

INTRODUCTION

A high proportion of the world's cultural heritage is built of stone, and it is slowly disappearing. Most stones undergo a gradual deterioration although they can also suffer sudden and catastrophic losses.

This may not matter too much if the stone is a part of a massive undecorated wall - but it doesn't need much deterioration of an art work for its meaning to be lost altogether.

If we are to do anything to reduce or prevent this loss, we need to characterize the stone involved.

CHARACTERIZING THE STONE

There are many ways to describe stone – petrologically, geologically, by surface hardness, porosity, capillarity, hygric and thermal expansion, pore size and distribution, mechanical strength, and so on.

And you can image stone with things like scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), X-ray diffraction (XRD), and polarised light micrographs or just with your own eyes.

However, information is only useful when it is linked to how a stone behaves, especially as although some stones are similar in mineralogy, their behaviours often differ.

For example, Istrian limestone, Lecce limestone, and Carrara marble are all calcium carbonate stones but their contrasting modes of deterioration depend more on the differences in their porosity, pore shape, pore size distribution, and grain size than there chemical similarity.

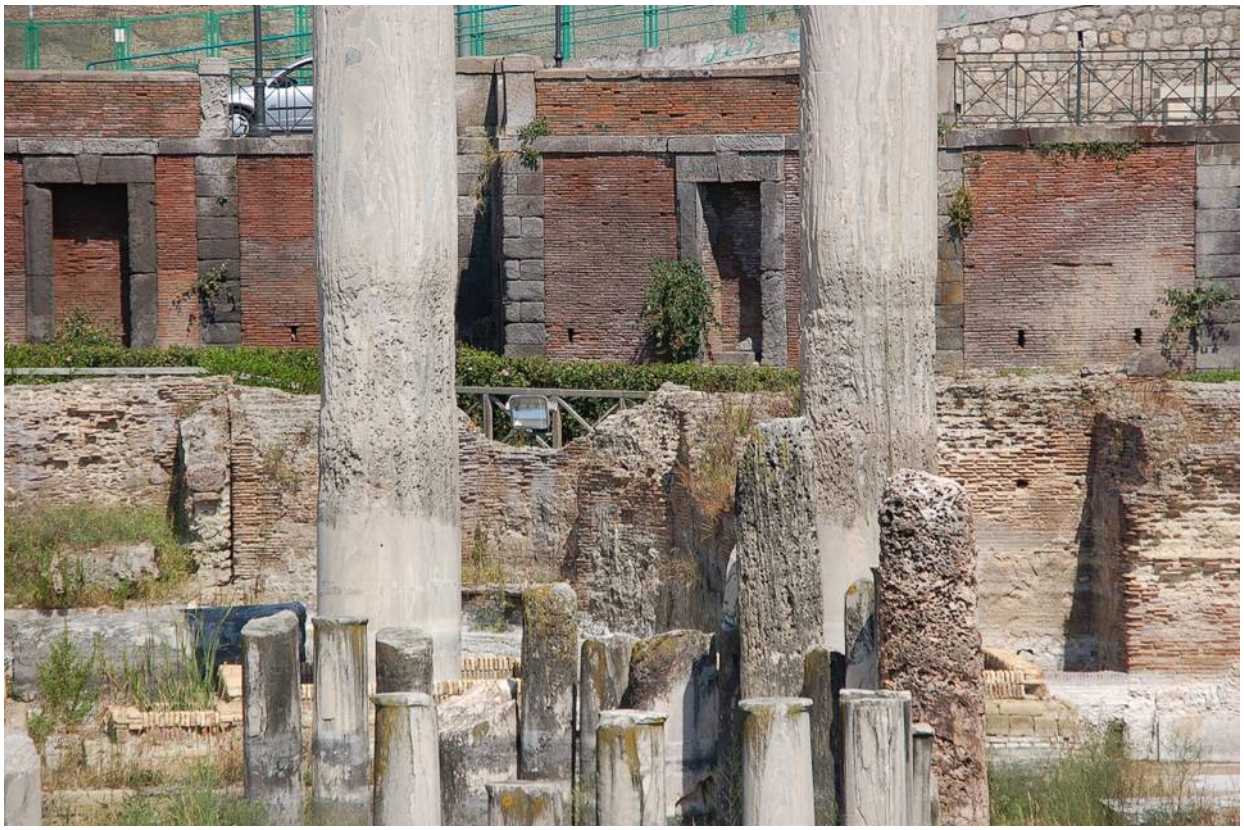
So one useful characterization of a stone is the percentage and relative ratio of its **pore spaces**.

A second characterization can be made on the degree of **hygric swelling** of the stone, that is its swelling and contraction due to moisture wetting and drying.

A third characterization is based on its **morphology** – its composition, texture, and homogeneity that affect its **strength**.

So stones with **high porosity, high rates of swelling**, and **low strength** tend to be relatively poor materials in terms of their preservation.

And it is the relationship between pore structure and these other characteristics that affects the rate and severity of a stone's decay.



DESCRIBING DECAY

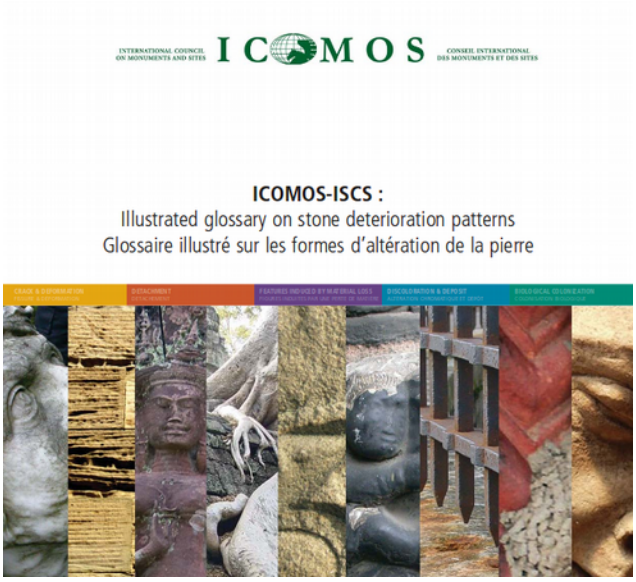
Stone decay takes many different forms and not always what might be reasonable to assume. For example, the holes columns in the image above were made by sea molluscs and not wind erosion (called 'aveloar decay') as might be suspected.

Stone may weather away gradually, or sometimes suddenly large flakes of stone may catastrophically collapse.

Sometimes the surface erupts into blisters; sometimes the stone simply crumbles away. Sometimes the stone may look perfectly sound to the naked eye, while below the outer surface it has lost its cohesion.

One of the problems about discussing stone decay is finding a common language.

For example, in English, there are a large number of terms that may mean different things to different people. And even if we can agree on terms to describe the types of decay that we observe, it can be difficult to determine the severity or rate of decay.



The ICOMOS Stone Committee have produced a useful glossary of stone decay terms in an effort to standardize terms (in English, German and French)
https://www.icomos.org/publications/monuments_and_sites/15/pdf/Monuments_and_Sites_15_ISCS_Glossary_Stone.pdf

For example, ‘Weathering’ is defined as the result of natural atmospheric phenomena, while ‘Decay’ is “any chemical or physical modification of the intrinsic stone properties leading to a loss of value or to the impairment of use”. ‘Deterioration’ is the “process of making or becoming worse or lower in quality, value, character, etc.”

