Morphology of the Enterprise Rupes Lobate Scarp on Mercury: Implications for Structural Kinematics and Fault Scaling

Undergraduate Thesis for Departmental Honors

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Abstract

This research addresses the development of a unique geologic structure on Mercury, Enterprise Rupes. Its purpose is to determine the change in the shape of the thrust fault that forms Enterprise and its implications for the strength of the crust on Mercury early in its history when it was formed ca 3.8 billion years ago. The large Rembrandt impact crater is offset by the forelimb of Enterprise Rupes, which is the largest lobate scarp identified on Mercury at close to 900 km in length with up to 6.7 kilometers of relief. Kinematic and Trishear models developed by Karl Mueller at the University of Colorado Boulder (CU) and Nestor Cardozo of Stavanger University of this structure, using a topographic profile across the scarp and a crater shortening analysis, have helped define the fault dip. Professor Cardozo's model showed a best model with a dip of 16.17°, this is still an estimate. The fault geometry supports a detachment at ~ 40 km depth. My work encompassed creating slope and curvature maps of the area, building topographic profiles from North to South across the uplift in the simplest areas that avoided regions affected by higher surface roughness associated with impact craters, as well as heterogeneous shear apparent across the forelimb. The topographic profiles were then used to better determine the shape of the forelimb and variation in vertical relief along it, which led to the calculation of the Displacement/Length value. This value in comparison to Dr. Schultz's work in "Displacement-length scaling relations for faults on the terrestrial planets", was at the upper end of his results meaning we obtained a higher displacement in comparison with length. Measurements of the scarp width led to the interpretation that the crust of Mercury seems largely isotropic, with similar rock strength implying that the scarp most likely propagated at the same depth. Additional work may be able to better validate our thrust dip value using the relationship between the younger trace of the forelimb and relief across the ejecta blanket around the margin of a smaller crater. This smaller crater was identified through this research and its relief across the scarp should be smaller in comparison with the main scarp.

1. **Introduction**

Evidence from the Mariner 10 flybys indicated that Mercury is a tectonic planet. Global contraction resulting from secular cooling of the planet's interior has developed compressive geologic structures, evident as lobate scarps on its surface (Fig. 1). Enterprise Rupes, the focus of this thesis, is one of those structures. Enterprise Rupes was offset by several craters as it formed (Fig. 2), which has allowed structural models to be developed that constrain its geometry and depth to detachment. This thesis examines how scaling and the displacement history of the thrust occurred and how this may be used to better constrain existing structural models.

Uncertainty in the structural models of this area is largely related to calculations of shortening of offset craters, because the exact shape or circularity of the craters is unknown. This is exacerbated by the large size of the crater, relative to the amount of shortening across it.

The work in this paper was designed to determine the change with time of the shape of the thrust fault that forms Enterprise and its implications for the strength of the crust on Mercury early in its history when the thrust was formed ca 3.8 billion years ago. Crustal strength and its influence on how any brittle fault forms on terrestrial planets is primarily related to temperature and crustal composition. This is used to estimate heat flow at the time the thrust fault was formed, which will provide an independent means of constraining fundamental aspects of how Mercury formed, its composition, and the abundance of radiogenic nuclides that create heat in addition to secular cooling. Although this estimate and analysis was not possible given the timeline of this thesis, future work will use the results of measurements to tighten structural models and estimates of depth to detachment, which is the primary means of estimating paleo heat flow.

The source of the Mercury data used for this research was the USGS Astrogeology Science Center. The MErcury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft was the first spacecraft to orbit Mercury, with the Mission's goals of defining the geology, magnetic field, and chemical composition of the planet. Using the Integrated Software for Imagers and Spectrometers (ISIS3) and observations from Mercury Dual Imaging System (MDIS) narrow-angle camera (NAC) and multispectral wide-angle camera (WAC), a global digital elevation model (DEM) of Mercury was derived. The resolution of this DEM is 665 meters per pixel (m).

2. **Geologic Setting**

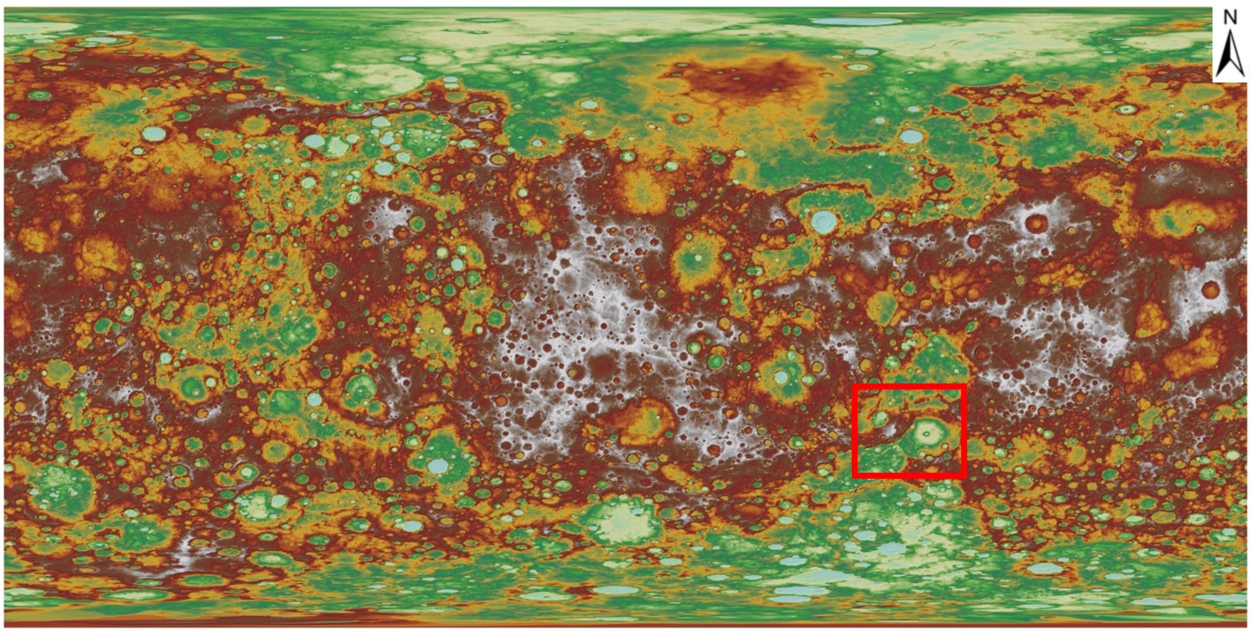

Fig. 1 - Shaded relief map of topography of Mercury, brown corresponds to higher elevation and light green represents low elevation. Red box represents area of interest (Fig. 2) (*USGS, image in review*).

The figure demonstrates a shaded relief map of the topography of Mercury (Fig.1). This data was derived from photogrammetric analysis of images produced by Messenger flybys. The Rembrandt Basin and Enterprise Rupes are located in lower-center-right section of the image. Nearly all the relief on the planet's surface is associated with impacts while the few geologic structures are thrust faults created by secular cooling and tidal despinning during the early history of the planet (*Byrne et al., 2014*)

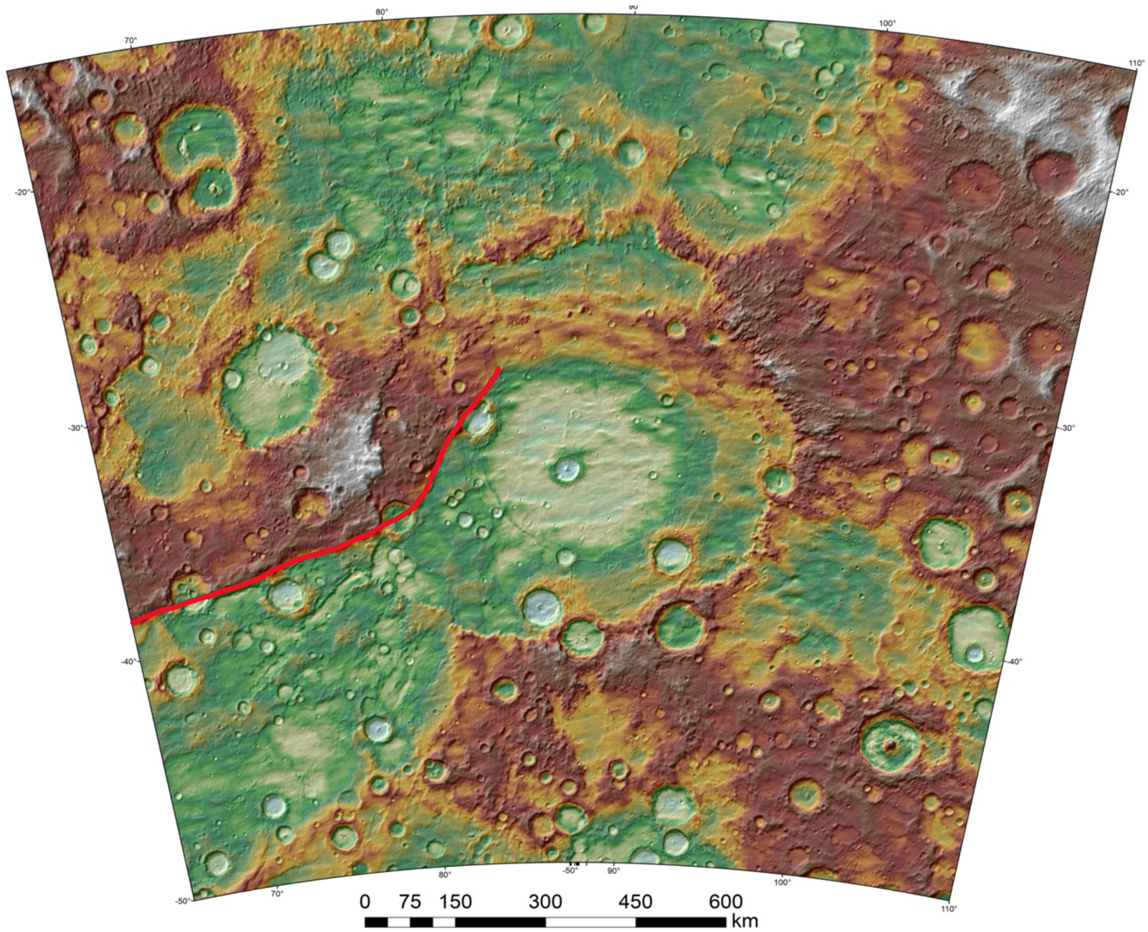

Fig. 2.1 - Shaded relief map of Rembrandt Basin and Enterprise Rupes, derived from Messenger optical imagery, brown corresponds to higher elevation and light green represents low elevation. Red line represents delineation of Enterprise (*USGS, image in review*).

The Rembrandt impact basin on Mercury is the second largest well-preserved basin on the planet and is ~715 km in diameter. Enterprise Rupes, the largest named lobate scarp on Mercury, accommodates 6.7 km of relief and extends WNW to the rim of Rembrandt for ~550 km before changing strike to NNE within Rembrandt and continuing a further ~400 km. The large impact crater is offset by the forelimb of Enterprise Rupes towards its northeast end. The brown area west of the scarp is the uplifted portion of the fault-related fold; the grey-white boundary is the western rim of the enormous Rembrandt Basin (Fig. 2.1). Vertical separation across the scarp ranges from 4620 - 6730 meters in height, comparable to that of Colorado's Front Range. The length of

Enterprise Rupes is ~900 km long, making it the largest single thrust in the Solar System. The ratio of displacement to length of Enterprise is consistent with scaling of faults on terrestrial planets, where lower gravity is proportional to decreased overburden stress and rock strength (i.e. smaller terrestrial planets have thrust faults that are proportionally longer for a given amount of maximum displacement) (*Schultz and others, 2006*).

