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INTRODUCTION

At any one site it is helpful to think of interpreting the evidence preserved in the rocks as a recurring pattern of events, often referred to as the rock cycle. These events are:

a) **Transport and deposition** of fragments, forming sedimentary rocks;
b) **Deformation** (including folding, faulting, intrusion by igneous rocks or metamorphism); and
c) **Uplift, weathering and erosion**, leading to deposition of sedimentary rocks at the beginning of the next cycle.

The evidence for the events in The Rock Cycle can be "read" from the rocks in any exposure. However, some parts of the story are always missing, because geological evidence has many "gaps" in it caused by a combination of sediments never having been deposited and preserved in the first place, loss by erosion, and the fact that much is still buried and unknown. This means it is important to remember that the "story" at any one site is but fragments of a single Earth Science story that has an invisible "prologue" and "epilogue" each millions of years long, but for which we cannot see the evidence at any one site, because it is not available to us. This is the story from the Mosedale sites and the evidence for two Rock Cycles, with the evidence for any intervening ones having been eroded away.

The First Rock Cycle.

a) Transport and Deposition:

The oldest rocks encountered in this itinerary are of Ordovician age, deposited about 470 million years ago. These rocks, now slates, were originally mudstones and fine sandstones and were deposited in a marine environment. The evidence for this is that they contain rare graptolites, (*Didymograptus diflexus)* an extinct form of marine plankton. These fossils also allow us to be sure of the relative age of these rocks since these particular fossil graptolites are characteristically Ordovician in age. The fine grained nature of these beds indicate quiet water conditions, deep enough to be below wave depth.

Plate tectonic reconstructions for the time suggest that this part of what is now the British Isles had recently rifted from Gondwana (formerly called Gondwanaland) and was still in the southern hemisphere.

On top of these black mudstones, but not encountered in this itinerary, are a thickness of lavas (andesite and rhyolite) and tuffs, which indicate a period of violent volcanic activity related, according to Plate Tectonics Theory, to a destructive plate boundary, which, in this area, was then followed by an ancient period of deformation (fold mountain building).

b) Deformation: Folding Metamorphism and Igneous Intrusion.

The deformation of these beds was complex, involving at least five separate events. The effects of this major period of deformation resulted in the heating and melting of a large volume of lithosphere to form igneous and metamorphic rocks which now crop out across the Lake District, Wales and southern Scotland. The amount of energy required to achieve this indicates a period of fold mountain activity associated with the closing of an ocean along a destructive plate boundary. This fold mountain belt would have been the equivalent of the present day Alps in length and height.

Here, at Mosedale, we will simplify things and treat the deformation as one event which occurred over a long period of time. The beds, now exposed at School House Quarry were originally black muds. They have been heated and compressed so that they became metamorphosed to slate with a strong cleavage that is almost parallel to the bedding planes.

This cleavage trends almost east – west (270° north) and formed at right angles to the pressure which caused it, suggesting compression in an almost north-south direction, resulting in the beds being tilted steeply to the south-south-west. In this area there is an anticline to the north, and a syncline to the south, both with trends almost east-west. (NOTE: In fact evidence from the folds in much of the rest of the Lake District suggest it was closer to compression in a South-east to North-west direction.)

Dykes of a basic igneous rock (dolerite) were then intruded along planes of weaknesses almost parallel to the cleavage and bedding. (NOTE: technically sheets of igneous rock parallel to the bedding are called sills, however, near vertical sheets are often referred to as dykes whether they cut the bedding planes or not.) Sometime afterwards quartz veins were emplaced in cooling joints cutting both the slates and the dolerite dykes.

The beds have then been flexed (as a result of thrust faulting) into small folds which are visible in the face at School House Quarry, and affect both the cleavage and the dyke, i.e. are later than both the cleavage and the dyke (**Principle of Cross Cutting Relationships**).

Slightly further north are larger intrusions of gabbro (a coarse grained igneous rock made of black and white minerals which crystallised from a magma, probably formed by melting of the upper mantle) dated by radio metric methods at 468 million years old, and a granophyre (a coarse grained igneous rock which weathers pink) dated at 421 million years.
NOTE: The Skiddaw granite which outcrops nearby to the west, but not seen on this visit, is dated at 395 million years old. Granite magmas are formed by the melting of rocks in the lithosphere and have more silica (quartz) in them than gabbroic magmas.

