ANOMALOUS RADIAL STRUCTURES AT IRNINI MONS, VENUS: A PARAMETRIC STUDY OF STRESSES ON A PRESSURIZED HOLE. D.L. Buczkowski, G.E. McGill and M.L. Cooke, University of Massachusetts, Amherst, MA, 01003, dbucz@geo.umass.edu, gmcgill@geo.umass.edu, cooke@geo.umass.edu

Observations: The V-20 quadrangle [1] is roughly centered on Irnini Mons, a volcano crossed by two rift systems, capped by Sappho Patera (a possible corona) and surrounded by structural complexities that include one other volcano and 4 coronae. Flows and other deposits from Irnini Mons are superimposed on an older, regional plains material with abundant wrinkle ridges in at least two sets: one trending generally east-west and another concentric to Irnini Mons. Radial features on top of the Irnini flows were mapped as lineations or grabens [1], as resolution allowed. However, from approximately N45E to N75E the difference in radar backscatter in high resolution images (75 m/pixel) indicates that the radial features are topographic highs, although they are too narrow to be resolved in altimetry data sets. The radial ridges are located on top of the Irnini flows, occurring between a set of radial grabens to the north and a small ridge belt to the south, interpreted by [1] as older than the adjacent regional plains.

Effects of Magma Pressure on a Hole: Radial grabens around a volcano have been explained mathematically [2,3,4]; the magma chamber of a volcano is simplistically described as a pressurized hole in an elastic plate. An empty hole in an elastic plate perturbs a regional stress field close to the hole, although not at infinity. For volcanoes, the change in material properties from the surrounding rock to a magma-filled chamber allows us to consider the chamber as "soft" and thus effectively empty. Equations (compression positive) have been derived [2] to describe the radial stresses σ_{RR} and circumferential stresses $\sigma_{\theta\theta}$ that result around the pressurized hole, where P is magma pressure, R is the magma chamber radius, r is the distance from the center of the hole, σ_{11} and σ_{22} are the regional stresses and θ is the orientation around the hole, relative to its center.

$$\sigma_{RR} = P\left(\frac{R}{r}\right)^2 + \frac{1}{2}(\sigma_{11}+\sigma_{22})\left(1-\left(\frac{R}{r}\right)^2\right) + \frac{1}{2}(\sigma_{11}-\sigma_{22})\left(1-4\left(\frac{R}{r}\right)^2+3\left(\frac{R}{r}\right)^2\right)\cos 2\theta$$

$$\sigma_{\theta\theta} = -P\left(\frac{R}{r}\right)^2 + \frac{1}{2}(\sigma_{11}+\sigma_{22})\left(1+\left(\frac{R}{r}\right)^2\right) - \frac{1}{2}(\sigma_{11}-\sigma_{22})\left(1+3\left(\frac{R}{r}\right)^2\right)\cos 2\theta$$

$$\tau_{R\theta} = \frac{1}{2}(\sigma_{11}-\sigma_{22})\left(1+2\left(\frac{R}{r}\right)^2-3\left(\frac{R}{r}\right)^4\right)\sin 2\theta$$

If regional stresses are negligible, these equations predict radial grabens and circumferential ridges everywhere around the hole.

Effects of a Uniaxial Regional Compressive Stress on a Pressurized Hole: Magma pressure alone can not explain the presence of radial ridges. However, the regional east-west (±20º) trending wrinkle ridges imply that at one time a regional north-south compression affected the Irnini Mons area. If this compression was ongoing while Irnini Mons was active, the regional stress field would be perturbed around the Irnini magma chamber. The perturbation of a uniaxial, north-south regional compressive stress σ_{11} around a pressurized hole is such that at angles 0º (north) and 180º (south) the maximum principal stresses close to the hole are tensile, while at angles 90º (east) and 270º (west) the maximum principal stresses close to the hole are compressive. The angle θ at which maximum principal stresses change from tension to compression depends upon the distance from the hole and the relative magnitudes of magma pressure and the regional compression. A parametric study was performed to see what effect changes in P and σ_{11} had on the magnitude of the maximum principal stresses and the orientation of resulting features.

Structures will only form where the maximum principal stresses are greater than the strength of the material. The brittle strength of Venus rocks are fairly well constrained to -0.2 to -2 MPa [5], but the compressive strength ranges anywhere between <10 to 50 MPa [5]. The existence of the wrinkle ridges implies that at some point the regional compression exceeded the compressive strength, so for this study it was assumed that σ_{11} is equal to compressive strength, except where noted otherwise.

1) If magma pressure and the regional N-S compression are equal then the model predicts that both ridges and grabens form radial to the volcano. Regardless of magma pressure and regional compression magnitude, grabens form radially north and northeast, but the distance these grabens extend from the volcano is dependent upon magma pressure magnitude (greater P yields longer grabens). Ridges form radial to the volcano from N55E to N80E, regardless of the magnitude of the stresses. These stress parameters also indicate that north-south trending ridges should form from N40E to N55E, eventually curving toward the west from N30E to N40E.

