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

Gwénaél Caravaca^{*1}, Nicolas Mangold¹, Stéphane Le Mouélic¹, Laetitia Le Deit¹, Marion Massé¹

^{*}Corresponding author; gwenael.caravaca@univ-nantes.fr

¹Laboratoire de Planétologie et Géodynamique, UMR 6112 CNRS, Université de Nantes, Université d’Angers, 2 Rue de la Houssinière, 44322 Nantes Cedex 3, France

Introduction:

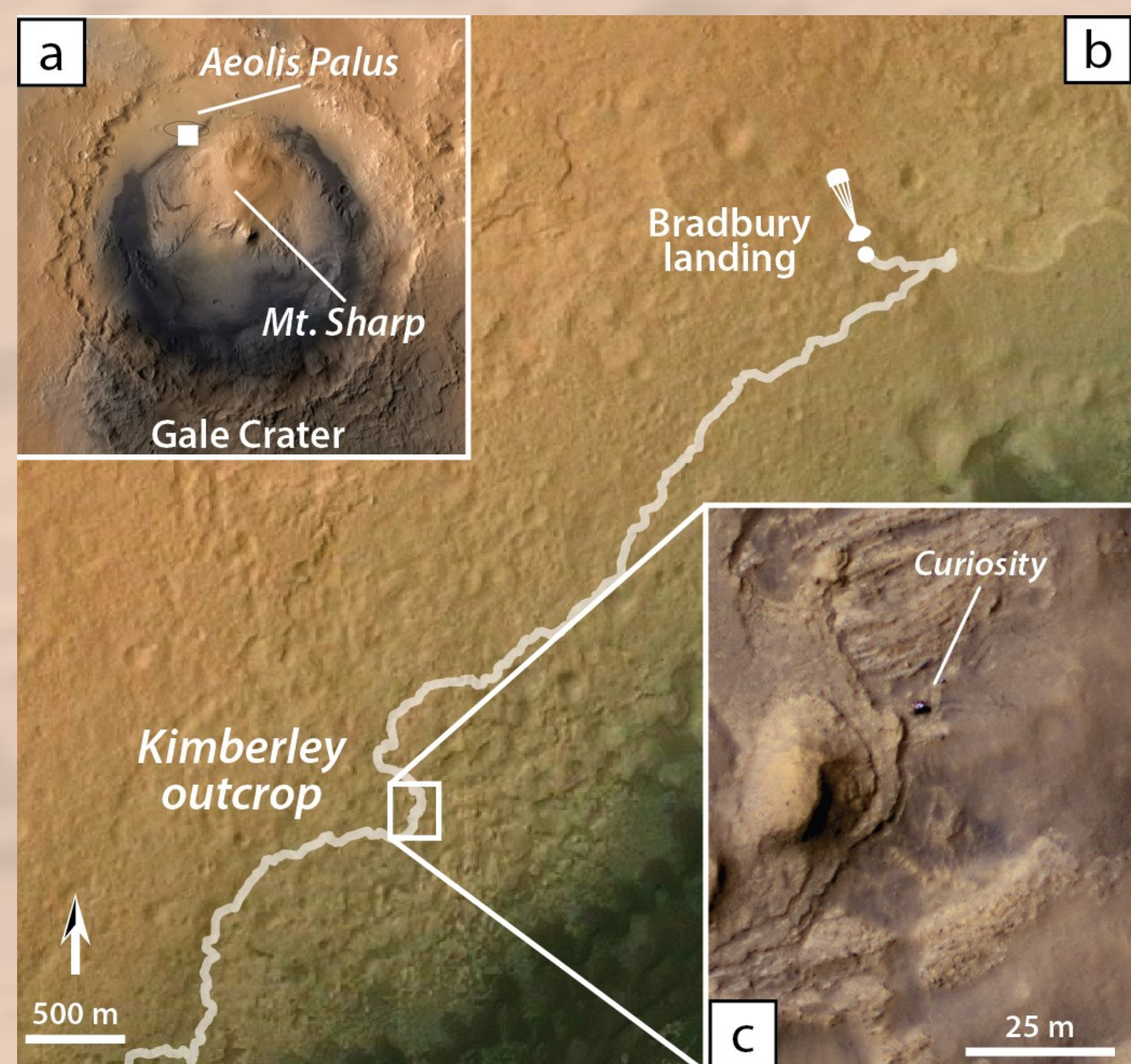
Reconstruction of highly-resolved Digital Outcrop Models (DOM) using Structure-from-Motion (SfM) photogrammetry from ground-based photos taken by Martian rovers such as Mars Science Laboratory’s *Curiosity* is a low-cost yet powerful and efficient method to obtain accurate and realistic 3D depictions of remote planetary outcrops.

