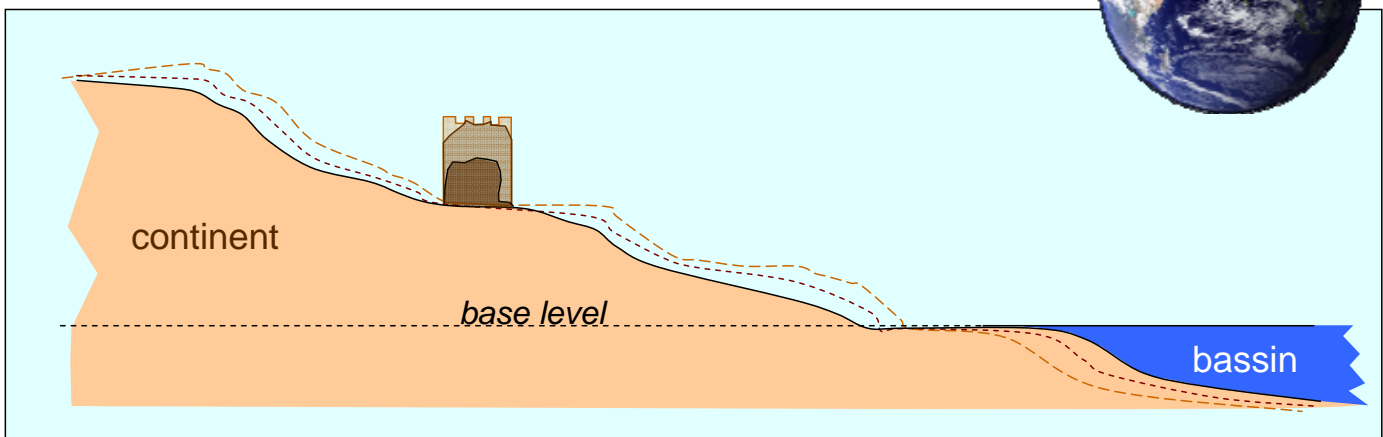




WEATHERING OF NATURAL BUILDING STONES



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 inevitable!**



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

Natural causes	Anthropogen causes	
<ul style="list-style-type: none"> - 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 	<ul style="list-style-type: none"> - air pollution: acceleration and/or modification of natural processes - chemical cleanings - salts brought by agriculture - conservation products - salt-rich mortars 	Physico-chemical
<ul style="list-style-type: none"> - natural disasters (earthquakes, floods, cyclones,...) - frost - wind abrasion - growth of the roots of plants 	<ul style="list-style-type: none"> - shocks (accidents, vandalism) - extraction, cut and laying - use (<i>mise en œuvre</i>) (unsuited stone, layering, orientation, statics) - unsuited materials (too hard mortars) - water damage, fires - mechanical cleanings - wear (<i>usure</i>) 	Mechanical



The weathering causes related to water

Natural causes	Anthropogen causes	
<ul style="list-style-type: none"> - 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 	<ul style="list-style-type: none"> - air pollution: acceleration and/or modification of natural processes - chemical cleanings - salts brought by agriculture - conservation products - salt-rich mortars 	Physico-chemical
<ul style="list-style-type: none"> - natural disasters (earthquakes, floods, cyclones,...) - frost - wind abrasion - growth of the roots of plants 	<ul style="list-style-type: none"> - shocks (accidents, vandalism) - extraction, cut and laying - use (<i>mise en œuvre</i>) (unsuited stone, layering, orientation, statics) - unsuited materials (too hard mortars) - water damage, fires - mechanical cleanings - wear (<i>usure</i>) 	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



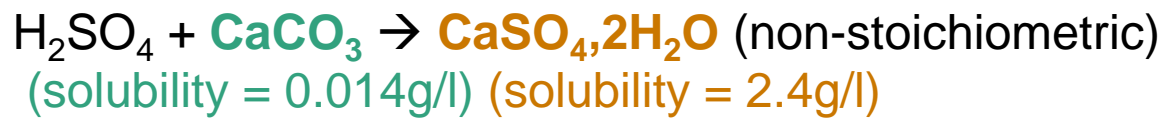
Little history of air pollution and weathering observations

- **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

SO₂ :

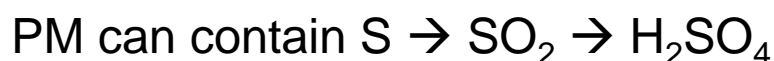


Sources: SO₂ is emitted during the combustion of fuels containing sulphur, such as coal and petroleum



The main air pollutants dangerous for stones

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

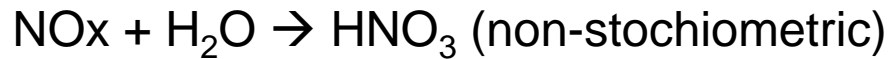


Sources: PM are emitted during the incomplete combustion of fossil fuels or wood and come also from ground/stone erosion, quarries, pollens ...



