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At present the most important task facing the community of geologists investigating Venus is to determine whether the surface fundamentally reflects formation during a relatively brief global cataclysm (with some evolution thereafter), or if the surface formed over a prolonged period of time as a result of uniformitarian-style activity akin to what we are familiar with on Earth. The data required to resolve these questions derive from detailed stratigraphic mapping efforts focused on deciphering the volcanic and tectonic history preserved on the current surface. As part of this broader effort, the scientific objective of the project reported on here was to assess the geological history preserved in the Ganiki Planitia[1] quadrangle (V14) of Venus, an area approximately one-third the size of the United States. Specifically, the stated objectives of the project were to:

1. Unravel and assess in detail the complex volcanic and tectonic history of two giant radiating fracture systems (possibly dike swarms) which formed in unusual geological settings—one centered at the triple junction of a Y-shaped ridge belt and the other lies upon the rim of an unusual fracture annulus.
2. Evaluate whether systematic variations in the dominant style of volcanism occurred within the region as a function of time, which included using the altitude distribution of volcanic features interpreted to be reservoir-derived to test the hypothesis that their formation is controlled in part by neutral buoyancy.
3. Characterize the origin and history of the regional stress field(s) by interpreting the distribution and relative timing of the diverse array of structural deformation preserved within the region.
4. Integrate the stress field and volcanic history interpretations within this lowland area in order to assist with ongoing efforts to constrain competing regional/global resurfacing models and test the hypothesis that a global stratigraphic sequence exists on Venus.

An informal goal of the project, consistent with my objectives as an instructor at a liberal arts undergraduate institution, was to promote substantive involvement of undergraduate students in the research effort. The research activities described below were carried out by the Principal Investigator, often in close cooperation with a number of undergraduates who worked during the summer and/or during the academic year.

Summary of Major Science Results, i.e. Goals 1-4

1. Giant Radiating Fracture Systems.

- **Dike Swarms?** Careful evaluation of the volcanic, tectonic and topographic evolution of the two known systems led unambiguously to the conclusion that they are giant radiating dike systems, not fracture systems formed solely in response to updoming-induced stresses. The dikes are inferred, from the combination of observations, to have injected laterally away from

[1] NOTE: When the proposal was submitted, and for several years thereafter, the V14 quadrangle was called Nemesis Tessera. More than two years into the work, the USGS realized that the names for quadrangles V13 and V14 were reversed in their nomenclature lists, and the USGS took formal steps to assign the intended name, Ganiki Planitia, to V14. I call the V14 quadrangle Ganiki Planitia throughout this terminal report.

a central crustal magma source. Calculations indicate that the magma reservoirs associated with each source were likely to be a few tens of kilometers in plan-view radius, and that the dikes fed from these reservoirs would need to be a few tens of meters across.

The first feature interpreted as a giant radiating dike swarm, centered at 40°N, 194°E, is characterized by fractures which fan over ~300 degrees of arc out to distances of at least 450 km. The volcano at the focus is provisionally named Xtoh Mons. The topography at the swarm's focus is a gentle dome 150 km across with up to 1.3 km of relief. Superimposed upon the dome are a fault-bounded depression interpreted as a caldera and a suite of radial lava flows. Intriguingly, the domical topography at the focus of the giant radiating dike swarm is centered at the point of intersection between three deformation belts, each of which can be described in general terms as a broad antiformal arch upon which compressional structures (ridges) are superimposed. Analysis of the regional stratigraphy reveals that the dike swarm and associated volcanic flows and structures are among the youngest features in this part of the quadrangle. A question raised by this result is whether numerical modeling can be used to constrain the relative timing of formation in a more absolute sense – how closely in time could the swarm have originated given the predominantly compressive tectonic nature of the setting in which it formed?

The second radiating system consists of two separate radiating swarm foci in a clear temporal sequence of emplacement. The younger swarm, centered upon a 25 km diameter volcanic edifice (provisionally named Waka Mons) with extensive radiating flows at 26°N, 207.5°E, is characterized by short fractures which fan through ~360 degrees of arc. The edifice sits at the northwest edge of a 125 km diameter annulus defined by a double ring of structural features (mostly fractures, but some ridges as well) which line the edges of a topographically depressed ring. In contrast, the older of the two swarms, centered at 25°N, 206.7°E (125 km to the southwest of the younger swarm), is characterized by significantly longer individual fractures which extend out across ~180 degrees of arc for distances of at least 150 km. There is also, however, a prominent set of northeastward fanning grabens which appear to be part of this swarm, and these longer fractures fan across an additional 90 degrees of arc.