MEASURING THE EXTENT AND SEVERITY OF DECAY

Sometimes we need to measure decay.

In other words, in addition to describing the type of decay, it is essential that we are able to measure the the area it covers; how bad the decay is; and the rate of decay over time.

There are 3 conditions for **quantifying decay**:

1) it is only by measuring that we can say with certainty that something (pollution, salts etc) is causing a stone to decay

2) we then need an objective means of assessing the extent and the rate of decay in order to decide whether remedial action is necessary or urgent

3) and we cannot know whether our remedial actions are having any effect unless we can monitor the condition of the stone afterwards

These are ideal conditions and they reinforce ***the common goal in conservation of making decisions based on data and not on assumptions.***

Generally, few conservation projects are able to meet these 3 conditions 100%.

So conservation decisions are often are made by conservators having the experience to understand certain patterns and follow general guidelines for treatment rather than relying on any real data or knowledge of the actual behaviour or rate of loss of a particular stone.

In fact documentation for most cultural heritage often consists of a few uncalibrated photographs taken under different lighting conditions over a few decades.

So recently more quantitative approaches has been the objective of many recent research projects across conservation, turning “weathering” or “decay” into numbers. And Juming’s 3D scanning project is a great step towards meeting the 3 conditions above.

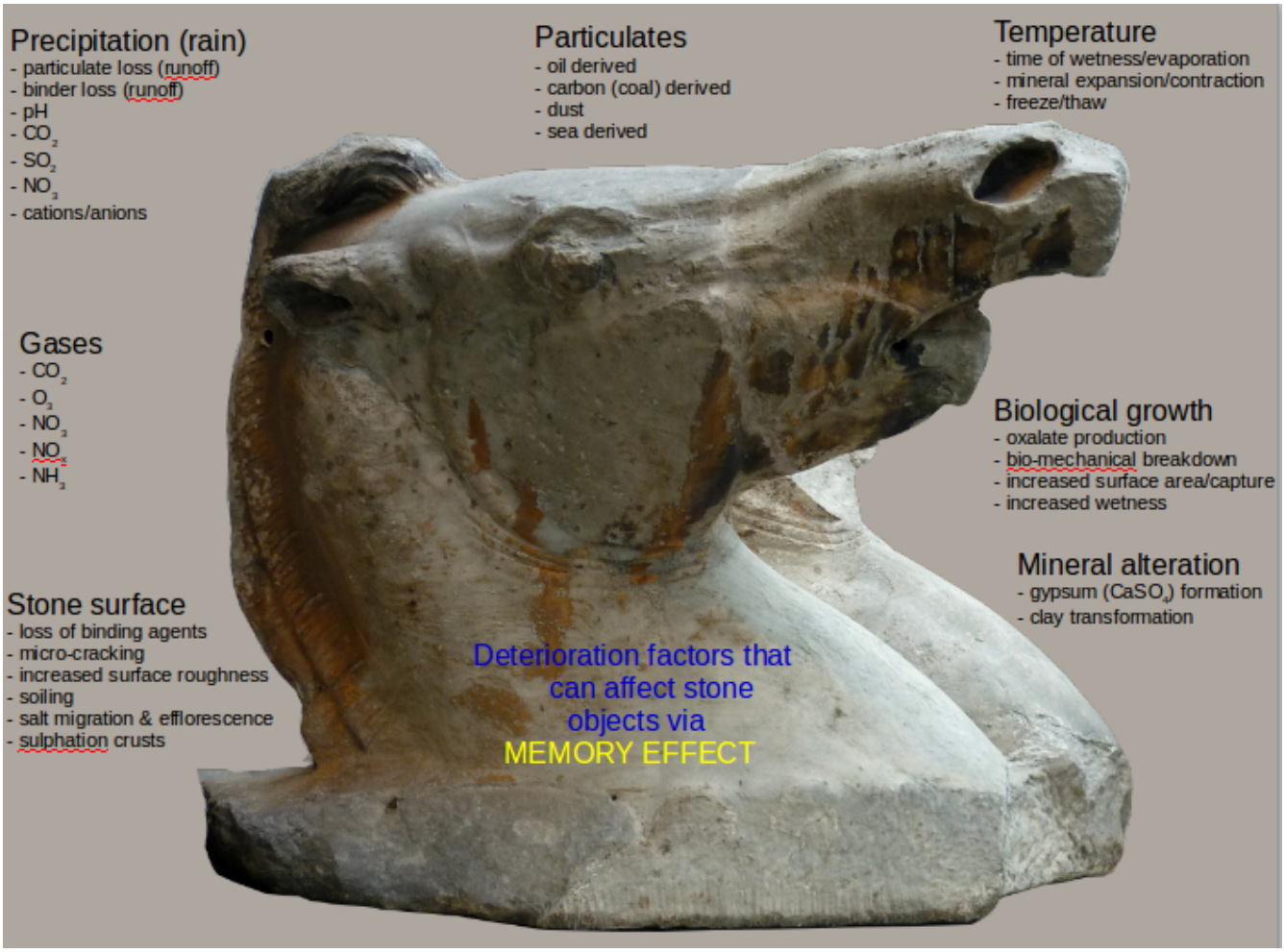
But actually no single technique is sufficient to measure stone deterioration as decay takes on many forms and has many causes.

CAUSES OF DECAY

Sometimes the cause of decay is obvious; but more often it is not as there may be several different causes acting at once.

For example, for salt decay to occur in stone, relative humidity (RH), airflow, substrate type, and temperature are all important factors together, rather than there being just one cause such as RH.

In fact a stone might have been subjected to some or all of the decay factors shown below, with some caused by weathering and some from anthropogenic, that is human-made, sources, or mixes of both.



Stone has what we can call a 'MEMORY EFFECT', where previous exposure to things like soluble salts and pollutants have been absorbed and retained by the stone and can be re-activated by any change in their current environment.

For example, salts are notoriously easy to re-activate from deep within a stone and can then cause its mechanical rupture and loss of surface when they crystallize.

We can look at some of the **major types of stone decay** by using **LIMESTONE** to introduce and discuss them.

Limestones are sedimentary rocks, made up of the remains of marine organisms such as coral and shellfish and its chemical composition is calcium carbonate (CaCO3).
As much cultural heritage made of stone is outside **air pollution** is a big factor in stone decay, especially with limestone.

They include the ‘traditional’ pollutants found in ‘acid rain’ - sulfur oxides, nitrogen oxides, and carbon dioxide. All naturally occur, but human activity has greatly increased their amounts.



All are capable of dissolving in water to create an acidic solution that will react with any calcium-based material, including limestone, marble and calcerous sandstones. They also affect sandstones and granite.

Since the early 1990s, progress has been made in reducing sulfur dioxide (SO 2) levels in some parts of the world but still an important problem in some industrialized regions.

Even with reductions in these pollutants their effects remain as a MEMORY EFFECT that can continue to influence the decay of stone for many years through continuing reactions with an object's environment.

Other airborne pollutants have increased dramatically.