The main air pollutants dangerous for stones

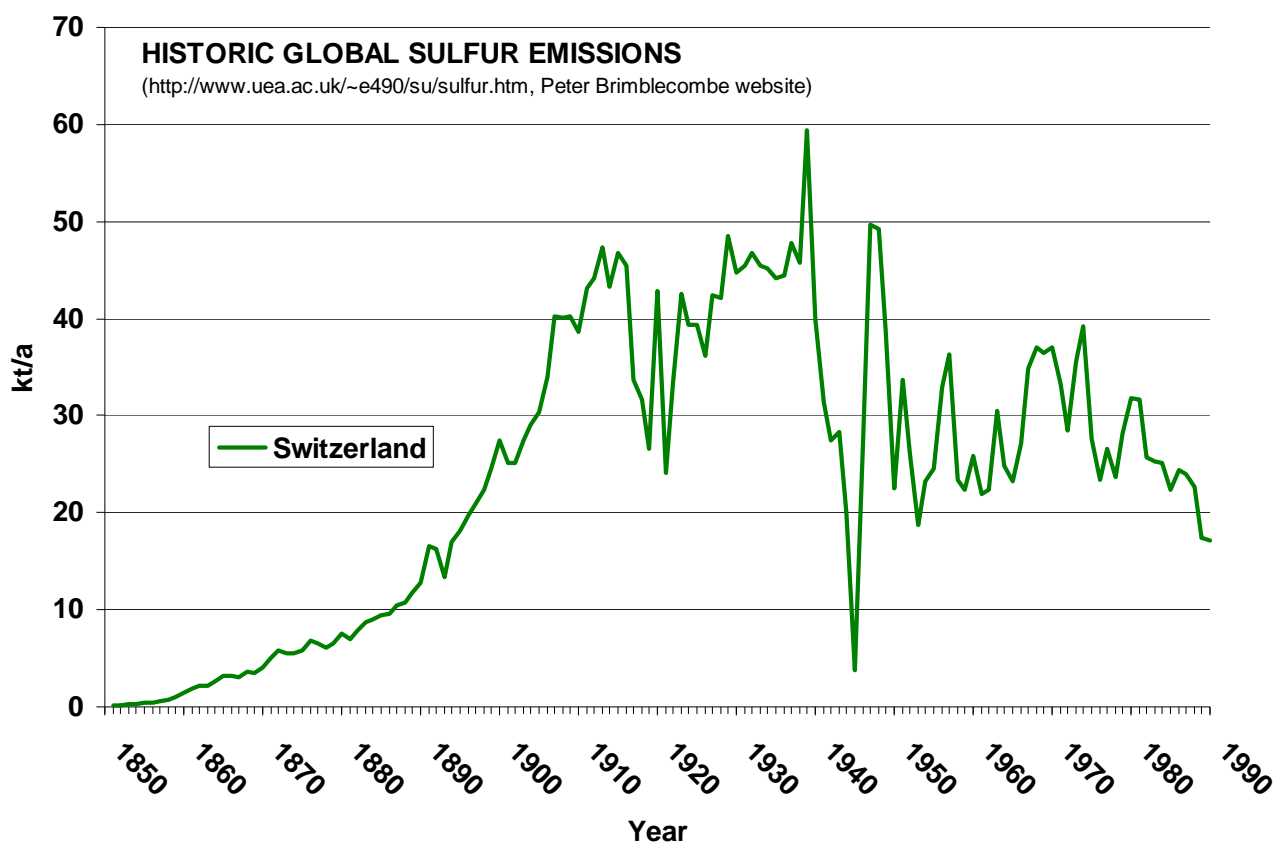
NOx (NO₂ + NO):



Sources: NO₂ is a secondary pollutant formed from NO. NO is formed itself from N₂ and O₂ during the combustion of fuels at high temperature