- **Identified New Radiating System.** Early mapping within the quadrangle led to the identification of a third radiating fracture system. This feature occupies part of a 500 km diameter dome characterized by intensive volcanism, and while it is clear from the volcanic evidence and lineament geometries that some of these radiating fractures are underlain by dikes, the majority of features could have formed either in response to formation of the broader domical construct or to subsurface dike injection.
- **Spur for Broader Collaborative Effort.** Efforts to identify radiating fracture systems within Ganiki Planitia have led to broader efforts to locate and characterize, with Dr. Richard Ernst, similar features across Guinevere Planitia as far west as the V14 quadrangle. Initial results from this effort have revealed that tectonic mapping efforts need to exceed quadrangle scale to promote complete recognition of radiating systems—many predominant, linear systems cutting across large, quadrangle-size areas are revealed as parts of radiating systems when larger areas are mapped.

2. *Volcanism in V14.*

- **Stratigraphic Sequence.** There is a clearly preserved variation in volcanic style within several major stratigraphically isolated sections of the quadrangle. The variations preserved are essentially identical from section to section, and suggest a processional volcanic sequence for the V14 quadrangle as a whole.

  First, a complex era of intermingled volcanic plains emplacement and deformation dominated within the quadrangle. This era yielded two distinct types of volcanic material units which locally are older than everything but the tessera; however, they do not occur in a consistent sequence relative to one another, exhibiting variable temporal relationships in different areas of the quadrangle. The first of these, plains characterized by pervasive extensional deformation (i.e., *pl*, *pla*, *plb*, *pLla,b*), are preserved as elevated kipukas. The second is a "garbage bag" plains unit *prb,* which in many instances is, at least locally, the oldest feature other than tessera. These plains have, relative to other plains units in the quadrangle, an intermediate radar backscatter and a highly blotchy appearance. They are distinctive yet defy further subdivision, displaying stratigraphically variable contact relationships which are often ambiguous locally but which, viewed collectively, indicate the unit has undergone a prolonged history of spatially and temporally patchy emplacement and modification.

  The next period of time is characterized predominantly by extensive plains volcanism, *prc*. These plains have a darker backscatter than other plains units observed, and contact embayment relationships with other material units as well as the superposition locally on different lineament sets both suggest a fairly thin deposit. Emplacement of this unit appears to have occurred over a prolonged interval, and though younger than *prb* in most places in a few the two are clearly contemporaneous. The dark plains *prc* are never older than the lineated plains or deformed belts, but locally they predate all other units with which they are in contact.

  The final distinct phase is characterized predominantly by edifice-related volcanism *fe* and emplacement of a final regional plains unit *pra* with a distinctly brighter radar backscatter than the other plains in the quadrangle. The majority of the *pra* plains occur as a single continuous and spatially extensive unit with no evident source. Onlap relationships reveal the unit is thicker in the middle and thin at the edges, and unlike the older *prb* and *prc* plains it appears to define a stratigraphically brief (single?) emplacement event. Other small patches of *pra* generally have identifiable local sources (a volcano, etc.) but all are similar in stratigraphic position. Complementing the bright plains several large (>100 km diameter) edifices formed, and the lobate surface flows from these constructs are everywhere superimposed on the surrounding materials, including the major bright plains unit. Similarly, there are several extensive plains units *pe* characterized by overlapping small shield deposits. The duration of time over which the small shields were emplaced is almost by definition unconstrained, but like *fe* the *pe* units are everywhere younger than the materials against which they abut; in no location are *pe* and a major volcanic edifice in stratigraphic contact.

- **Dike Swarm Timing and Formation.** Two of the three giant radiating dike swarms described above are part of unit *fe,* and these complex magmatic centers have prolonged emplacement histories that clearly postdate formation of the lineated plains units. The rapidity with which individual dikes are emplaced (days to a week or two for dikes ~1000 km long given thermal and fluid dynamical limitations on dike growth) make these features excellent stratigraphic tie points, and it is clear from the interplay between the dikes and material units with which they interact that thermal and hence volcanic activity at both centers occurred during a stratigraphically prolonged interval. The paucity of impact craters within the quadrangle is such that no absolute timeline can be established.

- **Corona**. Corona in V14, mostly in a relict state characterized by highly modified remnants of a topographically elevated annulus, appear to have formed predominantly prior to the era(s) characterized by extensive regional plains emplacement. Lineated plains units and *prb* occur upon the elevated rims which have been preserved, and the rims are embayed by *prc* and younger deposits. It is clear from the types of units that have been uplifted during cornoa formation that these subdued looking annuli tend as a whole to be fairly young stratigraphically in spite of their degraded appearance.

