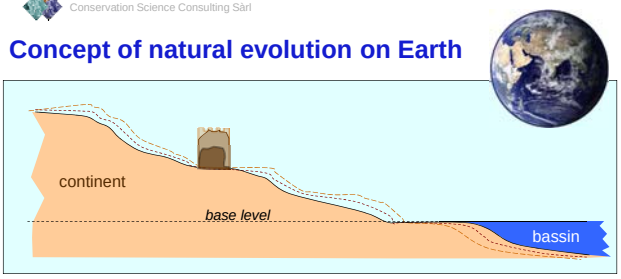
WEATHERING OF NATURAL BUILDING STONES

Concept of natural evolution on Earth



From the very moment when stones get in touch with atmosphere, they are subjected to weathering processes (because of non equilibrium & water cycle)
Buildings are also subjected to the natural laws
=> their deterioration is inescapable!

Definitions

Disorder ***(Altération ou désordre)*****:**

modification of material not necessarily meaning a marked reduction of material durability or static problems for the building

Deterioration ***(Dégradation)*****:**

modification meaning a marked reduction of the material durability and/or static problems for the building

Weathering is different on buildings from outcrops…

Hauterive (CH, NE)

(…because of extraction, work, exposure, contrasts,…)

Neuchâtel (CH, NE)

The weathering causes (related to water)

Natural causes	Anthropogen causes	
- dissolutions and chemical transformations by all sorts of waters - salts brought by marine sprays - salts brought by animals - dissolutions and chemical transformations by micro-organisms and plants	- air pollution: acceleration and/or modification of natural processes - chemical cleanings - salts brought by agriculture - conservation products - salt-rich mortars	**Physico-chemical**
- natural disasters (earthquakes, floods, cyclones,…) - frost - wind abrasion - growth of the roots of plants	- shocks (accidents, vandalism) - extraction, cut and laying - use (*mise en œuvre*) (unsuited stone, layering, orientation, statics) - unsuited materials (too hard mortars) - water damage, fires - mechanical cleanings - wear (*usure*)	**Mechanical**

Little history of air pollution and weathering observations

- **agro-pastoral age** (Neolithic – bronze to iron age): weak air pollution, development of the farming and agriculture

- **age of craftsmanship** (iron age to the 18th century): air pollution increases, related to the craft industry, heating with wood then with coal

Little history of air pollution and weathering observations

- **industrial age** (end of the 18th to 20th century): the industrial revolution starts at the end of 18th century. Use of new types of energy, increased mechanization. Modification and high increase in emissions (second half of the 19th century: beginning of the scientific work on building stone weathering)

- **urban age** (since the end of the 20th century): climax of the industrial society plus automobile pollution (after 1920 scientific research became very numerous (Germany, Austria, England, France, ...)

The main air pollutants dangerous for stones

SO_2 :

$SO_2 + H_2O \rightarrow H_2SO_4$ (non-stoichiometric)

$H_2SO_4 + CaCO_3 \rightarrow CaSO_4,2H_2O$ (non-stoichiometric)
(solubility = 0.014g/l) (solubility = 2.4g/l)

Sources: SO_2 comes from fuel combustion (especially high-sulfur coal); electric utilities and industrial processes as well as natural occurances like volcanoes

The main air pollutants dangerous for stones

PM10 or PM2.5 (particulate matter/ *particules fines*)**:**

PM can contain S → SO_2 → H_2SO_4

Sources: PM are emitted during the incomplete combustion of fossil fuels or wood and come also from ground/stone erosion, quarries, pollens …

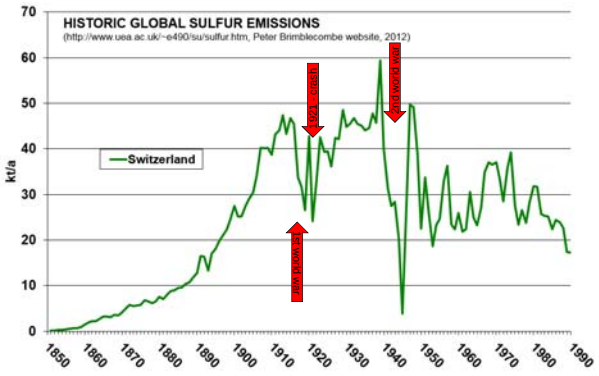
The main air pollutants dangerous for stones