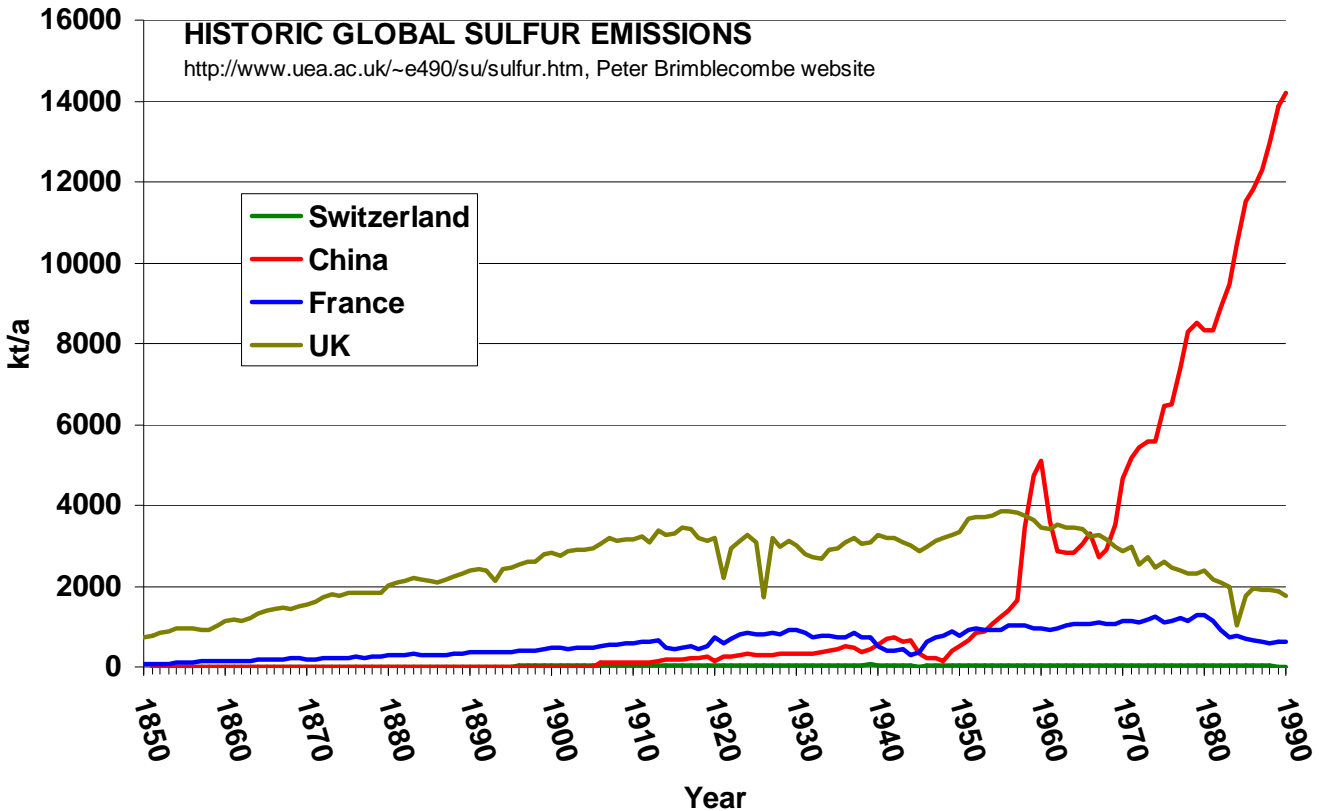


The evolution of the air pollution



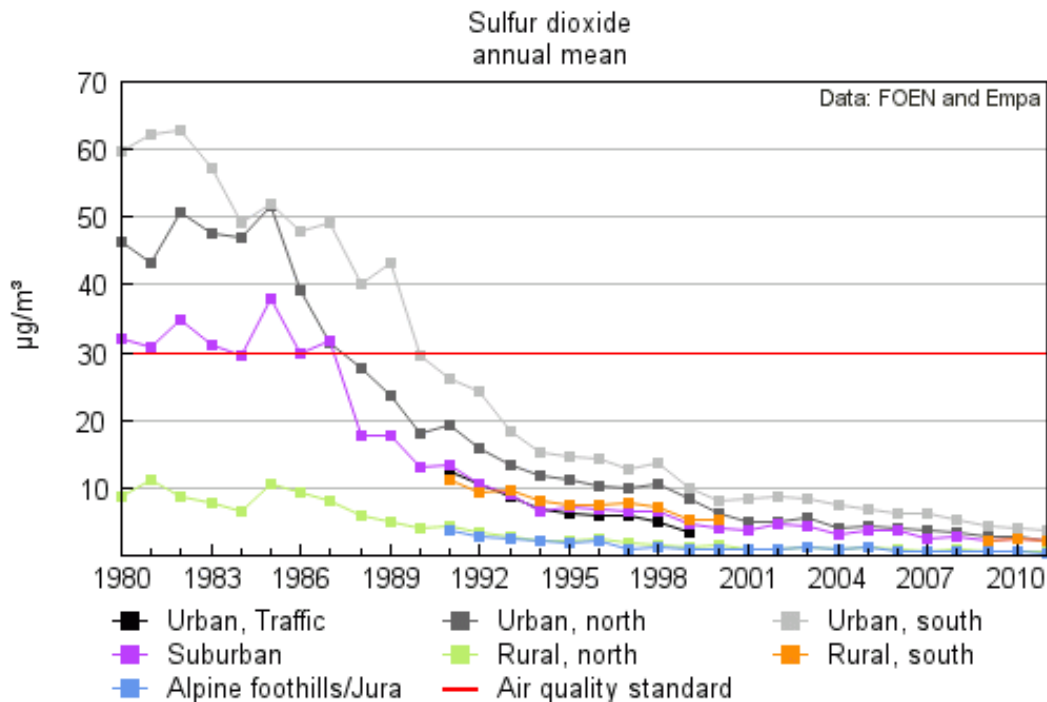


The evolution of the air pollution



The evolution of the air pollution

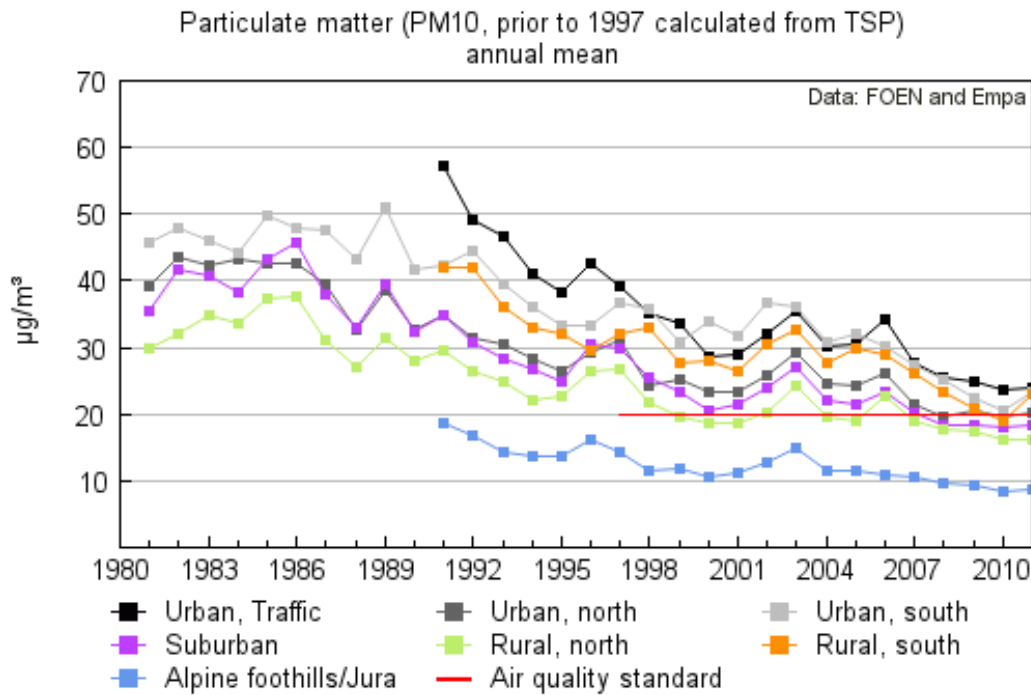
SO₂ concentration in Switzerland from 1980 to 2011





