# The tectonic origin of Planum Boreum spiral troughs, Mars

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## 1 Introduction

Planum Boreum, the ice plateau at the north pole of Mars, is composed of $H_2O$ ice with smaller percentage of dust and seasonal $CO_2$ frost. At the regional scale, its surface shows complex physiography characterized by curvilinear features with arcuate undulations disposed in spiral pattern approximately 10 - 300 km long. These are the spiral troughs whose equator-facing slopes show exposed layers, while no layering is observed in their pole-facing slopes [1]. The ground penetrating radars MARSIS (Mars Express) and SHARAD (MRO) acquired profiles that revealed the internal ice layering and the depth of Planum Boreum structures, including the spiral troughs. These cut and offset the internal ice layering from the surface down more than 1000 m of depth with a gentle slope lower than 5° towards the margin [2]. Buried troughs were found in radar profiles, in particular in the lobate extension of the plateau called Gemina Lingula.

Spiral through formation is still an open issue, and several interpretations have been proposed regarding exogenous and/or endogenous processes that affect Planum Boreum. Many suggestions attribute the spiral throughs to erosional features produced by eolian processes. Their development is influenced by the action of the katabatic winds that lead preferential erosion/ablation in the layered equator-facing slopes, followed by deposition/accumulation on the pole-facing slope due to solar ablation [1]. Alternative formation hypotheses support their structural origin, suggesting that they are dynamically induced by internal/basal melting flow [3].

In this contribution, we investigate the stress-related formation of the spiral throughs that show similarities with extensional structures on Earth. Planum Boreum spiral throughs are compared with a terrestrial analog recognized in the Antarctic Ice Sheet (i.e. the glacier feeding the Cook ice shelf) where ice covers the bedrock with approximately 1200 m of thickness and radar data show ice layering and buried structures with geometry comparable to those found in Gemina Lingula. Their formation is the effect of brittle deformation resulting from the internal dynamics and gravitational sliding typical of Earth glaciers. The trough setting, revealed by the SHARAD profiles, relate to low-angle normal faults [4] with compatible listric shape. We infer the presence of dynamic process within the northern ice cap that leads internal large-scale brittle deformation with the consequent trough formation. This is enabled by the presence of possible deep ductile/fluid detachment at depth.

## 2 Data

### PLANUM BOREUM

The depth data used for the investigation of the spiral through derive from the mission Mars Reconnaissance Orbiter (MRO). We investigated radargrams of the SHAllow RADar sounder (SHARAD) [5]. The analysed profile in Gemina Lingula (*on the right*) shows buried troughs at a depth of approximately 250 m.

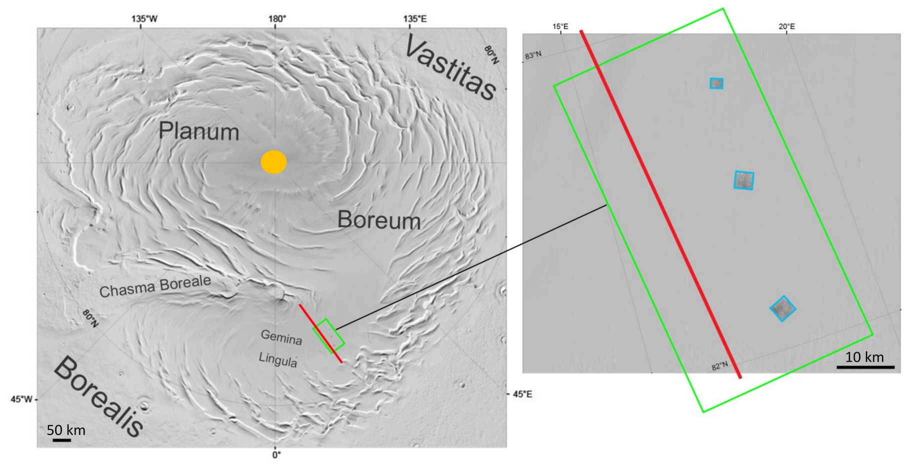
Image data were used to investigate the surface lineaments related to the depth features and derive from the Mars Orbiter Camera (MOC) (*on the left*).

