PLUMES AS A MECHANISM FOR EQUILIBRIUM RESURFACING OF VENUS. V. L. Hansen[1] and D. A. Young[2], [1,2]Department of Geological Sciences, University of Minnesota Duluth, Duluth, MN 55812 (vhansen@d.umn.edu; dyoung1@d.umn.edu).

Introduction: Venus hosts ~1000 apparently pristine impact craters distributed in near random fashion [1-3]. Two hypotheses have been proposed to account for crater observations: 1) catastrophic volcanic resurfacing [4], and equilibrium (steady state) volcanic resurfacing [5]. Neither hypothesis addresses all aspects of the crater database, and both assume that craters are removed only through volcanic burial. We propose that crater destruction by crustal annealing allows consideration of a hybrid hypothesis for Venus surface evolution.

Average model surface ages: Scientists have yet to unravel the significance of Venus'~1000 impact craters [1,2]. Attempts to date geologic units using crater density [6-9] lack statistical validity; crater densities cannot reflect unit formation ages [10]. Crater densities reflect average model surface ages (AMSA), AMSA is non-unique and, as such, a single AMSA value allows many possible surface histories (for example: a) catastrophic resurfacing at t=AMSA; b) 50% of surface forming at 0.5t and 50% forming at 1.5t; or c) 20% of surface forming at 2t and 80% forming at 0.75t).

Venus' impact craters yield a global AMSA of ~750 +350/-400 Ma [12]. End member hypotheses include: 1) catastrophic volcanic resurfacing (CVR) [4], 2) or equilibrium volcanic resurfacing (EVR) [5]. Given that these hypotheses are statistically indistinguishable we must consider geologic relations, which requires more information about the details of each hypothesis.

Existing Hypotheses: The CVR hypothesis is integral to a global stratigraphic interpretation of Venus history that calls on early global tessera formation and resulting crater destruction, followed by warping and crustal thickening forming local topographic highs (thick crust), and broad lowland regions that later collect thick volcanic flows [13,14]. CVR (occurring within 10-100 m.y.) filled lowland regions with flood-like lava flows ~1-3 km thick. Tessera is preserved at high elevation and covered by flood-lava at low elevation. Wrinkle ridges deform thick lava flows (called wrinkle ridge plains, unit *pwr*). This hypothesis predicts that tessera-formation destroyed early-formed craters. During the time between tessera formation and CVR new craters formed. CVR resulted in complete burial of lowland craters, whereas craters formed on elevated tessera survived. Following CVR new craters accumulated across the planet. The CVR hypothesis predicts that elevated tessera (preserved in crustal plateaus) should have higher crater density than *pwr*.

The EVR hypothesis [5] calls for steady-steady crater formation and burial through local volcanic activity at a scale of ~10x10^6 km^2. EVR does not address tessera formation.

Where EVR fails. Geologic mapping reveals few embayed (meaning covered or partially covered by surface lava flows) or deformed craters [15], observations generally been taken to support CVR over EVR. The argument: EVR calls for synchronous volcanism and crater formation providing ample embayment opportunities; thus a lack of embayed craters might indicate that EVR *did not* occur—(apparently) supporting CVR; but lack of support for one hypothesis is not support for another [16].

Both hypotheses make at least one, typically unstated, assumption: that craters can *only* be destroyed by volcanic burial. Given crater trough-to-rim heights of >0.2-1.5 km [*17*], complete crater burial requires thick lava units. However, there is very little data to support the presence of thick local (or regional) lava flows. Much mapping highlights evidence of relatively thin lava flows [e.g., 18-21].

Where CVR fails. Geologic arguments against CVR, yet favoring EVR, also exist. *Phillips & Izenberg* [22] compared crater density and morphology, specifically, whether craters had halos, or not. Their analysis reveals 3 average surface age provinces (ASA): young ASA (<1.5 craters/10^{6}km^2 *and* halo deficiency), intermediate ASA (2.5-1.5 craters/10^6 km^2 *and* no halo deficiency) and old ASA (>2.5 craters/10^{6}km^2 *and* halo deficiency). (Note: ASA is not the same as unit age). These workers assumed that halos, but not craters, disappear with time, and that volcanic resurfacing destroys both craters *and* halos. Young ASA correlates with Beta-Atla-Themis (BAT) and Lada volcanic provinces—regions marked by tectonism and constructional volcanism [23,*24*]. The occurrence of distinct ASAs is inconsistent with CVR, yet allowed by EVR. Thus robust arguments exist against both CVR and EVR hypotheses.

What can ASA tell us? Comparison of ASA with geologic provinces yields the following: 1) young ASA correlates with BAT-Lada regions; 2) old ASA correspond spatially to Phoebe Regio and 3 large regions of *pwr*; and 3) crustal plateaus and volcanic rises (except Phoebe) correlate with intermediate ASA. Additionally, *Price et al.* [6] noted slightly *higher* crater density associated with *pwr* compared to tessera (they noted this could be due to a lack of small craters on tessera, or within statistical variance). *Gilmore et al.* [30] indicated that tessera on average has crater density slightly higher than the global plains; however, they included the low-density BAT-Lada regions (young ASA) with the plains. Thus, based on these independent analyses there is no strong evidence to require, much less support, an interpretation that tessera is the oldest venusian unit or surface, a relation that would seem to be required by the global stratigraphic model (including CVR).