The evolution of the air pollution

PM10 concentration in Switzerland from 1981 to 2011

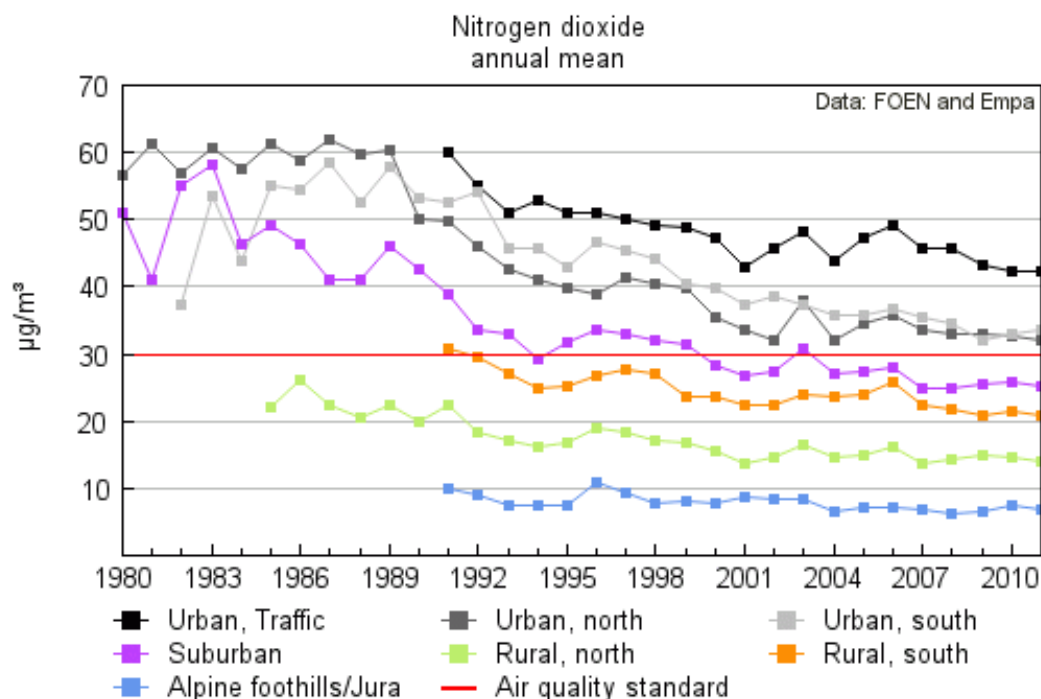


http://www.bafu.admin.ch/luft/luftbelastung/blick_zurueck/01693/09009/index.html?lang=en / 19.9.2012



The evolution of the air pollution

NO₂ concentration in Switzerland from 1980 to 2011



http://www.bafu.admin.ch/luft/luftbelastung/blick_zurueck/01693/09015/index.html?lang=en / 19.9.2012



Weathering forms and mechanisms

The weathering factors modify:

- the chemistry
- the mineralogy
- the porosity structures

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)
- **exposure on the building** (which controls the water and pollutant supplies)

=> Identical weathering forms are observed on stones of various nature



Chromatic alteration



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.



Chromatic alteration

Stains

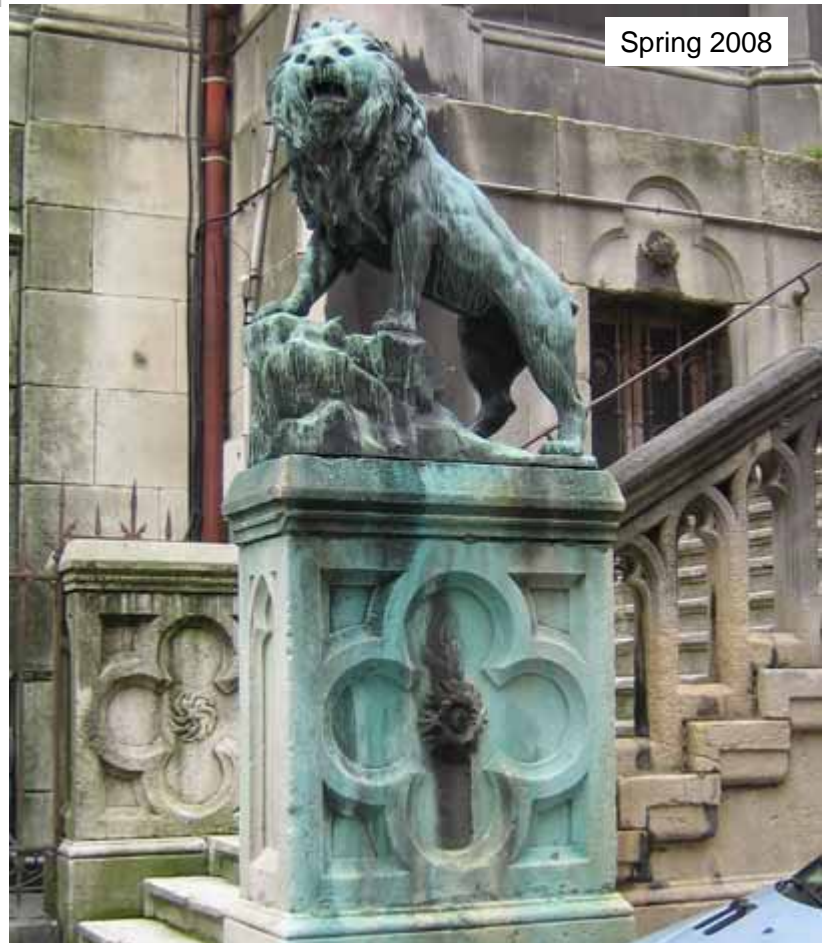
Cressier (CH, NE)
Pierre jaune
from Neuchâtel



Chromatic alteration

Stains

Nancy Cathedral
(France)
Limestone





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.



Chromatic alteration

Discolouration

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





Spring 2008

Chromatic alteration

Discolouration

Epinal Basilica
(France)
sandstone



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.