NOx (NO_2 + NO):

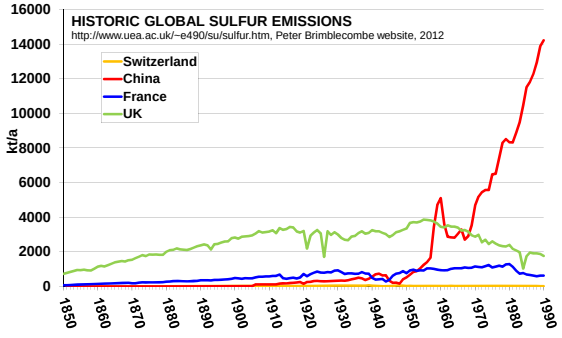
NOx + H_2O → HNO_3 (non-stochiometric)

Sources: NO_2 is a secondary pollutant formed from NO. NO is formed itself from N_2 and O_2 during the combustion of fuels at high temperature

The evolution of the air pollution



The evolution of the air pollution



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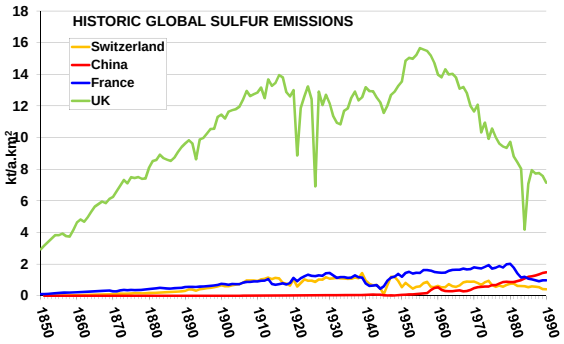
The evolution of the air pollution



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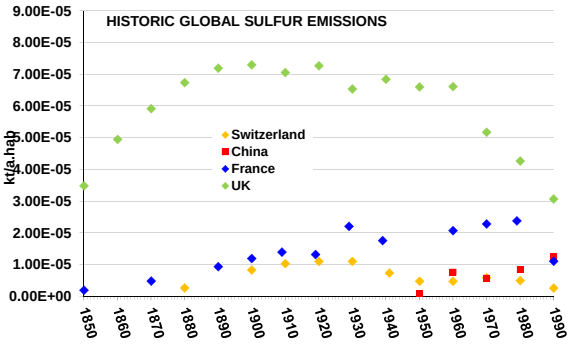
The evolution of the air pollution



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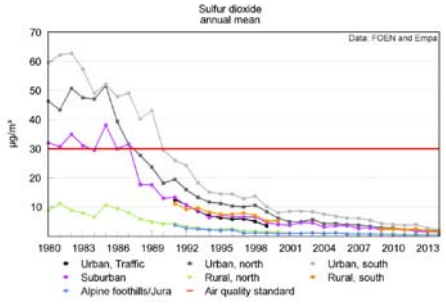
The evolution of the air pollution

SO_2 concentration in Switzerland from 1980 to 2014



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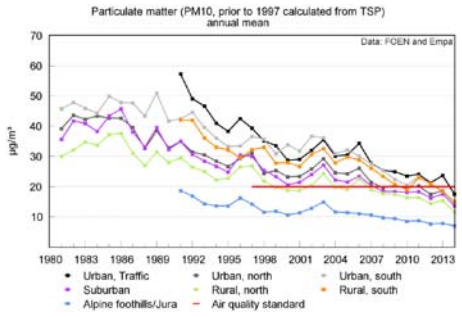
The evolution of the air pollution

