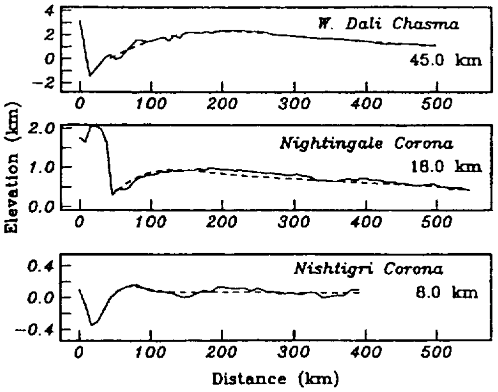

Fig. 1. Profiles (solid lines) and best-fit models (dashed lines) for three flexural features on Venus. The best-fit elastic thickness for each profile is indicated. Note the difference in vertical scales in each case. Elevation is relative to a datum of 6051.0 km.

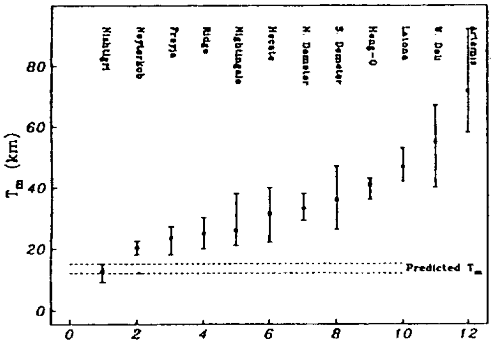

Fig. 2. Mechanical thicknesses obtained for 12 flexural features on Venus. Only Nishtigri Corona gives a lithospheric thickness compatible with that predicted (see text). The very high values obtained for Arcemis Corona and W. Dali Chasma are a result of the lithosphere being flexed beyond its elastic limit at these locations.

reveal circumferential fractures on the flexural outer rise, roughly coincident with the predicted location of high surface stresses.

Elastic thickness and curvature can be used to obtain mechanical thickness if the yield strength envelope for the lithosphere is known [4]. For features that are flexed beyond the elastic limit (i.e., moment saturated) an alternative approach is to calculate the thermal gradient directly from the saturation moment. Results from both these methods will be presented. Figure 2 shows the mechanical thicknesses obtained for Venus, assuming a dry olivine rheology, brittle behavior in the upper lithosphere, and ductile flow in the lower lithosphere [5]. Error bars are calculated from the range of best-fit elastic thickness for a given feature. The horizontal dashed lines are upper and lower bounds on the mechanical thickness expected for Venus, based on heat-flow scaling arguments [6]. It is evident that only one location studied gives a lithospheric thickness compatible with that predicted (15 km). The mechanical thickness at most other features is in the range 20–45 km. This implies mean heat flow values in the range 20–46 mW m^{-2}, much less than the predicted 74 mW m^{-2}. On Earth lithospheric thickness is related to age. Variation in lithospheric thickness obtained from different coronae on Venus may indicate relative ages and therefore provide a constraint on coronae evolution.

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IGNEOUS AND TECTONIC EVOLUTION OF VENUSIAN AND TERRESTRIAL CORONAE.

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A great variety of tectonic and volcanic features have been documented on Venus. It is widely appreciated that there are close spatial associations among certain types of tectonic structures and some classes of volcanic flows and constructs. Coronae are endowed with a particularly rich variety of volcanism [1,2,3]. It is thought that coupled tectonic and volcanic aspects of coronae are cogenetic manifestations of mantle plumes. An outstanding feature of most venusian coronae is their circular or elliptical shape defined by peripheral zones of fracturing and/or folding. Some coronae are composite, consisting of two or more small coronae within a larger enclosing corona, suggesting complex histories of structured diapirism analogous in some ways to salt dome tectonics [4]. Coronae range widely in size, from smaller than 100 km to over 1000 km in diameter [3].

Volcanic features associated with venusian coronae are further documented in Figs. 1–4. These include lunarlike sinuous rilles, thin lava flows, cinder cone-like constructs, shield volcanos, and pancake domes. Several types of volcanic features are often situated within or near a single corona, in many instances including landforms indicating effusions of both low- and high-viscosity lavas. In some cases stratigraphic evidence brackets emplacement of pancake domes during the period of tectonic development of the corona, thus supporting a close link between the igneous and tectonic histories of coronae. These associations suggest emplacement of huge diapirs and massive magmatic intrusions, thus producing the tectonic deformations defining these structures. Igneous differentiation of the intrusion could yield a range of lava compositions. Head and Wilson [5] suggested a mechanism that would cause development of neutral buoyancy zones in the shallow subsurface of Venus, thereby tending to promote development of massive igneous intrusions.

