able to list them in order of size.

Q. What is special about 0.064 mm?

A. This is the largest size of silt (or the smallest size of sand). Particles smaller than this size are carried very easily by rivers as wash load, and are only deposited if the river loses lots of energy. Thus you see, these sizes are not entirely arbitrary!

Some Key Words:

Deposit: rock fragments (silt, sand , gravel, etc.) that has sedimented (fallen under gravity) onto a surface. Also simply called a sediment.

Alluvium: a general term for clay, silt, sand, gravel or similar unconsolidated material deposited during comparatively recent geologic times by a stream or other body of running water. Many river beds are alluvial, that is made of alluvium. Other rivers flow over bedrock.

Bedrock: the solid rock that underlies all soil or other loose material; the rock that eventually breaks down to form alluvium and soil.

Consolidated deposit: a deposit that is made of tightly packed particles (rock fragments) that are not easily separated. Unconsolidated deposits are loose.

The Processes of River Erosion

Page 19 of BP gives a good account of river erosional processes, read that and then read the text below to reinforce your understanding (or confuse you?!).

Abrasion (corrasion): probably the main form of erosion by flowing water, abrasion is responsible for most of the vertical erosion of the channel. Abrasion occurs when rock fragments, carried by the water, scour away the river bed and banks as they collide with them. Eventually abrasion produces fine rock particles that are easily transported by the river. The large particles cause most of the abrasion, whilst smaller particles polish surfaces smooth (think of pebbles on a stream bed). Erosion of hard bedrock is best achieved by corrasion.
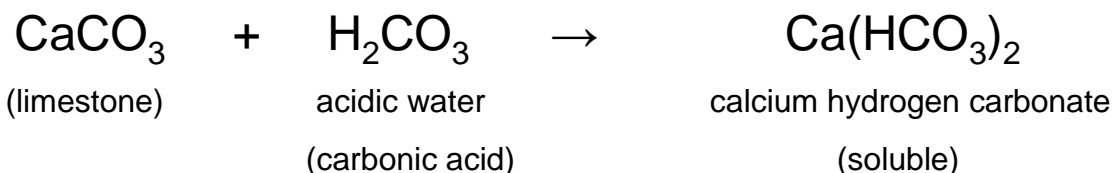
When the river is bankfull or in flood the river may pick-up sand and silt which increase the rate of abrasion. When flow is low, the river has not got sufficient energy to carry larger particles which are deposited on the river bed, and so abrasion is reduced.

Hydraulic Action: Water molecules have a force of their own when they hit things at speed, even if they are not carrying sediment particles. Water also exerts friction on any surface over which it flows, because water is 'sticky' it has a certain thickness or viscosity. It might not be as viscous as engine oil or treacle, but has significant viscosity nevertheless. When water flows over a surface, this friction alone can displace particles from the river bed and channel sides. Under most conditions, however, these forces are only strong enough to carry sand and gravel. Hydraulic action thus becomes a major player in rivers whose beds are alluvial.

(This force acting on a surface when water flows over it, which is due to the viscosity or stickiness of water, is called shear stress, however, don't worry about this term, it is rather technical!).

However, when a river bends, the water is forced to swerve and gets dragged along the outer bend at a greater speed and so generates greater friction and hydraulic action on the outer bend. This will accelerate erosion of the outer bank by hydraulic action.

Corrosion or solution: ever spilt battery acid and noticed how corrosive it is? (I don't recommend this!). Corrosion is a chemical process whereby a substance reacts chemically with a liquid and so dissolves into it to form a solution. Dissolving salt into water makes a salt solution. Rocks containing carbonates are particularly corrosive, like limestone (includes chalk, which is really a form of limestone). Limestone is principally calcium carbonate ($CaCO_3$) and calcium carbonate is very slightly soluble in acidic water. Water naturally absorbs carbon dioxide from the air to form a very weak solution of carbonic acid (H_2CO_3), which dissolves limestone by reacting with it to form soluble calcium hydrogen carbonate (which then readily dissolves in the water) according to the *chemical equation*:

$$CaCO_3 \quad + \quad H_2CO_3 \quad \rightarrow \quad Ca(HCO_3)_2$$

   (limestone)   acidic water   calcium hydrogen carbonate

                      (carbonic acid)   (soluble)

Don't be scared by this chemical formula of calcium carbonate, it simply tells us that one atom of calcium (Ca, a metal) is bonded to (i.e. stuck to) one atom of carbon (C) and three atoms of oxygen (O) to form a building block of calcium carbonate, of course many such building blocks repeat themselves. In fact 100 grams of $CaCO_3$ contains 6×10^{23} (6 followed by 23 zeros) of these units! A substance made up of more than one type of atom is called a compound. Water is a compound, consisting of H_2O units, that is two atoms of hydrogen (H) bonded to one atom of oxygen (O).

Often we call these compound units molecules, so we speak of water (H_2O) molecules, however, calcium carbonate is actually an ionic compound and so we refer to it being made up of ions rather than molecules as such. An ion is an atom or group of atoms that carries a net negative or positive electric charge. Opposite electric charges (+ and -) attract, and similar electric charges (+ and + or – and -) repel each other.

In calcium carbonate, calcium ions, Ca^{2+} (each with two positive charges) are attracted to negative carbonate ions, CO_3^{2-} (each with two negative charges) and this attractive force binds the limestone together. However, many ionic substances dissolve in water. However, in calcium carbonate the charges are normally too strong and so the stone does not dissolve, unlike halite, which is natural sodium chloride salt (NaCl, an ionic substance made up of sodium ions Na^+ and chloride ions Cl^-) and does easily dissolve in water.

