REMOTE CHARACTERISATION OF MARS:
PREPARATION FOR EXOMARS

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by

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Abstract

The ExoMars mission is a two-part ESA-Roscosmos mission to Mars, with the Trace Gas Orbiter (TGO) reaching Martian orbit in late 2016 and the rover launching in 2020. The mission will study the Martian surface, investigating signs of past or present life, water and trace gases.

A landing site must be chosen for the rover and this work summarises the proposed sites, in particular investigating the distribution of (and risk posed by) Transverse Aeolian Ridges (TARs). These are features that are between ripples and dunes in size and morphology. The density of these features over each of the landing sites has been mapped, finding that Oxia Planum has a density of 4.9 ± 5.9 %, Aram Dorsum has a density of 2.72 ± 2.75 % and Mawrth Vallis has a density of 16.9 ± 7.9 %. Comparisons to Mars Science Laboratory's Curiosity rover have shown that the ExoMars rover is expected to sink 1.4 times further into equivalent ripples, and so it is necessary to investigate the rover response to TARs as their implications may be more severe.

In addition, this work examines a sedimentological deposit in the Oxia Planum landing site and finds that it is likely to be deltaic. This is one of twelve deltas that are proposed to have been created by the presence of multiple instances of a northern ocean. Assuming an ocean shoreline would form an equipotential, it is proposed that an ocean was present in at least two distinct time periods, one in the late Noachian at an elevation of -2860 m (+/- 212 m) and one in the early Amazonian at an elevation of -2100 m (+/- 346 m). Recent studies have proposed the existence of an Amazonian active hydrological cycle, supporting the existence of the latter ocean, although having the largest ocean in the Amazonian era is unexpected.
ACKNOWLEDGEMENTS

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ABBREVIATIONS

ACS - The Atmospheric Chemistry Suite

AMELIA - Atmospheric Mars Entry and Landing Investigation and Analysis

CaSSIS - The Colour and Stereo Surface Imaging System

CCD - Charged Coupled Device

COMARS+ - The COMbined Aerothermal and Radiometer Sensors Instrument Package

CRISM - Compact Reconnaissance Imaging Spectrometer for Mars

CTX - The Context Camera

DECA - DEscent CAmera

DEM - Digital Elevation Model

DREAMS - Dust characterisation, Risk assessment and Environment Analyser on the Martian Surface

DTM - Digital Terrain Model

EDL - Entry, Descent and Landing

ESA - European Space Agency

ESP - Extended Science Phase

ESRI - Environmental Systems Research Institute

FREND - The Fine Resolution Epithermal Neutron Detector

GEL - Global Equivalent Layer

GIS - Geographic Information Software

HiRISE - The High Resolution Imaging Science Experiment

HRSC - The High Resolution Stereo Camera

INRRI - The INstrument for landing - Roving laser Retroreflector Investigations

ISEM - Infrared Spectrometer for ExoMars

LDD - Large Dark Dune

Ma_MISS - Mars Multispectral Imager for Subsurface Studies
MARSIS - Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVEN - Mars Atmosphere and Volatile EvolutioN
MGS - Mars Global Surveyor
MOC - Mars Orbiter Camera
MOLA - Mars Orbiter Laser Altimeter
MOMA - Mars Organic Molecule Analyser
MRO - Mars Reconnaissance Orbiter
MSL - Mars Science Laboratory
NASA - National Aeronautics and Space Administration
NOMAD - The Nadir and Occultation for MArs Discovery
PanCam - Panoramic Camera
RLS - Raman Laser Spectrometer
RSL - Recurring Slope Lineae
SRC - Super Resolution Channel
TAR - Transverse Aeolian Ridge
TES - Thermal Emission Spectrometer
TGO - Trace Gas Orbiter
THEMIS - The Thermal Emission Imaging System
USGS - United States Geological Survey
WISDOM - Water Ice and Subsurface Deposit Observation on Mars
1 INTRODUCTION

Since the first successful Mars mission in 1964, when Mariner 4 carried out a fly by and returned images, our knowledge of Mars has dramatically increased (Carr, 2006). Orbiters, landers and rovers have all enabled a variety of investigations of Mars, from returning images of higher resolution to analysing surface materials. Each mission has had different science goals, with an overarching theme of investigating the planet and searching for evidence of water and life.

The scientific return of these many missions has been enormous, and with eight missions currently on or orbiting Mars and a further three planned for launch in the next three years, this return will continue to grow. The ancient Martian surface has been found to have interacted with water significantly throughout its history, with missions finding hydrated phyllosilicate minerals and sedimentological features such as alluvial fans and deltas (Grotzinger, et al., 2012).

Mars Science Laboratory’s Curiosity rover is currently travelling from its landing site at Gale Crater toward Mount Sharp, and the data returned by the mission is allowing not only science in its own right, but also preparation for future missions such as ExoMars. The ExoMars mission is a joint ESA-Roscosmos mission which launched an orbiter and lander, which will be followed by a rover, to Mars with the aim of investigating water and potential signs of past or present life on the surface (European Space Agency, 2016c). A safe landing site must be selected for the rover, and one aim of this work will be to characterise the landing sites that have been proposed for the rover.

One of the proposed ExoMars landing sites, at Oxia Planum, contains a sedimentological feature which is hypothesised to be a delta. The discovery of water-related features on the Martian surface has fed into hypotheses that there was once an ocean in the northern Martian plains (Di Achille & Hynek, 2010; Parker, et al., 1989; Baker, et al., 1991). This naturally has implications for the evolution of the Martian surface and the potential for past or present life. A past ocean may have formed part of a global hydrosphere in parallel with the terrestrial situation, which would have involved many components, such as valley networks and deltas, to allow for the movement of water across the surface (Di Achille & Hynek, 2010). Remnants of these features have been found, and if they are related to a common ocean there should be
commonalities between the remnants. If there was indeed once a northern ocean, deltas feeding into the ocean would have formed at the same elevation if they formed during the same time period, assuming that the water level of the ocean formed a global equipotential.

A second aim of this work is therefore to investigate the deltaic features that may once have fed into an ancient northern ocean, and in particular the feature in Oxia Planum. This will also include determining a potential elevation (or elevations) for a historical northern ocean based on the features studied.

1.1 The ExoMars Mission

The ExoMars mission is a two-part European Space Agency and Roscosmos mission to Mars, with the Trace Gas Orbiter (TGO) having launched in 2016 and being followed by a rover which will launch in 2020. The mission is intended to address a number of scientific questions with the prime focus being on finding signs of past or present life, and investigating water, the geochemical environment and trace gases and their sources (European Space Agency, 2016c).

As the ExoMars mission includes a rover, it is necessary to identify an appropriate landing site. The proposed landing sites have been narrowed down to three potential sites: Oxia Planum, Aram Dorsum and Mawrth Vallis. Oxia Planum was selected as the landing site for a 2018 launch of the rover, but as this has now been delayed to 2020 the selection has been expanded again to include the other two sites. The locations of the three sites can be seen in Figure 1.

The Trace Gas Orbiter launched in March 2016 and has three key roles. The first is to investigate trace gases in the Martian atmosphere using four instruments. These are: CaSSIS, the Colour and Stereo Surface Imaging System which will take colour and stereo images at 4.6 metres per pixel looking for geological and dynamical context for gas sources and sinks; ACS, the Atmospheric Chemistry Suite which uses infrared spectrometers to investigate the chemistry and structure of the atmosphere; NOMAD, the Nadir and Occultation for MArs Discovery which uses spectrometers to identify atmospheric components; and FREND, which is the Fine Resolution Epithermal Neutron Detector and will map hydrogen to a depth of one metre on the surface, looking for near-surface water-ice (European Space Agency, 2016c).
The second role for TGO is to deliver the Schiaparelli lander to the surface, which will act as a technology demonstration for entry, descent and landing. It will also contain a short-duration science package, DREAMS (Dust Characterisation, Risk Assessment, and Environment Analyser on the Martian Surface) for studying the surface environment during its two to eight sol lifetime (European Space Agency, 2016c). The final role for TGO is to provide a communication relay, both for Schiaparelli and for the 2020 rover and surface platform.

![Figure 1: Chryse Planitia region showing the location of the three landing sites relative to each other and the northern plains. Background is MOLA interpolated global elevation map (MOLA Team, 2003).](image)

The 2020 mission will include a rover and surface science platform, on which the rover will land. The main scientific goals for the platform are to carry out climate monitoring, atmospheric investigations and to provide context imaging of the landing site. There are 13 instruments on board to achieve these goals, including seismometers, spectrometers and cameras (European Space Agency, 2016c).

The rover will land on the science platform before travelling across the surface to search for signs of life. It will have nine instruments, which include PanCam, a panoramic camera for identification of targets, a Raman Laser Spectrometer which will allow for non-destructive identification of organic pigments and identification of
geologic materials, and MicrOmega for carrying out mineralogical studies. It is also equipped with a 2 m drill for obtaining sub-surface samples (European Space Agency, 2016c). The rover will be highly autonomous as there will be at most two short communication opportunities per sol (European Space Agency, 2016c). The low availability of communications increases the need for an accessible landing site, as the rover will need to navigate the surface without real-time input.

There are five key scientific restrictions for the landing site for the rover, as set out in ESA’s ExoMars Landing Site Selection User’s Manual (European Space Agency, 2013).

1. The site must be older than 3.6 Ga (i.e. ancient), and must come from the pre- to late-Noachian or possibly the Hesperian era.
2. There must be abundant morphological and mineralogical evidence for aqueous activity.
3. There must be numerous sedimentary outcrops.
4. The outcrops must be distributed over the landing ellipse to allow the rover to access them.
5. There must be little dust coverage.

In addition, there are a number of engineering constraints that the chosen site must comply with, which are set out in Table 1.

Different aspects of the mission determine each of the engineering constraints. For example, the elevation, landing ellipse size and orientation are determined by the Entry, Descent and Landing (EDL) system, which uses a ballistic entry with a heat shield followed by a parachute deceleration and a powered final descent (European Space Agency, 2013). Each of the slope constraints is derived from different elements of the descent, with the 7 m constraint allowing more accurate altitude determination during landing, and the 2 km base length being required by the radar system used (European Space Agency, 2013). In addition, the rock distribution criteria is derived from the clearance on the landing platform, which has a clearance of 0.35 m before deformation and 0.18 m after deformation (European Space Agency, 2013).

While many of the constraints have been assessed for all of the sites, there is insufficient data for a couple of them to be determined. The radar reflectivity has not been determined and, while global climate models are available, the surface winds have
not been analysed for each site. In addition, rock counting is still being carried out across the landing sites so final values for this are not available.

Table 1: ExoMars rover engineering constraints (European Space Agency, 2013).

<table>
<thead>
<tr>
<th>Category</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>5° S to 25° N</td>
</tr>
<tr>
<td>Landing Elevation</td>
<td>Must be less than or equal to -2 km MOLA</td>
</tr>
<tr>
<td>Landing Ellipse</td>
<td>120 x 19 km</td>
</tr>
<tr>
<td>Terrain Relief and Slopes</td>
<td>Base Length</td>
</tr>
<tr>
<td></td>
<td>A</td>
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<td></td>
<td>B</td>
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<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>Rock Distribution</td>
<td>Must have 0.18 m of clearance for landing platform, and ≤ 7% rock abundance</td>
</tr>
<tr>
<td>Radar Reflectivity</td>
<td>- Terrain Backscattering at nadir: –15 dB to 27.5 dB</td>
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<tr>
<td></td>
<td>- Terrain Backscattering at 10° off-nadir: –17 dB to –10 dB</td>
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<tr>
<td></td>
<td>- Terrain Backscattering at 20° off-nadir: –18 dB to –13 dB</td>
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<tr>
<td></td>
<td>- Maximum Backscattering decay from 0° to 5° off-nadir: –30.4 dB</td>
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<tr>
<td></td>
<td>- Maximum Backscattering decay from 0° to 10° off-nadir: –37.3 dB</td>
</tr>
<tr>
<td></td>
<td>- Maximum Backscattering decay from 0° to 15° off-nadir: –40.6 dB</td>
</tr>
<tr>
<td>Surface Thermophysical Properties</td>
<td>Must have:</td>
</tr>
<tr>
<td></td>
<td>- Surfaces having thermal inertia ≥ 150 J m(^{-2}) s(^{-0.5}) K(^{-1})</td>
</tr>
<tr>
<td></td>
<td>- Surfaces having 0.1 ≤ albedo ≤ 0.26.</td>
</tr>
<tr>
<td>Surface Winds</td>
<td>Must have horizontal winds of ≤30 m/s and vertical winds of ≤ 12 m/s at 1 m above ground level.</td>
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1.2 Early Mars: was it warm and wet?

The ExoMars mission team has specified that the rover must land at an ancient Noachian or early Hesperian landing site, as discussed in Section 1.1. This era is thought to be particularly interesting as early Mars is thought to have had a very different climate than we see in the present day, although there are multiple theories as to what it would have been like. However they tend to agree that this time period is likely to have involved water on the Martian surface, and therefore landing a rover in these regions will allow for in-situ investigation of historical water locations.
There are two main theories for the presence of water on Mars in the Noachian era: the "cold and dry" theory, that water was caused by local heating in a cold global climate; or the "warm and wet" theory, where the atmosphere was warmed with greenhouse gases (Fairén, 2010). A third suggestion has been made for a "cold and wet" Mars, in which a hydrological system existed during periods of thick atmosphere, with periods of time having a thin atmosphere and low temperatures and therefore only having transient water flowing (Fairén, 2010).

The "warm and wet" theory is dependent on the greenhouse effect, and it is thought that an 80° greenhouse effect would be needed to raise the mean temperature to above 0° to allow the surface to sustain water (Catling, 2014). The thick atmosphere needed to sustain this greenhouse effect is thought to have been lost 3.7 Ga ago and so cannot be investigated presently and can only be traced through geological records (Catling, 2014).

There are three main processes that are thought to be responsible for the atmospheric loss. The first of these is the ejection of atmospheric gases through impacts, particularly during the late heavy bombardment where the flux of impacts was thought to be significant enough to raise the atmospheric pressure to allow water to flow on the surface (Melosh & Vickery, 1989). Losses due to impact cratering are thought to account for up to 90% of the atmospheric losses since the geologic record began (Brain & Jakosky, 1998). The second process is sputtering, a photochemical process which ionises atoms in the upper atmosphere and ejects them into space using the solar wind, and is thought to account for the loss of 85-95% of the argon, carbon, hydrogen and nitrogen reservoirs (Brain & Jakosky, 1998). The loss of the Martian magnetic field allowed the solar wind to interact with the atmosphere, worsening this effect (Brain & Jakosky, 1998). The final mechanism is sequestration of carbon dioxide into reservoirs, both in the subsurface and polar ice caps (Brain & Jakosky, 1998).

Carbon dioxide could have been used to increase the temperature of Mars sufficiently to allow for water to flow (Pollack, et al., 1987). It could also have been recycled, e.g. from thermal decomposition of carbonates, providing a source to sustain the atmosphere (Pollack, et al., 1987). In addition, it could have been removed relatively rapidly as carbonate rocks formed, which may also feed into the loss of the atmosphere (Pollack, et al., 1987).
Alternatively, it has been suggested that the surface may have warmed through large body impacts (Catling, 2014). These may have raised the temperature sufficiently for water to flow, which could explain why many valley networks appear to have formed around the Late Heavy Bombardment (Catling, 2014).

Mars Science Laboratory's Curiosity rover has found perchlorates in Gale Crater, which affect the ability of the soil to retain water (Nuding, et al., 2014). These salts alter surface-atmosphere interactions on Mars and maintain a stable aqueous solution on present-day Mars, providing a method for liquid water to exist (Nuding, et al., 2014). Increased salinity may therefore have allowed water to exist past the loss of the majority of the atmosphere, and late aqueous activity may have been caused by high salinity liquids rather than fresh water. This has been further supported by the findings of Ojha, et al., who used the Compact Reconnaissance Imaging Spectrometer for Mars on Mars Reconnaissance Orbiter to identify hydrated salts due to the presence of Recurring Slope Lineae (RSL) (Ojha, et al., 2015). RSL may provide evidence of transiently wet conditions near the surface of Mars, as the high salinity of the liquid lowers the freezing point of water by up to 80K (Ojha, et al., 2015).

Landing at an ancient site may be particularly interesting as the traditional breakdown of Martian history is increasingly being questioned due to increasing evidence that the post-Noachian era was also home to aqueous activity. Increasing numbers of fluvial valleys have been found which are thought to date to the Hesperian and Amazonian eras, which challenges the idea that these periods had limited aqueous activity that was restricted to occasional outburst floods and hydrothermal runoff (Wilson, et al., 2016). These shallow valleys are thought to be consistent with an active hydrological system near the Hesperian-Amazonian boundary (Wilson, et al., 2016). The possibility for multiple fluvial eras on the Martian surface will be of interest when studying deltas on the surface and investigating the proposal of a historical ocean in the northern plains of Mars, as it will not limit this ocean to the Noachian period.

1.3 Objectives

There are two main objectives for this work. The first is to use remote sensing to characterise the surface of Mars with the aim of aiding selection of an appropriate and safe landing site for the ExoMars rover from the three remaining proposals. This is primarily focused on the characterisation of aeolian features, as depending on the
abilities of the rover they could pose a significant threat to the traversability of the ExoMars rover.

The second objective is to characterise the sedimentological feature in the Oxia Planum landing site, which has been hypothesised to be a delta. The identification of this feature will support the comparison between the scientific nature of the remaining landing sites. The characterisation of this feature will feed into the larger science question of whether there was once an ocean in the northern plains of Mars. An elevation for the proposed northern ocean will be calculated, with the implications of the result being discussed, together with a discussion about the validity of the method. The implications of the proposed ocean for each of the landing sites will also be discussed.
2 INSTRUMENTATION AND METHODS

This chapter will discuss the remote instruments around Mars used to carry out this work and the additional tools used for analysis.

2.1 ArcGIS

ArcGIS by ESRI has been used to collect and arrange the data used in this work (ESRI, 2014). The Geographic Information Software allows multiple data sets to be geographically referenced and displayed visually, which allows for easy investigation of different locations on the Martian surface. By using geographically referenced data in the same projection system, it is straightforward to move between different data sets for the same region. ArcGIS has been used to carry out topographic analysis of both images and point data, and to combine and filter multiple data sets where appropriate. ArcGIS allows visual databases of sedimentary features to be generated alongside spreadsheets.

The functionality within ArcGIS has been used to extract point data from High Resolution Stereo Camera (HRSC) Digital Terrain Models (DTM). This has been carried out by extracting the elevation values that correspond to a series of points created over the surface of sedimentary features. This has allowed detailed analysis of the features, as it has extended the profiling functionality beyond the built-in profile generation.

2.1.1 Areocentric Grid for Mars

In order to view the data sets in ArcGIS, they must be projected into an areocentric coordinate system, i.e. one which is centred around Mars. As with geocentric coordinate systems, there are many different projections available, both in planetocentric and planetographic form. The Mars data sets do not all use a single projection, with HRSC images using both planetocentric and planetographic projections depending on the file type used. The images used herein have all been projected using ArcGIS onto a Mars2000 grid, which was obtained from the United States Geological Survey (United States Geological Survey, 2004). By projecting all the data and creating shapefiles in the same projection system, it is ensured that measurements across data sets are consistent and images are aligned with one another.
2.2 HiRISE: The High Resolution Imaging Science Experiment

HiRISE is the High Resolution Imaging Science Experiment on Mars Reconnaissance Orbiter (MRO). It is able to produce high resolution images at 0.3 to 1.3 m per pixel, allowing objects as small as ~90 cm to be resolved with a vertical precision of 25 cm (McEwen, et al., 2007).

