lutionary Phenomena in Galaxies, J. E. Beckmann and B. E. J. Pagel, Eds. (Cambridge Univ. Press, Cambridge, 1989), pp. 201–223.
22. A. M. Boesgaard, *Astrophys. J.* **336**, 798 (1989).
23. B. Edvardsson *et al., Astron. Astrophys.* **275**, 101 (1993).
24. G. Malinie, D. H. Hartmann, D. D. Clayton, G. J. Mathews, *Astrophys. J.* **413**, 633 (1993).
25. A. G. W. Cameron, P. Höflich, P. C. Meyers, *ibid.* **447**, L53 (1995).
26. L. Carigi, *ibid.* **424**, 181 (1994).
27. J.-R. Roy and D. Kunth, *Astron. Astrophys.* **294**, 432 (1995).
28. W. R. J. Rolleston, P. L. Dufton, A. Fitzsimmons, *ibid.* **284**, 72 (1994).
29. F. Matteuci and C. Chiosi, *ibid.* **123**, 121 (1983).
30. L. Buchmann *et al., Phys. Rev. Lett.* **70**, 726 (1993); Z. Zhao *et al., ibid.*, p. 2066.
31. U. Ott, *Nature* **364**, 25 (1993).
32. E. Anders and E. Zinner, *Meteoritics* **28**, 490 (1993).
33. S. Amari, E. Zinner, R. S. Lewis, *Astrophys. J.* **447**, L147 (1995).
34. C. Chyba and C. Sagan, *Nature* **355**, 125 (1992).
35. D. C. Morton, *Astrophys. J.* **197**, 85 (1975).
36. T. P. Snow, *ibid.* **204**, 759 (1976).
37. L. M. Hobbs, D. G. York, W. R. Oegerle, *ibid.* **252**, L21 (1982).
38. D. E. Welty, D. G. York, L. M. Hobbs, *Publ. Astron. Soc. Pac.* **98**, 857 (1986).
39. J. A. Cardelli *et al., Astrophys. J.* **377**, L57 (1991).
40. J. A. Cardelli, J. S. Mathis, D. C. Ebbets, B. D. Savage, *ibid.* **402**, L17 (1993).
41. T. P. Snow *et al., Astrophys. J.*, in press.
42. Z. Fang, V. H. S. Kwong, J. Wang, W. H. Parkinson, *Phys. Rev. A* **48**, 1114 (1993).
43. D. J. Lennon, P. L. Dufton, A. Hibbert, A. E. Kingston, *Astrophys. J.* **294**, 200 (1985).
44. R. Sancisi, in *Galactic Radio Astronomy*, F. J. Kerr and S. C. Simonson, Eds. (Reidel, Dordrecht, Netherlands, 1974), pp. 115–128.
45. R. C. Bohlin, B. D. Savage, J. F. Drake, *Astrophys. J.* **224**, 132 (1978).
46. D. C. B. Whittet, *Mon. Not. R. Astron. Soc.* **210**, 479 (1984).
47. E. B. Jenkins and E. J. Shaya, *Astrophys. J.* **231**, 55 (1979); E. B. Jenkins, M. Jura, M. Lowenstein, *ibid.* **270**, 88 (1983).
48. A. J. Adamson, D. C. B. Whittet, W. W. Duley, *Mon. Not. R. Astron. Soc.* **243**, 400 (1990).
49. R. Papoular, J. Breton, G. Gensterblum, I. Nenner, J.-J. Pireaux, *Astron. Astrophys.* **270**, L5 (1993).
50. S. A. Sandford *et al., Astrophys. J.* **371**, 607 (1991).
51. Y. J. Pendleton, S. A. Sandford, L. J. Allamandola, A. G. G. M. Tielens, K. Sellgren, *ibid.* **437**, 683 (1994).
52. T. P. Snow, Y. Pendleton, T. R. Geballe, P. Jenniskens, A. G. G. M. Tielens, in preparation.
53. A. G. G. M. Tielens and T. P. Snow, Eds., *The Diffuse Interstellar Bands* (Kluwer, Dordrecht, Netherlands, 1995).
54. W. W. Duley, *Mon. Not. R. Astron. Soc.* **215**, 259 (1985); D. G. Furton and A. N. Witt, *Astrophys. J.* **415**, L51 (1993).
55. S. S. Hong and J. M. Greenberg, *Astron. Astrophys.* **88**, 194 (1980) and references therein.
56. B. T. Draine and H. M. Lee, *Astrophys. J.* **285**, 89 (1984).
57. J. S. Mathis, W. Rumpl, K. H. Nordsieck, *ibid.* **217**, 425 (1977).
58. P. A. Aannestad, *ibid.* **443**, 653 (1995).
59. J. S. Mathis and G. Whiffen, *ibid.* **341**, 808 (1989).
60. F.-X. Dèsert, F. Boulanger, J. L. Puget, *Astron. Astrophys.* **237**, 215 (1990).
61. W. H. Sorrell, *Mon. Not. R. Astron. Soc.* **243**, 570 (1990).
62. J. Puget and A. Lèger, *Annu. Rev. Astron. Astrophys.* **27**, 161 (1989).
63. D. C. B. Whittet, in *Dust and Chemistry in Astronomy*, T. J. Millar and D. A. Williams, Eds. (Institute of Physics, Bristol, UK, 1993), pp. 9–35.
64. D. M. Meyer, M. Jura, I. Hawkins, J. A. Cardelli, *Astrophys. J.* **437**, L59 (1994).
64a. J. Cardelli, D. M. Meyer, M. Jura, B. D. Savage, *Astrophys. J.*, in press.
65. G. L. Withbroe, in *NBS SP-353*, K. B. Gebbie, Ed. (Government Printing Office, Washington, DC, 1971), p. 127.
66. A. G. W. Cameron, *Space Sci. Rev.* **15**, 121 (1973).
67. E. Anders and N. Grevesse, *Geochim. Cosmochim. Acta* **53**, 197 (1989).
68. J. A. Baldwin *et al., Astrophys. J.* **374**, 580 (1991).
69. R. H. Rubin, J. P. Simpson, M. R. Haas, E. F. Erickson, *ibid.*, p. 564.
70. R. H. Rubin, R. J. Dufour, D. K. Walter, *ibid.* **413**, 242 (1993).
71. R. H. Peimbert, P. J. Storey, S. Torres-Peimbert, *ibid.* **414**, 626 (1993).
72. L. J. Allamandola, A. G. G. M. Tielens, J. R. Barker, *Astrophys. J.* **290**, L25 (1985).
73. ———, *Astrophys. J. Suppl. Ser.* **71**, 733 (1989).
74. C. Joblin, A. Lèger, P. G. Martin, *Astrophys. J.* **393**, L79 (1992).
75. W. W. Duley and A. P. Jones, *ibid.* **351**, L49 (1990).
76. A. G. G. M. Tielens and L. J. Allamandola, in *Interstellar Processes*, D. J. Hollenbach and H. A. Thronson, Eds. (Reidel, Dordrecht, Netherlands, 1987), pp. 397–469.
77. D. C. B. Whittet, A. J. Adamson, W. W. Duley, T. R. Geballe, A. D. McFadzean, *Mon. Not. R. Astron. Soc.* **241**, 707 (1989).
78. W. W. Duley, in (*53*), pp. 359–362.
79. F. Salama and L. J. Allamandola, *Astrophys. J.* **395**, 301 (1992).
80. ———, *Nature* **358**, 42 (1992).
81. A. Lèger, L. d'Hendecourt, D. Dèfourneau, *Astron. Astrophys.* **293**, L53 (1995).
82. B. Foing and P. Ehrenfreund, *Nature* **369**, 296 (1994).
83. E. Busoletti, L. Colangeli, V. Orofino, *Astrophys. J.* **321**, L87 (1987).
84. B. T. Draine, in *Interstellar Dust*, L. J. Allamandola and A. G. G. M. Tielens, Eds. (Kluwer, Dordrecht, Netherlands, 1989), pp. 313–32.
85. W. W. Duley, *Mon. Not. R. Astron. Soc.* **229**, 203 (1987).
86. W. W. Duley, A. P. Jones, D. A. Williams, *ibid.* **236**, 709 (1989).
87. A. P. Jones, *ibid.* **247**, 305 (1990).
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Venus Reconsidered

