Reports

Venus Southern Hemisphere: Geologic Character and Age of Terrains in the Themis-Alpha-Lada Region

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Arecibo high-resolution radar images of the southern hemisphere of Venus extending to 78°S show that the surface of the Themis-Alpha-Lada region is characterized by linear deformation zones with volcanoes and corona-like features and by regional volcanic deposits (primarily plains, small shields, and large edifices). Large-scale areal deformation is limited to the tessera of Alpha Regio. Lada Terra, in the southern high latitudes, contains several large coronae, in contrast to Ishtar Terra in the northern high latitudes. The density of craters of possible impact origin is somewhat lower than that observed in the Venera 15 and 16 coverage; these data extend to 43 percent of the areas of the surface of Venus with ages of less than about 1 billion years.

PIONEER VENUS LOW-SPATIAL-RESOLUTION altimetry data (average footprint size about 100 km) provided a global view of the topography and geography of the planet (*1*). Venera 15 and 16 spacecraft imaging (resolution, 1 to 3 km) and altimetry data for the northern 25% of Venus revealed that the surface there is very young (250 to 1000 million years) (*2, 3*) compared to the moon, Mercury, and Mars and is dominated by volcanic plains (about 70% of the area) and a variety of tectonic landforms (areal, beltlike, and circular) (*4, 5*). Much of the deformation, particularly around Ishtar Terra, is characterized by compression and has the characteristics of terrestrial orogenic belts (*6*). Moderate-resolution (20 to 40 km) radar images and topography data from Pioneer Venus, together with regional high-resolution (1 to 4 km) Earth-based data (*7*), revealed that the equatorial highlands are the site of extensional deformation (*8, 9*) and possible crustal spreading (*10*), that the percentage of volcanic plains and tectonically deformed areas is comparable to that of the northern high latitudes (*7*), and that for the area between Beta and Eistla Regiones the age of the surface is comparable to that of the northern high latitudes (*11*). Altimetry data for the southern hemisphere (*1*) have shown the presence of a variety of topographic provinces (Regiones, Planitiae, Terrae, Montes), but the geology, age, and origin of these features have been uncertain. The Arecibo radar facility (wavelength, 12.6 cm) was used to make observations of this region during the summer of 1988 (*12*), and data were obtained with resolutions between 1.5 and 4 km for about 55.6×10^6 km^2 of the southern hemisphere extending to 78°S (Fig. 1). We describe here the major geographic and geologic features observed in four distinct upland-highland areas, discuss their similarity to features observed in other parts of Venus, and assess the age of this part of the planet.

Themis Regio (*13*) rises up to 1.5 to 2.5 km above the mean planetary radius (MPR = 6051.4 km) and represents the focal point of three major linear topographic and structural trends: (i) the Atla-Themis disrupted zone (*8*) (Parga Chasma) is 400 to 600 km wide and extends northwest along a topographic rise toward Atla Regio, about 8000 km away; (ii) eastern Themis trends generally east-west toward Hathor Mons for about 2200 km and appears to be a topographic and structural extension of the Atla-Themis disrupted zone; (iii) an 800-km-long trend extends south from Themis into Helen Planitia. This general structure is reminiscent of tectonic junctions mapped at Beta and Atla Regiones (*14*), although Themis is slightly smaller and differs from Beta in its associated features.

Themis is characterized by two major types of features: concentric ring to oval structures 250 to 500 km in diameter (Fig. 2, A and B) and volcanic edifices. Several