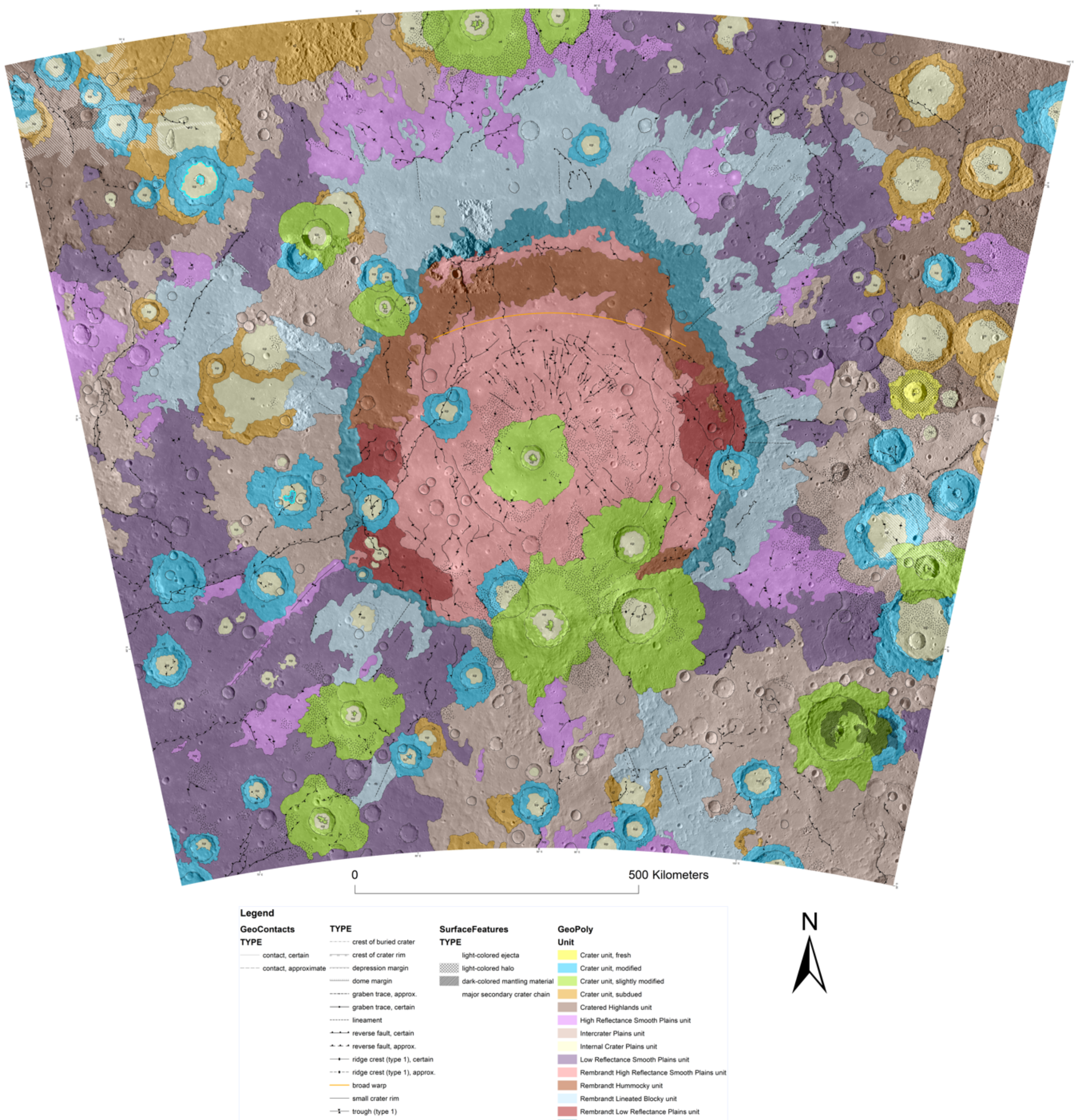

Fig. 2.2 - Geologic Map of the Rembrandt Region, Mercury (Brian M. Hynek, John D. Gemperline, Stuart J. Robbins, Karl J. Mueller)

Lobate scarps are long, curvilinear structures that are equivalent to the forelimbs of basement cored thrust faults. They are a term used in the planetary community to describe large compressive structures assumed to be surface thrust ruptures. In reality, they are the forelimbs of fault propagation folds formed by shear above an upward propagating thrust tip and upward widening triangular shear zone. Named trishear structures, they are structurally similar to the sheared strata defined by the Flatirons above Boulder, Colorado. On Mercury, lobate scarps are large and globally distributed. These are the result of global contraction as the planet cools. The total displacement accommodated by lobate scarps has been used to estimate that Mercury's radius has contracted by as much as 7 km due to the secular cooling of its core (Byrne and others, 2014). Enterprise Rupes is the largest lobate scarp identified on Mercury at close to 900 km in length with up to 6.7 km of relief.

3. **Previous Structural Modeling**

Considerable work on Enterprise Rupes has already been undertaken by Professor Karl Mueller and his collaborators at other universities, I made more detailed measurements of vertical displacement along Enterprise Rupes to validate their early results and provide a better understanding of the geology of this structure. Additionally, work in this area has also been produced within other projects by Prof. Brian Hynek (CU) and Dr. Stuart Robbins (Southwest Research Institute). Their work is also included in this thesis as a supplement for a better understanding of the present research.

The following crater couple is of interest because it can be used as a finite strain marker, which rarely are ideally placed with respect to geologic structures (Fig. 3). This offset crater provides a rare opportunity to define the deeper study of this structure on Mercury.

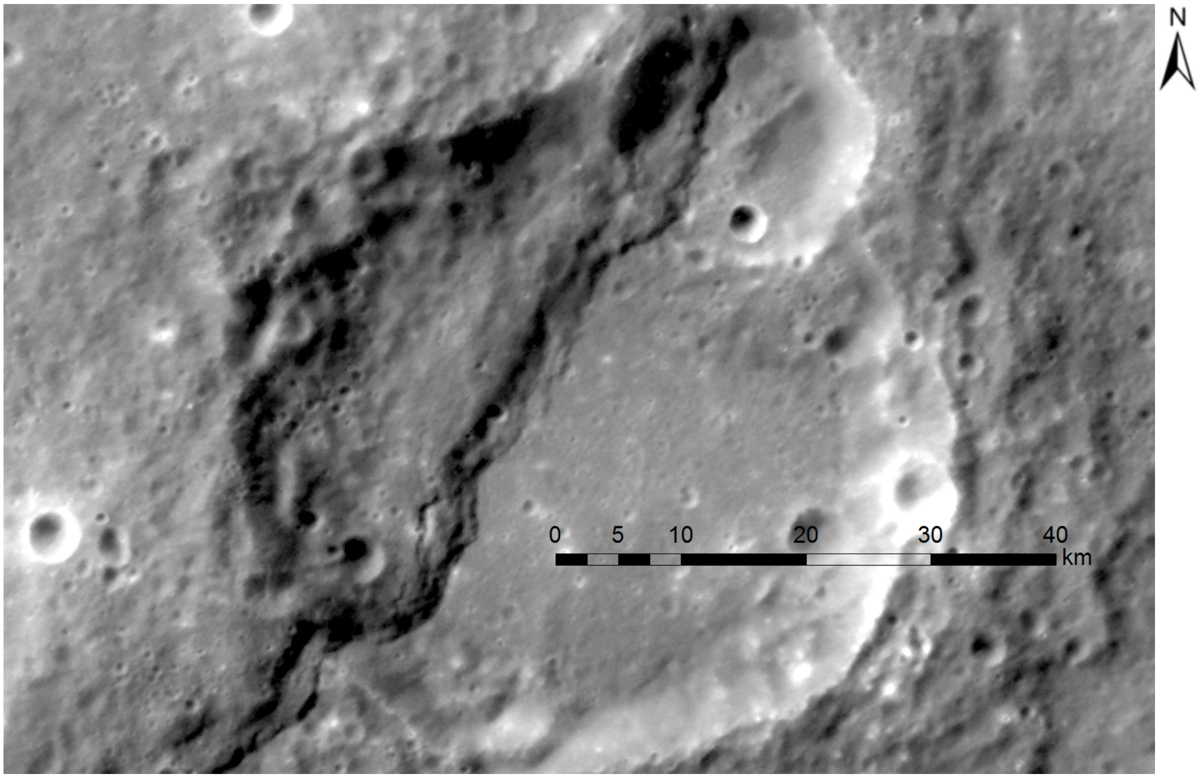

Fig. 3 - High resolution image of two small craters offset by Enterprise Rupes. (Hynek)

The height of the scarp south of the larger crater is about 515% higher than the displacement within the crater as measured by Professor Hynek with topographic data. This suggests the impact formed very late in the history of slip of the structure, which was at about 3.8 Ga, based on crater count statistics in Rembrandt itself (Ferrari et al, 2013). Professor Mueller has interpreted that the growth of the structure does not seem particularly affected by the impact or the topographic relief created by the crater. This is consistent with structural models that are interpreted to suggest the fault tip would have been located at about 30 km depth when the crater was first formed.

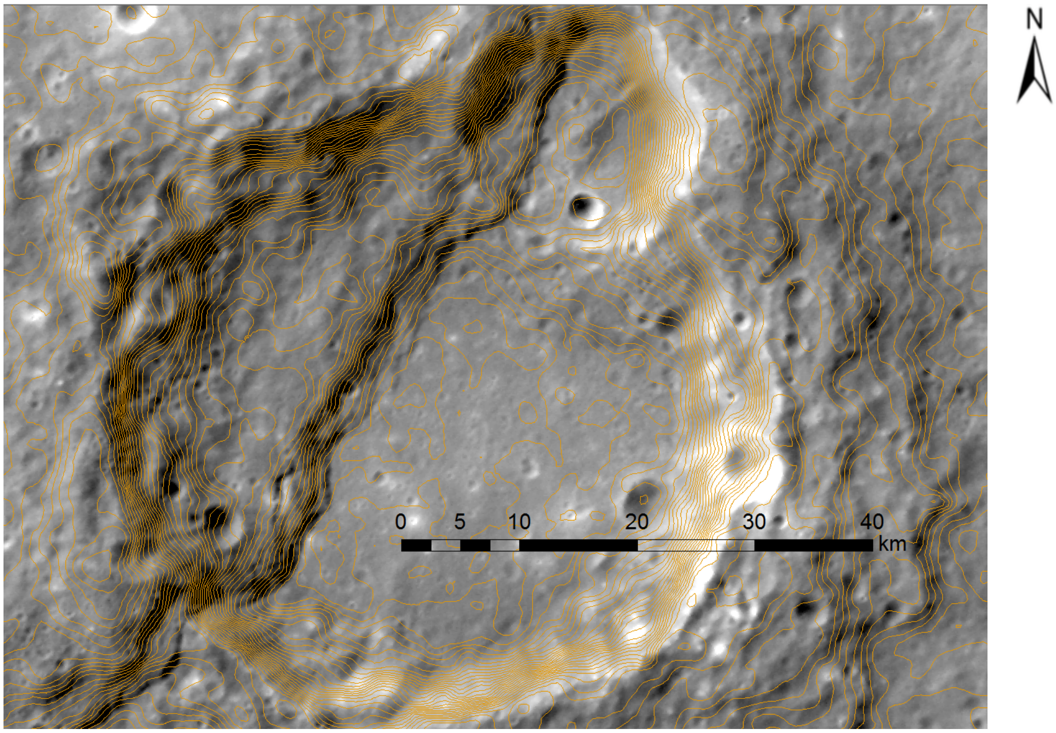

Fig. 4 - Topographic contours of small crater (contour interval = 100m) (Hynek)

Note the increase in scarp height from south to north, ~7000m across the main scarp, ~1300m across the floor of the large crater, and ~350m across the floor of the smaller crater (Fig. 4).