An Alternative Working Hypothesis. End member hypotheses only considered crater removal only by burial, yet studies indicate that craters may have been removed by crustal annealing [25,26]. Although crustal plateau formation is controversial, the plume hypothesis argues that crustal plateaus mark the surface signature of deep mantle plumes on relatively thin lithosphere [25-29]. This hypothesis calls for annealing of the crust above the plume head; plume heat places the overlying lithosphere in ductile flow effectively erasing pre-existing structures, including craters. Continued plume-lithosphere interaction results in crustal thickening. The area cools from the surface down; a strong surface membrane that develops with cooling records plume-lithosphere deformation; the membrane increases in thickness as the brittle-ductile transition moves deeper tracking the decaying thermal gradient [25-29,31]. The surface above a plume would be reset to ASA 0 during 'thin-lithosphere-time' at the site of plume-lithosphere interaction. The areal extent of crustal plateaus (~5-10x10^6km^2) is similar in size to the resurfacing area required by the EVR hypothesis.

Combining aspects from different resurfacing-evolution hypotheses we assemble a hybrid hypothesis that addresses all known aspects of Venus impact craters characteristics. During thin-lithosphere time crater formation and destruction are in steady state. Plumes impinging on the lithosphere anneal preexisting structures including craters; each plume leaves behind a crustal plateau, marked by tessera-ribbon terrain and thickened crust; plateaus topographically collapse with time [32]; local volcanism emplaces thin flows that embay and locally cover tessera fabrics, but topographically majestic craters remain relatively pristine [17]. At some point the global lithosphere transitions from thin to thick, likely accompanied by a move from mobile to stagnant lid [26]. At this point recently formed crustal plateaus would host few (if any) craters, whereas the rest of the planet would display a steady-state crater density. The majority of the planet would also be relatively radar smooth, the result of local volcanic processes. With the switch from globally thin to thick lithosphere recently formed crustal plateaus would be topographically 'locked' in, unable to collapse, and relative craters density (low at crustal plateaus, high elsewhere) would be preserved. But Venus' history did not stop there. Volcanic and tectonic activity became concentrated in BAT-Lada regions [23,24], where craters and halos were buried, thus displaying young ASA [22]. Volcanic rises formed on old ASA, but local young volcanic activity might lower the ASA to an intermediate ASA similar to the crustal plateaus that formed soon before lithosphere thickening. This hybrid hypothesis, which can accommodate all crater observations made to date by many workers, makes a number of testable predictions that can be tested by Monte Carlo simulations, flooding experiments, analytical and finite elements models, and a host of geologic mapping studies.

References: [1] R.J. Phillips et al., JGR 97, 15923-15948 (1992). [2] G.G. Schaber et al., JGR 97, 13257-13302 (1992). [3] S.A. Hauck, R.J. Phillips, M.H. Price, JGR 103, 13635-13642 (1998). [4] R.G. Strom, G.G. Schaber, D.D. Dawson, JGR 99, 10899-10926 (1994). [5] R.J. Phillips, Eos 74(16), 187 (1993). [6] M.H. Price, G. Watson, C. Brankman, JGR 101, 4657-4672 (1996). [7] N. Namiki & S.C. Solomon, Science 265, 929-933 (1994). [8] M. Price & J. Suppe, Nature 372, 756-759 (1994). [9] A.T. Basilevsky & J.W. Head, Geology 30, 1015-1018 (2002). [10] B.A. Campbell, JGR 104, 21951-21955 (1999). [12] W.B. McKinnon et al., in Venus II (U. AZ Press, 1997) 969-1014. [13] A.T. Basilevsky & J.W. Head, JGR 103, 8531-8544 (1998). [14] J.W. Head & A.T. Basilevsky, Geology **26**, 35-38 (1998). [15] R.R. Herrick et al., in Venus II (U. AZ Press, 1997) 1015-1046. [16] T.C. Chamberlin, J. Geol. 5, 837–848 (1897). [17] R.R. Herrick & V.L. Sharpton, JGR 105, 20245-20262 (2000). [18] H.R. Deshon, D.A. Young, V.L. Hansen, JGR 105, 6983-6995 (2000). [19] K. Bender, D. Senske, R. Greeley, USGS, I-2620, 1:5M, (2000). [20] E. Rosenberg & G.E. McGill, USGS, I-2721, 1:5M, (2001). [21] B.A. Campbell & P.G. Campbell, USGS, I-2743, 1:5M, (2002). [22] R.J. Phillips & N.R. Izenberg, GRL 22, 1517-1520 (1995). [23] J.W. Head et al., JGR 97, 13153-13198 (1992). [24] L.S. Crumpler et al., in Venus II (U. AZ Press, 1997) 697-756. [25] V.L. Hansen & J.J. Willis, Icarus 132, 321-343 (1998). [26] R.J. Phillips & V.L. Hansen, Science 279, 1492-1497 (1998). [27] R.R. Ghent & V.L. Hansen, Icarus 139, 116-136 (1999). [28] V.L. Hansen, B.K. Banks, R.R. Ghent, Geology 27, 1071-1074 (1999). [29] V.L. Hansen et al., JGR 105, 4135-4152 (2000). [30] M.S. Gilmore et al., JGR 102, 13357-13368 (1997). [31] C.D. Brown & R.E. Grimm, Icarus 139, 40-48 (1999). [32] D.C. Nunes et al., JGR 109 (2004).