The imager was designed in line with the scientific goals of MRO which include searching for aqueous and hydrothermal activity, studying geomorphology, stratigraphy and composition of surface features, and identifying sites with high scientific potential for future missions (McEwen, et al., 2007). It has a swath width of up to 6 km, and covered 0.55% of the Martian surface over 9137 images in the initial two-year primary science phase (McEwen, et al., 2010). This was lower than the possible total coverage in a two-year period due to repeat images for stereo, study of seasonal processes and to correct for poor image quality (McEwen, et al., 2010). The mission has since been extended, and HiRISE is still in operation seven years after the Extended Science Phase (ESP) began in January 2009 (McEwen, et al., 2010). Figure 2 shows the HiRISE coverage obtained up to 7 July 2016, with the black squares indicating the footprint of each HiRISE image. Repeat imaging is not explicitly shown in this map.

The HiRISE telescope uses push-broom imaging with 14 CCDs in the focal plane (Malin, et al., 2007). The CCDs are staggered, and are divided over the different bands: two for each of BG and NIR and 10 for the RED band (Malin, et al., 2007). The imager is capable of acquiring images containing up to 28 Gb of data in only six seconds (McEwen, et al., 2010). The short integration times allow detailed resolution of the Martian surface to be obtained, as the imager will have moved over a relatively short distance in the duration of one frame. The RED images have been used primarily in this work, as the HiRISE images have been used for morphology and surface examination rather than to examine composition through colour images.

HiRISE images are sorted into one of 18 science themes to allow for organisation and prioritisation of images (McEwen, et al., 2010). One of the important aims of HiRISE is to image both past and future landing sites (McEwen, et al., 2007). The images play a key part in this as they provide unprecedented resolution and therefore increased ability to identify hazards, both through the identification of dangerous features (e.g. rocks, aeolian features) and through the introduction of a shorter base length for slope
calculation. The HiRISE images have been used significantly in the study of aeolian features in this work, as the highest resolution of 0.3 m per pixel allows features down to a bedform length of 1 m to be resolved, allowing potentially dangerous objects in landing zones to be resolved.

Figure 2: Coverage of Mars by HiRISE up to 7 July 2016, with black boxes showing the footprint of each HiRISE image (National Aeronautics and Space Administration, 2016). Background is an interpolated MOLA map to show context (MOLA Team, 2003).

In order to maximise the scientific output from the camera, a public request system, HiWish, is used which allows anyone to enter targeting requests for the Martian surface, with all images being released publicly. In addition, the HiRISE team use fortnightly planning cycles to prioritise key science targets. For the planning cycles, ExoMars is a scientific priority, and therefore I have been using these cycles to maximise the coverage of the landing sites. Ideally, 100% coverage of the chosen landing site would be obtained, and so the planning cycles are being used to optimise this process. Both the existing images at each site and the requests that have been submitted to the HiRISE team have been catalogued, allowing for systematic submission of requests with the intention of maximising coverage across landing ellipses. Appendix 1 includes a table of the HiRISE images requested and collected over the duration of this project.

2.3 HRSC: The High Resolution Stereo Camera

HRSC is the High Resolution Stereo Camera on Mars Express. It launched in 2003 with a primary aim of addressing the scientific goals of providing high resolution photogeology and studying surface-atmosphere interactions, while also supporting the
remaining scientific goals of the mission of studying the atmosphere and carrying out mineralogical mapping (Neukum, et al., 2004). The images produced have since been used heavily in landing site selection as the camera has been used to provide stereo coverage and Digital Terrain Models (DTMs) of over 40% of Mars up to orbit 6509 (Gwinner, et al., 2016). In addition, the camera has mapped 97% of the surface at better than 100 m per pixel, and 70% of the surface in panchromatic images at 10-20 m per pixel (Gwinner, et al., 2016).

The camera is able to produce images with a resolution of ≥10 m per pixel and is capable of along-track acquisition of stereo imagery (Neukum, et al., 2004). The camera takes triple-stereo images in four colours and at up to five phase angles, which have been used to generate DTMs associated with the nadir images (Neukum, et al., 2004), with the stereo analysis used allowing for sub-pixel accuracy of 3D points (Gwinner, et al., 2016). These have a similar resolution to the nadir images, which is 10 m per pixel at a periapsis of 250 km altitude (Neukum, et al., 2004). The imaging principle can be seen in Figure 3, with the nadir image labelled as ND. There are also super-resolution channels (SRC) which are capable of reaching 2.3 m per pixel (Neukum, et al., 2004), but these have not been used in this work. The intention of having multiple images in a number of colours is to allow for terrain classification and allow for examination of the physical soil properties (Neukum, et al., 2004).

Figure 3: HRSC imaging principle showing the range of images taken by the camera. ND is the nadir channel, S1 and S2 are stereo channels, and P1 and P2 are photometry channels (Gwinner, et al., 2016).
HRSC DTMs have been created for many images, allowing a direct comparison between the image and the topography and easy generation of profiles through surface features. This method has been used previously for both Mercury (Mercury Dual Imaging System), and the Moon (Lunar Reconnaissance Orbiter Camera) to produce the Global Lunar DTM (Gwinner, et al., 2016). The use of along-track stereo to produce DTMs had also been tested on Earth before Mars Express launched (Gwinner, et al., 2016). One of the significant benefits of along-track stereo is that images are taken under the same illumination conditions, increasing the ease with which the images can be combined and the accuracy with which DTMs can be generated as the chance of false measurements, e.g. due to shadow changes, are reduced. However, multi-orbit DTMs have also been produced in some areas, as this introduces a wider selection of images for combining and also can bring improvements over single-strip DTMs, in particular filling in gaps which may be produced by shadows or caused by the image edges (Gwinner, et al., 2016). However, there is naturally additional processing required for the combination of these images. DTMs produced are registered to the MOLA global DTM (see Section 2.5), with variations due to the different point density taken into account (Gwinner, et al., 2016).

The density of HRSC images over the MC-11 quadrant of Mars is sufficiently high that it has been possible to produce a mosaic of the eastern half of the quadrant which covers the landing sites at Aram Dorsum and Mawrth Vallis and part of the site at Oxia Planum. This region has all been processed to be consistent in colour and to match the DTMs, and provides a regional reference for the landing site studies. As these mosaics are extended, this will significantly increase the ease with which wider regions can be studied.

Both the HRSC images and DTMs will be used in this work. The resolution of the HRSC images is such that they are able to be used for preliminary identification of features, in particular the deltas, before the detail of higher resolution images such as HiRISE and CTX will be used to view the features in more detail. The DTMs will be used to create line profiles and generate point data for creating point profiles, in particular for features which are too small to be studied using the MOLA point data.
2.4 CTX: The Context Camera

The Context Camera (CTX) on Mars Reconnaissance Orbiter provides context images for the other instruments on MRO at ~6 m per pixel (Malin, et al., 2007). The maximum coverage of Mars that was expected from CTX was ~9% of the surface, not allowing for repeat or overlapping images (Malin, et al., 2007). However, there is significant coverage of Mars in the regions being studied which has provided a useful compromise between the detail of HiRISE and the area seen in HRSC images to allow for identification of deltas and alluvial fans.

The camera was introduced to the MRO mission to provide context images for the HiRISE and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) images, but it has additional scientific objectives including studying the geology and geomorphology of surface features and processes (Malin, et al., 2007). These include rock outcrops, fluvial landforms, aeolian landforms and impact craters (Malin, et al., 2007). As the camera is a NASA Facility Instrument it is intended to be used to investigate features which the NASA Mars Exploration Program is interested in (Malin, et al., 2007).

Some stereo images have been generated using CTX images, and these have been used, for example, in Oxia Planum. However, as the imager does not take along-track stereo images, these are only produced from repeat imaging of a location, with re-imaging of gully locations being a priority for the operating team (Malin, et al., 2007). As discussed in reference to HRSC, there are benefits to using multi-track stereo images but also difficulties in processing. Stereo images for CTX are not as readily available as for HRSC, and therefore have not been used to the same extent in this work.

As can be seen from Figure 4, the CTX images provide an intermediate between HiRISE and HRSC images in respect of size and resolution. They are up to 30 km wide and 40 km long from the nominal orbit of MRO. Although CTX has a similar resolution to high resolution MOC images (Mars Orbiter Camera on Mars Global Surveyor), it has a wider field of view (~30 km) as compared to MOC's 3 km (Malin, et al., 2007). This has increased the ease with which fields such as gullies can be studied, as it allows many more gullies to be observed in a single image at a single time and therefore their changes can be more readily monitored (Malin, et al., 2007).
The intermediate size of CTX images has made them particularly useful in studying the sedimentological features, both in Oxia Planum and wider across the surface, and they have been used primarily to find additional data where either HiRISE or HRSC are insufficient in extent, image quality or resolution.

Figure 4: HRSC, CTX and HiRISE images of Gale Crater illustrating the different footprint sizes. Images are h1927_0000, P01_001422_1747, PSP_006288_1740 and ESP_023957_1755.

2.5 MOLA: The Mars Orbiter Laser Altimeter

The Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor (MGS) provides point data representing the elevation of the Martian surface with reference to a zero level. The primary objective of the MOLA instrument was to produce global maps of the topography of Mars, with additional objectives including studying the Martian atmosphere using secondary reflections and studying temporal changes (Smith, et al., 2001). Before the MOLA instrument, knowledge of Martian topography was limited to that obtained from the Mariner and Viking spacecraft, and a Digital Elevation Model.
(DEM) produced by the United States Geological Survey (USGS) using radar measurements from Earth (Smith, et al., 2001). This DEM had a pixel size of approximately 1/64° by 1/64° with vertical errors of ~1 km (Smith, et al., 2001). The Viking spacecraft used pressure variations at different points to obtain relative elevations, and the USGS global map struggled to match these relative elevations (Smith, et al., 2001). Subsequent analyses of the combined Viking and Mariner data were able to create global maps with improved vertical accuracy but reduced spatial resolution than the USGS map (Smith, et al., 2001). However, as there was still only a vertical accuracy of ~500 m, there was a significant need for the high accuracy and improved resolution global map which the MOLA instrument obtained (Smith, et al., 2001).

The MOLA instrument used a chromium- and neodymium-doped yttrium aluminium garnet (Cr:Nd:YAG) oscillator with aluminium gallium arsenide (AlGaAs) laser diodes (Smith, et al., 2001). Round-trip laser pulses are measured in order to determine the distance to the surface at each point, with the temporal accuracy of pulses being known to 0.004 s to allow for accurate positioning over the surface (Smith, et al., 2001). The sampling rate and orbit of MGS have combined to cause a spot size of 168 m, with approximately 300 m between adjacent measurements (Smith, et al., 2001). However, the vertical resolution of the measurements ranges between 0.375 m on smooth surfaces to 10 m on slopes of ~30° (Smith, et al., 2001). In addition, the pulse width of the measurements has allowed the roughness at a 100 m scale to be determined, providing an indication of large-scale vertical roughness (Smith, et al., 2001).

A topographic model of the Martian surface has been generated from the MOLA data, which can be seen in Figure 5. This has been referenced to the Mars 2000 projection discussed in Section 2.1.1, and has therefore been used as a reference data set for DTMs produced from more recent instruments. While the global map allows for easy examination of features at a global level, the availability of point data allows for a more precise examination where it is needed. The point data removes any smoothing artefacts introduced in the production of global maps, which are where the production of raster maps interpolates data to fill gaps in the point data which may not represent the actual topography. However, it is limited by the resolution, as the 300 m distance between measurements can cause many important features to be missed, e.g. for landing site characterisation. These point data have been used to produce smaller raster maps of
regions across features being examined, as the smaller range of elevations included in these maps can minimise artefacts from smoothing, although this must be balanced against the introduction of artefacts due to limited sample sizes. In addition, the point data has been used in the generation of point profiles across sedimentological features where possible. These profiles have allowed a wider section of a feature to be included, rather than selecting a potentially non-representative line profile through a feature.

Figure 5: MOLA topography interpolated global maps (Smith, et al., 2001)

Although instruments such as HRSC have since improved on the resolution available from MOLA, they do not provide global elevation maps, and available elevation models are co-registered to MOLA as it provides a global reference system from which elevation can be measured. It is therefore still an extremely significant data set, despite being of comparatively low resolution.
2.6 THEMIS: The THERmal EMIssion Imaging System

The Thermal Emission Imaging System (THEMIS) on Mars Odyssey produces multi-spectral thermal-infrared images in nine wavelengths to allow investigation of the thermal inertia and mineralogy of the surface (Christensen, et al., 2004). The entire planet has been imaged using the infrared imager at 100 m per pixel and global maps have been produced (Christensen, et al., 2004). These global data sets have allowed an increase in our understanding of the geologic history and active processes, amongst other aspects (Christensen, et al., 2004). In order to generate the global data sets, selection criteria had to be applied to the images acquired by THEMIS, selecting images with consistent solar incidence angles and relatively short times between image and calibration data collection in order to improve the quality of the overall mosaic (Edwards, et al., 2011).

THEMIS uses two separate cameras to record data: a pushbroom infrared line scanner and a visible imager (Edwards, et al., 2011). By using a pushbroom structure, the infrared imager does not have a fixed image length as each line of the image is read out in turn. They therefore have variable lengths which are formed in multiples of 256 lines, or 25.6 km (Christensen, et al., 2004). The visible imager has better resolution than the infrared imager, at 18 m per pixel from the 420 km orbit, and the images have a fixed size at 1024 samples crosstrack and 192 lines downtrack (Edwards, et al., 2011; Christensen, et al., 2004).

The THEMIS instrument is capable of both measuring the thermal inertia of the surface and identifying minerals in the surface. This can be carried out in a number of ways, which include thermal infrared emission spectroscopy and thermal infrared multispectral imaging (Christensen, et al., 2004). The former technique uses vibrational spectroscopy in the mid-infrared to identify minerals, as the mid-infrared spectra of mixtures are formed from linear combinations of the component spectra and so are easily identified (Christensen, et al., 2004). Unfortunately environmental effects such as dust and weathering cause issues for the imager, but as the imager uses mid-infrared wavelengths it is capable of penetrating through ~50 µm of coatings, which helps to mitigate these effects (Christensen, et al., 2004). In addition, as atmospheric dust creates a linear contribution to any spectra obtained, this can also be relatively easily subtracted (Christensen, et al., 2004).
The multi-spectral imager uses five filters to create narrowband filter strips, which together cover the full cross-track width of the detector (Christensen, et al., 2004). The multi-spectral imager allows further mineral identification and also allows for quantitative discussions about the abundance of different minerals on the surface (Christensen, et al., 2004). Investigations of the mineralogy are limited by the pixel size of THEMIS, with results providing an estimate of the mineralogy within each pixel. As some minerals can be more easily identified than others using infrared and visible imagery, this will also affect the results obtained by THEMIS, although combining the two image types and varying the ratios of different wavelengths will help to alleviate these issues. The ability to investigate mineralogy fits with the mission objectives for THEMIS, which include the identification of minerals and compositional units at 100 m scales (Christensen, et al., 2004).

The main results from the THEMIS imager which have been used here are the measurements of thermal inertia, in particular the global maps which have been obtained from the infrared data (Edwards, et al., 2011). These maps have been used to qualitatively examine the thermal inertia of different sedimentological features, looking at the variation in thermal inertia over a feature and the relative value compared to its surroundings.

2.7 CaSSIS: The Colour and Stereo Surface Imaging System

The CaSSIS camera on board the ExoMars Trace Gas Orbiter will be used in the later stages of landing site selection after it reaches a mapping orbit in late 2017. CaSSIS will produce colour and stereoscopic images of the surface at 4.6 m/pixel through four different filters: panchromatic, blue-green, red and infrared (Thomas, et al., 2016). CaSSIS will be in a 400 km, 74° inclination orbit which is not Sun-synchronous and therefore it will be capable of imaging the surface repeatedly over a year at different local times, making it possible to search for diurnal effects (Thomas, et al., 2016). This orbit will not allow CaSSIS to image the Martian poles, but it will allow for imaging of the equatorial regions, including the proposed ExoMars landing sites.

The stereo concept for CaSSIS is illustrated in Figure 6. In order to obtain stereo images along the same track, a first image is taken with the telescope pointing 10° forward before it rotates through 180° to take the second image (Thomas, et al., 2016).
There is therefore a convergence angle of 22.4°, with the two images taken 30 seconds apart (Thomas, et al., 2016).

Figure 6: Stereo concept for CaSSIS

TGO arrived at Mars in October 2016. The first images have been taken to carry out additional calibration, before the primary science phase begins in late 2017. The images produced will help both with selection of an appropriate landing site for the ExoMars rover and for the study of possible deltaic features. As part of the science team for CaSSIS, we have been able to contribute to the targeting for the telescope.

One of the key science drivers for CaSSIS is to look for surface variations and signatures related to trace gas sources (Thomas, et al., 2016). Variable amounts of methane have been detected in the Martian atmosphere and are thought to be plumes or patches, with discrete sources in Terra Sabae, Nili Fossae and Syrtis Major showing seasonal changes (Webster, et al., 2015). The orbit of TGO will allow CaSSIS to image potential sources in different seasons and at different times of day, which will allow physical changes on the surface associated with these sources to be identified (Thomas, et al., 2016). As measurements using Mars Science Laboratory in Gale Crater suggest that methane sources may be either local and weak or more distant and stronger, and that they do not create a well-mixed event, the temporal variation information available from CaSSIS will make investigation of these sources much easier (Webster, et al., 2015).
3 THE EXOMARS MISSION AND LANDING SITES

3.1 The ExoMars Landing Sites

There are currently three potential landing sites under consideration for the ExoMars rover in 2020. These are Oxia Planum (18.14N, 335.76E), Aram Dorsum (7.869N, 348.8E) and Mawrth Vallis (22.16N, 342.05E), which are all within the Chryse Planitia region. The locations of these sites are indicated in Figure 7, with ellipses shown demonstrating the maximum and minimum possible azimuth as calculated by the ExoMars Entry, Descent and Landing team (Lorenzoni, 2015). In order to allow for the most complete inspection possible of each landing site during the site selection and validation process, the HiRISE camera on Mars Reconnaissance Orbiter has been used to try and maximise the coverage of each site (as discussed in Section 2.2). The HiRISE mosaics that have been produced are shown in Figure 8, Figure 9 and Figure 10, together with a summary of the scientific knowledge about each site as highlighted by the proposing teams.

Figure 7: Positions of the three landing sites for ExoMars 2020. Oxia Planum is at (18.14N, 335.76E), Aram Dorsum is at (7.869N, 348.8E) and Mawrth Vallis is at (22.16N, 342.05E). The landing ellipses shown are the azimuth limits proposed by the ExoMars team (Lorenzoni, 2015). Background image is MOLA interpolated global elevation map (MOLA Team, 2003).
3.1.1 Oxia Planum

Figure 8: Oxia Planum landing site showing HiRISE coverage as of 18 September 2016. Background is THEMIS day mosaic (Edwards, et al., 2011).

Oxia Planum is thought to be a layered, clay-rich Noachian deposit that has undergone at least two distinct alteration environments: alteration of the Noachian layers and a fluvial system post-dating the Noachian units (Quantin, et al., 2015a; Bridges, et al., 2016).

A long-lived aqueous system including an early Hesperian delta (Quantin, et al., 2015b) is thought to have existed in Oxia Planum, although the nature of the deposit must be confirmed. The delta is thought to have existed for more than 3.5 Ga and has been eroded subsequently by fluvial valleys and channels, leaving the deposits that can be seen today (Quantin, et al., 2015a). Several valley systems converge at Oxia Planum, with the proposed delta being located at the end of a channel which started in Coogoon Valles (Quantin, et al., 2016). The channel is fed by a large catchment area in Coogoon Valles, which extends over a region of around 280 km in length and therefore could have experienced significant water flow in the past (Quantin, et al., 2015a).

Parts of the deposit have divergent finger-like terminations (Quantin, et al., 2014b), which support the feature being a delta rather than an alluvial fan. The surface has been
described as 80 m thick but flat and fine-grained with no obvious channels, which again has been used by the proposing team to identify it as deltaic (Quantin, et al., 2015a).

