Modelling the Martian Sub-surface: Trial Investigations Using Ground Penetrating Radar Data from the Martian North Pole

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ABSTRACT

Recent advances in planetary exploration instruments have returned unparallel data probing underneath the dusty surface of Mars to look for evidence of liquid water and Martian life. The SHARAD ground penetrating radar provides sub-surface imaging up to 1000m in depth and when combined with the extensive HiRISE data, allows unprecedented interpretation and analysis of strata, structure and topographic features. In this investigation, we look at a profile across the north ice cap and discover a network of compressional and extensional faulting in the upper 300m clearly demarked by the stratum present. Deeper imaging quality is poor but palaeo-topography infill is seen at 500 – 800m depth.

This paper presents an introduction to the SHARAD instrument, evaluates the prosperous future uses for sub-surface imaging from Mars and how our understanding of the red planet has and will change due to its obvention.

INTRODUCTION

As our closest planetary neighbour, Mars has long been regarded as a promising exploration prospect for geologic processes, water and life akin to what is found on Earth. The Mariner flybys and orbiters of the 1960's returned grainy images of a "large, moon like body with a thin atmosphere, no life and no surface characteristics that faintly resemble those seen on Earth" (Bruce Murray, Mariner 4 analyst; 1965). More recent exploration by the Mars Express Orbiter, Mars Reconnaissance Orbiter and surface landers such as Pathfinder, Spirit and Opportunity have greatly increased the quantity and quality of data we hold on the red planet.

A primary focus of modern Mars exploration is the research of underground water along with structural and geochemical analysis of the sub-surface. Knowledge of water, ice, structure and their relative distribution is, and will continue to have, a colossal impact on our understanding of the geologic, hydrologic and atmospheric evolution of Mars. To that extent, a geophysical approach has been adopted to analyse and image the sub-surface structure across the planet. In the last 8 years, 2 orbiting craft (Mars Reconnaissance Orbiter and the Mars Express) have been launched carrying ground penetrating radar (GPR) instruments which, when combined with high resolution photography and thermal emission/chemical spectral analysis provide unprecedented detail of the shallow Martian crust. The radar data has the potential to revolutionize our understanding of Mars in the same way that seismic exploration has transform our understanding of the sub-surface earth since the breakthrough in the 1920's.

BACKGROUND TO SHARAD

The SHARAD (Shallow Ground Penetrating Radar) instrument onboard the Mars Reconnaissance Orbiter is a wide-band radar sounder operating at peak frequencies of 15 – 25 MHz. This provides a vertical resolution limit as low as 10m with horizontal resolution between 300 – 1000m along track. Operational processes bear resemblance to modern seismic surveying techniques – an ultra high frequency source penetrates the subsurface resulting in differing amplitude reflections from primarily density contrasts within the strata. Pulses lasting 85 µseconds, are repeated at a frequency up to 775Hz to increase the signal/noise ratio (Alberti et al, 2007). Ultimately, SHARAD has a maximum penetration depth of ~1000m and is primarily used for modelling of the polar ice regions. This is in contrast with the MARSIS instrument onboard the Mars Express operating at lower frequencies but resolving depths up to 5000m with a maximum vertical resolution of 50m, used to image deeper into the rocky crust below the ice.

The data received from SHARAD varies in quality and is largely dependent on subsurface structure and atmospheric conditions at the time of imaging. For example; a strong density contrast near to the surface will have a high reflection coefficient and result in poor imaging of the lower strata. Equally ionosphere plasma in the outer Martian atmosphere removes all signals below ~3 MHz and can add unwanted noise to the radar image. The line presented in this report is taken from the north polar region above 80^{o} latitude as shown in Figure 1 below.

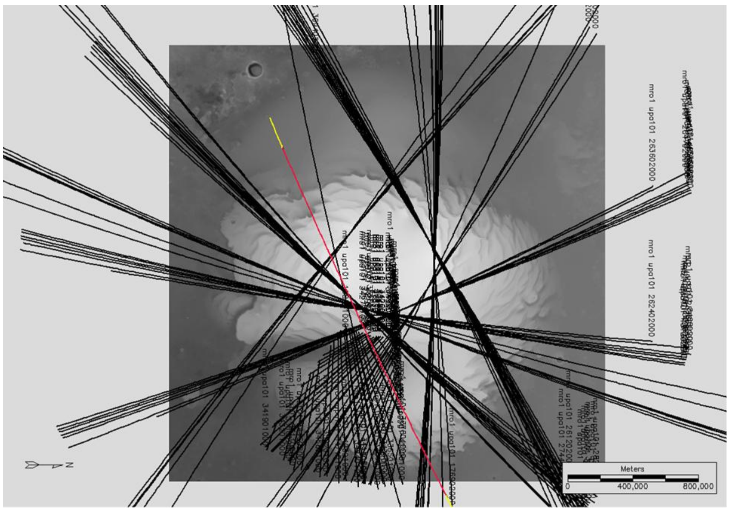

Figure 1: Martian North Polar Region showing array of SHARAD paths. Trace in red is line used in this study. The white region approximates the extent of the icecap – the focus of this research. Reproduced from SHARAD data base map courtesy of Prof J. Holt, University of Texas.

