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UCL HRSC DIGITAL TERRAIN MODEL AND TERRAIN-CORRECTED IMAGE MOSAICS OF VALLES MARINERIS OF MARS

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APPROVAL

CHANGE LOG

Reason for change	**Issue**	**Revision**	**Date**
Initial version	1	0	31/03/2021
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CHANGE RECORD

Issue 1	**Revision** 0		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Initial version	31/03/2021	All	All
First update to correct file-names	13/04/2021		
Second update to add tiling diagram and naming convention as well as new ESA template			

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1. INTRODUCTION

Within the UKSA Aurora funded VM-RSL (*Understanding the role of liquids in the formation of RSLs and slope streaks within Valles Marineris using 3D super-resolution restoration*) project, a seamless mosaic has been constructed including a 3D terrain model at 50 m grid-spacing and a corresponding terrain-corrected panchromatic orthoimage mosaic at 12.5 m using a novel approach applied to ESA Mars Express High Resolution Stereo Camera orbital (HRSC) images of Valles Marineris of Mars. This method consists of blending and harmonising 3D models and normalising reflectance to a global albedo map.

In this work, eleven HRSC image-pairs were processed by UCL to Digital Terrain Models (DTM) based on an open source stereo photogrammetric package called CASP-GO and merged with 71 published level-4 DTMs from the HRSC team available through the ESA PSA. In order to achieve high quality and complete DTM coverage, a new set of methods was developed to combine data derived from different stereo matching approaches to achieve a uniform outcome. This new approach was developed for high-accuracy data fusion of different DTMs at dissimilar grid-spacing and provenance which employs joint 3D and image co-registration, and B-spline fitting against the global Mars Orbiter Laser Altimeter (MOLA) standard reference. Each HRSC strip is normalised against a global Thermal Emission Spectrometer (TES) albedo map to ensure that the very different lighting conditions could be minimised resulting in a tiled set of seamless mosaics.

1.1 Instrument and Datasets

In this work, we use the MOLA areoid data as our baseline reference system. MOLA (from 1997 to 2001) was one of the five instruments onboard Mars Global Surveyor) MGS that measured the time-of-flight of laser pulses, at 1064nm, to measure the distance from the spacecraft to the Martian surface. Individual MOLA laser tracks were interpolated and extrapolated, and corrected, by the MOLA team to produce a global DTM of Mars at 463m grid spacing, which is available through the NASA Planetary Database System (https://pds-geosciences.wustl.edu/missions/mgs/megdr.html).

The HRSC stereo imaging instrument onboard the ESA's Mars Express (MeX) spacecraft is still orbiting Mars acquiring images having captured its first images in January 2004. HRSC was designed for photogrammetric mapping of the topography of the Martian surface via continuous acquisition of stereo push-broom images from multiple angles on a single orbital pass. HRSC captures multi-angular and multi-colour images mostly at 12.5-100 m pixel-scale over various swath-widths, providing near global (~98%) coverage of the Martian surface at 12.5-100 m/pixel. The DLR processed HRSC level 4 orbital strip DTMs cover as of the time of this document ~50% of the Martian surface. Only the nadir pointing panchromatic HRSC band is acquired at 12.5m with the two off-nadir (±18.9°) stereo channels usually acquired at 25 m.

Over Valles Marineris, the DLR HRSC level 4 strip DTMs cover a large proportion of the canyons, leaving only a few gaps of unprocessed or not acquired orbital strip data. In this work, we filled these gaps in the pre-existing DLR-generated HRSC products by creating a further 11 HRSC single-strip DTMs and Ortho-Rectified Images (ORIs; hereafter referred to UCL level 4 DTMs/ORIs) using HRSC level 2 (radiometrically-calibrated but not map-projected) stereo images. These UCL level 4 DTMs and ORIs were then co-registered with the existing DLR HRSC level 4 DTMs and ORIs to allow seamless mosaicing of the whole of Valles Marineris. A key component is to ensure that all DTMs have a common reference system, which in our case is the MOLA DTM. The UCL and DLR HRSC level 4 DTMs are co-aligned with the MOLA DTM to provide precise topographic information for future geological studies.

