SPALLING OF TUFFEAU LIMESTONE: STATISTICAL ANALYSIS OF SAMPLES FROM THE CASTLE OF CHAUMONT-SUR-LOIRE, FRANCE

K. BECK[1], V.CHEGANI[1], W. KLOPPMANN[2], S. JANVIER-BADOSA[3], A. DUFOUR[4], X. BRUNETAUD[1],

(1) Univ. Orléans, LaMé, Orléans, France (kevin.beck@univ-orleans.fr ; xavier.brunetaud@univ-orleans.fr)
(2) BRGM, Orléans, France (w.kloppmann@brgm.fr)
(3) Univ. Lorraine, CNRS, IJL, Nancy, France (sarah.janvier@univ-lorraine.fr)
(4) Univ. Orléans, CETRAHE, Orléans, France (audrey.dufour@univ-orleans.fr)

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Context

Tuffeau stone is the typical building stone of the famous castles of the Loire Valley, as the castle of Chambord or castle of Chaumont-sur-Loire. Tuffeau is a soft and white fine-grained sedimentary limestone, containing calcite, quartz, opal, micas and clay minerals, with high porosity about 45% and a low strength about 5-10 MPa. Spalling is a major degradation of tuffeau that involves the progressive cracking inside the stone and progressive separation of a plate of stone, parallel to the surface exposed to the environment. The