PM10 concentration in Switzerland from 1981 to 2014



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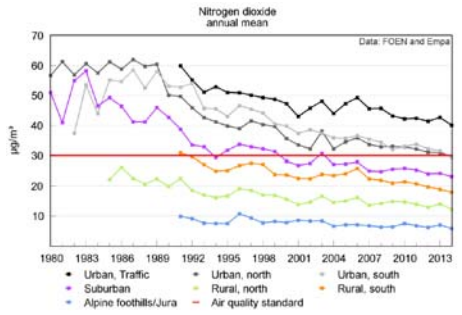
The evolution of the air pollution

NO_2 concentration in Switzerland from 1980 to 2014



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Weathering forms and mechanisms

The weathering factors modify:

- the porosity structures
- the chemistry and the mineralogy

But in spite of the diversity of the natural stones, their deteriorations can be **grouped in a few classes** according to their morphology and the physicochemical mechanisms which characterize them.

Weathering forms and mechanisms

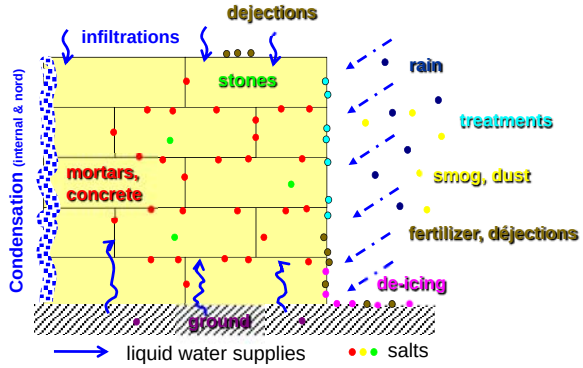
Mineralogy is not a major factor which determines the weathering forms. Major factors are:

- **kind** (liquid or vapour) **and amount of water transfers** (=> **porosity** is very important – quantity and quality)
- **exposure on the building** (which controls the **water and pollutant supplies**)

=> Identical weathering forms can be observed on various types of rocks

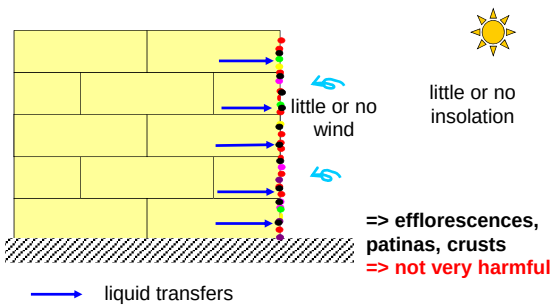
Weathering forms and salts

Origin of salts and water in buildings



Weathering forms and salts

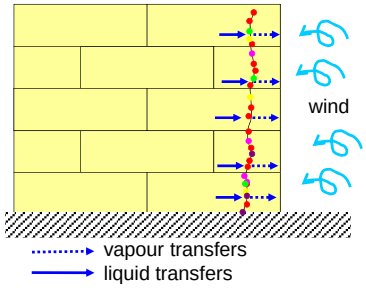
Evolution of water and salts in case of slow drying



=> efflorescences, patinas, crusts
=> not very harmful

Weathering forms and salts

Evolution of water and salts in case of fast drying



=> scaling, blistering, granular disintegration, differential weathering
=> very harmful

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Weathering forms
1/ Chromatic alteration

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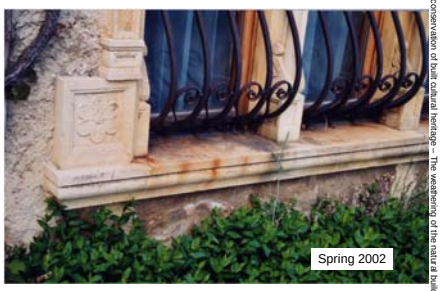
Weathering forms
1a - Chromatic alteration / Stains *(taches)*

- Generally correlated with alien materials like: rust (*rouille*), copper salts (*sels de cuivre*), organic substances, painting, varnish…
- This phenomenon does not strictly depend on exposure conditions of water supplies.

1a - Chromatic alteration

Stains

Cressier (CH, NE)
Pierre jaune
from Neuchâtel



1a - Chromatic alteration

Stains

Nancy Cathedral
(France)
Limestone

Weathering forms
1b - Chromatic alteration / Discolouration

• The original colour of a material changes because of processes like:
- water penetration (more or less permanent coloured stains);
- exposure to sunlight (fading);
- formation of metallic oxide in the structure; …

but not because of a deposit.