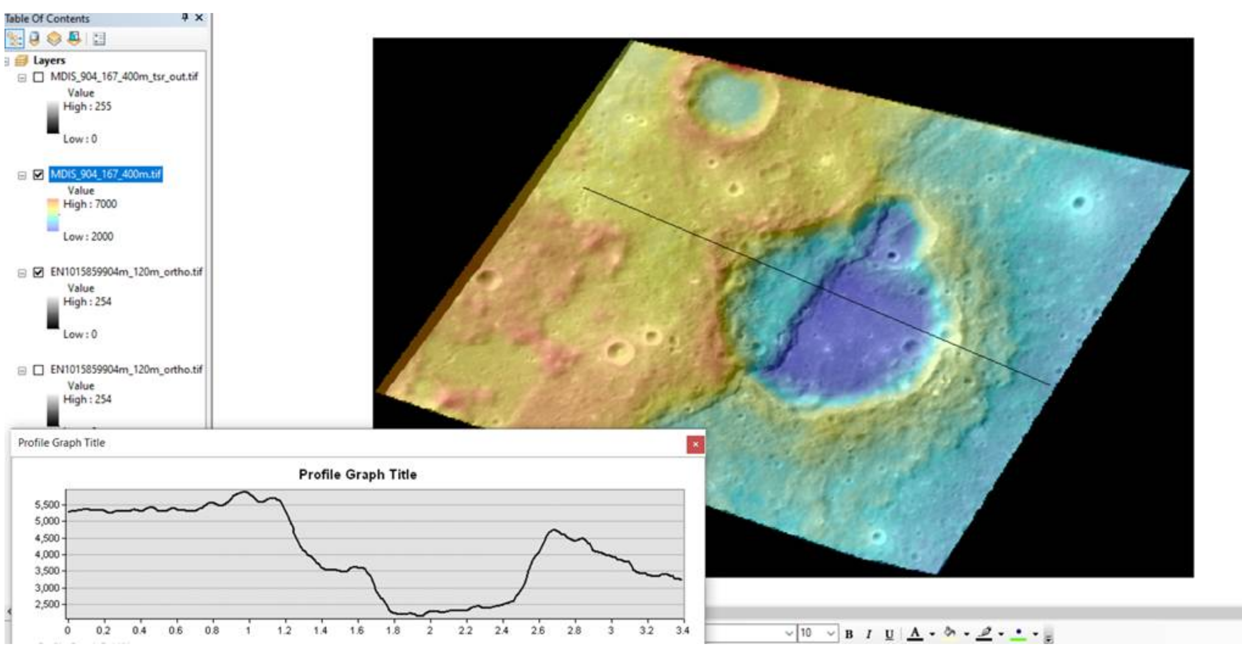

Fig. 5 - Oblique color shaded relief image of two offset craters and topographic profile. (Hynek)

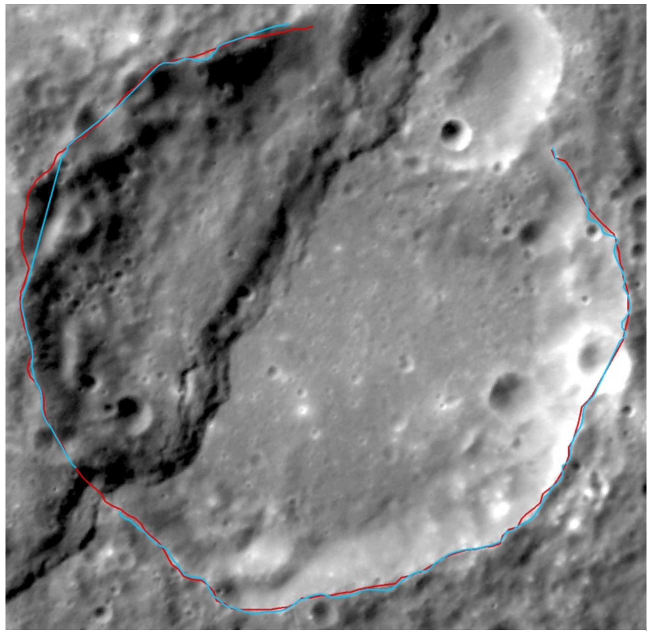

Fig. 6 - Map of crater rim defined by Prof Brian Hynek (CU) and Dr Stuart Robbins (SWRI).

These figures were used by professor Hynek to determine the amount of horizontal shortening across the crater, which provides constraints for the structural model used in the analysis by Prof. Karl Mueller (CU) and Prof. Nestor Cardozo (Univ Stavanger) (Fig. 5 & 6). Using a Great Circle to calculate the distance and bearing, with a body radius of 2439.7 km, Dr Robbins got a distance of 5.0483 km and a bearing of -89.95° (which is counter-clockwise from due north, so they're almost exactly on an E-W line) (*Stuart Robbins analysis 2016*).

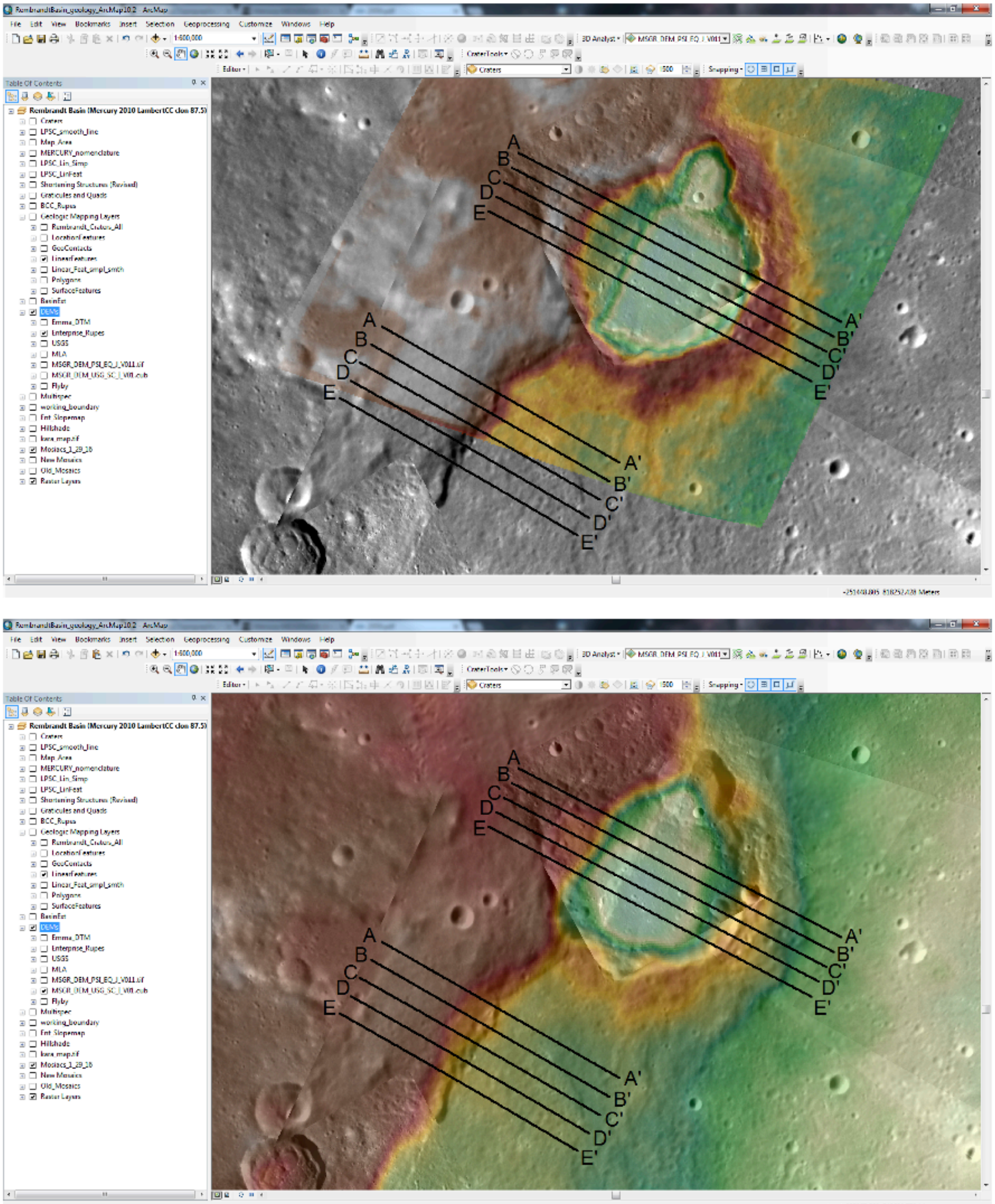

Fig. 7 - Topographic profiles across the floor of the large offset crater and further south, beyond the crater ejecta blanket.

