EVIDENCE FOR AN ENDOGENIC ORIGIN OF MOUNTAINS ON TITAN. Z.Y.C. Liu[1], J. Radebaugh[1], R. Harris[1], E.H Christiansen[1], R.L. Kirk[2], C.D. Neish[3], R.D. Lorenz[3], E.R. Stofan[4] and the Cassini Radar Team. [1]Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA., *zacqoo@byu.edu*. [2]Astrogeology Division, U.S. Geological Survey, Flagstaff, AZ 86001, USA. [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA. [4]Proxemy Research, P.O. Box 338, Rectortown, VA 20140.

Introduction: Currently, one of the unresolved problems regarding Titan's surface is still in debate: what is the origin of its mountains and was there tectonic activity on Titan? Two broad hypotheses have been extended for processes that produced mountains: exogenic and endogenic. Moore et al. [1], as part of the exogenic hypothesis, pointed out that the mountain ridges on Titan are similar in scale to those on Callisto, which owe their origin to multi-ring basin-forming impacts followed by erosion. However, the linear-to-arcuate ridges with relatively higher elevation on Titan's surface [2,3,4,5] have morphologies consistent with extensional or compressional tectonism [3; Fig. 1]. Analyzing topographic data and undertaking global and regional scale mapping of surface features are the keys to testing a possible tectonic contribution to shaping Titan's surface [1]. The purpose of this study is to test the hypothesis of the origin of mountains on Titan by analyzing (1) mountain heights and (2) structural mapping as a way of determining degree of lineatity of surface features and if linear features show evidence of crustal thickening or thinning.

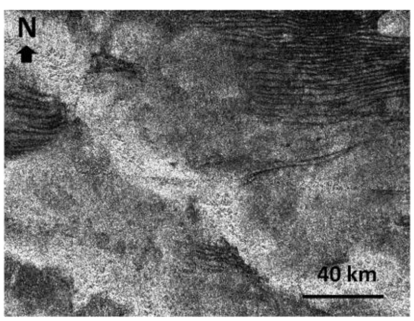


Figure 1. Mountain ridges in the T61 swath: SARTopo data show that these arcuate ridges are 1 km above the surrounding plains which suggest a tectonic origin for these mountains.

Mountain peak heights and global distribution: In this study, the heights of mountain peaks have been obtained by radarclinometry, or shape-from-shading, similar to the methods used for photoclinometry. This method uses the backscatter from a given surface, to determine slopes and heights of the peaks of isolated mountains and narrow mountain chains. We assume the backscatter law for mountainous materials to be $\sigma_0(i)$ α cos (incidence angle), which gives constant backscatter across a range of incidence angles and agrees well with scatterometry results [6]. Measurements are obtained across mountain peaks of modest widths, typically <30 km.

Initial results from the radarclinometry study of 300 mountains reveals that heights range from 120 m to 3300 m, and over 200 peaks exceed 1 km in height. In comparison, the rim height of Titan's Ksa crater (D ~ 30 km) is observed to be 210 m or less, while that of Sinlap (D ~ 79 km) is observed to be 460 m or less [7]. These are somewhat lower than the rim heights of fresh craters on Ganymede, which typically range in height between 0.3 and 1.2 km for D = 30-100 km [8]. Thus, crater rim heights on Titan are lower than those of mountain belt peaks. Moreover, erosion may have brought down the crater rims and mountains from their original values. Both effects mean that for Titan, with an ice lithosphere (100 km) [9] likely as thick as Ganymede's [10], tectonism could have created mountainous features initially much higher than impact crater rims. Given that we have thus far measured 200 mountains above 1 km in height around Titan, our results favor a tectonic origin of crustal thickening rather than impact origin for many mountains on Titan.

Initial results also reveal that most peaks > 1 km are located near the equator. However, because peaks were selectively measured in mountain belts, which are generally located near the equator, there was likely a bias introduced into the global distribution analysis. In order to improve this, we are undertaking a formal statistical distribution analysis. We have divided Titan's surface into 15 quadrangles [11] and will randomly select the mountain peaks to measure using radarclinometry. Then we will utilize the Kolmogorov-Smirnov test (KS-test) on the measured mountain height data to compare the distribution of mountains in each of these 15 quadrangles and globally.

Structural mapping: Structural mapping enables us to determine mountain origins by revealing key morphologies. We have made structural maps on global and regional scales using Cassini SAR images.

Global Structure map: We mapped mountain chains with peak heights > 1 km as tectonic units and traced the strike of mountain ridges across Titan using 350 m-resolution SAR images (Fig. 2). Rose diagrams show the regional distribution of mountain belt orientations, which are length-weighted by dividing segments of constant orientation into 1 km intervals. Four regions are studied: 30 W, Xanadu, 200 W, 300 W (Fig. 2).

Structure maps of curvilinear mountain belts highlight their general west-east orientation, with a strike of two dominant orientations of 80^o and 102^o in equatorial regions at 30 W, 200 W and 300 W. The similarity of the two dominant orientations of the three equatorial mountain belts (30 W, 200 W and 300 W) suggest they may have formed at the same time and by a common process, where energy was concentrated and stress orientations were systematic. This structural analysis strongly suggests a tectonic origin for mountain belts in equatorial areas. Ridge orientations related to impact should show a random or radial rose diagram pattern.