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The Magellan imagery shows that Venus has a crater abundance equivalent to a surface age of 300 million to 500 million years and a crater distribution close to random. Hence, the tectonics of Venus must be quiescent compared to those of Earth in the last few 100 million years. The main debate is whether the decline in tectonic activity on Venus is closer to monotonic or episodic, with enhanced tectonism and volcanism yet to come. The former hypothesis implies that most radioactive heat sources have been differentiated upward; the latter, that they have remained at depth. The low level of activity in the last few 100 million years inferred from imagery favors the monotonic hypothesis; some chemical evidence, particularly the low abundance of radiogenic argon, favors the episodic. A problem for both hypotheses is the rapid decline of thermal and tectonic activity some 300 million to 500 million years ago. The nature of the convective instabilities that caused the decline, and their propagation, are unclear.

Perceptions of Venus have changed significantly in the last 5 years, not only because of results returned by the Magellan spacecraft but also because of better experiments on the rheology of dry crustal rocks. As of 1990, it was generally but not universally agreed that plate tectonics was negligible on Venus, that Venus must have a stiff upper mantle, and that at least the northernmost 25% of the surface (the part observed by Venera orbiters) must average several 100 million years in age. The surface compositions measured at most Venera landing sites were considered to be consistent with a primitive basaltic crust, and two of the sites indicated further differentiations. The strength indicated by high depth/diameter ratios of craters was interpreted to limit the mean thickness of the crust to less than 20 km. Leading inferences in 1990 were (i) that Venus lacks water in its outer few hundreds of kilometers; (ii) that the energy delivery from the mantle must be less than Earth's, perhaps half as much; and (iii) that some appreciable energy sources persist at great depths to sustain the few great mountain complexes. The problem identified as the greatest was reconciling a voluminous crust with the indications of considerable strength at shallow depths of 20 to 100 km (*1*).