April 2003

Chromatic alteration

Red staining

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



13.07.2009

Chromatic alteration

Red staining

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





Chromatic alteration / Patinas

- Black to brown
- 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



Chromatic alteration

Patina

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





Conservation Science Consulting

13.07.2009

Chromatic alteration

Patina

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



Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /31



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Erosion

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /32



Chemical and/or mechanical erosion

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



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)



Erosion

Differential erosion

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



Erosion

Differential erosion

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

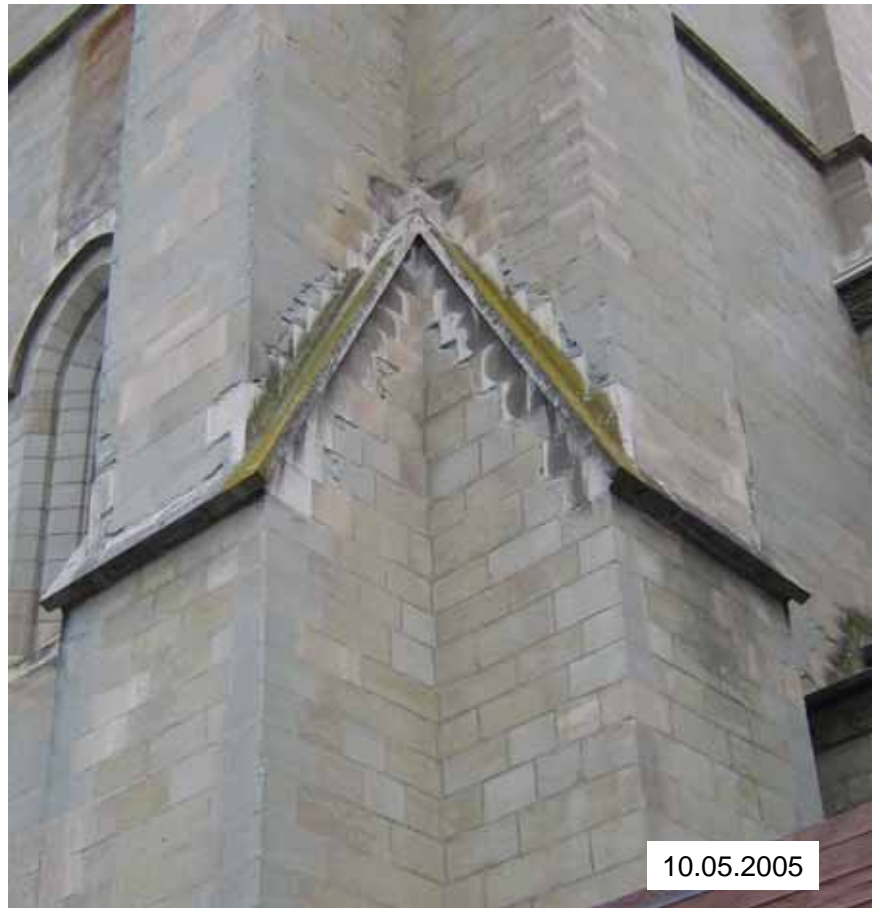




Erosion

Differential erosion

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



Erosion / Alveolization

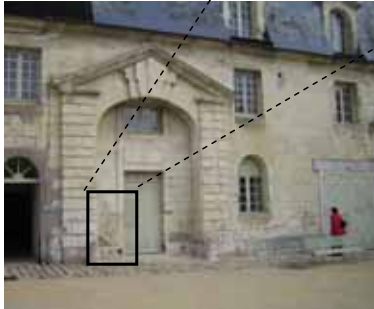
- Appears mainly on very porous materials
- Formation of cavities (alveoles) of variable shapes and sizes (cells, lines, often centimeter size)
- Differential weathering possibly due to inhomogeneity of the stone material
- Appears on the surfaces exposed to strong winds where the crystallization of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



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Erosion

Alveolization



Abbaye de Fontevraud
(France)
Loire Valley
Tuffeau stone



Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /39



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Erosion

Alveolization

Chinon
(France,
Loire Valley)
Tuffeau stone



Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /40



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.



Erosion

Anthropogen erosion

Neuchâtel
(CH, NE)
Pierre jaune
from Neuchâtel





Erosion

Anthropogen erosion

Neuchâtel (CH, NE)
Pierre jaune
from Neuchâtel



Erosion

Anthropogen erosion

Neuchâtel
(CH, NE)
Pierre jaune
from Neuchâtel





Erosion

Anthropogen erosion

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



Photo C. Félix



Surface (external) modifications linked to exogenous supplies



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.