- **Pyroclastic Flow Deposit**. Excitingly, we feel we have unearthed excellent evidence for the presence of a pyroclastic deposit within the V14 quadrangle. The basic geological observations (feathery edges, mantling appearance, association with young volcanic features, etc.) do not seem consistent with lava flow emplacement, nor are the remote sensing material properties (which indicate a very rough surface characterized by competent rock) consistent with an unconsolidated aeolian deposit. Taken together, however, the basic characteristics of the unit are most consistent with the interpretation that it is pyroclastic in origin.

  The unit is located on the flanks of a 500 km diameter domical rise characterized by a radial dike swarm, abundant small shield volcanism, and extensive sets of long lava flows; the latter are among the youngest deposits in an area covering roughly one quarter of the quadrangle, and the pyroclastic deposit embays these flows. No source vent is evident; it is possible that the materials are locally derived, implying that the vent has been buried, or perhaps they originated upon and flowed down the flanks of the large topographic dome. Since most models predict that a minimum of ~1.5-5.0 wt% CO2 is necessary to create sufficient basaltic magma disruption on Venus for pyroclastic volcanism to occur, it appears that the latest stage of volcanic activity in the region was characterized by an unusually high concentration of volatiles.

- **Origin of Baltis Vallis?** The V14 quadrangle is the probable location for the origin of Baltis Vallis, a sinuous channel more than 6000 km long. It has been suggested that the source of Baltis may be a volcano named Nijole Mons, but careful mapping reveals that Baltis simply fades away into a background plains unit which itself is older than Nijole. No connection between the two features is evident, and the closest mappable approach of Baltis to Nijole Mons is some 300 km or more. The terminus/origin of Baltis Vallis within V14 remains enigmatic—no source region, feature or deposit is evident there or nearby, nor is there any evidence to suggest obscuration of a source region.

- **Thirteen New Volcanic Features.** The quadrangle contains eighteen named volcanic features (not including Baltis Vallis or Ganiki Planitia itself), including coronae, mons, patera and a tholus. Thirteen of these features were identified and named (names provisionally approved) as a result of the current defined mapping effort. A list of the features, including their latitude, longitude, diameter, etc., is provided below. Newly named features are identified by a shaded box:

Name	Latitude	Longitude	Diam. (km)	Quad	Existing Map
Ganiki Planitia	40	202	5160	V-14	I-2457
Asintmah Corona	25.9	208	150	V-14	Unknown
Benzozia Corona	27.5	204.5	185	V-14	Unknown
Cerridwen Corona	49.6	201.8	217	V-14	I-2457
Embla Corona	28.9	205.4	132	V-14	Unknown
Madalait Corona	37.6	206.4	150	V-14	Unknown
Neyterkob Corona	49.7	204.7	211	V-14	I-2457
Nimba Corona	32.8	204.5	88	V-14	Unknown
Qakma Corona	35.5	207.1	130	V-14	Unknown
Nijole Mons	45	185	150	V-14	I-2457
Ninisinna Mons	25.7	197.5	110	V-14	Unknown
Shala Mons	39.4	208	90	V-14	Unknown
Waka Mons	26.3	207.7	60	V-14	Unknown
Xtoh Mons	39.7	194.2	110	V-14	Unknown
Dutrieu Patera	33.8	198.5	80	V-14	Unknown
Garland Patera	32.7	206.8	45	V-14	Unknown
Izumi Patera	50	193.6	74	V-14	I-2457
Razia Patera	46.2	197.8	157	V-14	I-2457
Apakura Tholus	40.3	208.8	10	V-14	Unknown

- **Small Shield Volcanism.** The quadrangle contains an abundance of small (generally <10 km diameter) shield volcanoes. As described above, in a few places the overlapping nature of these shields and their deposits creates a material unit, but in most instances the shields form individually or as small isolated clusters/fields. The low elevation regional plains as a whole tend to have very low concentrations of small shields, while areas at higher elevations tend to have enhanced concentrations, especially in those units that are stratigraphically older. Given the number of small shields and their geographic distribution, I have thus far been unable to devise a suitable test to examine whether (a) concentrations in older units reflect a greater accumulation period for temporally random shield emplacement, (b) small shield emplacement occurred predominantly during the period predating regional plains emplacement, suggesting that shields in the plains areas have been buried by the younger plains deposits, or (c) some process focuses melting and shield emplacement within higher elevation units, perhaps due to the presence of thicker crust, or because volcanism taking place at lower elevations occurs via different mechanisms (e.g., plains-forming surface eruptions) than those which occur at higher elevations (e.g., perhaps magma stalling and hence reservoir-derived volcanism predominates).

