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# ULTRASOUND TOMOGRAPHY AND 3D SCANNING TECHNOLOGIES AS A TOOL TO CONSTRAIN THE WEATHERING STATE OF OBJECTS MADE OF MARBLE

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## Abstract:

In recent years, the digitization of cultural assets plays an increasingly important role. While objects' surfaces can be displayed in high quality using 3D scanning technology; ultrasound tomography can be applied to monitor the internal state of deterioration. The combination of both techniques to document and evaluate the weathering condition of relevant objects is presented, to demonstrate its effectiveness.

Columns made of Prieborn and Kauffung marble as well as sculptures made of Carrara marble have been analyzed. In addition, conventional, manual decay mapping was applied to verify the benefits of the 3D reconstruction in this context.

The automatic preparation of textured surfaces can support and improve the quality of documentation techniques. Three dimensional digital models can serve as an intuitive frame for documentation purposes in the context of conservation and restoration. The combination of tomographic investigations and 3D-reconstruction can improve the accuracy of the weathering evaluation. The 3D-scanning technology provides an easier, contactless, faster and more precise documentation as compared to manual decay mapping. In order to capture the 3D geometry, the Fringe Projection Structured Light method has proven to be a viable approach to quality and practicality. Especially for statues and structural building elements the continuous monitoring of their deterioration degree is desirable. The investigations have shown, that quality and degree of detail achievable with recent digitization technologies can support, simplify and improve scientific investigations.

## Introduction

Potsdam (Germany) is famous for its cultural heritage. Many of the impressive buildings and statues in the parks of the Prussian Palaces and Gardens Foundation are made of marble. In order to scrutinise the application of 3D scanning techniques in combination with the ultrasound tomography under environmental conditions, marble columns of the Marmorpalais in Potsdam, have been investigated. The marble varieties used for the palace are from former Silasia (i. a. Kauffunger, and Prieborner marble) as well as Italy (Carrara marble). Two columns from this site have been reinvestigated, one made of Prieborner marble which is located close to the lake Heiligen See and one column of Kauffunger mable, located in the inner courtyard.

Here, ultrasonic velocities have been measured at different levels and are discussed by comparing their spatial distribution with the results of the traditional manual decay mapping and a 3D scan. The range within the velocities is caused by extrinsic effects as different weathering degrees and structural weaknesses as well as the intrinsic influences caused by the anisotropy of the marbles themselves. As both marble varieties are colourful and show a less complex shape, additionally, different sculptures from the Skulpturenhalle, made of white Carrara marble have been analysed too, with the focus on improving the scanning technique.

## Marble decay

The main decay phenomena for the homogeneous, fine-grained whitish Carrara and greyish Prieborn calcite marble is the back-weathering of the surface associated with a penetrative degradation of the whole fabric. This deterioration is initiated by a decohesion of the polygonal grain to grain contacts, caused by crack growth and finally the loss of material, producing a coarse surface. In the late stages, so-called sugaring will be the consequence. In contrast, the fine-grained Kauffunger marble with its seriate to interlobate grain fabric shows different back-weathering phenomena. Weathering is concentrated on preexisting crack systems, which have been mineralised or sealed within the formation of this type of calcite marble. Pitting can be found more frequently between already open macrocracks.

## Characterization techniques

### *Mapping*

Both marble columns have already been mapped in detail (1 : 1 scale) by Ruedrich et al. (2001). To determine the macroscopically visible structures, those maps were used to analyze the orientation of the foliation (layering), fracture populations and the crack densities. The Prieborn marble exhibits a foliation by alternating dark- and light layers, which developed a strong relief due to different back-weathering intensities. In 2019 this relief was no longer visible, as different conservation measures have been performed within the last 18 years. The mapping (Fig. 1a) showed an open crack system (C1) and a predominantly sealed crack population (C2). In contrast, the very