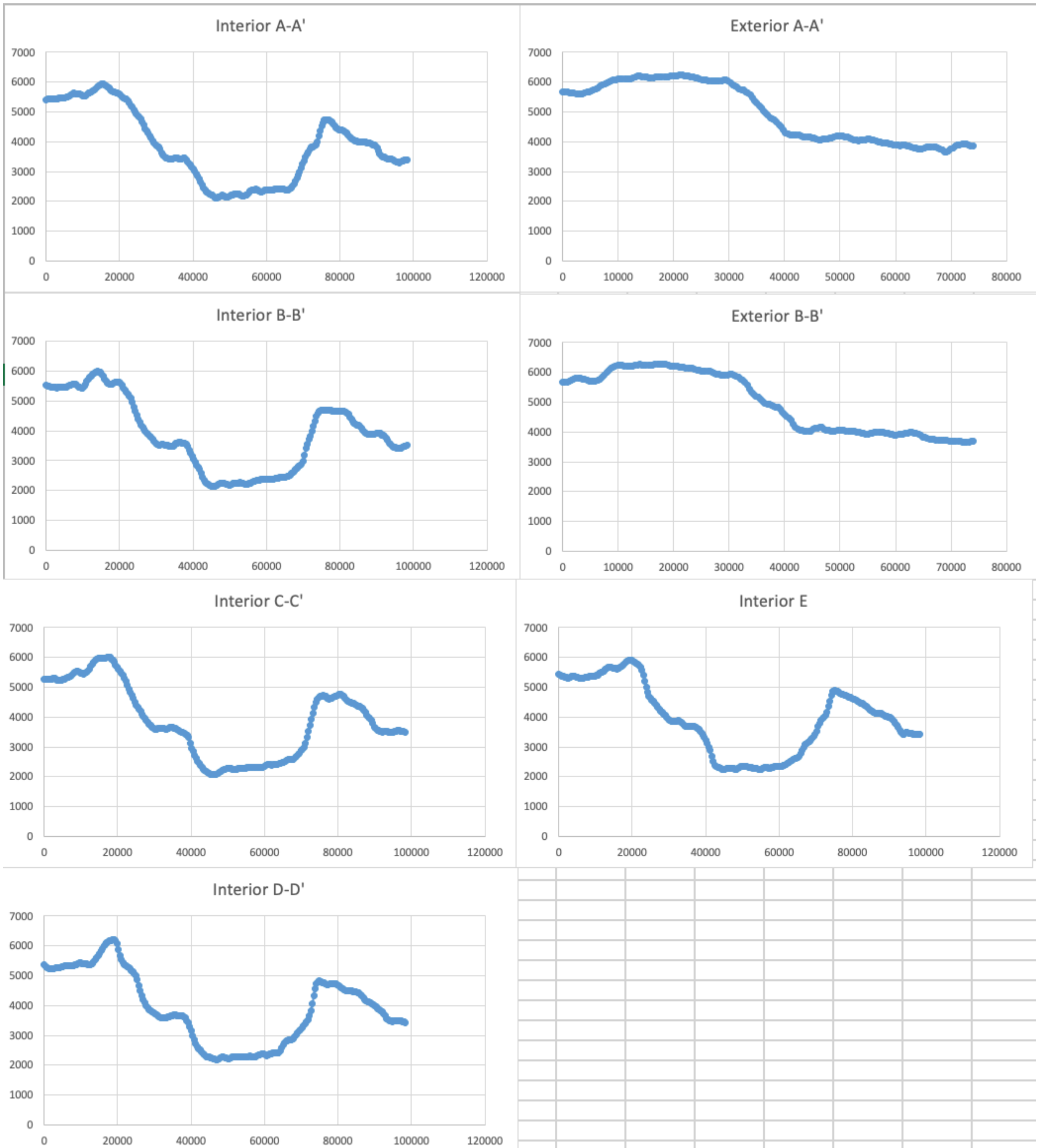

Fig. 8 - Local DEM graphs

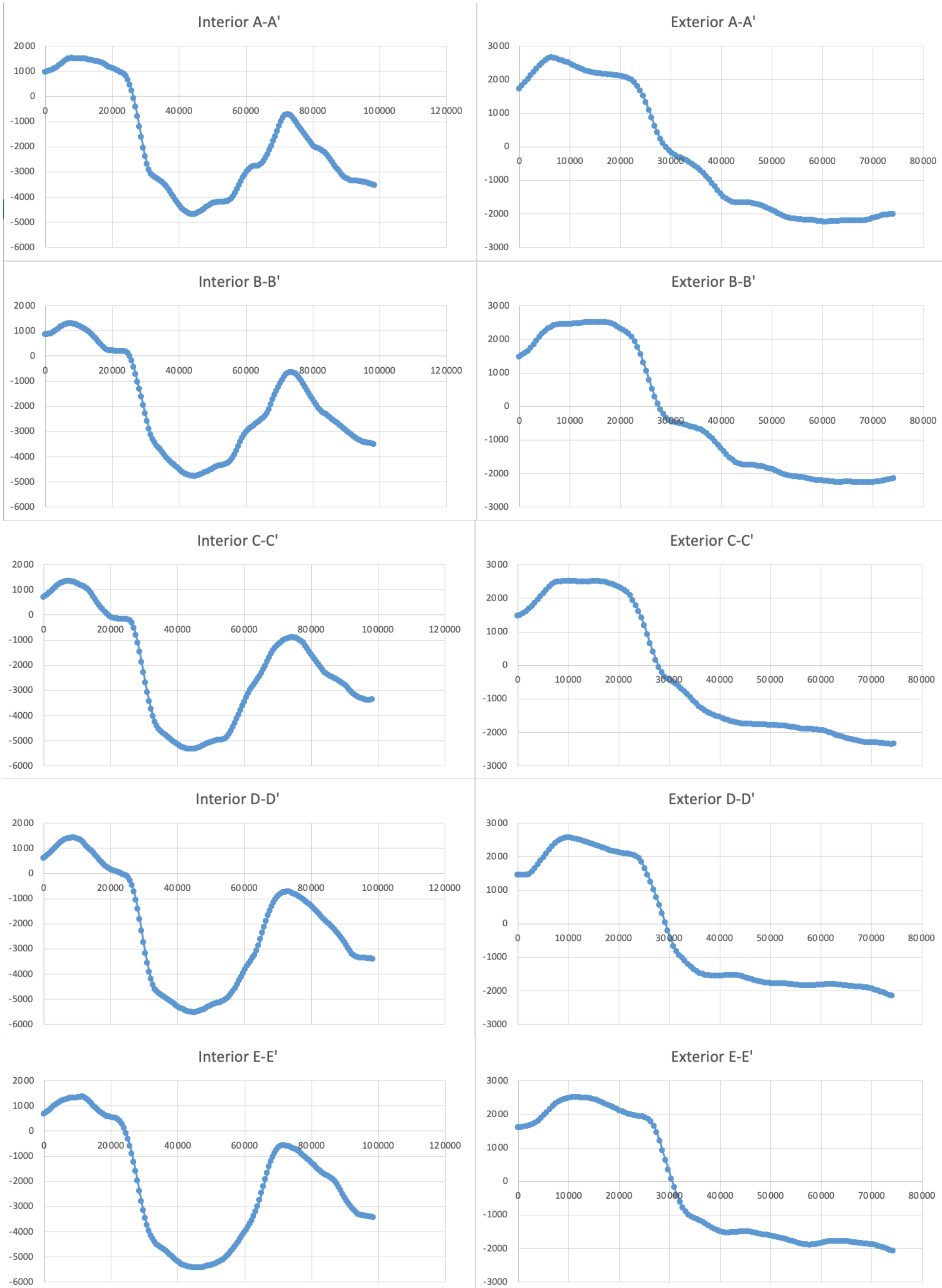

Fig. 9 - Global DEM graphs

The analysis of these graphs allowed the calculation of height increase from the displacement within the crater to total displacement across Enterprise south of the larger crater (Fig. 7, 8 & 9).

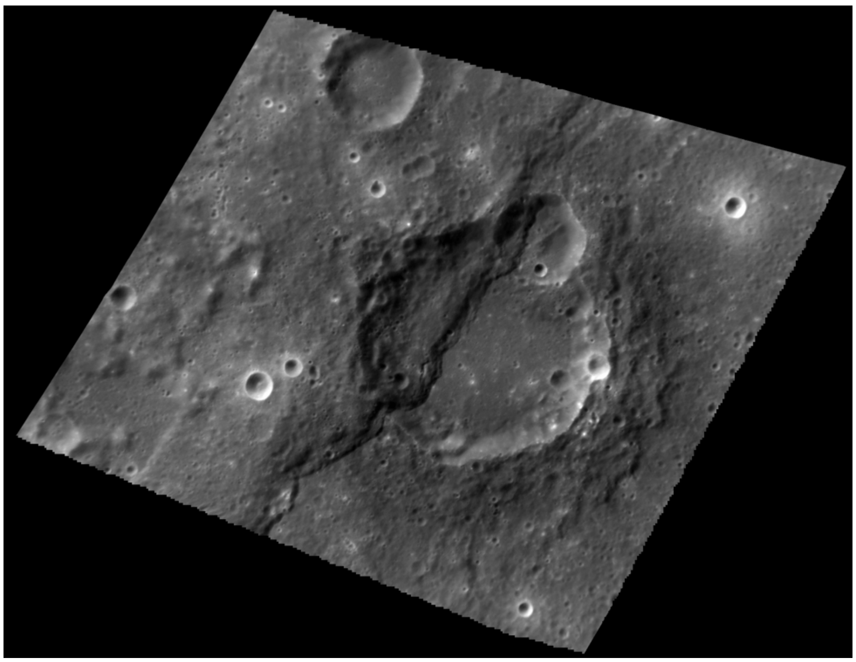

Fig. 10 - Different perspective of high-resolution image of two connected small craters offset by Enterprise Rupes. (Hynek)

The smaller crater located to the northeast is also offset by the scarp, which offers an opportunity to better constrain structural models (Fig. 10). Its analysis will provide information on a more recent period of slip since the relief across the scarp should be even smaller. The scarp changes its strike across the southern rim of the smaller crater, consistent with a west-dipping thrust. This relationship can be used to estimate the dip of the thrust.

The data we acquired did not have the same resolution as professor Hynek's therefore due to resolution restrictions and the coarseness of our data, further analysis of the smaller crater could not be accomplished. Given additional time and further collaboration, measurements of the average total scarp height across the large crater and shortening recorded by the smaller crater across the structure, shall be pursued and further analyzed in the future. Most importantly, the width of the scarp across both craters can be used to define upward propagation of the thrust, using assumptions for a constant trishear envelope and apical angle.

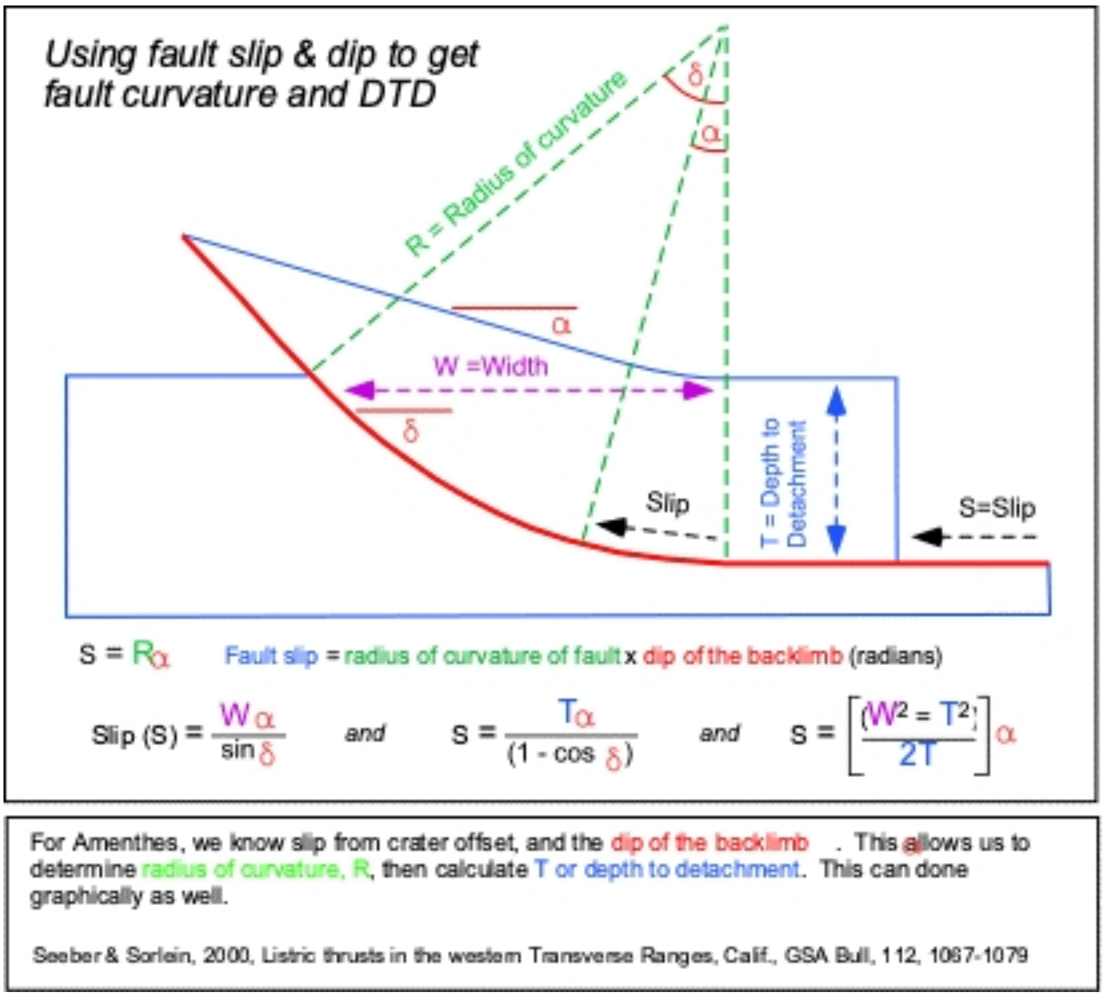

Fig. 11 - Listric model Mercury. Schematic diagram from Seeber and Sorlein, 2000 (see reference on figure).

This figure outlines the relationships between fault slip, fault geometry, in particular radius of curvature and the dip and width of the backlimb for listric thrust faults (Fig. 11). The method assumes slip along the fault and rotation of the hanging wall block, without internal shear or other deformation. Note this is broadly similar to one of Nestor Cardozo's trishear models that used fault parallel shear in the hanging wall to produce a fold shape that closely matched the uplift associated with Enterprise Rupes.

