INVESTIGATING WALL STONE (2)

Explaining why geological process creates variation

ABSTRACT

There are many subtle differences to be observed in the stones which make up Hadrian's Wall, but what caused that variation? In this guide the geological processes that cause this variation are explored.

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Differentiating Wall Stones

The overall aim of the Hadrian's Wall, Stone Sourcing and Dispersal project is to be able to categorise Wall-stones such that it is possible to work out where they were quarried from and to be able to identify them in post-Roman buildings. This is a big challenge as the Wall is almost entirely made of sandstone, and sandstones are not easy to distinguish one from another.

Rocks are made up of a variety of different materials arranged in different patterns. By looking in detail at both the materials and the patterns into which they are organised it is possible to differentiate one rock from another.

If there is any way of distinguishing different sandstones so that it is possible to tell which rock formation they have come from, it will be a consequence of the geological processes which cause variation within different sandstones. As an example, the flow rate in a river depositing sand (later to become a sandstone) controls the size of the sand particles. If the river is flowing fast, then it can pick up larger grains than when flowing more slowly. Flow rate is one of many variables which cause variation in sandstone.

It is possible to collect the data on the Wall sandstones simply by being shown what data to collect and how to do it. The guides on collecting Wall stone data explain this approach. However, for me as a geologist, this would miss out on being able bring this data to life by understanding how these rocks were made, and by using this to explore the ancient environments in which the rocks used to make the Wall were formed.

This introduction provides a sense of how sedimentary rocks form and why these processes are important in creating the observable variation in the rocks which may provide a key to this archaeological problem.

Associated with this guide are a series of guides which describe how it is proposed to collect Wall stone data as well as the most important attributes of sedimentary rocks and how to observe them. These are the observations which will provide the data required for the Stone Sourcing and Dispersal project. They also form the basis for studying and understanding the pre-history of these rocks, building a picture of what it was like when these rocks were being formed.

Rock Recycling and the Sedimentary Lifecycle

Rock gets recycled on planet Earth. Rock gets recycled in different ways and it is hit and miss as to what is recycled; some rocks remain more or less untouched for billions of years whilst others are made into new rock in less than 100 million years. There are two main mechanisms for this: ***tectonic*** and ***sedimentary***.

Tectonics, the turnover of the Earth's mantle and associated movement of the rigid crustal plates recycle rocks through subduction and mountain building, metamorphism and melting. Its work happens underground. One of the consequences of this tectonic turnover, is the continual refreshing of the earth's topography. As part of this process, mountains are made from which sediments are created, and basins are formed into which sediments may be deposited. In this way tectonics provide the setting in which the sedimentary lifecycle operates.

The ***sedimentary*** lifecycle provides a whole network of intertwining pathways at the earth's surface by which rock of all types are broken down, transported, and deposited to form new sedimentary rock. The sedimentary lifecycle is what will be described in the following sections

Geological Provenance

The processes which create a sedimentary rock occur in the journey from its source to the location where it is deposited. It is the combination of the diversity of source materials and the processes which act on them which create the diversity of sedimentary rocks which we can now observe. This combination of a rocks' source material and the journey its sedimentary material takes to its depositional site is referred to as its geological provenance. The study of geological provenance for a rock or a suite of rocks, is how geologists reconstruct ancient environments.

Archaeological provenance has a different meaning and it is important to be clear when talking about provenance which of the two meanings are being referred to.

For a Wall stone at Planetrees its geological provenance maybe the Caledonian mountains to the north where a mixture of granite and metamorphic rock is weathered and eroded by ice, bringing this material into rivers flowing out across the Northumberland plain to be laid down in a river-channel deposit. This material may then be exposed on a ridge somewhere near to Written Crag and spotted by a Roman Centurion as a useful source of Wall stone. At this point we move into the domain of history and archaeology. A quarry is made, becoming the source of Wall stone, and stone may be fashioned into blocks on site here and transported by bullock cart down the hill to be incorporated into the Wall.

We have the challenge of trying to understand both the geological and archaeological history of the Wall stones. The more precisely geological provenance can be understood using data about a particular rock formation, the more accurately it is possible to link Wall-stone to particular rock formations and to work out its geographical source as a key part of understanding the stone in archaeological terms.

Understanding the Sedimentary Lifecycle

How can we interpret the ancient environment that a sandstone was formed in?