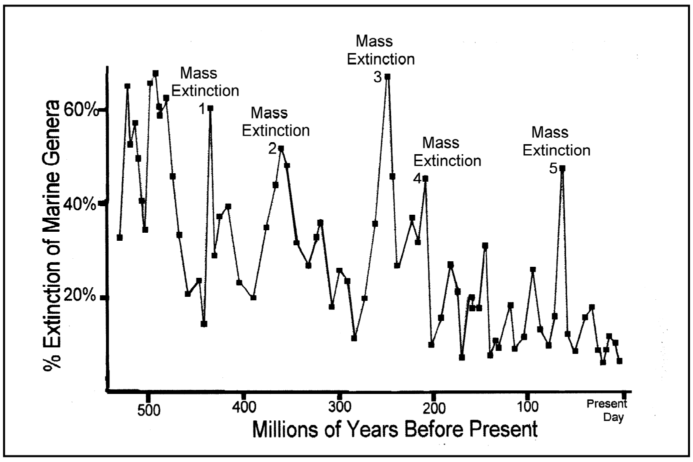
Mineral veins associated with these separate intrusions, contain sulphide minerals of lead, iron, copper, zinc and arsenic. They have been mined all around Carrock Fell. Entrances to the mines at Carrock End are visible when following this itinerary, but these workings are now disused and dangerous.

a) Uplift, Weathering and Erosion, and Mass Extinctions.

Uplift of these Ordovician rocks into a fold mountain belt resulted in them being (chemically and physically) weathered and eroded. By around 345 million years ago, these mountains in our area had been reduced to sea level, and become flooded by the sea, allowing the next layers of rock to be deposited. However, in the intervening 80 million years large changes appear to have occurred in the flora and fauna of the planet.

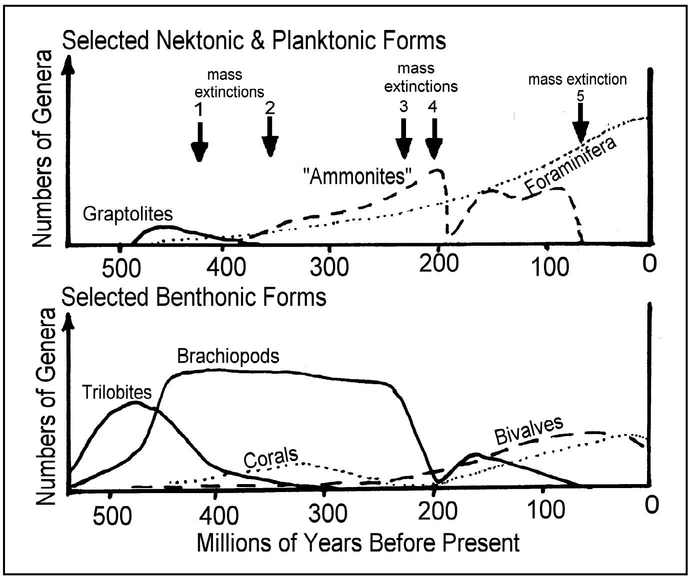
Mass extinction.

There are five recognised mass extinctions in the fossil record since the beginning of the Palaeozoic. This does not include the sixth mass extinction that some scientists think is currently being caused by human activity, and which could prompt useful discussion with groups. (See **Figure 1.**)



After the deposition of the Ordovician shales (now slates with graptolite fauna) mass extinctions 1 and 2 occurred before the deposition of the next rocks on our itinerary, which are the Carboniferous limestones. As a result, the fossils found before and after this period form very different collections of species. (See **Figure 2** for examples)

Figure 1. The occurrence of mass extinctions during the last 500 million years.



By the Carboniferous some genera and groups are gone forever, and new ones are present. For example: graptolites, common in the early Palaeozoic (old life), are gone; corals become common and brachiopods remain abundant, although there are many new species. "Ammonites" including straight forms as well as the more common coiled ones, become common.

Figure 2. Examples of changes in fossil genera over the last 500 Ma.