- **Neutral Buoyancy.** At a global scale, using the populations of small shield fields, intermediate volcanoes, large volcanoes and dike swarms (all reservoir-derived volcanic products), various researchers have tested an existing hypothesis that the depth and consequently size of magma reservoirs on Venus is controlled by depth to a level of magma neutral buoyancy which in turn, given the high atmospheric pressure on Venus, is predicted to be strongly altitude-dependent. Using V14 we had hoped to perform a similar test for a restricted area using all types of reservoir-derived features at once; this test proved unworkable on statistical grounds because the number of reservoir-derived features proved too small for the test to yield meaningful results.

3. *Tectonism in V14.*

- **Lateral Mantle Flow?** The V14 quadrangle lies between the Atla Regio domical highland, an area to the SSE inferred to be a site of active mantle upwelling, and the Atalanta Planitia lowlands to the NW, which some have interpreted to be a product of mantle downwelling. An explicit goal of this mapping project was to determine whether or not there is a tectonic signature within the quadrangle that suggests the presence of lateral mantle flow connecting Atla and Atalanta, a process which would be expected to generate (broadly) extensional deformation parallel to the flow (i.e., roughly NNW) and compressional deformation orthogonal to this direction (i.e., roughly ENE).

  Analysis of all mapped lineaments (excluding those within the tessera units) failed to reveal a quadrangle-wide pattern indicative of the hypothesized lateral mantle flow, and thus there is no evidence to support the idea that the two regions, Atla and Atalanta, are dynamically linked. There are several possible implications. First, since Atla is a modern center of upwelling, it is possible that stresses induced by mantle flow outward from Atla have not yet had sufficient time to manifest as tectonic deformation in V14. This seems unlikely, however, given the magnitude of the plume-related volcanic and tectonic activity in the Atla region, and the probability that activity in this site, though currently ongoing, has been long-lived. A second possibility is that mantle flow away from the Atla site is preferentially channeled into another direction, perhaps by inverted topographic variations along the base of the crust/lithosphere. One example that seems possible is flow along the course of the rift systems that cut Atla, which should look somewhat hourglass-shaped in cross section and which may therefore provide channels for preferential mantle flow away from Atla. Available gravity and radar data are currently insufficient to test this hypothesis rigorously. Third, it is possible that Atalanta is a relict downwelling site, meaning that flow out and away from Atla is not in any special sense directed toward the Atalanta site. Finally, it is possible that Atalanta is not (and was not) a site of downwelling, i.e. that it formed via other means.

- **Regional Patterns.** While quantitative analysis of tectonic deformation within V14 does not reveal a quadrangle-wide pattern of deformation, qualitative viewing suggests that discrete zones, roughly one fifth to one-fourth the area of the quadrangle in size, have distinctive tectonic patterns.

  Structural Organization. Quantitative analysis of the lineaments in these zones in some cases revealed clear evidence of structural organization across wide areas. For instance, in a zone stretching across the northern portion of the quadrangle (~2×10^{12} km^2), extensional and compressional lineaments exhibit clear orthogonality. This could indicate that the tectonic deformation occurred during a geologically brief interval, or it could indicate that the structures formed during a long-lived stress field aligned in a predominant direction. A similar orthogonal pattern (aligned in a very different direction) occurs in the southwest portion of the quadrangle. In other areas of the quadrangle, in contrast, quantitative analysis reveals similar alignments for both extensional and compressional lineaments, indicating variability in stress field alignment over time and possible reactivation of individual structural elements.

  Cumulative Length Data. Examination of cumulative length plots for the quadrangle as a whole, excepting tessera and radial/concentric lineaments clearly generated in response to highly localized stresses, reveal that compressional lineaments achieve a 20% greater net length than mapped extensional lineaments. Approximately 95% of the compressional lineaments are less than 100 km in length, whereas only 75% of the extensional lineaments are less than 100 km in length; maximum compressional lineaments lengths approach 200 km, whereas maximum extensional lineament lengths exceed 350 km. There are thus a lot of short compressional lineaments in the quadrangle, and significantly fewer but longer extensional lineaments.

Relationship to Topography, Material Units and Stratigraphy. Analysis of lineament distribution as a function of elevation reveals that both compressional and extensional lineaments cluster around an elevation of MPR (planetary radius of 6051.8 km), but that compressional lineaments are mostly focused at elevations from MPR to MPR-750 m whereas extensional lineaments tend to cluster most heavily from MPR+250 m to MPR-500 m. This reinforces the qualitative impression that lineaments in V14 are heavily clustered in the plains units.