Charles Lyell, a Victorian geologist and uniformitarian prominent in the history of geological study, wrote “the present is the key to the past”. By this he meant that the processes which operated when rocks are being formed are still operating today. By studying modern glaciers, rivers deserts and seas to understand how they move rock around we can extrapolate this back to ancient environments.

In the next sections we will explore the sedimentary lifecycle that operates around us today. The sedimentary lifecycle is divided into three parts, as many things in geology seem to be. The first part is about where the grains come from, the second describes how the grains are moved around, and lastly explores what the environment is like when the sedimentary particles finally come to rest.

First Make Your Grains

Weathering – the alteration of rock through chemical biological and mechanical action – is the starting point. When rocks are exposed (usually in a cycle of (tectonic) uplift their structure starts to modify and breakdown, in situ. Water, ice, sunlight, lichens, wind and rain are some of the main agents that make this happen.

Weathering processes are broken down into three types:

1. Physical – freezing-thawing, heating-cooling
2. Chemical – with mineral decomposition and dissolution
3. Biological – where plants and occasionally animals physically and chemically interact with the rock

Erosion is the process that wears away and transports rock. It frequently happens alongside weathering as weathered rock is easier to erode. However, weathering doesn’t always have much of a chance, for example in a freshly exposed cliff face, erosion starts immediately with little opportunity for weathering to have an effect.

Erosion happens in several ways:

1. Hydraulic action – for example waves smashing against a cliff, rain falling on rock
2. Abrasion – for example where rock is wind-blasted or water-scoured by grains of sand or where rock surfaces are ground by grit-filled ice.
3. Attrition – where boulders and pebbles bang against each other and knock bits off, in river currents or sea-waves; and finally
4. Solution – where the chemical elements in the rock are dissolved by water.

Figure 1: Wind eroded sandstone in the Peruvian altiplano

Different types of weathering and erosion can produce grains which are visibly different from each other. For example, erosion by sand blasting not only produces some fascinating landforms but also distinctive rock fragments. The combination of attrition and abrasion by the wind produces grains with a distinctive surface texture and which are rounded. These wind-blown grains are commonly described as having a millet seed texture. This is relevant to some of the Permian sandstones in the Hadrian’s Wall area in which these distinctive grains can be observed and which tells us that these sandstones were deposited in desert conditions.

Moving and Sorting

Having looked at the various ways in which a rock can be converted into rock fragments or into chemical components dissolved in water, the next step is to look at how these are moved around.

Transport is intertwined with erosion. As material is moved from its source to its eventual destination to be (re)deposited, chemical and physical breakdown of rock and mineral particles continues.

There are three media in which sedimentary materials are moved around: air, water, and ice and each has a particular effect on the rocks and minerals. Sedimentary material may be transported to their final resting place by one or many of these means and the route which they travel may be long or short. Understanding these processes helps answer the question: what is the effect that different routes and different media have on the sediments we can observe in rocks?

First let's consider the media: what are the effects that ice, water and air have on particles?

Ice is a solid that behaves as a fluid in effect like a high viscosity liquid. Because of this it can carry a very wide range of particle sizes from boulders to fine clay particles. As has already been discussed, icy environments are a primary source of new sedimentary material. The combination of rock fracture as water freezes and grinding of ice over stone surfaces produces fresh particles from large to extremely small. These particles will therefore tend to be angular, particularly if their source is igneous or metamorphic.

Water operates on particles much as a rock tumbler does where harder particles abrade rock as they are tumbled in the water. The longer the particles are tumbled in the water and the higher the energy and agitation of that water the more the particles progressively move from angular towards rounded. Water is (obviously) warmer than ice, this and its innate ability to take minerals into solution make it an effective medium through which chemical breakdown of minerals can be facilitated.

Air is the least viscous of the three media. *Attrition* (collision of particles and rock surfaces) rather than abrasion (rubbing together particles and rock surfaces) is the dominant process. Grains are winnowed and further rounded, to produce distinctive "millet seed" shaped grains. In desert conditions, where wind-blown processes are common, the surface of grains can also be patinated with a thin mineral coating, referred to as desert varnish. In consequence of this wind-blown grains are distinctive even when subsequently reworked in a fluvial environment.