morphology of the spalling observed in the constructions in tuffeau in the Loire Valley is generally the same, even if the thickness of the plate can vary from a few millimetres to a few centimetres. The mechanisms of formation of spalling in case of tuffeau are not well defined.

Castle of Chaumont-sur-Loire

Example of spalling on tuffeau stone

3D model and ortho-projections

The 3D survey consisted in a photogrammetric acquisition with images taken by a 20 Mpx camera aboard a drone DJI Mavic pro 2. About 4500 photos are used in the photogrammetric process for 3D reconstruction for the exteriors of the castle of Chaumont-sur-Loire. This dataset was processed using the photogrammetry software solution Reality Capture. For the mapping, the numbering of the facades was done with the following procedure: the numbering begins with the facade of the main entrance door (facade No. 1), and then the numbering progresses clockwise from the top view. Round towers generate one façade but several orientations.

3D model in point cloud of the castle of Chaumont-sur-Loire
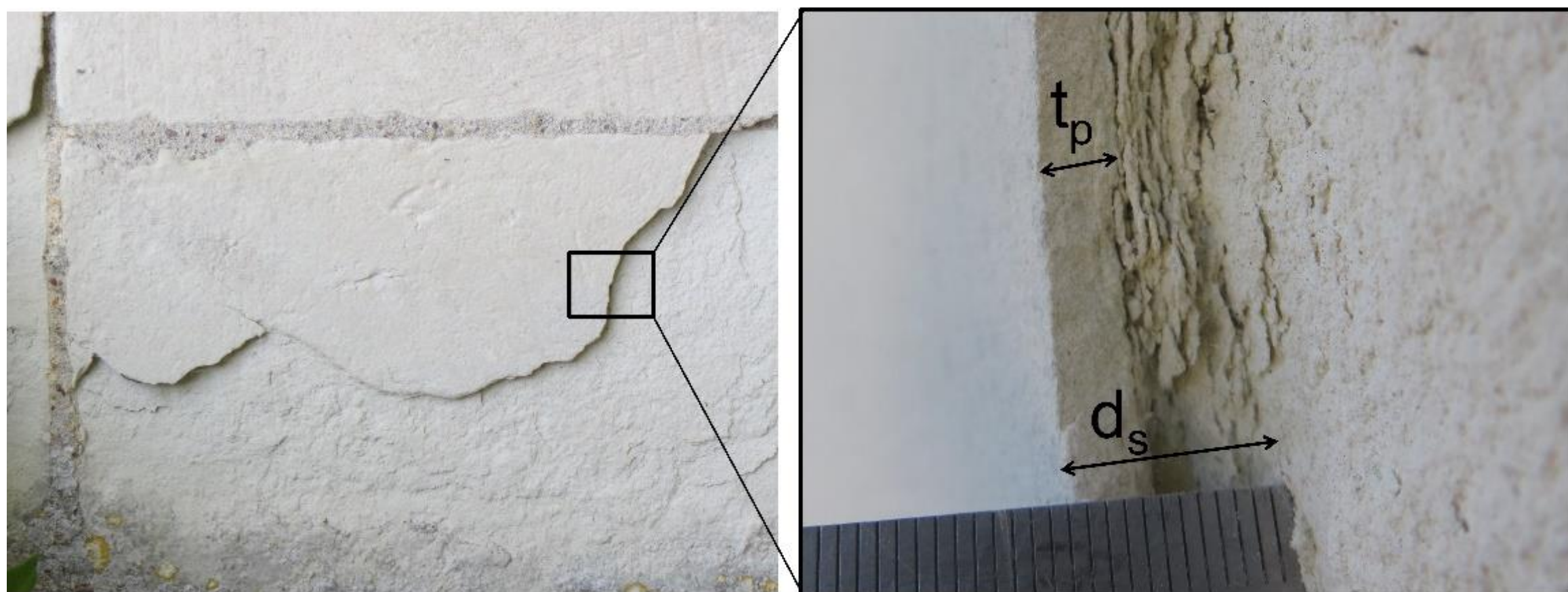