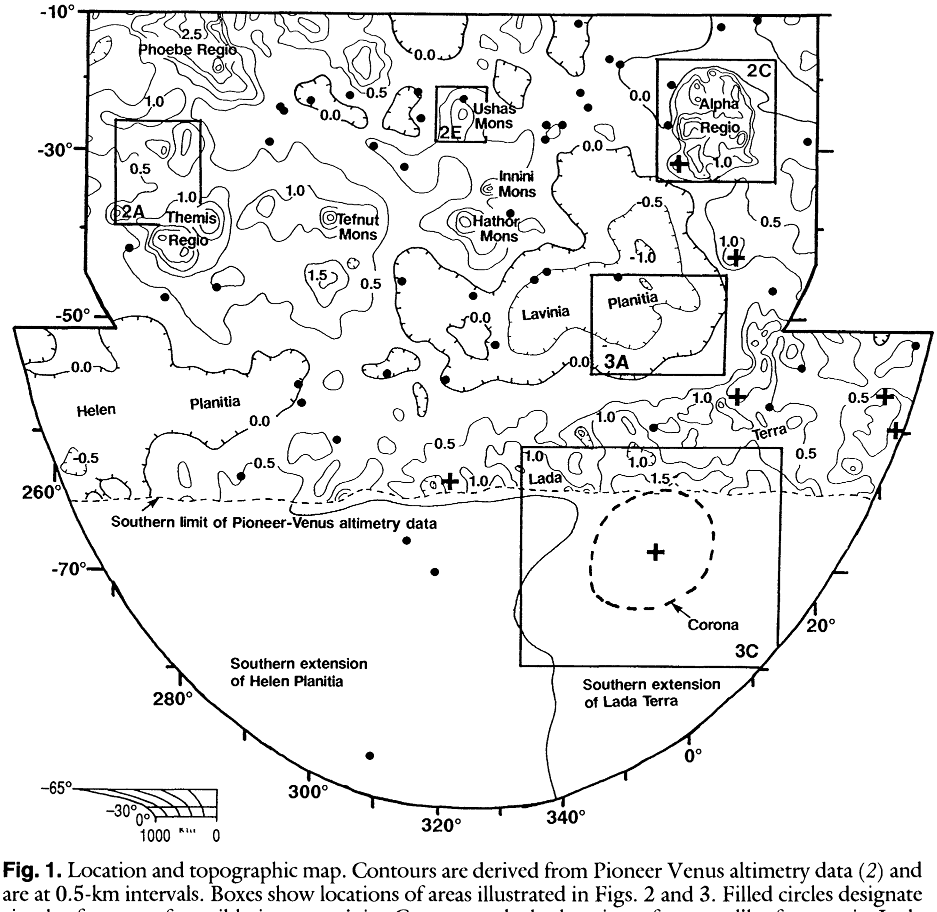

Fig. 1. Location and topographic map. Contours are derived from Pioneer Venus altimetry data (*2*) and are at 0.5-km intervals. Boxes show locations of areas illustrated in Figs. 2 and 3. Filled circles designate circular features of possible impact origin. Crosses mark the location of corona-like features in Lada Terra.

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large, densely packed, and interconnected ring or oval structures (ranging from 300 to 500 km in diameter) and superposed volcanoes form Themis itself (*13*). Chains of somewhat smaller (200 to 300 km in diameter) ring-oval structures and volcanoes extend from Themis out along its arms. These structures are similar to coronae (*15*) in size and in the presence of concentric annular ridges but differ in their close spacing, chainlike nature, and occasional polygonal shape. Detailed views of individual rings in these chains (Fig. 2, A and B) show that they are characterized by two radar-bright concentric arcs or ring segments about 5 to 20 km wide, with the radius of the outer ring typically 1.3 to 1.8 times the radius of the inner one. Their spacing in the chains of 150 to 300 km is less than that observed in central Themis (*13*). Bright lineaments about 5 km wide and separated by 5 to 10 km follow the trend of the rise and, where they are locally abundant, make up the bright rims of the rings or form linear patches along the rise crest. Many rings deviate from a purely circular concentric ring pattern. Most of these are separated into two halves by a linear zone parallel to the trend of the rise. In the example illustrated in Fig. 2, A and B (arrow 1), removal of the linear zone and joining of the two halves restores the circularity of the bead. This splitting may be as large as 30 to 35 km, 10 to 15% of its radius. Other paired concentric arcs may indicate even greater amounts of separation (Fig. 2, A and B; arrow 2). In several places within and adjacent to the rings bright lineaments have radial patterns resembling volcanoes (Fig. 2, A and B; arrow 3). On the basis of these characteristics, we interpret these alignments of rings as zones of upwelling, extension, and associated volcanism (*12*). The detailed structure of Themis is somewhat similar to that of the Beta-Eistla deformation zone (*15*) in the equatorial region.

