CALDERAS ON VENUS AND EARTH: COMPARISON AND MODELS OF FORMATION.

A. S. Krassilnikov[1, 2] and J. W. Head[2]; [1]Vernadsky Institute, Moscow, 119991, Russia, kras@geokhi.ru, [2]Department of Geological Science, Brown University, Providence, RI, 02912, USA

Introduction. Calderas on Earth are defined as large, more or less circular, volcanic collapse depressions with diameters considerably larger than any included vent [1,2] resulting from collapse into partially drained near-surface magma reservoir [2]. They have been defined as having diameters >1 km [3], with smaller depressions being called craters. Usage of the term caldera includes features described as "cauldrons", which represent a variably deeper erosional level of the same fundamental structures [4, 5]. Three morphological classes are important on the Earth [2]: basaltic shield volcano calderas, Crater-lake-type of calderas, and ash flow calderas. Calderas on Venus are described as "circular to elongate depressions not associated with a well-defined edifice and are characterized mainly by concentric patterns of enveloping fractures" [6]. They are most common 40-80 km in diameter [6-8]. The "Catalog of Volcanic structures of Venus" [7] includes 97 calderas. Our goals are to compare venusian and terrestrial caldera geology, topography and mechanism of formation.

Methods. We used our observations and previous work for analysis of venusian calderas [6-8]. We have studied the topography and geology of all 97 calderas from the list [7] and their surroundings by way of detailed geological mapping [8]. For comparison with terrestrial calderas we summarized aspects of terrestrial caldera formation using models of caldera formation [5,9], maps and description of typical calderas [10-12], and overviews of calderas formation and classification [2,5,9].

Observations.

(I) Diameter. Venus: The average diameter of calderas from "Catalog" [7] is 67.8 km, with a standard deviation of 36 km. Earth: Quaternary calderas vary widely in size (1.6-over 50 km), with 94% of examples being less than 20 km [5]. Shield calderas comprise about 65% of calderas with diameters D<2 km, but the frequency declines fairly rapidly to 0% at D=20 km. Stratovolcano calderas are the dominant class of terrestrial caldera in the range D=20 km. Ash flow calderas first occur at D=5 km, rise to dominance at D=13 km, and account for all tabulated terrestrial calderas with D>20 km [2,13,14].

(II) Topography. Venus: 53% of calderas are represented by simple depressions, 11% have an irregular flat shape, 6% are depressions with a very low rim (Fig. 1,4), 1% are dome-like, and 29% have insufficient topo data for analysis. The depth of caldera depressions is usually hundreds of meters, up to 1 km. Earth: Uneroded calderas usually have a prominent topographic rim and inner topographic wall [5,9].

(III) Tectonic structures. Venus: 4 sets of tectonic features are observed [8]: 1) Concentric extensional structures are observed in 63% of calderas; 2) Concentric extensional fracturing and radial compressional structures inside and/or outside of the concentric fracturing are observed in 29% and, in some cases, concentric ridges inside depressions are observed; 3) 7% of calderas have concentric and radial extensional fracturing; and, 4) 1% have radial fracturing only. Most characteristic concentric extensional fracturing of calderas is dense, fracture to fracture spacing is usually 200-300m or less, and is located in a broad belt (30-50 km wide) on the slope of the depression. In some cases the influence of regional stress on the distribution of fracturing is identified. Earth: Bounding caldera faults are mostly gravitational in nature formed by reservoir subsidence. Ring faults can accommodate uplift as well as subsidence [5]; ring dike formation often has a connection with fault formation. Ring faults may be vertical, inward and/or outward [5,9]. At many calderas regional tectonic trends have influenced the geometry of collapse to varying degree [5,9].