• Does not depend on exposure conditions to water supplies.

1b - Chromatic alteration

Discolouration

A flying buttress top, south façade, Lausanne cathedral
Arvel Limestone

1b - Chromatic alteration

Discolouration

Epinal Basilica (France)
sandstone

Weathering forms
1c - Chromatic alteration / Red staining
(Rubéfaction)

- Chromatic alteration due to local oxidation of iron components on the stone surface often caused by a fire.
- This phenomenon does not depend on weather exposure conditions.

1c - Chromatic alteration

Red staining

Abbey church
Romainmôtier (CH, VD)
Pierre jaune
from Neuchâtel

1c - Chromatic alteration

Red staining

Collegiate church
Neuchâtel(CH, NE)
Pierre jaune
from Neuchâtel

Weathering forms
1d - Chromatic alteration / Patinas

- Black, brown, ocher, yellow
- Natural modifications of the building stones surface = normal “ageing” in outdoor environment
- Quite uniform very thin layer which sticks to the substrate from which it is chemically different (enriched in iron/clay minerals and/or in biogenetic calcium oxalates). Origin of the patina materials: endogenous (calcite, salts) and exogenous (soots, dust, micro-organisms, salts)
- Physical and colour modification but do not lead to a deterioration
- Can gradually evolve to the formation of crusts
- Usually take place in the zones protected from water supplies

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1d - Chromatic alteration

Patina

City hall
Boudry (CH, NE)
Pierre jaune
from Neuchâtel

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1d - Chromatic alteration

Patina

Collegiate church
Neuchâtel (CH, NE)
Pierre jaune
from Neuchâtel

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Weathering forms
2/ Chemical and/or mechanical erosion

- Loss of solid particles from the surface of material
- Formation of reliefs, anfractuosities, etc..
- Can be due to water, wind, too aggressive methods of cleaning…

2a - Erosion / Differential erosion

- Erosion of variable intensity on various sectors of the material
- Due to the inhomogeneity of the stone material
- Weathering type common on the sedimentary stones made of different strata
- Takes place in zones exposed to more or less direct water supplies and to wind

2a - Erosion

Differential erosion

A city wall of Fribourg (CH, FR) Burdigalian Molasse sandstone

2a - Erosion

Differential erosion

Bell tower, south side, Lausanne cathedral (CH, VD) burdigalian molasse sandstone

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2b - Erosion / Alveolization

- Appears mainly on very porous materials
- Formation of cavities (alveoles) of variable shapes and sizes (cells, lines, often centimeter size)
- Differential weathering possibly due to inhomogeneity of the stone material
- Appears on the surfaces exposed to strong winds where the crystallization of **salts** occurs underneath the surface, eroding it gradually
- Takes place in zones exposed to direct water supplies and wind

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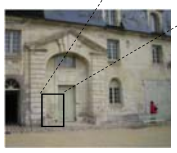
2b - Erosion

Alveolization



Abbaye de Fontevraud
(France)
Loire Valley
Tuffeau stone

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2b - Erosion

Alveolization

Chinon
(France,
Loire Valley)
Tuffeau stone

2c - Erosion / Chemical and/or physical erosion of anthropogen origin

- More or less harmful erosion provoked by cleanings
- According to the chosen process of cleaning, erosion will be mechanical and/or chemical
- Does not strictly depend on the exposure conditions.

2c - Erosion

Anthropogen erosion

Neuchâtel
(CH, NE)
Pierre jaune
from Neuchâtel

2c - Erosion

Anthropogen erosion

Neuchâtel
(CH, NE)
Pierre jaune
from Neuchâtel

2c - Erosion

Anthropogen erosion

Natural History Museum of Neuchâtel (CH, NE)
Pierre jaune of Neuchâtel


Photo C. Félix

Weathering forms
3 - Surface (external) modifications linked to exogenous supplies

3a - Surface modifications linked to exogenous supplies / Crust

- Surface layer, of colour, structure, chemistry and mineralogy different from the substrate
- The constitutive products are exogenous (soots, dust, micro-organisms, salts) and endogenous (calcite, salts).
- At the beginning, the crust sticks very well onto the substrate
- In more advanced stages, it can come off the substrate, which have then a powdering surface
- Formed in sheltered zone, where water can never dissolve and wash materials accumulated on the surface.