The most important data from Magellan radar imagery are the impact craters, of which 915 have been identified. They have an abundance indicating an average surface age of 300 million to 500 million years and a geographic distribution consistent with randomness on a global scale (*2*). Furthermore, the lack of clusters of older craters implies a rapid decline in the resurfacing of Venus, perhaps within a few tens of millions of years. Although more detailed examinations infer that Venus is not entirely dead (*3*), they generally confirm inferences from Pioneer Venus altimetry (*4*) that recent tectonic activity on Venus is slight compared to Earth's. An important general characteristic inferred from Magellan imagery is that deformation on Venus is distrib-

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Table 1. Abundances of radioactive elements on Venus. The numbers are based on gamma ray spectrometry, except for Venera 13 and 14, for which x-ray fluorescence was used to measure K_2O and K/U = 9000; K/Th = 3000 has been assumed. N-MORB, normal midocean ridge basalt.

Landing site	K_2O (%)	K/U	K/Th	Heat generation (10^{-12} W kg^{-1})
Venera 8 (*12*)	5.0	18,000	6000	531
Venera 9 (*12*)	0.8	7800	1300	172
Venera 10 (*12*)	0.3	6500	4300	74
Venera 13 (*12*)	4.0			768
Venera 14 (*12*)	0.2			107
Vega 1 (*12*)	0.6	7000	3000	118
Vega 2 (*12*)	0.5	5900	2000	134
N-MORB (*13*)	0.09	15,000	5600	14

uted, with strain patterns extending hundreds of kilometers, rather than concentrated in relatively narrow zones, as on Earth (*5*). The Magellan imagery also raised some compositional problems, such as the nature and source of lavas creating long sinuous rills (*6*), which may relate to the mechanisms of the resurfacing, and the cause of the high radar reflectivity of upland regions (*7*), which constrains the subsequent rate of change in the surface of Venus.

Important new experimental data on the rheology of dry diabase (*8*) showed it to have a viscosity as high as that of dry olivine (*9*), although at strain rates 10 orders of magnitude greater than those inferred for Venus (*10*). This finding removed the constraint on crustal thickness from the high depth/diameter ratios of craters (*11*), which was based on earlier rheological experiments that apparently failed to dry out the specimens. It may also remove the need for deep convective sources to support the highland regions.

Several problems remain. Those that appear most important to the long-term evolution of Venus are as follows: (i) Can the quiescent tectonics of Venus be attributed to the differentiation of most of its radioactive heat sources up into the crust, thus reducing temperature gradients? (ii) Are the apparent stiffness of the venusian upper mantle and the slow time scale of its tectonics explicable by the lack of water? (iii) What mechanisms caused the apparent rapid decline in resurfacing at 300 million to 500 million years ago?

Evolution of the Venus Crust

A quiescent Venus could be explained by upward differentiation of the radiogenic elements K, U, Th, which are the principal heat sources, to the crust. The abundances of the radiogenic elements were measured at seven Venera and Vega landing sites (Table 1). The five sites with K_2O concentrations of less than 1% (*12*) are often dismissed as resembling terrestrial tholeiites. However, they are actually high in K, U, and Th content, not only in measured values compared to the most comparable Earth rocks (*13*) but also with respect to their formation and circumstances of measurement. Most of Venus appears to be resurfaced by lavas. The area-dominant lavas should be those of the lowest viscosity. Low viscosity basalts have basic compositions and thus low contents of the radiogenic elements, which are all large ion lithophiles. It is likely that the lander sites were selected to minimize the chance that the lander would tip over; thus, they would have been smooth areas, indicated by radar darkness. Such selection would cause a bias in favor of low viscosity basic lavas. All the lander sites, as analyzed on Magellan imagery, are indeed in radar dark areas (*14*). The most radioactive rocks on Venus, as on Earth, were probably produced by remeltings of crust, which, normally being smaller scale events, are more often plutonic than volcanic (*15*). The ratio of plutonism to volcanism plausibly increases with the decline in the level of activity and hence could be higher on quiescent Venus than on active Earth (*16*). Finally, Venus lacks the dominant process, erosion, that brings highly radioactive plutonic rocks to the surface of Earth; Venus exhibits only tectonism, which characterizes a minor fraction of the surface.

Turcotte (*17*) argued that packing radioactive elements into the crust would cause it to melt. This process would have been even more likely when the rate of heat generation was much higher—twice as much at 2.7 billion years ago. The resulting intracrustal differentiation would have been an effective mechanism for moving radioactive elements upward, leaving ample time for the crust to cool. The high surface temperature of Venus would have helped to reduce temperature gradients at depth, because of the strong positive temperature dependence of thermal conductivity above 500 K (*18*).