Petrol exhausts produce gas-phases of Nitric Oxide (NO), Nitric Dioxide (NO2) Nitric Acid (HNO3), Ammonia (NH3) Nitrates (NO3), Ozone, and Carbon Dioxide CO2 – and there are many other pollutants such volatile organic compounds (VOCs) which are hundreds of compounds including unburned petrol and solvents from paints, aerosols, and various other anthropogenic sources.

Sulfation

CO2 dissolved in rainwater produces carbonic acid, making rain naturally slightly acidic.

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

Nitric oxide (NO), also contributes to the acidity of rainwater, and is formed by the reaction of nitrogen and oxygen with water to give nitric acid (HNO3) which yields nitrate ions (NO3) which lower the pH of the rain.

But the biggest contributor to ‘acid rain’ is sulfur dioxide (SO2) and air can contain 0.1 to 2 ppm. This can mean there can be 200 times more SO2 in polluted areas compared to unpolluted areas.

SO2 reacts with water to form sulfuric acid, the primary acid component of acid rain

$$SO_{2(g)} \xrightarrow{O_2} SO_{3(g)} \xrightarrow{H_2O} H_2SO_4$$

The can make the pH of rainwater in heavily polluted areas can be as low as 3.0

Limestone ($CaCO_3$) reacts with acid rain → dissolution of $CaCO_3$ → aqueous ions which are washed away in the rain and etch the stone

$$CaCO_{3(s)} + H_2SO_{4(aq)} \longrightarrow Ca^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)} + H_2O + CO_2$$

When rain containing calcium and sulfate ions dries, the ions crystallize as calcium sulfate CaSO4 which is gypsum. Gypsum is soluble in water, and is also washed away from areas that are rained on



A chemical reaction takes place between calcium carbonate (limestone) and acid rain to give aqueous ions, which are washed away - the dissolution of CaCO3 - in the water flow causing etching as in the image above.

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When rain containing calcium and sulfate ions dries, the ions crystallize as calcium sulfate CaSO4 which is gypsum.

Gypsum is soluble in water, so it is washed away from areas that receive rain.

But gypsum will accumulate in sheltered areas that are protected from the rain, and attract dust, carbon particles, ash, and other particulates. This results in the typical blackened sulfation crusts.



However, gypsum will accumulate in sheltered areas - this image is of an 18th Century sculpture from Westminster Abbey, London was taken on a rainy day. It shows both rain washed and sheltered areas. The gypsum has attracted dust, carbon particles, ash, and other particulates which has led to these typical black **sulfation crusts.**

Such particles can contain metal oxides that catalyze the oxidation of SO2 and hence promote growth of the crust.

In sheltered areas a crust of gypsum crusts build up because it has a larger volume than calcium carbonate (as calcite in limestone). The crust becomes blackened due to the incorporation of soot. Surface detail is preserved under the crust because it is not being washed away.



Sculpture brought into museums can show the effects of sulfation – here is a sculpture at the V&A Museum, London: Antonio Corradini's *Apollo flaying Marsyas* from around 1720 which was previously outdoors for some 200 years before the V&A bought it in 1967.

Looking more closely, the surface clearly shows signs of weathering and environmental pollution - the surface looks yellow and grey especially at the bottom, and is more rough and porous.



The greying is typical after sulfation has been removed - in this case it was removed in the 1980s using ammonium carbonate poultices and an ultrasonic dental tool which, at a specific frequency, stimulates a material to vibrate, resulting in its ‘separation’ from the substrate, and as common with the tool, leaving the stone surface mottled.

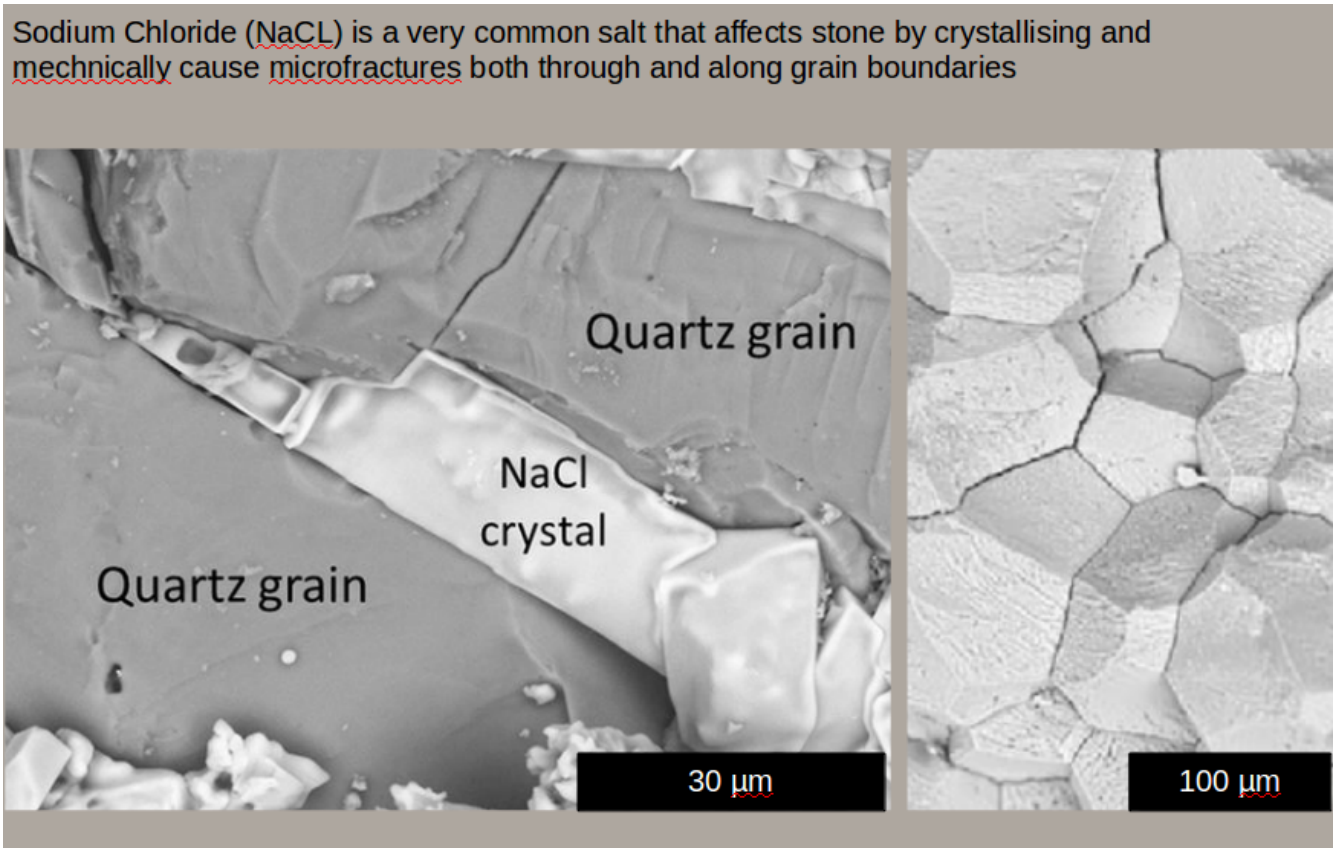
The yellowing is most probably calcium oxalate, a patina formed by the action of oxalic acid produced either by lichens or industrial pollutants - calcium oxalate (CaC_2O_4) is colourless but organic fragments in it give a yellow to brown coloured patina.

