THE EFFECTS OF VENUS' THERMAL CONDITIONS ON MULTIRING BASIN FORMATION.

E. Bjonnes[1], B. C. Johnson[2], and Alexander J. Evans[1], [1]Department of Earth, Environmental, and Planetary Sciences, Brown University, 324 Brook St, Providence, RI 02912, USA, [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA. (evan_bjonnes@brown.edu)

Introduction: The surfaces of Earth and Venus highlight how differently the two planets evolved: whereas Earth has portions of old and young crust separated by plate tectonic boundaries, Venus has a statistically-uniform surface age, no discernible plate boundaries [1,2], and appears to be a one-plate planet [3–5]. These differences continue to fuel debate regarding Venus' geologic history—has Venus undergone global resurfacing events, or has geologic activity been consistent and smaller-scale throughout time? A thick lithosphere will have a lower thermal gradient and resist deformation due to underlying mantle convection and, leading to a characterization of "stagnant lid." On the other hand, a thin lithosphere, termed "active lid," will have higher lithospheric thermal gradients and will be more likely to fault and fracture in response to mantle convection. Determining thermomechanical properties of a planet without surface-based measurements is challenging, but fortunately impact basin formation is sensitive to thermal and rheologic conditions at depth (e.g. [6–8]). Studying the formation of large basins on Venus may provide insights into its lithospheric thickness, and thereby lid tectonic state, at the time of basin formation.

Here we focus on the formation of Mead Basin, the largest multiring basin on Venus, to constrain its thermomechanical state. Mead has a diameter of 270 km and two circumferential ring faults at approximately 194 and 270 km [9]. The basin's rim-to-floor height is 1.1 km with the floor sitting 700 m below the surrounding terrain [10]; however, post-impact processes such as viscous relaxation or volcanic infill may have modified these elevations. We hope to establish the relationship between lithospheric thermal gradient and multiring basin ring fault location, unlikely to have been affected by post-impact modification, to determine the lid tectonic state of Venus at the time of impact.

Methods: Our goal is to determine Venus' lithospheric thickness, and thereby its lid tectonic state, by replicating the faults observed surrounding Mead Basin. To do this, we simulate impact basin formation using the shock-physics code iSALE2D [11–15]. Our models are comprised of a spherical dunite impactor between 24 and 36 km diameter striking a flat target at 17.5 km/s and vertical incidence. Our target consists of either 20 or 30 km thick basalt layer overlying a dunite mantle. All models are run at a 500 m resolution.

Temperature profiles are determined by both surface temperature and lithospheric thermal gradient. Although its surface temperature is currently 723 K, Venus may have been considerably cooler in its past [16]. Consequently, we test surface temperatures of both 350 K and 723 K. We also vary the lithospheric thermal gradient, related to lithospheric thickness and therefore lid tectonic state, between 3 K/km and 25 K/km to study extremely cold conditions (3 K/km) up to Earth-like conditions (25 K/km). In all cases, the thermal gradient transitions to an adiabat at 1400 K. We evaluate our models by determining if and where ring faults develop surrounding the impact basin and compare these results to the observed ring faults at 194 and 270 km surrounding Mead.

Results: Here we describe the results of our most Mead-like suite of tests: basins formed with a 36 km projectile impacting a Venus-like planet with the current surface temperature of 723 K and 30 km thick basalt crust (Figure 1). These basins have diameters ranging from 250–350 km and have rim-to-floor depths of 10.3–4.2 km, where cooler thermal gradients correspond to the former values and warmer thermal gradients correspond to the latter values. We find that lower thermal gradients produce narrower, deeper basins than those with higher thermal gradients. Additionally, all basins contain at least one discrete ring fault, identifiable as organized kinks in line plots such as Figure 1. Basins formed in models with higher thermal gradients develop faults farther from the basin center, and thermal gradients higher than 16 K/km show deformation style changing from discrete fault planes with high offset to instead diffuse deformation zones encompassing many faults with small displacements. These faults have displacements of 1.4–4.5 km.

Changing projectile size affects final basin morphology in accordance with established scaling relationships [17]. For smaller projectiles of 24 km or 30 km diameter, both final basin width and depth are reduced. These models also show that lower thermal gradients producing narrower, deeper basins. These smaller projectiles make basins which are notably smaller than Mead Basin, indicating that Mead likely formed from a projectile that was larger than 30 km wide.

We find that characteristic ring faults matching those surrounding Mead Basin only form under certain thermal conditions. For a 723 K surface temperature, characteristic ring faults form at observed locations only if the lithospheric thermal gradient is 10 K/km or less (Figure 1). This finding holds for both 20 km and 30 km