Alpha Regio, a rectangular 1300-km-wide upland plateau rising up to about 2 km above the MPR, is characterized by high surface roughness and low Fresnel reflectivity and was predicted to be tessera on the basis of its radar properties (*16*). The new data (Fig. 2, C and D) confirm this prediction and show that the plateau is characterized by a system of 5- to 10-km-wide parallel ridges and troughs that are oriented N15°E to N20°E (parallel to the east and west edges of Alpha) and range in length from the limits of resolution to over 200 km. A second set of less prominent linear structures is oriented approximately orthogonal to these ridges and troughs and includes a major topographic and morphologic lineament zone at least 900 km long that bisects Alpha. A third set of linear structures trending N75°E to N80°E is restricted to the southern half of Alpha. Numerous oval to linear patches of radar-dark plains 20 to 300 km long are oriented parallel to the structural trends. Alpha is surrounded by volcanic plains that appear to embay the flanks of the tessera and are thus interpreted to be relatively younger. The abrupt termination of linear trends at the edge of the tessera and the embayment relationships suggest that tessera terrain underlies some of the adjacent plains. Alpha is very similar to tessera terrain mapped elsewhere in Venera images (*4*) and has elements of several of the tessera terrain subtypes observed there (*17*). Small patches of tessera-like terrain are also observed in Lada Terra. Tessera terrain comprises considerably less area than the 14% average observed in the northern high latitudes and,