2) If magma pressure magnitude is twice the regional N-S compression, grabens can form to greater lengths to the north than when P and σ_{11} are equal, but their lengths are shortened to the northeast. The region of radial ridges is reduced to N55E to N70E.

3) If the regional N-S compression is twice magma pressure, graben lengths to the north are reduced significantly, although they still extend some distance to the northeast. These stress parameters enable radial ridges to form from N55E to due east.

4) If the regional N-S compression is twice magma pressure, but less than the compressive strength, ridge location is different from case 3. Unlike situations where regional compression = compressive strength, the ridge extent is limited. Radial ridges are still found from N55E to due east (as in case 3), but the distances they extend from the magma chamber are curtailed with increasing compressive strength. When the compressive strength is more than 5 MPa greater than σ_{11}, no ridges will form. With these stress parameters, the regional set of wrinkle ridges has stopped forming before radial ridge formation occurs.

Effects of Multiple Pressurized Holes: While in the simple model resultant stresses would be symmetric around the hole, structural complexities to the south and west of Irnini Mons restrict the predicted pattern of radial ridges as well as grabens to the region northeast of the volcano. Incorporating these complexities into the model can increase our understanding of the sequence of events that resulted in the observed features.

Anala Mons is a volcano located to the south of Irnini Mons and can be modeled as due to a second pressurized hole. Previous models have explored the perturbation of regional stress fields around multiple, interacting holes [3]. Anala Mons is roughly aligned with Irnini Mons parallel to the direction of regional compression; the interaction of the two holes should yield grabens in those areas between the two holes where perturbation of the regional stress field around a single hole would yield radial ridges [3]. These graben are not radial to either hole, but rather connect them. Thus the lack of either radial ridges or graben to the southeast and southwest of Irnini is consistent with the model.

Effects of a Regional Extensional Stress: Extending roughly north-south through Irnini Mons (and Anala Mons) is the rift system Badb Linea. There are indications that this rift was active both before and after flows from the volcano. Although this rift was due to local extension, for areas close to Irnini the rift extension can be modeled as a regional east-west tensile stress, σ_{22}.

The perturbation of a uniaxial, east-west regional tensile stress σ_{22} around a pressurized hole yields radial grabens everywhere around the hole when σ_{22} magnitude equals the material's brittle strength (-2 MPa); the radial compressive stress produced does not exceed the compressive strength of the material, and no circumferential ridges form. This pattern continues as long the absolute value of the magnitude of σ_{22} is less than 9 MPa, regardless of the magnitude of P. However, when the absolute value of σ_{22} magnitude is greater than 9 MPa, radial grabens occur only to the north; as the orientation around the hole θ approaches N90E, the orientation of the grabens changes from radial to the hole, to E-W trending, to circumferential to the hole. The predictions of this model are not observed near Irnini Mons.

Adding a tensile E-W σ_{22} to a compressive N-S σ_{11} yields radial ridges and radial graben, similar to those produced by a uniaxial compressive N-S σ_{11}. However, the model now also predicts short circumferential graben due east of the magma chamber, starting several r/R away from its center. Unlike in the uniaxial, east-west, tensile σ_{22} model, these circumferential grabens are limited in length, occur far from the volcano, and are not connected to the radial graben to the north by an east-west trending set of graben.

There are, in fact, circumferential grabens around Irnini Mons. The most obvious is a set of large (up to 120 km long, 6 km wide) circumferential graben at the summit of the volcano, which are probably due to collapse of the magma chamber. However, there is also a set circumferential graben down the Irnini slope which first appear more than 130 km to the east of the summit circumferential graben, and are less than 50 km long and 1 km wide. This short set of graben fit a model in which Badb Linea rifting and Irnini magma pressure were occurring concurrent with a north-south regional compression.

Possible Timeline of Events: Thus, the existence of radial ridges on the Irnini flows implies that the regional north-south compression that caused the east-west trending wrinkle ridges was still active during the formation of Irnini Mons. A rough timeline for events in the region could be: 1) formation of east-west wrinkle ridges on regional plains, 2) coeval formation of graben radial to Irnini due to magma pressure and formation of radial ridges due to a combination of magma pressure and ongoing regional compression, 3) start of Badb Linea rifting and possible lessening of regional compression encourages graben formation at a broader range of azimuths, 4)cessation of magma pressure and formation of concentric grabens at summit, and 5) formation of concentric wrinkle ridges, perhaps due to gravitational relaxation of the topographic rise.

References: [1] McGill G.E. (2000) *USGS, Geo. Inv. Map I-2627*. [2] Jaeger J.C. and N.G.W. Cook (1979) *Fundamentals of Rock Mechanics*, Chapman Hall. [3] McKenzie D. et al. (1992) *JGR, 97*, 15,977-15,990. [4] Koenig E. and D.D. Pollard (1998) *JGR, 103*, 15,183-15,202. [5] Schultz R.A. (1993) *JGR, 98*, 10,883-10,895.