Finally, **sulfation** generally occurs on calcareous stones: limestones, marbles, and calcareous sandstones, that is sandstone with a calcium based binder. But it can also appear on stones geochemically unrelated to calcium such as granite as we will see below.

Salts

When rain containing calcium and sulfate ions penetrates the stone's pores and then dries, the ions form salt crystals within the pore system. Sodium chloride is the salt found in the sea - such as at Juming – and is carried by wind and rain and deposited directly on stone and from there and depending on porosity, it enters the body of the stone.

Most salts such as the chlorides, sulphates, and nitrates of sodium, potassium, ammonium, magnesium and calcium – can cause decay in stone.



Salts are a combination of a metal ion (a positive *cation*) and a negative ion – *anion* - from an acid.

They are often referred to in conservation literature by the anion: eg. as 'nitrates' or 'chlorides', etc. However it is important to know what the cation is as well – for example, magnesium chloride goes into solution at 33% RH compared to sodium chloride which goes into solution at 76% RH.

Salts may be present in stone from its environment including the ground water and salts will be present in the stone at the time of quarrying. Salts can also enter the stone due to burial, its location, use, treatments, etc.

It is the process of the salt going into solution – hydrating - and then crystallizing that causes damage to porous materials. Crystallization occurs as the RH drops causing moisture in the stone to travel towards the front of evaporation, at or just below the surface of the stone.

When crystallisation occurs on the surface its called **efflorescence** and either small white crystals, needle-like structures or powder are visible.

This is not as damaging as **subflorescence** which occurs below the surface – here the forces generated by crystallisation in the pores can cause sub-surface cracking and granular disintegration as we see in the image above - research has also shown how water repellent treatments can form a barrier and provoke such subflorescence and lead to the delamination of the stone surface.

A salt crystal in a pore will exert a pressure on the pore walls. If the crystal is to grow any further, and thereby do damage, it is necessary for the salt solution to be able to get in between the crystal and the pore walls. If the pressure gets so high that this solution is squeezed out, no further growth can occur and there will be no damage. If not then the crystal can grow and exert more pressure.

A struggle takes place related to the surface energies of the stone, salt solution and salt crystal and is resolved by ejection of the salt solution or incorporation in the salt crystal causing the pressure that cracks the pore walls.

If the stone's structure is disrupted sufficiently, it may suffer micro-cracking around the grain boundaries and binder and this can lead to more significant failures, such as surface scaling, grain cracking (as we can see in the quartz grain above), expansion, surface powdering, pitting and granular-disintegration

Thus **porosity** is an important factor in determining a stone's durability in terms of the penetration, mobilisation or re-mobilisation of any salt content.

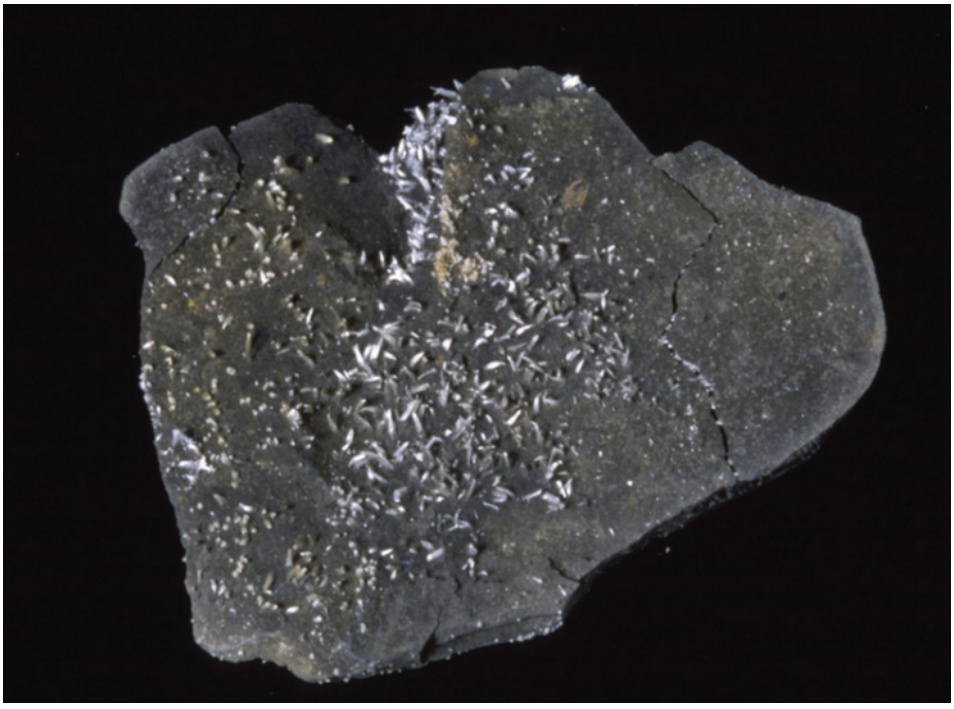


So salt efflorescence is a common and very visible form of deterioration

Salt crystallisation on archaeological stone on site in Egypt, Amenhotep III Temple Conservation Project



So now we can understand a bit more of what the memory effect of stone is - although levels of some human-made pollution such as SO2 have generally declined we still see the effects from those previously high levels including damage from blackened gypsum crusts and remnants of CaSO4 in the pore matrix of the stone that include nitrate and sulfate ions.
This means that such an already weakened stone is more likely to decay quicker than ‘good’ stone.



MARBLE

Marble is a metamorphic stone. It is a limestone that has been subjected to thermal and pressure changes in some kind of geological upheaval. Marble is composed of compacted calcite crystals and, unlike limestone, it has no binder.

But although marble is harder and more dense than most limestones, chemically it is the same material, so it is also affected by sulfation and acid rain in the same way as limestone.



One difference between limestone and marble is that if water, soluble salt solutions or acid rain penetrate between the crystals, the edges can erode and the crystals, often the size and shape of white sugar, can become detached - this is often referred to as ‘sugaring’.

These 2 letters are from the same 200 year old marble tomb - one letter has been protected from rain and one has not and shows the granular disaggregation and the sugary surface typical of exposed marble.

SANDSTONE

Sandstones are also sedimentary rocks, formed by the erosion of pre-existing rocks – igneous (that is volcanic), metamorphic or sedimentary - into ‘sand-sized’ fragments which are transported by water, wind or glaciation to the place of deposition where they are laid down in beds.

The constituents of the pre-existing rock - predominantly silicon dioxide as quartz or feldspar - are held together with a cementing material in which the particles have become embedded.



There are a variety of cementing materials which give each type of sandstone its characteristic colour, texture, working properties and weathering behaviour. The degree and duration of transportation determines whether the grains are angular or rounded.