However, calcium carbonate reacts with acidic water and dissolves. Natural water is acidic because it absorbs carbon dioxide (CO_2) from the air to form a very weakly acidic solution of carbonic acid (some H_2CO_3 in lots of water, H_2O). This acid attacks and dissolves limestone, but only very slowly, too slow to see in fact, but over centuries whole caves may be carved out of limestone by acidic water, such as the Cheddar Caves in Somerset. These caves took thousands of years to form. You will come across other examples of ionic compounds later in the course. Ionic compounds are often called 'salts' of which table salt, sodium chloride (NaCl) is just one familiar example.

Attrition: Rock fragments strike against each other and grind and rub together and against the river bed as they are transported downstream. Eventually, not only are smaller particles produced as larger particles chip and fragment, but the fragments become smoother, think of pebbles.

Q. How do transported particles (and hence river bed particles) differ downstream from those upstream?

A. This depends on many factors, but there is a tendency for particles further downstream to be smaller and more rounded, especially in alluvial rivers. This is due to attrition and also particle sorting. Particle sorting occurs by two processes: 1) only particles that are small enough will be transported downstream and 2) smaller particles are more easily transported and so are transported faster and further downstream.

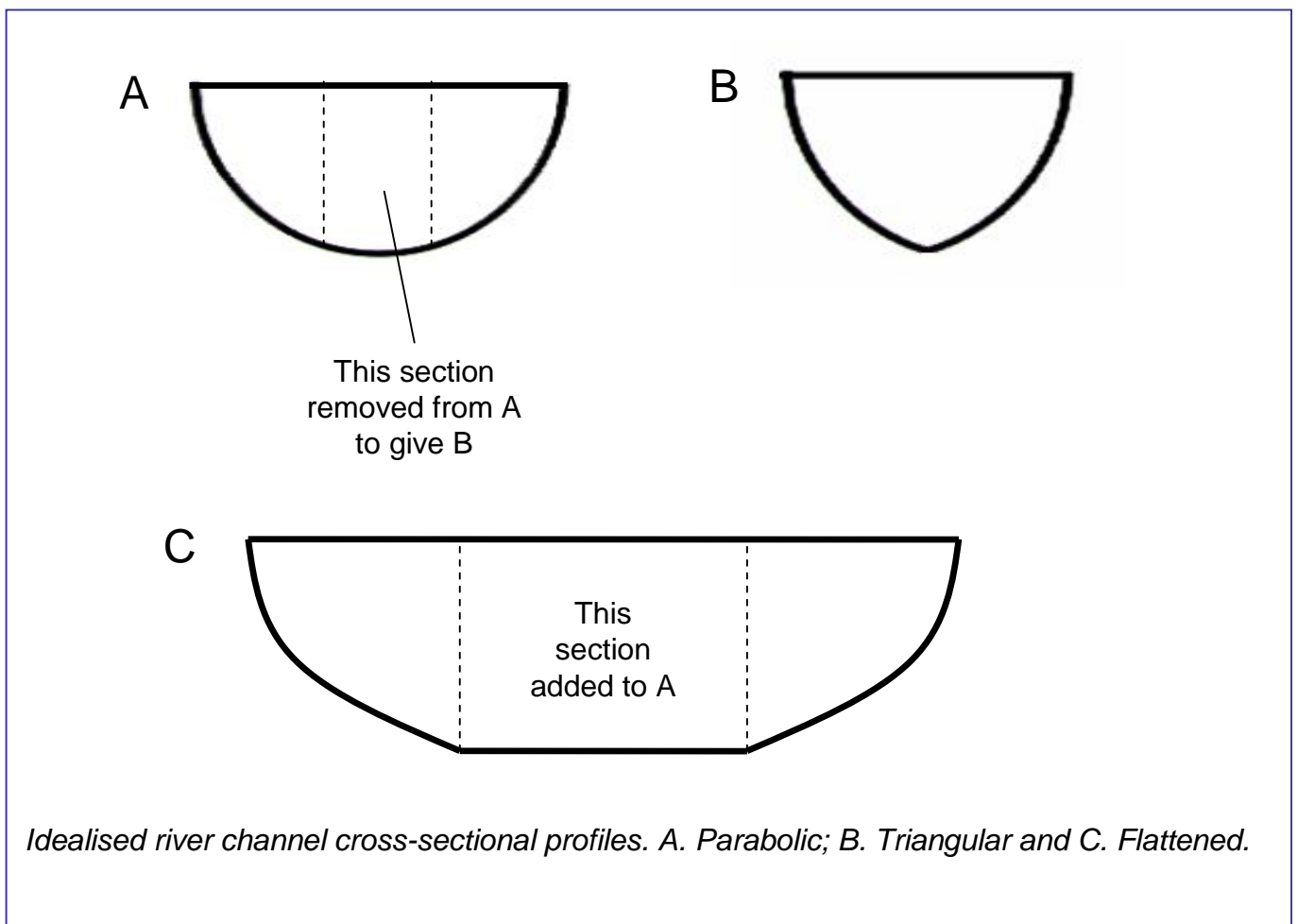# Hjulström Diagram: the relationship between flow velocity, particle erosion, transportation and deposition.
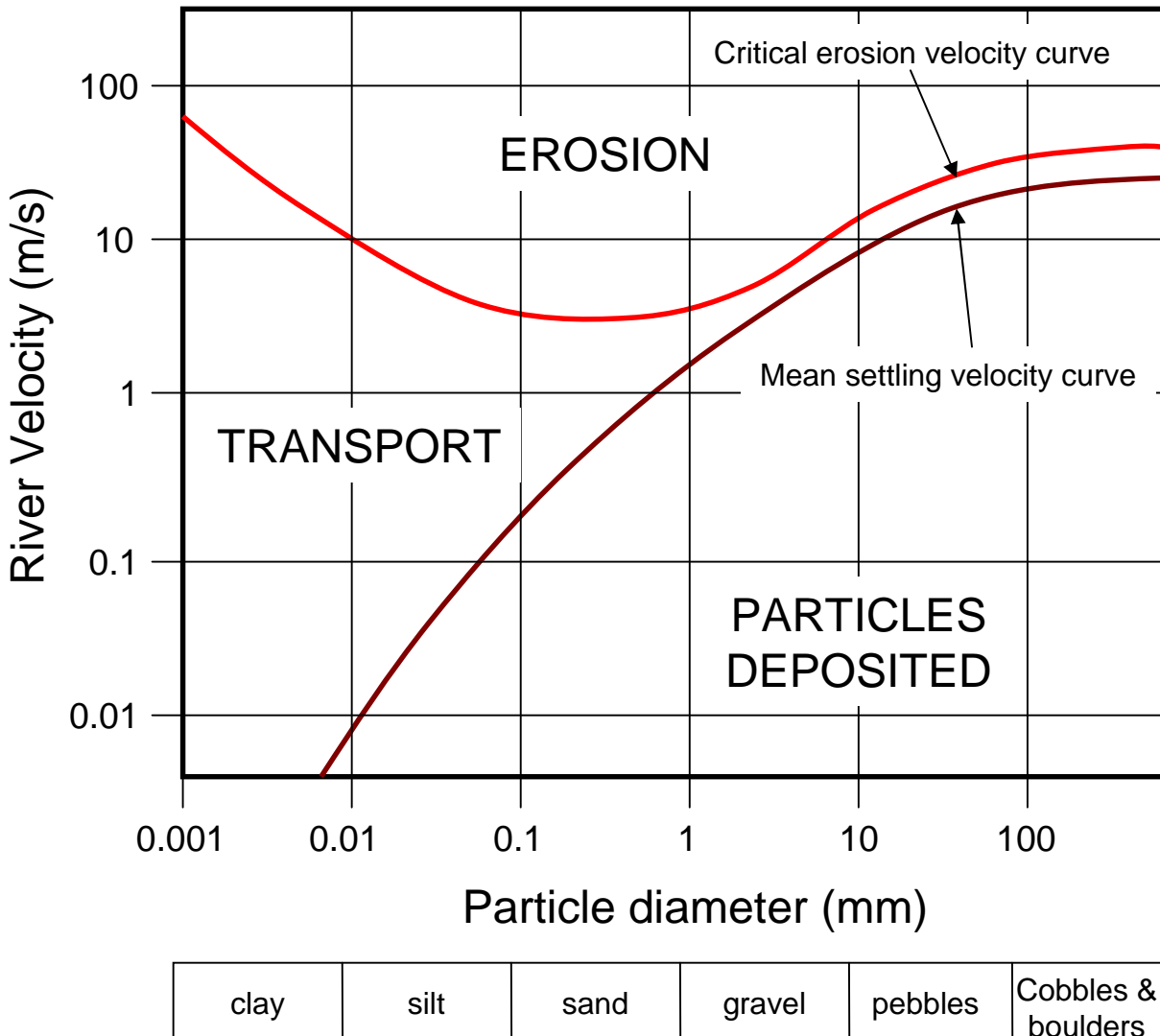
The graph above is called the Hjulström diagram and shows whether, for a given velocity, particles will be transported, deposited or eroded. For particles of a given size, at flow velocities above the critical erosion velocity, that is in the erosion zone of the graph, stationary particles on the river bed will be set into motion (they will be scoured from the river bed and transported by the river). Below the velocity needed to set particles in motion, particles that are already being carried by the river will continue to be transported, so long as the velocity remains in the transport zone of the graph. Only when the velocity drops below the mean (average) settling velocity, and enters the deposition zone will the particles be deposited by the river.