A similar analysis can be performed to look at lineament concentrations by material unit type within the quadrangle as a whole, normalizing them to the area of a given unit in the quadrangle. The oldest units examined, including lineated plains and deformation belts, showed concentrations of up to ~3x the concentration of extensional and compressional lineaments that would be expected if lineaments were randomly distributed as a function of available area. The oldest regional plains unit, Prb, shows lineament concentrations up to 9x would would be expected in a random distribution, the next oldest regional plains unit, Prc, shows concentrations only slightly more than 1x would would be expected, and the youngest unit, Pra, again shows concentrations of ~1x. All younger units show similar concentrations at or below ~1x. There is clearly not a sequence preserved in which the oldest units show the most deformation and the youngest units the least, suggesting that at some level deformation concentration has occurred. There are several possible interpretations of these data. The most obvious one is temporal, that a pulse of enhanced tectonic deformation occurred during the interval of emplacement represented by the units coeval with and predating plains unit Prb. Another possibility is spatial, that earlier tectonic deformation, preserved on the deformation belt kipukas, may not have been followed by an enhanced pulse, that instead the deformation was concentrated into the plains units due to some factor related to their pre-existing stress state, their material properties, their thickness, etc. To test these ideas in more detail, we have identified all mapped lineaments which cut across material unit boundaries and are in the process of assessing the stratigraphic details they can reveal.

- **Radiating Dike Lineaments.** Dike-induced lineaments extending radially away from volcanic centers achieve lengths of up to 1000 km or more. Emplaced rapidly, and with alignments guided by the stress state of the crust, these features are stratigraphic markers that yield powerful insight into the alignment of tectonic stresses within the dike-intruded region at the time the dikes were emplaced. The dikes radiating away from Waka Mons extend well beyond the focal region where edifice- and reservoir-related stresses would be expected to dominate, and as they do so they either continue radially (E/W) or re-align toward a preferred N-S trend (N/S). They appear to react very little to the deformation belts they pass and/or cut, suggesting that the stresses which formed the deformation characterizing these belts had relaxed to very low levels by the time the dikes were emplaced. In contrast, the short lineaments extending away from the younger focal region at Waka Mons react strongly to the presence of the nearby Asintmah Corona and the older radial lineament center located 125 km to the southwest of Waka Mons which lacks an edifice but has fed longer substantially longer dikes. Within 300-500 km or so of this focal center the dikes are gently arcuate, but beyond that they have clearly been influenced by local stress concentrations. For example, within V14 the dikes swing one way and then another in response to stress concentrations at different coronae and paterae, while beyond V14 the dikes concentrate into a narrow belt of deformation called Bellona Fossae, the namesake feature for quadrangle V15. The dikes are thus highly useful for understanding areas in which regional tectonic forces dominate, and those where such stresses are minimal leaving the stress field geometries to be defined by local stress concentrators.

- **Tessera.** This mapping study did not concentrate heavily upon the structural deformation recorded by tessera bodies, but several points are worth noting. First, there are three bodies of tessera in the quadrangle—Nemesis Tessera, Athena Tessera, and Lahevhev Tessera—and each has its own particular geological character.

  Nemesis Tessera is an elongate belt that cuts E-W across the north-central portion of the quadrangle. It is preserved as elevated kipukas that have been embayed by surrounding plains units, and there is no progression of deformation observed, i.e. there are not structures which deform the tessera and parts of the surrounding plains. Deformation within this tessera was complete by the time the surrounding plains and topography were emplaced.

  In contrast, Athena Tessera is an equant block of tessera (contained mostly within V13 to the west) that exhibits clearly an interplay between tectonic deformation, plains emplacement, and uplift. For example, along the eastern edge, the tessera was embayed by plains deposits, then both the plains and tessera underwent an episode of structural deformation perpendicular to the embayment boundary that cut across them both. The contact between the two material units was subsequently uplifted, and a second plains emplacement event embayed both the structural lineaments and the older plains unit where they occurred at lower elevations. This then is an example where late-stage tectonic deformation of the tessera was coeval with regional plains emplacement and ongoing topographic adjustment.

  Finally, Lahevhev Tessera appears to be the remnants of a larger coherent block of tessera which is in the process of being torn apart by tectonic and volcanic activity. It is cut in several places by rift-like topography within which flooding and subsequent development of lineaments with a braided and/or feathery geometry (shear?) has occurred. The larger coherent blocks of tessera currently preserved within Lahevhev resemble Nemesis Tessera in that their deformation is clearly not coeval with emplacement of the surrounding plains.