Overview of the castle

Top view of the 3D model showing the numbering of the facades

Delimitation of orientations for the round towers

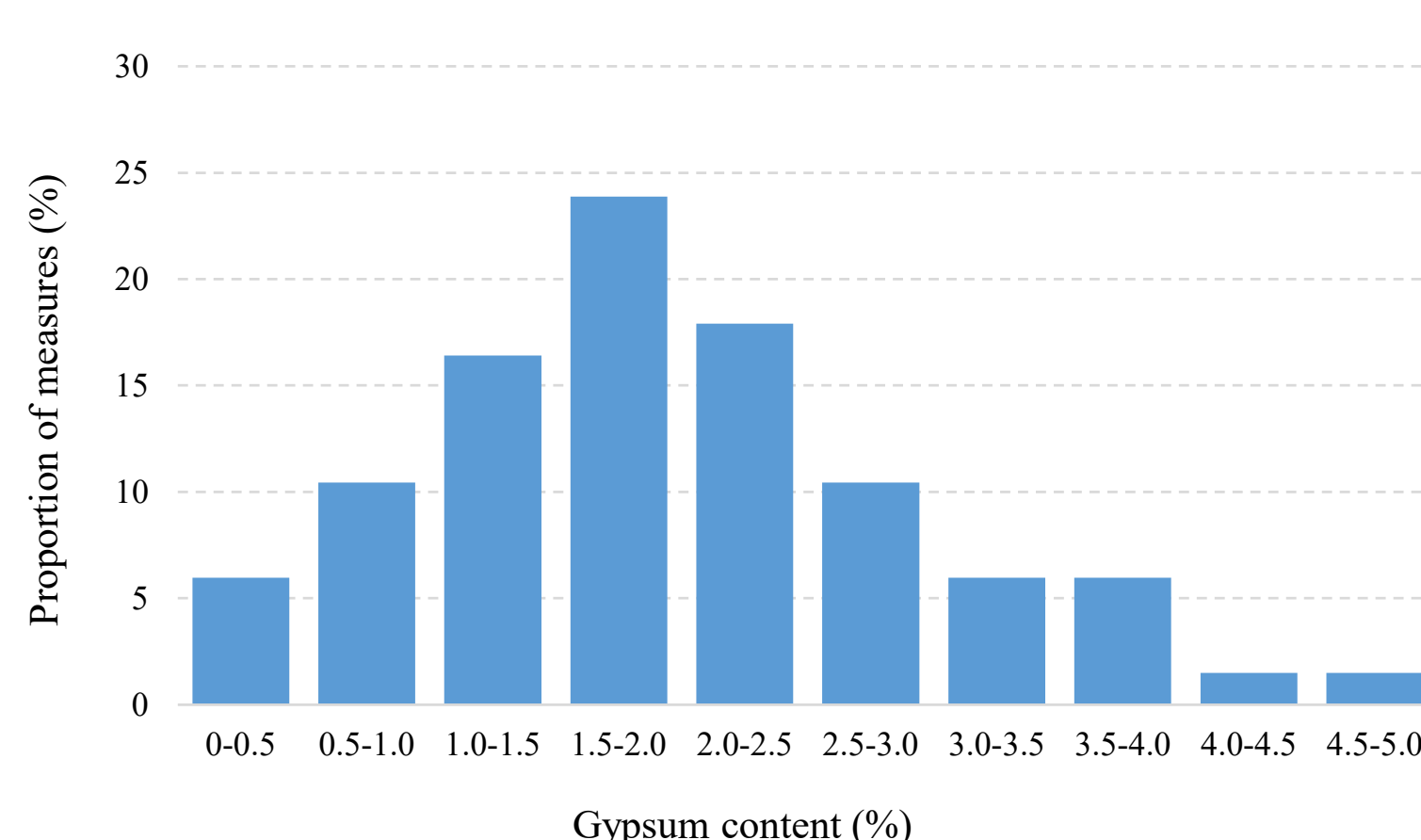## Statistics of spalling morphology and gypsum content