Their integration into a Virtual Reality (VR) environment and the use of purposely-developed tools offers an unique opportunity to assess the poorly constrained stratigraphy of the Kimberley outcrop. This new edge technique allows to observe in 3D and at real scale the lateral variations in the sedimentary record of Kimberley that are usually hardly observable using traditional observation methods.

Context:

The Kimberley outcrop was traversed by *Curiosity* between sols 603 and 630 [1, 2]. This area presents **poorly constrained stratigraphic relations** though they are critical to the signification of the local unusually high potassic accumulations [2, 3].

Therefore, the integration of the Kimberley DOM into VR allows a **new and more accurate geological “*in situ*” analysis of the outcrop**, aiming to new understandings of the local to regional paleoenvironments.



a) White square: area of operations of Mars Science Laboratory rover *Curiosity* in the Gale Crater. b) *Curiosity*’s traverse since Bradbury landing (Aug., ’12) and localization of the Kimberley outcrop (sols 603-630; base image: NASA / JPL / MSSS / ESA / DLR / FU Berlin (G. Neukum) / Tanya Harrison / Emily Lakdawalla). c) *Curiosity* rover on sol 595, arriving at Kimberley (base image: HiRISE ESP_036128_1755 full color tile).

Reconstruction of the DOM and integration within a Virtual Reality environment

Using Agisoft Metashape SfM photogrammetry software, a **high-resolution DOM of the Kimberley outcrop** (covering a surface of ~1670 m²) and a **micro-DOM of the Windjana drill hole** [4] were reconstructed using *Curiosity* imagery available on the PDS [5].

These DOM were then **integrated into a Virtual Reality environment**, allowing **one or several networked users**:

- **Visualization and exploration** of the model at **real-scale** and **without deformation**
- **Contextualization** of the sampling targets (e.g. Windjana drill)
- **Accurate characterization, description and mapping** of the **geological features and stratigraphic relations** at Kimberley.

View the DOM on Sketchfab:

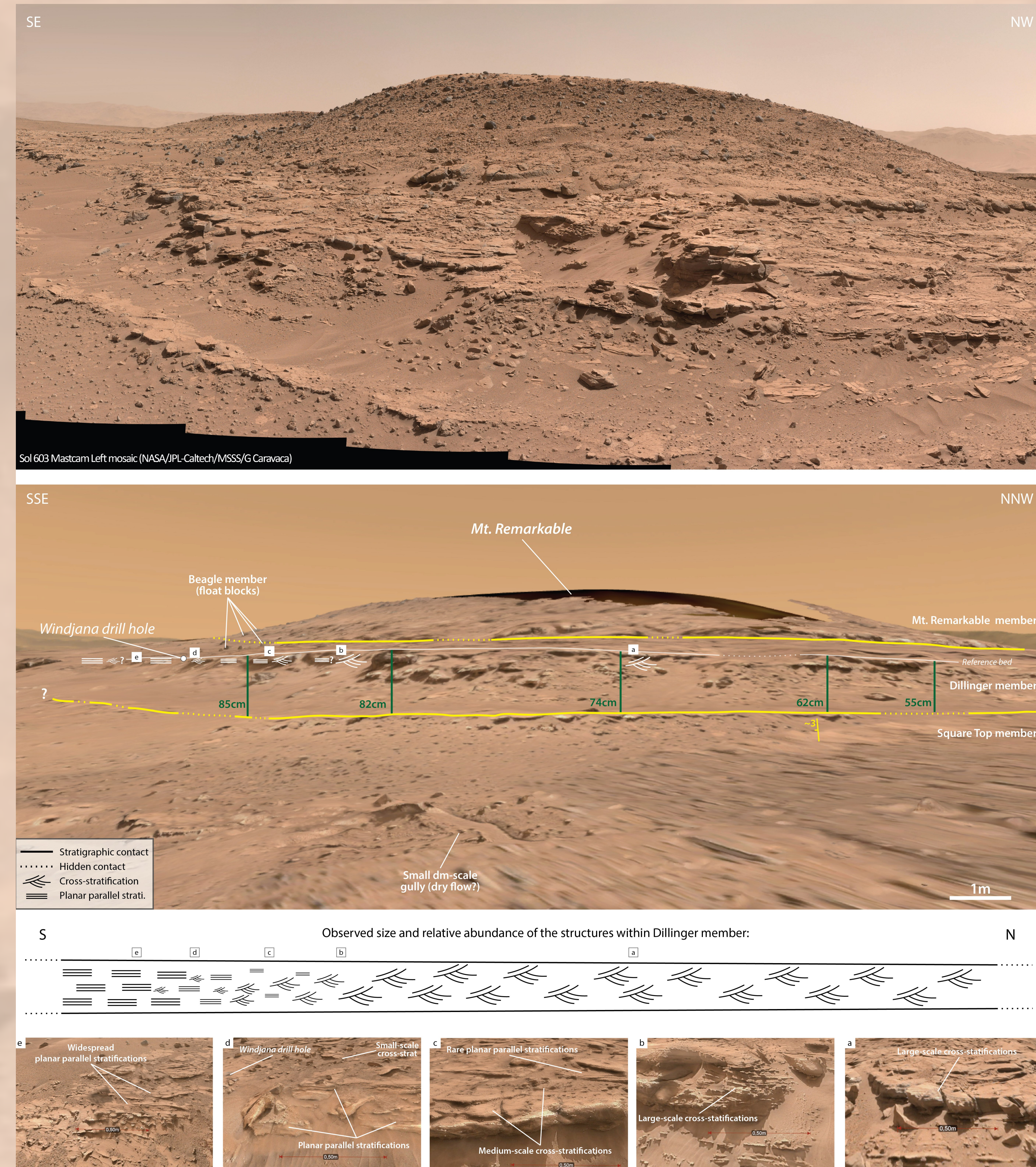
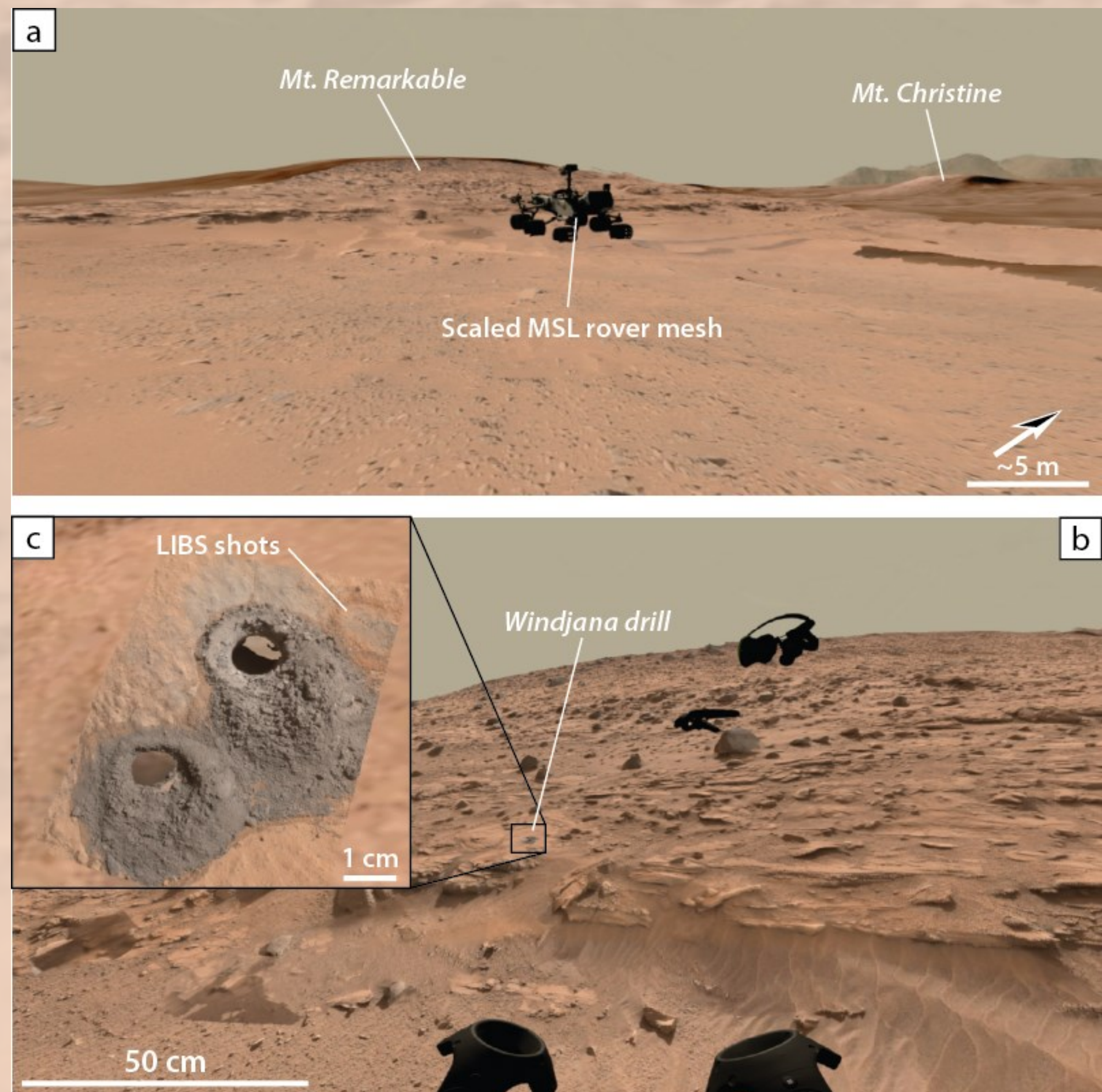
Kimberley outcrop



