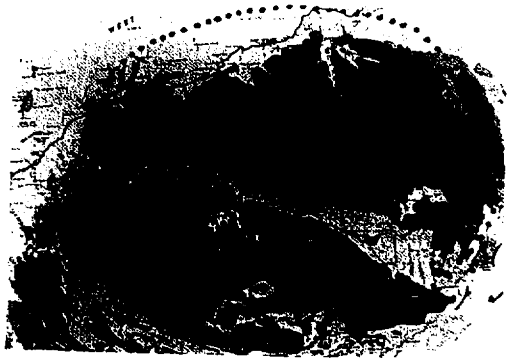

Fig. 5. Portion of geologic map of Pilbara Block and vicinity. Pilbara ellipse has dotted outline. Major granitoid intrusions are in solid outline. Box shows areas of Fig. 6.

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.

References: [1] Head J. W. et al. (1991) *Science, 252*, 276–287. [2] Solomon S. C. et al. (1991) *Science, 252*, 297–311. [3] Stofan E. R. et al. (1991) *JGR, 96*, 20933–20946. [4] Jackson M. P. A. et al. (1990) *GSA Mem., 177*, 139 pp. [5] Head J. W. and Wilson L. (1992) *JGR, 97*, 3877–3904. [6] Pitcher W. S. (1978) *Geol. Soc. Lond., 135*, 157–182. [7] Wager L. R. and W. A. Deer (1939) *Medd. om Gronland, 105*, 4, 1–352. [8] Baker V. R. et al. (1992) in press. [9] Trendall A. F. (1983) In *Iron-Formations: Facts and Problems*, 69–129, Elsevier, Amsterdam. [10] Hickman A. R. (1983) *Geol. Surv. West. Aust. Bull.*, 127. [12] Kargel J. S. and Sonnett C. P. (1992) *EPSL*, submitted.

N93-14331

VENUS: THE CASE FOR A WET ORIGIN AND A RUNAWAY GREENHOUSE. J. F. Kasting, Department of Geosciences, 211 Deike, Pennsylvania State University, University Park PA 16802, USA.

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_o, 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_o, 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

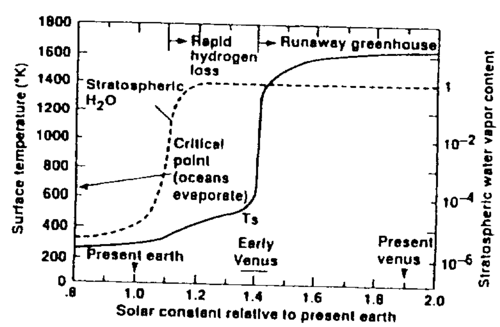

Fig. 1. Diagram illustrating the two key solar fluxes for water loss, as calculated in [9]. The critical point for pure water (above which the oceans evaporate entirely) is at 647 K and 220.6 bar. Figure courtesy of J. Pollack.

solar radiation, the actual solar flux required to create "moist" or "runaway" conditions would be higher than the values quoted above. (Indeed, some authors [12] have argued that cloud feedback would prevent a runaway greenhouse from ever occurring.) Early in solar system history, solar luminosity was about 25% to 30% less than today, putting the flux at Venus' orbit in the range of 1.34 S_0 to 1.43 S_0. Thus, it is possible that Venus had liquid water on its surface for several hundred million years following its formation. Paradoxically, this might have facilitated water loss by sequestering atmospheric CO_2 in carbonate rocks and by providing an effective medium for surface oxidation.

Continued progress in understanding the history of water on Venus requires information on the redox state of the atmosphere and surface. The loss of an ocean of water (or some fraction thereof) should have left substantial amounts of oxygen behind to react with the crust. This oxygen would presumably be detectable if we had core samples of crustal material. Barring this, its presence or absence might be inferred from accurate measurements of lower atmospheric composition. Another spacecraft mission to Venus could help to resolve this issue and, at the same time, shed light on the question of whether clouds will tend to counteract global warming on Earth.

References: [1] Donahue T. M. and Hodges R. R. Jr. (1992) *Icarus*, in press. [2] Lewis J. S. (1972) *Icarus, 16*, 241–252. [3] Wetherill G. W. (1980) *Annu. Rev. Astron. Astrophys., 18*, 77–113. [4] Prinn R. G. and Fegley B. Jr. (1989) In *Origin and Evolution of Planetary and Satellite Atmospheres* (S. K. Atreya et al., eds.), 78–136, Univ. of Arizona, Tucson. [5] Donahue T. M. et al. (1982) *Science, 216*, 630–633. [6] McElroy M. B. et al. (1982) *Science, 215*, 1614–1618. [7] Grinspoon D. H. and Lewis J. S. (1988) *Icarus, 74*, 21–35. [8] Kasting J. F. et al. (1984) *Icarus, 57*, 335–355. [9] Kasting J. F. (1988) *Icarus, 74*, 472–494. [10] Kasting J. F. and Pollack J. B. (1983) *Icarus, 53*, 479–508. [11] Kumar S. et al. (1983) *Icarus, 55*, 369–389. [12] Ramanathan V. and Collins W. (1991) *Nature, 351*, 27–32.