- **Deformation Belts.** There are a few small deformation belts located within the quadrangle. These materials are deformed in such a way that the precursor material cannot be identified, and they are preserved as elevated kipukas within the surrounding plains. These features are among the oldest within the quadrangle, but due to their isolated and limited occurrences it is not possible to definitively relate their time of formation to the tessera and lineated plains units, which along with the deformation belts form the oldest materials in the mapped area.

- **Named Features.** The Ganiki Planitia quadrangle is characterized mostly by diffusely spread tectonic deformation rather than distinct belts. Mapping conducted during the course of this project did not reveal any new, significant tectonic features requiring naming, and thus the list below is the final one for the quadrangle.

Name	Latitude	Longitude	Diam. (km)	Quad	Existing Map
Akewa Dorsa	45.5	184	900	V-14	I-2457
Fornax Rupes	30.3	201.1	729	V-14	I-2457
Athena Tessera	35	175	1800	V-13	I-2467
Lahevhev Tesserae	29	189	1300	V-14	I-2457
Nemesis Tesserae	40	181	355	V-14	I-2457

4. *Implications for Resurfacing Models.*

Exploring whether or not Venus was by and large resurfaced catastrophically or if it was resurfaced in a uniformitarianism fashion, an absolutely critical question, requires a global-scale interpretation of the stratigraphy which has been preserved, and no mapping effort in a single quadrangle-sized area can address this question definitively. However, it is the amalgamation of observations from individual quadrangles that will yield the data necessary to address the matter, and the hope is that stand-alone results from individual areas like V14 will provide insight into which hypothesis is most strongly supported.

- *Cratering*. There are eleven confirmed impact craters in V14, five of which (green boxes, below) were assigned provisional names during the course of the current mapping project:

Name	Latitude	Longitude	Diam. (km)	Quad	Existing Map
Akiko	30.6	187.3	17.4	V-14	I-2457
Clementina	35.9	208.6	4	V-14	Unknown
Lisa	29	182	4.5	V-14	Unknown
Nadira	44.1	201.5	31.4	V-14	I-2457
Olivia	37.2	207.9	10.2	V-14	I-2457
Raymonde	48.4	191.5	5.3	V-14	Unknown
Ugne	34.9	205.8	10.3	V-14	I-2457
Uleken	33.7	185.1	10.9	V-14	I-2457
Unitkak	40.8	199.5	8	V-14	Unknown
Yablochkina	48.3	195.3	64.3	V-14	I-2457
Yambika	32.6	208.7	6.5	V-14	Unknown

  This yields a crater density of approximately 1.68 per million square kilometers, a value well below the global average of 2 craters per million square kilometers but well above the values calculated globally for rifts, coronae, major lava flow sequences, and large volcanoes, which range from approximately 0.4 to 1.4 craters per million square kilometers.

  While only one crater in the quadrangle, Yablochkina, is associated with a massive parabolic deposit, many of the others which are smaller (e.g. Lisa, Olivia, Ugne, Uleken, Yambika) are surrounded by diffuse radar-dark deposits akin to the larger parabolic deposit of Yablochkina. In addition, the small crater Unitkak is associated with a narrow (tens of kilometers) and long (500-1000 km) radar dark streak, which I infer to be possible evidence for a low-angle trajectory event. Of the remaining craters, Raymonde lies close to Yablochkina and within its parabolic deposit, preventing clear identification of any such signature from Raymonde alone; Clementina is not associated with any radar-dark deposits; Akiko impacted into the edge of Lahevhev Tessera, and while no radar-dark signature is evident on the tessera itself a diffuse radar-dark signature extends westward off the edge of the tessera onto the surrounding plains; and, Nadira is the only crater that has clearly been modified subsequent to emplacement aws it has been embayed by flows of the youngest regional plains unit *pra*. Erosion/weathering time predicted to remove diffuse, radar-dark deposits like the parabolas and similar features is predicted to be on the order of 50 million years, suggesting that the bulk of the cratering in the region may be disproportionately young, which may in turn suggest a younger bulk age for the quadrangle than is inferred from the crater density alone.