1.2 Abbreviations and Acronyms

ASP	Ames Stereo Pipeline
CASP-GO	Co-registered ASP with Gotcha and Optimisations
DLR	German Aerospace Centre
DTM	Digital Terrain Model
DUG	Data User Guide
ESA	European Space Agency
HRSC	High-Resolution Stereo Camera
MeX	Mars Express (ESA)
MGS	Mars Global Surveyor (NASA)
MOLA	Mars Orbiter Laser Altimeter
NASA	National Aeronautics and Space Administration (United States)
ORI	Ortho-Rectified Image
PSA	Planetary Science Archive
RSL	Recurring Slope Lineae
TES	Thermal Emission Spectrometer
UCL	University College London
VM	Valles Marineris

1.3 Reference and Applicable Documents

Beyer, R.; Alexandrov, O.; McMichael, S. The Ames Stereo Pipeline: NASA's Opensource Software for Deriving and Processing Terrain Data. Earth and Space Science **2018**, Volume 5(9), pp. 537-548. DOI: 10.1029/2018EA000409.

Michael, G.G.; Walter, S.H.G.; Kneissl, T.; Zuschneid, W.; Gross, C.; McGuire, P.C.; Dumke, A.; Schreiner, B.; Van Gasselt, S.; Gwinner, K.; Jaumann, R.; Systematic processing of Mars Express HRSC panchromatic and colour image mosaics: Image equalisation using an external brightness reference. Planetary and Space Science 2016, Volume 121, pp. 18-26.

Neukum, G.; Jaumann, R. HRSC: The high resolution stereo camera of Mars Express. In Mars Express: The Scientific Payload **2004**, Volume 1240, pp. 17-35.

Shin, D.; Muller, J.-P. Progressively weighted affine adaptive correlation matching for quasi-dense 3D reconstruction. Pattern Recognition 2012; Volume 45, Issue 10, pp. 3795 -3809. DOI: 10.1016/j.patcog.2012.03.023

Tao, Y.; Muller, J-P.; Sidiropoulos, P.; Xiong, S-T.; Putri, A. R. D.; Walter, S. H. G.; Veitch-Michaelis, J.; Yershov, V. Massive Stereo-based DTM Production for Mars on Cloud Computers. Planetary Space Science **2018**, Volume 154, pp. 30–58.

Tao, Y.; Muller, J-P.; Poole, W.D. Automated localisation of Mars rovers using co-registered HiRISE-CTX-HRSC orthorectified images and DTMs. Icarus **2016**; Volume 280, pp. 139-157.

Tao,Y.; Michael,G.; Muller, J.-P.; Conway, S.J.; Putri, A.R.D. Seamless 3D Image Mapping and Mosaicing of Valles Marineris on Mars Using Orbital HRSC Stereo and Panchromatic Images. *Remote Sens.* **2021**, *13*, 1385. https://doi.org/10.3390/rs13071385

2. SCIENTIFIC OBJECTIVES

Valles Marineris (VM) on Mars is the largest system of canyons in the Solar System. The system is more than 4,000 km long, 200 km wide, and up to 10 km deep with respect to the surrounding plateaus. Because of its sheer size Valles Marineris have been a subject of a growing number of studies since the Viking era and we now know that the VM has been subject to a wide variety of processes throughout their history.

Estimated to be approximately 3.5 Ga old, the superstructure is related to tectonic rifting of the crust related in part to the loading induced by the Tharsis Volcanic province. This overall tectonic structure has been modified by outflows, fluvial processes (delta, melas), volcanic processes, aeolian processes and it also thought to contain evidence of glacial modification.

Its extreme topographic relief influences the atmospheric circulation and creates weather systems unique to the canyon. Vast sediment accumulations have formed on its floor, whose geochemical signature attests to standing bodies of water in the past. Giant rock avalanches have affected the walls throughout its history, and whose study has been influential in understanding landslides throughout the Solar System.

The Valles Marineris also host a particularly high concentration of Recurring Slope Lineae, which could be signs of liquid water seeps at the present-day. These low albedo streaks are diminutive compared to the canyon, being that they usually only attain hundreds of metres in length for metres to tens of metres in width. Their downslope growth during the warmest times of year and annual fading strongly suggests the involvement of liquid water, which is usually unstable under current Martian conditions. Studying the examples in Valles Marineris has been key to understanding the conditions required for RSL growth and their seasonality with different slope expositions.

3D mapping is essential to improving our understanding of the geology and geomorphology of Valles Marineris. A key aspect of this mapping is to construct a base-map of co-aligned 3D and mosaiced terrain-corrected images covering the area.