Exogenous (and endogenous) deposits

Crust

Neuchâtel
Jehanne-de-Hochberg
street, (CH, NE)
Pierre jaune of Neuchâtel



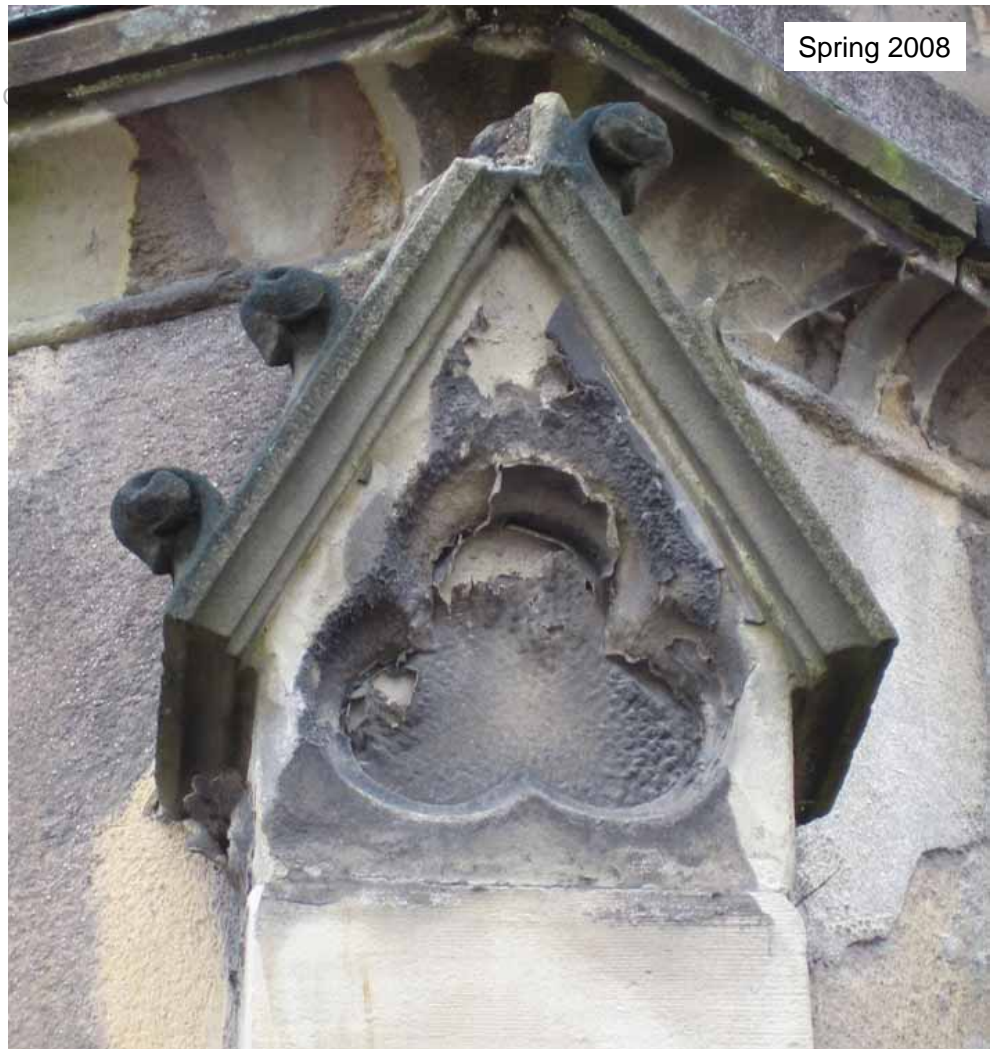


Spring 2008

Exogenous (and endogenous) deposits

Crust

Epinal Basilica
(France)
Sandstone



Spring 2008

Exogenous (and endogenous) deposits

Crust

(Nancy, France)
Savonnières
limestone





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.



Exogenous deposits

Film (antigraffiti)

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



Spring 2002



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Exogenous deposits

Film (antigraffiti)

Neuchâtel (CH, NE)
Pierre jaune
from Neuchâtel



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Exogenous supplies

Film (antigraffiti)

Neuchâtel
(CH, NE)
Pierre jaune
from Neuchâtel



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Exogenous supplies

Film (antigraffiti)

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



Exogenous supplies

Film (paint layer)

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





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.