It is important to remember that, although representing a vast technological advance in space exploration, GPR is still in its infancy, much like pre-war seismic exploration. To maximize its potential, it must be used in juxtaposition with HiRISE imagery, CRISM spectral mapping and THEMIS emission analysis. In this preliminary research, I have used HiRISE data to support interpretations from the GPR section and scrutinize smaller scale structures beyond the resolution of the sounder.

QUALITATIVE DATA ANALYSIS

Figure 2 overleaf shows the pre-migration GPR run used in this research. The colour is independent of lithology and represents the relative amplitude of the reflection off a density or velocity contrast within the sub-surface. 2B shows the data after a band-pass filter to remove some of the unwanted noise. Correlating the horizons provides information on the strata and structure present and later, I have drawn some initial conclusions to the geological history of the north pole.

Due to the large scale of the data involved, only broad and regionally significant structures can be resolved but clear faulting is seen across the profile indicating separate stages of compression and extension. Thrust faults, seen dipping predominantly to the north-west, are cross cut by tensile normal faults dipping south east indicating the extension post-dates the compression. A broad imbricate thrust system some 500km north-west of Chasm Boreale (see Figure 2D) has been rotated vertically by a half graben complex formed by a shallow normal fault. The imbricate system formed due to lateral compressional forces acting on the glacial strata producing planes of failure linked by a basal fault.

Some mild folding is seen in the best resolved, upper 300m of strata but constraining geometry and orientation is difficult in a 2 dimensional analysis. A migration analysis would help constrain these. Deeper into the profile, the imaging quality decreases but sub-horizontal sediments are seen to fill in the palaeo-topography highlighted in maroon in figures 2C and 2D. The depth to the bedrock is ~1000m +/- 200m and only the upper contact is resolved using SHARAD giving an uneven palaeo-topographic surface pitted by impact craters ahead of the widespread glaciation.

Unconformities are seen atleast twice in the geologic profile. A major unconforming relationship is seen between the bedrock and glacial deposits and a second near the surface beneath recent, possibly seasonal, ice formations.

CONCLUSIONS FROM TRIAL INVESTIGATIONS

From this brief investigation, we can draw basic conclusions on the geologic history of the region and speculate on processes active at the time of deposition. Smaller structures and layering is very much open to interpretation in GPR profiles but HiRISE images combine to give a more complete model with unparalleled levels of clarity.

Imaging the rock/ice interface is at the limit of SHARAD penetration but the upper bedrock contact is clearly defined with sedimentary strata infilling the palaeo-topography at depths of ~800m. The finest imaging is achieved in the upper 300m of sediments and this is where most of the interpretations are focused.

