Supplementary Material for:

Eskers Associated with Buried Glaciers in Mars' Mid Latitudes: Recent Advances and Future Directions

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Tutorial: Get started with exploring orbital image data for Mars

The best place to start exploring Mars' surface with minimal set-up is via free Google Earth Pro software. Google Earth Pro is frequently used by Mars scientists as it is an efficient way to explore the surface before undertaking more detailed analyses in Geographic Information System (GIS) software such as ArcGIS or QGIS. There is also a free GIS for planetary science called JMARS (https://jmars.asu.edu/), which was developed by Arizona State University's Mars Space Flight Facility (Christensen and others, 2009). Relative to Google Earth Pro, JMARS has more data products (for numerous planetary bodies), with frequent data updates, and additional analytical functionality. However, we focus on Google Earth Pro for this introductory tutorial, since most Earth-focussed scientists are likely to have pre-existing experience with this software.

1. Start exploring images of Mars in Google Earth Pro for desktop.
    - Download Google Earth Pro for desktop (https://www.google.com/intl/en_uk/earth/versions/).
    - Open Google Earth Pro and switch planet by clicking the 'Switch between Earth, Sky, and other planets' icon in the toolbar, and selecting 'Mars'.
    - Open the 'Global Maps' tab in the 'Layers' pane. This lists the various basemaps available to explore in Google Earth Pro.
    - Click on the name of a layer that interests you. This will bring up information about the constituent data for that basemap. We recommend that you first switch on the 'Colourized Terrain'. This is a colourised, shaded relief map of Mars from orbital laser altimetry, which helps to orientate the user to the global-scale geography and topography of the planet.
    - See if you can spot Olympus Mons: the largest volcano in the Solar System! You can search for major features like this using the main search bar. Smaller feature names aren't pre-loaded, but you can import them as a .kml file (available from the International Astronomical Union's Gazetteer of Planetary Nomenclature webpage: https://planetarynames.wr.usgs.gov/Page/MARS/target), then search by feature name using the search bar in the Google Earth 'Places' pane.
    - To start exploring Mars' detailed surface geomorphology, we recommend switching on the 'CTX mosaic' basemap. This comprises ~6 m/pixel Context images covering most of the planet. It should be noted that, at the time of publication, the Google Earth Pro CTX mosaic is not frequently updated with new coverage. Despite this, it still provides excellent coverage of most of the planet, with a few small gaps. CTX images now cover >99% of Mars, with multiple repeat images in many places. Further information on ways to access recent CTX coverage is included below.
    - Pan and zoom around Mars, and have fun exploring! You might want to search for the candidate glacier-linked eskers described in the main manuscript; their coordinates are included in the caption of Figure 1, and you can zoom to them using the Google Earth Pro search bar.

2. Explore putative buried glaciers on Mars.
    - Next, you might wish to find some more features interpreted as relict buried glaciers in Mars' mid latitudes (called 'viscous flow features', VFFs). We recommend that you start with 'glacier-like forms' (e.g., Hubbard and others, 2011). Search the coordinates '50.52°E, 42.27°N' in the Google Earth Pro search bar. This will take you to a classic example of a glacier-like form in Protonilus Mensae, which flows down a kilometre-scale valley, and resembles a piedmont glacier beyond the valley outlet. Glacier-like forms are the smallest morphological subtype of VFFs, but they have perhaps the closest visual resemblance to valley glaciers here on Earth. They are commonly spatially associated with larger subtypes of viscous flow features (which were mapped by Levy et al. (2014)), such as those which fill impact craters, flow along large, flat-floored valleys, or extend over flat plains. The Protonilus Mensae glacier-like form

flows out over the top of a larger valley-filling VFF (see e.g., Hepburn and others, 2020). Pan around this region; there are lots of features which look very much like glaciers on Earth.

Tip: The outlines of 1243 glacier-like forms across Mars' mid latitudes (along with other metadata such as area, volume, elevation, aspect etc.) are available in GIS shapefile format in Appendix A of Brough et al. (2019). While we recommend viewing this in software such as ArcGIS or QGIS, it can be imported into Google Earth Pro to help you explore more glacial landscapes on Mars.

3. Access/view individual CTX images, including those that aren't available in Google Earth Pro.
   - Still in Google Earth Pro, click the arrow next to 'Spacecraft Imagery' in the Layers pane, and turn on the 'CTX image browser' layer. The Spacecraft Imagery layer shows the outlines ('footprints') of individual CTX images in orange (but, again, these are not frequently updated with new coverage).
   - Each footprint has an associated placemarker; click on this and follow the link to the data page for the individual image. For CTX images, Google Earth Pro directs you to the Arizona State University Mars Space Flight Facility Image Explorer, which allows you to view previews of Mars images, see their parameters, and download the images: http://viewer.mars.asu.edu/viewer/ctx.