An amount of 75 samples were collected in the most representative degraded stone of each area. For each area, the number of stones degraded by spalling is recorded, as well as the thickness of the plate and the total depth of spalling. The mineralogical characterization of samples was performed by X-ray powder diffraction (XRD). The soluble compounds were quantified via aqueous phase ionic chromatography, and sulfate SO_4^{2-} anions to determine gypsum content.

Example of spalling on the stone from the castle of Chaumont-sur-Loire with a view of the thickness of the plate "t_p" and the total depth of spalling "d_s"

	thickness of the plate "t_p"	depth of spalling "d_s"	number of stones degraded per area	Gypsum content
	(mm)	(mm)		(%)
Average (± standard deviation)	3.9 (± 1.3)	10.2 (± 5.5)	5.1 (± 4.8)	1.9 (± 0.9)
Minimum value	2.0	4.0	1	0.2
Maximum value	8.0	32.0	26	4.8

Statistics of spalling morphology of tuffeau (castle of Chaumont-sur-Loire)

Distribution of gypsum content among the 75 samples collected in powdery zone of spalling
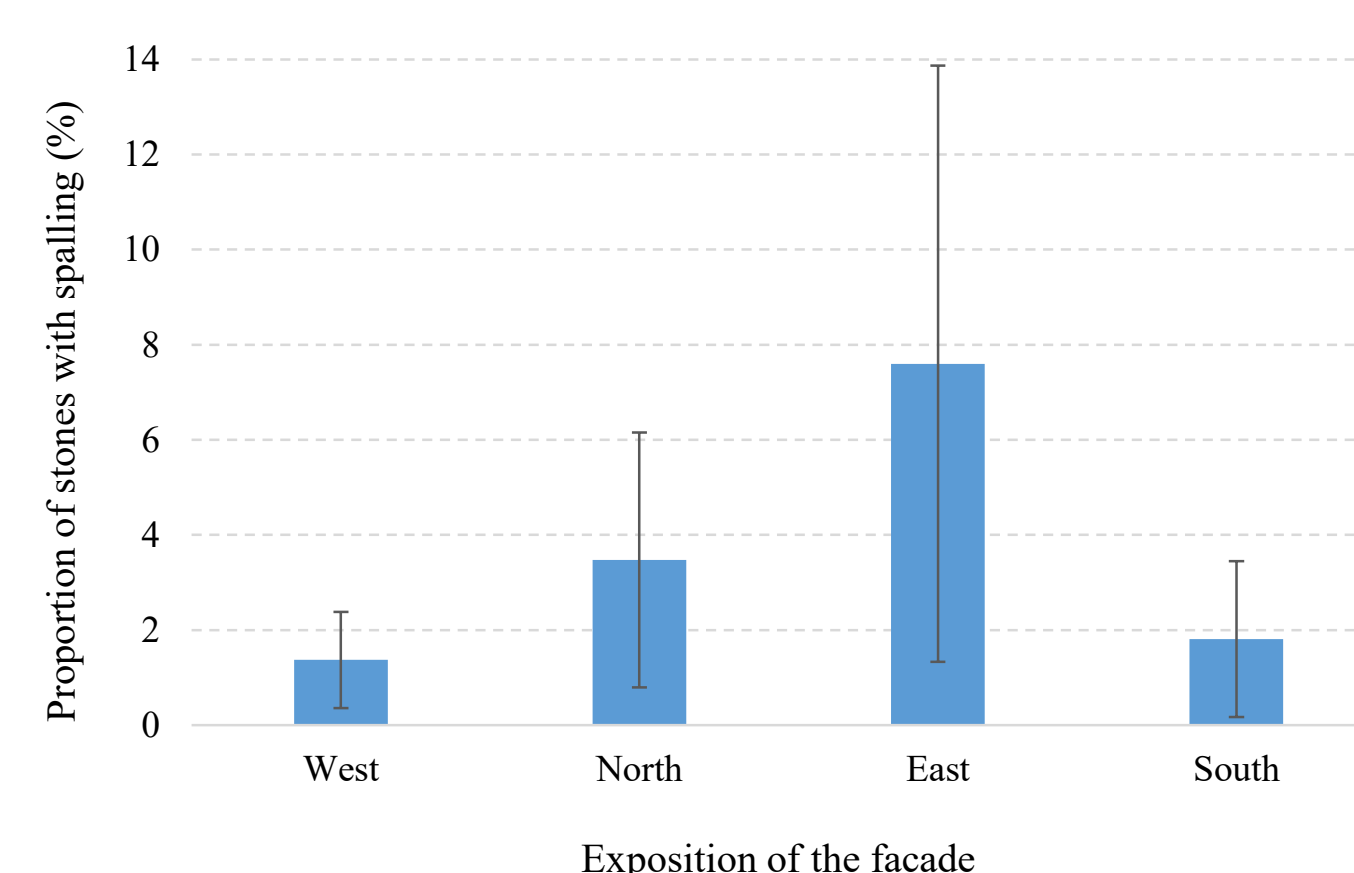
The thickness of the plate t_p is nearly constant with an average value of 3.9 mm.
The total depth of spalling d_s is quite dispersive with an average value of 10 mm.
The gypsum content has an average value of 1.9% where almost 40% of gypsum content are between 1% and 2%.
Spalling can affect only a single stone as well as a continuous set of several stones