Windjana drill hole



a) General view of the Kimberley outcrop within a VR environment; *Curiosity* rover mesh placed for scale. b) Close-up toward the Windjana drill at the base of Mt. Remarkable, with VR avatars of two users exploring the outcrop. c) Detailed view of the very high-resolution mesh of the Windjana drill. Marks left by the Laser-Induced Breakdown Spectroscopy (LIBS) shots on the model are <1 mm.



“In situ” characterization of the Kimberley outcrop sedimentology

The Kimberley formation studied here displays 4 distinct members [1 - 3]: Square Top, Dillinger, Mt. Remarkable and Beagle (from bottom to top). They are composed by siliciclastic rocks ranging from fine sandstones to pebble conglomerates.

Outcropping conditions makes it difficult to characterize whether the intraformational contacts are conformable or not (hence the use of new VR techniques). Our observations however seems to corroborate the idea of a **conformable and continuous contact between Dillinger and Mt. Remarkable** members.

Further down the section, the conformability of the **continuous contact between Square Top and Dillinger** members cannot be ascertained. Moreover, the surface of this contact is seemingly presents a **dip around 3° southwestward**. This contact is also mapped lower on the section than previous observations [3].

We observe a **lateral variation of the thickness of the Dillinger member**. Between the lower Square Top/Dillinger contact and the reference bed in the upper half of the member (defined as the continuous bed on which the Windjana drill as been made), thicknesses vary between 55 cm at the northern end of Mount Remarkable and ~ 85 cm toward the drill site and southern part of the butte. This southward thickening trend may result from a **deposition of the Dillinger onto a slight paleotopography** made by the top of the Square Top member and illustrated by the ~3° southwestward dip of the Square Top/Dillinger contact.

We also observe **lateral variations in the sedimentary structures of the Dillinger**. In the northern part, several sets of **well-preserved dm-scale cross-stratifications** (plausible trough cross-stratifications, a and b) are present. Towards the South, the size of these cross-stratifications gradually decrease down to a few cm (c and d). Together with this decrease, we can note the apparition around the middle of the butte of **mm– to cm-scale planar parallel stratification** (c). These planar stratifications first **alternate with the cross-stratifications before completely replacing them** in the southern part of the outcrop (c to e).

Both the distribution of these structures and the thickening might result from a lateral **variation of the local hydrodynamism**. This variation may be the consequence of an **increase in accommodation space due to the local paleotopography**. These results are in agreement with previous interpretations of the Kimberley as a **fluvial paleoenvironment**, but bring new ideas in favor of a **much more dynamic and laterally-evolving pattern**.

The DOM also allows to observe much more recent features, such as the presence of **dm-scale gullies that may have been formed very recently** and could be still active today (dry flow?).

Acknowledgments:

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References:

[1] Stack *et al.* (2016). *Icarus*, 280, 3-21. [2] Rice *et al.* (2017) *J. Geophys. Res. Planets*, 122, 2-20. [3] Le Deit *et al.* (2016) *J. Geophys. Res. Planets*, 121, 784-804. [4] Caravaca *et al.* (2019) *Geophys. Res. Abs.*, 21, EGU2019-3877. [5] Planetary Data System archive node, https://pds-imaging.jpl.nasa.gov/portal/msl_mission.html

Conclusion:

At Kimberley, use of a **reliable photorealistic DOM within a VR environment** made possible to observe up-close previously underrated **lateral variations in thickness and in both size and abundance of key sedimentary structures** of the Dillinger member, as well as **reevaluating the position of the intraformational contacts**, or estimating the dip of the latter.

These information bring new insights towards the understanding of the laterally-evolving and dynamic fluvial environment that led to the deposition of these series.