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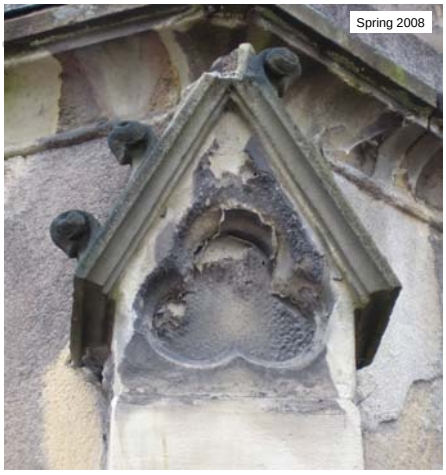
3a – Exogenous (and endogenous) deposits

Crust

Epinal Basilica (France)
Sandstone



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3a – Exogenous (and endogenous) deposits

Crust

(Nancy, France)
Savonnières limestone

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3b - Surface modifications linked to exogenous supplies / Film, pellicle, surface treatment

- Very thin covering or coating layer, usually homogeneous and of organic nature
- More or less easy to remove it from the substrate
- Does not strictly depend on the exposure conditions to water supplies.

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3b - Exogenous deposits

Film (antigraffiti)

D. de Rougemont Lycée, Neuchâtel (CH, NE)
Jaumont limestone

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3b - Exogenous deposits

Film (antigraffiti)

Neuchâtel (CH, NE)
Pierre jaune
from Neuchâtel

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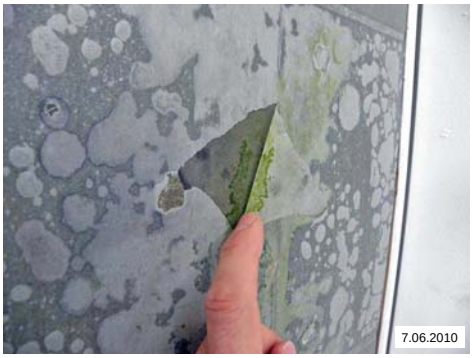
3b – Exogenous supplies

Film (antigraffiti)

Geneva
(CH, GE)
(photo O. Fawer)



3b – Exogenous supplies

Film (antigraffiti)

Neuchâtel (CH, NE) Pierre jaune from Neuchâtel

3b – Exogenous supplies

Film (paint layer)

Lausanne (CH, VD) (photo O. Fawer)

3c - Surface modifications due to exogenous supplies / Graffiti

- Results from the engraving, scratching or application of paint, ink or similar matter on the stone surface
- This phenomenon does not depend on the exposure conditions to water supplies.

3c - Exogenous supplies

Graffiti

Ruelle Vaucher
Neuchâtel (CH, NE)
Pierre jaune from Neuchâtel, bricks & rendering *(crépi)*


Spring 2002

Weathering forms
4 - Modification linked to stone decoherence

4a - Modification linked to stone decoherence / Granular disintegration

- Advanced state of decoherence characterized by the detachment of fragments of stone, grains or crystals under lightest mechanical stimulation
- Considerable reduction in the original mechanical resistance and a marked increase in porosity
- This phenomenon takes place in zones more or less exposed to water supplies

4a - Decoherence

Granular disintegration

Bell tower, west
Lausanne Cathedral
(CH, VD)
Aquitanian molasse sandstone

4a - Decoherence

Granular disintegration

Musée d'Art et d'Histoire
Fribourg (CH, FR)
Statue from the south cathedral portal
Burdigalian molasse sandstone

4b - Modification linked to stone decoherence / Delamination *(délitage)*

- Physical separation of layers, plates, sheets following the bedding planes extension of laminated stones (sedimentary or metamorphic rocks)
- Easily formed when laminated stones are posed with their stratification parallel to the exposed surface
- Phenomenon supported by the presence of soluble salts, micro-organisms, and by cycles of freeze/thaw
- Takes place in zones more or less exposed to water supplies