2.1 Acknowledgements

Users are requested to acknowledge the dataset by mentioning it within their publications to cite both the DOI of the dataset and the paper describing the processing system, assessment, and mosaic generation:

Tao,Y.;Michael,G.; Muller, J.-P.; Conway, S.J.; Putri, A.R.D. Seamless 3D Image Mapping and Mosaicing of Valles Marineris on Mars Using Orbital HRSC Stereo and Panchromatic Images. *Remote Sens.* **2021**, *13*, 1385. https://doi.org/10.3390/rs13071385

The research leading to these results has received funding from the UKSA Aurora programme (2018-2021) under grant no. ST/S001891/1. SJC is thankful to the CNES for supporting her HRSC-related work.

3. DATA PRODUCT GENERATION

This data product is created within our 3D mapping and mosaicing work of Valles Marineris using HRSC level 2 stereo images and pre-existing level 4 products. The processing system contains a collection of different methods that are described in detail in (Tao et al., 2021), including a new hybrid HRSC DTM processing chain for single-strip DTM production, a joint 3D and image co-registration system to co-align all single-strip products with each other and simultaneously co-align with MOLA DTM, and finally an ORI co-registration and mosaicing method to create the ORI mosaic.

4. ARCHIVE FORMAT AND CONTENT

4.1 Product Type

The product contains a single Geotiff image for the DTM mosaic and a sequence of tiled Geotiff images for the ORI mosaic.

4.2 Naming Convention

DTM: VM-HRSC-DTM-Mosaic.tif

ORI: VM-HRSC-ORI-Mosaic-tiles/tile_xx.tif

Pixel Format Type

- DTM: 32bit float; single channel; Geotiff image.
- ORI: 8bit byte; single channel; Geotiff image.

4.3 DTM/ORI Specification

- Projection: Equirectangular (Longitude of natural origin: 0)
- Mars radius reference: MOLA aeroid (da)
- DTM resolution: 50m/ pixel
- ORI resolution: 12.5m/pixel
- NoData value: INF (DTM), 0 (ORI)

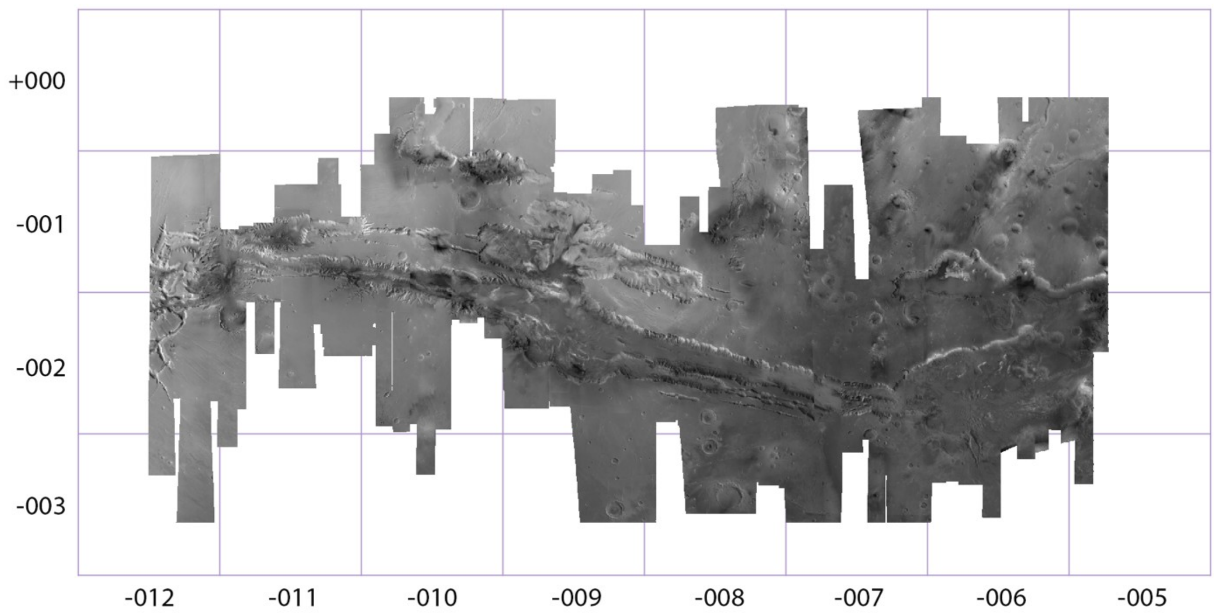

Figure 1. The mosaic is split into tiles named tile_xxxxyyyy.tif where xxxx and yyyy represent the signed x and y offsets in units of 500 km (40,000 pixels of 12.5 m) from the map projection origin at 0°E 0°N.