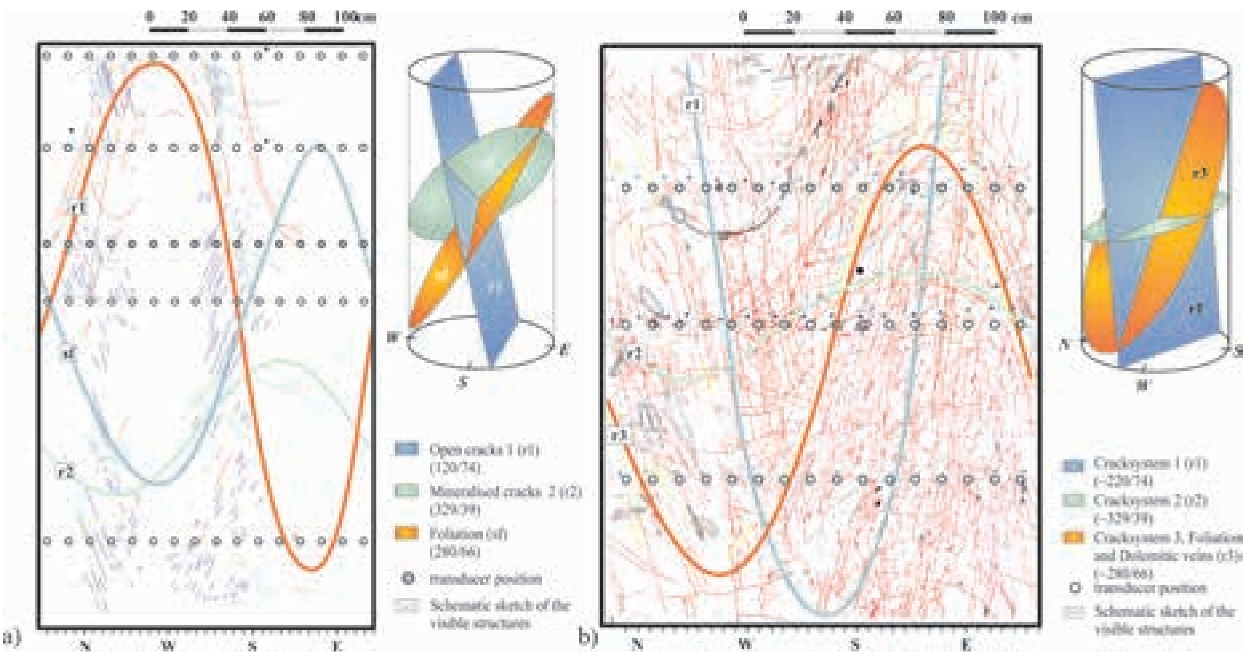


**Figure 1**: Mapping of visible structures and decay phenomena for the Prieborn column (a) and the Kauffung column (b) modified after Rüdrich 2001.

heterogeneous, fine-grained calcitic Kauffunger marble is transected by fine-grained yellow to reddish irregular calcitic and subordinately dolomitic veins. The foliation is crosscut by two different systems and accompanied by one system of healed and open cracks, which are schematically shown in Fig. 1b. This marble shows an intense cataclastic fabric, where most of the cracks are sealed. As for the Prieborn column, restoration measures have also been applied to this column.

### *3D-Scanning Technologies*

In order to achieve 3D reconstructions, several technologies are common. Time-of-flight methods send laser pulses and measure the time it takes to reflect them off the object's surface to the receiver. From this information, the distance of the object to the sensor and its geometry can be estimated. These methods are user-friendly and fast, but the data generated in this way may not provide the quality of depth information required in the field of cultural heritage. In particular, large angles between the object surface and the viewing direction can cause problems. Reconstructing certain colors and surfaces can also be difficult. For example, in the case of marble objects, subsurface scattering can falsify the measured depth information (Levoy et al. 2000).

Optical measurement techniques with one or more cameras are somewhat more complex in application, but can achieve significantly higher accuracy in certain scenarios. Standard Structure-from-Motion techniques depend on conspicuous feature points that need to be detected in the camera images and are not always available. The structured light approach, which uses a projector in addition to the cameras, is suitable for circumventing this problem. The active device projects several patterns onto the scene in order to encode the surface independent from features. In this way, dense correspondences can be generated between the cameras and the projector, enabling high precision reconstructions even of uniformly colored objects. In the scenario of marble objects discussed here, it was found that the influence of subsurface scattering on the method is negligibly low and hardly influences the quality of the result. In addition, the influence of object colors and material properties can be further reduced by newly developed methods such as described in Fetzer et al. (2020a). The method of choice in terms of accuracy and applicability has been a structured light approach with two cameras and a projector using multiple frequencies of phase-shifted sine waves for surface coding (further details can be found in Zhang and Yau 2008).