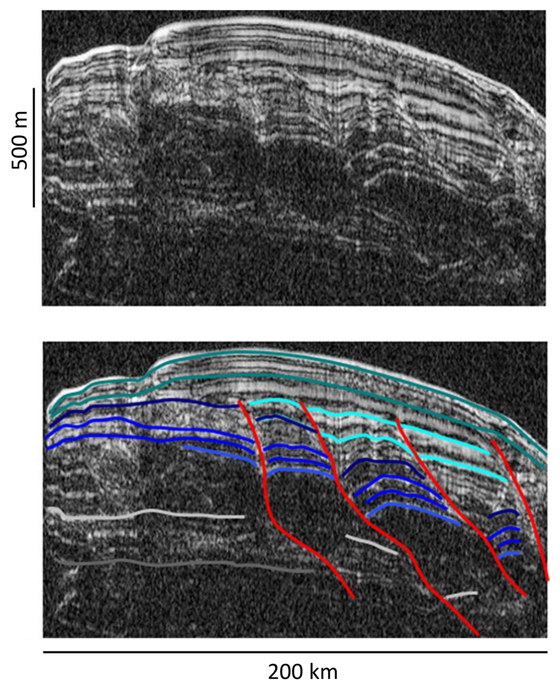
### ANTARCTICA

Antarctic analog data include the radar echo-strength profiles from the IceBridge High-Capability Radar Sounder dataset (HiCARS, [6]) (*right*).

Surface data have been selected from the LANDSAT-8 and Sentinel-2 imagery dataset (*left*).

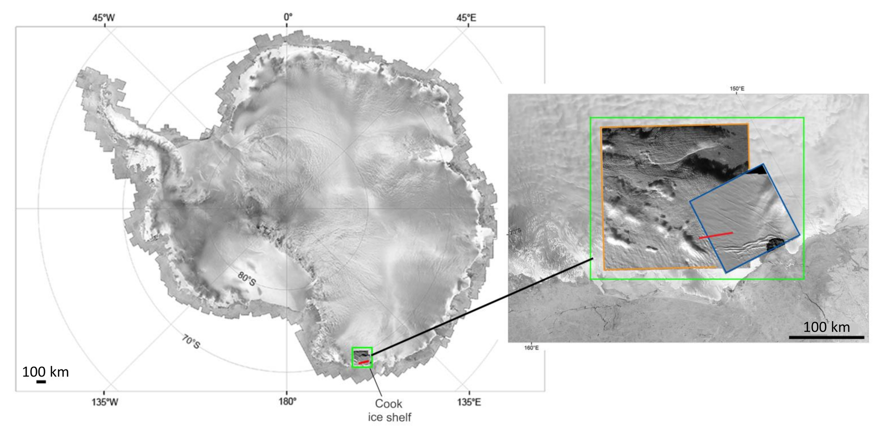
Mars north pole region, shaded relief surface from MOLA. The orange circle shows the north pole location. The red line in Gemina Lingula trace the used SHARAD profile, the green square frames the location of the used MOC images (light blue squares).