3.4 Product Example and Usage

The DTM and ORI file in GeoTiff format can be opened in GIS/image processing software such as ArcGIS, QGIS, and ENVI. Projection and mapping information is embedded in the header of the Geotiff file. The final resulting HRSC DTM mosaic (50m/pixel), used 71 existing DLR DTMs and 11 newly created DTMs from UCL, is shown in Figure 2.

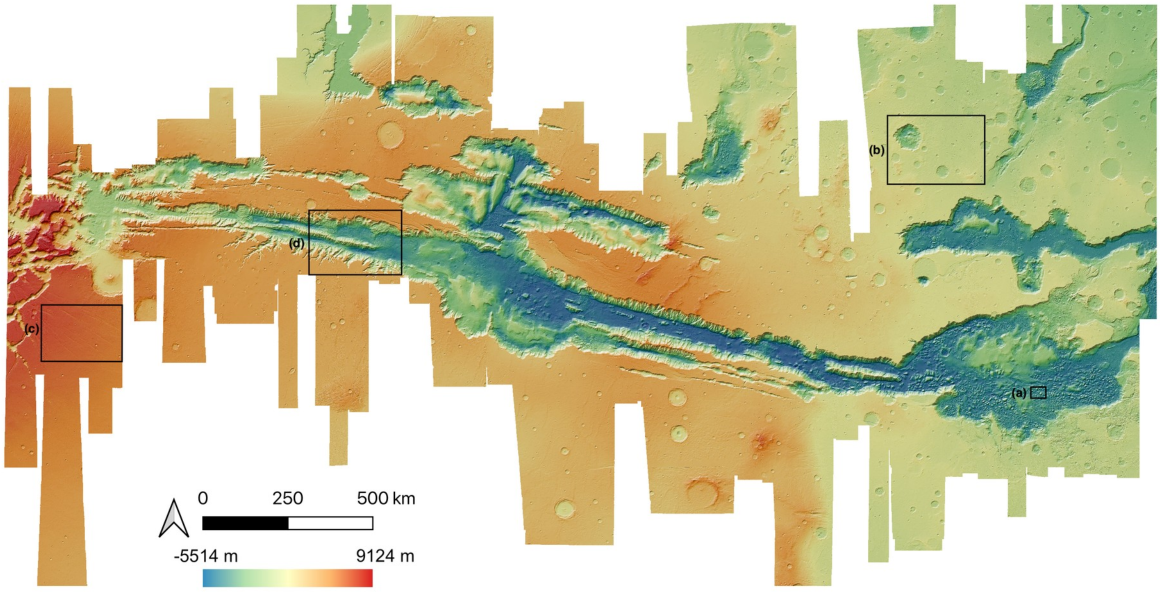

Figure 2 The final resulting HRSC DTM mosaic at 50m/pixel, covering the whole of Valles Marineris.

Some cropped examples are provided in Figure 3 over different terrain types, including hill/rock chaos, craters, flat surface, and valley/cliffs, within the Valles Marineris area.