Secondly let us consider the time spent in transport and the durability of the sedimentary material being transported. The more physically and chemically durable a mineral or rock is, the longer it will survive in the slow attrition of sedimentary transport. Quartz is particularly good at lasting the course as it is hard (7 on the Mohs scale) and chemically inert. In comparison to feldspar which is softer (6- 6.5 on the Mohs scale) and less chemically stable breaks down more quickly. By just looking at this pair of minerals it is possible to see an indication of how long the sedimentary material in a rock has been in transit. A high percentage of feldspar suggests little transport, a high percentage of quartz a lot of transport. This is, though, only an indication as the mineral mix being transported will depend on the source rocks(s).

Sediments are referred to as mature when they are mineralogically homogenous, well sorted and with rounded grains (see section on grain size and shape); in other words, they have had a lot of interaction with the transport system. Conversely an immature sediment will be a poorly sorted mix of quartz, clay and other minerals which are angular. These will have only a little interaction with the transport system.

The time spent by sedimentary material in transport can, in general, be related to the distance it has travelled from its source. The terms proximal and distal are used in various geological contexts to identify how far away a rock was from its source of geological action. For example, a lava on the top slope of a volcano may be described as proximal, whereas an ash deposit, tens of kilometres away from that volcano may be described as distal. In general, we may therefore think of an immature sandstone as proximal; deposited close to its source. Conversely a mature sandstone may be thought of as distal; deposited a long way from its source. Some care needs to be given to these relationships as the source of sedimentary material is highly likely to be a collection of different locations.

We can however infer useful idea about a rock's origin with these ideas in mind. For example, the earliest sediments laid down in the Permian in the western part of the Hadrian's Wall area are mixed sandstones and breccias which are angular and poorly sorted. These were laid down at the edge of a newly formed sedimentary basin and have only been transported a short distance from their source on the edge of that basin. As such they may be considered as proximal. In contrast the fluvial (river laid) sandstones of the St Bees Sandstone Formation in the Triassic have sub-sounded grains which are well sorted. These were transported from the south by a large river system (the Budlieghensis River) over many hundreds of kilometres. These sandstones may be considered as distal. It should be noted that these interpretations have been worked out by looking at many rock formations and not just by extrapolation from the observable data on individual rocks.

As a final thought on transport, whilst quartz is pervasive in its occurrence in sandstones it is not the only durable mineral. There are some rare minerals which find their way through weathering, erosion, and transport intact. Diamond and zircon are good examples. Diamonds are unknown in the sandstones (and source rocks) for the Hadrian's Wall area. Zircons, however, are a possible find, though a microscope and thin sections would be required to make the discovery. Zircons would be an exciting find as they have the potential to unlock information about their source (parent) rock including its age.

Depositional Environment - Time to Lie Down!

Eventually mineral and rock grains will come to rest in a place where they become buried and preserved and changed into rock. At some later date, some of these rocks will once more be uplifted and exposed to the cycle of weathering and erosion, as well as to the enquiring eyes of geologists, quarrymen, and archaeologists.

The depositional environment within which its sedimentary material is laid down is the most important factor in controlling what gets laid down and preserved. Working backwards from what we see in a rock will therefore tell us most about what was going on at the time the sediments were being laid down. This is not to say that the other parts of the lifecycle through weathering, erosion and transport do not play their part. Clearly the material which the depositional environment must work with are controlled by these other, earlier, processes.

In the context of the Hadrian's Wall area, there are three major depositional environments to consider. Rivers (fluvial), shallow marine and desert. What happens in each of these environments is controlled by several physical parameters. Here are some of them:

- Media – ice (glacial), water (fluvial, marine, lacustrine), air (aeolian).
- Flow rate, related to energy

- Channel dimensions – depth, width, straight, sinuous etc.
- Flow direction – uni-directional or bi-directional.

The media has a major influence on the make up of the sediments which are deposited. The factors already described in the section on transporting sedimentary material, also apply to the sediments they deposit. Ice-laid deposits can be found covering large areas of the Hadrian's Wall landscape in the form of the, extremely poorly sorted, glacial till. The sandstones used for the Wall are predominantly fluvial and as such have high percentages of quartz grains which tend to be sub-rounded. Within the Permian and Triassic successions in the western part of the region there are many sandstones which are either formed in desert conditions or have wind-blown grains which have been incorporated into fluvial deposits. In both cases the grains are rounded and may be patinated.

The *flow rate,* the amount of energy in the environment, controls the grain size which can be moved and deposited by a given media type. A fast-flowing river can move larger grains than a slow-flowing river. Flow can also have a winnowing effect on sedimentary particles with fine grains being picked up in a slow flowing river, but as the flow rate increases (in consequence of a rain storm perhaps) the river will progressively and selectively pick up larger grains.