Note that to deposit clay, the river would almost have to come to a complete standstill. However, quite a high velocity is needed to get the clay moving, because of cohesion, that is because particles of clay stick together – clay is sticky. Note also that only a small drop in velocity is needed to deposit the larger particles, like pebbles, cobbles and boulders.
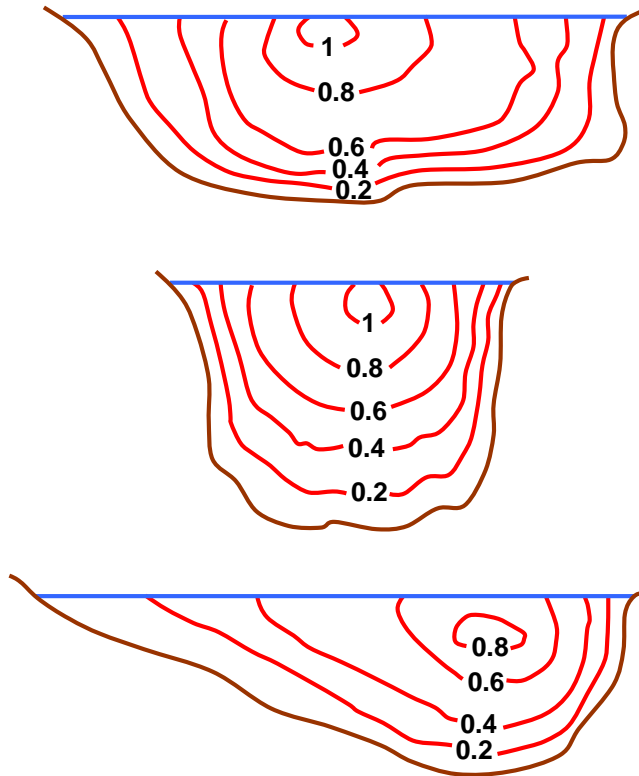
River Channel Cross-Sections