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4b - Decoherence

Delamination

Salle du Grand Conseil,
Neuchâtel (CH, NE)
Pierre jaune from
Neuchâtel

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4b - Decoherence

Delamination

Morat (CH, FR)
walkway on the
city wall
Burdigalian molasse
sandstone

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4c - Modification by stone decoherence / Scaling *(exfoliation)*

- Detachment of stone layers (scales/*plaques*) parallel to the stone surface BUT not following any stone structure
- These layers have a homogeneous thickness from a few millimetres to a few centimetres
- Takes place in zones exposed to direct water supplies

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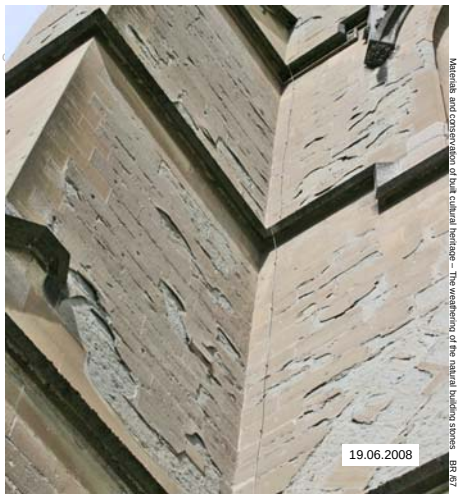
4c – Decoherence

Scaling

Fribourg Cathedral (CH, FR) Burdigalian molasse sandstone



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4c – Decoherence

Scaling

Chaumont castel France, Loire Valley Tuffeau stone

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4c – Decoherence

Scaling (because of water repellent)

Rue de l'Evole Neuchâtel (CH, NE) Burdigalian molasse sandstone

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Weathering forms
5 - Modifications linked to water supplies

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5a - Modification linked to water supplies / Rising damp

- Caused by water absorption by capillarity from the ground at the base of walls or from a surface of retention
- Moisture goes through the walls, wets the internal and external surfaces where a horizontally limited stain is visible
- Takes place in zones where water supplies from the wall bases (or from a surface of retention) are important.

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5a - Water supplies
Rising damp?

Kaysersberg castel, France, Haut Rhin

Kapellbrücke, Luzerne, (CH, LU)

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Weathering forms
6 - Modifications linked to water and salt supplies

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6a - Modification linked to water and salt supplies / Damp patches *(taches humides)*

• The material surface shows wet spots or zones of different color, generally darker

• Can be caused for example by the penetration of water (by rising damp) and/or by the hygroscopic behaviour of salt.

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6a - Water and salt supplies

Damp patches

Ballenberg museum (CH, BE) (farmhouse from Tessin)

Water and salt supplies

Damp patches

Ballenberg museum (CH, BE) (farmhouse from Tessin)

6a - Water and salt supplies

Damp patches

Montheron temple (CH, VD)

6b - Modification linked to water and salts supplies / Subflorescence, efflorescence

• **Subflorescence**: accumulation of salt crystals just under the external surface of building stones. They are HARMFUL: the pressure exerted by crystals can cause damages

• **Efflorescence**: any visible salt deposit on the surface of the building stones (=> LESS HARMFUL) (washed by every water supply)

• Caused by the salt concentration and precipitation in the water evaporation zones

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6a & 6b – Water and salts supplies

Damp patches + efflorescences

Berne (CH, BE)
Nydegg bridge, south side
Burdigalian molasse sandstone

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6b - Water and salts supplies

Efflorescences

City wall of Nancy (France)
Bricks

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6b - Water and salts supplies

Efflorescences

Chur
(CH, GR)

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Weathering forms
7 - Modification of biological origin

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7a - Modification of biological origin / Algae, bacteria

- In general at the stone surface, outside the buildings, but also inside
- Require water (liquid supplies or condensation), a certain luminosity and the adequate nutrients
- Form powdery deposits (more or less visible macroscopically) made up of filaments. They usually are green, red, pink, brown or black.