Cementing materials include:

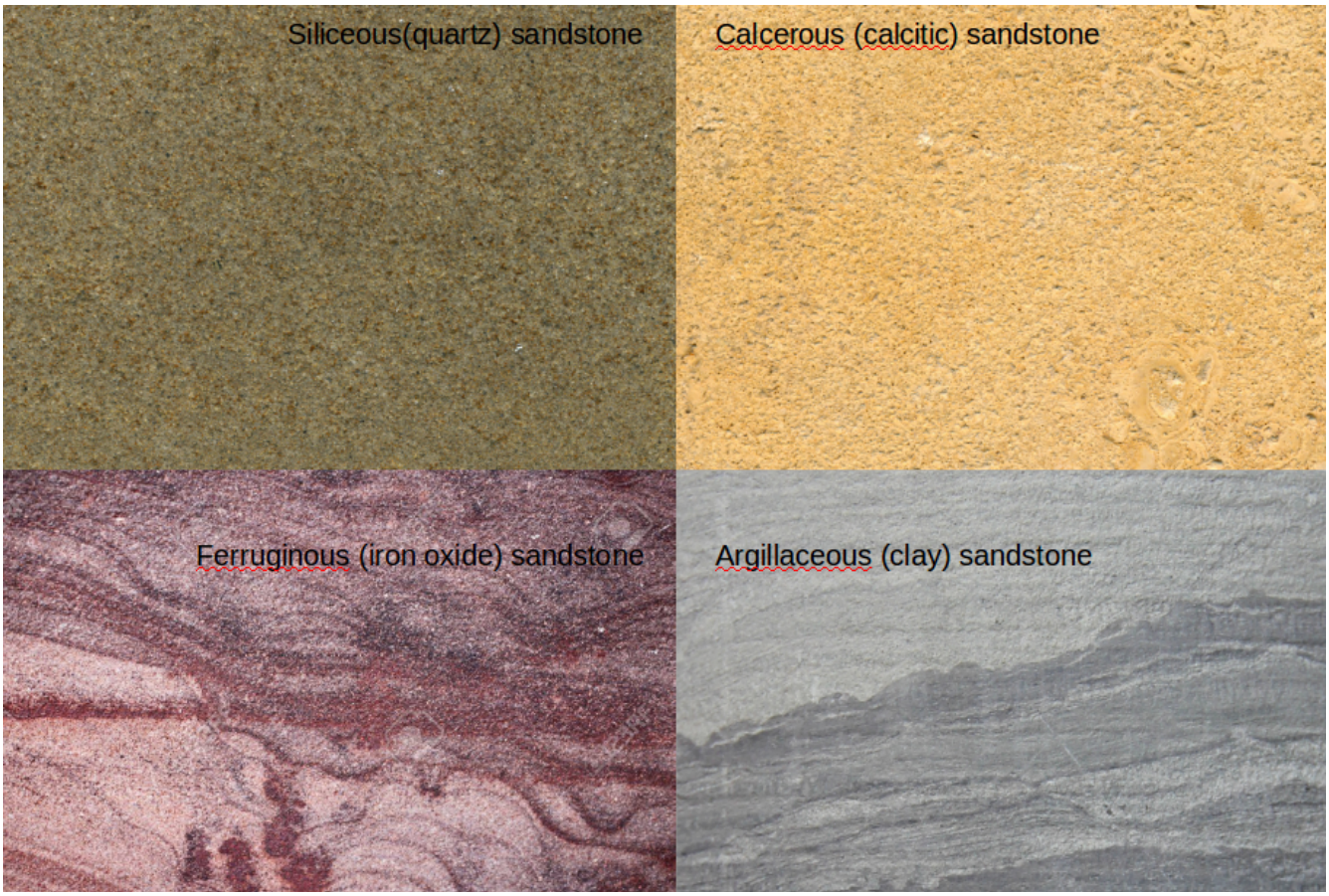
Silica: siliceous sandstones are commonly made from quartz where the spaces between component grains are filled with silica dioxide (SiO_2) making them hard, durable and, if pure, white.

Calcite: calcareous sandstones are pale in colour and can be quite durable but are susceptible to attack by acid rain. Grains are cemented in a calcium carbonate matrix

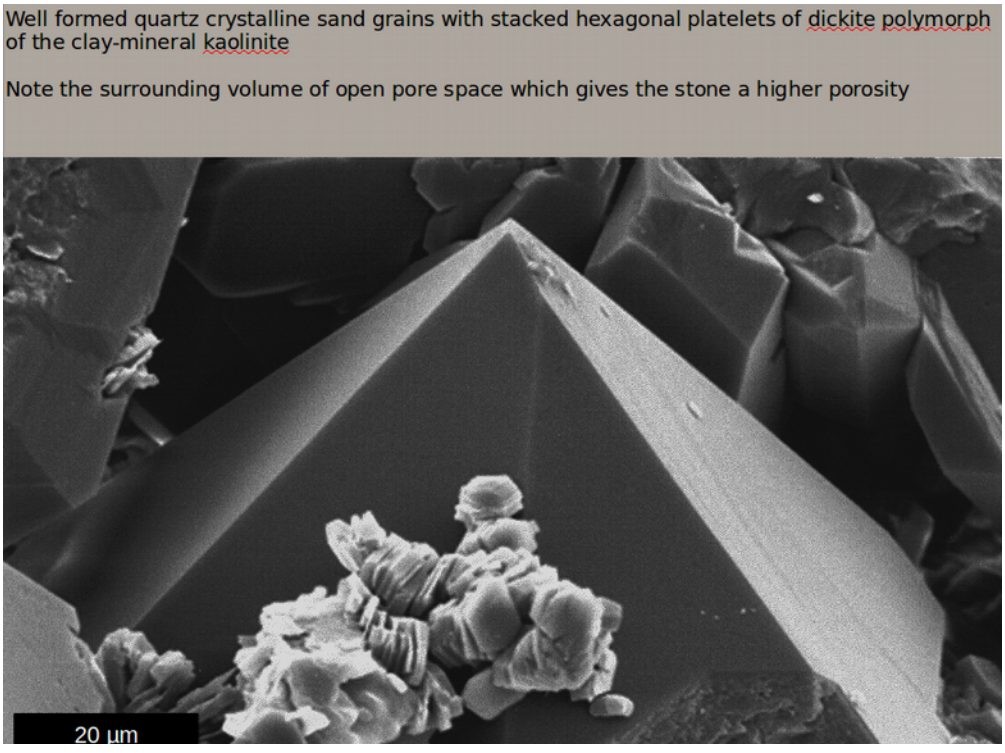
Iron oxides: ferruginous sandstones, can be quite hard, and colour varies from red to yellow to orange to purple to brown and green which can be banded.

Clay: argillaceous sandstones are where the spaces between grains are filled with clay minerals – they are generally quite soft and have a poor resistance to weathering because the clay swells in the presence of water, causing disruption of the beds. They are often greys, browns or slightly green.

As we see in the image of the quarry in England mixtures of cementing materials can exist, either dispersed through the stone or zoned in beds. And Juming's sculptures show this mix as they are made from a mainly quartz-mica sandstone but also have iron (Fe) and Potassium (K) clay and feldspar related components.



The **porosity** of sandstone varies widely from almost zero to approximately 35% - compared to limestone which is generally around 5-30%. High porosity means that some sandstones can readily absorb moisture and soluble salts etc.



The effects of moisture on sandstone is made worse by the fact that sandstones are composed of fairly large grains so a greater volume of material is lost for each grain which becomes detached.