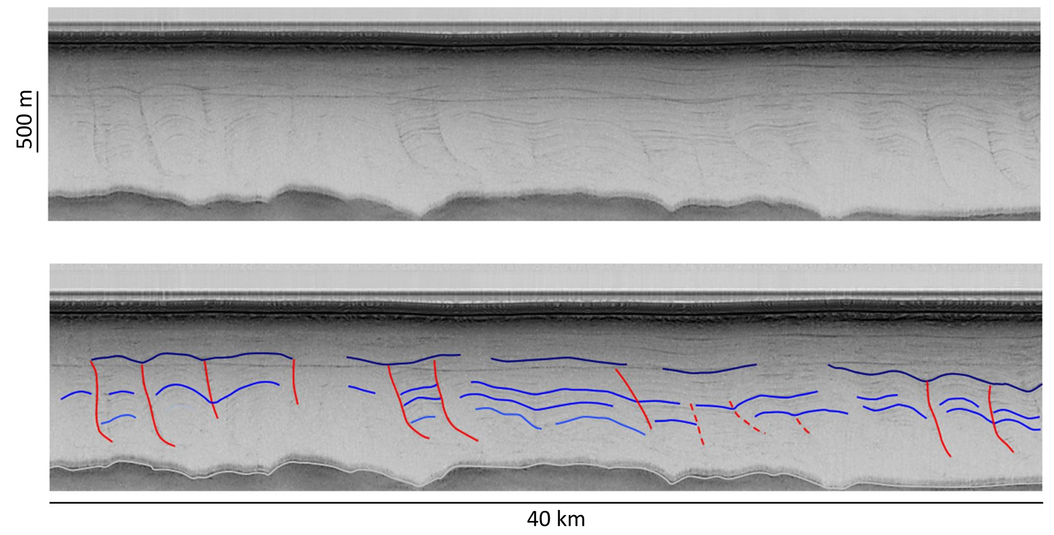




SHARAD observation S_00725402 in Gemina Lingula (vertical exaggeration 90:1).

SHARAD layer picking. The blue, light blue and green lines represent the top and bottom of the main ice reflectors, and the red lines the troughs/faults.




Antarctica analog. The red line in the Cook glacier represents the used HiCARS profile, the green square the location of the Landsat (orange square) and Sentinel (blue square) images.




HiCARS observation ID: IR1HI1B in the glacier of the Cook ice shelf (vertical exaggeration 5:1).

HiCARS layer picking. The blue lines represent the top and bottom of the ice layers and the red lines the blind faults. The dashed red lines represent secondary faint structures.

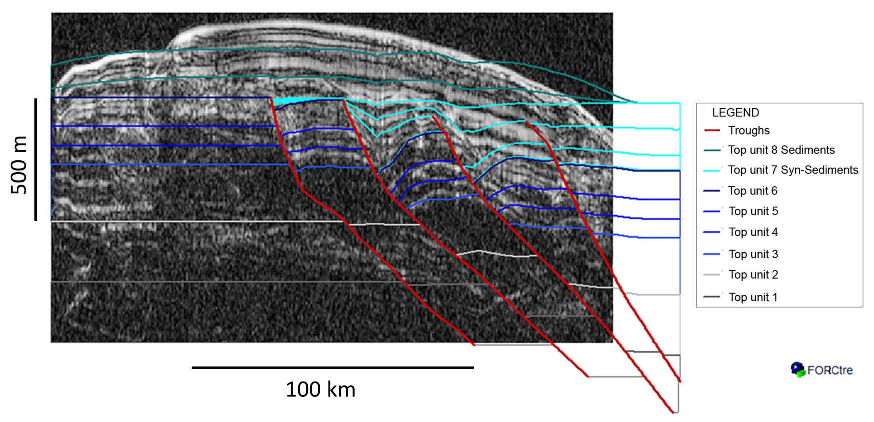
## 3 Numerical Modelling

### *Hybrid Cellular Automata*

We performed numerical modeling by simulating the kinematic evolution of the troughs.

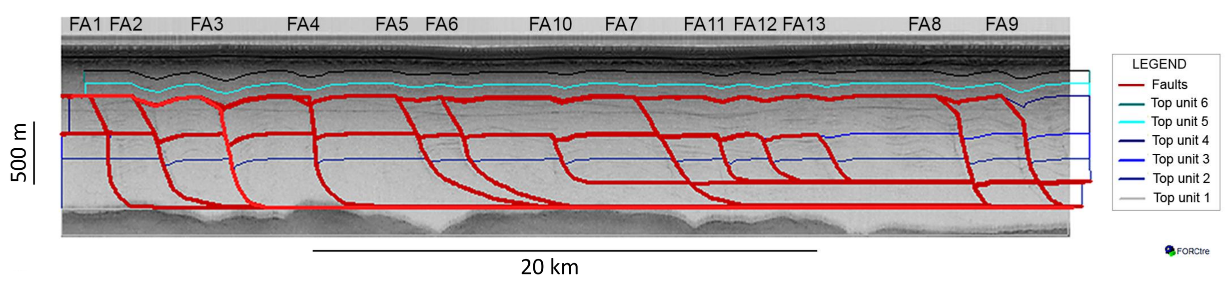
The Hybrid Cellular Automata (HCA)-derived numerical algorithm by means of the FORCtre software allows to replicate the complex evolution of dip-slip geological structures [7].