Thus, it is plausible for a Venus crust to evolve to a strong upward concentration of radioactive elements, with a maximum concentration a few kilometers below the surface because of the absence of erosion. This would have kept crustal temperatures low enough, and hence viscosities high enough (*8*), to ensure strong coupling of the dry crust to the dry lithosphere and hence to dry mantle. This coupling would inhibit broad-scale plate tectonics (*19*) and hence Earth-like subduction as a mechanism of crustal recycling. The evident mechanism of crustal recycling on Venus thus becomes the gabbro-to-eclogite transition (*20*), dependent on the phase transformation of low density feldspars to garnet. The resulting rock eclogite has a density higher than that of ferromagnesian silicates, which constitute the bulk of the mantle. Hence, this mechanism would cause detachment, and thus recycling, of crust. This transition occurs at depths of 50 to 70 km under Venus conditions, thus requiring a thick crust to be effective.

The main evidence contrary to this scenario of a high content of radiogenic elements in Venus's crust is the low abundance of radiogenic Ar, ^{40}Ar, in the Venus atmosphere, about one-third that of Earth (*21*). Although Venus does not exhibit erosion, which would release Ar from rocks, the temperatures of 740 K or more should cause Ar to diffuse easily. There are some explanations, such as intracrustal differentiations and nonrepresentativeness of the lander measurements, but none are fully persuasive (*22*).

Another consequence of intracrustal differentiation would be a reduction in the density of shallow crustal rocks compared to that of deep rocks, as occurs in Earth's continents, where shallow igneous layers are estimated to be less dense by at least 300 kg m^{-3} than typical oceanic crustal rocks. This mechanism appears essential to explain the highest region on Venus, Maxwell Montes. The radar imagery strongly indicates that Maxwell Montes was created by convergent flow (*23*). The revised diabase rheology (*8*) now predicts that the topographic height would take several 100 million years to slump away (*24*). Models that assume a crust of uniform lateral density cannot posit sufficient crust to compensate for the 10 km of topography by purely Airy isostasy within the gabbro-to-eclogite transition (*20*). But a model of convergent flow, followed by intracrustal differentiation to create a Pratt compensation, in which the more mafic component sinks below the position of the gabbro-to-eclogite transition, satisfies the topography and gravity quite well (*25*). The parallel ridge belts of about 20-km spacing, indicating instability of a competent layer over a weaker substratum (*26*), would have to be frozen in from the terminal phase of such an evolution. This crustal differentiation pertains to the support of regional features that are less than 1000 km in extent. Ishtar Terra as a whole (as well as the edifices of Beta Regio and Atla Regio) must be supported by mantle mechanisms, thermal or compositional, because the apparent depths of compensation inferred from the long wavelengths of gravity and topography exceed 100 km (*25*).

Effects of Dryness on Tectonics and Mantle Convection in Venus

The high ratio of correlated gravity to topography on Venus, implying apparent depths of compensation of greater than 100 km in the long wavelengths, requires a strong coupling of the mantle to the lithosphere and hence no Earth-like asthenosphere (*19*). It was conjectured that this characteristic of Venus arose from a lack of water in its outer parts (*1*). Turcotte (*17*) has criticized this conjecture on the grounds that if Venus's mantle lacked water but still had a comparable amount of heat to lose, then it would merely heat up enough to lower the viscosity so as to ensure the necessary rate of convection. This is true to the zeroth order but is not applicable to the first-order problem of an asthenosphere, which is a quite distinct layer under Earth's oceans, being less viscous than both the material above it and the material below it. This property is sometimes ascribed to pressure release melting. But if all else were equal except surface temperature, as in the Turcotte conjecture, then this explanation indicates that Venus should have an asthenosphere as well.

Packing most of the heat sources in the crust, as suggested above, would help to prevent an asthenosphere on Venus. But this would be a circular argument, because the inability to recycle crust underlying the crust depends on the strong rheological coupling between lithosphere and mantle. Hence, in principle, the absence of an asthenosphere on Venus should occur even though there was significant heat delivery from the mantle. If the dryness of Venus is the explanation, it must affect the gradient of viscosity with respect to depth.

The solidus of wet mantle rock on Venus is markedly lower than that of dry rock at pressures corresponding to the depth of Earth's asthenosphere (*27*). If there were an analogous effect on viscosity, then dryness might explain the absence of an asthenosphere on Venus, even if heat sources remained at depth; the important thing is not the temperature dependence of viscosity per se, but the gradient of this dependence with respect to pressure. It is desirable that this conjecture be verified experimentally, but sufficient pressures have not been attained in the laboratory. Meanwhile, there is ample room for theoretical speculation. The effect of water on the solidus arises from the breakdown of hydrated phases (mainly hornblende) at asthenospheric pressures, whereas its effect on viscosity probably arises from intergranular flow plus intragranular diffusion at large grain sizes (*9*). These effects are rather different, but a connection cannot be summarily ruled out; in particular, lowered viscosity in Earth's asthenosphere may be in part caused by, as well as correlated with, small degrees of partial melting.