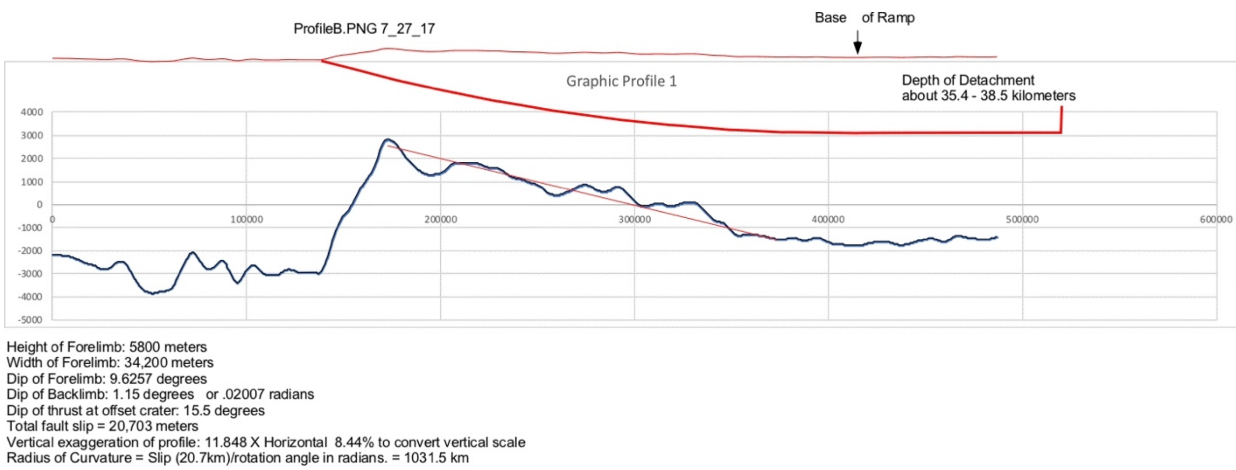

Fig. 12 - Balanced cross section of the Enterprise Rupes Thrust, using the methods outlined in *Seeber and Sorlein, 2000*

Depth of detachment is about 35.4-38.5 km depth (yielding a 3.8 Ga geotherm of about 16.9 - 18.4°C / km.) (Fig. 12). 650 °C used for the onset of plasticity in dry plagioclase.

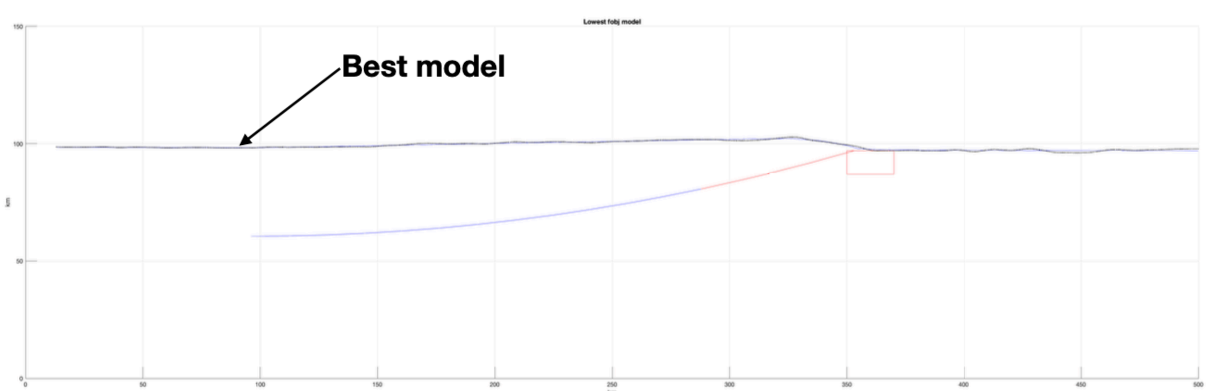

Fig. 13 - Kinematic model of Enterprise Rupes that best restores the topographic profile to a straight line. Blue and red is the whole fault, and red is the fault propagation trajectory, i.e. the fault started to propagate at the change between blue and red. Model starts at surface level (Cardozo, 2021).

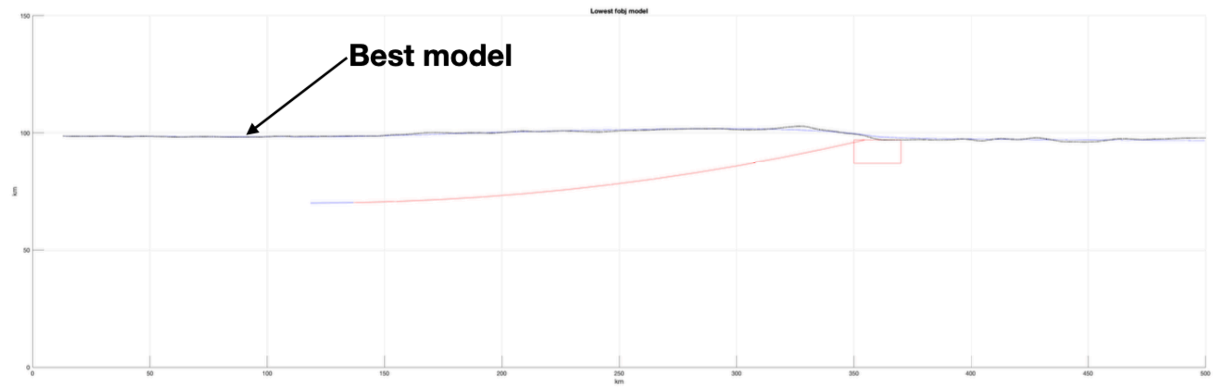

Fig. 14 - Kinematic model of Enterprise Rupes that best restores the topographic profile to a straight line. Blue and red is the whole fault, and red is the fault propagation trajectory, i.e. the fault started to propagate at the change between blue and red. Model starts at detachment level. More subtle structure. Not as good fit as before (Cardozo, 2021).

The figures above represent trishear models developed by Nestor Cardozo of Stavanger University of Enterprise Rupes, using a topographic profile across the scarp, and the fault dip derived from the crater shortening analysis. Fault geometry supports a detachment at ~40 km depth (Fig. 13 & 14).

Less displacement per unit length is accumulated along faults on Mars and Mercury than along terrestrial (Earth-based) ones. Thrust faults from Mercury also show D/L (Displacement/Length) ratios of 6.5×10^{-3} (Watters et al., 2000, 2002). This is background information and following will be my own measurement of this ratio. The magnitude of maximum displacement for a fault on Mercury should be about 16%

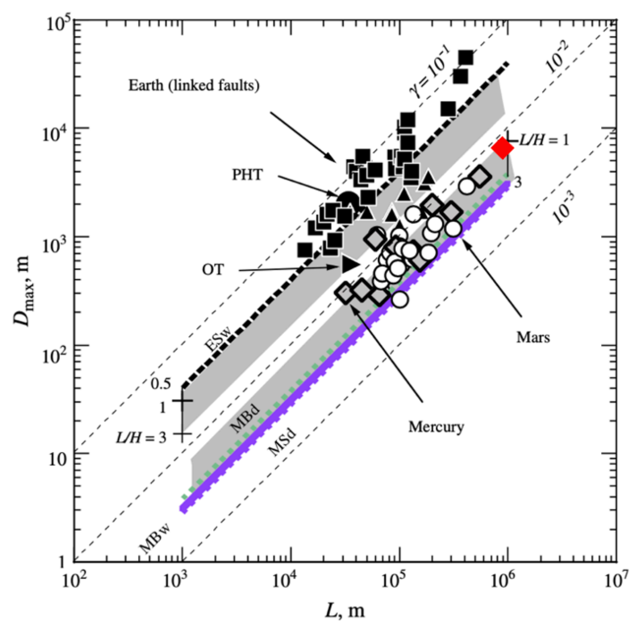

Fig. 15 - D-L data for thrust faults from Earth (black squares and triangles), Mars (open circles) and Mercury (gray diamonds). Additional shapes relate to other sources unnecessary for our purposes. L/H = 3.0 for Mercurian thrust faults with upper tick at L/H = 1.0 (lower shaded region) (L/H is fault aspect ratio) (Schultz et al, 2016)

of a fault of comparable length on Earth (Schultz et al, 2016). Total slip for this model is about 6.7 km, and the total length of the fault is 893km. D/L is roughly 6.7km/893km or 7.5×10^{-3}. This value is at the upper end of Schultz's results, represented by the red diamond (Fig. 15). In the figure, H represents the Vertical fault height measured in fault plain; γ represents ratio D_max/L; ESw, Earth sandstone rock mass with wet conditions; MBd, Mars basaltic rock mass with wet conditions; MBw, Mars basaltic rock mass with wet conditions; MSd, Mars sandstone rock mass with dry conditions; PHT, Puente Hills Blind-thrust System (on Earth); and OT, Ostler Thrust (on Earth) (Schultz et al paper, 2016).

4. **Methods**

4.1 **Work on Mars**

In the Spring of 2022, Professor Mueller and I initially started looking at serial topographic profiles on Amenthes Rupes on Mars, and after weeks of work we realized that the ambient noise relative to the size of the structures precluded any kind of meaningful results. That work is not included in this thesis. The Mercury work started in the Fall of 2022, and for that I created a set of profiles to test whether we could use a "trade distance for time" relationship (change with time in the structure's shape) and scaling laws with inherent assumptions to constrain how the structure grows, and whether it is segmented.

4.2 **Work on Mercury (ArcMap)**

Data collection methods: The Digital Elevation Model (DEM) data used in this work was sourced from the Astrogeology United States Geological Survey (USGS). This model of Mercury was derived using the Integrated Software for Imagers and Spectrometers (ISIS3) and observations from Mercury Dual Imaging System (MDIS) narrow-angle camera (NAC) and multispectral wide-angle camera (WAC). The MDIS resolution was of 250m/pixel and for regions of geologic interest it was at 20-50m/pixel.

After transferring the data to ArcMap, I began by cropping the DEM layer to the area of the structure being studied, Enterprise Rupes. With this layer, a slope and a curvature map of the area was created to determine the top and base of the forelimb and its width (Fig. 17 and 18).