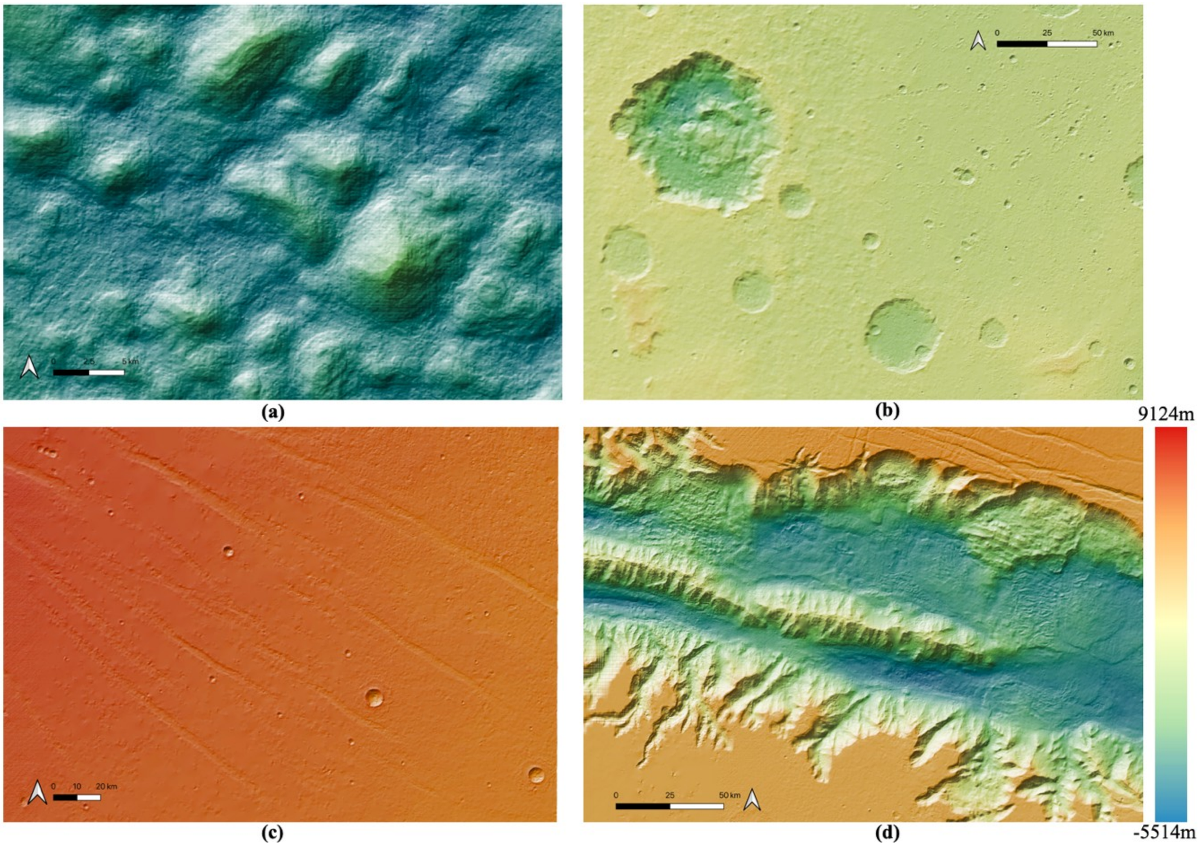

Figure 3 Examples of zoom-in views using colourised by height and hill-shaded DTMs over different features within the Valles Marineris DTM mosaic, including (a) hilly/rock chaos area; (b) crater area; (c) flat surfaced area; (d) valley/cliff area.

The mosaic from the orthoimages have been brightness adjusted including Lambertian phase angle correction, brightness normalisation, manual contrast adjustment and image sequencing. An example is shown in Figure 4.

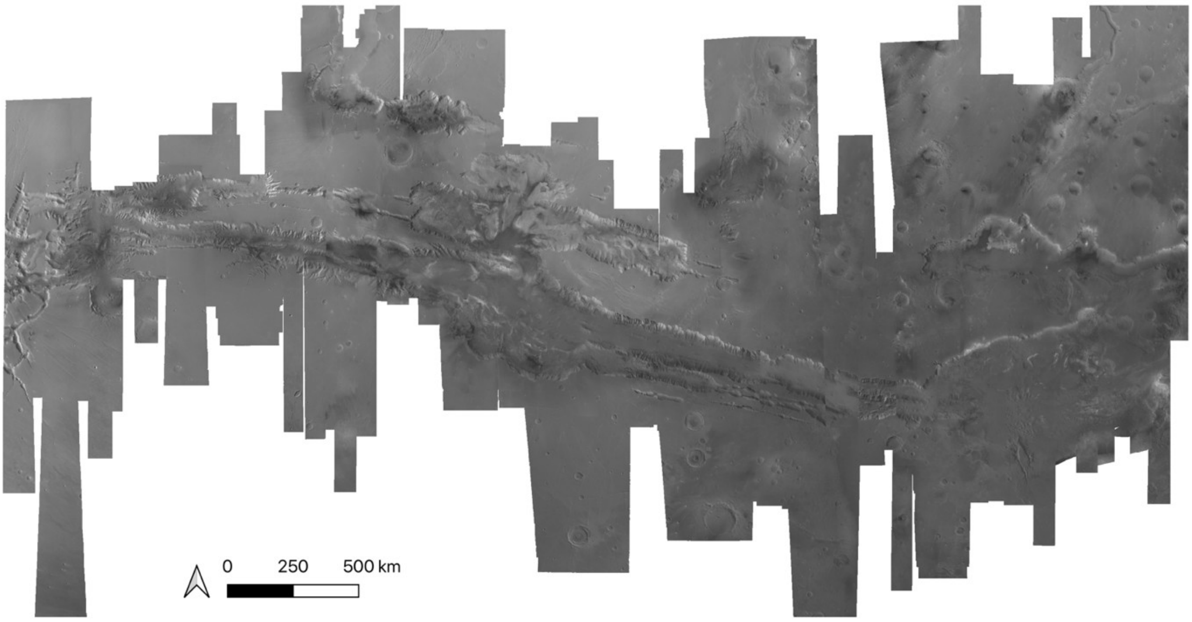

Figure 4 HRSC 12.5 m/pixel orthorectified image mosaic of Valles Marineris.