The most important consequence of the stiff upper mantle on Venus is the inhibition of crustal recycling. On Earth, this process is dominated by the subduction of tectonic plates (*28*). On Venus, the distributed deformation arising from the tight coupling of lithosphere to mantle (*19*) could prevent the concentration necessary for such an instability. There are asymmetric chasms on Venus suggestive of subduction trenches, but they are limited in extent (*29*). The lack of water may make the lithosphere more difficult to break; marginal zones on Earth are characterized by a high abundance of hydrated rocks (*30*). In the past, the mechanism of crustal recycling by the gabbro-to-eclogite phase transition may have been quite effective, but the present high subcrustal viscosity must slow any sinkings substantially. Another consequence of the prevention of subduction is that the mantle convective pattern is more influenced by internal, rather than by upper boundary layer, instabilities. This would lead to more regional flow patterns, characterized by plumes or internal avalanches associated with phase transitions, as occur in three-dimensional computer experiments (*31*). But the effect of internal flow patterns on thermal evolution should be less than the inhibition of crustal recycling, which leads to the concentration of radioactive energy sources in the crust.

Models of Venus Evolution Satisfying the Evidence of Rapid Decline

The crater distribution on Venus is consistent with randomness (*2*). However, to infer therefrom that the distribution is random (*32*) is a misapplication of Ockham's razor. The actual distribution of craters per unit area has a lower peak and higher extremes than the centroid of a Poisson distribution (*33*). The question then becomes what is the range of models consistent with the observed distribution. This is difficult to define systematically, because volcanism and tectonism on Venus are obviously nonrandom, as they are on any planet. The evident reference frame, the topography, is quite non-Gaussian, with positive skewness and excess (*34*). Relatively recent volcanic occurrences do have fewer than average craters (*3*), whereas old-appearing tesserae have an abundance of larger craters 40% higher than average but a deficiency of small craters (*35*).

Hence, the time scale of the shutdown of tectonic activity in Venus could be several times 10 million years, perhaps more than 100 million years. This is still difficult to reconcile with a decrease in average strain rate by at least a factor of 100 (*10*). Clearly, the decline cannot be due solely to the interaction of nonlinear rheology with a global, nearly uniform thermal state; it must entail nonlinearities of the flow system, compositional as well as thermal. The significant tectonic activity probably was widespread but involved only a minor, tectonically active part of the globe (analogous to contemporary Earth); however, the lavas produced thereby must have been voluminous and fluid enough to resurface the entire planet within 100 million years or so. Factors that have been suggested to affect evolution and the rapid decline include the following: (i) upward concentration of radioactive heat sources in the crust; (ii) a lithosphere hotter than Earth's, leading to a more free top boundary (*36*); (iii) the accumulation of a high Mg-Fe residuum in the upper mantle (*37*); (iv) a transition of the lithosphere to positive buoyancy with cooling (*38*); (v) increased rigidity of the lithosphere with cooling (*39*); (vi) nonlinear dependence of viscosity on temperature and strain rate (*11*, *39*); and (vii) the absence of water (*1*).

A transition of dominance from factors i and ii, which promote the escape of heat from the mantle, to factors iii through v, which act to shut off heat escape, is characteristic of most scenarios, implicitly if not explicitly. Dominance of factors ii through vi, coupled with retention of heat sources at depth, would have caused a temperature rise leading to massive melting, rupturing the lithosphere. The nonlinearity of factor vi enhances instabilities that propagate rupture, whereas factor vii acts to strengthen the lithosphere, thus increasing the temperature buildup required for rupture.

The lack of water may also have acted to prevent plate tectonics, which depends on weak lithospheric margins (*30*), throughout Venus's history. This idea is contrary to the hypothesis of Herrick (*38*) but is consistent with the more distributed deformation implied by the models of Arkani-Hamed (*39*). But factor i, the removal of heat sources from the interior, still seems essential.

Instabilities require density inhomogeneities, thermal or compositional, which in turn are normally associated with interfaces. The more pronounced the density differential at the interface, the more likely it is that an instability can occur. Possible locations include (i) the surface, from development of a thick, dense lithosphere, which breaks and sinks, as in Earth's subduction (abetted by lateral variations in crustal density and thickness); (ii) the base of a crust thick enough to reach the basalt-to-eclogite transition; (iii) the upper mantle, after accumulation of a Mg-rich layer residual to crustal differentiation (*37*); as the convective vigor slowed, such a layer may not have been swept aside so quickly (as it is on Earth); (iv) the zone, 400 to 700 km deep, of olivine-spinel-perovskite phase transitions, which in three-dimensional computer experiments trigger avalanche downflows (*31*); and (v) the core mantle interface, about 2800 km deep in Venus, which has the largest density change and is often conjectured to originate plumes in both Earth and Venus. A combination of mechanisms associated with locations i and iii seems most plausible. Both mechanisms depend on crustal differentiation, but not on the growth of crust to a thickness of more than 50 km or more, as do mechanisms associated with location ii. Mechanisms associated with location iv depend on the smallest density difference, whereas the development of a density excess sufficient to penetrate the core mantle boundary seems impossible.