Detachment happens during weathering as it often involves the solubilisation of the mineral cement from below the stone surface and its re-deposition near the surface in a process of whats called ‘case-hardening’ or more formally, contour scaling by ICOMOS

This hardening produces a zoned effect where

1 - soiling (carbon), pollutants, biological growths and weathering affect the outermost layer and change it chemically– *on the left of the Scottish gravestone*
2 – this decomposes minerals to releases ions and colloids of silica (from any feldspars present) or calcite in the case of calcereous sandstone, as well as other mineral such as iron, magnesium, and sulphur, which all *leach* and
3 – become richer at the surface – *note the similar orange skins on both stones*
4 – which depletes the stone’s mineral cement which leaves the mineral grains below this surface more weakly bound which leads to the collapse and loss of the case-hardened skins
5 – which reveals the untouched inner stone, which is generally paler in colour – *the lighter grey areas on both stones*

Excessive wetting of the stone, freeze-thaw cycles, soluble salt contamination, as well as inappropriate coating or cleaning procedures can cause the loss of the case-hardened skin which then exposes the weakened inner stone until it is washed away, revealing the un-weathered surface. This is then susceptible to the same process *ad infinitum.*

And although its not obvious, case-hardening is associated with a weathering form of stone called *tafoni*, which often starts out as alveoli decay, that is, where small holes in the stone are created by grit in any small depression in the stone being blown around in a circular motion by the wind until they get bigger and more hole-like - which we can also see in a very developed form here in Taiwan:

Honeycomb weathering (tafoni) at Yehliu



So case-hardening is interesting beyond the museum and is a common weathering decay form that also affects some limestones and granites as well as sandstone.

GRANITE

Granite is a volcanic rock that contains large crystals due to the slow cooling of magma beneath the earth's mantle. Its minerals include: quartz (Si), feldspar (K, Al, Na), and mica (Si, Fe) – often the main minerals found in sandstones.

Over a long time the alkaline constituents in the feldspars are slowly leached by water as is the iron from the mica in a process of **hydrolysis** - oxygen and water then enter the what has become a disrupted lattice structure to form hydroxides of aluminium and silicon which are clay minerals.



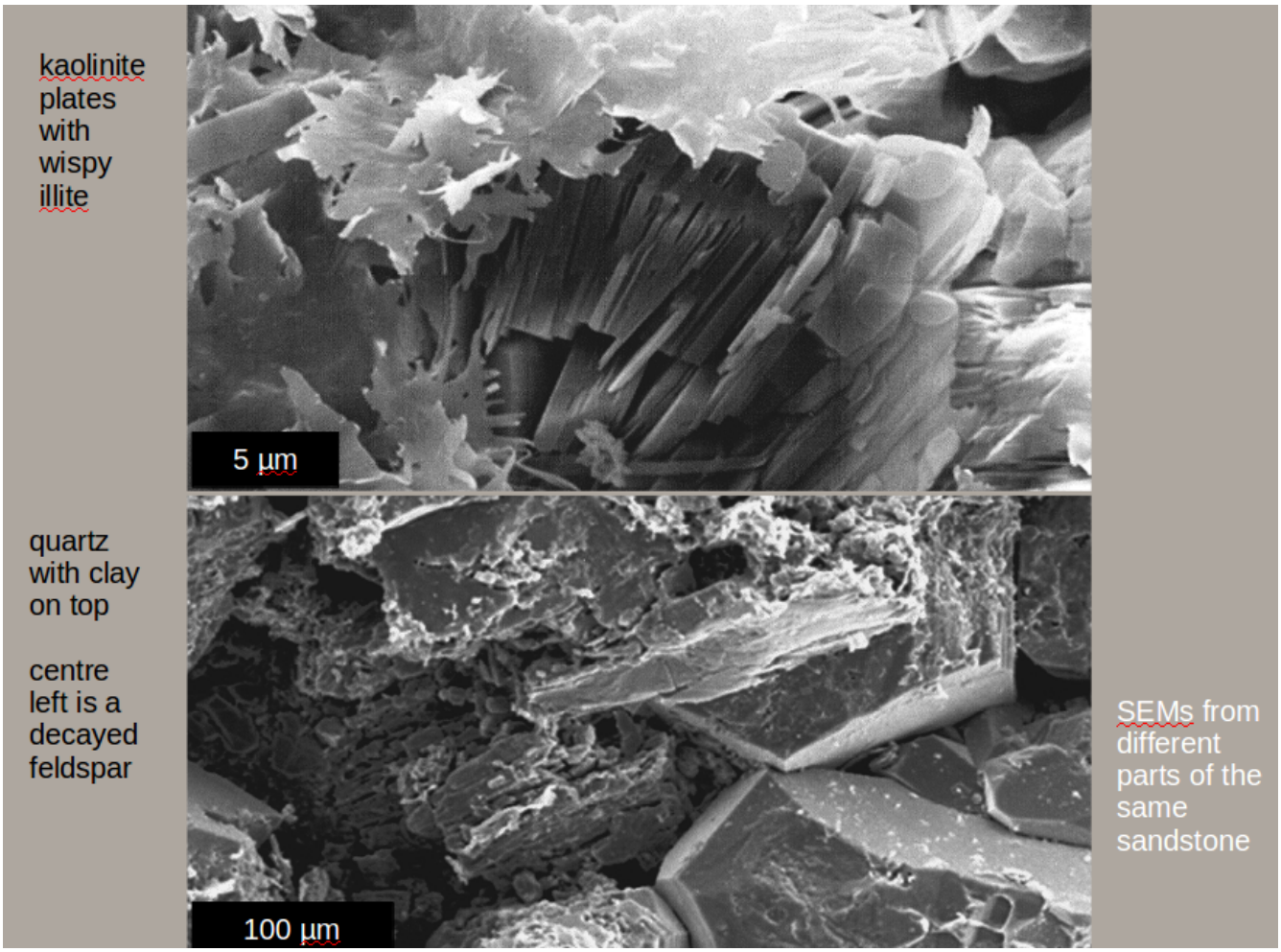
The resulting granite is much softer, duller in appearance, more vulnerable to mechanical damage and weathering. This process - kaolinization - is generally very very slow but it can be accelerated by the presence of dissolved CO2 in rain, carbonic acid and any sulfuric acid content as described earlier.

Sulfation in the form of black crusts can occur but the crusts are generally geochemically unrelated to the stone and are thus accumulated from purely atmospheric and anthropogenic sources. Granite is also affected by freeze-thaw cycles which can produce micro-cracking.

Granite can also suffer from salt attack. Condensation causes salts to go into solution which then rapidly crystallise with the heating of the surface. Attack occurs along grain boundaries where kaolinization may also be occurring. Because the individual crystals of granite may be quite large when they are dislodged this may result in substantial loss of the carved surface.