Rose diagrams show the orientations of mountains in Xanadu vary widely (with three or four dominant directions, compared to one or two elsewhere), suggesting a long or complex tectonic history. This, in addition to the relatively high numbers of impact craters [12], indicates the tectonic features in Xanadu may have started to develop earlier than other mountain belts [3]. Alternatively, the large variation in mountain orientations in Xanadu may have resulted from emphasis of preexisting features in an elevated plateau through intensive fluvial erosion [1].

Regional structural analysis: slope, shapes, stress field and sinuosity: We analyzed the structure of mountain belts in four regions, at 200 W (Fig. 3), 130 W, 100 W and 90 W. The average slopes of mountain chains were obtained from DTMs from Cassini SAR stereo data, which also facilitates the interpretation of cross sectional profiles. The arcuate planform morphology of mountains at 200 W is similar to the structures of fold-thrust belt salients on Earth [13], which leads to the interpretion of them being thrust faults generated by compressional tectonism (Fig. 3). Salient structures can lead to map thrust belts with two dominant orientations (Fig. 4). The spacing of mountain ridges on Titan under study (and in [14]) is 50 km, which is similar to the scale of thrust belt salient structures in Pennsylvania [13].

Thus, stress field analysis of rose diagram on mountain ridges at 200 W (Figure 4) implies a north-south maximum stress (σ_1) direction and crustal shortening to generate the west-east thust belts.

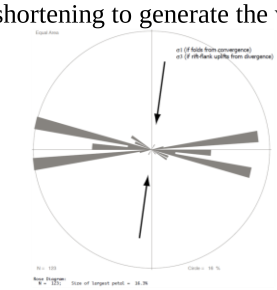
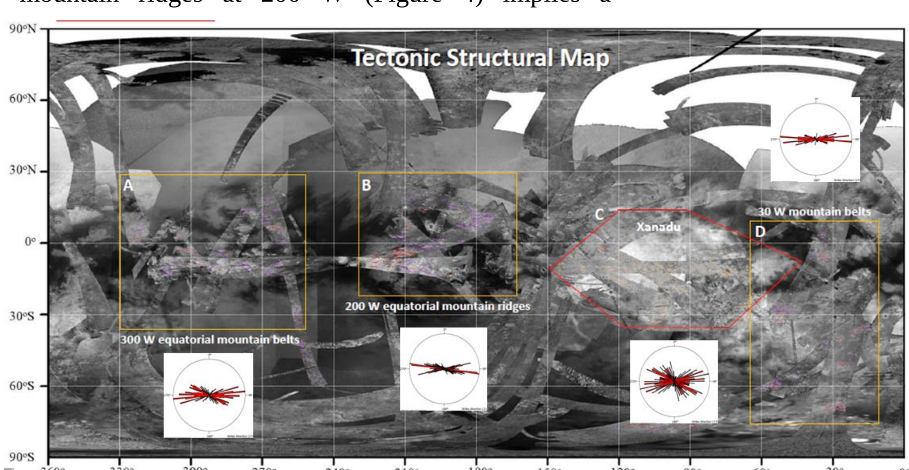


Figure 4. Stress analysis of mountain ridges at 200 W: stress arrows are (1) σ_1 if folds are formed from convergence or (2) σ_3 if rift-flank uplifts from divergence

The sinuosity ratio of the rims of Titan's Ksa and Sinlap impact craters is 2 and that of mountain belts in T61 and T8 is 1.0 to 1.3. The amount of curvature of "mountainous" rims at impact craters is higher than what we see for mountain belts, implying a nonsimilar origin for the features.

Conclusion: Mountain heights as well as global and regional scale structural and stress analyses lead us to conclude that the origin of most mountain belts on Titan is endogenic, formed by regional tectonic stresses. This conclusion is consistent with thermal modeling by Mitri et al. [14], which showed that several sets of Titan's ridges could have been formed by contractional tectonism through volume change of Titan's interior. Our structural analysis provides constraints on surficial, geological, and interior evolution and may be tested by more sophisticated global contraction or despinning and reorientation [15] models for Titan.

References: [1] Moore et al. (2011) *Icarus 212, 790-806.* [2] Paganelli et al. (2010) *LPS 41st*. [3] Radebaugh J. et al. (2011) *Icarus 211, 672-685.*[4] Wood, C. et al. (2012) *LPS* 43rd. [5] Cook and Barnes (2012) *LPS* 43rd . [6] Radebaugh J. et al. (2007) *Icarus 192,77-91.* [7] Neish et al. (2012) LPSC 43rd. [8] Bray et al. (2012) *Icarus 217, 115*.[9] Nimmo and Bills (2010) *Icarus 208, 896-904.* [10] Spohn and Schubert (2003) *Icarus 161, 456-467.* [11] Greeley and Batson (1990), *Planetary Mapping*. [12] Wood et al. (2010) *Icarus 206, 334-344*. [13] Macedo and Marshak (1999) *GSA Bulletin, v. 111; no. 12; p. 1808–1822.* [14] Mitri G. et al. (2010) *JGR, vol 115*.[15] Matsuyama and Nimmo (2011) *GRL, vol 38*.



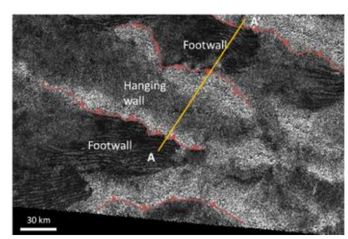


Figure 3. Regional structural analysis in 200 W ridges: the curvlinear mountain belts suggest the compressional tectonism

(Left) Figure 2. Global tectonic structural mapping and rose diagram.