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7a - Biology

Algae

Lausanne Cathedral (CH, VD) Border between burdigalian molasse sandstone and the dense Arvel limestone

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7a - Biology

Algae

Sully-sur-Loire castel
France, Loire Valley
Tuffeau stone

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7a - Biology

Algae or bacteria

Sully-sur-Loire castel
France, Loire Valley
Tuffeau stone

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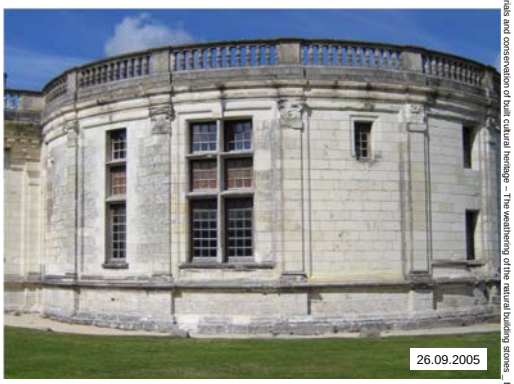
7a – Biology

Algae

Chambord
castel
France,
Loire
Valley
Tuffeau
stone



7b - Modification of biological origin / Lichen, mosse

• **Lichen** develop on the exposed parts of the building stones and present a flaking aspect; they usually are orange, green, gray or black.

• **Moss** develop on the exposed parts of the building stones, in the form of green cushions or of hairy tufts. They plunge their roots in the substrate. These roots produce acids which dissolve certain minerals or the binder of the mortars.

7a & 7b Biology

Algae, lichen

Loches castel, France, Loire Valley, Tuffeau stone

7a & 7b Biology

Algae, lichen, mosses

Neuchâtel Hôtel du Peyrou (CH, NE) limestone

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7a & 7 b Biology

Algae, lichen, mosses

Neuchâtel Rue de la Main (CH, NE) limestone

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7c - Modification of biological origin / Plants

- In the badly-maintained mortars

Or

- On the architectural elements where enough earthy materials can accumulate

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7c - Biology

Plants (grass and shrubs)

Reims Cathedral (France) Limestone

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Weathering forms
8 - Physical and/or mechanical modification

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8a - Physical and/or mechanical modification / Splinter *(éclat, esquille)*

- Fragments of variable shapes and forms, separating from masonry, often starting from corners or from the joints of mortar
- Fragments consist of unchanged material
- Can result from damage caused by the use of a too hard mortar, an accident, vandalism,...

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8a - Mechanical modifications

Splinter

Montheron Temple
(CH, VD)
Burdigalian molasse sandstone

8b - Physical and/or mechanical modification / Bursting *(éclatement)*

- Caused by the swelling of a mortar

Or

- Metal elements inside masonry

8b – Mechanical modifications

Bursting

Epinal Basilica,
France
Sandstone

8b – Mechanical modifications

Bursting

Colombier
(CH, NE)
Pierre jaune

8c - Physical and/or mechanical modification / Crack, fracture *(fissure, fracture)*

• Discontinuity which separates macroscopically one part of the stone of another, with or without relative displacement of the two parts

• Can be limited at the material surface or can affect the material in depth

• Can result from static problems, use of a too hard mortar, accident…

8c – Mechanical modification

Crack, fracture
(frost)

Fribourg
Cathedral
(CH, FR)
Sandstone

8c - Mechanical modification

Crack, fracture
(static)

Prague
(Czech Republic)

Weathering forms cartography

Fig. 30. El-Merdani Mosque, southern wall, Cairo (Egypt).

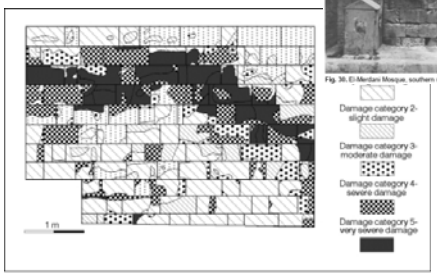

Fig. 31. Map of damage categories. El-Merdani Mosque, southern wall, Cairo (Egypt).

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