The river channel consists of the river bed and the river banks. If we imagine taking a slice across a river from bank to bank (at right angles to the channel) then we have a river channel cross-section. Different rivers and different parts of the same river will have various shapes in cross-section. Calculations based on the physics of an ideal well-established river yield channels that are roughly parabolic in shape (fig. A below), which is similar to the shape seen in many natural channels (in which more complex physical factors are involved which are not included when considering an 'ideal' river).
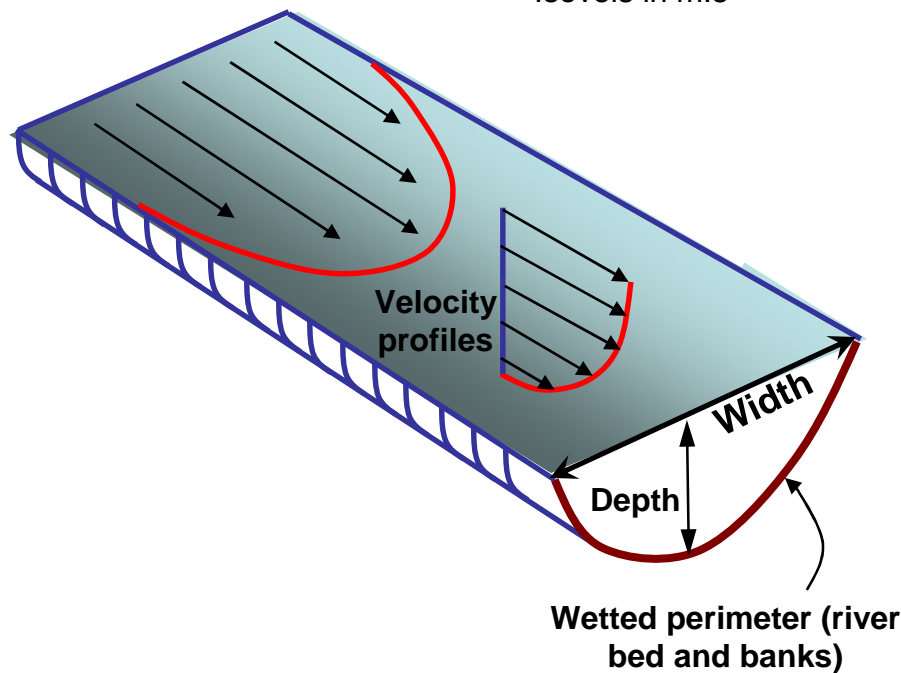
A

B

This section
removed from A
to give B

C

This
section
added to A

Idealised river channel cross-sectional profiles. A. Parabolic; B. Triangular and C. Flattened.

In most rivers the channel walls are not perfectly smooth. This channel roughness increases friction between the water and the channel, and makes the water flow more slowly than it otherwise would. In very few channels does the water flow smoothly, obstacles on the river bed cause swirling vortices to form. In most rivers the water flow is turbulent. This means that, although the primary flow is down the channel, within this the water flows in chaotic swirls and eddies (secondary flow) that come and go unpredictably. This turbulence actually helps the river to lift heavier objects off the river bed and transport them downstream.

The diagram below shows three actual (natural) river channels in cross-section. Notice that they only loosely conform to the ideal shapes already discussed. The isovels are lines that connect points of equal flow velocity and are labeled in m/s. notice that the highest velocity is in the middle of a channel that is roughly symmetrical and just below the surface. Notice that when a channel is asymmetric in cross-section, the highest velocity is over to one side.

1
0.8
0.6
0.4
0.2

1
0.8
0.6
0.4
0.2

0.8
0.6
0.4
0.2

Isovels in m.s^{-1}

Velocity data from Knighton, 1984. Fluvial Forms and processes.

Velocity profiles

Width

Depth

Wetted perimeter (river bed and banks)

Left: A portion of a river channel illustrating the velocity profiles. Notice that the flow rate is lowest near to the 'walls' (shorter arrows) of the channel (the river bed and banks) and fastest at the surface and middle of the channel (longest arrows). This if for an ideal, perfectly straight channel. In reality the highest velocity is somewhere just beneath the water's surface, and to one side of the centre-line of the channel because of turbulence, channel roughness and asymmetrical cross-profile.

Flow Regimes

If we plot the velocity profile of a river, that is a curve showing how the flow velocity varies with depth (depth = distance below the surface, or we could use height above the river bed) then we get two main types of velocity profile, each corresponding to a different flow regime.

The first type is the laminar flow regime, which is rare in natural rivers, but can occur when the river channel is smooth and straight and maximum flow velocity is low and may occur especially in the lower course of a river. In this case the water flows smoothly in sheets parallel to the river bed. Water at the surface flows faster than water close to the river bed, where flow is slowed by friction with the river bed.

The second type is the turbulent flow regime, which occurs in complex winding channels and in rivers with riffle and pool sequences and especially in fast flowing water. This is the most common type of flow. The water no longer flows in calm sheets, but swirls about in chaotic eddies that are unpredictable. Again flow velocity is fastest at the surface of the water and slows toward the channel bed.