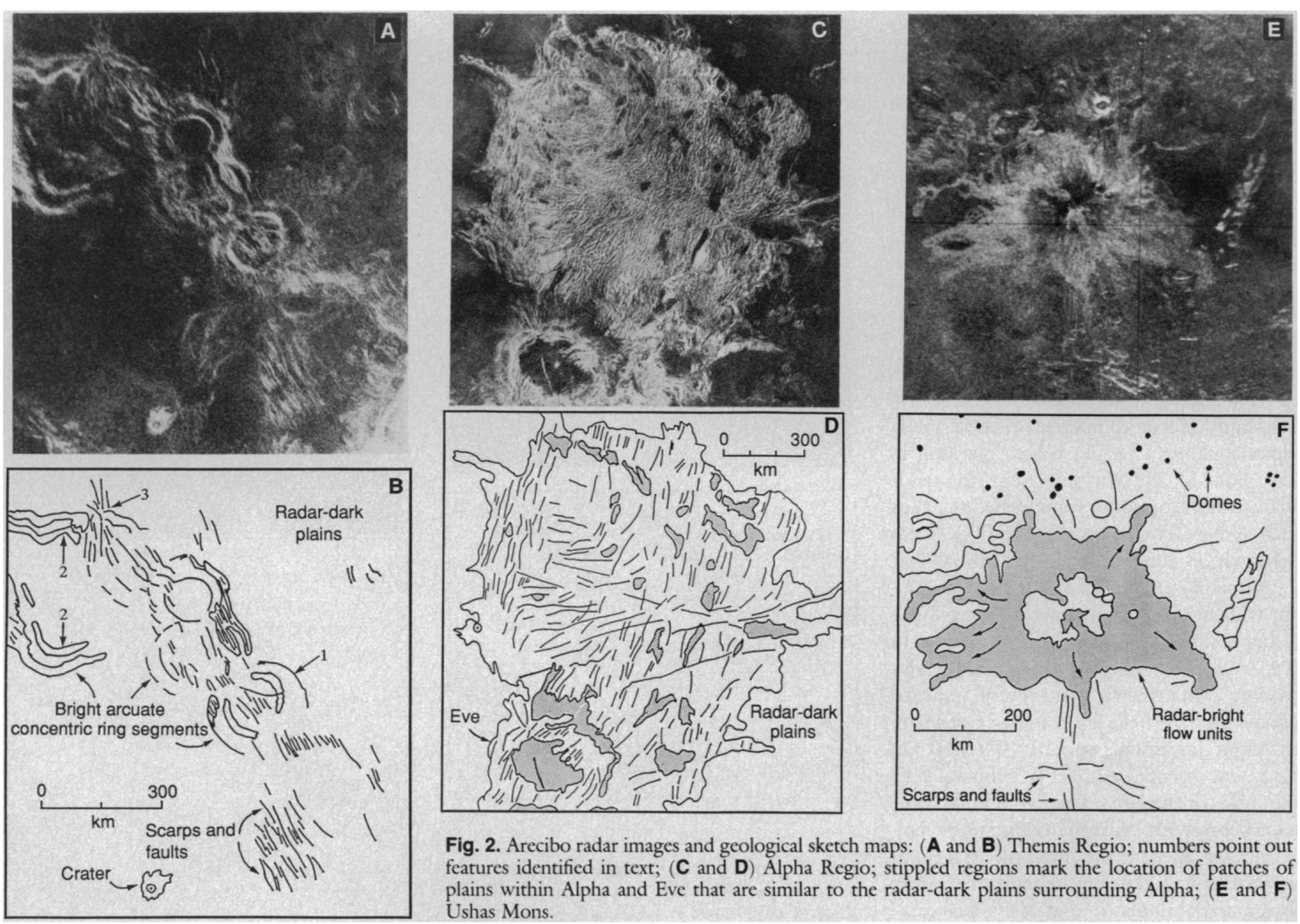

Fig. 2. Arecibo radar images and geological sketch maps: (**A** and **B**) Themis Regio; numbers point out features identified in text; (**C** and **D**) Alpha Regio; stippled regions mark the location of patches of plains within Alpha and Eve that are similar to the radar-dark plains surrounding Alpha; (**E** and **F**) Ushas Mons.

unless it underlies much of the volcanic plains, areal deformation (*4*) was not as significant in this region.

Three prominent montes (Ushas, Innini, and Hathor) form a generally north-south–trending upland rise between Themis and Alpha Regiones (Fig. 1 and Fig. 2, E and F). These peaks rise 1.5 to 2.0 km, are separated from each other by 800 to 1200 km, and are the locus of flow-like deposits that in many places appear to embay surrounding structures; they are interpreted to be volcanic edifices (*18*) similar to those in the northern hemisphere (Sif, Theia, and others) (*11*). Several types of linear or belt-like structures are radial to these features, including paired bright lineaments forming 20- to 40-km-wide zones and broader zones of bright lineaments 50 to 150 km wide. Ushas Mons (Fig. 2, E and F) is characterized by a 200-km-wide radar-dark summit region superposed on an irregularly shaped 400- to 600-km-wide radar-bright deposit. Several radar-bright flow units 20 to 80 km wide and extending up to 300 km from the summit are observed. The bright deposit is asymmetric, bright lineaments indicative of linear scarps and faults are present parallel to the rise, and some flow units embay the fault zone, suggesting that the faults are extensional. Abundant small domes interpreted to be volcanic (*11*) are also observed.

The planitiae (Lavinia, Navka-Guinevere, and Helen) are low in elevation and form broad areas of plains of apparent volcanic origin between the uplands and highlands (Fig. 1). Navka and Lavinia contain numerous apparent volcanic sources (domes and flow centers) as does Guinevere Planitia to the north (*11*). Lavinia is disrupted by abundant linear deformation zones and mottled bright and dark flow features (Fig. 3, A and B). The distinctive radar-bright flow features are volcanic flows that largely originated from sources at the edges of Lavinia and flow hundreds of kilometers down very low regional slopes (Fig. 1) before ponding in low parts of the basin. Helen Planitia is characterized by more homogeneous plains than either Lavinia or Navka. The linear deformation zones in Lavinia Planitia (Fig. 3, A and B) are composed of 40- to 200-km-wide bright belts that are topographically high, up to 1000 km long, oriented in N45°W and N45°E directions, and separated from each other by up to several hundred kilometers. The belts are composed of smaller bright lineaments spaced 10 to 40 km apart and oriented parallel to subparallel to the strike of the belts. Overlapping of some lineaments with different orientations suggests that there were multiple stages of deformation. Relatively undeformed radar-dark material similar to that of the surrounding plains is seen in the belts. Many of the flow units in the plains appear to embay or are diverted by the belts (Fig. 3, A and B; northeast end of major lineament belt). These observations suggest that plains material was deformed and that the path of subsequent volcanic flows followed the resulting topography. In some cases, however, bright lineaments cut relatively recent flows (Fig. 3, A and B; northeast end of major lineament belt); this relation suggests that volcanism and deformation were contemporaneous. These features have similarities to ridge belts seen in the Venera 15 and 16 coverage (*4*), and we interpret them to be primarily of compressional origin (*19*) on the basis of their occurrence in a regional low, their local positive topography, and the lack of evidence for split and separated topography.

The Arecibo data reveal the nature of the northern part of Lada Terra, a southern high-latitude region of elevated topography rising up to 2 km (Fig. 1). A 150- to 400-km-wide belt of bright lineaments parallels the northern edge of Lada. The belt extends about 3000 km before it turns northward and connects along an arm to Alpha Regio, about 2500 km to the north. Four corona-like structures (300 to 400 km in diameter; crosses in Fig. 1), several volcanic edifices, and the source regions of the bright flows that extend down into Lavinia Planitia (Fig. 3, A and B) occur along the edge of Lada and its extension toward Alpha. On the basis of cross-cutting and deformation relations between the linear elements and the corona-like features, we interpret the linear deformation zones to be of extensional origin.