Characteristic Mesozoic (middle life) forms, popularly associated with dinosaurs and large marine reptiles, occur in even younger rocks (not seen in this itinerary) as a result of mass extinctions 3, 4 and subsequent evolution.

Mass extinction 5 is the one popularised as ending the reign of the dinosaurs at the end of the Cretaceous and may have been the result of a bolide (asteroid) collision at Chicxulub at Yucatan, South America. The following evolution of new species resulted in a further change in life on Earth to the animals we know today, including Homo sapiens. This is called the Cenozoic (seen life) and these changes in fossilised life allow us to broadly identify the relative age of the rocks by the fossils they contain (**Principle of Rocks Identified by their Contained Fossils)**.

Interestingly the numbers of foraminifera, which are marine planktonic (floating) organisms with a mode of life similar to graptolites, continue their steady increase of numbers through all five periods of mass extinctions that have been recognised in the fossil record of the last 500 million years.

An important feature of this evidence is that species with very similar habitats show very different responses during these periods of mass extinction. Theories about the possible explanations for mass extinctions has included: planetary collision with an asteroid; reduction of marine shallow water habitats due to continental collision; sudden increases in volcanic activity changing the opacity of the atmosphere and reducing sunlight (and photosynthesis.); increased predation, or competition from other newly evolved species.

Time of Mass Extinction (approx)	% Loss Of Species	Suggestions on Possible / Likely Cause
440 million years ago	-50%	May be linked to changes due to glacial conditions in the southern hemisphere, for which there is good evidence.
380 million years ago	-50%	The decline spreads over a large period and may be linked to drop in sea level reducing circulation and oxygen content.
260 million years ago	-80% to -90%	This huge loss of life, linked in time to massive volcanic eruptions in India which may have blocked out sunlight.
200 million years ago	-50%	Impact by asteroid has been suggested, but the evidence for changes in sea level reducing circulation and oxygen content is perhaps more convincing.
65 million years ago	-50%	Very strong evidence for an impact crater at Chicxulub, Yucatan and related rock deposits around the Caribbean. There were also volcanic eruptions at this time

Table 1. Summary of mass extinctions.

The Second Rock Cycle.

b) Transport and Deposition.

Physical weathering of these fold mountain ranges of Ordovician sedimentary rocks and igneous intrusions would have produced fragments which would have been washed down slopes by rivers and into seas to form new sedimentary rocks in the next rock cycle e.g. sandstones.

Chemical weathering of minerals in the igneous rocks would have released soluble weathering products, transported in solution by rivers to the ocean waters. These weathering products would form sedimentary rocks in the next rock cycle as a result of biological activity e.g. marine animals creating shells, or, in certain special circumstances, not seen here, the evaporation of seawater to precipitate calcite (and other minerals).

During the Carboniferous period, about 345 million years ago, our area was eroded down to sea level, and flooded by a sea which deposited limestones. These Carboniferous rocks can be seen in "The Howk" gorge at Caldbeck in this itinerary. These rocks are made up of fine grained calcium carbonate and the skeletons of Palaeozoic marine animals, like brachiopods, corals and algae amongst others. By analogy with similar modern animals (**Principle Of Uniformitarianism**) it is thought that the presence of this fauna indicates a warm, clear shallow sea environment with very little sand or mud being washed in. Plate tectonic reconstructions suggest this piece of crust had moved much closer to the equator by Carboniferous times.

The **calcium** component of calcite ($CaCO_3$) arrived in the sea water as a result of chemical weathering of rocks on land, being transported as ions in solution by rivers. The **carbonate** component arrived partly by the same process in the form of hydrogen carbonate ions and partly by direct solution of carbon dioxide in the sea. Marine animals, like corals and brachiopods, used the material in solution to make their shells. The presence of these fossilised animals indicate that the sea was warm, and of normal salinity and well oxygenated, suggesting that the area was close to the Equator at this time. After the animals died, their shells became buried in the fine grained calcite "mud" (i.e. calcite, not clay mud) to form the fine grained limestone.

e) Deformation: Folding and Faulting.

Elsewhere these beds have been folded and faulted, but here these limestone beds have been uplifted, but not tilted very much during this second period of deformation which occurred about 300 million years ago.
There is evidence from other sites that there have been more rock cycles following this one, but there is no evidence here for them.

f) Uplift, Weathering and Erosion.