(IV) Associated volcanism. Venus: Unlike calderas on Earth, Venus calderas show almost no evidence for formation by collaps on the summit of an individual large edifice. Secondary shield volcanoes (smaller associated volcanoes) are associated with 47% of calderas, extensive lava flows with 24%, both are associated with 17%, and 12% show no volcanic activity. Calderas also have related pit craters, pit chains and canali. Most volcanic activity has a connection with dense concentric fracturing. Earth: 1) Basaltic shield volcano calderas. The summit regions of many active shield volcanoes are marked by calderas (e.g. Makuaweoweo caldera, Maona Loa volcano). It is generally believed that shield caldera formation is due principally to drainage of magma rather than explosive removal of it from a magma chamber [2]. Instead, they subside in increments to produce a nested structure of pits and terraces. Basaltic calderas like these are gradually enlarged by episodic collapse due to the extraction of lava from shallow-level magma reservoirs underlying the summit areas. Shield calderas form in basaltic volcanoes, with tholeiites being typical rock types for both large and small shields, sometimes in aluminious basalts and basaltic andesites [2,15]. 2) Crater-lake-type of calderas is generated after the main phase of a Plinian eruption, during collapse of a stratovolcano (Mt. Mazama in Crater-lake caldera) into the void of the underlying, depleted magma chamber. Although the waning phase of a Plinian eruption is often associated with the generation of pyroclastic flows, piston-like collapse of the volcanic edifice can be related to the additional eruption of voluminous (0.1-100 km^3), pumice-dominated sheet flows along ring fractures surrounding the collapsing mass. These sheet flows form thick deposits of ignimbrite, the hallmark of both Crater-lake-type and ash flow calderas. Caldera formation has occurred two or more times in many stratovolcanoes; many stratovolcanoes have a caldera as their final evolutionary stage. These stratocone calderas usually form in volcanoes made of basaltic andesite or andesite, with occasional basaltic, trachytic, and phonolitic structures [13]. Ejecta associated with caldera formation is typically dacitic to rhyolitic. 3) Ash flow calderas result from collapse following the eruption of extremely large (100-1000 km^3) volumes of dacitic to rhyolitic ash flows (e.g. Yellowstone caldera). These calderas are the largest,

and most were not formed on existing massive volcanoes. Ash flow calderas also dominantly erupt dacite to rhyolitic ignimbrite or alkalic rocks. Many calderas larger than about 20 km diameter have resurgent centers, apparently updomed during or by the refilling of the underlying magma reservoir [2,16]. With diameters ranging from 15 to 100 km, resurgent calderas dwarf those of the Crater-lake-type. They are similar to Crater-lake-type calderas in that they are also generated by crustal collapse above shallow magma reservoirs. Resurgent calderas, however, are too large to have been associated with a Crater-lake-type central volcano. Apart from their large size, the definitive feature of resurgent calderas is a broad topographic depression with a central elevated mass resulting from post-collapse upheaval of the caldera floor. The caldera floor is typically filled with rhyolitic lavas, obsidian flows, and domes. The uplifted centers often contain elongate rifts (graben) along their crests.

(V) Subsidence depth. Venus: In most cases the caldera depression is not totally covered by lava plains [8], and depth of subsidence is no more than 1 km, in a few cases 1.5 km. Earth: Almost in all cases calderas are filled by lavas and ash deposits, the best solution for total subsidence depths at large calderas (excluding ash deposits) are typically at least 3-4 km, sometimes more [5,9].

(VI) Resurgence. Venus: There is no structural evidence for resurgence [8]. Only volcanism is observed after caldera subsidence. Earth: Many terrestrial calderas have traces of resurgence; e.g. Yellowstone caldera has two resurgent domes [17].

(VII) Geodynamic position. Venus: Calderas are clustered in Atla-Beta-Themis triangle [6,7,8]. On Venus (one-plate planet) we can correlate caldera location with location of rift systems only [8]. Eighty-three percent of calderas are located outside of rifts and/or fracture belts, and only 17% are located inside rifts and/or fracture belts. Earth: Shield calderas are most common at ocean hot spots such as Hawaii, Galapagos, etc. [2]. Smaller shields also occur at subduction zones (Oregon, California) and spreading centers. Most of Crater-lake-type calderas occur at subduction zones, at extensional zones/rifts, and at both oceanic and continental hot spots [2]. Ash flow calderas are concentrated mostly at subduction zones and rifts [2].