Probably the greater difficulty is the propagation of instability, a problem somewhat analogous to that of earthquake occurrence: relief of an instability in one place enhances instabilities elsewhere. It is particularly a problem if the upper mantle were already stiff. Propagation would be greatly aided by the presence of an asthenosphere, as in Turcotte's episodic model (*17*), to which the main objection is that if heat sources remained at depth, their effects should be seen within a time much less than 300 million years after the resurfacing event (as with secondary convection under Earth's oceans). Any monotonic model (*40*) would require that the instabilities not return too many heat sources to the interior and hence would be facilitated by intracrustal differentiations and the stripping off of the upper crust in downflows.

Constraints on the nature of activity more than 500 million years ago are slight. The occurrence of contorted tessera terrain in many areas is generally thought to indicate a regime of more vigorous distributed tectonics. The thoroughness of the latest resurfacing and the decline of radioactivity indicate that convection was more vigorous in the past, and hence the tendency for oscillatory behavior was greater, as is characteristic of convection at higher Rayleigh numbers. Arkani-Hamed (*39*) suggested that the high temperatures on Venus led to a surface condition closer to stress-free, and hence a greater cooling of the mantle, than has occurred in Earth. This makes the radiogenic Ar deficiency a greater problem; if the Arkani-Hamed model is correct, then on Venus there must have been an initial deficiency of K, relative to that on Earth.

A consequence of the greater cooling of the mantle on Venus could be to freeze the core, thus accounting for the absence of a magnetic field (*39*). Another hypothesis is that the core is entirely fluid, thus lacking the solidification of the inner core generally thought to be the energy source for Earth's magnetic field (*41*). This question is accessible to observational testing, by inference of Venus's Love number k_2, a measure of its nonrigid yielding to tides. Early estimates from Magellan orbiter tracking obtained a relatively high Love number, 0.28 ± 0.07, tending to favor a fluid core (*42*).

Conclusions

The striking differences between Venus and Earth stimulate hypotheses that may seem contrived, even though they depend on effects that are known to exist but are of secondary significance on Earth. Insight would be aided by computer experiments, but such experiments are time-consuming if nonlinear rheology and compositional differentiations in three dimensions are included, and there is a danger of wish fulfillment in the macroscale simulation of magmatism.

Describing the debate as monotonic versus episodic is an oversimplification; the question is more the magnitude of the oscillations about an inevitably declining trend. But certainly Venus's activity in the last 300 million years has been slight compared to Earth's. During this period, the magnitude of sea-floor spreading on Earth has varied by a factor of ~ 2 (*43*). It is hard to believe that the oscillations could be much greater for a Venus that is now so quiescent. Perhaps a requisite condition for catastrophic episodicity is the dryness, by making the lithosphere more difficult to break. It is also difficult to adjust Earth-conditioned intuitions to the long time scales indicated by the stiff dry rheology on Venus.

The greatest observational constraint on packing radioactive elements in the crust of Venus is the low abundance of radiogenic Ar in the atmosphere, which requires either a K/U ratio much lower than that on Earth or a much lower average level of activity in Venus's entire thermal and compositional evolution. If the K/U ratio on Venus is as high as Earth's, the material could not have been brought close to Venus's surface at a rate comparable to that by Earth's mantle convection (*44*), in view of the transparency to Ar diffusion of rocks at Venus's temperatures. The observations we would most like to have of Venus are chemical samplings to depths of at least 10 cm, preferably 30 cm, to avoid atmospheric effects that concentrate volatiles (including K) in the upper few centimeters. These appear to be unlikely within the near future. In laboratory experiments, it would be desirable to extend rheological experiments on wet and dry olivine or peridotite to pressures of 6.0 GPa or more, a procedure that is of considerable technical difficulty, to verify the extent to which water makes a difference at depths up to 200 km in the mantle.