Exogenous supplies

Graffiti

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





Modification linked to stone decoherence



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



Decoherence

Granular disintegration

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



Decoherence

Granular disintegration

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





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



Decoherence

Delamination

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





Decoherence

Delamination

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



21.06.2009



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

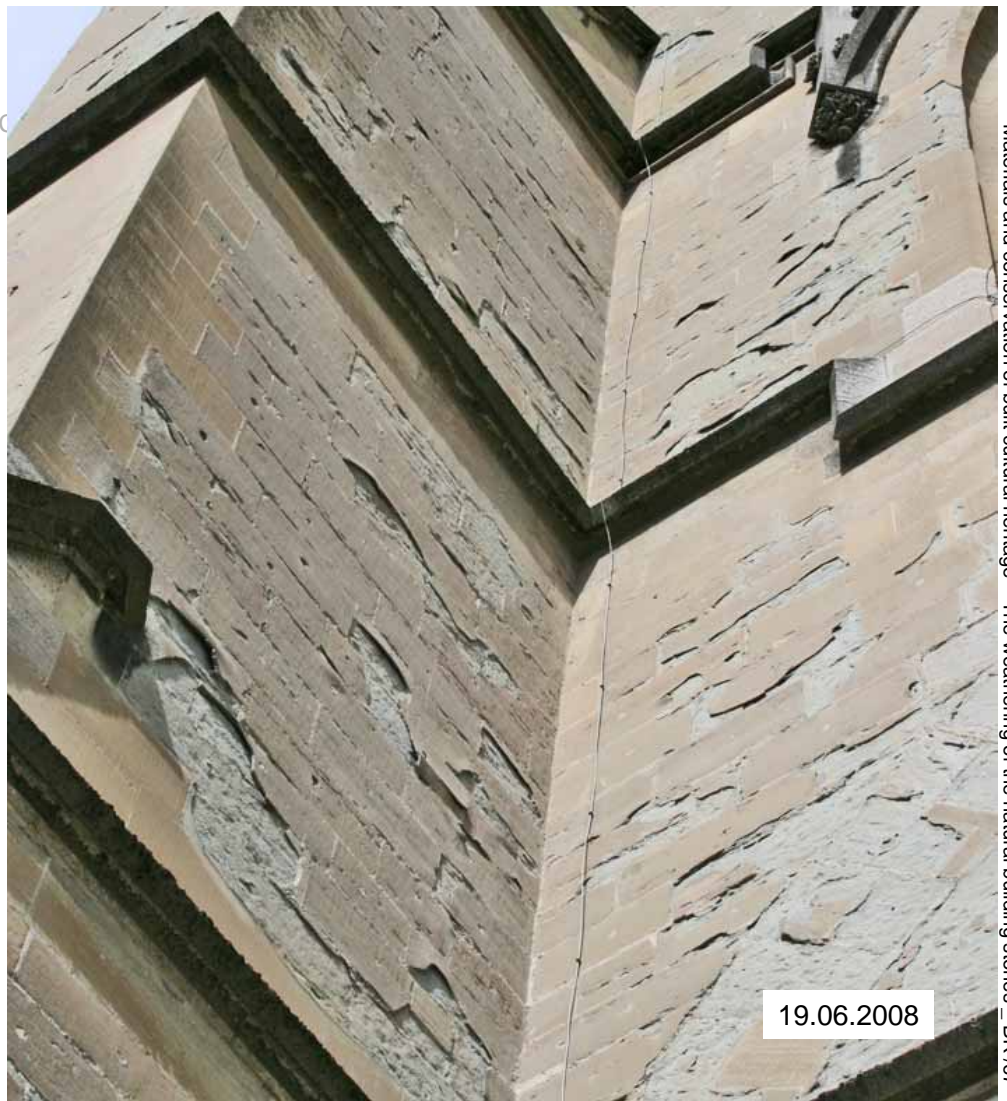


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Decoherence

Scaling

Fribourg
Cathedral
(CH, FR)
Burdigalian
molasse
sandstone



19.06.2008

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /67

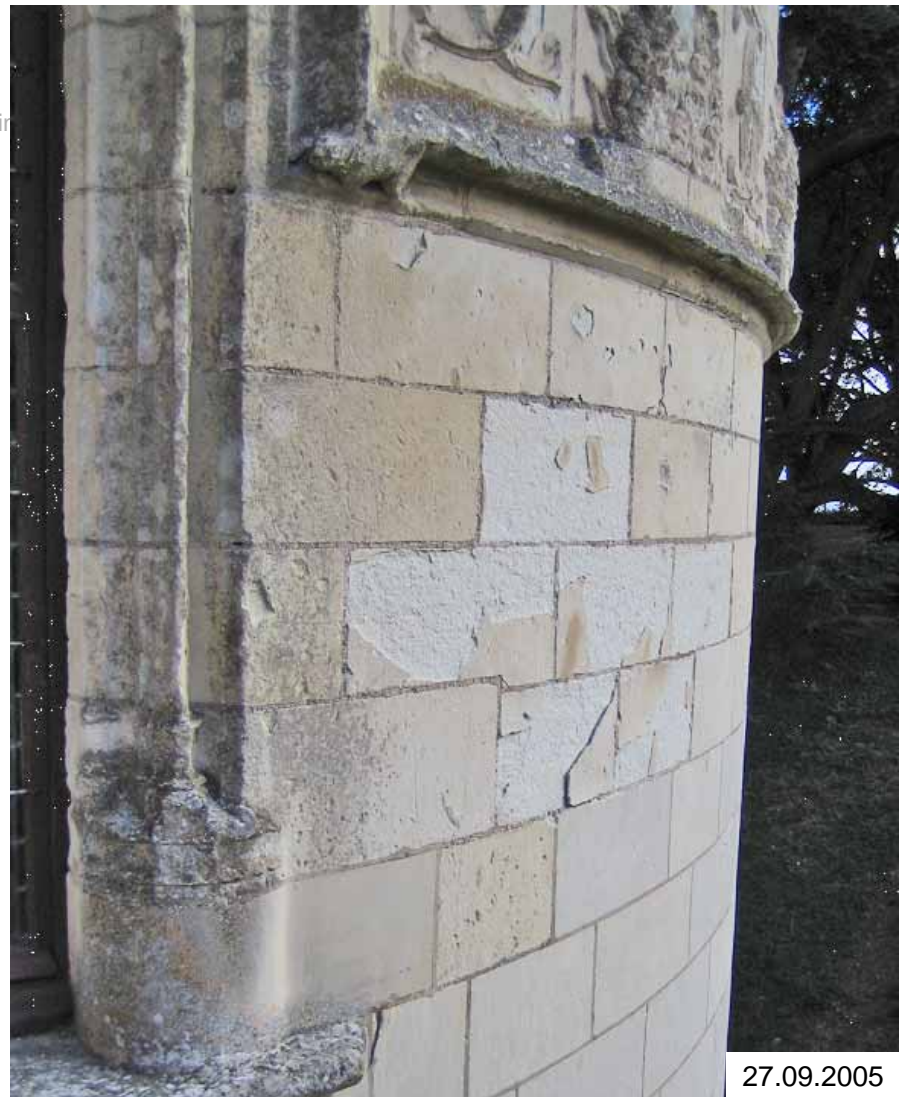


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Decoherence

Scaling

Chaumont castle
France, Loire Valley
Tuffeau stone



27.09.2005

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /68



Decoherence

Scaling (because of water repellent)

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



Modifications linked to water supplies



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.



Water supplies

Rising damp? (remontées capillaires ?)

Kaysersberg castel,
France, Haut Rhin



Kapellbrücke, Luzerne,
(CH, LU)





Modifications linked to water and salts supplies



Modification linked to water and salts 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.



Water and salts supplies

Damp patches

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



Water and salts supplies

Damp patches

Montheron temple
(CH, VD)





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



Water and salts supplies

Damp patches + efflorescences

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





Water and salts supplies

Efflorescences

City wall of Nancy
(France)
Bricks



Water and salts supplies

Efflorescences

Chur
(CH, GR)





Modification of biological origin



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.