Porosity

So one of the properties of stone important as to how it decays is **porosity.**



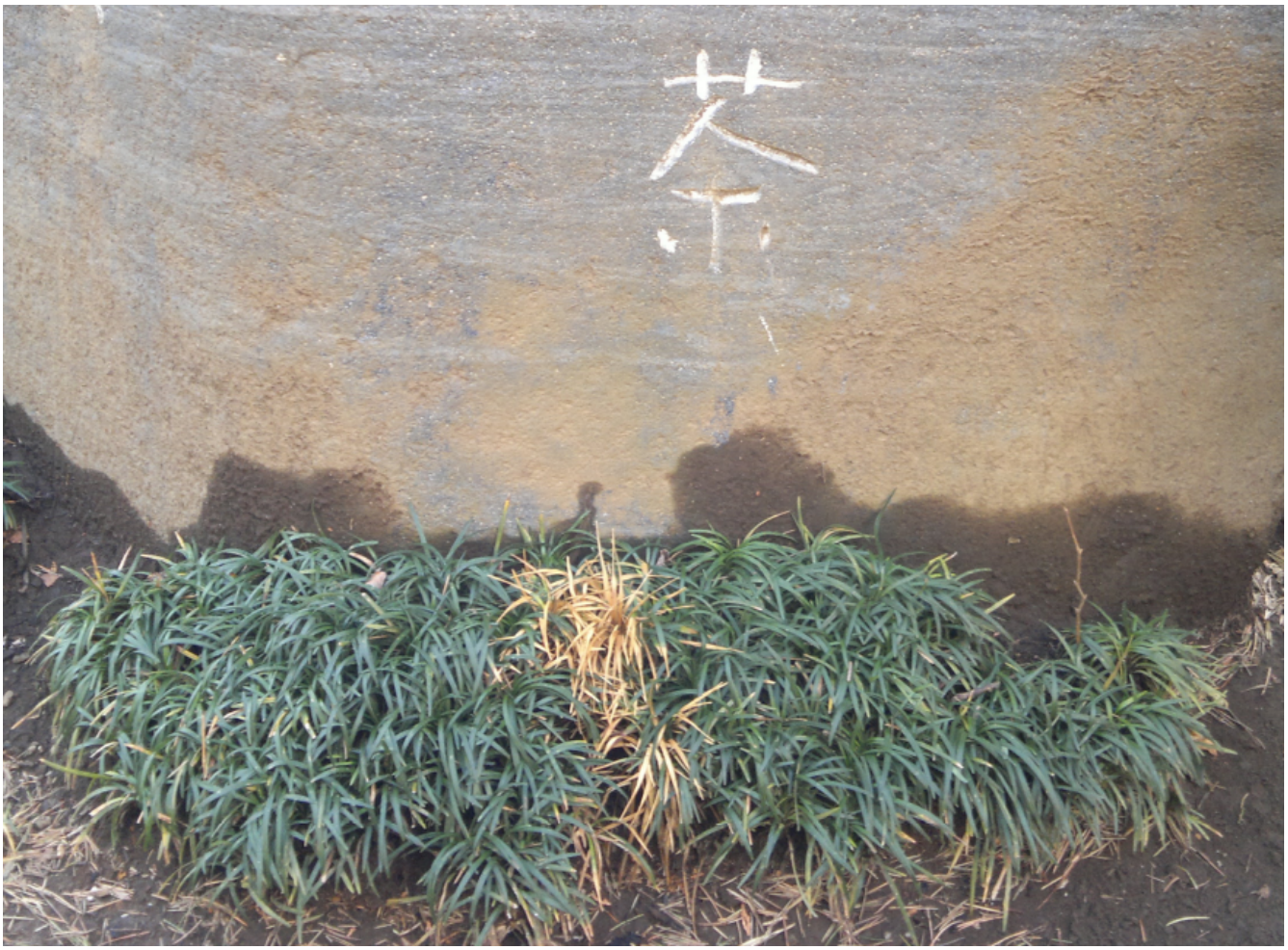
All types of stone are porous to a greater or lesser extent. Porosity exists because of spaces incorporated into the structure of the stone during formation. All stone are composed of particles either cemented or compacted together.

Particles may be angular and interlocking, resulting in low porosity as in many marbles and granites. Or they may be round or complex, as in the image above with a quartz sandstone, and have larger and more irregular spaces in between.

So pore spaces can be different even in the same stone as we can see in the image.

The fact that there are spaces within the stone allows moisture to move through. This can occur through capillary action where surface tension pulls any liquid into the narrow pore spaces to absorb it up into the stone.

So stone is described as being permeable if at least some of the pores are connected so that liquid water and/or water vapour can travel up and through the stone.



This image shows capillary action in a stone with a fairly low porosity after the ground was wet with rain.

Water can then leave the stone because of evaporation. This occurs when there is less moisture in the air at the surface than in the stone.

When the air is still it will quickly equilibrate with the stone: they will have the same moisture content and little drying will take place.

When there is movement of air across the surface, the air will quickly move water molecules away and thus will not be in equilibrium with the surface and more drying and potential evaporation of other solubles, including salts, will occur as we saw earlier with the crystallisation of salts on the surface or subsurface of the stone.

Thus **porosity** is essential for understanding decay caused by salt migration and crystallisation.



Museum dust and greasy dirt on a 16th Cent. marble figure, Moyle Finch Tomb, V&A Museum (before and during cleaning)

And **porosity** is part of the mechanism for the absorption of dirt: so even museum dust on a surface can be absorbed if there is any condensation from high RH; and greasy and oily dirt can be taken in by porous surfaces, such as handling dirt, even relatively compact stones like this example of marble from the V&A Museum shows where even after cleaning greasy dirt residues remain.

A stone's porosity can mean that any inappropriate wet cleaning can drive dirt further into the stone.

So while geological composition might appear to be the most obvious way of grouping stone types the relationships between porosity, pore size and distribution, grain size and grain-to-grain relations and most importantly a stone's history outside in relation to its 'MEMORY EFFECT' can all be of greater importance to its decay especially as many modes of deterioration are triggered by and through the transport of soluble materials in and out of the stone. Knowledge of this helps determine the treatment options available for particular stones.



Another important agent in stone decay is **BIODETERIORATION**

The biological degradation of rocks is well known and has been studied for a long time: it is one of the weathering mechanisms responsible for the formation of soil and the deterioration of stone in buildings and monuments through the action of biological organisms has long been known.

But research suggests they can also be protective and biological organisms such as lichens and moss can contribute to an aesthetic of age, authenticity and even romance to a monument, and their removal can leave the stone looking very bare.



Nevertheless, many organisms contribute to the deterioration of stone, and it is necessary to find the right balance between aesthetics and preservation.

The discussion around this topic has become more complex as evidence has accumulated that complex biofilms may help to stabilize fragile stone surfaces but in other cases may accelerate decay.

For example, bacteria typically produce slime or *extracellular polymeric substances* (EPS) as part of a complex biofilm made up of polysaccharides, water, and proteins. This has been shown to change the dissolution rate and etched morphology on samples of limestone, suggesting that some surface patinas may be an effective natural protection at least for carbonate stones.

However, *cyanobacteria* have been found to affect cave painting along with *heterotrophic bacteria* as they both increase stone deterioration through their metabolic products, biomediated dissolution, causing mechanical alteration such as the scaling of painted surfaces.

And biofilms like cyanobacterias and algae and higher level infestations like moss and lichen can also change the thermal, hygric, and mechanical behaviour of stone, thus enhancing decay by increasing the duration of surface wetting and providing a source of organic acids and complexing agents.

Lichens can also effect stone physically by causing mechanical damage through the penetration of the hyphae (like a root) into the stone and by the expansion and contraction of the thallus (the vegetative part of the fungus) under changes in RH.



Chemical damage from lichens is important and may arise in three ways:
1) by the secretion of oxalic acid
2) by the generation of carbonic acid,
3) by the generation of other acids capable of chelating ions such as calcium.

The secretion of oxalic acid, which reacts with a calcareous stone to produce calcium oxalate, is often seen as a protective layer known as *scialbatura*, and it was known about by the Romans.