- *Material Unit Stratigraphy*. The stratigraphy within the quadrangle unfortunately cannot be organized into a single comprehensive sequence due to the presence and extent of (1) a morphologically and temporally diverse "garbage bag" plains unit *prb* that cuts several broad swaths across the quadrangle, and (2) a few extensive, crater-related, radar-dark deposits—most notably from the crater Yablochkina— which obscure stratigraphic details within the affected areas. Several local sequences can be defined clearly, however, covering in sum roughly two-thirds of the quadrangle. It is important to note that each stratigraphic sub-region is characterized by a common sequence of transitions from one predominant style of geological activity to another. *This could suggest that each local region records a similar sequence of transitions occurring at different times and/or rates, or that some/all of the local regions endured a general sequence of geologic events at about the same time and rate.*

  The self-similar regional sequences of events preserved here are more or less identical to what has been observed elsewhere, and critically to my mind there are (a) no locations where tessera isn't the oldest unit preserved (if it exists in the area), and (b) no locations where evidence of "overlap zones" occur, i.e. places where one region's tessera (or other unit) is forming at the expense of a younger unit in the same sequence from another area in an unexpected fashion. Put another way, there is no evidence to suggest that the common stratigraphies observed in different regions formed at different times. Occam's Razor suggests that the data in the V14 quadrangle are most consistent with models of catastrophic (or at least, effectively sequential at a global scale) evolution of the surface.

Summary of Important Non-Science Results

While the science issues summarized above constitute the major findings to date derived from mapping of the V14 quadrangle, the process of performing this research yielded several additional advances and activities worth reporting here. Each is summarized briefly below.

1. ARCGIS Mapping

This mapping project was conducted in its entirety within ArcView, beginning with ArcView 3.1 and ending in ArcGIS 9.x. While this approach to mapping is beginning to be used with some regularity by planetary mappers at this stage, the current project was one of the first to use GIS, and a great deal of effort was spent, working in conjunction with the USGS in Flagstaff which has really championed the effort overall, to ensure that this approach to mapping could be employed successfully. As part of this effort I gave several presentations at Planetary Mappers Meetings that focused heavily on the advantages of using GIS for mapping planetary surfaces, and I have worked with several colleagues (e.g., Zimbelman) to help them investigate the strengths of this methodology. Examples of key advantages include: superposition of different datasets (e.g., radar backscatter and topography); on-the-fly mapping of units and lineaments (permitting, for example, lineaments mapped at 75 m/pixel sinusoidally-projected FMAP data to be reprojected in a cut-and-paste transfer onto 225 m/pixel Lambert-projected reference frame); accurate area and length calculations; the ability to manipulate unit properties; the ability to identify via simple queries all linements of a certain orientation, or length range, or within a certain unit; etc. The possibilities for enhanced analytical assessment are almost limitless within the constraints of the available data. Most of the remaining points discussed below would not have been possible had mapping occurred in a different type of mapping program like Illustrator that lacks geographically-scaled and projected context for the mapped units.

2. Material Unit Properties

In past mapping studies, the remote sensing properties of mapped units—backscatter, RMS slope, reflectivity, emmissivity—have been assessed using small samples of a given unit. This approach is almost mandated for the backscatter because the data in the files received must be corrected for latitudinal position on a pixel by pixel basis before the backscatter can be correctly compared from one region to the next in a quantitative way. This approach has the advantage that the mapper can select areas that lack structural deformation and other artifacts that can serve to alter the backscatter properties yet which do not reflect material properties for the unit; however, it suffers from the disadvantage that the properties for the unit as a whole may not be well represented by the area chosen, and the statistical error for the unit will be larger due to the small number of pixels sampled.

For our mapping and quantitative analysis of units within the V14 quadrangle, we developed a fairly straightforward (though still computing-intensive) means of correcting the raw backscatter image for latitude-related effects throughout the entire quadrangle. This is a powerful new approach and yields very useful insight during the mapping process. Essentially, it provides the opportunity to examine the bulk material properties of the units, and also ensures that, by viewing a corrected dataset for the entire unit prior to selection of a "representative sample," that the best visual guidance possible for sampling is available. This is particularly important for plains units that are widespread across a range of latitudes. The bulk calculation of statistical data for given units complements strategies that have been used in the past. This approach has the advantage that the large number of pixels beats down the statistical error to the extent possible, and also provides an opportunity to assess the degree to which, say, structural deformation has affected a unit—an extensive dark plains unit with many radar-bright wrinkle ridges superimposed upon it and a similar unit without much deformation will yield nearly identical mean backscatter values, but the standard deviation errors will reflect the presence of the enhanced deformation. It is also possible, though we have not yet experimented with this approach, to exclude mapped lineaments from the calculations for the unit as a whole, essentially by buffering each lineament and then calculating the backscatter mean (etc.) only for those areas of the unit which do not correspond to the location of a structural element.

3. Robustness of Material Unit Definition

One problem that plagues planetary mappers, perhaps most acutely those who must rely on radar data, is the difficulties associated with defining robust material units. Put another way, if three people mapped the same area and then compared their results, some percentage of their boundaries and unit definitions would be very closely matched, while other areas would bear little resemblance from one person to the next. How, then, can one develop a sense of confidence that the material units being defined have qualitative and quantitative meaning?