Oxia Planum contains an ancient, finely layered clay-bearing unit with surfaces as young as 100 My, and the clays are thought to be representative of those found globally on Mars (Quantin, et al., 2015a). The region is part of a 200 m thick phyllosilicate unit, which provides primary science targets throughout the landing ellipse (Quantin, et al., 2014b). There are Noachian outcrops over much of the region, but the formation context for the clay-rich Noachian layer is unclear (Quantin, et al., 2015a; Quantin, et al., 2016). CRISM images of the delta have identified kaolinite and opal, including opal ‘strata’ (Quantin, et al., 2015a). Kaolinite is an aluminium-rich clay and therefore is indicative of aqueous alteration on the iron-rich planet (Cuadros & Michalski, 2013).

The region also includes an Amazonian capping unit that is thought to be volcanic, and clays within the capping unit should be accessible through excavation in impact craters (Quantin, et al., 2014a). The capping unit has a depth of approximately 20 m within the landing ellipse, and has been highly eroded since its formation (Quantin, et al., 2014b; Quantin, et al., 2015a). In addition, the regions of the phyllosilicate unit that are closest to the capping unit have the strongest CRISM signatures for Fe/Mg phyllosilicate clays (Quantin, et al., 2014b; Quantin, et al., 2015a). While the capping unit has likely been eroded since formation, it has high preservation potential for biosignatures as material below the capping unit will have been shielded from the Martian environment for a portion of its history (Quantin, et al., 2015a). Biosignatures may take a number of forms, including organic molecules and morphological structures (e.g. cells or cellular products) (Westall, et al., 2015). There are two proposed volcanic edifices in the vicinity of Oxia Planum, which are similar to a supervolcano detected in Arabia Terra and have been suggested as a possible source for the capping unit (Quantin, et al., 2014b).

Oxia Planum is thought to have both interesting morphological and mineralogical features and so was selected as the primary landing site for a 2018 launch. It remains one of the candidates for a 2020 launch.

3.1.2 Aram Dorsum

Aram Dorsum is part of an exhumed channel system in a regional alluvial system, which is thought to be part of a wider alluvial landscape (Balme, et al., 2015; Sefton-
Nash, et al., 2015; Bridges, et al., 2016). There are Noachian age sedimentary rocks throughout the ellipse, providing ample scientific targets. As most valley systems formed in the Noachian period, it is likely to be an ancient channel system (Hynek, et al., 2010).

Aram Dorsum hosts a central inverted channel with subsidiary channels at multiple levels, with the pattern of channels suggesting that the water flowed from east to west (Balme, et al., 2015). The variation in channel level implies long duration deposition of sediment that was later exhumed, possibly significantly after the channel formed and was buried (Sefton-Nash, et al., 2015; Balme, et al., 2016). The channel has been preserved in positive relief because of differential erosion in the system (Balme, et al., 2016). The exposed region of the system is of the order of 10 km wide and 100 km long, and both vertical and lateral channel migration are visible within sedimentary terrain around the channel system (Balme, et al., 2014). There are a number of smaller non-inverted channels surrounding the main inverted channel, including some younger channels overlaying older channels which implies the fluvial system was long lived (Balme, et al., 2014). The Aram Dorsum landing site has potential to contain well-preserved biosignatures and fine-grained sediments as the system was long lasting with both aggradation and degradation of sediment. The meanders in the channel imply that the banks were stable and potentially formed from ice-rich regolith or fine-grained sediments (Balme, et al., 2014). If associated lacustrine or ancient groundwater systems
are identified, either from remote imaging or in-situ chemical investigations, the biomarker preservation potential of the landing site would be assumed to be higher (Balme, et al., 2014; Balme, et al., 2016).

At present there are very few CRISM images available for Aram Dorsum as dust coverage obscures the images that are available, so a similar inverted channel in Miyamoto crater has been used to understand the potential mineralogy (Balme, et al., 2015). Fe/Mg phyllosilicates were found on both sides of the channel capping layer in polygonal terrain, implying that the narrow-margin polygonal terrain seen around Aram Dorsum may contain similar phyllosilicates (Balme, et al., 2015; Marzo, et al., 2009). The landing site at Aram Dorsum has been buried for the majority of Mars’ geological history so it has been well protected from the environment (Balme, et al., 2014). It also has a clear exhumation history, with the material being exhumed from below a Noachian aged surface (Balme, et al., 2014). It is thought to be representative of regional Noachian alluvial plains, and therefore would be an advantageous landing site (Balme, et al., 2015).

3.1.3 Mawrth Vallis

Two separate proposals were put forward for Mawrth Vallis, which was also one of the final four landing sites for the Mars Science Laboratory. Numerous studies have been performed on the region, although as can be seen from Figure 10 there is a much lower proportion of HiRISE coverage than for the other two sites.

Mawrth Vallis is a mineralogically diverse location, and has been found to have abundant Fe/Mg phyllosilicates and associated layered terrains (Poulet, et al., 2014; Poulet, et al., 2015; Bridges, et al., 2016). The landing site shows similar stratigraphy to phyllosilicate-bearing regions in the wider region (of approximately 300 x 300 km) around Mawrth Vallis (Poulet, et al., 2014). As the most common clay in the region is likely Fe-rich nontronite associated with Al-rich phyllosilicates, Mawrth Vallis may have had a different alteration setting to the rest of the circum-Chryse region (Carter, et al., 2015). Alternatively, Mawrth Vallis may have been exposed to localised re-surfacing mechanisms that have caused this variation in mineralogy (Carter, et al., 2015). The mineral diversity and stratigraphy in Mawrth Vallis suggest multiple forms of aqueous systems and therefore a rich aqueous history (Poulet, et al., 2014).
It is thought that biosignatures could be retained in the phyllosilicate and hydrated silica deposits, especially as there is no evidence for mixed layer clays that would degrade the biosignatures (Poulet, et al., 2014). The high clay content in Mawrth Vallis allows organic preservation in paleosols, which are thought to be excellent scientific targets as reducing soils cause immediate preservation and therefore can concentrate organics increasing the likelihood of detection (Poulet, et al., 2015; Gross, et al., 2016).

The landing site shows diverse responses to erosion such as inverted channels and craters (Poulet, et al., 2014). Furthermore, as there are no ‘boulder forming’ units and the thermal inertia is low, it is assumed that the region is formed, at least in part, from fine-grained sediments (Poulet, et al., 2014). Regions of interest are thought to have been buried by the capping unit and only recently been exhumed, increasing the chance of finding biosignatures in Mawrth Vallis (Poulet, et al., 2015).

The Mawrth Vallis outflow channel is thought to be from the Late Noachian or Early Hesperian and is one of the main channels cutting through Noachian plateaus (Poulet, et al., 2005; Scott & Tanaka, 1986). It is one of the key outflow channels thought to have fed a northern ocean based around Chryse Planitia (which will be discussed later), and is thought to be the oldest of the six channels identified (Ivanov & Head, 2001).
The area has a varied history and is thought to have been exposed to progressive deposition and alteration of sediments, followed by fluvial activities and erosion in the mid to late Noachian, and finally followed by weathering and erosion by the wind (Poulet, et al., 2015).

Mawrth Vallis is one of the potential sites for 2020, and is thought to be highly likely to have been habitable in the past which would make it a scientifically interesting landing site (Gross, et al., 2016; Bridges, et al., 2016).

3.1.4 Application of ExoMars Instruments to the Landing Sites

The ExoMars rover contains nine different instruments which it will use to investigate the Martian surface, and finding a landing site which can efficiently make use of the instruments would be beneficial. Both the landing sites and instruments have been designed in line with the scientific aims of ExoMars, but this does not guarantee that each of the sites are equally suitable. The applicability of the ExoMars instruments to the landing sites will therefore be discussed.

PanCam will operate equally well whatever the location, as it will provide images for identification of targets and selection of the rover traverse. However, spectrometers such as ISEM, Ma_MISS and RLS will be more dependent on the location. Each of these instruments will produce results in any location, but due to the nature of spectrometry the quality of the results obtained will depend on the surfaces they are used on. Smoother surfaces with lower dust levels will be easier to obtain results from, as there will be less scattering and dilution of the results. The same can be said for CLUPI, which will produce more interesting images depending on where it is used, with outcrops in Oxia Planum or Noachian rocks in Aram Dorsum being potential targets. In addition, CLUPI could be used to identify biosignatures which take the form of morphological structures. While the suitability of each landing site is difficult to assess using remote imaging, it is assumed that there will be accessible and suitable targets at each site due to the wide spread of scientific targets identified by the proposing teams.

The combination of WISDOM and Adron will be used to search for subsurface water and hydrated minerals (European Space Agency, 2016b). While all three potential sites have signs of aqueous histories, they do not show the same signatures of aqueously altered minerals, although this may in part be due to the different information available.
about the sites as clear CRISM images are not available at Aram Dorsum. Hydrated minerals, such as those available at Mawrth Vallis, may be identified by Adron, which is also capable of finding subsurface water although this has not been explicitly identified at any of the sites.

The stratigraphy in Mawrth Vallis is thought to be similar to that in the wider Chryse Planitia region (Poulet, et al., 2014), and therefore investigation of the stratigraphy with WISDOM may inform us about more than just that site. However, as the alteration setting is thought to have been different and to have caused different mineralogy, any mineralogical investigations at Mawrth Vallis may be less widely applicable.

MOMA and RLS are both intended to identify biological or organic features, with RLS being able to identify organic pigments non-destructively and MOMA targeting biomarkers to investigate life on Mars (European Space Agency, 2016b). These instruments will therefore be able to highlight the presence of biosignatures. The capping unit in Oxia Planum may be a suitable location for these instruments as the recently eroded capping unit may have exposed previously covered (and therefore preserved) biosignatures. If the systems in Aram Dorsum are identified as being lacustrine or fluvial, these regions would also be prime targets for these instruments, in particular the fine-grained sediments in river-edge material. In addition, paleosols in Mawrth Vallis are thought to contain well-preserved biosignatures, which once again could be targets for MOMA and RLS.

The three landing sites therefore all seem to be appropriate for ExoMars scientific investigations, although the remote sensing indicates that different instruments may respond more favourably at different sites.

### 3.1.4.1 Application of CaSSIS on ExoMars Trace Gas Orbiter to the Landing Sites

As discussed in Section 2.7, CaSSIS is one of the instruments on the ExoMars Trace Gas Orbiter (TGO). It will arrive in a mapping orbit around Mars in late 2017, and therefore will be available to use during the late stages of the landing site characterisation process.

The stereo images produced by CaSSIS will have a base length of approximately 10 m due to the pixel size of 4.6 m (Thomas, et al., 2016). These images can therefore be used to determine slope maps at this additional base length to complement the slope
calculations already carried out for each landing site which will be summarised in Section 3.1.5. A 7 m slope constraint is supplied in order to allow for easier slope determination during landing (European Space Agency, 2013), and these measurements may be able to inform the Entry, Descent and Landing teams about the type of surface they will experience at this baselength. Furthermore, the stereo images produced may highlight additional dangerous objects within the landing regions, such as rocks that the rover would not be able to drive over.

CaSSIS will produce images through three colour filters (blue-green, red, infrared) which can be combined in different ratios to produce a variety of colour images over the landing sites. These can be used to highlight different aspects of the surface which may allow for the identification of minerals in the surface layer. This would be particularly helpful in Aram Dorsum, where there is poor direct mineralogy available due to the CRISM images being obscured by dust. While CaSSIS is not a spectrometer like CRISM, varying the ratios between the colour images in post-processing will allow for some investigation of the mineralogy at the resolution of CaSSIS.

The colour images produced will also allow for investigation of the surface features in the landing sites, and in particular the different surface colours. One example of where this will be helpful is in Oxia Planum. In the HiRISE images the capping unit seems to have a different colour compared to the majority of the surface, showing up as a much darker region (see Figure 8).

Colour images would therefore allow us to see how the two units interact with one another. Similarly, there appear to be different colour units in Mawrth Vallis (see Figure 10). Again, these can be investigated using the CaSSIS images to study what causes the different colours (e.g. whether they have a link to local topography) and how they interact with one another.

Unfortunately, the pixel size for CaSSIS is too large to study the small-scale aeolian features that will be discussed in Section 3.2, as these typically have wavelengths of under 10 m and therefore will not be distinct in the CaSSIS images.

### 3.1.5 Landing Site Characteristics

The landing site that is finally selected must be compliant with the engineering constraints determined by ESA (European Space Agency, 2013). A summary of the compliance of each site (where data is available) can be seen in Table 2. The
percentages stated correspond to a wider landing region rather than a single specific ellipse, as the ellipse positioning may change during the optimisation process. The exception to this is the slope data, which has been calculated by the proposing teams for the ellipses discussed at Landing Site Selection Workshops (Quantin, et al., 2014b; Balme, et al., 2014; Poulet, et al., 2015). There may be an inconsistent method of calculation across sites, and it will be necessary to produce a consistent data set across all of the landing sites to be able to truly compare the slopes.

Table 2: Summary of each of the proposed landing sites. References for slope calculations: \(^1\) (Quantin, et al., 2014b) \(^2\) (Balme, et al., 2014) \(^3\) (Poulet, et al., 2015).

<table>
<thead>
<tr>
<th>Lat, Long</th>
<th>Oxia Planum</th>
<th>Aram Dorsum</th>
<th>Mawrth Vallis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth Range</td>
<td>18.14 N, 335.76 E</td>
<td>7.869 N, 348.8 E</td>
<td>22.16 N, 342.05 E</td>
</tr>
<tr>
<td>Elevation</td>
<td>2018: 50 km</td>
<td>2018: 50 km</td>
<td>2018: -</td>
</tr>
<tr>
<td></td>
<td>2020: 60 km</td>
<td>2020: 50 km</td>
<td>2020: 60 km</td>
</tr>
<tr>
<td>Slopes Baseline</td>
<td>100% &lt;-2 km</td>
<td>≥ 93% &lt;-2 km</td>
<td>≥ 89% &lt;-2 km</td>
</tr>
<tr>
<td></td>
<td>-3.6 km to -2.66 km</td>
<td>-2.57 km to -1.88 km</td>
<td>-3.02 km to -1.46 km</td>
</tr>
<tr>
<td>Baseline</td>
<td>96.1 (^1)</td>
<td>96.2 (^2)</td>
<td>97.2 (^2)</td>
</tr>
<tr>
<td>Baseline</td>
<td>96.1 (^1)</td>
<td>96.2 (^2)</td>
<td>97.2 (^2)</td>
</tr>
<tr>
<td>Albedo</td>
<td>100% 0.1 - 0.26</td>
<td>100% 0.1 - 0.26</td>
<td>100% 0.1 - 0.26</td>
</tr>
<tr>
<td>TAR Coverage</td>
<td>4.9 ± 5.9 %</td>
<td>2.72 ± 2.75 %</td>
<td>16.9 ± 7.9 %</td>
</tr>
<tr>
<td>Thermal Inertia</td>
<td>100% ≥ 150 J m(^{-2}) s(^{0.5}) K(^{-1})</td>
<td>99% ≥ 150 J m(^{-2}) s(^{0.5}) K(^{-1})</td>
<td>99.5% ≥ 150 J m(^{-2}) s(^{0.5}) K(^{-1})</td>
</tr>
</tbody>
</table>

3.1.6 The Schiaparelli Landing Site at Meridiani Planum

The ExoMars Trace Gas Orbiter is carrying an Entry, Descent and Landing Demonstrator Module (EDM) called Schiaparelli. This will land in late 2016, and is being used as a demonstration of the entry, descent and landing system that will be used for the ExoMars rover (European Space Agency, 2016c).
In order to test the entry, descent and landing system and to obtain results that can be applied to the ExoMars rover, it is equipped with the AMELIA package for analysing the trajectory and atmospheric conditions, the COMARS+ package of sensors to determine how the outer surface of Schiaparelli is affected by the entry, and the DECA camera to image the descent (European Space Agency, 2016a). In addition, the lander will contain INRRI, which is a laser retroreflector that can be used both for the various Mars orbiters (such as MRO) to find the lander, and as a fixed point on the surface for future experiments, e.g. testing laser communications (European Space Agency, 2016a).

The landing site for the Schiaparelli module has been selected to be Meridiani Planum (European Space Agency, 2016c). A landing ellipse of 115 by 25 km centred on 2.05 S, 6.1 E has been chosen which is highlighted in Figure 11. The high density of HiRISE images in the eastern portion of the image is due to the presence of the Opportunity rover, as HiRISE has been used to track its position.

The Schiaparelli lander also contains the DREAMS scientific package, which houses six different instruments to investigate the Martian environment and surface (European Space Agency, 2016a). DREAMS includes temperature, pressure, wind, humidity, optical depth and atmospheric charging sensors (European Space Agency, 2016a). The latter two will measure the concentration of atmospheric dust and the strength of the electric fields respectively (European Space Agency, 2016a). The two instruments will
complement one another, and it is hoped that the information gained will increase our understanding of the lifting of dust from the surface and the formation of dust storms (European Space Agency, 2016a).

The presence of Opportunity at Meridiani Planum means that we have some in-situ information about the region, although this is limited to the eastern portion of the landing ellipse. The mini-TES instrument on Opportunity has provided some measurements of dust in the region, but the instruments on DREAMS will hopefully be able to provide additional information over the short lifetime of the lander (Squyres, et al., 2004).

### 3.2 Aeolian Hazards

#### 3.2.1 Introduction and Theory

Oxia Planum had been selected as the primary landing site for a 2018 launch of ExoMars, and therefore a validation process had begun on the site before the mission was delayed. The initial validation process has indicated that while the site generally complies with the engineering constraints as shown in Section 3.1.5, there are a high number of Transverse Aeolian Ridges (TARs) over the landing site, particularly in the east of the site. The identification of these features in the landing site has led to a more detailed study of these features and their implications for the ExoMars mission.

Transverse Aeolian Ridges (TARs) were first identified in Viking images and are aeolian features that have a wavelength or bedform length in the order of metres, and therefore are between ripples and dunes in size (Balme, et al., 2008). They are also morphologically distinct to dunes, being more 'ripple-like' in morphology (Balme, et al., 2008). Different studies of TARs have used varying terminology to discuss the features, and Fenton, et al. (2015), suggest that TARs, plains ripples, plains-type ripples and superposed ripples may all be different developmental stages of the same bedform, and therefore it is helpful to map all of these ripple-like forms when mapping TARs (Fenton, et al., 2015).

The morphology of a TAR has been defined by Balme, et al. (2008), and can be seen in Figure 12. The parameters shown will be used throughout this discussion. It is necessary to define both a bedform length $L$ and a wavelength $\lambda$ as the TARs that will be mapped on the Martian surface occur both individually and in saturated fields, as can be seen in the examples from MSL Curiosity in Section 3.2.3.
In addition to the parameters defined in Figure 12, there are a number of additional parameters that can be defined, and the morphology can also be categorised into five categories, again as defined by Balme, et al. (2008). The first of these is the aspect ratio \( a \), which is defined as \( a=W/L \), and the second is the inter-bedform spacing \( s \), which is \( s=\lambda/L \), where both \( \lambda \) and \( L \) are the average over a field (Balme, et al., 2008).

TARs generally have high aspect ratios of \( a>6 \), and are elongate ripples, although TARs have been identified with aspect ratios less than this (Balme, et al., 2008). However, the range of inter-bedform spacings is much greater, and can be split into two categories: closely spaced TARs with \( s<2 \), and widely spaced or discontinuous TARs with \( s>2 \) (Balme, et al., 2008). The TARs seen in Figure 12 are a widely spaced field of TARs, with \( s>2 \). TARs are typically found in fields containing tens to thousands of TARs, with variable values of \( s \) and \( a \) (Balme, et al., 2008).