Large igneous intrusive complexes are common on the modern Earth, especially in magmatic arcs associated with subduction zones. Extensive igneous evolution occurs in magma arc batholiths [6], yielding compositionally diverse magmas. Large terrestrial layered basaltic intrusions, usually not associated with subduction zones, also have been common through Earth history. Some of these, including the famous Skaergaard Intrusion, have undergone considerable igneous differentiation without involving processes directly related to plate tectonics [7].

Although coronae are especially numerous and varied on Venus, Earth also has coronalike structures [8]. Whether terrestrial coronalike analogues truly involved the same tectonic processes responsible for venusian coronae is uncertain, but development of these struc-

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Fig. 1. Corona with pancake dome some 20 km in diameter (left center), and field of cinder cones and/or shield volcanos (top center). Scene width 200 km. Radar illumination is from the left.

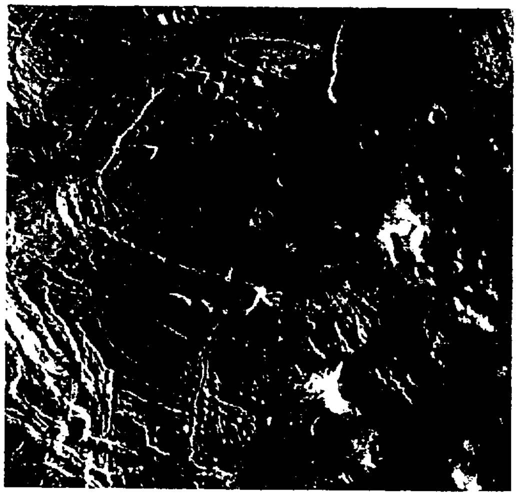

Fig. 3. Small corona containing a pancake dome and associated with other domes and flow fields having high radar contrast. Scene width 460 km. Radar illumination from the left.

Fig. 2. Corona with pancake domes and other steep-sided volcanic constructs (right half) and lunarlike sinuous rilles (upper right). Radar illumination from the left.

Fig. 4. Corona associated with pancake domes ranging from 20 to 60 km in diameter (lower left quadrant) and thin flows having high radar contrast (bottom third of scene). Scene width 570 km. Radar illumination is from the left.

tures was especially common during the Archaean. The Pilbara-Hamersley Craton in Western Australia is among the most compelling terrestrial corona analogues. The principal phase of igneous and tectonic development of this early continental crustal fragment occurred between 2900 and 3500 m.y. ago [9,10] when massive tectonic and igneous activity occurred within a precisely elliptical region (a = 560 km, b = 400 km) bounded by tectonic compressional folds and faults [9]. This tectonic ellipse (Fig. 5) is one of several similar blocks forming most of the Australian shield. These blocks are interpreted as first-order diapiric structures (coronae). The early phase of activity in the Pilbara Craton involved intrusion of 20 or more granitoid batholiths, each typically 30–60 km in diameter. Each pluton caused complex deformation around its periphery (Fig. 6), producing structures resembling the larger-scale Pilbara ellipse. Sedimentation and extrusive volcanic activity (mainly basaltic) occurred simultaneously with granitoid plutonism, forming inter-pluton volcano-sedimentary piles (the Pilbara Supergroup) up to 30 km thick [10]. These large granitoid batholiths are termed second-order diapirs, which themselves are composed of discrete third-order structures with diameters of order 10 km, many of which also have marginal deformation zones [10,11].

This phase in the evolution of the Pilbara Block was followed by a decline in igneous and tectonic activity. 2700 m.y. ago Pilbara was a rugged landmass, but the principal geologic agents tended to

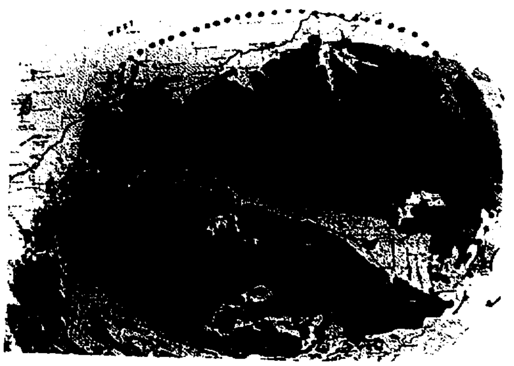

Fig. 5. Portion of geologic map of Pilbara Block and vicinity. Pilbara ellipse has dotted outline. Major granitoid intrusions are in solid outline. Box shows areas of Fig. 6.