The simulation was performed on the SHARAD and HiCARS radargrams, that both show buried similar structures. A trial-and-error forward modelling approach was followed and consisted in the careful tuning of the fault geometries and displacements in order to achieve the best fit between the model and the interpreted radargram.



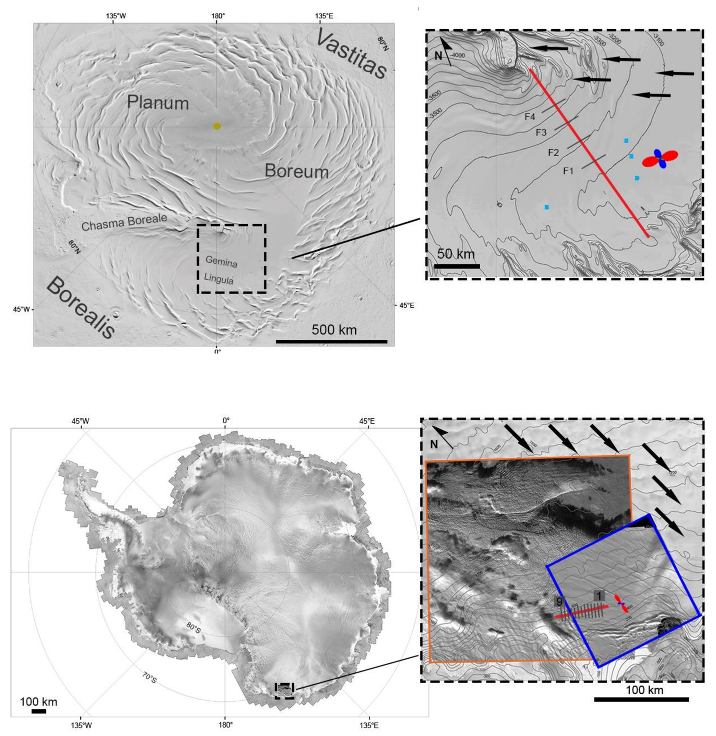

HCA model of the SHARAD profile (in background) where the limits of 8 layers/units (blue and light-blue) and 4 buried throughs (red) are reported.

HCA model of the HiCARS profile (in background) where the limits of 6 layers/units (blue and light-blue) and a total of 13 faults (red) are reported.