In addition to the parameters discussed, it is possible to classify TARs according to their plan-view morphology, with five categories to a first order (Balme, et al., 2008). These can be seen in Figure 13 and are identified as simple, sinuous, forked, barchan-like and networked (Balme, et al., 2008). Simple and forked TARs have been seen most frequently over the regions mapped, with networked TARs being found primarily in closed basins such as impact craters, although fields of networked TARs have also been seen on plains. The different TAR morphologies and orientations are influenced by the
control mechanism on the TAR formation, in particular whether they are controlled by topography or meteorology (Balme, et al., 2008).

Four topographic environments can also be defined, as set out in Balme, et al. (2008):

- confined, where the TARs are in a closed topographic basin and therefore may have multiple orientations due to the influence of the basin boundaries;
- controlled, where the TARs are in an open depression next to a topographic high and therefore have orientations and spacings defined by the depression shape and local wind directions;
- influenced, where the orientation of some TARs is influenced by local topography (e.g. hills) but the TARs as a whole are not controlled by the terrain;
- independent, where the TARs form perpendicular to the wind direction and uninfluenced by local terrain, causing large fields of roughly parallel TARs.

For example, in Figure 13, (a) and (b) demonstrate influenced TARs as they vary around terrain boundaries, particularly at the bottom of (b), and (e) shows confined TARs. In order to accurately map the TAR coverage in the ExoMars landing sites it is necessary to be aware of all of these TAR classifications, as Figure 13 shows the variation in appearance they can have, and it is important to get an accurate value for the TAR coverage.

TARs are distinct from Large Dark Dunes (LDDs) both in size and morphology, and therefore are thought to have differences in at least one of composition, age, stage of development and formation process (Balme, et al., 2008). They are typically of higher albedo than their surroundings, having an albedo approximately twice that of LDDs, but this is not always the case and some have been found with lower albedos (Balme, et al., 2014). This variation is thought to be due to dust coverage over older, immobile TARs, as both TARs and LDDs have been seen to have largely basaltic signatures and therefore would be expected to be of similar composition (Balme, et al., 2008). The difference between them may be explained by the fact that TARs are thought to have a core of fine-grained material which is armoured by a monolayer of coarser grained material, making them less mobile than larger Large Dark Dunes (Balme, et al., 2008). This immobility would therefore allow dust to settle on the surface of TARs, increasing their relative albedo (Balme, et al., 2008). If TARs are as immobile as is expected, using HiRISE images from different times over the 10 year operational period is
acceptable as they would not have migrated and therefore there would be minimal risk of double counting. It would also mean that TAR mapping carried out on early HiRISE images would still be representative when the rover launches in 2020.

Figure 13: TAR morphologies (Balme, et al., 2008). (a) Simple TARs (MOC NA image M1104208) (b) Forked TARs (MOC NA image M0303703) (c) Sinuous TARs (MOC NA image R0802177) (d) Barchan-like TARs (MOC NA image M1800277) (e) Networked TARs (MOC NA image R2300801).

TARs are abundant on the surface of Mars, but no clear correlation has been found between their location and the gross morphology of the region as they have been found in terrains that range from volcanoes to the base of impact basins (Balme, et al., 2008). They are generally found in mid- to low-latitudes, and all of the landing sites are found in this region (Balme, et al., 2008). It is therefore necessary to fully map their coverage over each of the landing sites as it is not possible to exclude the landing regions on the basis of their gross morphology.

3.2.2 Transverse Aeolian Ridge Mapping

The presence of TARs at the landing site may cause traversability issues for the rover. The capabilities of the rover must be clarified in order to ensure that it is capable of
traversing such ridges, and this process is currently under way (Bridges, 2016). However, the three landing sites are also being mapped using HiRISE images to understand the coverage that the rover will have to be capable of coping with, such that this information can help determine the testing required. The resolution provided by HiRISE images has significantly improved the accuracy with which TARs can be mapped, as the resolution of the images used for mapping creates a limiting size of TAR that can be mapped. HiRISE has therefore allowed this to be reduced to $\lambda > 2 \text{ m}$. In order to determine the percentage coverage of TARs at Oxia Planum, a number of HiRISE images over the landing site were mapped at 1:2000 resolution. This mapping was carried out in collaboration with a number of others as part of this work. The percentage coverage of each selection was categorised, with three levels being mapped: 20% coverage, 50% coverage and 100% coverage. Figure 14 shows examples of the three levels. Regions with less than 20% coverage of TARs have not been mapped, as it is assumed that the coverage is sufficiently low that any TARs could be manoeuvred around. Single large megaripples have been mapped as small regions of 100% to ensure they are accounted for.

![Figure 14: TAR density examples with (a) 20% coverage, (b) 50% coverage, (c) 100% coverage. Images are from HiRISE image ESP_037136_1985.](image)

Mapping was carried out within grid squares of 2.5 km side length. This mapping was carried out by a team from the University of Leicester, the Open University, University College London and Birkbeck University, and I carried out approximately 20% of the mapping at Oxia Planum. Once a grid square has been mapped, an overall percentage for the square can be calculated to give an overview over the region, rather than knowing specific small densities. These may become more important once the final
landing site has been selected and as the landing ellipse reduces in size during the rover transit, but for the process of site selection it is the overall percentage of a square or an ellipse that will be more useful. Figure 15 shows an example section of the mapping carried out over Oxia Planum.

Figure 15: A portion of the mapping of TARs over Oxia Planum. Red corresponds to 100% coverage, yellow to 50% coverage and green to 20% coverage. Background is HiRISE images (ESP_037558_1985, ESP_042134_1985, PSP_002694_1985, ESP_040433_1985, ESP_041422_1985, ESP_039299_1985 and ESP_037136_1985) and THEMIS day mosaic (Edwards, et al., 2011).

An extended version of the mapping of Oxia Planum seen in Figure 15 has been processed to obtain a percentage coverage for each grid square, as seen in Figure 16. Only a portion of the mapping is shown in Figure 15 in order for the detail in the map to be seen. As the lower percentage coverage grid squares can still have small s, these regions could be extremely dangerous if the rover cannot cross the size of TARs in that region. As the rover will have a nominal speed of 40 m/h and is expected to travel 500 m between six experiment sites over its entire mission, it could remain within a single grid square during the whole mission (European Space Agency, 2013). However, it will not be possible to select the landing site as accurately as a single grid square, and therefore it is necessary to study each landing site as a whole, selecting the best overall region.
Oxia Planum has an overall TAR percentage of 4.9% (+/- 5.9%). This variation can be seen in Figure 16 where there is a significantly higher density of TARs in the eastern portion of the ellipse over the visible channels and proposed delta. The highest grid square has a density of 42.7%, whereas the lowest has a density of 0.4%. Based on the grid densities, the western portion of Oxia Planum is the safest region to land the rover. However, the eastern portion contains the significant aqueous features such as the proposed delta and therefore may be a more interesting portion of the ellipse. It will therefore be necessary to trade off the dangers posed by the TARs with the scientific gain of the region once rover tests have been completed to determine how capable it is of crossing TARs.

The mapping of TARs in Oxia Planum that has been carried out so far has shown that there are a very high number of small TARs with \( \lambda = 2-3 \) m or \( L = 2-3 \) m. The mapping of these features has only been possible due to the use of HiRISE images, and as they are widespread across the site they will be a key size to test the rover mobility against.
A number of HiRISE images over the landing site at Aram Dorsum have been mapped and the results can be seen in Figure 17. The overall coverage is much lower than observed in Oxia Planum. The TAR densities instead range from 0% to 16.7%, with an average density of 2.72% (+/- 2.75%). The significantly lower density would improve the traversability of the rover at Aram Dorsum as compared to Oxia Planum. However, the small region of mapping carried out in the north-west of the region show that the TAR density is likely to be higher in this region, and therefore it would be beneficial to avoid it.

Part of Mawrth Vallis has also been mapped, and can be seen in Figure 18. The areas for mapping have been selected to represent different terrains in the region and different parts of the landing ellipses. The TAR densities in Mawrth Vallis are much higher than has been seen in either of Oxia Planum or Aram Dorsum, ranging from 5.4% to 39.3%, with an average of 16.9% (+/- 7.9%). There are high percentage areas across the full region mapped, which may make it difficult to select a landing ellipse at this site with a sufficiently low TAR percentage for the rover to be able to traverse.
These data do not take into account the distribution of TAR sizes, but simply show the average density (and standard deviation). The three sites may in fact have very different TAR profiles, potentially having a different dominant TAR size, morphology, orientation and topographic environment. It may become necessary to investigate the dominant TAR profile as the rover research progresses, depending on the outcomes of the rover traversability tests.

Mapping has been performed over a much larger region of Oxia Planum (1788 km$^2$) than either Aram Dorsum (863 km$^2$) or Mawrth Vallis (138 km$^2$). It would be necessary to fully map each of the sites to allow for a complete comparison, but the percentages calculated herein can still be taken as representative of the coverage. Based solely on the percentage coverage calculated herein, Aram Dorsum would be the most suitable site for the ExoMars rover to land. However, further investigation of the types of TARs at each site would be necessary to fully understand the consequences of the terrain found at each of the sites. As the landing ellipse is reduced in size during the rover development process and transit to Mars, the TAR percentage coverage can be calculated for new ellipses using the data herein, to provide a more accurate analysis of the final site.
3.2.3 **Significance of TARs to Rover Mobility**

Megaripple crossings by Mars Science Laboratory’s Curiosity rover can be used to understand the depth of the TARs and the difficulties that could be faced when crossing them. They also provide a ground truth against which HiRISE images can be referenced. This allows the rover team to determine the TAR sizes that should be used to test the rover, with particular focus on testing the most extreme sizes. If the rover will not be able to traverse the most common TARs that are visible in the landing sites, its abilities will be drastically reduced.

Arvidson, et al. (2016) summarised the megaripple crossings carried out so far by MSL Curiosity, and focussed on three main regions: Dingo Gap, Moonlight Valley and Moosilauke Valley (Arvidson, et al., 2016). The region over Dingo Gap and Moonlight Valley is shown in Figure 19. Dingo Gap is a single large TAR which has been heavily constrained by the local topography, whereas Moonlight Valley is a controlled field of TARs where the surroundings have caused a dominant wind direction to create the field. The ripples in Moonlight Valley caused MSL Curiosity to sink by a maximum of 7 cm (of the 50 cm wheel diameter), but it was still able to traverse the field, with maximum slip occurring in the centre of the field and reduced slip when traversing the western edge (Arvidson, et al., 2016).

![Figure 19: Dingo Gap and Moonlight Valley, Gale Crater. HiRISE image ESP_018920_1755.](image)

The rover monitors slippage and sinkage as it traverses, and when the slippage or sinkage values become too great, it stops automatically in order to prevent an
irreversible sink and the loss of rover mobility (Arvidson, et al., 2016). However this process takes time, so although ripples such as those in the Moonlight Valley field may be traversable after multiple attempts, it is not an efficient method of travel. Ripples which would cause this should ideally be avoided in order to maximise the travel time for the mission.

The results measured for MSL Curiosity can be extrapolated to try to understand how ExoMars will respond to similar ripples. In order to do so, it is necessary to understand how sinkage is affected by the mass and contact surface area of the rover. Wong (2012) used the Reece pressure-sinkage relation to extrapolate terrestrial measurements of sinkage to reduced gravity environments, and the relation can also be used to scale the results from MSL Curiosity to ExoMars (Wong, 2012; Reece, 1965-66). The relation is given as:

\[ p = \left( \frac{ck'_c}{b^n} + \frac{\gamma_m g k'_\phi}{b^{n-1}} \right) z^n = (K_c + K_{\phi} g)z^n \]

where \( p \) is the pressure (kPa), \( z \) is the sinkage (m), \( b \) is the smaller dimension of the contact area (m), \( n, k'_c \) and \( k'_\phi \) are non-dimensional pressure-sinkage parameters, \( g \) is the acceleration due to gravity and \( \gamma_m \) is the mass density of the soil (Wong, 2012; Reece, 1965-66). \( K_{\phi} \) is generally significantly smaller than \( K_c \) and therefore can be neglected, reducing the equation to a power law (Wong, 2012). The values of both of the constants \( K_c \) and \( n \) vary significantly depending on the situation, with \( n \) being determined by the soil which is traversed (Wong, 2012).

Studies by the ExoMars Rover Mobility Team have found that it is possible to apply a linear scaling factor to the depth of sinkage experienced by MSL Curiosity to obtain a theoretical sinkage depth for ExoMars, and have found that a value of 1.4 is representative of the interaction (Poulakis, 2016). This value has been given as an absolute scaling factor, and takes into account the non-linear relationship between pressure and sinkage discussed, as ExoMars exerts 2.46 times more pressure on the Martian surface than MSL Curiosity. The higher pressure is because the ExoMars rover is significantly lighter than MSL Curiosity but it also has much smaller wheels, as can be seen from Figure 20. ExoMars' wheels have a diameter of 0.25 m and width of 0.11 m, as compared to diameter of 0.5 m and width of 0.4 m for MSL's wheels (Lindemann, 2011; Pruiksma, et al., 2011).
Using this scaling factor, it is possible to obtain predicted sinkage values for ExoMars if it were to traverse the same megaripples crossed by MSL Curiosity. The maximum depths measured by Arvidson, et al., have been used for these calculations, as they then show the worst-case scenario for ExoMars (Arvidson, et al., 2016). There are many implicit assumptions in this scaling relation, with the most significant being that the two rovers would interact with similar materials and therefore would sink in a similar manner.

For example, when crossing the 2-3 m bedform length megaripples in Moonlight Valley discussed previously, which have heights of up to 15 cm, MSL was found to sink by up to 7 cm which corresponds to 10 cm for ExoMars or 39% of the wheel diameter. By contrast, the single 7 m wavelength megaripple at Dingo Gap, which has a height of 1 m, also caused a 7 cm sink for MSL, which again would be a 10 cm sink for ExoMars. These two measurements illustrate the need for further study into the rover interactions with megaripples, as it is not as simple as the rover sinkage scaling with the ripple size and therefore avoiding all ripples above a certain size. It will be necessary to test how the rover traverses over a number of different aspect ratios, materials and heights to get a better understanding of its performance.

Furthermore, the megaripple crossings at Moosilauke Valley obtained some very different results. A ripple field with a wavelength of 5-10 m and heights of at most 0.2 m caused MSL to sink by 5 cm, which is a smaller sinkage than obtained at the shorter bedforms in Moonlight Valley (Arvidson, et al., 2016). However, in the same region, slightly inclined ripples with a wavelength of 1-2 m and heights of 0.1 m caused MSL to sink by 17 cm, which was sufficiently high to cause the rover to automatically stop.
as it had exceeded sinkage and slippage thresholds (Arvidson, et al., 2016). These two sinkages would correspond to 7 cm and 24 cm respectively, with the latter corresponding to 95% of the wheel diameter. The first measurement adds weight to the idea (discussed previously) that the sinkage experienced by a rover is not related to the ripple height. The second measurement indicates the danger posed by ripples on inclined surfaces, as the smallest ripples encountered by MSL caused the greatest sinkage.

The ExoMars rover is expected to be able to extract itself if the two front wheels sink by 50% of the wheel diameter, with this being the limit allowed for sinkage (Poulakis, 2016). The potential sinkages discussed herein would therefore be approaching the limits of what is acceptable (and significantly beyond the limit in the case of Moonlight Valley), and therefore are extremely significant.

It is therefore necessary to examine the TAR coverage and rover capabilities closely for two reasons. Firstly, the megaripple crossings by MSL Curiosity have shown that there is no clear correlation between ripple size and rover response, with slight inclines causing a significantly different response from the rover to flat surfaces. Secondly, the scaling between the rovers has shown that relatively insignificant ripples for MSL Curiosity are much more dangerous for ExoMars, with a sinkage of only 14% of MSL's wheel diameter corresponding to a sinkage of 39% of ExoMars's wheel diameter. The megaripple crossings by the Opportunity rover could be used in this investigation, as it not only provides additional data points but also introduces a third rover size (in terms of mass, wheel diameter and wheel width) (Poulakis, 2016).
4 A POSSIBLE DELTA IN OXIA PLANUM AND IMPLICATIONS FOR A NORTHERN OCEAN

The ExoMars landing site proposal for Oxia Planum indicated that the proposing team believe there is an ancient delta in eastern Oxia Planum (Quantin, et al., 2015b). The presence of a delta would indicate that there was once a long-standing body of water in the region, which increases the likelihood of finding traces of past life. Identification of this feature is therefore extremely important in the validation of the landing site as it underlies the scientific goals of the ExoMars mission. This chapter will combine knowledge about terrestrial aqueous features with an investigation into known deltas and alluvial fans on the Martian surface, and in particular in the Chryse Planitia region, with the aim of classifying the feature in Oxia Planum. Furthermore, it will investigate whether the distribution of deltas around the northern plains of Mars indicates the presence of a historical northern ocean, and whether an ocean measured purely from deltaic studies is consistent with previously published estimates for a northern ocean.

4.1 Terrestrial Deltas and Alluvial Fans

Alluvial sediments are weakly resistant to erosion, transportation and deposition, and therefore can be readily transported by rivers to form depositional structures such as depositional fans (Summerfield, 1991). Both deltas and alluvial fans can be classified as depositional fans, with the conditions under which the sediment moves causing different fan morphologies.

Alluvial fans can be defined as "a body of sediment whose surface approximates to the segment of a cone which radiates downstream from a point on a mountain front, usually where a stream emerges" (Summerfield, 1991). The deposition that causes the formation of an alluvial fan occurs due to a sudden change in environment from being confined to unconfined as can be seen in Figure 21, with the area of the fan formed being positively correlated with the area of the source basin (Summerfield, 1991). The fan radius is affected by the magnitude and persistence of fluvial processes and typically ranges from 200 m to 20 km on Earth (Chorley, et al., 1984). In addition, the overall shape of terrestrial fans is dependent on the quantity of sediment supplied (Chorley, et al., 1984). The morphology of the fan produced is therefore affected by a number of factors, both upstream and downstream, and it is expected that this would also be the case for Martian fans.
In a terrestrial context, clear examples of alluvial fans can be found in Death Valley, California, as illustrated in Figure 22. The aerial image in Figure 22(a) will provide a reference point when studying the feature in Oxia Planum, as it provides a clear aerial image of the fan as it emerges from the confined region (i.e. the mountains). However, as alluvium is so easily eroded and transported, it may not be possible to find examples of fans as clear as this as they will have undergone millions of years of erosion since their formation.

Figure 23 demonstrates through-fan profiles of a number of terrestrial alluvial fans, including the one in Trail Canyon shown in Figure 22. The fans all show fairly similar profiles, having a steady decrease in elevation before flattening as a local plain or valley is reached. Profiles through the surrounding regions are not shown in this graph,
but it would be reasonable to assume that the fan profiles would be similar to profiles of
their surroundings. As each of the alluvial fans featured in this graph show a similar
overall profile, this will be used as a comparison for Martian alluvial fans.

![Profiles of terrestrial alluvial fans (Parsons & Abrahams, 2009).](image)

While alluvial fans form subaerially, deltas form subaqueously. They form when
sediment heavy rivers flow into standing bodies of water (Chorley, et al., 1984). As
with alluvial fans their morphology is affected by both upstream and downstream
conditions, but the conditions and effects vary between the two fan types. In delta
formation, these conditions include the relative water densities, the basin or coastal
geometry, the river flow rate and the climate (Chorley, et al., 1984).

Deltas can be defined as "protuberances extending out from shorelines formed where
rivers enter the ocean, partially enclosed seas, barrier-sheltered lagoons or lakes, and
supply sediment more rapidly than it can be redistributed by coastal processes"
(Summerfield, 1991). They can be divided into three broad categories depending on the
most dominant processes: fluviually dominated, such as the Mississippi delta (USA);
wave dominated such as the Niger delta (Nigeria); or tidal dominated such as the Fly
delta (Papua New Guinea) (Summerfield, 1991). Images of these three deltas can be
seen in Figure 24. These images are indicative of the variation that can occur between
the different categories, but as there are many additional influential factors their
morphologies will be dependent on a combination of factors.
One key factor that determines the delta morphology is the relative water densities. Figure 25 shows the different modes of delta formation depending on the relative water density. When the water densities are equal, this is homopycnal flow and the river sediment settles immediately and forms a semi-circular delta (Summerfield, 1991; Chorley, et al., 1984). This is a common situation in lakes, and can create a simple, Gilbert-type delta which can often be found with braided, horizontal topsets and steadily declining foresets (Smith & Jol, 1997; McConnico & Bassett, 2007).