Variation in flow rate will be reflected in a variation in the grain-size (shape and mass) being moved and deposited. This is the primary cause of laminations which may be observed in sandstones. A commonly observed variation is one of fine layers rich in mica interleaving quartz rich layers. Here the lighter flakes of mica are deposited when the current wanes, and the quartz grains deposited when the current is stronger.

The *channel dimensions* (and flow rate) control two things, the flow regime, and the shape of the deposits. The flow regime (laminar or turbulent) in turn controls the types of bedforms, particularly ripples, which are formed. Note that the cross-lamination found in rock-outcrops reflects the different types of bedform; by looking at the different types of cross-lamination, the bedforms in an ancient environment can be interpreted. For a given size of channel as the flow rate increases the bedform will change from flat (laminar) to rippled. The size of the ripples and their growth pattern progressively changes as the flow rate continues to increase. At high flow rates the bedform returns once more to being laminar. The shape of deposit formed will vary too. Sand being deposited on a shoreline will be broadly linear, whereas sand being deposited in a meandering stream will have sinuous deposits.

The *flow direction* also has an impact on bedforms. Ripples formed in rivers where flow direction is one-way have characteristically asymmetric ripples. The face of the ripple facing into the current is shallow and that in the lee of the current steeper. Those formed in a tidal environment or where they are created by waves and where the current is bi-directional are symmetrical in form.

It should also be noted that the angle of repose for the leeward, steeper, part of ripples is controlled by various factors including grain shape and grain size. However, the medium in which the ripples are formed has the most significant effect. For wind blow dunes the angle of repose will be about 30-34^{o} and for fluvial deposits it is smaller at 5-10^{o}. Wind blown deposits also tend to have much larger ripples (dunes) that in either rivers or in the sea. As such if you find a sandstone outcrop with cross-lamination of a metre or more in height with an angle of repose of 31^{o} and the sand grains are well sorted and rounded it is highly likely that the rock was deposited in an aeolian environment.

Volcanic Sediments

There is one more important process which creates sedimentary material, and that is volcanic activity. Violent volcanic eruptions produce ash which maybe spread in an exceptionally large radius around the locus of eruption. The ash (tephra) may land on the ground or in water. In either case it may form a layer of sedimentary material which once consolidated is known as a tuff. This is not a route for sandstone formation and no tuffs are used in making Hadrian's Wall. However, these unusual sediments are of interest in two different ways. Firstly, the tuffs are a helpful material to geologists as they can be accurately dated using radiometric methods. For example, some thin layers of volcanic ash are found in the Pennine Coal Measures Formation. This is valuable as it helps solve some difficulties in dating these rocks through more traditional methods. Secondly Romans discovered that tuff deposits, notably from Santorini, when mixed with lime can make a hard cement which will set underwater. It is, therefore, to tuff deposits that the Romans owe their invention of concrete.

Afterwords – turning sediments into stone

Rocks are not just made at one instant of time. Whilst the deposition of sedimentary rocks, and the cooling of igneous rocks defines what those rocks are and gives the recognised age of those rocks, there are processes which continue acting on the rocks after their creation. In some cases, the effects are minor; often they are fundamental to turning the sediments into rock. This afterlife also includes structural changes to the rock sequence (folding and faulting) and their eventual emergence at the surface through uplift and erosion. This latter process is the final set of actions which has shaped the landscape we now see.

Diagenesis and cementation

Sediments are by their nature porous. Water is good at finding its way into things, and groundwater is not static. Water is also good at dissolving a range of different ions, particularly calcium and iron. Groundwater flowing through sediments will precipitate minerals between the sedimentary grains, binding them together and turning them from loose unconsolidated material into rock. The degree to which this happens and the minerals that are precipitated as cement govern the hardness of the sedimentary rocks formed. This explains why some sandstones are more useful as building stones than others.

The precipitation of minerals from the ground water can also lead to some interesting effects from beautiful water marks left by precipitated iron to ball-like concretions found within both sandstones and limestones. Precipitated iron is particularly marked in sandstones close to the highly weathered surface of the Carboniferous sequence onto which Permian sediments were laid down. Movement of ground water near to the surface in hot climates is commonly in a vertical direction and can be extreme. This iron staining is particularly marked in the vertical sandstone joints.

Figure 2: Diagenetic iron markings, St Edwards Bay Tynemouth