Tips: Many individual instruments have their own data access webpages optimised for exploring their specific data products. Key examples are listed in Supplementary Table S1. For advanced search of multiple datasets, you can also use the various Mars Orbital Data Explorer search tools on NASA's Planetary Data System (PDS; https://ode.rsl.wustl.edu/mars/index.aspx).

The up-to-date footprints for Mars orbital data are also available in Google Earth KMZ and GIS shapefile format on the PDS at: https://ode.rsl.wustl.edu/mars/tools?displaypage=footprint. These files can be loaded into Google Earth Pro or GIS software and contain data outlines, product IDs, and data access links for individual data products.

There is now a global CTX mosaic for Mars, produced by The Murray Lab (http://murray-lab.caltech.edu/CTX/), which can be streamed over the internet, for example into ArcGIS software (Dickson and others, 2018). However, the beta01 version (available at the time of publication) is a preliminary product and comes with cautionary statement on its use for scientific analysis (see 'Limitations of the beta01 release' at the above URL). We recommend that future readers check for version updates to the MurrayLab CTX mosaic.

4. Explore beyond CTX images.

While CTX is currently the highest-resolution global-scale image data for Mars, there are plenty of other fascinating datasets to explore too, including more localised ~25 cm/pixel images from the High Resolution Imaging Science Experiment (HiRISE) camera, colour and day/night thermal images, and digital elevation models up to ~1 m/pixel horizontal resolution. Key image and topographic data products are summarised in Supplementary Table S1.

- As an example, still in Google Earth Pro, switch on the 'HiRISE Image Browser' in the Spacecraft Imagery tab. These appear as red outlines, but the images are more localised so you might need to pan around to find a footprint. Like CTX, these are not frequently updated with new coverage.
- Click on the footprints in Google Earth Pro and follow the link to access the image data page at the HiRISE website (https://www.uahirise.org/).
- To preview a HiRISE image in your browser, click the 'map projected' link under 'JPEG Black and White' on the HiRISE image page.

Tips: If you wish to load the full-resolution image into ArcGIS, download the both map-projected JP2 file and the 'B&W label' file (under 'additional information'), store them in the same directory, and load only the label file into ArcGIS. You can also request new HiRISE images using ‘HiWISH’: https://www.uahirise.org/hiwish/.

The information in this tutorial is correct at the time of publication. Please contact the corresponding author if you require updated instructions, or would like more information.

References for Supplementary Information 1

Brough S, Hubbard B and Hubbard A (2019) Area and volume of mid-latitude glacier-like forms on Mars. *Earth Planet Sc Lett* **507**, 10–20. doi:10.1016/j.epsl.2018.11.031.

Christensen PR and 6 others (2009) JMARS - A Planetary GIS. American Geophysical Union, Fall Meeting Abstract ID: IN22A-06. doi:https://ui.adsabs.harvard.edu/abs/2009AGUFMIN22A..06C/abstract.

Dickson JL, Kerber LA, Fassett, CI and Ehlmann BL (2018) A global, blended CTX mosaic of Mars with vectorized seam mapping: a new mosaicking pipeline using principles of non-destructive image editing. 49th Lunar and Planetary Science Conference **Abstract #2480**. doi:https://www.hou.usra.edu/meetings/lpsc2018/pdf/2480.pdf.

Hepburn AJ, Ng FSL, Livingstone SJ, Holt TO and Hubbard B (2020) Polyphase Mid-Latitude Glaciation on Mars: Chronology of the Formation of Superposed Glacier-Like Forms from Crater-Count Dating. *J Geophys Res-Planet* **125**(2), e2019JE006102. doi:https://doi.org/10.1029/2019JE006102.

Hubbard B, Milliken RE, Kargel JS, Limaye A and Souness C (2011) Geomorphological characterisation and interpretation of a mid-latitude glacier-like form: Hellas Planitia, Mars. *Icarus* **211**(1), 330–346. doi:10.1016/j.icarus.2010.10.021.

Levy JS, Fassett CI, Head JW, Schwartz C and Watters JL (2014) Sequestered glacial ice contribution to the global Martian water budget: Geometric constraints on the volume of remnant, midlatitude debris-covered glaciers. *J Geophys Res-Planet* **119**(10), 2188–2196. doi:10.1002/2014JE004685.