If the river density is greater than the basin water density, this is hyperpycnal flow and a large mixing zone is created, causing graded beds of fine sediment which can spread far into the depositional basin (Summerfield, 1991; Chorley, et al., 1984). This is a rare situation, and could occur when very cold river water enters a warm lake.

Finally, if the basin water is denser than the river water, for example when fresh water rivers mix with sea water, the river water will spread out as a jet and can travel a long distance out to sea before becoming indistinguishable from the sea water (Summerfield, 1991). This causes the coarse bedload to be deposited near the river mouth, while finer sediment is carried out in the jet and creates a gently sloping delta front (Chorley, et al., 1984).

The variation in delta morphologies caused by the upstream and downstream conditions make identifying clear hallmarks of a delta very difficult. However, the overall cross-sections of deltas and alluvial fans are distinct, and can be seen in Figure 26. While the details of the profile may vary from case to case, deltas generally have a clear delta front that extends from the surrounding topography, and follow a topset-clinoform-bottomset structure. By contrast, alluvial fans approximately follow the topography of
their surroundings. This distinction will therefore form a starting point for the identification of the feature in Oxia Planum.

Figure 25: Delta formation at different relative water densities. (a) Homopycnal flow, where water densities are equal. (b) Hyperpycnal flow, where the river water is more dense than the standing water. (c) Hypopycnal flow, where the river density is lower than the standing water density. (Summerfield, 1991)

4.2 Proposed Oxia Planum Delta

Quantin, et al., proposed that the landing site in Oxia Planum contains an early Hesperian-aged delta (at least 3.5 Ga old) due to standing water on the plains during the early Hesperian (Quantin, et al., 2015b). As the water level receded over time, the deltaic deposit is thought to have been eroded by fluvial valleys and channels, with continual erosion during the Hesperian and early Amazonian (Quantin, et al., 2015b). The deposits are proposed to have been covered with an Amazonian lava flow around 2.6 Ga ago, which has since been eroded to reveal the deposit that can be seen today (Quantin, et al., 2015b). The deposit is thought to be 80 m thick, finely layered and fine-grained (Quantin, et al., 2015b).

The proposing team have argued that the feature in Oxia Planum is a subaqueous delta rather than an alluvial fan (Quantin, et al., 2015b). The main arguments they have used
for this is the fine-grained nature of the deposit, as can be seen from the thermal inertia measurements, and the finger-like terminations of the deposit, which they say are overlapping and divergent (Quantin, et al., 2015b). Furthermore, the deposit is downstream of the Coogoon Valles catchment area, which may have provided an infilling point for the standing body of water (Quantin, et al., 2015b).

Figure 27: HiRISE coverage of Oxia Planum landing site (as of 5 July 2016) showing the 2020 landing ellipse (maximum and minimum azimuths) and the location of the proposed delta. Background is THEMIS day mosaic (Edwards, et al., 2011). The location of the Oxia Planum landing site relative to the wider landing region can be seen in Figure 1.

The feature was identified as a delta extending from the Coogoon Valles system, and is approximately centred on 17.9N, 336.1E. The feeder channel has been included in the HRSC line profile taken to determine the overall shape of the system.

There are a high number of MOLA points spread over the delta region, but there is not continuous coverage over the site. As a rectangular spread of points is used, some data in the profile does not correspond to the delta itself, and therefore this profile may instead better inform us about the basin shape. In order to supplement the profile data that has been generated from the MOLA point data and the HRSC line data, ArcGIS was used to generate point data from the HRSC Digital Terrain Models. This was carried out by producing a series of points across the feature shape, before extracting the latitude, longitude and elevation of the points. It was therefore possible to generate
a complete point profile across the surface deposits, which should demonstrate any overall trends across the deposit rather than being localised to a single line. This is particularly important for an extended feature like Oxia Planum, which has multiple separate digitate deposits so different line profiles would intersect with different portions of the deposit and therefore could produce very different results. The variation in point density over the profile is caused by the variable width of the deposit.

Figure 28: Oxia Planum feature. (a) HRSC image h3037_0000 showing the context for the feature and the position of the line profile taken. (b) Profile through the HRSC image from west to east. (c) Approximate feature outline (Quantin, et al., 2015a) and MOLA point data showing selection of points. (d) MOLA point profile from data in (c). The distance along the profile is ~8 km from East to West in (e). (e) HRSC point data profile across the feature, with data points chosen across the outline shown in (c) but at a higher density than the MOLA data points shown.
As can be seen from Figure 28, the HRSC line profile, MOLA point profile and the HRSC point profile all show a steady decrease in elevation as you move across the deposit, with all three profiles running from the apex to the distal end of the deposit. The variation seen in the HRSC line profile is replicated in the HRSC point profile, with the distribution of elevations at each level demonstrating the surface characteristics such as channels and craters in the deposit and the drop to the bottomset, as some points were selected to slightly outline the deposit. The variation in elevation at a single distance ranges from approximately 10 m to 100 m, but this is not surprising as the delta has a width of 12 km at its widest part.

Both the MOLA and HRSC profiles do not have a clear topset-clinoform-bottomset shape as would be expected for a delta, showing a more gradual decrease in elevation. However, closer investigation using HiRISE images shows areas where a small clinoform is visible despite apparent heavy erosion, as will be shown in Section 4.4.1.1.

4.3 Comparison Features

The classification of the feature in Oxia Planum will be carried out through comparisons to similar known features elsewhere on the Martian surface. Typical hallmarks of deltas that have been identified through Earth-based studies, such as lobate features, will also be used for identification. However, due to the reduced gravity on Mars as compared to Earth and the different atmospheric conditions, deltas may take a slightly different form and therefore patterns identified in Martian deltas will be used as the starting point for identification, rather than comparisons to terrestrial deltas.

A total of 46 comparison features have been used, made up of 34 deltas and 12 alluvial fans which have all been identified and classified in the literature. A number of these features will be discussed in detail as examples of the analysis carried out and to discuss any notable points about the features. The features chosen are either particularly similar to the Oxia feature or are good examples of Martian deposits and therefore of the ideal characteristics that would be looked for.

4.3.1 Deltas Used For Comparison

4.3.1.1 Sabrina Delta

The Sabrina delta formed at the end of Sabrina Vallis in Magong Crater, and is centred on 11.69N, 307.05E (Platz, et al., 2014). The position and shape of Sabrina delta has
been identified from Platz, et al. (2014). The delta is thought to be around 3.43 Ga old (Hauber, et al., 2013a). It is found in a degraded impact crater and the edges of the fan resemble shallow-water deposits found on Earth (Hauber, et al., 2009). These are formed from channels protruding into a standing body of water, which creates a lobate fan body, as can be seen on the Sabrina deposit (Hauber, et al., 2009). Due to the eroded state of the deposit in Sabrina, it has been suggested previously that it cannot be definitively said to be a delta as opposed to an alluvial fan, although later studies have classified it as a delta and so it has been considered a delta in this study (Hauber, et al., 2009; Platz, et al., 2014).

The deposit has a clearly defined shape, and an HRSC line profile has been taken along part of the feeding channel as well as through the delta itself. Sabrina delta has one of the highest densities of MOLA point data of the regions examined, and due to its shape the majority of the rectangular selection of data points are within the delta itself.

Figure 29: Sabrina delta. (a) HRSC image h0894_0000 showing the context for the feature and position of the line profile taken. (b) HRSC profile through the feature from h0894_0000 from South to North (c) MOLA point data used for the profile in (d). (d) MOLA point profile through the feature. The distance along the profile is ~24 km from SW to NE.
However, there are a number of points outside this region, as can be seen by the outliers at the start and end of the graph in Figure 29(d). Both profiles show a 300 m drop over the length of the deposit, although no clear clinoform can be seen from the profiles. This may be a feature of the resolution and spread of the elevation points used, as it appears from HiRISE images that there are slight clinoforms around part of the deposit. As was noted with the Oxia deposit, Sabrina delta appears to be heavily eroded, and therefore surface features that are linked to the deposit may actually have been caused in later stage erosion, particularly due to the old age of the deposit, and may not be suitable for use as hallmarks of Martian deltaic deposits.

4.3.1.2 Hypanis Delta

Hypanis delta formed at the end of Hypanis Vallis, centred on 11.3N, 314.57E, and is the largest delta in Xanthe Terra (Hauber, et al., 2009). It is also the largest delta examined in this study, having an area of 1270 km$^2$. HRSC coverage was not available for the entire region, and therefore the distal end of the delta is cut off in the image and profile. However, CTX images and MOLA point data were available over the entire region and were used for this analysis together with the partial HRSC data. Due to the large size of Hypanis delta, there are a very high number of MOLA points across the region. The large size also implies that sediment settled to form the deposit over a long period of time (Hauber, et al., 2009). The delta is a similar age to Sabrina delta, being 3.45 Ga old (Hauber, et al., 2013a).

As with Sabrina delta, the nature of the Hypanis deposit has been debated as there is no clear delta front or shorelines, which may imply that it was instead of an alluvial nature (Hauber, et al., 2009). However, discussions since the publishing of Hauber, et al., indicates that it is indeed deltaic and so it is being treated as so for the purpose of this study (Hauber & Bridges, 2016).

The MOLA and HRSC profiles correspond closely to one another, and show a steady decrease in elevation along the delta. The MOLA point data allows the variation in elevation across the delta to be seen, with a range of 140 m in elevation in some parts despite a total elevation drop of only 280 m over the entire deposit. The profile does not show a clear topset, clinoform or bottomset in the profiles, instead having a steady decrease in elevation. However, the lack of evidence for a standing water level may
indicate a high level of post-formation erosion, and therefore this could also account for the lack of clear clinoform.

Hypanis delta shows similar layering at the edges of the deposit to that seen in Sabrina delta (Hauber, et al., 2009). The two deltas are located in the same region of Mars, with as little as 65 km between them in some places. As they are also of similar age, it could be expected that they formed in similar circumstances. Part of the evidence discussed for why Hypanis could not be a delta is that there is no local topographic low for water to have pooled in (Hauber, et al., 2009). However, as will be discussed later, a gravitational equipotential can be traced around the Hypanis delta that instead encircles the entire northern plains, meaning that the delta would instead have formed due to a northern ocean. This will be discussed in more detail in Section 4.6. An oceanic nature to the delta may explain the channel running through the deposit, as it may have been
formed at a later stage when the ocean water level receded and the feeder channel was required to extend further to reach the shoreline.

### 4.3.1.3 Eberswalde Delta

Eberswalde is a large delta centred on 24S, 33W in the Margaritifer Sinus region, and is fed by the valley network that connects Argyre and Ares Vallis (Pondrelli, et al., 2011). It is a well documented feature and has been proposed as a landing site location for past missions as it is thought to be “smoking gun” evidence for fluvial activity on Mars (Rice & Bell III, 2010). However, it is a relatively young deposit, having an age of 0.197 Ga and therefore being from the Amazonian period (Pondrelli, et al., 2011).

The delta demonstrates more characteristics of fluvial activity (deposition, erosion and transport) than any other feature found, with the evolution of the channels through erosion also visible (Malin & Edgett, 2003). The deposit has distinct lobe patterns (see Figure 31(a)), which are a key feature to look for when identifying deltas and can be easily identified from remote imagery. Holden NE crater, in which the fan is held, is said to be a "textbook" drainage basin, having multiple valleys that converge on a trunk valley entering the basin (Malin & Edgett, 2003). This basin is thought to have been partly buried and partly exhumed, creating the deposit that can be seen now (Malin & Edgett, 2003).

There is very little MOLA data over the centre of Eberswalde delta and therefore only an incomplete profile can be produced from this data set. However, it is possible to produce HRSC line profiles, and the HRSC DTMs have been used to generate an HRSC point profile so that a broader view can be seen. From the HRSC profiles, it can be seen that Eberswalde delta has a slowly decreasing gradient across the topset, before a presumed short clinoform at the edge of the delta (seen by the drop in elevation in the HRSC line profile).

The single data point at the lowest elevation in the MOLA point profile would form part of the bottomset, but the profiles in general focus on the deposit itself rather than the surroundings. A small margin of points were produced around the deposit in the HRSC point profile in order to ensure that the full shape of the deposit was captured. The small range in elevation at the far end of the profile may therefore be representative of the elevation of the bottomset, as the deposit tapers away at this point.
Figure 31: Eberswalde delta. (a) HRSC image h2002_0000 showing the positions of the line profile taken. (b) HRSC profile from West to East. (c) Data selected for MOLA point profile over an interpolated MOLA background. (d) MOLA point profile of the delta. Distance along the profile is ~12 km from West to East. (e) HRSC point profile over Eberswalde delta. Distance along profile is taken as the distance from West-East of the data points due to the orientation of Eberswalde delta.

The HRSC point profile demonstrates how the deposit elevation varies towards the distal end of the deposit, being much more tightly constrained in elevation towards the apex than at the distal end. This may in part be due to the greater number of data points at the distal end due to the increased width of the deposit. However, it is not a
surprising result as the deposit has a very textured surface, with lobate features and channels cross-cutting the surface as can be seen from Figure 31(a). These features may also account for the points between 8000 and 10000 m along the profile which sit below a gap in the profile, as the surface features may have steep sides so the profile only shows their top and bottom elevations.

4.3.1.4 Jezero Delta

Jezero delta is the northern depositional fan in the Jezero crater in Nili Fossae, and is centred on approximately 18.5 N, 77.4 E (Goudge, et al., 2013). The delta is said to be paleolacustrine, and as with Eberswalde shows clear examples of features that are found on terrestrial deltas (Goudge, et al., 2013). As with Eberswalde delta, it is thought to be from the Amazonian period, having an age of 1.4 Ga (Schon, et al., 2012).

Jezero crater shows sustained deposition of sediments, with a lake in the crater thought to have existed for at least 1000 years (Ehlmann, et al., 2008). The sediments found in the delta record the aqueous activity in the region, and they are thought to show multiple episodes of activity and therefore be suited for preserving organic material (Ehlmann, et al., 2008). Finding similar sediments in the Oxia feature would therefore increase the potential for biosignatures being discovered if it was selected as the ExoMars rover landing site. However, there is no guarantee that biosignatures would be found at either site, or that there would be sufficient levels to be detectable.

The Jezero delta system is thought to have undergone post-formation aeolian erosion, altering the development and resulting surface features of the deposit (Schon, et al., 2012). The sedimentation is said to be consistent with a stable water level in the crater which was consistently overfilled, causing water to flow away from the crater (Schon, et al., 2012).

The delta deposit seen in Figure 32(a) shows channels and craters through the surface, which are reflected in the variation in the HRSC profile shown in (b). The small-scale surface variations mean that a line profile will not necessarily be representative of the overall deposit profile. It is therefore better to use the point data, as it will instead sample the entire region.
There is a low density of MOLA data points over Jezero crater, with the majority of the points being at the distal end of the deposit. The MOLA profile therefore does not show a complete picture of the deposit shape. However, Jezero delta shows one of the clearest profiles of all of the features studied in the HRSC point data. As can be seen from Figure 32(e), it has a clear topset, clinoform and bottomset, and it mimics the delta profile demonstrated in Figure 26. However, the clinoform decreases only ~150 m
over a distance of 4000 m. For the majority of the clinoform, there is a range of ~80 m of elevation at a single distance. As can be seen from Figure 32(a), the surface texture of the deposit means this could be expected, as there are clear channels and craters cutting through the surface which create variations as deep as 10 m in the line profile seen in (b). Both Eberswalde and Jezero show topsets and clinoforms of different proportions, with Jezero showing a clearer bottomset than Eberswalde. The similarity in the profile style is unsurprising as the HRSC images show similar deposits, although Jezero is more eroded than Eberswalde with channel features over the deposit surface being less evident.

4.3.2 Alluvial Fans Used For Comparison

4.3.2.1 Peace Vallis Alluvial Fan
Peace Vallis alluvial fan is in Gale Crater, which is the location of MSL's Curiosity rover (Williams, et al., 2013). Peace Vallis is a useful comparison to introduce as there are ground truths available from MSL Curiosity. The fan is a more complex feature than the other sedimentological features studied, as it is an alluvial fan over the remnants of an ancient delta (Palucis, et al., 2014). The fan deposit itself is thought to be late-Hesperian to early-Amazonian in age, assuming that it formed synchronously with a wider fan construction period across Margaritifer Terra (Palucis, et al., 2014). However, Gale Crater as a whole is thought to have an age of approximately 3.6 Ga, based on crater counts in the ejecta, so the fan formed late in the crater evolution.

It is thought that Gale Crater was filled from highland valley networks causing a lake and deltaic features (Palucis, et al., 2014). This was followed by gullies forming in Aeolis Mons at the same time as the crater wall was breached, causing fans to be formed (Palucis, et al., 2014). The instruments on board MSL's Curiosity rover have allowed the sediments to be examined, finding that they are consistent with water-transported sediment, although it has also been proposed that the entirety of Gale Crater was once sediment-filled and has subsequently been eroded (Williams, et al., 2013).
Figure 33: Peace Vallis Alluvial Fan. (a) CTX image T01_000815_1749 showing the fan and the location of the HRSC line profile. (b) HRSC line profile using h4235_0001. (c) Approximate shape outline and MOLA point data locations, showing which data is used for the profile in (d). (d) MOLA point profile using the data shown in (c). (e) HRSC point data profile over the entire shape shown in (c).

The Peace Vallis fan can be divided into two main portions, which take the form of a high and low thermal inertia unit, as will be discussed in Section 4.4.1. It is thought that the higher thermal inertia material (which forms the lower part of the fan) has been
eroded from the upper part of the fan, exposing inverted channels and historic debris flows (Palucis, et al., 2014).

The Peace Vallis fan shows a steadily declining profile, not unlike those seen in the deltas discussed previously. However, there is a clear textural difference between this fan and the deltas, which will be discussed in Section 4.4. It is a relatively smooth region that is not raised from the surrounding region, which is typical of alluvial fans and can be seen in the theoretical profile in Figure 23.

The MOLA point data incorporates the majority of the length of the fan, but there is a much higher density of points at the upper end, and a number of points which are not actually within the fan shape, so this region may not be fully representative of the alluvial fan and instead may be representative of the crater wall topography. However, the HRSC point profile can be used to confirm the deposit shape, as this has a much more consistent spread of data over the deposit. The concavity seen in this profile is consistent with that of a fluvially-dominated alluvial fan, and shows similarities to the terrestrial profiles in Figure 23.

Figure 34: Gale Crater wall. (a) HRSC images h1927_0000 and h4235_0001 showing the location and selection of MOLA data used. (b) MOLA point profile of Gale Crater wall as a comparison to the Peace Vallis profile in Figure 33(d) and (e).

A reference profile has been generated for the crater wall adjacent to Peace Vallis, and can be seen in Figure 34. It shows a clear concave shape, indicating that the profile for the Peace Vallis fan may be following the topography of the crater wall, rather than having a clear topographic profile of its own. The relatively high density of HRSC data points (as compared to the MOLA data) allows the similarities between the Peace Vallis and crater wall profiles to be confirmed. The reference profile is initially much
steeped than that of the alluvial fan as it begins higher up the crater wall, but the lower portion of the profile, which is adjacent to the fan, has a similar shape. The wall profile covers a width of approximately 6.5 km and length of 22 km, and the crater has a radius of approximately 70 km.