### *Ultrasound tomography*

To characterize the inner state of weathering, ultrasonic measurments have been applied in a tomographic approach (e. g. Menningen et al. 2018). The basic principle of ultrasonic analyses is that the magnitude of the rock degradation is monitored by decreasing Vp according to increasing porosity (e. g. Weiss et al. 2002). Therefore, the P-wave velocities were measured by transducers of 350 kHz. An array of 16 transmitter and reciever positions was oriented along the horizontal plane of the columns and 12 positions for the leg of the Diane. A 2D-velocity distribution based on the measurements was computed by tomographic wavefront migration using the Software Geotom CG (see Jackson and Tweeton, 1994).

## Auto-Calibration of the Setup

All reconstruction systems have to be calibrated in order to obtain accurate measurements. Pre-calibrated systems are usually expensive to purchase, have a limited range of use and decalibrate over time. Therefore, they are usually calibrated before each use. In the past, for camera setups, this was done with the help of checkerboards, which had to be placed by the user at several positions and orientations in the scene. This was a considerable effort and made the use of these techniques difficult for amateurs. New auto-calibration methods such as described by Fetzer at al. (2020b) and Fetzer at al. (2019) calibrate the devices directly from point correspondences. These correspondences can be robustly obtained from the object surface, that has been encoded by the structured light approach.