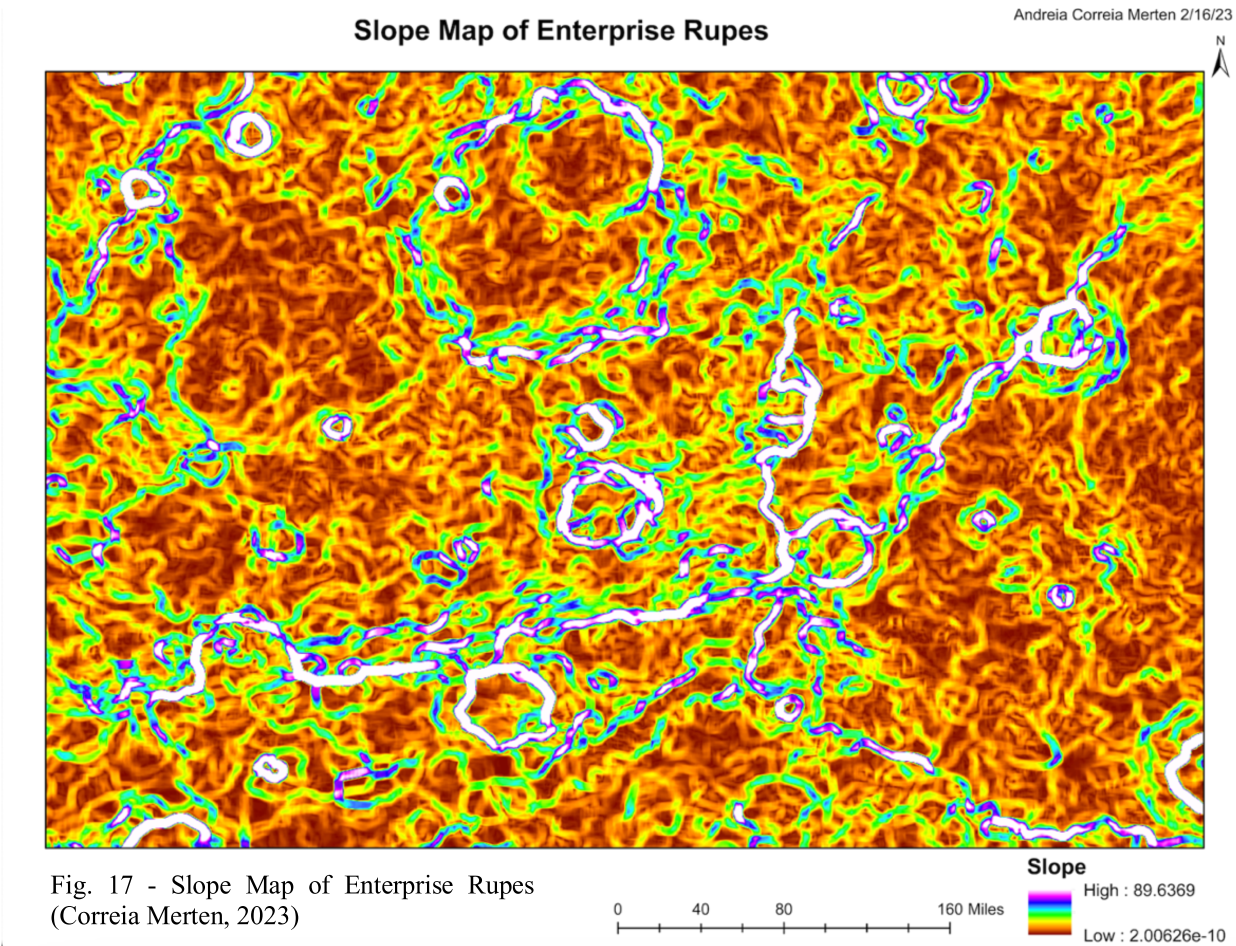

Fig. 17 - Slope Map of Enterprise Rupes (Correia Merten, 2023)

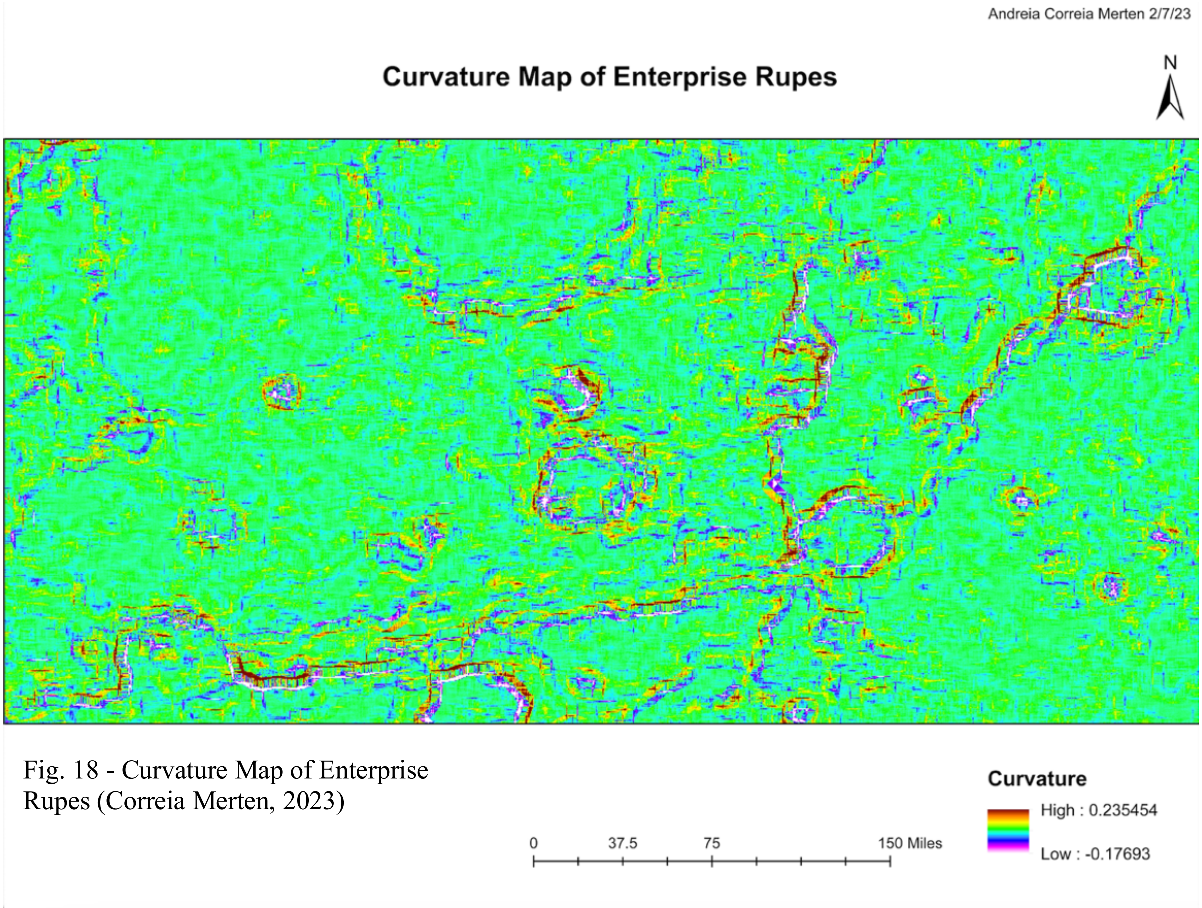

Fig. 18 - Curvature Map of Enterprise Rupes (Correia Merten, 2023)

Sample selection: Professor Mueller and I selected 11 sections of the fault from the maps that were the simplest and avoided regions affected by higher surface roughness associated with impact craters, as well as heterogeneous shear apparent across the forelimb (Fig. 19). With those sections, I was able to build topographic profiles from North to South across the uplift created above the Enterprise Thrust. Two topographic profiles were made for each section (Fig. 20, 21, 22 & 23). Given uncertainty in the shortening direction associated with the analysis of the large offset crater, I created a profile perpendicular to the scarp locally ("a" values) and one perpendicular to the overall strike of the scarp (i.e. using the bow and arrow rule) ("b" values).

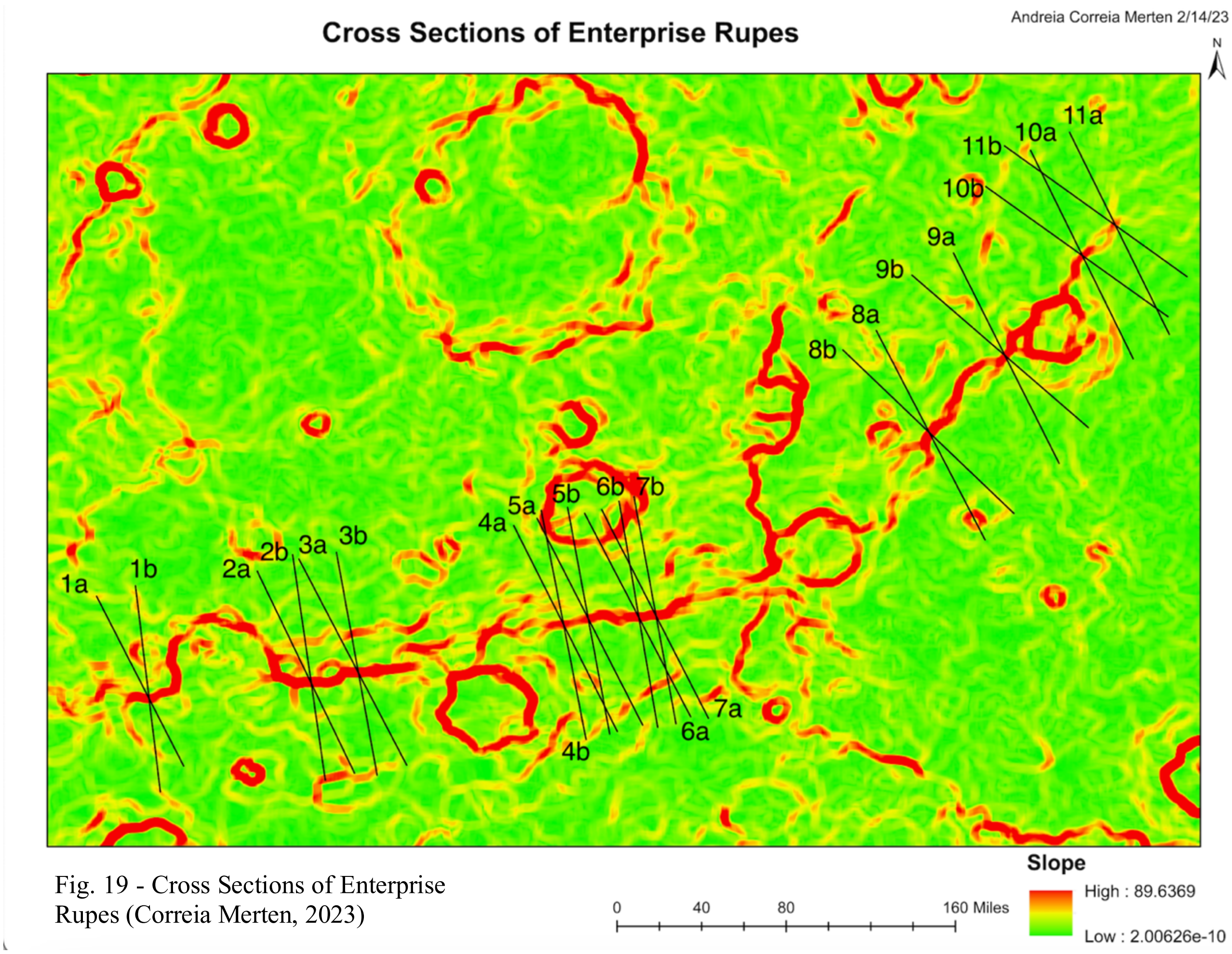

Fig. 19 - Cross Sections of Enterprise Rupes (Correia Merten, 2023)

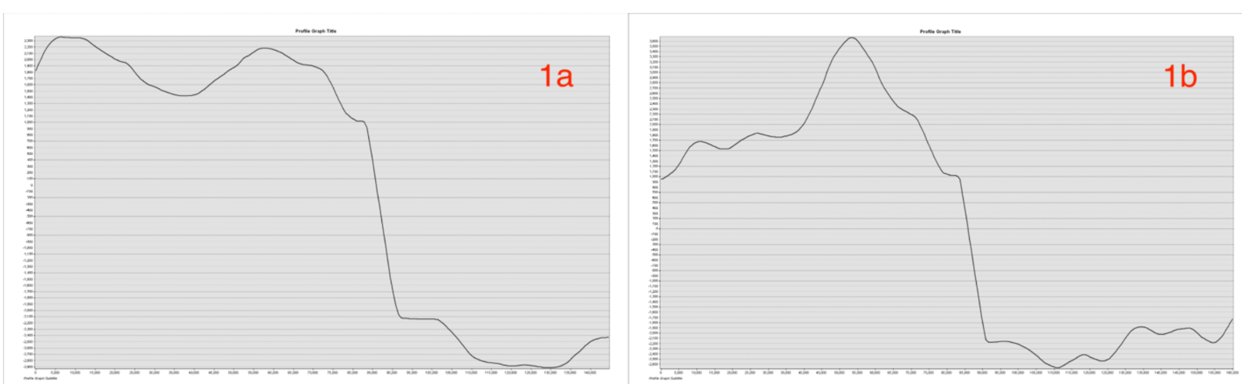

Fig. 20 - Topographic profiles of cross sections 1a and 1b. x-axis corresponds to length and y-axis corresponds to height. (Correia Merten, 2023)