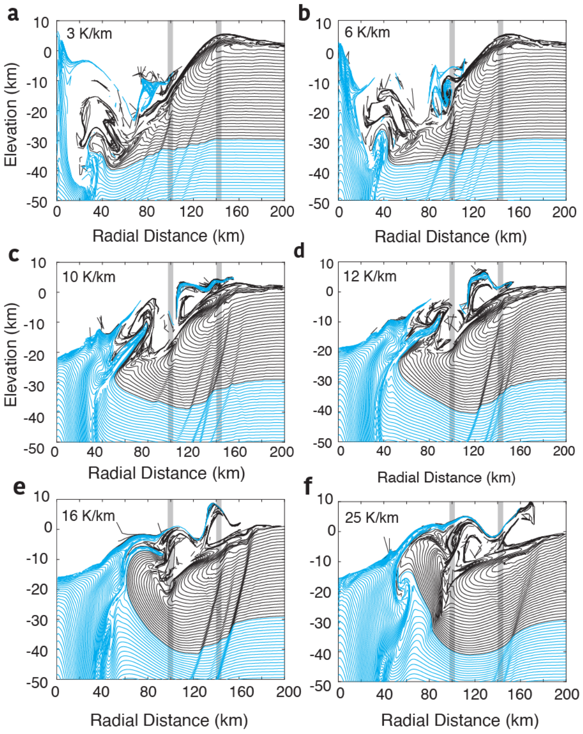

Figure 1: 3x vertically exaggerated plots highlighting the relationship between ring fault locations and the lithospheric thermal gradient (top left). Vertical gray bars approximate the current surface locations of Mead Basin's ring faults. All plots are taken 500 seconds after impact, after the ring faults develop but before the final basin development has completed. Tracer lines indicate composition, with black lines representing a basalt crust and blue lines representing a dunite mantle. Tracer lines are initially horizontal and spaced 1 km apart.

crustal thickness. Conversely, for 350 K surface temperature, the upper limit of consistent lithospheric thermal gradients increases to 14 K/km.

Discussion: These results showcase the relationship between ring fault development and material strength in Venus' lithosphere. Strength is affected by both composition and temperature, and both lowering the surface temperature and thinning the crust increase overall lithospheric strength. Replicating Mead's ring faults in a stronger lithosphere, either through thermal or compositional variation, shifts the maximum thermal gradient from 10 K/km to 14 K/km to replicate the observed fault locations.

We can use these findings of maximum thermal gradient to then estimate surficial heat flow on Venus. With a basalt thermal conductivity of 2 W m^{-1} K^{-1}, a lithospheric thermal gradient of 14 K/km corresponds with surficial heat flows of approximately 30 mW m^{-2}. For a lower surface temperature of 350 K, lithospheric thermal gradients of up to 25 K/km are possible and give surficial heat flow estimates of up to 50 mW m^{-2}. Although these surficial heat flow estimates are lower than heat flows on Earth, these estimates are consistent with other Venusian features such as Maxwell Montes [18]. The other three impact basins on Venus also show similar 2-ring morphologies, suggesting that similar strength constraints from Mead Basin also apply to these smaller multiring basins.

Conclusions: Venus, although very similar to Earth in many ways, has undergone a very different geologic evolution. There are several smaller multiring basins across the surface of Venus, implying that our findings for Mead Basin are applicable to the rest of the planet. By using multiring basin morphology which is more sensitive to rheologic conditions at depth within the planet, we are able to show that Venus would have had a thick and likely stagnant lid at the time Mead Basin formed.

Acknowledgments: We acknowledge and thank the developers of iSALE-2D (www.isale-code.de) and pySALEplot, including Gareth Collins, Kai Wünnemann, Dirk Elbeshausen, Tom Davidson, Boris Ivanov, and Jay Melosh.

References: [1] Kaula, W. M. and Phillips, R. J. (1981) Geophys. Res. Lett., 8, 1187–1190. [2] Solomon, S. C. et al. (1992) J. Geophys. Res. Planets, 97, 13199–13255. [3] McKinnon, W. B. et al. in: Bougher, S.W. et al. (Eds.), Venus II, University of Arizona, Tucson, AZ (1997), pp. 969–1014. [4] Phillips, R. J. et al. (1992) J. Geophys. Res. Planets, 97, 15923–15948. [5] Strom, R. G. et al. (1994) J. Geophys. Res. Planets, 99, 10899–10926. [6] Ivanov, B. A. et al. Large Meteorite Impacts and Planetary Evolution IV, Geological Society of America (2010), pp. 29–49. [7] Miljković, K. et al. (2013) Science, 342, 724–726. [8] Johnson, B. C. et al. (2016) Science, 354, 441–444. [9] Alexopoulos, J. S. and McKinnon, W. B. in: Dressler, B.O. et al. (Eds.), Large Meteorite Impacts and Planetary Evolution, Boulder, CO (1994), pp. 29–50. [10] Herrick, R. R. and Sharpton, V. L. (1996) Geology, 24, 11–14. [11] Amsden, A. A. et al. SALE: A Simplified ALE Computer Program for Fluid Flow at All Speeds, Los Alamos National Laboratories Report, Los Alamos, NM (1980). [12] Collins, G. S. et al. (2004) Meteorit Planet Sci, 39, 217–231. [13] Melosh, H. J. et al. (1992) J. Geophys. Res. Planets, 97, 14735–14759. [14] Ivanov, B. A. et al. (1997) Int. J. Impact Eng., 20, 411–430. [15] Wünnemann, K. et al. (2006) Icarus, 180, 514–527. [16] Way, M. J. and Genio, A. D. D. (2020) J. Geophys. Res. Planets, 125, e2019JE006276. [17] Melosh, H. J. Impact Cratering: A Geologic Process, Oxford University Press, New York (1989). [18] James, P. B. et al. (2013) J. Geophys. Res. Planets, 118, 859–875.