N93-14332

VENUS TECTONIC STYLES AND CRUSTAL DIFFERENTIATION.

W. M. Kaula and A. Lenardic, University of California, Los Angeles CA 90024, USA. P. 2

Two of the most important constraints are known from Pioneer Venus data: the lack of a system of spreading rises, indicating distributed deformation rather than plate tectonics; and the high gravity:topography ratio, indicating the absence of an asthenosphere. In addition, the high depth:diameter ratios of craters on Venus [1] indicate that Venus probably has no more crust than Earth. The problems of the character of tectonics and crustal formation and recycling are closely coupled. Venus appears to lack a recycling mechanism as effective as subduction, but may also have a low rate of crustal differentiation because of a mantle convection pattern that is more "distributed," less "concentrated," than Earth's. Distributed convection, coupled with the nonlinear dependence of volcanism on heat flow, would lead to much less magmatism, despite only moderately less heat flow, compared to Earth. The plausible reason for this difference in convective style is the absence of water in the upper mantle of Venus [2].

The most objective measure of the nature of motion that we can hope to infer is the spherical harmonic spectrum of its surface, or near-surface, velocities. A compact expression of this spectrum is a spectral magnitude M and slope n

$$\sigma_1(v) = M\,1^{-n} \tag{1}$$

where $\sigma_1(v)$ is the rms magnitude of a normalized spherical harmonic coefficient of degree 1. A concentrated flow, characterized by large segments moving together, has a steep slope, thence a high value of n, while a distributed flow, with small segments, has a small value of n. We cannot measure velocities directly on Venus. But in a planet dominated by a strong outer layer, in which the peak stresses are at a rather shallow depth, the magnitudes of gravitational potential V and poloidal velocity v_s are coupled [3]

$$M(\delta V)/M(v_s) = 12\pi G\eta/g \tag{2}$$

where η is the effective viscosity of the lithosphere, the ratio of stress to strain rate over long durations. The value inferred from the magnitudes M for Earth is 4×10^{21} Pa-s, probably most influenced by subduction zones. Support for this model is that the gravity and velocity spectra on Earth have the same slope n to two significant figures, 2.3 [3,4]. On Venus the spectral slope of gravity, n(δV), is appreciably lower over degrees that can be determined reliably—about 1.4 [4], strongly suggesting a more regional, less global, velocity field than on Earth.

A basic constraint on the velocity field that is somewhat independent of stresses, and thence rheology, is that, at the mantle depth where convection dominates—more than 150 km—there must be a correlation of vertical velocity v_r (coupled to the poloidal velocity v_s by continuity) and temperature variations ΔT that lead to an integral accounting for most of the total heat delivery Q from greater depths

$$Q = \int \rho C v_r \Delta T dS \tag{3}$$

For a mean heat flow of 60 mW/m^2 and average temperature variation ΔT of 100°C, equation (3) gives an estimate of 0.6 cm/yr for v_r. In the Earth, plate tectonics lead to such concentrations of v_r and ΔT at shallower depths that it is difficult to draw inferences from observed heat flow relevant to equation (3). However, the constraint exists, and its implication for the velocity spectrum of Venus should be explored.

The altimetry and imagery of Venus also indicate a regionality of Venus tectonics, even though magnitudes of velocities cannot be inferred because of dependence on unknown viscosity. For example, Maxwell Montes is comparable to the Andes in height and steepness (suboceanic). But the material subducted under the Andes clearly comes from the southeast Pacific Rise, over 4000 km away (despite the interruption of the Nazca Rise), while only 500 km from the Maxwell front is a scarp, and beyond that a much more mixed, apparently unrelated, variety of features. Clearly, Maxwell is more local than the Andes. A significant difference of Venus tectonics from Earth is the absence of erosion, which removes more than 1 km/100 m.y. from uplands.

Hypotheses for why Venus does not have crustal formation in a ridge system, but rather a more distributed magmatism correlated with a more regional tectonism, include (1) the lack of plate pull-apart due to inadequate subduction; (2) the lack of plate pull-apart due to drag on the lithosphere from higher viscosity: i.e., no asthenosphere; (3) the lesser concentration of flow from within the mantle, also due to higher viscosity; (4) lower temperatures, due to less initial heating and more effective retention of lithophiles in the crust; (5) higher melting temperatures, due to lack of water content, and (6) lower mobility of magma relative to matrix, due to (a) low