Supplementary Table *S1:* Key, freely-available orbital image and digital elevation model data products for Mars, with data access links. These data can be analysed in software such as ArcGIS or open-source QGIS. This list is not exhaustive, and we recommend using the search tools in the Mars Orbital Data Explorer (https://ode.rsl.wustl.edu/mars/) to explore the range of data available. See also Supplementary Information 1. Detailed visualisations and analyses of typical mid-latitude glacial landscapes on Mars require metre-scale spatial resolution or better, but some landforms are resolvable in decametre-resolution products. Larger viscous flow features (putative buried glaciers) and their host landscapes are visible in 100 m-scale products. Table adapted from Butcher (2019).

Spacecraft	Instrument	Acronym	Typical resolution	Typical footprint width	Coverage in late-2022	Data access URL*	Reference
Visible image products							
Mars Reconnaissance Orbiter	Context Camera	CTX	6 m	~26.5 km	~Global	[1]	(Malin and others, 2007; Dickson and others, 2018)
Mars Reconnaissance Orbiter	High Resolution Imaging Science Experiment	HiRISE	25–50 cm	~5 km	~3% of planet	[2]	(McEwen and others, 2007)
Mars Express	High Resolution Stereo Camera	HRSC	~15–30 m	~80 km	~Global	[3]	(Neukum and others, 2004; Jaumann and others, 2007)
ExoMars Trace Gas Orbiter	Colour and Stereo Surface Imaging System	CaSSIS	5 m	~10 km	~6% of planet	[4]	(Thomas and others, 2017)
Thermal image products							
Mars Odyssey	Thermal Emission Imaging System	THEMIS	100 m	Global mosaic	Global	[5] (Day IR) [6] (Night IR: 60°N–60°S)	(Christensen and others, 2004; Edwards and others, 2011)

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Spacecraft	Instrument	Acronym	Typical resolution	Typical footprint width	Coverage at end-2022	Data access URL*	Reference
Digital elevation models (DEMs)							
Mars Global Surveyor	Mars Orbiter Laser Altimeter	MOLA	463 m	Global grid	Global	[7]	(Smith and others, 2001)
Mars Express	High Resolution Stereo Camera	HRSC	50–100 m	~80 km	~41% of planet	[3]	(Neukum and others, 2004; Jaumann and others, 2007)
Mars Reconnaissance Orbiter	High Resolution Imaging Science Experiment	HiRISE	1–2 m	~5 km	~0.05% of planet	[8]	(McEwen and others, 2007; Kirk and others, 2008)

*See also the NASA Planetary Data System (https://ode.rsl.wustl.edu/mars/index.aspx) and ESA Planetary Science Archive (https:/archives.esac.esa.int/psa/%23!Home%20View)

[1] http://viewer.mars.asu.edu/viewer/ctx or http://global-data.mars.asu.edu/bin/ctx.pl
See also Supplementary Information 1: Google Earth Pro provides an easy way to browse CTX images, but coverage is not frequently updated. There is also a preliminary global CTX mosaic (http://murray-lab.caltech.edu/CTX/), but users are advised to read the 'Limitations of the beta01 release' information on the webpage, which advises caution in use of the beta01 version for detailed scientific analysis.

[2] https://www.uahirise.org/hiwish/browse
Note that this webmap includes both acquired images and requested images not yet taken ('targets')

[3]: https://maps.planet.fu-berlin.de/

[4]: https://cassis.halimede.unibe.ch/observations and https:/archives.esac.esa.int/psa/%23!Home%20View

[5]: https://astrogeology.usgs.gov/search/map/Mars/Odyssey/THEMIS-IR-Mosaic-ASU/Mars_MO_THEMIS-IR-Day_mosaic_global_100m_v12

[6]: https://astrogeology.usgs.gov/search/map/Mars/Odyssey/THEMIS-IR-Mosaic-ASU/Mars_MO_THEMIS-IR-Night_mosaic_60N60S_100m_v14

[7]: https://astrogeology.usgs.gov/search/map/Mars/GlobalSurveyor/MOLA/Mars_MGS_MOLA_DEM_mosaic_global_463m
115 m/pixel (512 ppd) and 230 m/pixel (256 ppd) DEMs are also available for the poles (access via NASA Planetary Data System)

[8]: https://www.uahirise.org/hiwish/maps/dtms.jsp
There are more image stereo pairs than have been processed into publicly available DEMs. Additional DEMs can be generated from stereo-pair images using NASA Ames Stereo Pipeline (https://github.com/NeoGeographyToolkit/StereoPipeline)

References for Supplementary Table S1

Butcher FEG (2019) Wet-Based Glaciation on Mars. PhD Thesis, The Open University, Milton Keynes, UK. http://oro.open.ac.uk/id/eprint/60703.

Christensen PR and 10 others (2004) The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci Rev* **110**(1–2), 85–130. doi:10.1023/B:SPAC.0000021008.16305.94.