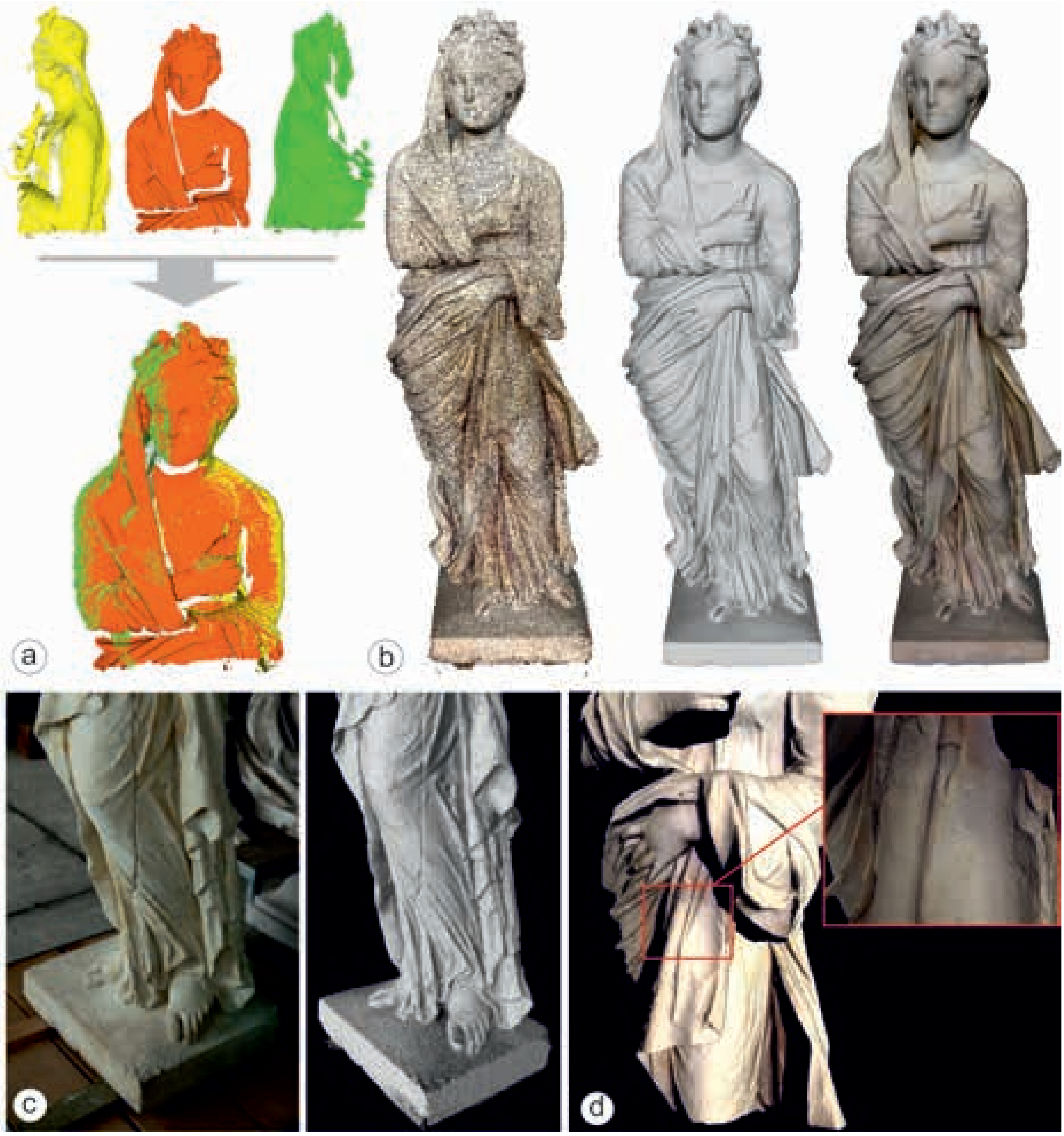


**Figure 2**: Steps to generate complete reconstructions from multiple views. (a) Alignment of partial point clouds. (b) Point cloud, mesh and textured mesh of the reconstruction. (c) and (d) show how the high-resolution reconstructions can document even small damages in the object's surface.

Thus, no user interaction is necessary and the procedure is easy to use even for non-specialists, making it suitable for practical application such as in restorations. In addition, the calibration can be carried out separately for each position in order to achieve very accurate reconstructions, without loss of quality over time. Moreover, variable hardware setups and adjustments of camera settings to specific scenarios are no longer a problem.

## Merging, Meshing and Texture Mapping

In order to obtain a complete reconstruction from all sides, several partial reconstructions must be performed from different perspectives. The partial point clouds have to be merged afterwards, which is one of the main challenges in the creation of a digital copy of an object. However, if asymmetric geometry and/or sufficient texture characterize the object, this is possible automatically. Figure 2(a) illustrates how point clouds from three views are merged. The pictures demonstrate the process on a Vestalin statue from the Skulpturenhalle Potsdam. In order to achieve a closed, high-precision reconstruction with appropriate data size, a mesh is generated from the point cloud that approximates the surface of the object. A well established method that is Poisson Meshing (see Kazhdan et al. 2006). Finally, a texture and optionally a normal map are mapped onto the mesh (see Noll and Stricker 2011). Figure 2(b) visualizes this process. In this way, high-resolution detailed objects with comparatively low memory requirements can be rendered and displayed according to modern standards. Figure 2(c) and (d) illustrate the high quality of the reconstructions. Even very small damages such as cracks or spallings in the surface can be detected and documented. Figure 2(c) shows on the left a high resolution image and on the right the reconstructed point cloud of this region. Figure 2(d) depicts a colored point cloud, where the damaged area is enlarged in the inset.

## Documentation of Measuring Positions

The 3D reconstructions are intended to provide visual access to the cultural assets and further information about them. Apart from this, they are ideal for documentation and as basis for monitoring campaigns. In this study, for example, the exact position of the measuring points for the applied ultrasound tomography could be documented. In this way they can be clearly assigned and improve the repeatability of further measurements. In addition, they enhance the aligning of the computed tomogramms, which helps to compare them with visible decay phenomena. In order to augment the reconstruction, we perform high quality 3D scans to obtain the model. The ultrasound tomography is then applied and the measuring points are marked on the object. Again a reconstruction of the areas with the marked measuring points on the object is carried out. The coarse reconstruction is aligned with the previous one and the measuring positions are extracted according to this alignment. They are stored separately and can be augmented to the high-resolution reconstruction if required. Note that the accuracy of the measuring points depends on the resolution of the second scan and the alignment, which can be tuned accordingly. Fig. 3 shows a reconstruction of Apoll from the Skulpturenhalle Potsdam, for which measuring points are shown (right) and hidden (left) if required.

**Figure 3:** Reconstruction of Apoll without (left) and with (right) measuring points of ultrasound tomography.

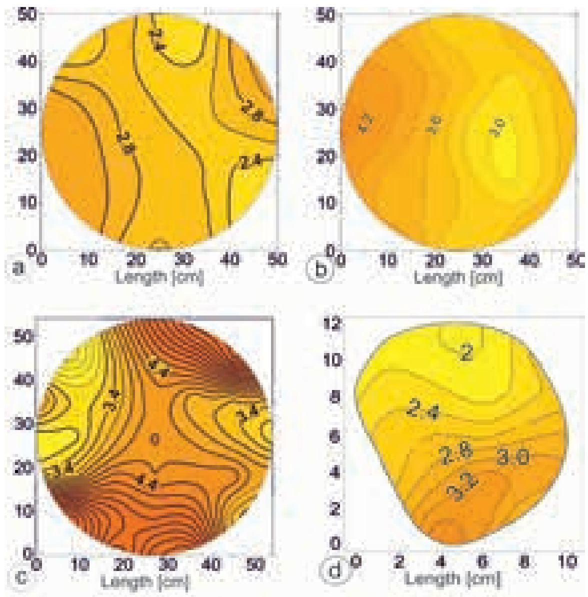


**Figure 4**: Tomograms of the Prieborner Column (a) Tomograms of the Prieborner Column in 2019 (a) and 2001 (b), (modified after Rüdrich et al. 2001), Kauffunger Column (c) as well as the tomogram for the calf of the Diane (d).

