# 3D DIGITAL RECONSTRUCTION OF THE KIMBERLEY OUTCROP (GALE CRATER, MARS) FROM PHOTOGRAMMETRY USING MULTI-SCALE IMAGERY FROM MARS SCIENCE LABORATORY.

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**Introduction:** Structure-from-Motion (SfM) photogrammetry is an efficient, low-cost and powerful method to reconstruct Digital Outcrop Models (DOM) and/or specific geological object, only from a set of photos [1]. This method is particularly well-suited in remote planetary exploration such as that of Gale Crater, Mars, using extensive imagery data from the *Curiosity* rover mission [2]. Using a set of multi-scale images from 3 different instruments aboard *Curiosity*, we were able to compute a high-resolution and highly-detailed full color DOM of the Kimberley outcrop (sols 603-630), that was then integrated into a Virtual Reality (VR) environment for visualization and geological characterization.

**Photogrammetry using Structure-from-Motion approach:** To reconstruct detailed DOM, we perform SfM photogrammetry using the Agisoft PhotoScan Professional software. SfM allows to transform a set of multiple overlapping photos into geometric 3D meshes. The software analyses and aligns multiple photos to detect similar points across the photoset [1]. These matching tie-points are then linked to create a scarce point cloud where each tie-point is projected into 3D space given its X,Y,Z position, calculated from the apparent displacement of these points observed across several photos [1] (Fig. 1).

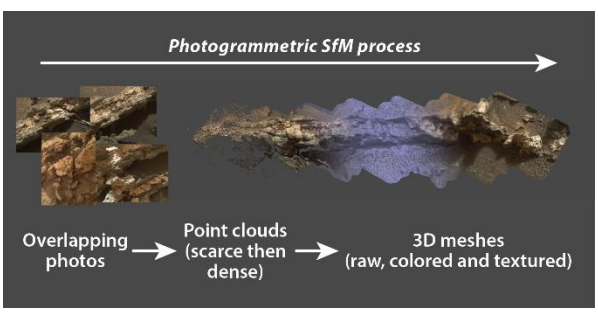


**Fig. 1** Schematic representation of the photogrammetric reconstruction process in Agisoft PhotoScan Professional software, applied to a sulfate vein of the Garden City outcrop (Gale Crater, Mars) using 57 MAHLI photos taken on sol 930.

Once the scarce point cloud is computed, a dense point cloud is generated (Fig. 1), whose numerous points will then be linked as to create a network of vertices delimitating triangular polygons that compose the actual resulting 3D mesh (Fig. 1) [1,2]. Vertices can be colored according to original source photos and a texture can also be applied (or UV mapped) to the model in order to get a photorealistic rendering of the DOM as seen on the Figure 1. Although several limits to this method have been raised before by e.g. [2], SfM photogrammetry remains extremely useful and powerful in providing an accurate reconstruction of the geological features.

**Processing multi-scale data:** Mars Science Laboratory (MSL) rover *Curiosity* is equipped with different imaging instruments such as the navigational cameras (NavCam), the mast cameras (MastCam), ChemCam RMI and the Mars Hand Lens Imager (MAHLI). Those camera have different resolutions, focal lengths and overlap between successive photos, which allow them to be more or less prone to photogrammetric treatment. Straightforward results are generally obtained with NavCam: images are acquired as a stereoscopic pair using both left and right cameras, these data being used by internal navigational computer of *Curiosity* to decipher its way on the Martian ground [3]. These pictures are useful to reconstruct terrains, but are greyscale and show generally only a low level of details, restraining their use for science purposes. MAHLI can be operated locally to take high resolution full color photos with a good overlap, allowing an accurate reconstruction of small-scale geological features, such as the sulfate vein from Garden City outcrop (sols 930) partially illustrated on Figure 1. Finally, MastCam data come from a pair of two high-resolution full color cameras. But unlike the NavCam, their focal length are different (34 mm for left MastCam and 100 mm for right MastCam [3]). This difference prevents any systematic overlap and therefore a direct use for photogrammetric application. Our objective is to integrate photos taken using these two cameras along with NavCam and MAHLI data. Multi-scale and multi-resolution data from the various instruments allow to reconstruct DOM with higher accuracy and grater details for geological analysis.

**Reconstruction of the Kimberley Digital Outcrop Model:** In this study, we focus on the Kimberley outcrop, for which a large set of imagery data from NavCam and MastCam is available, as well as several views taken using MAHLI. Such amount and quality of the data is of paramount importance regarding photogrammetric treatment and provides us with a good mm-

to pluri-meter-scale database for the reconstruction process. Data were retrieved from the public Planetary Data System servers [4]. Even though Agisoft PhotoScan is able to help reconstruct the traverse path only by computing the DOM from NavCam imagery [2], we chose a different approach. We created a pipeline to reintegrate metadata within our entry *Curiosity* images such as geocentric coordinates (projected within the Mars2000 system). This allowed us to use PhotoScan's embedded advanced geospatial features to obtain a geographically constrained DOM (Fig. 2) and a direct and proper scaling of the model (validated using the rover's tracks on the model).