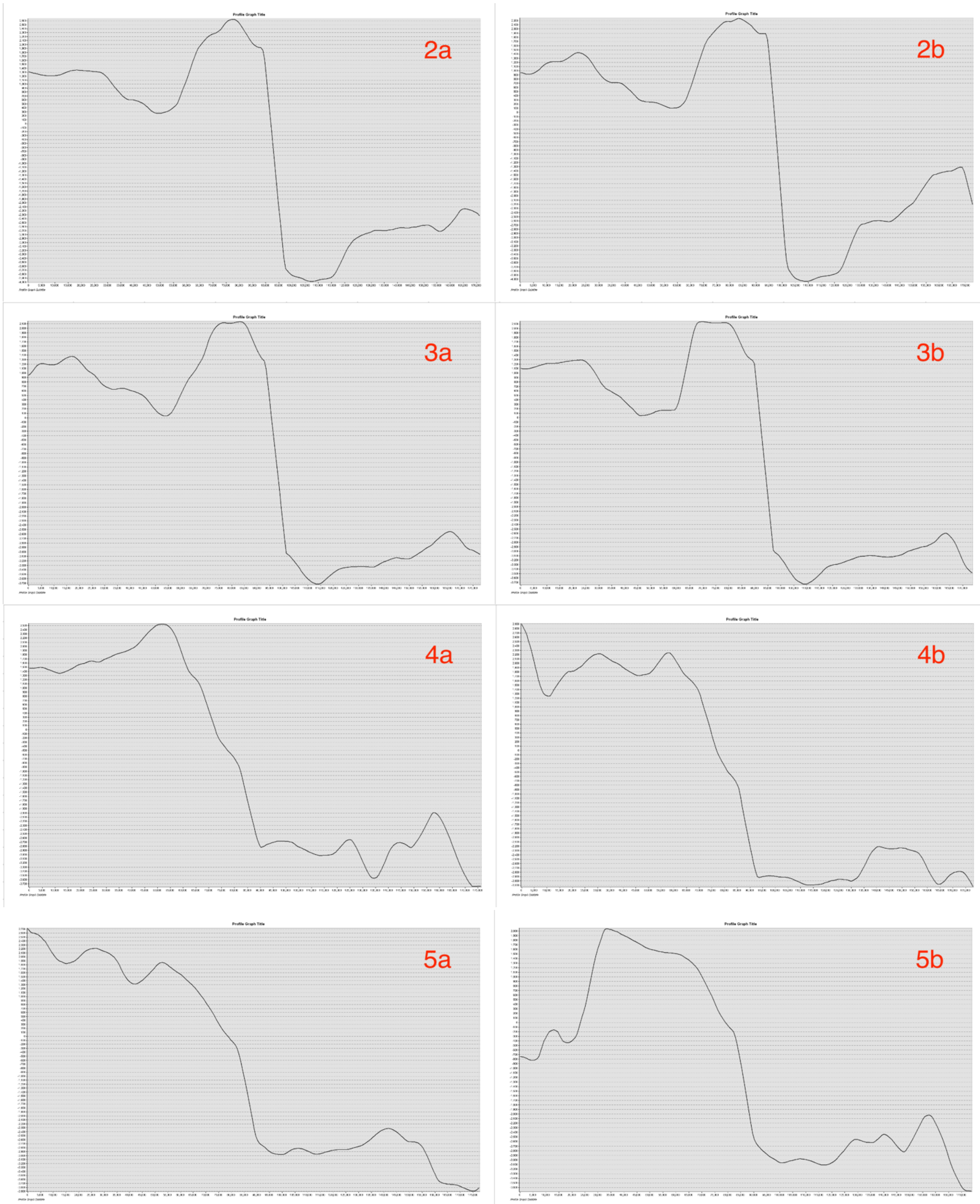

Fig. 21 - Topographic profiles of cross sections 2a through 5b. x-axis corresponds to length and y-axis corresponds to height. (Correia Merten, 2023)

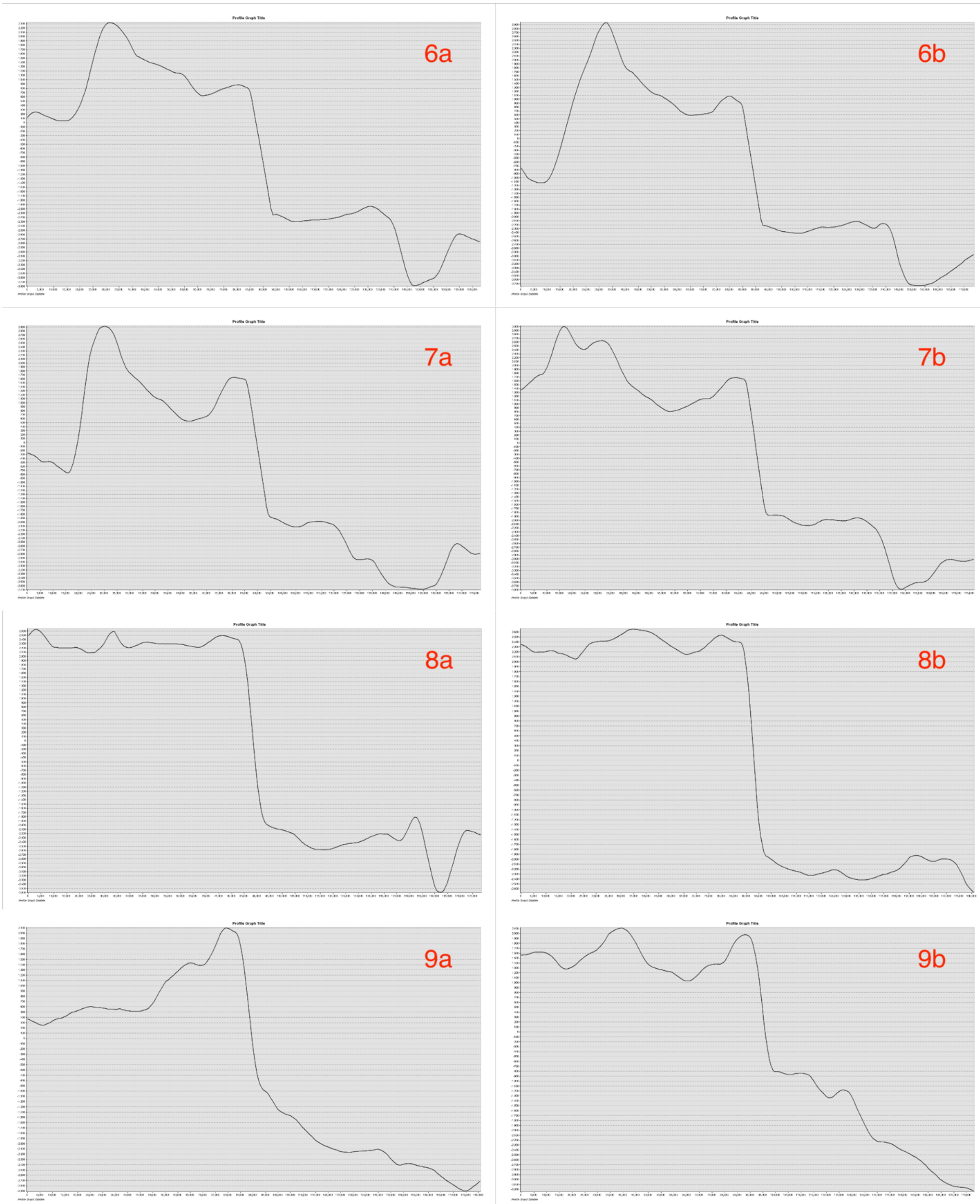

Fig. 22 - Topographic profiles of cross sections 6a through 9b. x-axis corresponds to length and y-axis corresponds to height. (Correia Merten, 2023)

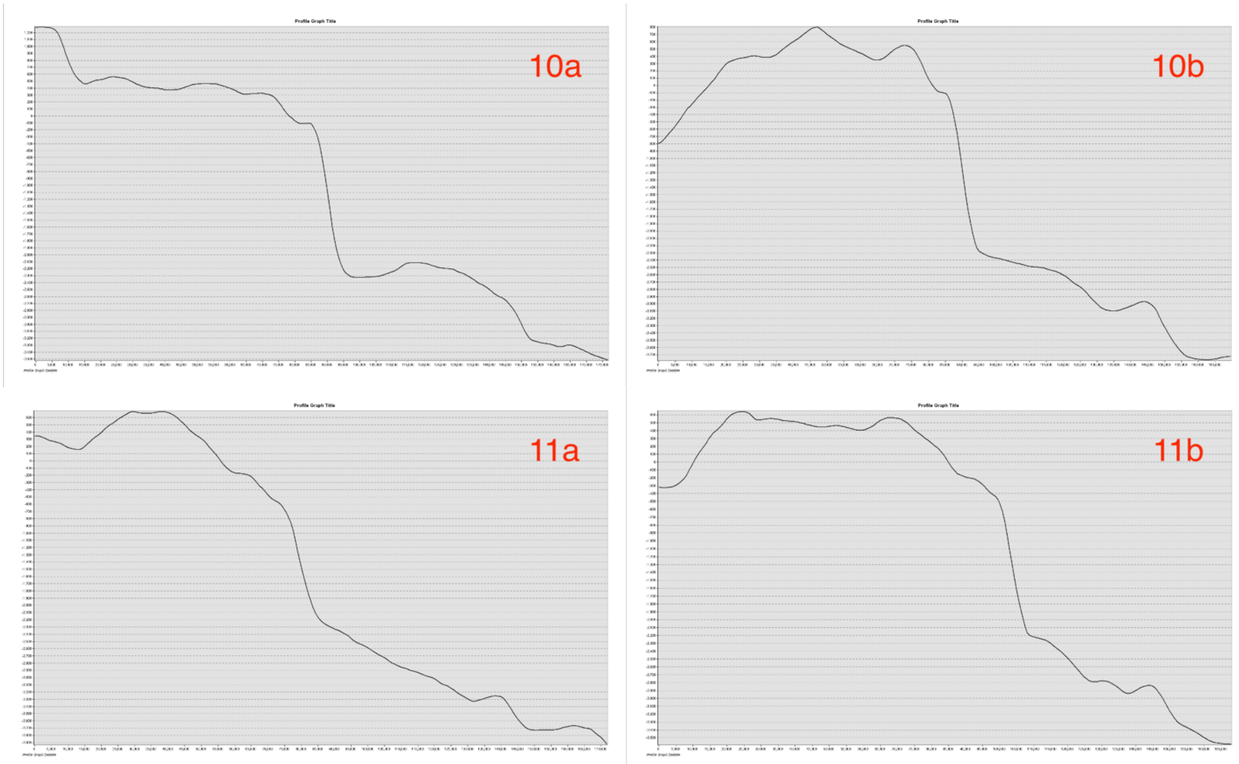

Fig. 23 - Topographic profiles of cross sections 10a through 11b. x-axis corresponds to length and y-axis corresponds to height. (Correia Merten, 2023)

These cross sections will be used as the starting point for additional modeling using techniques that consider a more comprehensive evolution of geologic structures, which is expressed on Enterprise by a decrease in elevation towards its endpoints.

Data analysis: The topographic profiles were then used to determine the limits of the scarp and establish the geometry of this structure (Fig. 24). Furthermore, the analysis of these profiles and the measurement of the length from one of the endpoints of the scarp to each chosen section, allowed the construction of two D:L plots, one using the "a" displacement values and another using the "b" values (Fig. 25).