Dickson JL, Kerber LA, Fassett, CI and Ehlmann BL (2018) A global, blended CTX mosaic of Mars with vectorized seam mapping: a new mosaicking pipeline using principles of non-destructive image editing. 49th Lunar and Planetary Science Conference **Abstract #2480**. doi:https://www.hou.usra.edu/meetings/lpsc2018/pdf/2480.pdf.

Edwards CS, Nowicki KJ, Christensen PR, Hill J, Gorelick N and Murray K (2011) Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. *J Geophys Res-Planet* **116**(E10), E10008. doi:10.1029/2010JE003755.

Jaumann R and 49 others (2007) The high-resolution stereo camera (HRSC) experiment on Mars Express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. *Planet Space Sci* **55**(7–8), 928–952. doi:10.1016/j.pss.2006.12.003.

Kirk RL and 18 others (2008) Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites. *J Geophys Res-Planet* **113**(E3), E00A24. doi:10.1029/2007JE003000.

Malin MC and 13 others (2007) Context Camera Investigation on board the Mars Reconnaissance Orbiter. *J Geophys Res-Planet* **112**(E5), E05S04. doi:10.1029/2006JE002808.

McEwen AS and 14 others (2007) Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *J Geophys Res* **112**(E5), E05S02. doi:10.1029/2005JE002605.

Neukum G, Jaumann R and the HRSC Co-Investigator and Experiment Team (2004) HRSC: The high resolution stereo camera of Mars Express. Mars Express: The Scientific Payload ESA Special Publication, SP-1240, Noordwijk, Netherlands: ESA Publications Division, 17–35.

Smith DE and 23 others (2001) Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars. *J Geophys Res-Planet* **106**(E10), 23689–23722. doi:10.1029/2000JE001364.

Thomas N and 60 others (2017) The Colour and Stereo Surface Imaging System (CaSSIS) for the ExoMars Trace Gas Orbiter. *Space Science Rev* **212**(3), 1897–1944. doi:10.1007/s11214-017-0421-1.

Supplementary Table *S2*: Codes of image products displayed in Figure 1. CTX is Context Camera, and HiRISE is High Resolution Imaging Science Experiment. Both instruments are on NASA's Mars Reconnaissance Orbiter. See Supplementary Table S1 for more information on these data products.

Figure panel	Instrument	Image code (links to data URL)
a	CTX	Processed mosaic comprising images: B05_011706_2116_XN_31N198W G20_026224_2116_XN_31N196W G23_027279_2132_XN_33N198W P18_007935_2132_XN_33N197W P22_009583_2132_XN_33N197W
b	HiRISE	ESP_044316_2130_RED
c	CTX	F22_044382_2130_XN_33N197W
d	CTX	P05_002907_2258_XN_45N083W
f	CTX	P15_006731_2257_XN_45N084W
g	CTX	P18_007878_2258_XN_45N083W

Supplementary Table *S3*: Orbital infrared datasets which could be used to analyse mineral classes associated with sinuous ridges on Mars. Note that the majority of these data require processing for quantitative analyses.

Instrument	Acronym	Spectral range	Spatial resolution	Data URL	Reference
Compact Reconnaissance Imaging Spectrometer for Mars	CRISM	0.4–4.0 μm	18–200 m/pixel	[1]	Murchie and others (2007)
Observatoire pour la Mineralogie, l'Eau, les Glaces, et l'Activité	OMEGA	0.4–5.0 μm	200–2000 m/pixel	[2]	Bibring and others (2005)
Thermal Emission Imaging System	THEMIS	6.7–14.8 μm	100 m/pixel	[3]	Christensen and others (2004)
Thermal Emission Spectrometer	TES	~6–50 μm	3×6 km spots	[4]	Christensen and others (2001)

[1] http://crism-map.jhuapl.edu/ and https://pds-geosciences.wustl.edu/missions/mro/crism.htm
[2] https://pds-geosciences.wustl.edu/missions/mars_express/omega.htm
[3] http://global-data.mars.asu.edu/bin/themis.pl
[4] http://tes.asu.edu/data_tool/

References for Supplementary Table S3

Murchie S and 49 others (2007) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). *J Geophys Res-Planet* 112(E5). doi:https://doi.org/10.1029/2006JE002682.

Bibring J-P and 30 others (2005) Mars Surface Diversity as Revealed by the OMEGA/Mars Express Observations. *Science* 307(5715), 1576–1581. doi:10.1126/science.1108806.

Christensen PR and 10 others (2004) The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci Rev* 110(1–2), 85–130. doi:doi:10.1023/B:SPAC.0000021008.16305.94.

Christensen PR and 25 others (2001) Mars Global Surveyor Thermal Emission Spectrometer experiment: Investigation description and surface science results. *J Geophys Res-Planet* **106**(E10), 23823–23871. doi:10.1029/2000JE001370.