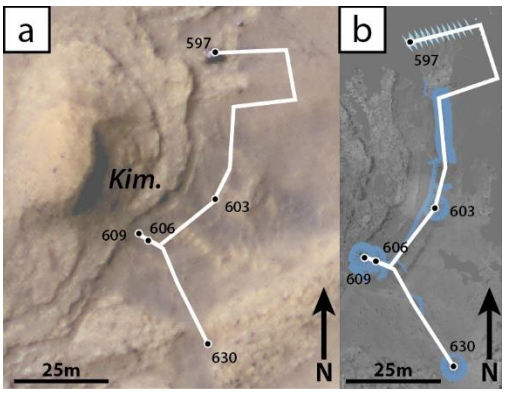


**Fig. 2** (a) Actual path of Curiosity's traverse between sols 603 and 630 (white line) and estimated position of the rover (black points). Kim.: Kimberley outcrop. HiRISE image ESP_036128_1755_COLOR (b) Low-resolution greyscale DOM of Kimberley outcrop (sols 603-630, using NavCam imagery) and reconstructed traverse of the rover.

A first "draft" DOM was computed using NavCam imagery only (530 photos), resulting in a low-resolution greyscale model with a good spatial coverage of the outcrop (Fig. 2b). This "draft" model was then used as a base to align a set of 1505 high-resolution full color MastCam photos, using known positions of the existing NavCam cameras within the workspace. This allowed a fairly good amount of the available MastCam cameras (~96 %, 1443 photos) to be projected and converted into tie-points by PhotoScan in spite of the lack of overlap across MastCam images. We therefore obtained a full color, scaled, highly resolved DOM of the Kimberley outcrop (Fig. 3a). We completed our multi-scale reconstruction by adding a full-scale color model of the Windjana drill hole (sol 615) computed from 32 MAHLI photos (Fig. 3b).

**Perspectives for the geological analysis of the multiscale Kimberley DOM:** The Kimberley outcrop presents a sedimentary succession with unusually high potassic content [5]. Stratigraphic relations within this series and with its immediate to local surroundings are therefore critical to understand the extent of these potassic accumulations and their signification from a paleoenvironmental point of view. We thus integrated the high resolution multiscale DOM into a VR environment (Fig. 3). This enables one or several users to observe at full-scale the various sedimentary series and structures of the Kimberley outcrop. This way, precise and accurate description, quantification and mapping of the outcrop is possible. Moreover, integration of the multiscale DOM into VR also allows us to contextualize the data gathered by *Curiosity* at real scale and within their geological setting (e.g. ChemCam LIBS and RMI data), which can be tricky on 2D images. SfM photogrammetry is an efficient method for the reconstruction of multiscale (object to terrain) DOM from existing data generated by MSL's rover *Curiosity*. Integration of these models into a collaborative VR environment allows for accurate geological interpretations based on reliable and realistic depiction of the actual geometries of the geological features, paving the way for future exploration of remote Martian outcrops.

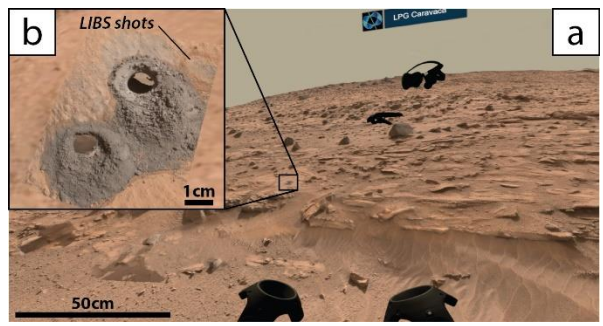


**Fig. 3** (a) Screen capture of the high-resolution full color DOM of Kimberley outcrop (sols 603-630) as experienced within the VR environment. (b) High-resolution full color DOM of the Windjana drill hole at Kimberley (sol 615) as seen within the VR environment. Sub-mm-scale LIBS shots can be seen in VR.

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**References:** [1] Westoby M.J. et al. (2012) Geomorphology, 179, 300-314. [2] Ostwald A.M. & Hurtado J.M. Jr. (2017) *LPS XLVIII*, Abstract #1787. [3] Alexander, D., Deen, R. (2015) *Mars Science Laboratory Project Software Interface Specification*, Version 3.5. [4] Planetary Data System (PDS) archive node, https://pds-imaging.jpl.nasa.gov/portal/msl_mission.html [5] Le Deit et al. (2016) *J. Geophys. Res. Planets*, 121, 784-804. [5]