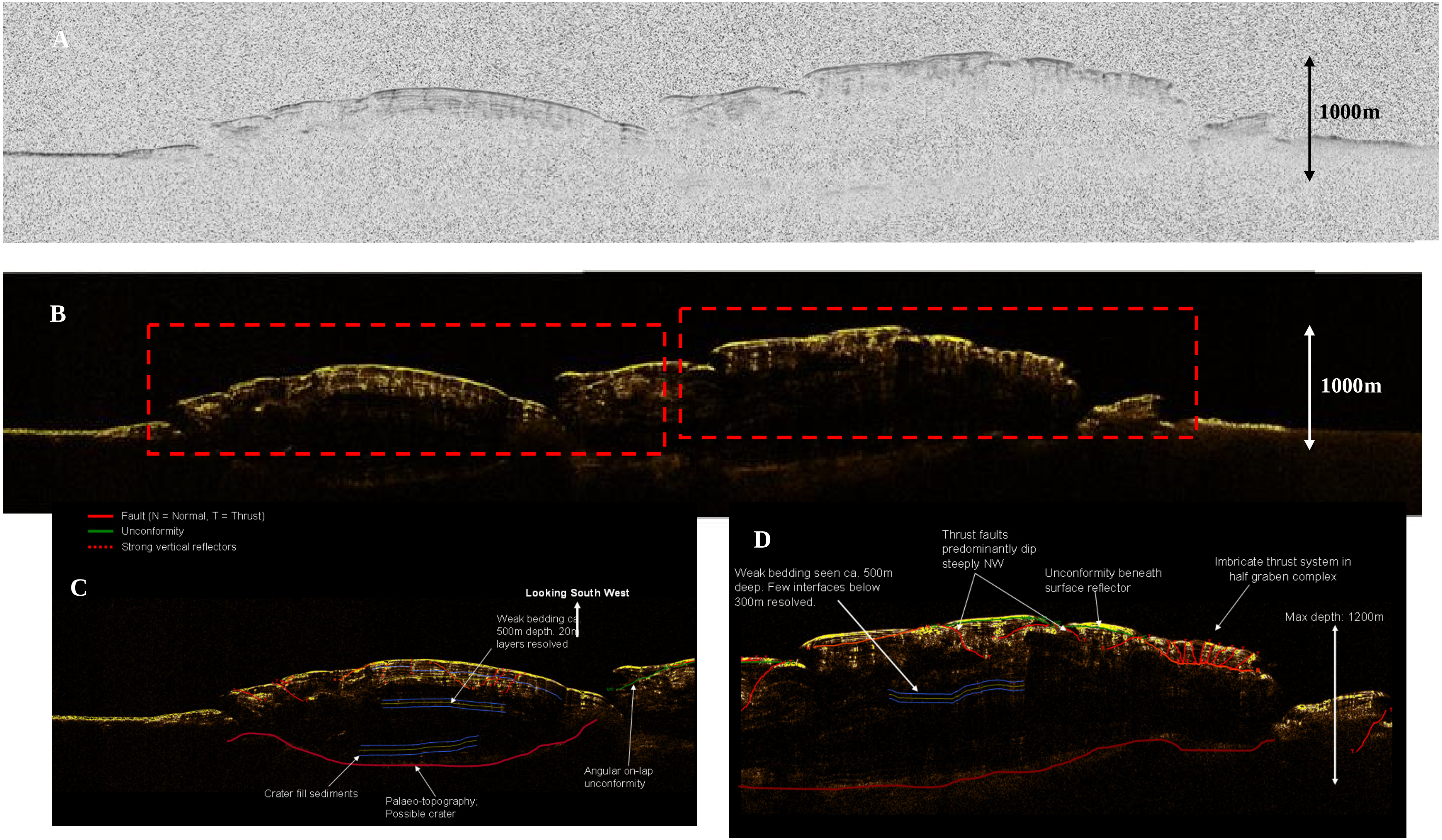

Figure 2: SHARAD GPR image from Martian North Pole. Vertical scale has been exaggerated in both A and B to aid interpretations. Approximate width – 1000km, maximum depth – 1km. *A*: Unprocessed radar data approximately centred on Chasm Boreale. *B*: Black – brown – yellow amplitude contrast spectrum with single stage band-pass filter. Yellow represents positive amplitude reflections, whereas brown is negative. *C and D*: Annotated sections showing structure and correlated horizons.

We can select atleast 2 stages of post glaciation brittle deformation within the upper 250m of strata – firstly compressional, thrust faulting followed by intersecting extensional tectonics. Half graben complexes cause rotation of strata and preceding structure in the polar margins. Some of the faults are seen to cut close to the surface but constraining absolute ages is beyond the scope of this initial study.

The presence of unconforming relationships is hardly surprising given the clear evidence of tectonic and glacial activity. I would predict the itinerant ice sheet created the near-surface unconformity showed in Figure 2D and may also be responsible for the shallow faulting seen in the same area. Gravitational relaxation of the crust as the core cool and/or ice regresses could cause fractures to form. The main problem here is that ice is comparatively ductile and can 'flow' over a relatively short timescale when compared to typical rocks. Ice also would probably not have enough tensile strength to fracture on a single plane but instead over a broad zone. The fact that clear faults are seen implies that there is a significant proportion of dust grains within the layering – possibly up to 20%.

DATA POTENTIAL AND FURTHER WORK

The quantity of SHARAD data available for analysis and evaluation is vast and the understanding potential for the Martian sub-surface is virtually unlimited. Using SHARAD along with MARSIS, HiRISE, CRISM and THEMIS, it is surely only a matter of time before detailed 3-dimensional models of potential water bearing regions enter the scientific journals.

We can now study and appraise theories for liquid water and life on the planet and potential reasons for the decline of the Martian atmosphere. GPR and CRISM can be used to image potential carbonates – the theoretical but, as of yet unproven, sink for carbon dioxide. Once we have carefully constrained the geologic processes and events that have shaped the planet, continuous potential exists to date, correlate and catalogue the history to more accurately predict periods when life could have existed and whether life still remains in some regions thus satisfying the primary initial goal of space exploration.

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