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# Sedimentology of Kimberley outcrop (Gale Crater, Mars), using "*in situ*" simulated field work in Virtual Reality

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## Abstract

The Kimberley outcrop, traversed by *Curiosity* in 2014, shows a siliciclastic depositional record with an unexpectedly high potassic content. However, its intra- and inter-formational relations are still poorly constrained yet critical to understand the paleoenvironmental implication of this geochemical anomaly. To answer these questions, we use a high-resolution Digital Outcrop Model integrated into a Virtual Reality environment. We therefore characterize multi-scale sedimentary features, highlighting laterally evolving depositional conditions.

## Introduction

Structure-from-Motion photogrammetry is a low-cost yet effective method to reconstruct Digital Outcrop Models (DOM). These models allow to explore and study hardly accessible and/or remote outcrops such as those explored by Mars Science Laboratory rover *Curiosity*. Using high-quality imagery data produced by 3 different cameras onboard the rover and publicly available on the Planetary Data System [1], we were able to produce a highly-resolved and highly-detailed DOM of the Kimberly outcrop. Integration of this DOM into a Virtual Reality (VR) headset offers new perspectives for simulated "*in situ*" geological characterizations of Martian outcrops.

## 1. The Kimberley outcrop

This work focuses on the Kimberley outcrop, traversed by *Curiosity* between sols 597 and 630. The sedimentary succession presents a suite of siliciclastic rocks (fine sandstones to pebble conglomerates) of the Kimberley formation. This section particularly stands out in the regional fluvio-deltaic sequence due to the unusually high potassium content within its rocks [2]. However, poorly constrained stratigraphic relations between the series of the Kimberley Fm. and their local to regional surroundings are problematic in the broader Gale Crater paleoenvironmental scheme. Such questions highlight the need for a new finer study of the area to notably characterize the precise nature and morphology of the sedimentary structures and contacts observed on the outcrop itself and in its immediate vicinity.

## 2. Reconstructing the DOM and integration into a VR environment

The DOM for Kimberley was reconstructed using ~2000 georeferenced images taken by the wide angle stereoscopic Navcam, both left wide angle and right telelens Mastcam and MAHLI microscope onboard *Curiosity*. Despite the variations in optical parameters of these different imagers, we were able to compute a highly-resolved, full color and multi-scale DOM of the outcrop [3]. The multi-scale data used for the photogrammetric reconstruction also result in a sub-cm-scale resolution of the DOM, allowing a very accurate depiction of the sedimentary series at Kimberley (Fig. 1).

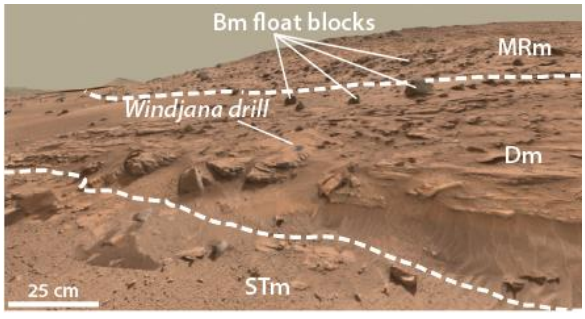


Figure 1: Interpreted VR panorama of the Kimberley DOM. Conformable contacts between Square Top (STm), Dillinger (Dm) and Mt. Remarkable (MRm)

members are shown, as well as Beagle member float blocks (Bm).

Integration into a Virtual Reality (VR) environment of this DOM enables one or several users to experience a reliable and realistic depiction of the actual geometries of the geological features (Figs. 1 & 2), which is usually prevented by classic viewing methods on flat 2D screens. Also, the use of a VR environment authorizes the observation at real scale of the various sedimentary series and structures present on the reconstructed outcrop. This allows for a very precise and accurate characterization of the features, as well as the contextualization of the sampling and remote analyses underwent by the *Curiosity* rover within their geological setting (e.g. Windjana drill and ChemCam Laser-Induced Breakdown Spectrometer LIBS data; Fig. 2b). New dedicated VR tools were thus purposely developed to enable measurement directly within the VR simulated outcrop, in a similar way they would be done on a real field trip.

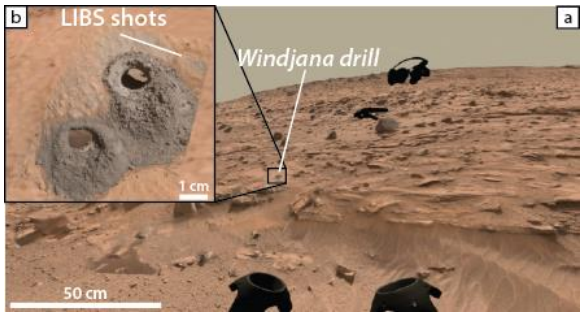


Figure 2: (a) View of the Kimberley DOM as explored by two VR users. (b) Detail on the Windjana drill hole. Sub-mm-scale LIBS shots can be seen in VR.

## 3. New assessment of the depositional record

Taking advantage of the high resolution and accuracy of our DOM and using dedicated VR tools, we were able to observe and characterize several previously underrated sedimentary structures and contacts, as well as their spatial extension throughout the simulated area of Kimberley. We notably mapped with unprecedented precision both conformable contacts on the Mt. Remarkable butte (Fig. 1) and angular unconformities on the eastern part of the reconstructed outcrop. This mapping allows us to propose new measurements of the thickness of the members forming the Kimberley Fm. with a cm-scale precision. We could also observe several sets of varying scale cross-stratifications (from cm- to pluri-meter scale) throughout the outcrop. Our observations of the Dillinger member (Fig. 1) notably highlight lateral variations of the sedimentary structures within these beds. These results tend to corroborate the idea of a complex and diachroneous evolution of the area, with the possibility of laterally evolving depositional settings, spanning a significant amount of time.

## 4. Summary and Conclusions

In spite of its critical implications in the broader Gale Crater paleoenvironmental scheme, the stratigraphic relations at Kimberley and with the outcrop's surrounding are still poorly constrained. In a first step toward better understanding of the intra- and inter-formational relations of the series, we therefore propose to use a true color highly resolved DOM of the Kimberley outcrop reconstructed using photogrammetry based on *Curiosity*'s imagery. Integration into a VR environment and use of dedicated VR measurement tools allow us to achieve precise and accurate characterization of the area and of the different geomorphological and sedimentological features (beds, structures and contacts alike). This new technique allows us to observe and describe with unprecedented precision the Kimberley Fm. and its multi-scale sedimentary structures, highlighting laterally evolving depositional settings. Newly developed tools in Virtual Reality therefore give us the opportunity to study "*in situ*" digital reconstructions of Martian outcrops such as Kimberley and represent a major advance for the characterization and interpretation of remote planetary outcrops and their paleoenvironments.

## Acknowledgements

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## References

[1] Planetary Data System (PDS) archive node, *https://pds-imaging.jpl.nasa.gov/portal/msl_mis-sion.html* [2] Le Deit et al. (2016) *J. Geophys. Res. Pla-nets*, 121, 784-804. [3] Caravaca et al. (2019) Geophys. Res. Abs., 21, EGU2019-3877.