Biology

Algae

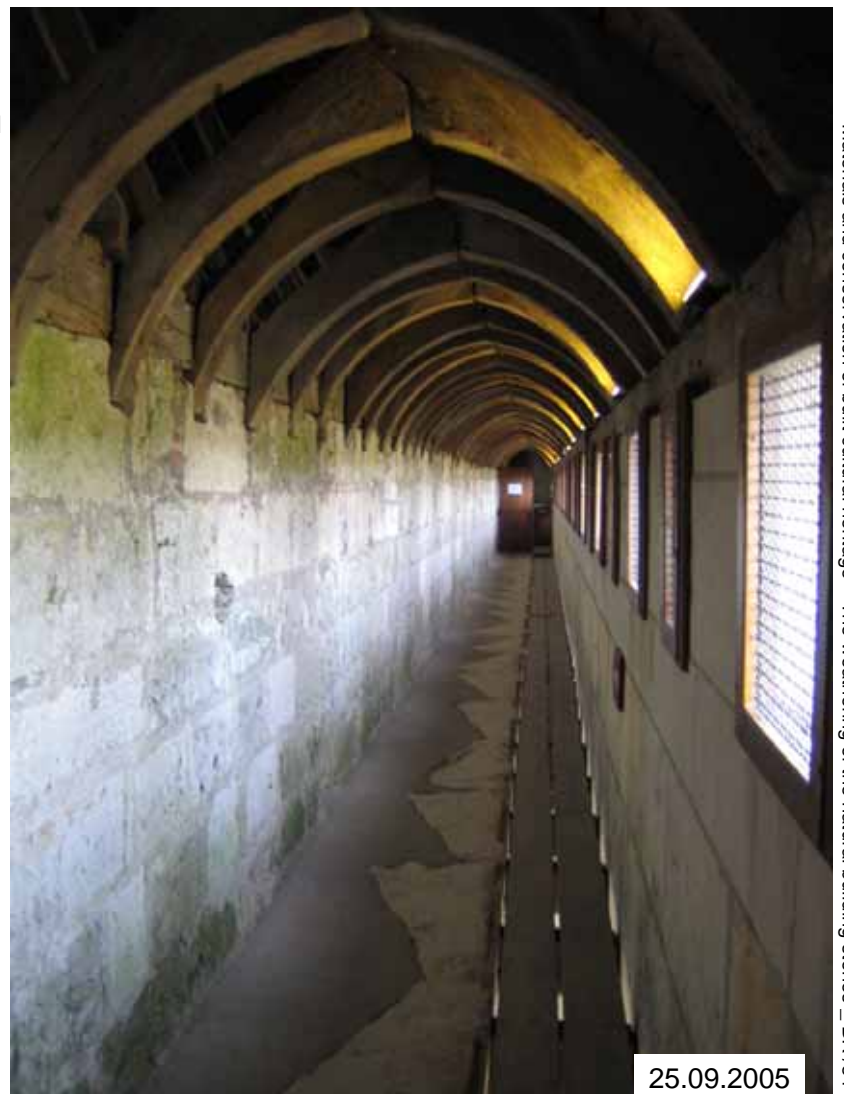
Lausanne
Cathedral (CH, VD)
Border between
burdigalian molasse
sandstone and
the dense
Arvel limestone



Biology

Algae

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





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Biology

Algae

Epinal Basilica
France
Sandstone



Spring 2008

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /85



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Biology

Algae or bacteria

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



25.09.2005

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /86



Biology

Algae

Chambord
castel
France,
Loire
Valley
Tuffeau
stone



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.



Biology

Algae, lichen

Loches
castel,
France,
Loire
Valley,
Tuffeau
stone



Biology

Algae, lichen, mosses

Neuchâtel
Hôtel
du Peyrou
(CH, NE)
limestone





Biology

Algae, lichen, mosses

Neuchâtel
Rue de
la Main
(CH, NE)
limestone



Modification of biological origin / Plants

- In the badly-maintained mortars

Or

- On the architectural elements where enough earthy materials can accumulate



Biology

Plants

(grass and shrubs)

Reims Cathedral
(France)
Limestone



Biology

Plants

(ivy)

Neuchâtel,
Rue du Château,
Pierre jaune





Physical and/or mechanical modification



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,...



Mechanical modifications

Splinter

Montheron Temple
(CH, VD)
Burdigalian molasse
sandstone



Physical and/or mechanical modification/ Bursting (*éclatement*)

- Caused by the swelling of a mortar
- Or
- Metal elements inside masonry



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Mechanical modifications

Bursting

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



Photo C. Félix

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Conservation Science Co

Mechanical modifications

Bursting

Epinal Basilica,
France
Sandstone



Spring 2008

Materials and conservation of built cultural heritage – The weathering of the natural building stones _ BR /100



Mechanical modifications

Bursting

Colombier
(CH, NE)
Pierre jaune



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...



Mechanical modification

Crack, fracture (frost)

Fribourg
Cathedral
(CH, FR)
Sandstone



Mechanical modification

Crack, fracture (static)

Prague
(Czech Republic)





Weathering forms cartography

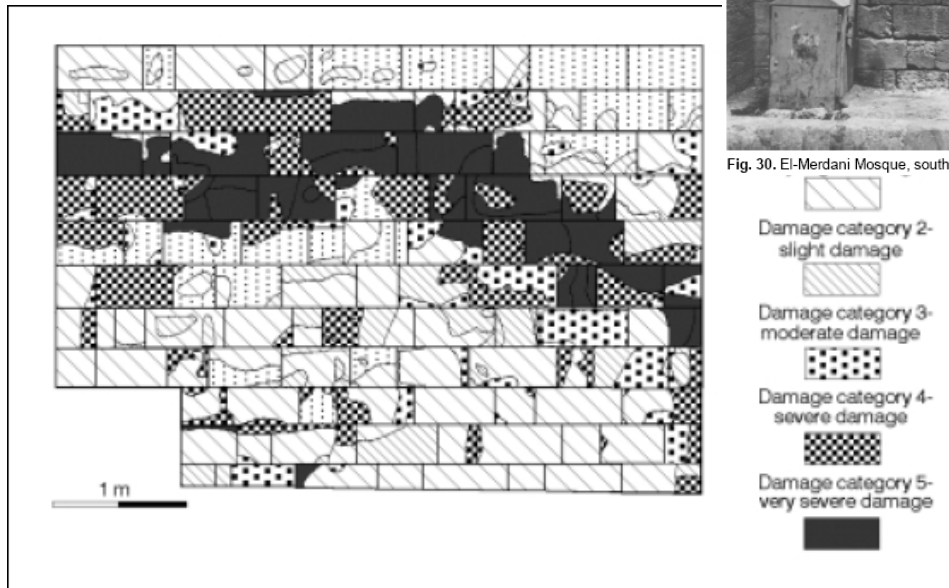


Fig. 31. Map of damage categories. El-Merdani Mosque, southern wall, Cairo (Egypt).



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



FITZNER B., HEINRICH K., 2002. Damage diagnosis on stone monuments – weathering forms, damage categories and damage indices. In R. Prikryl & H.A. Viles (eds), *Understanding and managing stone decay*. The Karolinum Press, Charles University in Prague p11-56



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Elements (international magazine) "Atmospheric Particles", August 2010, vol. 6, No 4 (<http://elements.geoscienceworld.org/content/vol6/issue4/index.dtl>)

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