Interpretation and discussion. 1) The average diameter of venusian calderas is more than twice that of terrestrial examples; therefore their formation should have a connection with the evolution of larger magmatic reservoirs than on Earth or be due to other causes. Only a few terrestrial calderas connected with uplift of large magmatic diapirs (as Yellowstone caldera) may be compared in size with venusian ones. 2) A smaller depth of subsidence in venusian calderas is evidence for rather small volume of melt in formation of these calderas (and/or deep position of reservoir) relative to terrestrial structures, whose formation is connected with collapse of rather small magmatic reservoir inside the crust. 3) Both venusian and terrestrial calderas have similar sets of tectonic structures, but concentric fracturing of venusian calderas is much more dense and prominent in a wider area at the caldera periphery. Also, venusian calderas tectonic features are observed which are not usual for terrestrial calderas: radial compressional structures and sometimes radial extensional fracturing. Formation of these tectonic features on Venus is usually described as traces of influence of evolving magmatic diapirs [6,18-20]. 4) Most of the volcanic activity of venusian calderas is connected with dense concentric fracturing, which is evidence for transport of melt to the surface through this fracturing, or for possible formation of this fracturing by ring dikes. 5) All venusian calderas, opposite to the majority of terrestrial ones, have no connection with collapse of a volcanic construct. 6) We do not see traces of resurgence in venusian calderas. 7) Most of venusian calderas have no association with rifts. Their spatial distribution with a concentration in Atla-Beta-Themis region [7-9] is not distinguished from distribution of coronae and arachnoids, which are believed to be produced by diapiric uplift [18-20]. 8) The topographical shape and tectonic structures of venusian calderas are evidence for a downsag subsidence model of formation of these calderas [5,9]. Some calderas have an asymmetric topographical profile, which is evidence for possible trap-door subsidence [5,9]. Both of these models favor deep magma chambers and/or small eruptive volumes [5,9].

Summary. Summarizing all observation and interpretations we see evidence that formation of venusian calderas occurs under different conditions than the majority of terrestrial calderas. Formation of venusian calderas appears to be related to evolution of large magmatic diapirs and a small volume of pressure release melting in a diapir head perhaps due to thicker lithosphere than on Earth, similar to arachnoid and coronae on Venus [18-20]. The morphology of sets of tectonic structures, topography, and also volume and style of volcanism may be evidence for formation of concentric fracturing due to downsag or trap-door subsidence and ring dike emplacement from a rather small and deep magmatic reservoir on the diapir head. In this case formation of venusian calderas may be mechanically similar to formation of large cauldrons [14] and large ash flow calderas (as Yellowstone) on Earth above large magmatic diapirs without previous formation of large strato- or shield volcano. The difference in style of volcanic eruption is also influenced by the low likelihood of explosive eruption on Venus [21], that leads to the possible replacement of ash deposits in terrestrial calderas by lava flows in venusian volcanic structures.

Acknowledgements. The authors thank A.T. Basilevsky for help and RFBR grant # 02-05-65068 for support.

References. [1] Williams H (1941) *Univ. Calif. Berkley Pub. Geol. Sci., 25,* 239-346. [2] Wood C.A. (1984) *JGR, 89,* 8391-8406. [3] Francis P. (1976) Volcanoes, 368 pp., Penguin, Middlesex, England. [4] Elston W.E. (1984) *JGR, 89,* 8733-8750. [5] Lipman W.P. (1997) *Bull Volcanol, 59,* 198-218. [6] Head J.W. et al. (1992) *JGR, 97,* 13153-13197. [7] Crumpler L.S. and Aubele J.C. (2000) in *Encyclopedia of Volcanoes,* Acad. Press. [8] Pace K.R. and Krassilnikov A.S. (2003) *LPS XXXIV,* 1309. [9] Lipman W.P. (2000) in *Encyclopedia of Volcanoes,* Acad. Press. [10] Bacon et al. (1997) *USGS Open File Report, 97-487*. [11] Gardner et al. (2001) *U.S. Geol. Surv. Water Resources Inv. Rep. 01-4046,* scale 1:15 000. [12] Christiansen R.L. (2001) *U.S. Geol. Surv. Prof. Paper, 729-G*. [13] Pike R.J. and Clow G.D. (1981) *U.S. Geol. Surv. Open File Rep., 81-038,* 40 pp. [14] Pike R.J. (1978) *Proc. LPS IV,* 3239-3273. [15] Taylor E.M. (1980) *Bull. Oreg. Dep. Geol. Miner. Ind., 101,* 7. [16] Smith R.L. and Bailey R.A. (1968) in *Studies in Volcanology, Mem. Geol. Soc. Am., 116.*[17] Hildreth et al. (1984) *JGR, 89,* 8339-8369. [18] Krassilnikov A.S. and Head J.W. (2003) *JGR, 108,* 5108. [19] Stofan E.R. et al. (1997), in *Venus II,* Univ. Ariz. Press. [20] Krassilnikov A.S. and Head J.W. (2003) *LPS XXXIV,* 1220. [21] Head J.W. and Wilson L. (1992) *JGR, 97,* 3877-3903.