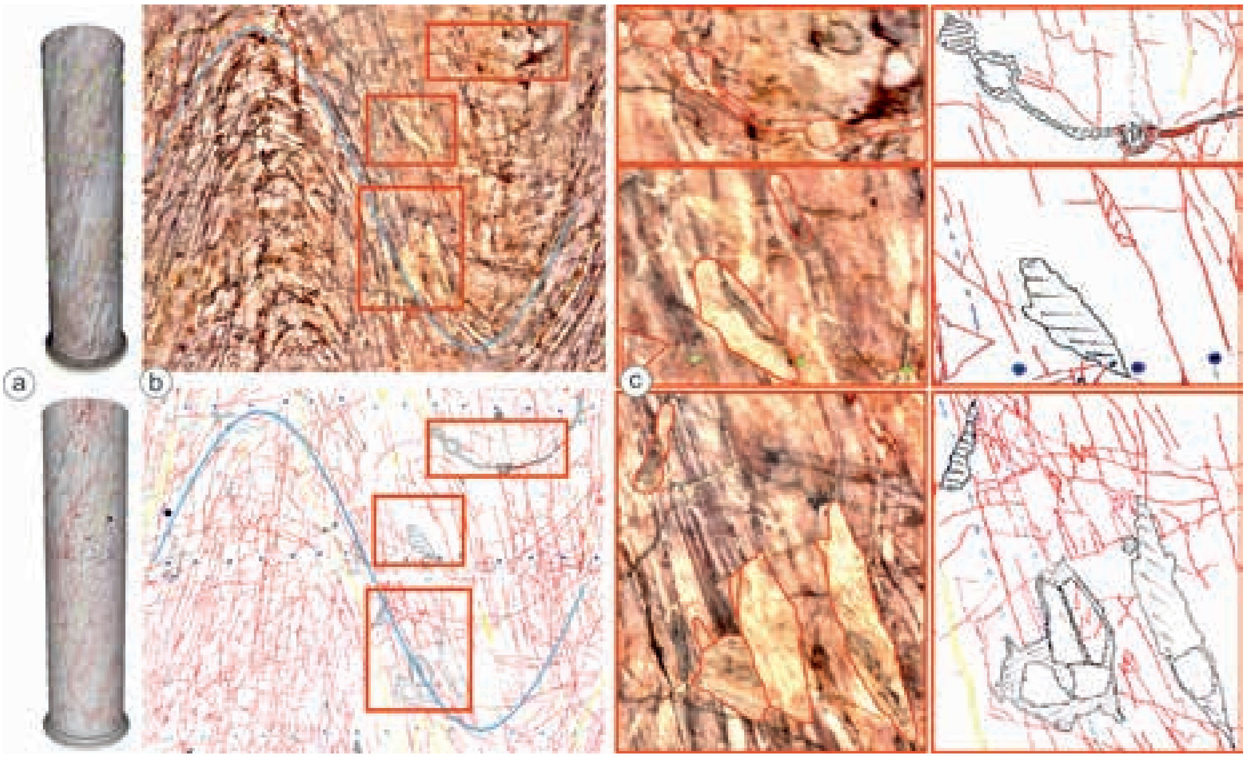

**Figure 5**: Reconstruction of a marble column of the Marmorpalais in Potsdam (a). (b) shows the manually traced (bottom) and automatically developed (top) texture of the column. (c) depicts enlarged versions of the marked red boxes in order to visualize matching features in the textures.

## Texture Analysis of Object Surfaces

Another field of application for the digitization of cultural objects is to document the surface changes of objects, e.g. due to weathering. For monitoring purposes, decay phenomena as cracks and back-weathering of the surface need to be documented as well as restoration and conservation measures. Structural elements of natural stone such as foliation or sealed cracks can be investigated and documented in this way. Here the texture can be mapped onto a two-dimensional surface. With the help of 3D reconstructions this can be done in an automated way and the surface structures can be digitized and documented over many years.