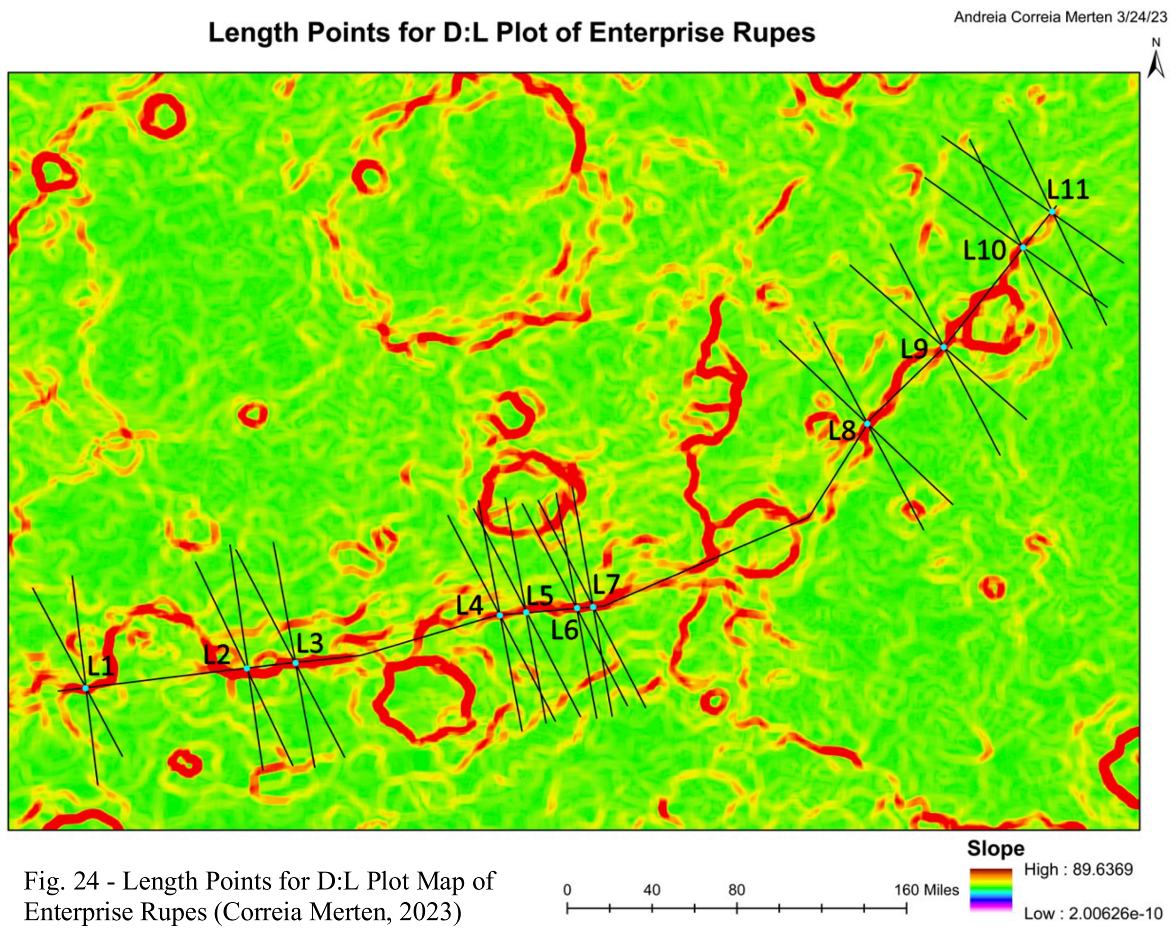

Fig. 24 - Length Points for D:L Plot Map of Enterprise Rupes (Correia Merten, 2023)

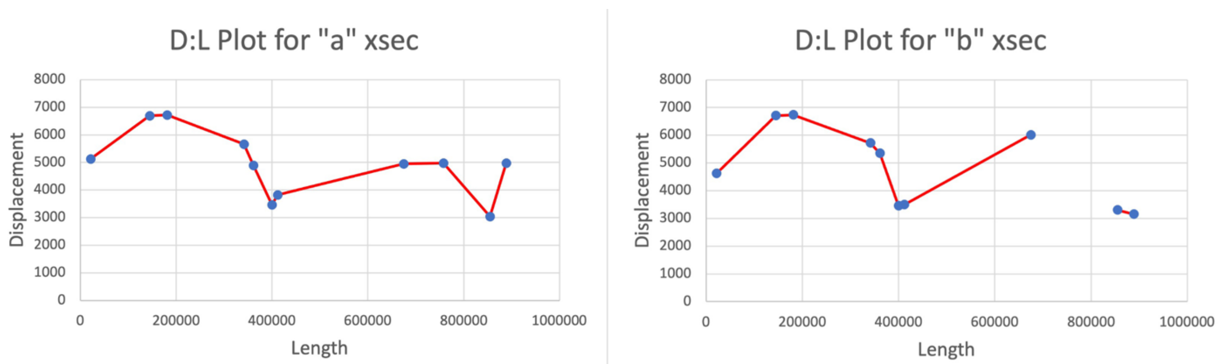

Fig. 25 - D:L plots, one using the “a” displacement values (left) and another using the “b” displacement values (right) (Correia Merten, 2023)

In association with the work performed by Professor Hynek on a small crater offset by Enterprise Rupes, I made several topographic profiles across the smaller crater connected to the previous one in the northwest section. This gave us information on a more recent period of slip –

where relief across the scarp is even less. Note that the scarp changes its strike across the southern rim of the smaller crater, consistent with a west-dipping thrust. With the analysis of these topographic profiles, additional work may be able to estimate the dip of the thrust using this relationship (Fig. 26).

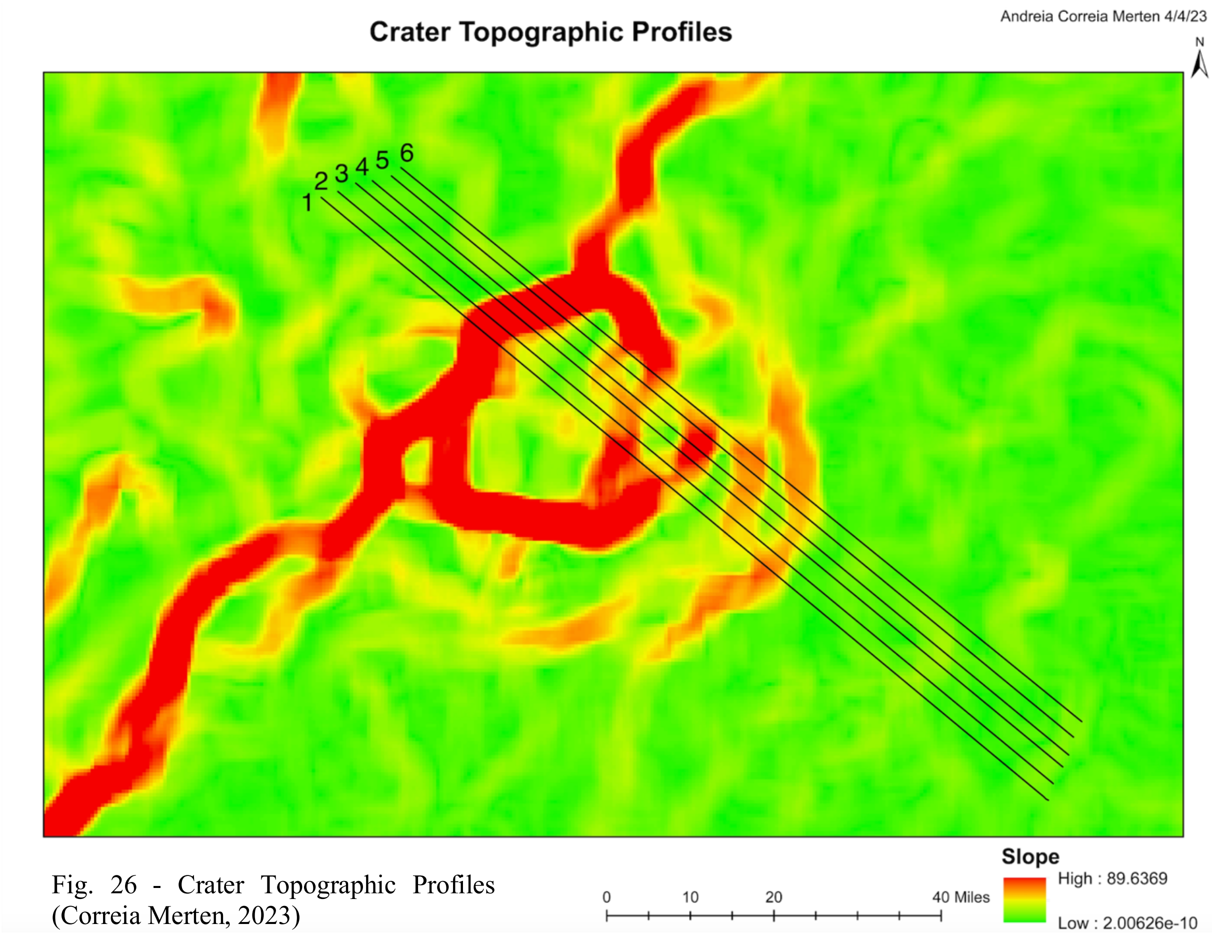

Fig. 26 - Crater Topographic Profiles (Correia Merten, 2023)

As mentioned previously, although several topographic profiles were made across the smaller crater, due to resolution restrictions and coarseness of our data in comparison to Professor Hynek's, further analysis of the smaller crater could not be accomplished, and those profiles were not available for study.

5. **Results**

After measuring the forelimb width on ArcMap, it was observed that it possessed the same width along its length. The measurements are presented below.

Measurements of scarp width: Mean is 6589.8 meters, σ = 248.3 m (standard deviation)

6065.1	6821.8	6752.3	6393.5	6752.3	6729.0	6821.8	6729.0	6563.4	6269.3

These measurements and their proximity in value, imply that the material is isotropic, and that the rock strength is consistent. This also suggests that the scarp propagated at the same depth.

Using each topographic profiles from the 11 chosen sections of the fault, my advisor was able to measure vertical relief. With the map of these 11 sections, I measured the length from the west end of the structure to each individual point of interception between the cross-sections and the fault. Those measurements are presented below. Uncertainty in picking exact scarp height may have been hampered by heterogenous shear that was not fully recognized in the available dataset.

Vertical relief measurements (meters):

1a	5125	1b	4620
2a	6700	2b	6700
3a	6720	3b	6730
4a	5660	4b	5720
5a	4900	5b	5350
6a	3470	6b	3450
7a	3820	7b	3490
8a	4950	8b	6010
9a	4980	9b	XXXX
10a	3040	10b	3300
11a	4980	11b	3150

Total Length: 893795.2 m

Point	Length (m)
L1	21466.4
L2	144812.8
L3	181338.4
L4	341518.9
L5	361383.4
L6	399898.8
L7	412045
L8	674647.5
L9	757475.2
L10	854603.3
L11	888787.5

These measurements were then used to build the D:L plots, present in the Methods section in Figure 24.

6. **Conclusion**

In conclusion, this thesis and my results lend further support and incentive for future work being performed by my advisor, Professor Karl Mueller, in collaboration with Professor Nestor Cardozo with the purpose of publishing their research in this area. I will continue to contribute for further work by building more topographic profiles as their work progresses. One of the serendipitous aspects that resulted from this work was that my advisor realized that the scarp crossed a smaller crater. This will help him and Professor Cardozo immensely with trishear modeling because it will provide the narrower scarp which can be related to an upwardly propagating fault tip with an associated trishear envelope with a consistent apical angle that also grows upward. It is likely to improve future trishear modeling of the structure, with a resulting better fit between models and surface topography and lobate scarp morphology across Enterprise Rupes.

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Image references:

- Professor Hynek’s previous work as well as from sources referenced above.
- My own work, Andreia Correia Merten, over the course of the academic year of 2022/2023