In both cases flow is fastest on the water's surface and in the middle of the channel, equidistant from either bank. In most real rivers, secondary flow vortices that form at meanders affect these velocity distributions, such that maximum flow velocity occurs a short depth below the water's surface rather than at the surface.
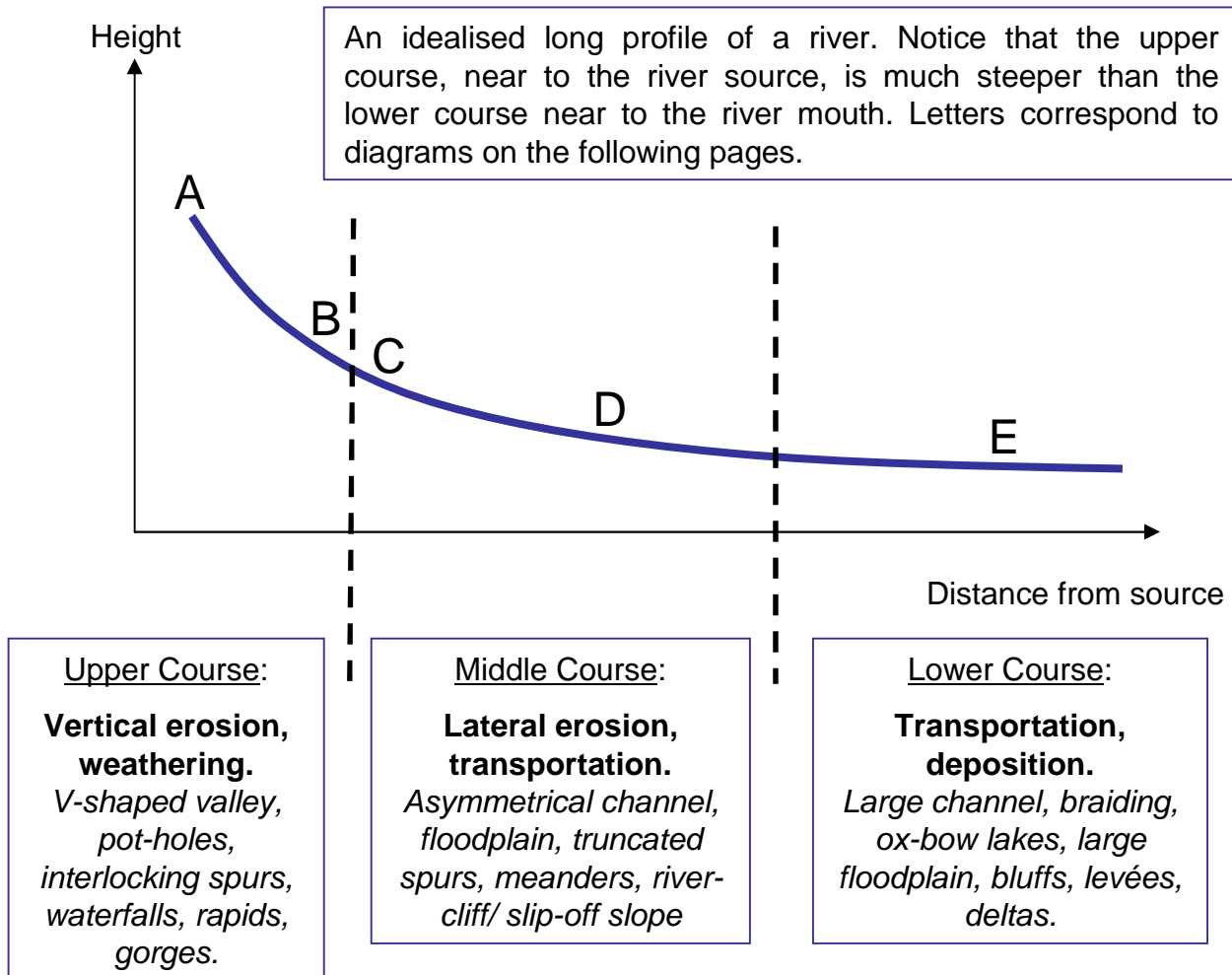
Laminar Flow