4.4 Textural Comparisons

4.4.1 Surface Textures

4.4.1.1 Oxia Planum
The aqueous feature in Oxia Planum is much more segmented than traditional deltas such as Eberswalde, which may indicate that it has undergone much more erosion since its formation making the hallmarks of a delta much harder to identify. As can be seen from Figure 35(a), there is a slight clinoform visible around the edges of the feature. It is much less distinct than that of Eberswalde or Jezero, and is only visible in some regions of the deposit.

There is a very different texture on the deltaic material than on Eberswalde and Jezero, with very few visible channels. The few channels that can be seen are heavily eroded. There are small numbers of TARs visible around the edges of the deposit, but very few over the topset. In contrast to Eberswalde and Jezero deltas, the topset of the feature is smoother than the surroundings.

Figure 35(b) shows an elongate portion of the feature in Oxia Planum. It has a slight clinoform around one edge, but no distinct change on the other edge (at this resolution). Once again, the aqueous feature appears to be formed from smoother material than the surroundings, without clear channels or substantial TARs. There are TARs within the craters but not across the topset.

This central portion of the Oxia Planum aqueous feature (shown in Figure 35(c)) has been eroded such that any variation in elevation (i.e. clinoform) is no longer visible. There is an additional slight clinoform around the north-western edge of the deposit. Again, the deposit can be identified by the smooth surface with no clear channels, which is distinct from the rough terrain surrounding it.
If Eberswalde and Jezero deltas are used as the only comparison points, it would be unclear as to whether Oxia is a delta. It does not bear the same hallmarks as the two deltas, but it may be that these features used to be visible and have been greatly eroded.
over time. There are a high number of large craters in the deltaic material in Oxia Planum, supporting the suggestion that it may be over 3.5 Ga old (Quantin, et al., 2015a). As Eberswalde and Jezero have ages of 0.197 and 1.4 Ga respectively, it would be expected that the deposit would be significantly more eroded and therefore lack distinct deltaic features (Pondrelli, et al., 2011; Schon, et al., 2012).

4.4.1.2 Hypanis Vallis

Figure 36: Hypanis delta. (a) Slight clinoform around the edge of the delta (ESP_034394_1920). (b) Textural difference between delta edge material (Gupta, et al., 2015) and bottomset of delta (ESP_034394_1920).

The feature in Oxia Planum appears to be heavily eroded, and therefore may more closely resemble the eroded delta in Hypanis, which has a similar age of 3.45 Ga (Hauber, et al., 2013a). This delta does not have clear clinoforms at the majority of its limits, with only small sections showing any distinct drop in elevation such as that seen in Figure 36(a). The majority of the deposit instead shows a textural difference to its surroundings, with a clear example of this being seen in Figure 36(b). The delta edge
material (Gupta, et al., 2015) is highly ridged, whereas the bottomset has a more bedrock-like texture. However, there may be clearer clinoforms between the delta topset and the delta edge, rather than between the delta material and the bottomset.

Figure 37: Hypanis delta. (a) Clinoforms at boundary between topset and delta edge material (ESP_036131_1920). (b) Central portion of Hypanis delta, showing channels and TARs in topset material (ESP_036517_1920).

Clinoforms are visible intermittently at the boundary between the delta top and delta edge material, as can be seen from Figure 37(a). As was discussed with the deposit in Oxia, this may be due to erosion of the deltaic material due to the age of the deposit. The images show a high density of ridges which may affect the presence of clinoforms.
in two ways. Firstly, erosion of material from steep slopes is thought to be a key source of material for TARs (Berman, et al., 2011), and so the clinoforms may have been eroded to provide material for the ridges visible in the delta edge material. Secondly, the high density of ridges disguises the slopes and textural boundaries present in the images, so there may be slight clinoforms beneath the ridges, particularly in regions with high densities of ridges.

The centre of the Hypanis delta, which is clearly delta top material (Gupta, et al., 2015), once again shows channel features and TARs as have been seen in Eberswalde and Jezero. The large size of Hypanis delta accentuates these features where they occur, with the channels seen in Figure 37(b) having widths between 400 and 1000 m. However, these channels may have formed through the deposits after formation, and may not be part of the original delta deposit.

4.4.1.3 Eberswalde Delta

Eberswalde delta has a very distinct surface texture and pattern and therefore forms a reference point when studying Martian deltas. It is thought to record the entire “life cycle” of the location, with evolving channels imprinted onto its surface (Malin & Edgett, 2003). It is hoped that Eberswalde delta can be used as an example of key features to look for in Oxia, although as mentioned previously the delta in Eberswalde is significantly younger than that in Oxia, and therefore may not show later-stage erosional features.

As can be seen from Figure 38(a), there are clear lobate features within the delta. These are thought to represent the erosional remnants of other deltaic materials (Rice & Bell III, 2010). The edges of the delta deposit have a clinoform structure from the settling of sediments within what would have been a standing body of water, as expected from Figure 26. There is a distinct textural difference between the delta deposit and the bottomset over which they are deposited. The bottomset at the edges of the delta has a very smooth texture with boulders and TARs on the surface as can be seen from the right-hand side of Figure 38(b). However in the delta deposit, there are clear layers which are assumed to have been created during deposition.
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Figure 38: Eberswalde delta. (a) Lobate features (PSP_001534_1560). (b) Clinoform structure at the limits of the delta (PSP_004000_1560). (c) Channels and TARs in the delta sediments (PSP_001534_1560).

The delta landform has distinct channels as can be seen in Figure 38(c) and there are a large number of Transverse Aeolian Ridges (TARs) within these channels. These can
be caused by the liberation of sediments through erosion (Balme, et al., 2008), and are influenced by topography (Geissler, 2014) which is why they have formed within the channels. TARs seem to form in-situ in regions with substantial layered sedimentary terrains which may give an indication of the local composition, as was the case in the Meridiani region (Berman, et al., 2011).

4.4.1.4 Peace Vallis Alluvial Fan

The Peace Vallis alluvial fan is found to have two distinct textures in HiRISE images, which is consistent with descriptions from Palucis, et al., (2014) where they describe a "smooth, lower thermal inertia unit" in the North and a "rockier, high thermal inertia unit" in the South (Palucis, et al., 2014).

The upper region is shown in Figure 39(a) and although the surface is clearly very cratered, the craters seem to have either been filled by sediments or eroded as they have a smooth appearance and do not have clearly defined ejecta blankets around them. When contrasted with Figure 39(b) which shows the lower region, the smooth edges of the craters are more noticeable, as the craters in (b) appear much more distinct, although there are fewer of them.

The higher thermal inertia unit shown in Figure 39(b) also shows polygonally fractured material in the right of the image. These fractures are often thought to be associated with fine-grained sediments which can cause an overall high thermal inertia when they are densely packed. Both (a) and (b) are images at the same scale but there is a noticeable textural difference between the two units, with the upper unit having a much smoother surface texture than the lower unit.

Figure 39(c) shows the western edge of the deposit, where the lower unit meets the crater wall. The lower unit appears to be much brighter than the surrounding wall and has a more complicated surface texture. The surrounding wall has a more similar texture to the upper unit, but is less eroded than the upper unit.

Both the upper and lower units in Peace Vallis have rougher, more cratered surface textures than the deltas. The deltas studied have varied surfaces, and may be covered by TARs, but they do not show the rough, cratered and rocky appearance that the Peace Vallis fan does.
Figure 39: Peace Vallis alluvial fan. (a) Low thermal inertia unit in the upper region of the fan. (b) Higher thermal inertia unit in the lower region of the fan. Polygonal fractures generally identified with fine-grained sediments can be seen in the right hand side of the image. (c) Boundary region at the bottom of the fan between higher thermal inertia unit and the surroundings on the crater wall. Images are from HiRISE image PSP_010573_1755.

4.4.2 Thermal Inertia

The thermal inertia of a region will help us identify the type of material therein, with a lower thermal inertia indicating smaller particles (Edgett & Christensen, 1991). By
identifying the grain size we may be able to identify the nature of the deposits, as alluvial fans are expected to have coarser sediments and be less well-sorted than water-lain deltas (Chorley, et al., 1984; Schon, et al., 2012).

THEMIS IR night global mosaics have been used to obtain images of four of the deltaic features to determine the relative thermal inertia of each of the sites. These can be seen in Figure 40. Relative thermal inertia have been used as it will allow us to compare the overall thermal inertia trends in a region, taking into account the potential for different regions to have a different starting material, and therefore a different thermal inertia baseline.

Hypanis, Sabrina and Oxia all have similar appearances and are significantly darker (i.e. lower thermal inertia and smaller particles) than their surroundings. Eberswalde, on the other hand, is less distinct and of similar thermal inertia to its surroundings, although it is still slightly darker.

The surface deposits in Hypanis are finer grained than their surroundings, showing up as a dark region in the THEMIS IR night mosaic. The material is more fine-grained around the distal regions of the deposit. This depositional sorting of material as it extends from the feeder channel is consistent with the deltaic nature of the deposit.

Sabrina delta also shows a lower thermal inertia than the surrounding material, which may indicate that the deposit material is finer grained or less consolidated than its surroundings. It is worth noting that this can be caused by a higher surface roughness that traps the fine grains, but visual inspections of CTX images suggest that this is not likely to be the case (Hauber, et al., 2009). Similarly to the Hypanis deposit, the material appears to become increasingly fine-grained as it extends across the deposit with the exception of a channel through the centre, which again is consistent with it being a well-sorted delta.

The Oxia deposit follows the same trend as those in Hypanis and Sabrina. It has a much lower thermal inertia than the surroundings, forming a very clear shape that is more easily distinguished than in visible images. In addition, the thermal inertia of the deposit seems to decrease towards the distal end, again becoming more finely sorted as it extends along the deposit. This implies that the deposit is likely to be deltaic.

The deposit at Eberswalde delta does not have the same distinct difference in thermal inertia as seen at Hypanis, Sabrina and Oxia. The deposit is darker than parts of the
immediate surroundings but overall is approximately the same. The deposit seems to increase in thermal inertia towards the distal end, with the feeder channel having a lower thermal inertia than the deposit itself. This may be indicative of erosion at Eberswalde delta, which may have preferentially eroded away the weakly cemented, fine-grained material (Fedo, et al., 2008).

As a comparison, the thermal inertia was also found for Peace Vallis and can be seen in Figure 41. The two portions of the fan can be clearly seen in this image, with the lower portion being much brighter in the night-time IR image, indicating a high thermal inertia. There is a much clearer division between the upper and lower fan in the thermal image than in visible images, where the fan has to be inspected much more closely to distinguish between the different units. What may have once been channels can be seen in the upper unit as a combination of high and low thermal inertia regions running from the apex of the fan towards the distal end. These may have been buried and become visible due to erosion of the higher thermal inertia material as discussed previously, or they may alternatively have been formed by the erosive materials. The fan has a more
mixed thermal inertia overall, with varying thermal inertia throughout the deposit as would be expected with an alluvial fan.

The Peace Vallis alluvial fan has a very distinct thermal inertia signature as compared to the deltaic features shown, as it does not show the overall difference to the surroundings seen in the deltas. From the thermal inertia images seen in Figure 40 and Figure 41, it would be more appropriate to classify the feature in Oxia as a delta than an alluvial fan.

Figure 41: Peace Vallis fan shown in THEMIS day IR image at 100 m per pixel (Edwards, et al., 2011).

4.5 Discussion

A total of 47 features were studied, comprising 12 known alluvial fans, 34 known deltas and the feature being identified in Oxia Planum. It was anticipated that patterns could be found in the morphological characteristics, in particular distinctions between the alluvial fans and deltas, so that the feature in Oxia could be associated with either class of features.

Before attempting to classify the Oxia feature, it is worth considering whether an earlier assumption, that the outline used by Quantin, et al., was suitable to represent the delta area, was appropriate to make. This assumption has been tested by comparing the Oxia feature to the features found in the circum-Chryse region, rather than by comparison to theoretical models for Earth, as it is assumed that there would be similar environmental factors affecting the delta formation. The delta areas plotted against elevation as shown in Figure 42. The feature in Oxia Planum has a similar area to the majority of the features in the circum-Chryse region, with Sabrina and Hypanis being the two
significant exceptions at 221 km² and 1271 km² respectively. The outline used for the feature in Oxia Planum has therefore been seen to be appropriate, as it has an area which is largely consistent with similar features in the same region of Mars and a shape which has been confirmed using thermal inertia images.

Delta Area against Elevation for Circum-Chryse Deltas

Figure 42: Delta area against elevation for circum-Chryse deltas, with the Oxia feature being shown as a separate category for clarity. Circum-Chryse deltas have been defined as those between 0° and 30°N, and 300° and 360°E.

Minimum Elevation against Longitude for Features Studied

Figure 43: Minimum elevation against longitude for all features studied split into three categories - alluvial fans, deltas, and the feature in Oxia Planum.

The first aspect of the features that will be discussed is the elevation. In order to study the features, the maximum elevation, minimum elevation and average elevation of each feature has been calculated from the HRSC point profiles generated, with the average
being an arithmetic mean calculated from the data points taken across each feature. The elevation points generated using HRSC data were selected to be representative of the features themselves rather than the surrounding topographic depressions as they were manually fitted to the deposit shapes, although the lowest elevation points are expected to correspond to the bottomset.

Figure 43 shows the distribution of elevation against longitude across Mars. The majority of the features can be found at elevations below 0 km MOLA, but there are three each of deltas and alluvial fans above this threshold. The majority of the features can be found between -1000 km and -3000 km MOLA, with the Oxia feature being found within this boundary. However, there is no clear distinction in elevation between deltas and alluvial fans, and therefore this alone cannot be used as a distinguishing characteristic.

The variation in elevation for the features may be caused by the variable nature of the features. In deltas in particular, the body of water in which they are formed may be influential on their morphology and elevation. Previous comparisons between Martian and terrestrial deltas have found that the upstream and downstream conditions that affected delta formation on Mars were much more limited than on Earth, but the water level (and its variability) was one of the determining factors (de Villiers, et al., 2013).

As discussed in Di Achille and Hynek (2010), if there was once an ocean in the northern plains, marine deltas would be expected to form at the same elevation across the planet creating a reference elevation for the “sea level” (Di Achille & Hynek, 2010). The oceanic hypothesis will be discussed in more detail in Section 4.6. However, it may therefore be necessary to divide the deltas into those in closed basins and those that appear to form at the mouths of tributaries opening into channels or basins that are connected to the northern plains. This may demonstrate if there are elevation trends within subsets of the features, and may show whether the categories of delta and alluvial fan are in fact too broad for classifying the feature in Oxia Planum.

Figure 44 shows the same data as Figure 43, except the deltas have been further split into deltas in craters or deltas in oceans. This division has highlighted that the deltas in oceans have a smaller range of elevations than the deltas in craters, which account for both the extreme highs and lows in elevation for the deltas. The feature in Oxia Planum sits within the same elevation band as the ocean deltas, and is toward the lower end of
this band. However, there are no clear distinctions between the different features, with the band containing the ocean deltas also containing alluvial fans and crater deltas, so while this could indicate that the feature in Oxia Planum is an ocean delta it is very difficult to conclude this solely from the data seen in Figure 44.

![Minimum Elevation against Longitude of Features Studied](image)

**Figure 44: Minimum elevation against longitude of the sedimentary features studied, with deltas classified according to whether they open into a local or global topographic basin.**

It is worth noting that all of the alluvial fans included in this study have been found in the southern hemisphere, whereas deltas have been found in both the northern and southern hemisphere. This may be a selection effect due to the comparatively small sample size of alluvial fans used. However, as the feature in Oxia Planum is in the northern hemisphere, this may strengthen the argument that it is a delta.

HRSC point profiles were generated for all the features studied herein in order to look for a common shape within feature classes. Terrestrial deltas typically show a topset-clinoform-bottomset profile as discussed in Section 4.1, but the deltas studied herein seem to indicate that this is not as clear-cut a profile on Martian deltas as they generally show a more steady decrease in elevation over the full length before a very short clinoform. However, some of the deltas (e.g. Kolonga) have a traditional Gilbert-type profile, which may be a more common delta shape on Mars, indicating that they formed under homopycnal conditions. Terrestrial Gilbert-type deltas were initially thought to be limited to lacustrine deposits but have also been found in marine environments.
By comparison, alluvial fans typically have concave profiles. They do not protrude extensively from their enclosing topographic basins, and therefore approximately follow the gradient of their surroundings. This can be seen from the profile and texture of Peace Vallis, where there are no steep clinoforms around the edges and it instead seems to be a more gradual decline at the edges of the deposit. The edge effects of a deposit are therefore a helpful point to examine to determine whether a feature is deltaic or an alluvial fan, and the deposit in Oxia seems to have more deltaic edge effects with clinoforms being located in parts of the deposit (see Figure 35).

The topographic gradient has also been calculated for each feature, where the gradient is calculated as the elevation drop over the feature divided by the feature length. The feature length has been taken as the distance from the apex to a visible end of the feature, e.g. as signified by the intersection between a clinoform and bottomset. Figure 45 shows the variation in topographic gradient with longitude according to classification, and Figure 46 shows the topographic gradient against maximum elevation of each feature. As can be seen from these two graphs, there is no clear relationship between the topographic gradient of the feature and either the location (as given by the longitude) or the elevation of the feature. The full range of topographic gradients measured seems to be present at certain locations and elevations, without any selection according to elevation or longitude. This would therefore seem to confirm that the feature morphology is controlled more by the aqueous environment than the physical environment, with basin type and feeder network size potentially contributing
more strongly to the deposit formation than the physical location. As the features have not been divided according to the types of aqueous environment, any potential correlations to these types are not visible. It is therefore not feasible to use the topographic gradient of the Oxia feature to attempt to identify it with either class of features.

Figure 45: Topographic gradient against longitude for the features studied. Topographic gradient is defined as the elevation drop over a feature divided by the length of the profile.

Figure 46: Topographic gradient against elevation for the features studied, split by feature classification.
In addition to the morphological comparisons, textural comparisons have also been carried out both to deltas and alluvial fans as demonstrated in Section 4.4. As mentioned previously, one distinction between deltas and alluvial fans is the absence of a clinoform of any size in the alluvial fans. Some of the deltas investigated only have partial clinoforms due to erosion, but there is still evidence for a larger clinoform having historically been present around the deposit.

The textural investigations of the features have shown that the feature in Oxia is similar texturally to those in Hypanis and Sabrina. This is clear both from the HiRISE imagery and the THEMIS mosaics, with similar levels of erosion, similar surface textures such as depressions containing TARs, and similar thermal inertia relative to their surroundings. However, as there has in the past been some debate as to the nature of these deposits (Hauber, et al., 2009), identifying the feature with Hypanis and Sabrina may not be considered to be a definitive categorisation.

It is very difficult to come up with a definitive set of characteristics that a feature must obey to categorise it as a delta or an alluvial fan from the remote sensing data available for the Martian surface. The deposits studied vary so widely that there are no clear large-scale morphological or location trends for either feature type, with the only possible trend being that there are only alluvial fans in the southern hemisphere of Mars. The surface texture therefore shows a more significant distinction between alluvial fans and deltas.

The thermal inertia gives a broad sense of the surface texture, and from Figure 40 and Figure 41 it can be seen that deltas typically have a lower thermal inertia than their surroundings, whereas alluvial fans have a higher thermal inertia. Furthermore, while the deposits discussed in Figure 35 to Figure 38 have different surface textures, they are all texturally distinct from their surroundings, and show some form of textural edge effects such as small clinoforms. Although clinoforms are a morphological characteristic, due to the high levels of erosion on a number of the deposits they cannot be distinguished in profiles, but they can be seen in high resolution images and therefore have been considered to be a textural factor. In addition, the deltas studied have much higher numbers of ridges over their surface, either in the form of TARs (see Figure 35) or as indurated ridges (see Figure 36 and Figure 37). These are largely absent from the alluvial fans (e.g. Figure 39), which is consistent with the higher thermal inertia in these regions. While these features are not definitive in their own
right, a combination of them could indicate that a feature is deltaic rather than an alluvial fan.