I am aware of two approaches that have been used in the past. The first is simply to compare the edges of independently mapped but adjacent quadrangles to see if the mapping results agree; often they are not. In this instance, comparison with mapping results for V13 (Head and Ivanov), V15 (Zimbelman) and V5 (McGill) revealed a high degree of consistency, with mapped unit boundaries and unit types/interpretations agreeing at the 90-95% level. The second is to use the material unit means from unit subsections, as described above, to test whether units indeed appear to be different from one another, i.e. that the backscatter of materials mapped as a dark plains unit look more like one another and not like materials mapped as a light plains unit.

In this study we went a bit further to try and find a better way to allocate geologic units into groups corresponding to unit type. We extracted the quantitative data corresponding to radar backscatter, elevation, slope, surface emissivity, and surface reflectivity from available images and then, using the existing geologic map as a baseline, we employed mixture models and the Expectation-Maximization (EM) algorithm to devise an optimal geologic map based on the full suite of quantitative data which are available. We specifically sought to identify units whose quantitative properties fit more closely with a different unit type than what was assigned by the mapping. The results from a variety of different tests, including tests weighted by area, showed that most units were classified the same way as specified by the original geologic map, i.e. that most units given the same label on the map did indeed resemble one another more than any other unit type available. A handful of units were consistently assigned to different groups, and we assessed why this was the case. In nearly every instance, a geologically important piece of data used when defining the unit during the mapping process wasn't picked up by the algorithms employed to test the robustness of the units. For instance, two units with very similar material properties could form via large-scale flow of lavas from a large central edifice, leading to the designation *fe*, and from emplacement of lavas that are in no way related to an edifice, leading to a regional plains designation (e.g., *prb*). Depending on the size of the edifice and the flow, the *fe* unit could be reclassified as *prb*.

The bottom line from the study is that we have a high degree of confidence in the robustness of the units we have defined. They are internally self-consistent and each type of unit is statistically distinctive from all the others when the full suite of quantitative data at our disposal are employed. This does not mean that someone else mapping the same quadrangle could not end up with similarly robust levels of self-consistency, but when the statistical clustering results are integrated with the unit boundary agreement, we are confident that the current map results form a solid base for a meaningful geological interpretation of the quadrangle.

4. A Comment on Involving Undergraduates.

Extensive involvement of undergraduates during the course of this research has been an important component of the "methods" employed for the project to date, and I report briefly on my experiences here in the hope that they will be of benefit to others who seek to involve undergraduates productively in their mapping efforts. Leveraging student funding provided by this grant with funds from PGGURP and Pomona College, fifteen different students have contributed substantially to the mapping and interpretation effort for periods that ranged from a single summer or semester to a group of students who have been involved for nearly two full years. This group has authored or co-authored nine *Lunar and Planetary Science Conference* abstracts (all but one of these were first authored by students), all but two of the fifteen students participated as authors, and all but three of the fifteen students have attended *Lunar and Planetary Science Conference* to present the results of their work. The students, 47% men and 53% women, have ranged in background when starting their work from freshman and sophomores (the majority) to one who had just completed his senior year of college. The results of their productive efforts are documented thoroughly in the list of publications at the end of this report.

My experiences suggest strongly that the most productive way to involve undergraduate students is to engage a large group at a single time; there are pros and cons to doing this during the summer or within an academic semester. Either configuration, however, allows the group to solve many problems (software issues, etc.) with minimal assistance. It also promotes a healthy and synergistic opportunity for the students to compare observations and test hypotheses—an important component of their education as science students—and allows me to focus my collaborative time with them upon exploring and helping to guide their scientific efforts and upon integrating the mapping and science results they produce, maximizing forward progress for the quadrangle mapping effort as a whole. Other configurations I have tried have not been as productive for the students and have generally hindered my ability during that period to make forward progress on the project as a whole, requiring as much or more of my time and yielding less science return. I would be happy to discuss these matters further with interested parties.

5. Project Web Page.

At the commencement of the project I designed a web page describing the intent of the project and the work of the students involved. This was intended both as a mechanism for informing others of the results we were achieving as time rolled on, and as a way to highlight the activities of the undergraduates. The page was updated irregularly as my time allowed, and a near-final version of the web pages describing the project is currently in the final stage of development. The current and soon-to-be-finished final product can currently be viewed at the following web address (should this change in the future, it can be located most readily within my research page results starting from www.geology.pomona.edu):

http://www.geology.pomona.edu/research/Venus/index.htm .

Publications (* denotes student author)

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