Uplift of these beds has exposed them, and the underlying slates and igneous rocks, to weathering and erosion which has continued to the present day. Over the last two million years or so these rocks have been affected by periods of glaciation during the Quaternary Period when ice erosion, physical weathering and frost shattering were more powerful processes than seen in Cumbria today. At its height, ice flowed over the top of Carrock Fell, indicating that the ice in the valley was probably 1,500 metres thick. Towards the end of the glacial episode the ice would not only retreat, but would also get thinner. The last ice in the valley would be an immobile mass of ice and rock, slowly melting away, leaving the rock in hummocks and layers across the valley floor, washed over by melt-water.

Melt water running across the glacier surface, through the crevasses in the ice and out across the moraine on the valley bottom, would transport and deposit fragments in beds, sorting them and rounding them in the process. After the ice had gone the climate would still be very cold, and freeze thaw (physical weathering) would be much more common than today on the exposed steep crags in the valley. The large stones lying across the valley floor north of Stone Ends will include glacial erratics, some from the central Lakes area, whilst others might be post glacial fallen blocks, physically weathered from the cliffs.

These processes of physical weathering produced many angular fragments, some quite large and moved by glaciers, or, after the ice melted, moved by gravity to form screes. This set of events has led to deposition of gravels and moraine (formerly called boulder clay) across the area, and screes at the valley sides. (See the final section below for more details on valley train deposits.)

More recently river erosion has cut valleys and gorges, e.g. "The Howk" and has exposed the limestones to chemical weathering, the evidence for which is seen in the river bed upstream of "The Howk", where limestone joints have been widened by solution. Chemical weathering of the limestones produces calcium bicarbonate in solution, which is taken by rivers to the sea to be part of the next cycle. This material, along with sand and pebbles, is now being moved to the Caldew and Eden rivers, and the sea, through the Solway Firth.

A Brief Summary Of Valley Train Deposits.

During the last 2 million years as climates cooled and ice accumulated leading to a stadial (or "cold period"), glaciers formed and flowed along pre-glacial river valleys. Often, as in Mosedale, the ice cut valleys along the line of faults where the rocks were broken and more easily weathered and eroded. The glaciers flowed away from the maximum ice pressure, which in this case was in the central Lake District further south. As a result ice flowed northwards through Mosedale, bringing rocks fragments (erratics) from further south, which are now used to confirm the direction of movement.

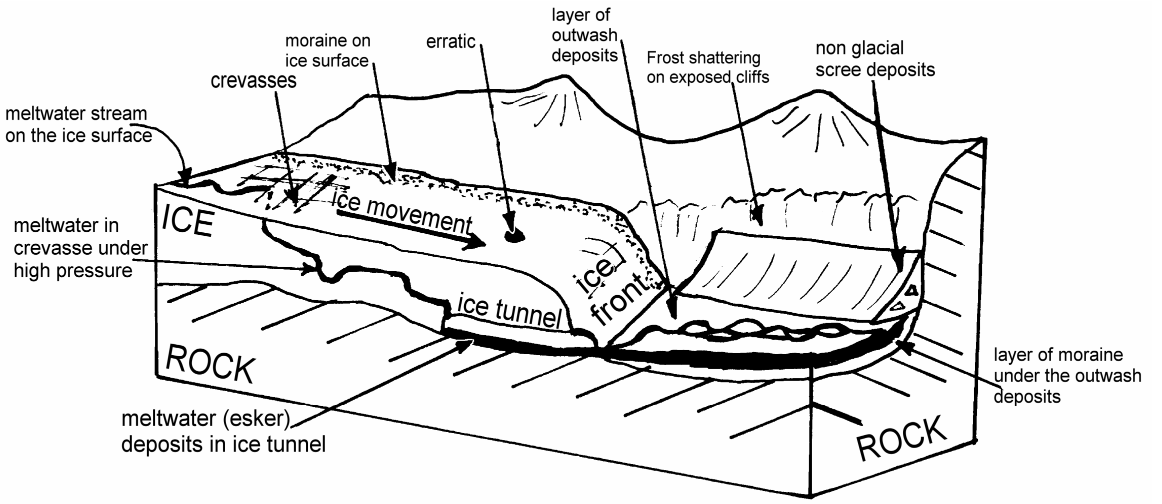


Figure 3. Valley Train Deposits

A glacier flowing along a valley carries with it a large amount of rock debris plucked and ground from the valley floors and sides. This material is called **moraine** and is carried on the top, inside and at the bottom of the ice.