REFERENCES AND NOTES

1. W. M. Kaula, *Science* **247**, 1191 (1990).
2. G. G. Schaber *et al.*, *J. Geophys. Res.* **97**, 13257 (1992); R. J. Phillips *et al.*, *ibid.*, p. 15923.
3. N. Namiki and S. C. Solomon, *Science* **265**, 929 (1994); M. Price and J. Suppe, *Nature* **372**, 756 (1994); R. J. Phillips and N. R. Izenberg, *Geophys. Res. Lett.* **22**, 1517 (1995).
4. W. M. Kaula and R. J. Phillips, *Geophys. Res. Lett.* **8**, 1187 (1981).
5. R. J. Phillips and V. L. Hansen, *Annu. Rev. Earth Planet. Sci.* **22**, 597 (1994).
6. V. R. Baker *et al.*, *J. Geophys. Res.* **97**, 13421 (1992).
7. K. B. Klose, J. A. Wood, A. Hashimoto, *ibid.*, p. 16353; R. A. Brackett, B. Fegley, R. E. Arvidson, *ibid.* **100**, 1553 (1995).
8. S. J. Mackwell, M. E. Zimmerman, D. L. Kohlstedt, D. S. Scherber, in *Rock Mechanics*, J. J. K. Daemen and R. A. Schultz, Eds. (Balkema, Rotterdam, 1995), p. 207.
9. S.-I. Karato, M. S. Paterson, J. D. FitzGerald, *J. Geophys. Res.* **91**, 8151 (1986).
10. R. E. Grimm, *ibid.* **99**, 23163 (1994).
11. ——— and S. C. Solomon, *ibid.* **93**, 11911 (1988).
12. Y. A. Surkov, V. L. Barsukov, L. P. Moskalyeva, V. P. Kharyukova, A. L. Kemurd-zhian, *ibid.* **89**, B383 (1984); Y. A. Surkov *et al.*, *ibid.* **92**, E537 (1987).
13. O. V. Nikolayeva, *Lunar Planet. Sci. Conf.* **26**, 1049 (1995).
14. J. S. Kargel, G. Komatgsu, V. R. Baker, R. G. Strom, *Icarus* **103**, 253 (1993).
15. A. H. Lachenbruch, *J. Geophys. Res.* **75**, 3291 (1970).
16. But an opposite hypothesis is that Earth would have the higher ratio of plutonism to volcanism because water-saturated magmas are more likely to freeze upon ascent, as a result of the negative slope of the phase transition [C. W. Burnham, in *The Evolution of Igneous Rocks*, H. S. Yoder, Ed. (Princeton Univ. Press, Princeton, NJ, 1979), p. 439].
17. D. L. Turcotte, *J. Geophys. Res.* **98**, 17061 (1993).
18. If we use the formula for thermal conductivity of J. F. Schatz and G. Simmons [*J. Geophys. Res.* **77**, 6966 (1972)] and assume a heat flow from the mantle of 0.03 W m^{-2}, plus a surface heat source density of 275×10^{-12} W kg^{-1} with a decay depth of 40 km, a numerical integration of the thermal conduction equation gives, at a depth of 60 km, a temperature of 1550 K and a thermal conductivity of 4.0 m^{-1} per degree Celsius. If we assume a strain rate of 10^{-17} s^{-1} (*9*), the effective viscosity for dry diabase (*17*) is 10^{23} Pa-s.
19. R. J. Phillips, *J. Geophys. Res.* **95**, 1301 (1990); ———, R. E. Grimm, M. C. Malin, *Science* **252**, 651 (1991); W. S. Kiefer, M. A. Richards, B. H. Hager, B. G. Bills, *Geophys. Res. Lett.* **13**, 14 (1986).
20. N. Namiki and S. C. Solomon, *J. Geophys. Res.* **98**, 15025 (1993); S. G. Herzog, P. C. Hess, E. M. Parmentier, *Lunar Planet. Sci. Conf.* **26**, 591 (1995); M. G. Jull and J. Arkani-Hamed, *Phys. Earth Planet. Inter.* **89**, 163 (1995).
21. J. B. Pollack and D. C. Black, *Icarus* **51**, 169 (1992); N. Namiki and S. C. Solomon, *Lunar Planet. Sci. Conf.* **26**, 1029 (1995).
22. W. M. Kaula and T. M. Harrison, in preparation.
23. W. M. Kaula *et al.*, *J. Geophys. Res.* **97**, 16085 (1992).
24. A. M. Freed and H. J. Melosh, *Lunar Planet. Sci. Conf.* **26**, 421 (1995).
25. Using the model of D. W. Forsyth [*J. Geophys. Res.* **90**, 12623 (1985)] plus the assumption of a deep

positive load, one obtains from the gravimetry and altimetry of the Maxwell Montes region a crust to a depth of 50 km with a negative density anomaly of about 500 kg m^{-3}.
26. M. T. Zuber, *J. Geophys. Res.* **92**, E541 (1987).
27. D. H. Green, *Earth Planet. Sci. Lett.* **19**, 37 (1973).
28. R. W. Carlson, *Rev. Geophys.* **32**, 337 (1994).
29. D. T. Sandwell and G. Schubert, *Science* **257**, 766 (1992).
30. G. P. Bird, *Rev. Geophys.* **33**, Suppl. (*U.S. Natl. Rep. 1991–1994*), 379 (1995).
31. P. J. Tackley, D. J. Stevenson, G. A. Glatzmaier, G. Schubert, *Nature* **361**, 699 (1993).
32. R. G. Strom, G. G. Schaber, D. D. Dawson, *J. Geophys. Res.* **99**, 10899 (1994).
33. W. M. Kaula, *Lunar Planet. Sci. Conf.* **24**, 767 (1993).
34. Both the third and the fourth moments are higher than those of a Gaussian distribution of the same mean square σ^2: >0 and >$3(\sigma^2)^2$ [W. M. Kaula, *Geophys. Res. Lett.* **20**, 2583 (1993)].
35. M. A. Ivanov and A. T. Basilevsky, *Geophys. Res. Lett.* **20**, 2579 (1993).
36. J. Arkani-Hamed, G. G. Schaber, R. G. Strom, *J. Geophys. Res.* **98**, 5309 (1993).
37. R. J. Phillips and R. E. Grimm, *Lunar Planet. Sci. Conf.* **21**, 1065 (1990); E. M. Parmentier and P. C. Hess, *Geophys. Res. Lett.* **19**, 2015 (1992).
38. R. R. Herrick, *Geology* **22**, 703 (1994).
39. J. Arkani-Hamed, *Phys. Earth Planet Inter.* **76**, 75 (1993); *J. Geophys. Res.* **99**, 2019 (1994).
40. S. C. Solomon, *Lunar Planet. Sci. Conf.* **24**, 1331 (1993).
41. D. J. Stevenson, T. Spohn, G. Schubert, *Icarus* **54**, 466 (1983).
42. A. S. Konopliv and C. M. Yoder, unpublished results.
43. C. Lithgow-Bertelloni, M. A. Richards, Y. Ricard, R. J. O'Connell, D. C. Engebretson, *Geophys. Res. Lett.* **20**, 375 (1993).
44. Currently, about 20 km^3 of crust, averaging about 6 km thick, is differentiated per year in Earth. This crust is the product of multiple differentiations extending 60 km deep, and so the volume rate of material associated with magmatism, which would release Ar, is about 200 km^3 $year^{-1}$. The volume of the mantle is 9×10^{11} km^3. Hence, if it were uniformly sampled, the entire mantle would have been cycled through the near surface layer in 4.5×10^9 years. However, convection, and hence magmatism, was much more vigorous in the past, whereas the sources of comtemporary basalts are clearly recycled. But, regardless of the numbers, the comment in the text applies.
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RESEARCH ARTICLE