Fig. 6. Landsat image portraying three granitoid plutons and intervening volcanic and sedimentary Pilbara Supergroup. The latter originally accumulated in interpluton troughs and were deformed as the plutons intruded. Scene is 150 km left to right.

produce an increasingly graded topography, including mafic volcanism and fluvial and lacustrine processes [9,10]. By 2500 m.y. ago the region had evolved to a tectonically fairly stable marine platform or continental shelf inundated by an epeiric sea, and was dominated by deposition of evaporites (banded iron formation and dolomite) [9,12]. By the end of this phase, the region had acquired essentially its present configuration, although the Pilbara Craton possibly may not have been integrated with the rest of Australia.

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VENUS: THE CASE FOR A WET ORIGIN AND A RUNAWAY GREENHOUSE.

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To one interested in atmospheric evolution, the most intriguing aspect of our neighboring planet Venus is its lack of water. Measurements made by Pioneer Venus and by several Venera spacecraft indicate that the present water abundance in Venus' lower atmosphere is of the order of 20 to 200 ppmv [1], or 3×10^{-6} to 3×10^{-5} of the amount of water in Earth's oceans. The exact depletion factor is uncertain, in part because of an unexplained vertical gradient in H_2O concentration in the lowest 10 km of the venusian atmosphere [1], but the general scarcity of water is well established. The interesting question, then, is: Was Venus deficient in water when it formed and, if not, where did its water go?

Planetary formation models developed 20 years ago by Lewis [2] predicted that Venus should have formed dry because of the higher temperatures prevailing at its location in the solar nebula, which would have precluded the condensation of hydrated silicate minerals. The predictions of this "equilibrium condensation" model have since been challenged on two different grounds: (1) Accretionary models now predict extensive gravitational mixing of planetesimals throughout the inner solar system [3] and (2) the condensation of hydrated silicates from the gas phase is now thought to be kinetically infeasible [4]; thus, planetary water must be imported in the form of H_2O ice. Taken together, these new ideas imply that Earth's water was derived from materials that condensed in the asteroid belt or beyond and were subsequently scattered into the inner solar system. If this inference is correct, it is difficult to imagine how Venus could have avoided getting plastered with a substantial amount of water-rich material by this same process. The conclusion that Venus was originally wet is consistent with its large endowment of other volatiles (N_2, CO_2, and rare gases) and with the enhanced D/H ratio in the present atmosphere [5,6]. Maintenance of a steady-state water inventory by cometary impacts [7] cannot explain the present D/H ratio if the water abundance is higher than 20 ppmv because the time constant for reaching isotopic equilibrium is too long [1].

The most likely mechanism by which Venus could have lost its water is by the development of a "runaway" or "moist" greenhouse atmosphere followed by photodissociation of water vapor and escape of hydrogen to space [8–11]. Climate model calculations that neglect cloud albedo feedback [9] predict the existence of two critical transitions in atmospheric behavior at high solar fluxes (Fig. 1): (1) at a solar flux of ~1.1 times the value at Earth's orbit, S_0, the abundance of stratospheric water vapor increases dramatically, permitting rapid escape of hydrogen to space (termed a "moist greenhouse") and (2) at a solar flux of ~1.4 S_0, the oceans vaporize entirely, creating a true "runaway greenhouse." If cloudiness increases at high surface temperatures, as seems likely, and if the dominant effect of clouds is to cool the planet by reflecting incident

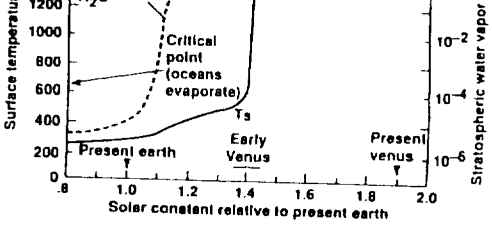

Fig. 1. Diagram illustrating the two key solar fluxes for water loss, as calculated in [9]. The critical point for pure water (above which the oceans evaporate entirely) is at 647 K and 220.6 bar. Figure courtesy of J. Pollack.