Depth

Flow Velocity

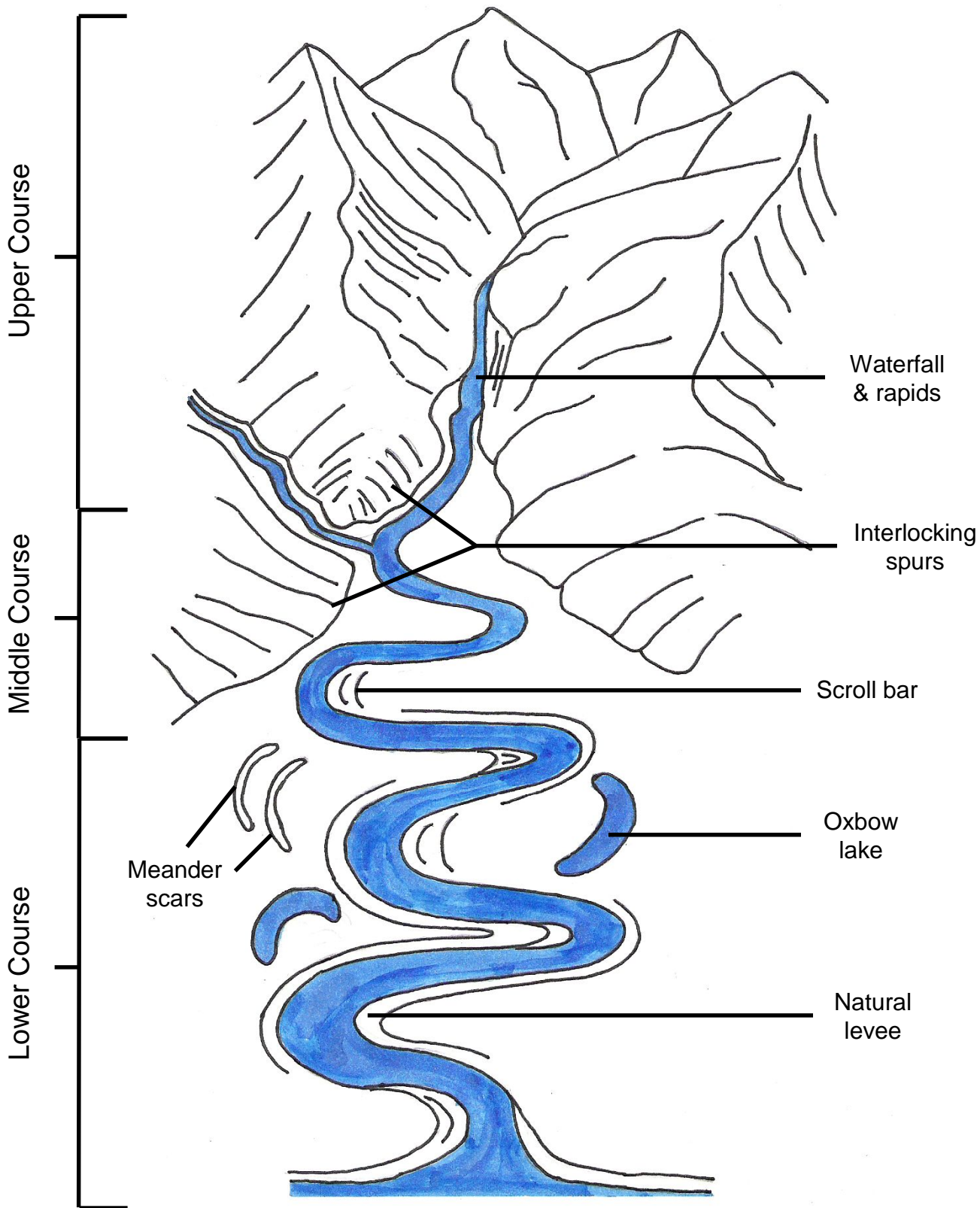## Turbulent Flow

Depth

Flow Velocity
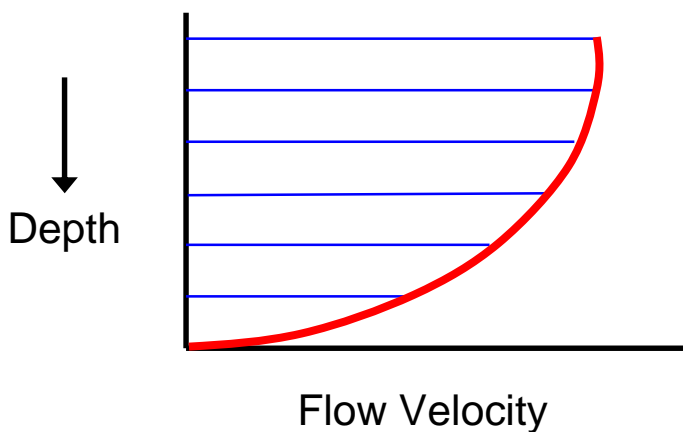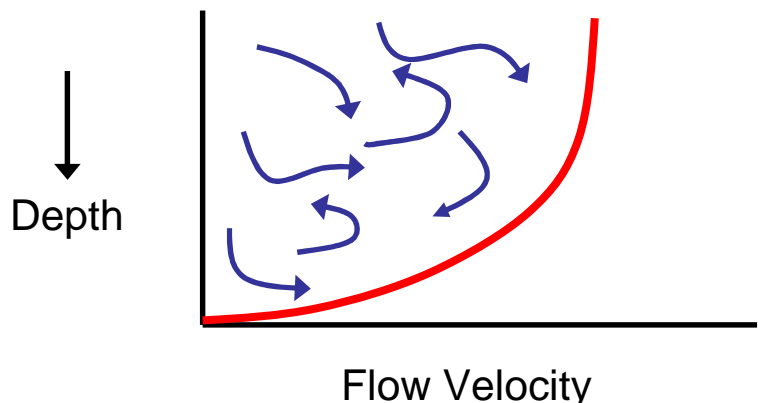
Long Profile of a River

As well as thinking of a river in cross-section, we can think of it lengthwise from source to mouth and plot the height of the river bed against distance from the river source. Fig () below illustrates a typical river long profile and the features most commonly associated with each part of the profile. **River processes** are shown in bold, *landforms* produced by river processes in italics. (See also p. 22 of BP).

Height

An idealised long profile of a river. Notice that the upper course, near to the river source, is much steeper than the lower course near to the river mouth. Letters correspond to diagrams on the following pages.

A

B

C

D

E

Distance from source

Upper Course:	Middle Course:	Lower Course:
Vertical erosion, weathering. *V-shaped valley, pot-holes, interlocking spurs, waterfalls, rapids, gorges.*	**Lateral erosion, transportation.** *Asymmetrical channel, floodplain, truncated spurs, meanders, river-cliff/ slip-off slope*	**Transportation, deposition.** *Large channel, braiding, ox-bow lakes, large floodplain, bluffs, levées, deltas.*

Energy changes along a river profile. Water can possess potential energy, thermal energy and heat energy. Potential energy is energy that some object, in this case water, possesses due to its position. If you lift up a ball and drop it then it falls to the ground under gravity. It starts to move (it accelerates at a constant rate) and gains kinetic energy. Now, since energy is conserved (can not be created or destroyed, at least as far as we are concerned) that kinetic energy must have come from another source of energy. We say that before it was dropped the ball had potential energy (specifically potential gravitational energy), which you actually gave to the ball by using the energy in your muscles to lift it up. The higher an object is, the more potential energy it has and so the faster it will be moving when it hits the ground. As it travels through the air, some of its kinetic energy will turn into heat energy due to friction with the air. When it hits the ground all of its remaining kinetic energy will turn into sound and heat energy. Likewise water at the source has potential energy, but this is turned into kinetic energy as the water flows downhill and into heat energy (due to friction with the channel banks and river bed) and also sound energy (the sound of turbulent water).