Three structures having characteristics similar to those of coronae are also observed south of this linear zone along a second linear zone trending generally northeast-southwest. The largest of the three features in the southern linear zone is 800 to 1000 km in diameter (68°S, 355°) (Fig. 1 and Fig. 3, C and D). This feature has many of the characteristics of coronae mapped elsewhere (*20, 21*) including (i) a partial annulus of ridged terrain along its northwest edge, (ii) an outer moat in this region partially filled with lava flows, and (iii) a large source region in the corona interior (offset to the southeast from the center of the corona). Abundant mottled flow units appear to originate from this source region (an oval radar-dark area 200 to 400 km wide) and extend for hundreds of kilometers. These units partly overlie the corona edge to the southeast and southwest and are partly contained by it to the northwest. Bright, scallop-like lineaments in this central region suggest that this central radar-dark area may be a complex caldera. Most coronae have diameters in the 160- to 670-km range (*20*); this corona is asymmetrical (*20*) and is one of the largest coronae yet identified. Narrow radar-bright

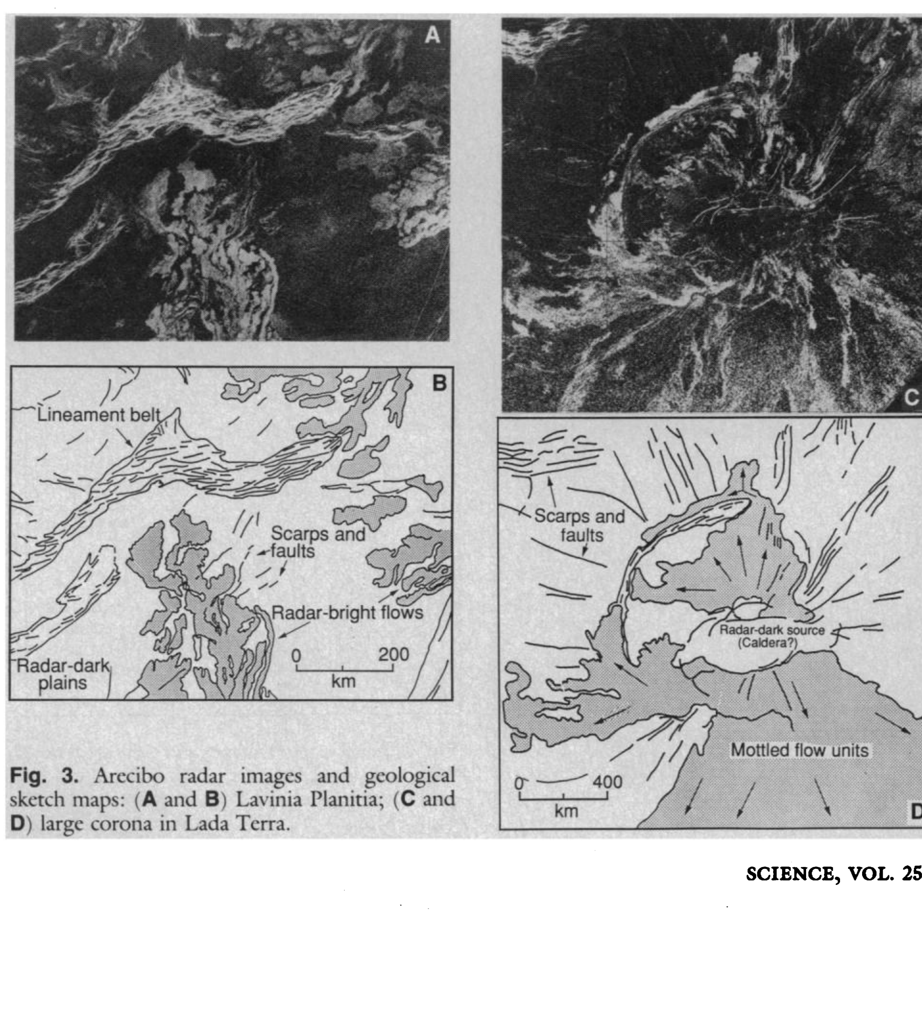

Fig. 3. Arecibo radar images and geological sketch maps: (**A** and **B**) Lavinia Planitia; (**C** and **D**) large corona in Lada Terra.