Degradation mapping and role of the orientation in the presence of spalling

From the 3D model, 34 maps resulting from ortho-projection of the oriented wall was established for degradation patterns made with QGIS, open-source software. The various layers represent the total surface area of the stone masonry, the total surface area of the degraded stones showing spalling.
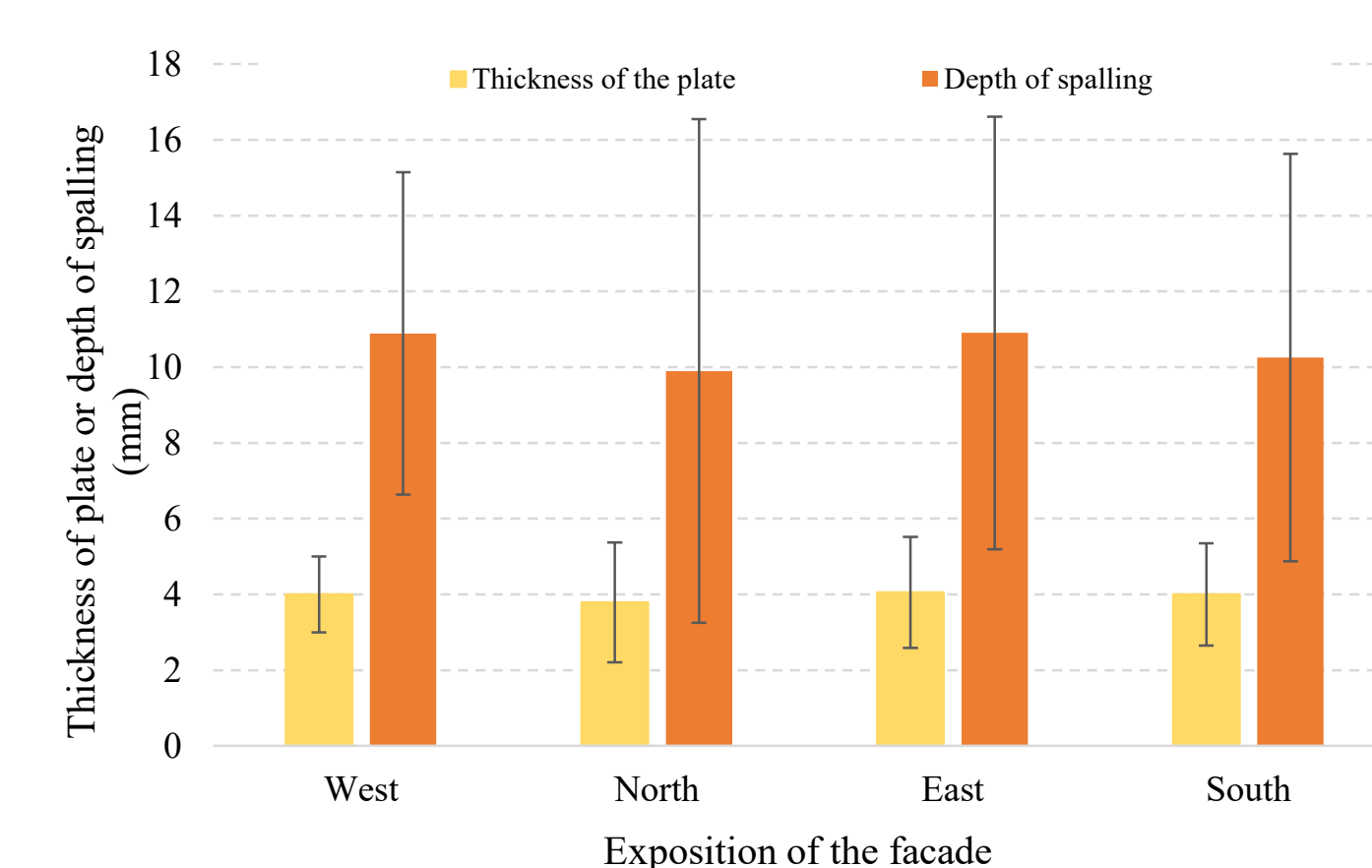

Orthoprojection of the façade No.13 with degradation mapping (QGIS)

Proportion of stones with spalling according to the exposition of the façade from QGIS measurement

Gypsum content according to the exposition of the façade

Spalling morphology according to the exposition of the façade

A total of 917 degraded stones by spalling were counted for all the facades. No significant difference between the spalling morphology is observed according to the orientations, as well as the gypsum content. More spalling was observed in the degraded areas facing east. But observation of the castle shows that the eastern facades are the least restored.

Conclusion :

This statistical study highlights the typical morphology of spalling of tuffeau on the castle of Chaumont-sur-Loire with a thickness of the plate about 4 mm, a depth of spalling about 10 mm, and a gypsum content in the flaked and cracked zone about 2%. Concerning the role of the orientation in the presence of spalling, no real correlation between spalling and external parameters such as exposure to North, South, East, West are shown. These observations lead to questioning the possible role of gypsum, the exposure to water and the mineralogical composition of degraded stones (clay content) for the formation of spalling.