Stages of a river course

Upper Course

Middle Course

Lower Course

Waterfall & rapids

Interlocking spurs

Scroll bar

Oxbow lake

Natural levee

Meander scars

Upper Course landforms

V-shaped valleys

In the upper course vertical erosion dominates as the stream cuts down. Weathering and erosion on the valley sides removes material which may eventually end up in the river. These are so-called slope processes, and include mass movements such as rock slides for example. A mass movement is any movement which involves the movement of a large quantity of material in bulk, such as a mudslide. As material moves into the river, it will eventually be eroded and transported downstream. If this material is removed faster than it enters the river, then a steeper valley results.

Three main factors affect the steepness of the V-shaped valley:

Climate affects the steepness of this valley: If there is more precipitation, then weathering of the valley sides may increase, but so will the discharge and the eroding and transporting powers of the river. Material may move into the river more quickly but it will be eroded and transported away more quickly. Dramatic changes in temperature may also cause rock to fracture, since the rock expands when hot and shrinks when cold. Frost can also break-open rocks as ice grows into the cracks and pushes them apart.

Rock type and rock structure also affect the valley steepness. Hard rocks that resist weathering and mass movement often produce very steep gorges, since the rock face can support itself in the vertical or near-vertical position without collapsing. Hard rocks may have fractures or cracks in them, which makes them more erodable by the formation of ice, for example.

Vegetation: plant roots help to hold the surface soil together, and also protect it from rainsplash, and so reduce slope erosion.

Interlocking spurs: In the upper course, streams are rarely straight, but wind in and out of interlocking spurs of more resistant rock, and so the stream is also eroding laterally, though downward erosion generally dominates along the upper course. A spur is the foot of a mountain or slope.

Vertical Erosion (down-cutting)

Vertical erosion deepens the river bed, causing the river bed to lower. This process is particularly obvious in the upper stage of the river as it cuts down through the highlands near to the river source. Highlands are made of hard rock and so the dominant process in vertical erosion is corrasion. The particles carried by the river abrade the stone and wear it down. Large particles (stones etc.) abrade the river bed to form potholes which can lower a river bed fairly quickly. The sides of the channel erode more slowly. The resulting river channel is a narrow, deep gorge.

Pothole: Potholes develop in the depressions of rocky channels. These depressions trap boulders and pebbles which get swirled around by eddies and drill down into the river bed. This drilling of potholes is one of the most powerful mechanisms of vertical erosion. As the holes deepen, the water plunges in and keeps the stones spiraling and drilling. As the boulders wear away and are swept out as finer material, new boulders take their place and carry on drilling. Potholes may join together to greatly deepen a river channel. In front of a waterfall very large potholes may develop in the floor of the plunge pool.

Eddie: a rotating current of water. Eddies develop in fast-flowing turbulent water.
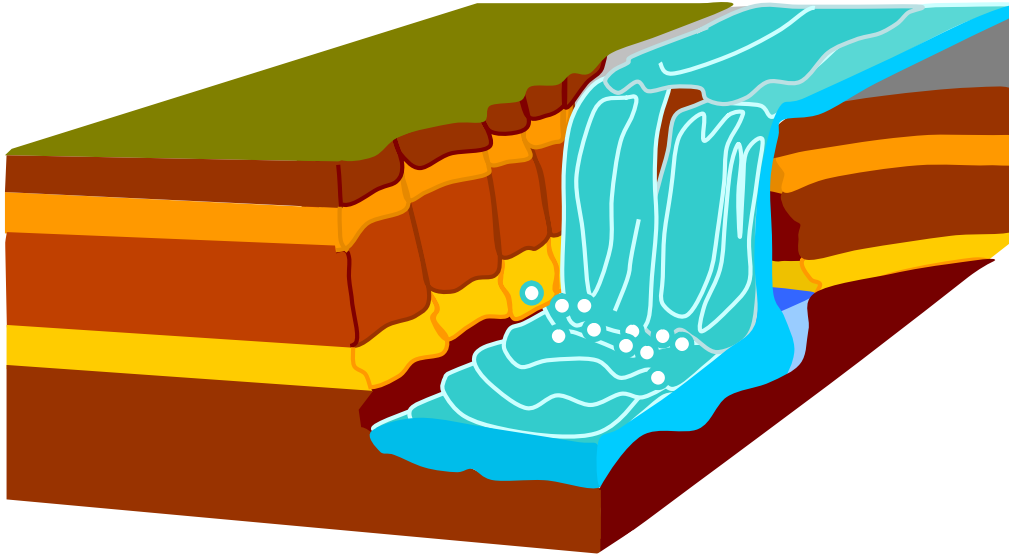
Waterfall: waterfalls occur wherever the long profile is steep. This is usually where an outcrop of hard resistant rock, called the cap rock, is underlain downstream by weaker rock, the weaker rock is rapidly worn away and the resistant rock is undercut. If the face of the resistant rock becomes vertical then the river plunges over it as a waterfall.