## 4 Lineament domain analysis

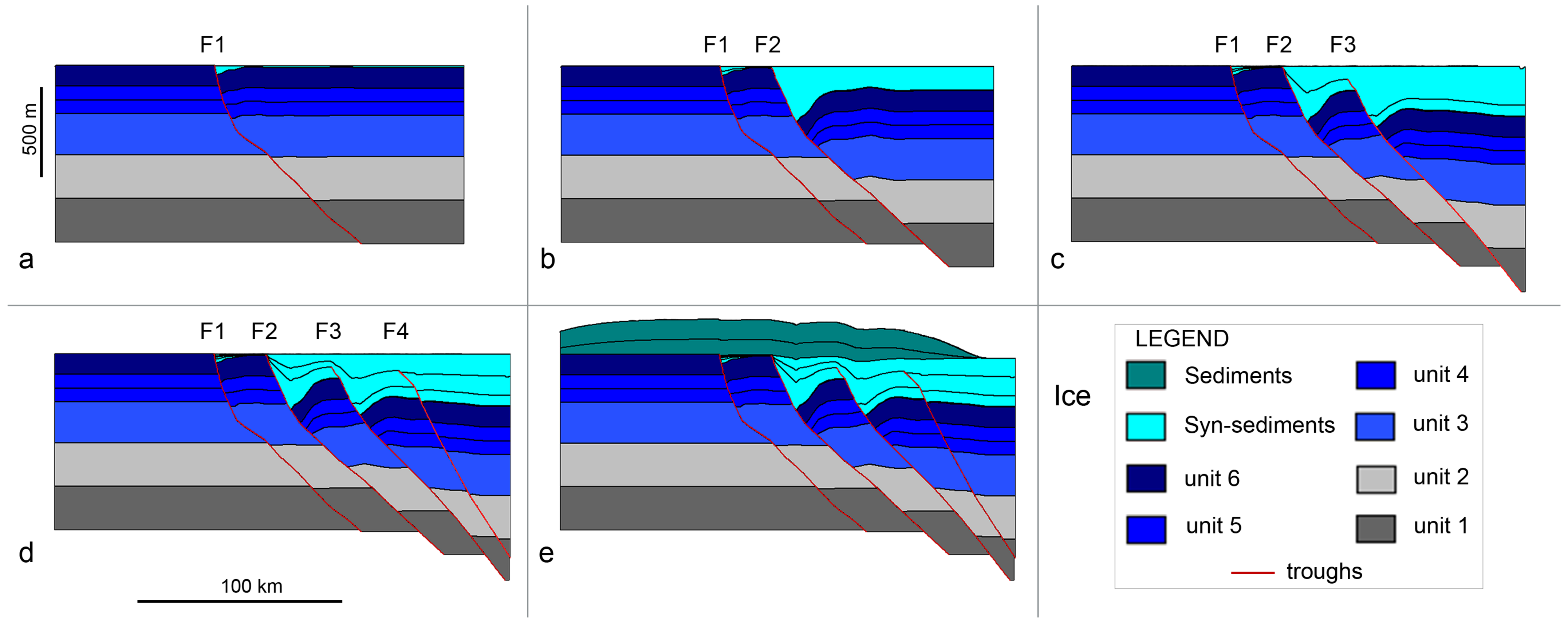
Lineaments represent feature alignments in the topography variation enhanced by preferential erosion directions and induced by upper crustal stresses/kinematic conditions [8]. Their spatial distribution defines lineament clusters that form lineament domains that are organized around preferential orientations and allow to infer the crustal stresses of the planetary upper crust at the regional scale. This analysis was performed in the selected satellite images that follow the tracks of the SHARAD and HiCARS data to investigate the connection between the surface and the depth structural setting. We performed a polymodal Gaussian fit by frequency to infer the azimuthal trends that characterize lineament domains [8]. The recognized lineament domains were compared with the katabatic wind vectors (from both Gemina Lingula and Cook Ice Shelf glacier) to investigate on their eolian versus ice cap dynamic-related origin. The main lineament domain (the red peak of the rose diagram), closely parallel to the wind direction, trace the buried trough orientation of the investigated depth profile. This setting is compatible with the presence of an extensional regime at depth, orthogonal to the main lineament domain.




The red lines depict the track of the radar profiles dissected by black lines that represent the through/fault locations. The black arrows show the katabatic wind vectors [9] [10] and the rose diagrams represent the lineament domains recognized in the images (blue and orange squares).

## 5 Structural evolution of Planum Boreum spiral troughs

HCA evolutionary model of the buried trough section in Gemina Lingula. Gravitational collapse and internal dynamics produce extensional regime that characterizes the activity of listric faults connected at depth with a ductile detachment located deeper than the base of the model. Faults migrate with normal propagation sequence from the oldest fault-1 (F1) to the youngest fault-4 (F4).




Fault (F1 to F4) normal displacements offset the internal ice layering with listric geometry, maintaining a gentle slope. Fault activity bends the hanging-wall ice layers that form a rollover anticline and create a site of preferential deposition where syn-sediments (ice) are accumulated by possible eolian activity. The modelled troughs/faults relate to a ductile detachment at more than 1000 m depth in the interior of the ice cap (deeper than the base of the section). The increasing of the ice cap by condensation creates the typical dome form of the cap that in turn buries the described faults.

## 6 Conclusions

Tectonic processes play a key role in the formation of Planum Boreum troughs. Horizontal slip induced by a deep detachment layer (more than 1000 m deep) and glacial flow are responsible of internal dynamics. This induces extensional tectonic regime that produces brittle deformation (faulting) expressed by the troughs with listric shape. Katabatic winds are responsible of the subsequent syn-sediment deposition and the trough preservation at the surface. The modelled structural setting of the martian spiral troughs through the activity of listric normal faults shows similarities with blind faults recognized in the Antarctica analog. The suggestion that troughs relate to fault activity provides the possibility to investigate preferential ways that connect the ice cap interior with the surface. The inferred presence of a detachment is significative for future investigation on the identification of internal ductile/fluid ($H_2O$) layers.

## References

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