## Ultrasound tomography

According to ultrasonic measurements in 2001 (see Rüdrich et al. 2001, (see Rüdrich et al. 2001, Siegesmund et al. 2004) Siegesmund et al. 2004), the ultrasonic velocities for the Prieborn column have been investigated at four different cross sections. This study presents the data for the section at a height of 3.23 m, considering the same amount of 20 % anisotropy as in the former study (see Rüdrich et al. 2001). In 2019, the velocities range between 2.4 and 3.0 km/s (Fig. 4a), while in 2001 the velocities for the same column at the same eight ranged between 3.0 and 4.2 km/s (Fig. 4b). The velocities decreased, but the spatial velocity distribution did not change much. This indicates, that the crack growth caused by weathering is mainly influenced by the intrinsic rock properties. The velocity measurements for the Kauffunger column were performed at three different cross sections at a height of 0.92 m, 1.59 m and 2.12 m. The results for the cross section of 2.12 m are given in Fig. 4(c) and display a wide range of velocities between 2.4 km/s up to 5.8 km/s. In 2001 this range was smaller with velocities between 3.8 and 5.6 km/s. The spatial velocity distribution fits to the analysed crack distribution (see Rüdrich et al. 2001), indicating that the velocities are mainly

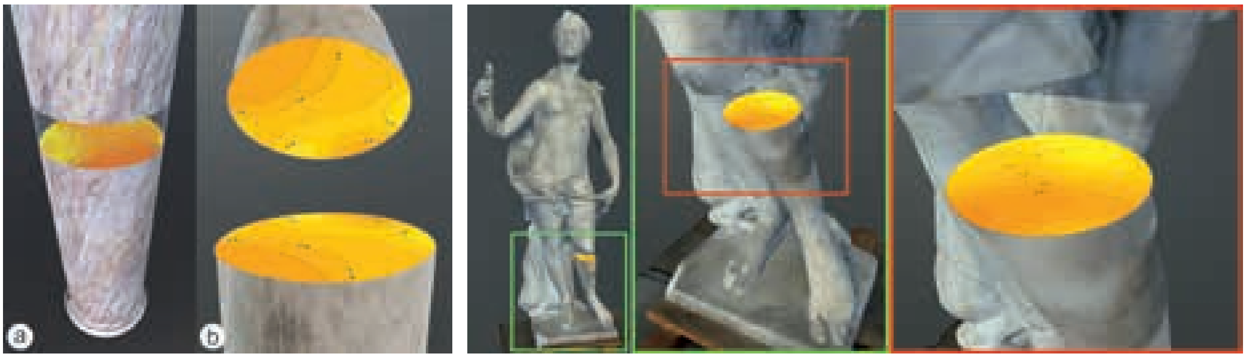

**Figure 6 and 7**: Reconstruction of Kauffunger column (a), Prieborner column (b) and Diane (c) Potsdam including the computed tomograms. The left carf is cut off to make the measured tomography visible(d).

controlled by the crack system and the intrinsic effects.
Along with these columns, a sculpture at the Skulpturenhalle has been measured by the tomographic approach. The calf of the Diane, a sculpture made of Carrara marble, was measured and a tomogramm computed (Fig. 4d). The velocities range between 2.0 and 3.4 km/s, while the area of her upper tibia shows the highest velocities.

## Discussion and Conclusion

To determine the benefits of a 3D reconstruction in terms of documentation, mapping and reorientation the conventional mapping method has been compared to the results of the reconstruction. Fig. 5(a) shows the reconstruction of the Kauffunger column. On the right the developed textures are shown. An elaborated manually traced version using a transparent foil (b, bottom) and the automatically developed texture of the reconstruction (b, top). Note that the colors were intensified and the contrast increased to make features and information visible in this paper. For comparison reasons, the manual texture has been mapped to the reconstruction as well (a, top). The foliation is marked by a sine wave (blue) in both the reconstructed and hand drawn textures. To illustrate the comparability of the two textures, (c) shows magnifications of the marked regions in the textures. Features and cracks are clearly and better visible in both variants. Moreover, while manual traces are extremely time-consuming and error-prone due to slippage and movement of the foil, these problems do not occur at all with the automatic approach. In Figures 6 and 7 the computed tomograms are placed at the reconstructions. Due to the documentation of the transducer positions as described before, it is possible to position the tomograms perfectly at the reconstruction. Therefore, correlations between macroscopically visible decay phenomena, structural properties as the orientation of the foliation and the tomograms can be analysed immediately. The combination of both previously described methods, allows an accurate, and in depth investigation as well as being a great monitoring basis and allows many visualization possibilities.

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