When the ice melts at the end of the glacier this moraine is deposited as an unsorted (i.e. composed of a wide variety of sizes) material called **moraine**. It contains all grain sizes from ground-up rock and clay to large boulders. If the ice front is stationary this till is deposited as a ridge of unsorted material parallel to the edge of the ice, called **terminal moraine**. If the ice front is retreating back along the valley, however, it is deposited as an uneven layer of unsorted clays, cobbles and boulders, called **ground moraine**.
Large boulders may be carried long distances, even uphill, by the ice and left as **erratic boulders**, lying on top of rock types which are different (hence, the name “erratic”).

The breaking of fragments from the main outcrop is, by definition, called physical weathering. In glacial and peri-glacial conditions this is often done by freeze thaw to form screes, or glacial plucking of pieces frozen into the base of the moving ice to form moraine. In both cases the corners will be very angular, usually guided by the planes of weakness (joints and bedding) in the original rock. These very angular edges may become very slightly “rounded” and described as sub angular by being rolled on scree slopes, or by the effect of weathering attacking the thin edges of the sharp corner. (See **Figure 5.**)

For a pebble to become rounded and well rounded, however, requires a prolonged period of being trundled along by water action, by rivers (or waves). During this time the abrasion caused by the rolling effect can produce very well rounded corners, and are indicative of water borne deposits. This can be helpful, especially in glacial valley deposits where some fragments started off as scree or moraine, and later were picked up and moved by meltwater rivers. Many large sub angular boulders in present day streams are probably washed from the moraine and have hardly been moved by the rivers at all, as they are not powerful enough to transport them. Meanwhile, the smaller cobbles and pebbles have become sub rounded or rounded. (See **Figure 5** and **Table 2** below.)

Deposits made of large and well rounded fragments suggest that very powerful currents of water were involved in their transportation and deposition. In a glacier this may occur when meltwater flowing over the ice surface plunges into, and completely fills, a series of cracks in the ice leading from the glacier surface down towards the ice front. This can create a powerful water current with several tens of metres of head behind it. These meltwater streams flowing under pressure can transport large amounts of very large fragments which can become rapidly deposited as the pressure drops and the current slows down. This can happen close to the ice front in an ice tunnel. As the glacier retreats the ice melts away, the sides of this deposit collapse leaving ridges of very coarse deposits of well rounded fragments, often far away from present day river channels. These ridges are called eskers. (See **Figure 4.**)