lineaments hundreds of kilometers long and interpreted to be scarps and faults are arrayed generally radially around the corona, and there is a particularly well-developed trend of lineaments in the northeast-southwest direction that extends to the northeast in a linear belt toward Western Aphrodite Terra. The characteristics of Lada Terra (linear deformed zones of probable extensional origin, coronae) are quite different from those of the northern high-latitude highland, Ishtar Terra (compressional mountain belts, steep bounding slopes, and abundant tessera terrain), but in many respects they are similar to the characteristics of the cluster of coronae seen in Mnemosyne Regio, to the west of Ishtar Terra (*21*).

A total of 49 features of possible impact origin have been mapped in this region. The craters tend to be concentrated in the plains rather than in the uplands-highlands, opposite to the trend in the Beta-Eistla region (*11, 22*). The density of craters observed in the region mapped in Fig. 1 (55.6×10^6 km^2) is 0.88 crater per 10^6 km^2, similar to the 0.92 per 10^6 km^2 seen in the Beta-Eistla region (*22*) and less than that observed for the northern high-latitude Venera coverage (1.3 per 10^6 km^2). This density indicates that the age of this region is similar to the age (250 to 1000 million years) interpreted for the northern high latitudes (*2, 3*). Adding this part of the southern hemisphere (12% of the surface of Venus) to that previously dated brings the total area estimated to have formed during the last 20% of the history of the planet to approximately 43%.

Of the three types of deformation outlined by Basilevsky *et al.* (*5*) in the Venera coverage (beltlike, circular, areal), linear beltlike deformation appears to dominate this region; the lineament belts of Themis and Lada Terrae occupy many thousands of kilometers and extend out of the region to connect with major tectonic zones elsewhere. These belts are interpreted to be of extensional origin, whereas the additional lineament belts mapped in Lavinia Planitia are interpreted to be of compressional origin. Orogenic belts such as those surrounding Lakshmi Planum (*6*) are not observed. Circular deformation is common in the form of abundant corona-like features associated with the linear deformation belts of Lada and Themis and in the isolated coronae of Lada Terra. Areal deformation is well developed only in Alpha Regio and is not as abundant as in the Venera coverage, although additional tessera may underlie the plains, particularly around Alpha Regio. Plains units of apparent volcanic origin are common, and the style of plains volcanism is similar to that seen elsewhere (*4, 5, 11*). Large volcanic edifices are commonly associated with topographic rises (Ushas-Hathor trend) or linear belt deformation (Themis and northern Lada Terra).

One of the most distinctive characteristics of the mapped region is the presence and abundance of the linear deformation zones with associated corona-like features. These zones further delineate the presence of regional and global zones of upwelling and extension, and the different scales of corona-like features provide evidence for different scales of mantle instabilities and upwelling. The Magellan mission (*23*) will provide complementary viewing geometry and higher resolution imaging and altimetry data so that more detailed characteristics and relations among these basic units can be determined.

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Atomic-Resolution Electrochemistry with the Atomic Force Microscope: Copper Deposition on Gold

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The atomic force microscope (AFM) was used to image an electrode surface at atomic resolution while the electrode was under potential control in a fluid electrolyte. A new level of subtlety was observed for each step of a complete electrochemical cycle that started with an Au(111) surface onto which bulk Cu was electrodeposited. The Cu was stripped down to an underpotential-deposited monolayer and finally returned to a bare Au(111) surface. The images revealed that the underpotential-deposited monolayer has different structures in different electrolytes. Specifically, for a perchloric acid electrolyte the Cu atoms are in a close-packed lattice with a spacing of 0.29 ± 0.02 nanometer (nm). For a sulfate electrolyte they are in a more open lattice with a spacing of 0.49 ± 0.02 nm. As the deposited Cu layer grew thicker, the Cu atoms converged to a (111)-oriented layer with a lattice spacing of 0.26 ± 0.02 nm for both electrolytes. A terrace pattern was observed during dissolution of bulk Cu. Images were obtained of an atomically resolved Cu monolayer in one region and an atomically resolved Au substrate in another in which a 30° rotation of the Cu monolayer lattice from the Au lattice is clearly visible.

We report atom-resolved AFM images (*1, 2*) of bulk and underpotential-deposited Cu on a Au surface in two different electrolytes. Underpotential deposition (upd) is an electrochemical process in which one to several monolay-