Scialbatura is often associated with the deliberate application of a protective coating like linseed oil but also it seems to be produced by some lichens. However correlating the distribution of lichens with the distribution of oxalate on Trajan's Column in Rome (see image above) shows that lichens are not the best explanation for the column's scialbatura.

Some lichens are also endolithic - an endolith is an organism that lives inside stone. They colonize the pore space of the stone by taking advantage of the light, moisture, and shelter found inside it and as such they affect moisture transport.

Decayed stone presents a habitat for bacteria and some bacteria attack stone. Chemically they fall into two groups:

autotrophic bacteria derive their carbon from carbon dioxide (CO 2), such as cyanobacteria that derive their energy from light

heterotrophic bacteria utilize organic compounds on the stone to derive their carbon.

Autotrophic bacteria include those that are capable of oxidizing sulfur and nitrogen compounds to produce sulfuric acid and nitric acid. They are one more means, therefore, by which air pollutants such as sulfur dioxide and nitrogen oxide are turned into sulfates and nitrates.

This underlines the difficulty of separating out the individual causes of stone decay; several different factors may play essential roles in the overall decay process.

For example, is it bacteria or those catalyzing metal compounds blown around in dust, that is the main routes for sulfate production? Or a combination of both?



Earlier freeze/thaw cycles were mentioned - as water freezes it increases its volume by around 9% and this can create a form of **Differential Stress**

Differential stress is caused by the effects of cycles of wetting and drying as well as freezing and thawing, clay swelling, differential hygric stress, differential thermal stress, and stress from differential thermal expansion rates of material in pores (such as salts or organic material) and the stone.

The general idea is that treatments, salts, water films, or biofilms—anything that causes the stone surface to react differently than the interior—can result in a shear stress, crack propagation, and, eventually, surface parallel detachment (such as flaking).

For example, significant shear stress is generated when, during rain, the surface of a clay-containing stone swells, while the interior of the stone remains dry.

This would be considered an example of differential hygric stress and is typically found on the corners of stones where wetting and drying is quicker. The image above shows a famous case from Lausanne in Switzerland.

Clay swelling can impart shear forces that can cause buckling of wetted stone surfaces.

Intracrystalline swelling of clay occurs in some sandstones if it is present as a cement between the sand grains. Salt-activated clay swelling can also affect stone especially sepiolite-rich limestone or smectite rich sandstone.

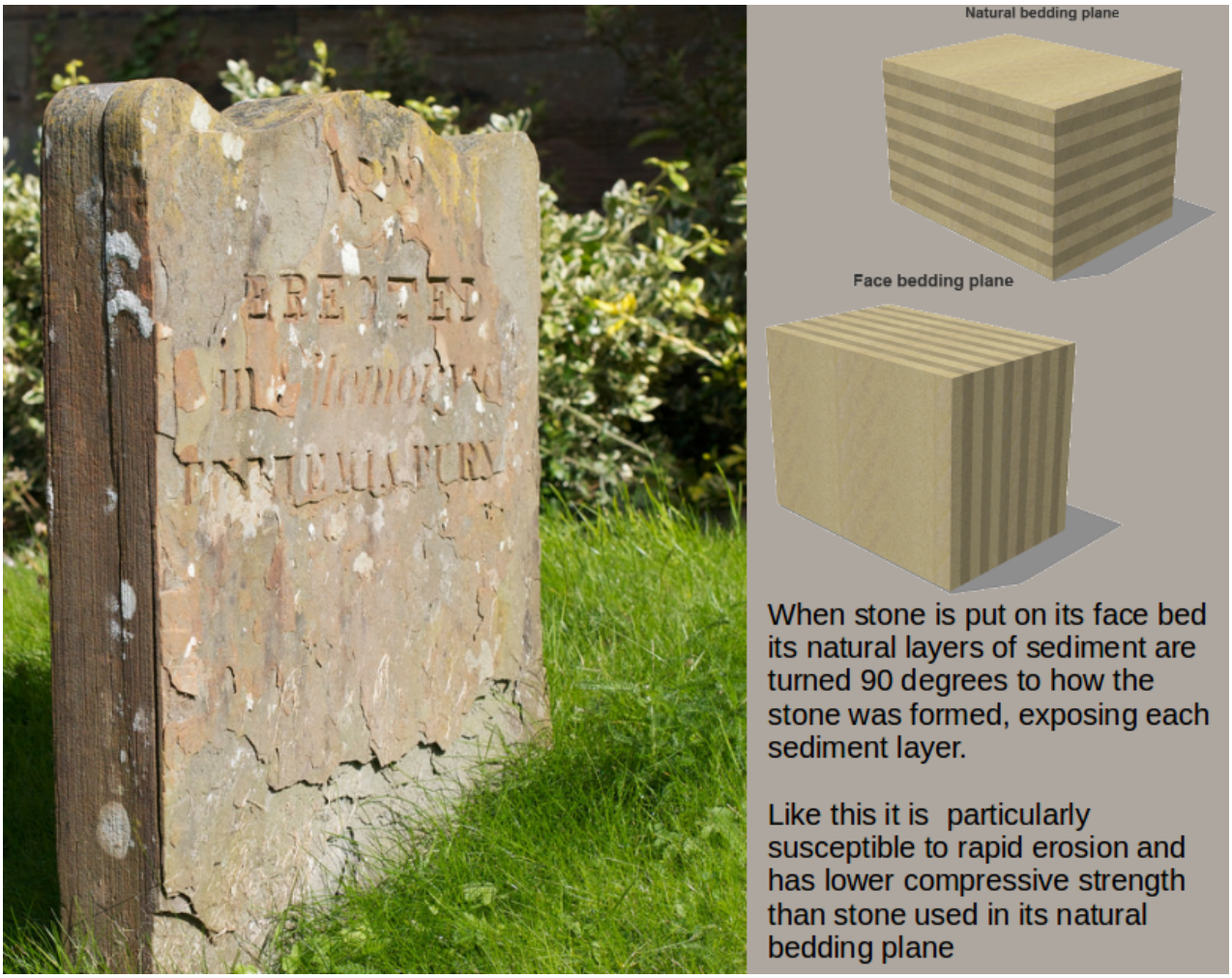
Also salts naturally tend to accumulate near the stone surface, setting up differences in how the two parts of the stone (surface and interior) react to environmental changes. This can contribute to contour scaling and the loss of surfaces and can also be combined with differential thermal expansion stresses induced at the interface between minerals that have different colours.



Intrinsic Problems

Every region seems to have a stone type that should not have been used to create sculpture or monuments - some examples include Reigate stone in the UK which contains unstable silica, glauconite, and smectite, Lausanne molasse in Switzerland as discussed as it contains clays that swell, and the Lecce limestone from Italy which has a porosity of >50%.

Marble has also been used for panels which have then warped and bent and fallen off such as the Amoco building in Chicago, the Grande Arch de la Defénse in Paris, and Alvar Aalto’s Finlandia city hall in Helsinki. The image shows marble that has bent under its own weight combined with differential expansion of calcite enhanced by moisture, microstructure, and differential residual strains in the marble.



Finally, sometimes a stone is not really suitable for the task it is used for. Sedimentary stone is sometimes laid down in quite thin layers so sometimes people turn them 90° upwards and ‘face bed’ the stone. This makes it more open to delamination and any extremity is more likely to fall off.



Dr Jonathan Kemp March/June 2018