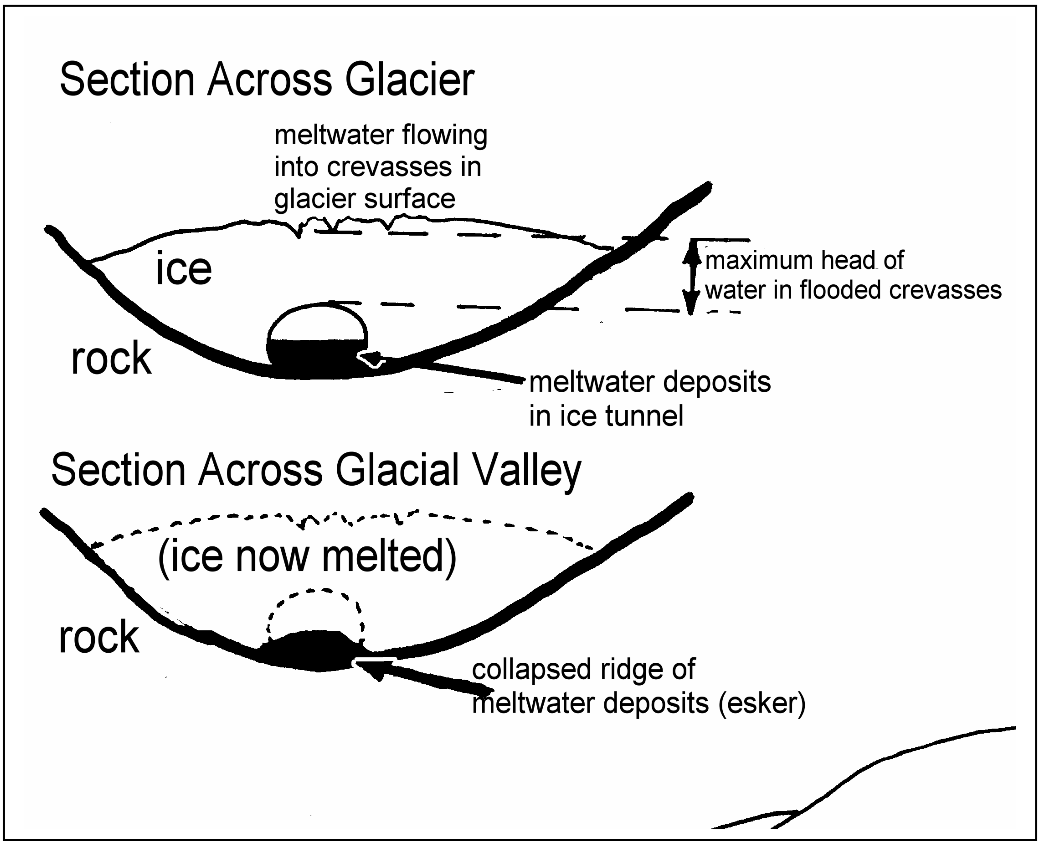


Figure 4. Formation of eskers.

After the ice has melted away the area is affected by peri-glacial conditions, when freeze thaw attacks the exposed rocks. At this time large boulders can be weathered from the steep cliffs along the valley sides and fall onto the **screes** below. Visually these blocks can look very like erratics, and may only be distinguished by a close examination of their rock type.

When more temperate climates become established, rivers begin to flow over the hummocky terrain and find their way to the sea. Often these rivers show peculiarities, such as the two rivers in Mosedale which flow in opposite directions: for example, the Glenderamackin flows south, whilst the River Caldew flows north.

Valley train deposits, then, are a complex mix of glacial, outwash and periglacial deposits, however, it is often fairly easy to sort out which is which:
Glacial till is unsorted, angular material which may be in layers and ridges. Some of the boulders may have been brought a long distance and be different from the local rocks;
Outwash deposits are sorted and layered, and the fragments are usually rounded by transport in the water. They may be in layers, or in ridges, called eskers.
Scree deposits are mainly made up of angular boulders from the cliffs above, and are found at the foot of cliffs, or rolled a little way away from them.
Modern river deposits are closely associated with the channels in which they are temporarily deposited and may well include sediment washed from any of the other sources.

Rounded and Angular Fragments.
The feature of rounding and angularity of a pebble can be helpful when trying to separate different kinds of valley train deposits. The term “rounding” of material refers to the sharpness (or bluntness) of the corners. Fragments with corners which have large radius curvature are well rounded. Angular fragments have sharp corners which have not been rounded off by long periods of transport. In areas of valley train deposits the angularity of the corners of a pebble is a useful piece of information about its history: the further along the scale towards 6, the more likely the pebble has spent a significant time transported by water, usually rolled along the stream bed as traction load.