5. KNOWN ISSUES

Regarding the final HRSC DTM mosaic, overall quality has been visually checked and co-alignment accuracy has been quantified (*ibid*). However, the dataset is very large, and the stereo images are limited in quality due to atmospheric effects, onboard Discrete Cosine Transform (DCT) compression, so some local artefacts cannot be fully removed. There are known artefacts, including: tiling artefacts (seam lines), small interpolated-regions, smoothed area that are caused by using persistently "foggy" HRSC stereo images (no other options were available after checking), occasional artefacts inside small craters, quilting artefacts in heavily shaded cliff areas, and the junction of lower resolution with higher resolution single-strip DTMs. Some of these artefacts are illustrated in Figure 5. Methods have been developed for their removal, where feasible but the additional effort was not available.

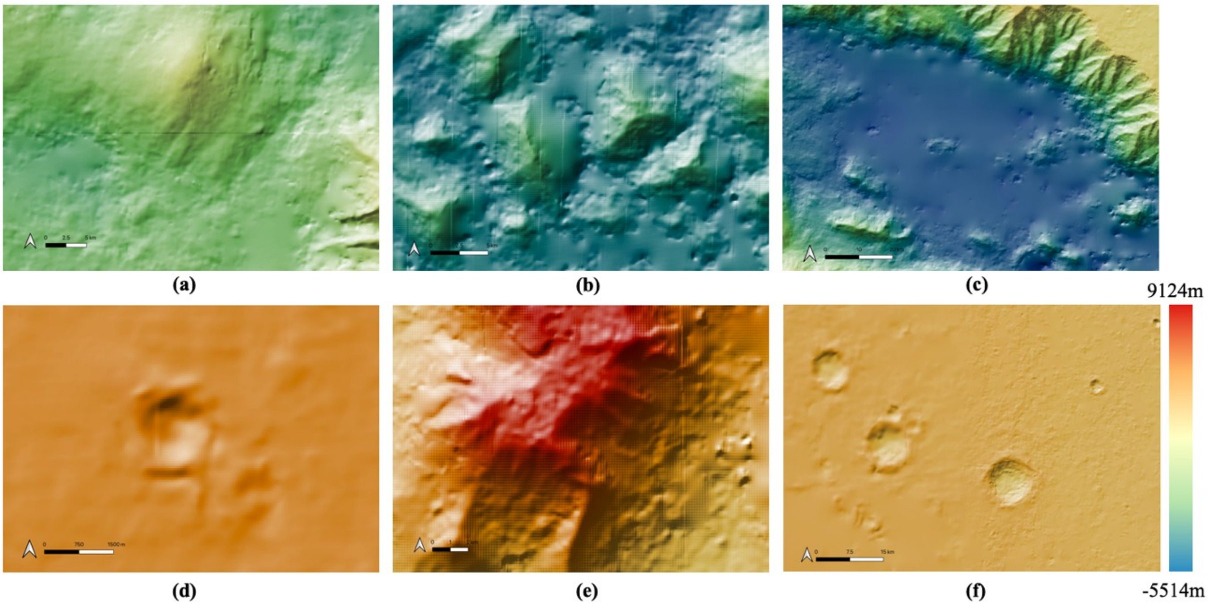

Figure 5 Examples of "known artefacts" that appeared in the Valles Marineris HRSC DTM mosaic. (a) large scale tiling artefact (seam lines); (b) finer scale tiling artefact (seam lines) and small interpolated areas where matching has failed; (c) large "smoothed out" region inside the valley caused by using foggy input images that are not replaceable; (d) some minor artefact in very small craters; (e) quilting artefact at heavily shaded cliff areas; (f) the effect of joining higher resolution (50m/pixel; from the left side) and lower resolution (150m/pixel; from the right side) single-strip DTMs.

6. SOFTWARE

CASP-GO: https://github.com/mssl-imaging/CASP-GO
ASP: https://ti.arc.nasa.gov/tech/asr/groups/intelligent-robotics/ngt/stereo/

These datasets will load automatically into GIS packages such as ARCgis or QGIS as well as into image processing systems such as ENVI®.