While some smaller-scale morphological characteristics, such as lobate features and cross-cutting channels, can be used to identify deltas, the different delta morphologies available and the highly degraded state of many of the features means that these are not often visible, particularly in Noachian aged deposits. Furthermore, as a number of the deltas are proposed to have been oceanic, these formation features are much less distinct than they seem to be for deposits formed in smaller basins. It should be noted that due to the depositional processes in delta formation (as discussed in Section 4.1), deltas protrude from their surrounding surfaces whereas alluvial fans lie much more closely to the surrounding basins, and this is still true of the oceanic features even where they are much less distinct than their lacustrine counterparts.

The two notable and consistent features across the deltas are the presence of at least a small clinoform around part of the deposit, and the lower thermal inertia of the deposit than its surroundings with the thermal inertia decreasing toward the distal end of the deposit. As the deposit in Oxia Planum has both of these features, and is in the northern hemisphere, it would therefore seem logical to label the feature as a delta. However, without in-situ measurements of the feature, it is very difficult to classify it definitively. It would therefore be a benefit to the ExoMars rover to land at Oxia Planum, so that in-situ measurements of a degraded, ancient deltaic structure could be carried out to help the study of these features across the Martian surface.

4.6 A Northern Ocean?

It has long been proposed that there may have been an ancient ocean in the northern plains of Mars, with shorelines previously identified through topographic analysis (Di Achille & Hynek, 2010; Clifford & Parker, 2001; Parker, et al., 1989). Parker, et al. proposed in 1989 that a northern ocean (either of water or ice) would be the best explanation for the fretted and gradational terrain boundaries found between the lowlands and highlands on Mars, and remote sensing of the surface since then has been used to further study the theory of a historical northern ocean (Parker, et al., 1989).

Parker, et al. (1989) found that the topographic contacts sensed on the surface could have been caused by different methods, with one of these being repeated flooding of the northern plains with water from outflow channels. They found that the volume of water
required to flood the lowlands within the boundaries seen is consistent with both global inventories and the water requirement to create the Chryse outflow channels, and that this volume of water must have at some point formed a standing body (Parker, et al., 1989). Furthermore, they suggest that the lowlands may have been resurfaced by sediments and wave action, creating the relatively smooth surface with low crater density seen (Parker, et al., 1989). They question the possibility of surface temperatures being sufficient to allow for standing bodies of water, and instead suggest that the sedimentary deposits closer resemble cold terrestrial lakes and therefore may have been caused by an ice-covered sea. However, as discussed in Section 1.2, it has since been suggested that the carbon dioxide inventory may have been sufficient to cause a greenhouse effect, and may subsequently have been removed, e.g. in the formation of carbonate rocks, to produce levels seen today (Pollack, et al., 1987).

The high number of large outflow channels that extend into the northern lowlands supports the hypothesis of there having once been a northern ocean, with Valles Marineris being the most notable example. In addition, the unusual flatness of the lowlands is indicative of them having been home to a watershed in the past (Head III, et al., 1999). The formation of an ocean has been hypothesised to be accompanied by sedimentation that would smooth the terrain below the ocean, so the smoothness of this region may again indicate the historical presence of an ocean (Parker, et al., 1989; Head III, et al., 1999). Measurements from MARSIS on Mars Express have found that the surface in the northern lowlands has a low dielectric value, which corresponds to low density materials or ice rather than volcanic materials, so it is more likely that this smooth surface was caused by an ocean than through lava flows (Mouginot, et al., 2012).

In addition, studies of craters with rampart and lobe morphologies have found that the smallest of these craters (diameter <2 km) correlate with large basins in the northern lowlands (Head III, et al., 1999). Rampart craters are associated with groundwater or ground ice, as the ejecta features correspond to material flowing across the surface rather than following a ballistic trajectory.

If there was historically a northern ocean, water must have flowed into it from different points on the surface, notably from the feeder channels surrounding the terrain boundary. There should therefore be remnants of these transitional environments, which may take the form of deltas. Di Achille and Hynek analysed 52 deltaic deposits,
Identifying whether there was once an ocean in the northern plains of Mars would be of benefit to the ExoMars mission. One of the key scientific goals is to search for signs of past or present life, and as water is a key element to the existence of life, a former ocean would be a strong starting point for the mission. If an elevation at which a past ocean existed can be identified, the proposed landing sites can be sorted as to whether they are within this region. Being within the ocean basin would be evidence for sustained and extensive aqueous activity, which would be a strong scientific benefit of landing at one of those sites.

### 4.6.1 Global Context

The global distribution of the deltas and alluvial fans studied in Section 4.3 have been mapped and is shown in Figure 47. They are distributed over a large portion of the Martian surface but appear to cluster in some regions. Furthermore, when they are plotted over a MOLA map of the surface a large number of the features, in particular the deltas, can often be seen around the boundary between the topographic highlands and lowlands, as can be seen from Figure 47. There are a number of deltas and fans that are not arranged around this boundary, and localised closed basins can often be seen around these features. For the purpose of this study, the feature in Oxia Planum has been considered to be a delta, as the discussion in Section 4.5 indicated that this was the most likely conclusion that could be obtained from the data used herein.

The arrangement of the features, and in particular the deltas, around the edges of the northern lowlands initially supports the idea that there was once a northern ocean as is suggests that there may have been a standing body of water therein. It was discussed in Section 4.5 that when studying the morphology and location of features, it may be appropriate to split the deltas according to whether they are located in a localised closed basin (i.e. a crater) or instead do not show this localisation and would require a much larger basin (i.e. an ocean).

In order to determine whether each of the deltas was confined to a crater or an ocean, contour lines were produced at the elevation of each delta apex using global interpolated MOLA maps. The closed loop produced by these contours was then used to determine whether it was confined to a crater or an ocean, with HRSC and CTX
imagery used to confirm whether the decision was reasonable. The first features studied were Oxia (-2820 m), Hypanis (-2560 m) and Sabrina (-2400 m). Hypanis and Sabrina were chosen as the deltaic study showed them to be similar to Oxia, and the three features seem quite different to Eberswalde delta which is clearly formed in a crater. In addition, Hypanis and Sabrina both fall within the range discussed by Di Achille and Hynek, whereas Oxia is at a lower elevation and falls slightly outside their range (Di Achille & Hynek, 2010).

Figure 47: MOLA map showing the location of the deltas and fans in this study (MOLA Team, 2003).

Figure 48: Maximum elevation against longitude of deltas (MOLA Team, 2003).

In total, 23 of the deltas studied were found to be in craters or localised closed basins and 12 of the deltas formed closed basins that encircled the northern plains. The
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elevation of these features can be seen in Figure 48. The maximum elevation of crater
deltas varies much more widely than that of oceanic deltas, which are limited between -3000 m and -1000 m in elevation, whereas the crater deltas range between -3800 m and 3500 m. In addition, the oceanic deltas can be seen to form in clusters of similar elevation, with two main clusters at around 130° and 320° longitude. These two clusters correspond to the Gale Crater and Chryse Planitia regions respectively. The Chryse Planitia region is known to be home to a number of outflow channels, which may explain the high density of deltas in this location. The maximum elevation has been assumed to be the apex elevation, and hence has been used for these plots.

Figure 49: Contour lines for Oxia (green), Hypanis (purple) and Sabrina (purple) deltas. Background is MOLA interpolated elevation map (MOLA Team, 2003).

Figure 49 demonstrates the contour lines produced by Oxia, Hypanis and Sabrina. They do not form localised closed basins around each aqueous feature, and instead form a closed contour around the entire northern plains. Hypanis and Sabrina have been plotted together as they are within the range suggested by Di Achille and Hynek, whereas Oxia is outside the range they suggest (Di Achille & Hynek, 2010). Furthermore, the Hypanis and Sabrina contours also correspond to contours surrounding Hellas and Argyre, which Di Achille and Hynek discuss as being home to water ponding if a northern ocean were to have existed (Di Achille & Hynek, 2010).
As Mars Science Laboratory's Curiosity rover has been studying Gale Crater (Arvidson, et al., 2016), this region was examined to see how it corresponds to the closed basins created by the Hypanis, Sabrina and Oxia equipotentials. While Gale Crater itself sits within a lower elevation region bound in a closed loop by the Oxia contour, the -2560 m contour (Hypanis) approaches the crater as part of its loop around the northern plains and the -2400 m contour (Sabrina) encloses the crater as part of its closed loop around the plains. Gale Crater would therefore have been within the ocean boundaries if an ocean formed at the elevation of Sabrina. This can be seen in Figure 50, which shows a section of Figure 49 around Gale Crater. The ‘opening’ into the crater from what would have been the ocean is aligned with the Peace Vallis alluvial fan, which may have been formed due to the location of an in-filling point for the crater from the ocean when the crater initially flooded.

4.6.2 Potential Ocean Elevations

The oceanic features studied vary in elevation as mentioned previously, but they have been found to have an average minimum elevation of -2616 m, with a standard deviation of 410 m. This value assumes that all of the deltas were formed from a single incidence of the ocean which only had one elevation. Figure 51 demonstrates the size of the ocean that would be formed from this single elevation. The regions that would be filled with water are shown in colour, with those that would have been land being dark. Hellas and Argyre are also shown as water filled, as if there was a northern ocean the global hydrosphere may have been such that they would also be filled, as discussed.
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previously. Black contours pick out the ocean elevation and +/- 1 standard deviation of this value, to demonstrate the variation that could be expected from the ocean level. This variation is particularly visible around 150° and 240° longitude.

An ocean formed at -2616 m MOLA would have a volume of $1.06 \times 10^8 \text{ km}^3$ ($\pm 3 \times 10^7 \text{ km}^3$), which would be equivalent to a 468 m thick layer of water over the entire surface of Mars (a Global Equivalent Layer or GEL). For comparison, the Earth has a total surface inventory of 3 km GEL (Carr & Head III, 2003). This calculation does not include the water that would have filled Hellas and Argyre, and only includes the large northern basin. The volumes calculated in this study also exclude the polar ice caps, and act on the assumption that the polar ice cap has maintained the same size throughout Martian history. Studies using MOLA data have found the northern ice cap to have a volume of between $1.2 \times 10^6$ and $1.7 \times 10^6 \text{ km}^3$, which is less than 2% of the ocean volume calculated here, and therefore would not significantly impact these results (Zuber, et al., 1998).

If the crater-based deltas were also included, the average elevation increases to -2188 m ($\pm 1208 \text{ m}$), which would then create an ocean $1.4 \times 10^8 \text{ km}^3$ in volume, corresponding to 616 m GEL. This ocean is significantly larger, and would begin to include some of the ancient highlands too. It seems a less likely elevation, and reinforces the idea that the deltas that would appear to be oceanic should be classified differently.

Figure 51: MOLA elevation map showing the location of the proposed ocean if all of the deltas formed from a single incidence of the ocean in blue/purple (MOLA Team, 2003). Regions which are not included in the ocean are faded. Black lines show the contours at the ocean elevation, and +/- 1 standard deviation of this value to show the variation that could be expected.
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This ocean level has been calculated on the assumption that all of the deltas identified as oceanic formed due to a single incidence of the ocean which had a single shoreline. However, as there is no longer an ocean in the northern plains of Mars, it would be reasonable to assume that the ocean receded over time before disappearing entirely. The variation in delta elevation may therefore indicate a variation in the ocean depth over time and a shifting shoreline. It has also been suggested that the ocean may have periodically formed over the northern plains producing temporary warm, wet climates, so different features may correspond to different incidences of the northern oceans (Baker, et al., 1991).

If there were multiple incidences of a northern ocean, or even a single incidence that changed shoreline over time, deltas would form at different elevations according to the shoreline level at the time of their formation. There may therefore be subsets of the deltas studied which correspond to certain instances of the ocean.

One subset that has been investigated is the idea that the circum-Chryse deltas formed from the same instance of the ocean. The region is home to a number of large outflow channels including Valles Marineris, and therefore would have seen significant water transport if an ocean had been present. It could therefore be expected that the deltas in that region formed at a similar time. Both crater and ocean deltas have been included in this investigation as some of the craters may have existed below the ocean line. Using only the circum-Chryse deltas (defined herein as any delta between 0-45°N and 300-360°E), an average minimum elevation of -2451 m (+/-642 m) is found for the ocean shoreline, which corresponds to an ocean volume of \(1.19 \times 10^8\) km\(^3\), or a GEL of 523 m.

The elevation of the circum-Chryse deltas can be seen in Figure 52, which have again been classified depending on whether they are in a crater or an ocean. However, if they are treated as a single group, it can be seen that they approximately follow the shape of the circum-Chryse basin, with the elevation of the deltas increasing away from the entrance to Valles Marineris. The deepest deltas are closest to this entrance, which is a deep valley through the region, reaching lows of around -4800 m. Figure 53 shows a MOLA map demonstrating the locations of the circum-Chryse deltas, together with a contour illustrating what may have been the shoreline for the ocean. While the elevation is appropriate for a number of the deltas, or nearly appropriate for others, the range of distances between the contour and the deltas shows the difficulty of fitting a single elevation to the deltas, even for a relatively small geographic region.
If it is not possible to fit all of the deltas to a single shoreline, it would seem reasonable to assume that the deltas have formed from different shorelines and therefore presumably at different times. To test this hypothesis, the deltas will be grouped according to their age. Ages have not been found for all of the features as they have
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been taken from the literature (see Appendix 2). It may be possible to age additional
deltas using crater counting, but the small sample areas in use make this difficult and
may generate inaccurate results. However, based on the ages obtained from Hauber, et
al. (2013), Pondrelli, et al. (2011) and Schon, et al. (2012), it has been possible to split
the deltas into two main groups based on the geologic era in which the deposit formed.
There are seven deltas from the late-Noachian/early-Hesperian era, and a further nine
deltas from the Amazonian era.

The late-Noachian/early-Hesperian era deposits have ages ranging from 3.35 to 3.63
Ga, and if they were to have formed from the same incidence of an ocean would create
a shoreline at -2701 m (± 420 m). This can be contrasted with the Amazonian era
deposits, which range from 0.197 to 1.8 Ga in age and would require an ocean at -2163
m (± 657 m). There is therefore a difference in elevation of 538 m between the two
ocean incidences.

Figure 54: MOLA interpolated map showing the shorelines of the late-Noachian/early-Hesperian ocean at -2905 m (brown) and the Amazonian ocean at -2100 m (red) (MOLA Team, 2003).

However, if only the oceanic deltas are used to calculate the average elevation, to be
consistent with the earlier discussion, the results for the two eras diverge further. There
are three deltas in the Amazonian data set and four in the Noachian/Hesperian data set,
and therefore this small sample size must be considered when examining the
significance of these results. The late-Noachian/early-Hesperian deltas would form an
ocean shoreline at -2905 m ± 195 m, whereas the Amazonian deltas would have an
elevation of -2100 m ± 346 m. There would therefore be variation of 805 m between
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The location of the two shorelines can be seen in Figure 54. The two diverge most drastically around 120° and 240° longitude, although there is a noticeable difference in shoreline location at most points across the surface.

The older ocean would be smaller than the younger ocean, having a volume of $8.55 \times 10^7$ km$^3$ (or 375 m GEL) as compared to $1.47 \times 10^8$ km$^3$ (or 648 m GEL). This may be seen to be inconsistent with the general understanding that the Hesperian/Amazonian boundary was the transition from wet Mars to the dry Mars seen today. It may therefore suggest that some of the features identified as Amazonian deltas are not actually deltas, and that a closer study of these features is required. However, as discussed in Baker, et al., there are Amazonian outflow channels in the northern plains and Amazonian-age glacial landforms in Hellas and Argyre and therefore there may have been sufficient aqueous activity to allow for an ocean (Baker, et al., 1991). A northern ocean would require aqueous activity in Hellas and Argyre, as discussed previously, and therefore by the same logic if there was glacial activity in the southern regions, there may have been liquid water in the northern plains. Furthermore, Eberswalde delta has been found to have an age of 0.197 Ga, making it Amazonian in age, and as this is considered to be a defining example of a delta on Mars there must have been standing bodies of water on the surface in this era. However, it may be that there was still water ponding without enough atmosphere to support an entire northern ocean and associated global hydrosphere.

A study by Wilson, et al., of Fresh Shallow Valleys (FSVs) and paleolakes in mid-latitudes of Mars has proposed that there was aqueous activity as late as the mid-Amazonian, suggesting that there may even have been an active hydrological cycle at this time (Wilson, et al., 2016). Their study focused on Arabia Terra, finding that FSVs likely formed from snowmelt, which contradicts the general belief that this era would not have supported precipitation or runoff (Wilson, et al., 2016). The suggestion that as late as the mid-Amazonian, Mars may have had an active hydrological system and been habitable would therefore support the proposal herein of an Amazonian-era ocean (Wilson, et al., 2016).

The surfaces around the shoreline of the Noachian/Hesperian ocean appear to be smoother than those at the Amazonian shoreline (at the resolution of MOLA data), which could be said to be consistent with the region having been resurfaced by a later ocean, smoothing craters that had been created between the two ocean incidences or...
above the shoreline of the earlier ocean. Rodriguez, et al. suggest that the lack of distinct shoreline in the northern plains and in particular in the circum-Chryse region may be due to tsunami events triggered by impacts causing craters with a diameter of ~30 km (Rodriguez, et al., 2016). The two tsunamis proposed are thought to have been sediment rich and have originated from a late Hesperian ocean (Rodriguez, et al., 2016). This ocean may have corresponded to the Amazonian ocean discussed previously, as the deltas used for this ocean incidence are as old as 1.8 Ga and the absolute creation or destruction dates of each ocean have not been discussed. The two tsunamis discussed are thought to have been of slightly different sizes, with the younger tsunami deposit being mostly formed of water-ice, which would be consistent with the suggestion from Parker, et al., that an ocean may have been ice-covered (Rodriguez, et al., 2016; Parker, et al., 1989). As each tsunami resurfaced the coastline, this may be an alternative explanation as to why there are deltas at a multitude of elevations, as they may have formed as the water level settled following each tsunami.

Even when discussing multiple incidences of a northern ocean, there will naturally be some variation in the elevation of the deltas created by the ocean. An ocean will not just appear at its final elevation, or disappear instantly, and therefore there will have been a period of change over which the ocean level increases or decreases. Deltas formed during these periods will therefore vary from the mean shoreline elevation, whether the ocean has been created by flooding or due to catastrophic events such as tsunamis.

The same logic could in theory be extended to suggest that there was only a single instance of a northern ocean which extended from the late Noachian to the early Amazonian era, and that the variation in elevation of the deltas is caused by changes in the ocean level over time. However, this would require the ocean to be on the surface of Mars for over 3.4 Ga, and if an ocean had been present for this length of time there would likely be more evidence as to its existence. Furthermore, the lack of mid-Hesperian deltas in this study would imply that there was not a northern ocean into which water could feed during at least part of this era, although as mentioned previously this could be a selection effect from the study size. It would be necessary to expand the number of deltas included in the study to determine more conclusively whether there are any mid-Hesperian deltas. However, even with a more expansive study it would only be possible to prove that there were deltas formed in this era, it
would be not be possible to definitively say there were not, as there may have been deltas which had since been resurfaced or eroded.

For the purposes of this discussion, a shoreline has been considered to be a gravitational equipotential, being indicated by a contour on the surface of Mars. Geological indicators of a shoreline (other than the deltas) have not been studied.

### 4.6.3 Discussion

While this deltaic study points to at least one historical northern ocean, it is necessary to look at other aspects of the theory and in particular to compare the results obtained to other studies, especially those that identify an ocean boundary using geological features.

As mentioned in Section 4.6.2, the shorelines discussed in Section 4.6.2 are gravitational equipotentials determined from the elevation of deltas. They have not been studied as geological boundaries like Contact 1 and Contact 2 as discussed by Parker, et al., which were derived from surface features and are approximately parallel to the southern boundary of the northern plains (Parker, et al., 1989). It was later found that Contact 1 as proposed by Parker, et al., exceeds the vertical displacement that is thought to be possible for a shoreline, having 11 km in variation (Head III, et al., 1999). Contact 2, on the other hand, was found to approximately follow an equipotential line, having a variation of 4.7 km (Head III, et al., 1999). This contact is at a much lower elevation than the shorelines discussed herein, having a mean elevation of -3760 m (with an error of +/- 560 m) (Head III, et al., 1999).