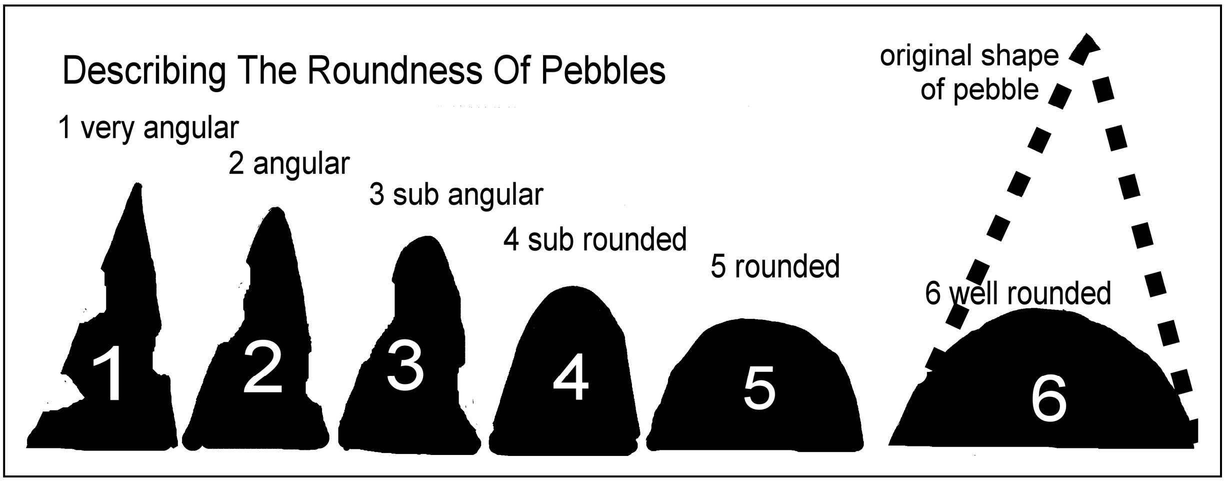


Figure 5. Describing the roundness / angularity of pebbles.

Sorted deposits.

The density of most common rocks at the earth's surface is close to 2.8 grams per cubic centimetre. The energy needed to transport a single rock fragment larger than sand size, therefore, often varies with the size of the fragment. Clearly, as a fast flowing current slows down, it passes through a series of threshold velocities which allow decreasing sizes of fragments to be deposited. (See **Table 2** below.) The sizes of these fragments, therefore, are evidence of the speed of flow in the past; **The Principle Of Uniformitarianism**. It is for this reason that many water-lain deposits are well sorted by size, since similar size (weight) fragments are deposited together, often in layers, as the current slows down to a particular threshold velocity.
[NOTE: the velocity required to erode (pick up and move) the same pebble from rest is slightly higher, as the flow of water has to overcome the inertia of the fragment and the frictional drag.]

Empirical studies have established the relationship between current strength and the velocity needed to deposit different sized fragments. Using the **Principle Of Uniformitarianism**, we can suggest these relationships probably hold for ancient deposits, as well as modern ones.

Name of Fragment	Diameter of Fragment in mm.	Approximate Minimum Flow Velocity to Deposit this Sized Fragment
COBBLE	Over 100 mm	400 cm per second (extremely high shooting flow)
COBBLE	Over 64mm	300 cm per second. (extremely high flow)
PEBBLE	4mm to 64 mm	100 cm per second (very strong flow)
GRAVEL	2mm to 4 mm	60cm per second (fast flowing stream)
COARSE SAND	2mm to 0.5 mm	12 to 15 cm per second (more normal stream flow)

Table 2. Depositional threshold velocities for coarse grained fragments in water.

Some of the well rounded fragments in the Long Hill Esker deposits are much larger than 100 mm, and suggest velocities in excess of 400 cm per second.

EARTH SCIENCE PRINCIPLES
In this area it is possible to demonstrate the following Earth Science principles.

1) **The Principle of Uniformitarianism:** The biological, physical and chemical processes we see today, operated in much the same way in the past. "The present is the key to the past."

2) **The Principle of Original Horizontality**: bedding planes represent the original horizontal at the time of deposition of sedimentary rocks. Their current angle shows the accumulated amount of distortion caused by earth movements since deposition. An exception to this principle is the underwater scree slopes at this locality which were deposited at a steep angle.

3) **The Principle of Lateral Continuity of Beds**: this states that sedimentary layers extend in three dimensions and might therefore be found elsewhere.

4) **The Principle of Superposition**: in a bedded sequence of strata, the oldest layers were deposited first, and are found below the younger layers, which were deposited later.

5) **The Principle of Rocks Identified by the Fossils they Contain**: this states that, because animal species have evolved and changed over time, that any sedimentary rock containing fossils, must have been formed at the time those animals existed on earth. (Unless those fossils are in pebbles worn from older rocks and cemented into much younger ones. It does happen – but not on this visit).

6) **The Principle of Cross-Cutting Relationships:** Structures, like faults and joints, which cut through rocks must be later, and therefore, younger than the structures they cross cut. They must also be older than the ones that cut across them.