As the river flows along, it passes over different kinds of rocks underneath it. Some of these rocks are hard and do not erode easily, while other rocks are soft and erode very easily. The water starts to erode or wear away the soft rock. Over thousands of years, the soft rock is eroded and the river begins to cut down vertically into this rock. This makes a cliff over which the water can topple. Over time, the cliff becomes steeper and deeper and a waterfall is formed. At the bottom of the waterfall a plunge pool is created by erosion due mostly to the hydraulic action of the water.. Some of the water splashes onto the cliff as splashback which erodes and undercuts the softer rock and widens the plunge pool. Continued undercutting causes the cap-rock to collapse periodically and the waterfall retreats upstream in a process of headward erosion and a gorge of recession is formed. The fallen blocks of hard rock may contribute to the formation of potholes in the plunge pool, with the help of the strong eddies that form beneath waterfalls.
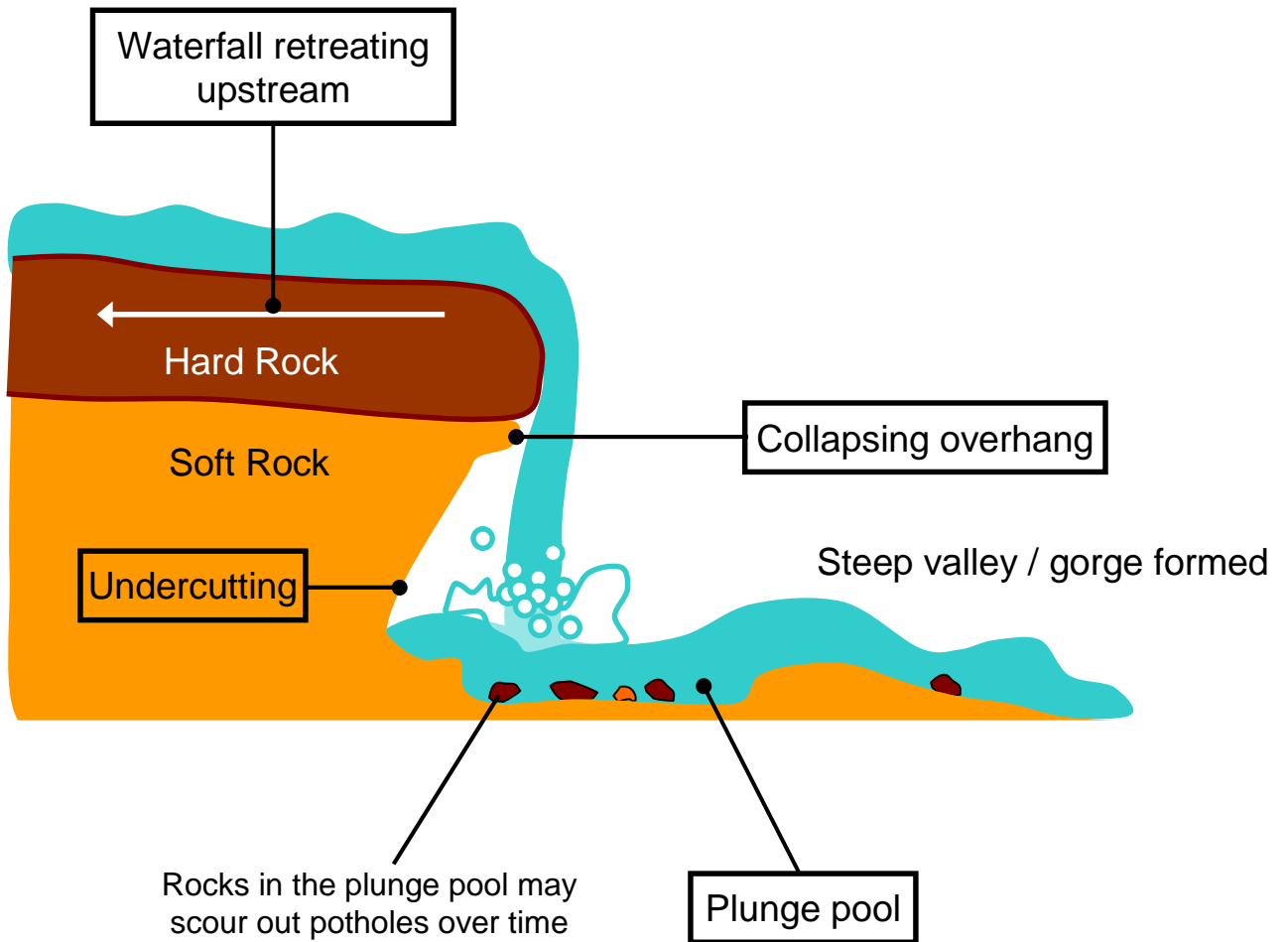
Sometimes a waterfall will appear when an earthquake suddenly steepens the long profile or causes land to heave up or down at a fault. Other waterfalls are created by hanging valleys caused by past glaciation, but you need not worry about these until module 4 of A2!

The river channel does not stay steep enough for waterfalls to form for ever! Eventually the river erodes downwards and the long profile becomes less steep and waterfalls turn into rapids and the rapids eventually become calmer.

The Niagara Falls were created at the end of the Ice Age about 10 000 years ago and has retreated about 10 km since then and will disappear in about 25 000 years time.

The dynamic features of a waterfall

Waterfall retreating upstream

Hard Rock

Soft Rock

Undercutting

Collapsing overhang

Steep valley / gorge formed

Rocks in the plunge pool may scour out potholes over time

Plunge pool

Some links to more nice pictures of potholes!

http://vinyl2.sentex.ca/~tcc/TMI/tmiph.html

Internet Exercise.

The tallest waterfalls in the World are the Angel Falls, in Venezuela, at about 980m. Go to WWW.Google.com and click on "Images" and type in "Angel Falls" and have a look at some of the photos. The second tallest waterfalls in the World, are the Tugela falls. Do a "Web" search on Google to find out where these falls are and how tall they are. Also perform an image search to see some photos. Do the same for the Niagara falls and the Victoria Falls.

The Hardraw Force is the tallest unbroken waterfall in Britain (near to the village of Hardraw in Wensleydale) and is about 30m tall. Have a look at some photos of these waterfalls too. Can you find a picture showing the waterfall frozen in winter?