Parker, et al. (1993) found that geological landforms suggest at least two instances of a northern ocean, with the latest potentially being as recent as the Early Amazonian era, which is consistent with the results in this study. However the oceans discussed in Parker, et al., relate to Contact 1 and Contact 2 discussed above, which do not correspond to the ocean elevations discussed herein. These contacts are supported by gradational boundaries, which are identified as a sharp albedo contact which have darker plains surfaces than upland surfaces, and interior plains boundaries which are expressed as a "sharply defined, smooth, lobate or arcuate contact with its concave segments tending to face the plains interior" (Parker, et al., 1993). These two boundary types were tracked along the locations of Contact 1 and Contact 2, and form the basis of
the identification of these shorelines, rather than from aqueous calculations as carried out herein (Parker, et al., 1993).

The variation in the elevation of Contact 1 and Contact 2 has been said to be due to post-formation movement of surface materials and vertical movement of the surface (Head III, et al., 1999). In addition, true polar wander has been said to explain the elevation deviations in potential shorelines such as those identified by Parker, et al. (Perron, et al., 2007). It has been proposed that true polar wander causes long-wavelength variation in the elevation of the shoreline, and that due to this Contact 2 may not be the same at present as it was when the ocean existed (Perron, et al., 2007).

Furthermore, it is suggested in Parker, et al., that if catastrophic floods had taken place towards the northern ocean, depending on the size of the ocean in place at that time there may have been significant changes in sea level due to the large size of the outflow channels (particularly around Chryse Planitia) and the volume of water they could carry (Parker, et al., 1993). This would therefore cause sedimentary features to be created at a number of different elevations, creating the variation seen herein.

This study has assumed that the topography of Mars today is representative of how it was when the sedimentary features were formed. However, the studies discussed above suggest that finding a past shoreline may not be as simple as looking for an equipotential level in the present surface, particularly with more ancient shorelines where factors such as true polar wander will have taken effect over a much longer period of time. However, younger instances of a northern ocean could have removed evidence of previous ocean incidences (Parker, et al., 1993), which supports the idea that some evidence for the smaller, older ocean may have been destroyed by the younger, larger ocean, if the two ocean instances discussed in Section 4.6.2 existed.

Section 4.6.2 proposed a number of different ocean elevations based on subsets of the delta sample used. These are summarised in Table 3, and there is a large variation between the five elevations. The largest ocean is 173% of the volume of the smallest ocean, with the two extreme values being the oceans determined by the delta age. The Amazonian ocean is the largest ocean, and while it is within ranges discussed in other papers (e.g. (Carr & Head III, 2003)) it may be unlikely to have such a large ocean so late in Martian history.
There are few Amazonian valleys on the Martian surface and those that are found tend
to be localised and found on steep slopes, and are thought to have only been able to
form under specific local conditions (Carr, 1999). This may imply that there was not
the widespread availability or movement of water in the Amazonian period to support
this ocean. By contrast, the existence of a Noachian ocean is more strongly supported
by valley formation on the surface. Most of the Martian valley networks are Noachian
or Hesperian in age, and it is thought that valley formation was most effective at this
time (Carr, 1999).

However, studies of the northern Martian plains using MARSIS on Mars Express have
found a low dielectric constant in the surface, which they say is consistent with wide-
spread deposition of aqueous sediments or ice that they believe is linked to a late-
Hesperian northern ocean (Mouginot, et al., 2012). They suggest that the ocean may
have either sublimated into the atmosphere or frozen and been preserved underground
(Mouginot, et al., 2012). As MARSIS is capable of measuring to depths of around 100
m due to the radar reflection process, the low dielectric constant measured could
indicate that ice reservoirs are present at a great depth below the surface, and could
explain the fate of the ocean (Mouginot, et al., 2012).

Table 3: Summary of proposed ocean elevations and volumes, together with the sample type and sample size.

<table>
<thead>
<tr>
<th>Elevation (+/- 1 Standard Deviation) (m)</th>
<th>Volume (km³)</th>
<th>GEL (m)</th>
<th>Reasoning</th>
<th>Number of deltas in sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2616 (+/- 410)</td>
<td>1.06E+08</td>
<td>468</td>
<td>Deltas without a localised closed basin</td>
<td>12</td>
</tr>
<tr>
<td>-2188 (+/- 1208)</td>
<td>1.40E+08</td>
<td>616</td>
<td>All deltas in sample</td>
<td>35</td>
</tr>
<tr>
<td>-2451 (+/- 642)</td>
<td>1.19E+08</td>
<td>523</td>
<td>Circum-Chryse deltas</td>
<td>14</td>
</tr>
<tr>
<td>-2905 (+/- 195)</td>
<td>8.55E+07</td>
<td>375</td>
<td>Noachian/Hesperian-age deltas</td>
<td>4</td>
</tr>
<tr>
<td>-2100 (+/- 346)</td>
<td>1.47E+08</td>
<td>648</td>
<td>Amazonian-age deltas</td>
<td>3</td>
</tr>
</tbody>
</table>

All of the ocean volumes determined are within the same range as previous discussions,
and all are below the 3x10⁶ km³ limit that Carr and Head (2003) found to be
unsupported. It is estimated that the Martian megaregolith could have held 8x10⁷ -
20x10⁷ km³ of water which may have been released as flooding, with channels on the
surface capable of carrying as much as 4x10⁹ km³ s⁻¹ of material, so it would be possible
for oceans of this size to have been generated (Carr & Head III, 2003). The key
question is then where did all of the water go, especially for the Amazonian-age ocean
which would require significant water movement in a relatively short time.
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It is thought that $7.25 \times 10^6 \text{ km}^3$ (or 31 m GEL) could have been lost to space since the end of the Noachian era, which would leave between 340 m and 620 m to be removed elsewhere (Carr & Head III, 2003; Kass, 2001). The polar ice caps are thought to hold up to $3.4 \times 10^6 \text{ km}^3$ (or 15 m GEL) between them, but the volume of the northern polar cap has not been included in these ocean calculations as it has been assumed to be a land mass (Carr & Head III, 2003). The megaregolith is said to be able to hold up to $2 \times 10^8 \text{ km}^3$ of water if it has 50% surface porosity or $7.8 \times 10^7 \text{ km}^3$ at 20% porosity, which may have been released in the form of floods earlier in Martian history but would also be available to absorb water from the oceans (Carr & Head III, 2003; Clifford, 1993). This would therefore absorb between 343 m and 878 m GEL of water, which would more than account for all of the ocean depths discussed herein. If the Martian regolith holds such a significant volume of water, it is not inconceivable that an ocean could have historically existed on the northern plains of Mars.

In addition, the MAVEN mission has found that water loss from Mars may have been more variable over time than previously thought, based on measurements of hydrogen loss from the upper atmosphere (Zubritsky, 2016). Water vapour in the lower atmosphere can be broken up into hydrogen and water, and then hydrogen is lost from the upper atmosphere. MAVEN has found that this hydrogen loss is an "episodic flow", thought to be seasonal and have additional bursts (Zubritsky, 2016). The rate of hydrogen loss is expected to be controlled in part by the availability of water vapour at lower altitudes, and a historical ocean would have significantly increased the availability of water (Zubritsky, 2016). As hydrogen loss is no longer thought to be a slow, steady process, there may have been higher losses to the atmosphere than previously thought, accounting for an additional destination for the historical ocean.

Although there are reasonable assumptions as to where the water from an ocean could have gone, it is necessary to investigate whether the Martian atmosphere would have been thick enough to sustain standing bodies of water. Modelling of a strong greenhouse effect on Mars has suggested that there may have been up to 1 bar of CO$_2$ left in the atmosphere at the end of the Late Heavy Bombardment (i.e. in the Noachian era), with temperatures significantly above freezing in this period (Carr, 1999). While this may support the existence of a Noachian/Hesperian ocean, the models used in Carr (1999) do not study the Amazonian era, and therefore the evolution to the Amazonian period in these models is not known. However, a study of late-Amazonian glaciation on
Mars using global climate models found that an atmosphere containing a high dust content would have a higher water holding capacity, allowing topographically-controlled precipitation events and surface ice formation (Madeleine, et al., 2009). There may therefore have been sufficient atmosphere to support both the late-Noachian ocean and the Amazonian ocean, although the atmosphere may have had different compositions due to global changes between these eras.

Furthermore, a study of shallow valleys in equatorial and mid-latitudes, and in particular in Arabia Terra, has found that they are consistent with an active hydrological system at the Hesperian-Amazonian boundary (Wilson, et al., 2016). They found that modelling of paleolakes implies a "considerable depth" of water at this time, which may have been consistent with the Amazonian ocean measured from delta locations (Wilson, et al., 2016).

An additional factor to consider is how an oceanic body could have been replenished during its existence. It has been discussed that the volume of water that could be held within the regolith would be sufficient to support an ocean, but such an ocean would need to be replenished over time. Precipitation is one option for how this could happen, but it has also been suggested that aquifers can be filled using hydrothermal convection, which could then be released into oceans (Squyres & Kasting, 1994). Magmatic activity and impact heating could have been used to drive the convection, keeping aquifers supplied with water for long periods of time (Squyres & Kasting, 1994). This does not preclude the existence of precipitation, and instead may provide an additional water source for the ocean. However, there is not strong evidence for precipitation on early Mars in the time of the Noachian ocean, as the morphology of valley systems does not require it and can actually argue against it (Squyres & Kasting, 1994). This is because valley systems formed from precipitation are space-filling, which has not been observed on Mars (Squyres & Kasting, 1994).

The variation in ocean depth seen in Table 3 shows the difficulty in finding a single elevation at which an ocean could have existed. While this may be in part caused by selection effects of the small sample size of deltas used, it is also due to the improbability of the ocean having had a single elevation. Whatever the size of ocean that may have existed, it will have to have formed from somewhere and been removed to somewhere. Depending on the time period over which this happened, it is likely that aqueous features like deltas will have formed at a variety of elevations as the ocean
grew or receded. Using all of the deltas found on the surface in a single calculation therefore does not seem a reasonable method of estimating the ocean depth and volume, no matter what sample size is used.

Splitting the deltas first according to their basin type (whether they appear to be in a closed or open basin) and then secondly by their age seems to be the most logical way of sizing a past northern ocean. While this reduces the number of samples in any selection, it then accounts to some extent for variation in the ocean elevation over time and for multiple instances of a northern ocean.

Assuming that there were two ocean instances, one in the late-Noachian/early-Hesperian and a later one in the Amazonian as discussed herein, the three landing sites proposed for ExoMars all overlap with the oceanic region to some extent. Oxia Planum is the lowest elevation site, and therefore at least part of the landing region is within the boundaries for both ocean incidences. Mawrth Vallis sits between the two shorelines, with slight overlap into the lower ocean region depending on the azimuth selected. Aram Dorsum, however, sits at a higher elevation. It has regions which overlap with the past Amazonian ocean, but no overlap with the lower Noachian/Hesperian ocean. On the basis of these results, the landing site at Oxia Planum would have been exposed to the most oceanic activity, making it a logical landing site as the ExoMars mission aims to study water and look for signs of past or present life.
5 CONCLUSIONS

The ExoMars rover will launch in 2020 and will land in one of three sites on Mars: Oxia Planum, Aram Dorsum or Mawrth Vallis. However, before it launches it is necessary to validate the three sites and select a final site. The initial validation process for Oxia Planum has indicated that aeolian features may cause traversability issues for the rover. Mapping of the three landing sites has shown that Oxia Planum has 4.9 +/- 5.9 % TAR coverage, Aram Dorsum has 2.72 +/- 2.75 % TAR coverage and Mawrth Vallis has 16.9 +/- 7.9 % TAR coverage. Both remote sensing and ground truths from Mars Science Laboratory's Curiosity rover have been used to provide initial guidelines for testing the rover, with aeolian features that have a bedform length of 2-3 m thought to be the most dangerous for the rover as they are ubiquitous across large portions of Oxia Planum and would cause a predicted sinkage of 39% of the wheel diameter. Further testing of the rover will determine the aeolian feature size it is capable of crossing, which combined with the mapping of the landing sites will inform the landing site selection.

As part of the characterisation of the landing sites for the ExoMars rover, a sedimentological feature in Oxia Planum has been studied. Comparisons of the texture and morphology of the feature with a list of 34 known deltas and 12 known alluvial fans has found that there are few large-scale morphological features which can be used to identify a feature categorically as either a delta or an alluvial fan. However, studying the surface textures and thermal inertia has shown that deltas have a lower thermal inertia than their surroundings, which decreases toward the distal end of a deposit, and that they show at least some form of clinoform around the edges. For many of the deposits examined, the clinoform was small and heavily eroded, but it was still identifiable in HiRISE images even if it was not clear from a profile through the feature. The feature in Oxia Planum was found to be particularly similar to the deltas in Hypanis and Sabrina. It was determined that the feature is likely to be deltaic, although it is thought to be ancient and therefore heavily eroded which is why it is difficult to definitively classify it.

Study of the context of the delta in Oxia Planum indicated that it may once have fed into a northern ocean, as the closed basin formed by a contour at the apex elevation surrounds the northern plains of Mars. By studying all of the deltas included herein, it
has been possible to determine a number of potential elevations for a historic northern ocean by assuming the ocean formed an equipotential shoreline. The ocean elevations calculated vary by 805 m in elevation, depending on the selection criteria used to identify the subset of features used.

Trying to fit a single elevation to all of the features would seem to be a naive method, as in order for an ocean to have existed in the past it must have appeared from somewhere and disappeared to somewhere, so there will have been variation in the elevation. Deltas will therefore have formed at different elevations as the ocean level varied. By limiting to only deltas which appear to open into the northern plains, the range of delta elevations reduces significantly, forming an equipotential at -2616 (+/- 410) m. However, if these deltas are further divided according to their age (where known), they form two clusters: one of late-Noachian/early-Hesperian age features at -2905 m, and one of Amazonian age features at -2100 m. The existence of two oceans is consistent with previous studies, although the elevations of the oceans calculated by different studies vary. The elevations calculated herein use small sample sizes of only three or four deltas per ocean, and therefore the applicability of the elevations calculated is limited. It would be necessary to extend the sample size of deltas in order to confirm the presence of these two oceans and to refine their elevations. However, it may be that increasing the sample size would introduce further age subsets for the ocean, indicating either a slow elevation change for one of the ocean instances or possibly additional instances of the ocean.

Sending the ExoMars rover to a deltaic or oceanic landing site would provide the potential for interesting scientific investigations as the rover would be able to study a possible ocean floor in-situ. All three of the landing sites overlap with the ocean shoreline or floor for the higher elevation Amazonian ocean, with Oxia Planum also overlapping the lower elevation Noachian/Hesperian ocean floor. Investigating the possibility of an ocean fits within the scientific goals of ExoMars, which include the investigation of water in the surface and subsurface. As a historic ocean may have been absorbed into the Martian regolith, subsurface investigations in a historic ocean bed may be able to confirm this. Furthermore, regions of extensive aqueous activity are thought to be likely to have been home to life, and therefore an oceanic site would allow for investigations into past or present life. If ExoMars could help to prove the
existence of an ancient northern ocean, there would be significant implications for the evolution of the Martian surface and a past hydrological cycle on Mars.

In order to maximise the scientific return of the ExoMars mission, it is necessary to determine the priorities of the mission, and to establish a ranking of the different mission aspects. This will aid in decision making throughout the mission planning process, from landing site selection to planning rover traverses, as scientific and engineering limitations and requirements may conflict with one another. My recommendation would be to prioritise rover mobility over the expected benefits of a particular landing site or region. For example, while the deltaic region of Oxia Planum is thought to be particularly interesting as it is a historical aqueous system, the comparatively high TAR density makes it a more dangerous region for the rover. If the rover were to land successfully and then be incapable of moving, it would not be possible to determine whether the measurements taken on a single spot are representative of the region. I believe it would be better to be able to move and corroborate results in different locations, even if the materials in a location are less appropriate for certain instruments, than to be able to take a series of measurements from a single spot and not be able to determine their context.

5.1 Future Work

The work presented here concerns two main aspects related to the ExoMars rover mission that is due to launch in 2020: the characterisation of the landing sites, in particular the aeolian hazards; and the deltaic feature in Oxia Planum, which would be a key scientific target if the rover were to land at that site. The study of the deltaic feature has led to an investigation as to whether there was a northern Martian ocean in the past, and at which elevation it may have existed. Landing the ExoMars rover within the boundaries of the historical ocean would allow for in-situ investigation of the ocean floor, and therefore would provide additional support for selecting a landing site within the region.

5.1.1 Aeolian Hazards

The impact of aeolian hazards on the ExoMars rover has been investigated, with comparisons to the Mars Science Laboratory's Curiosity Rover being used to predict the impact of these features on the ExoMars rover. However, the extent of this study has been limited as it has only considered published measurements of ripple sizes and the
corresponding sinkages incurred. To obtain a more definite idea of the impact of ripples on the rover mobility, it would be necessary to extend this study throughout the MSL Curiosity data sets, and if possible through the Opportunity data sets. The three rovers have fundamentally different designs, including different masses and wheel dimensions, so comparisons cannot be taken to definitively describe the potential outcomes, but they would provide a guideline. This would need to be carried out in combination with the testing being carried out on the rover to truly understand how different ripple sizes, orientations and morphologies could impact on the rover.

Furthermore, while aeolian mapping has been carried out over a significant proportion of the landing sites, they have not been fully mapped and therefore completing the aeolian mapping of the sites would be necessary. It would also be helpful to extend this mapping to label ripples according to their size rather than just density, as this would help to create exclusion zones based on the results of rover testing.

5.1.2 Oxia Planum Feature

The feature in Oxia Planum has been identified as a delta based on this study. However, not all aspects of the deposit have been studied, with the focus having been primarily on the large scale morphology (location, elevation, basin type and profile) and the surface texture. The up-stream network has not been investigated, nor have details such as the depositional history or stratigraphy of the deposits. To confirm the deltaic nature of the deposit, more aspects of its geology such as the mineralogy and stratigraphy would therefore need to be investigated.

In addition, the number of comparison deltas and alluvial fans included could be expanded. This may allow trends within each feature classification to be exposed that had not been identified so far.

5.1.3 Northern Ocean

A proposed northern ocean has been calculated using multiple subsets of the delta data collected. From the results obtained it would appear to be most appropriate to calculate ocean elevations according to delta age, as any ocean would have changed elevation over time and an ocean may have had multiple occurrences. However, the small number of oceanic features for which there is a published age has limited the scope of the study, with only four data points for a Noachian/Hesperian ocean and three for an Amazonian ocean. It would therefore be essential to age more of the deposits in order
to increase the sample size available. One method of doing this would be to count
craters over the deposits, but these results may be limited by the deposit size as this
affects the ability to model the surface age.
## APPENDIX 1

Table 4: Catalogue of HiRISE images and requests. Any images without a request ID existed before this project. Any requests without image IDs have not yet had images captured. Latitude and longitude correspond to the centre of each image as specified in the HiReport database (The University of Arizona, 2016).

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### APPENDIX 2

Table 5: List of alluvial fans and deltas used in this work. Features are named where known, and are assigned a letter where the name could not easily be identified. Thanks to Joel Davis for the ArcGIS shapefiles that allowed a number of the features in this list to be identified. Sources listed are: [1] (Kraal, et al., 2008) [2] (Palucis, et al., 2014)[3] (Di Achille & Hynek, 2010) [4] (Hauber, et al., 2013a) [5] (Hauber, et al., 2013b) [6] (Pondrelli, et al., 2011) [7] (Schon, et al., 2012) [8] (Quantin, et al., 2015b).

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