Crystal Structure of the Ternary Complex of Phe-tRNA^{Phe}, EF-Tu, and a GTP Analog

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The structure of the ternary complex consisting of yeast phenylalanyl–transfer RNA (Phe-tRNA^{Phe}), *Thermus aquaticus* elongation factor Tu (EF-Tu), and the guanosine triphosphate (GTP) analog GDPNP was determined by x-ray crystallography at 2.7 angstrom resolution. The ternary complex participates in placing the amino acids in their correct order when messenger RNA is translated into a protein sequence on the ribosome. The EF-Tu–GDPNP component binds to one side of the acceptor helix of Phe-tRNA^{Phe} involving all three domains of EF-Tu. Binding sites for the phenylalanylated CCA end and the phosphorylated 5′ end are located at domain interfaces, whereas the T stem interacts with the surface of the β-barrel domain 3. The binding involves many conserved residues in EF-Tu. The overall shape of the ternary complex is similar to that of the translocation factor, EF-G–GDP, and this suggests a novel mechanism involving "molecular mimicry" in the translational apparatus.

Protein biosynthesis is a central process in every organism. It provides the link between the genetic information encoded in DNA and functional proteins. Understanding the steps of protein biosynthesis should have an impact on our overall perception of the process of translation. An essential participant in protein biosynthesis is the ternary complex of aminoacyl transfer RNA (aa-tRNA), elongation factor Tu (EF-Tu or EF-1α), and guanosine triphosphate (GTP), yet its three-dimensional structure has hitherto been unknown. The determination of this structure allows a much more precise and testable description of the molecular mechanism of protein biosynthesis.

The process of synthesizing proteins on the ribosome can be divided into initiation, elongation, and termination. Initiation and termination are punctuation events in that they deal with starting and stopping synthesis as a response to specific start and stop codons on messenger RNA (mRNA). These steps are assisted by initiation and release factors, respectively.

The central step in protein biosynthesis is elongation, in which amino acids are added one at a time to the growing polypeptide chain according to the sequence of codons present on mRNA. In prokaryotes, three elongation factors are involved as catalysts in this process: EF-Tu, the EF-Tu specific nucleotide exchange factor EF-Ts, and the translocation factor EF-G. Both EF-Tu and EF-G are members of the G protein superfamily, which consists of proteins with a conserved, common structural design (*1*). Thus EF-Tu exists in one of two states, either bound to guanosine diphosphate (GDP) as the inactive complex EF-Tu–GDP, or in the active form EF-Tu–GTP. The active EF-Tu–GTP binds aa-tRNA to form the ternary complex aa-tRNA–EF-Tu–GTP. The exposed anticodon of aa-tRNA is recognized on the ribosome by interaction with a codon on mRNA. This is part of the overall interaction between the ternary complex and the so-called A site of the ribosome. The ribosome induces hydrolysis of EF-Tu–GTP to EF-Tu–GDP, which is released from the ribosome (*2*). This inactive form of EF-Tu is recycled by the exchange of GDP for GTP, a process catalyzed by EF-Ts. The third elongation factor, EF-G, catalyzes the translocation reaction whereby the ribosome advances to the next codon on mRNA and translocates the peptidyl tRNA from the A site to the P site.

Both EF-Tu and aa-tRNA synthetases (aaRS) are proteins that can bind tRNA. However, in contrast to an aaRS, EF-Tu forms complexes with all aa-tRNAs. It is therefore expected that EF-Tu recognizes common features of all aa-tRNAs. Some structural information on how an aaRS binds to its cognate tRNA is available (*3*). A survey of features of tRNAs believed to be involved in ternary complex formation has been presented by Faulhammer and Joshi (*4*). Investigations of the specific parts or residues of aa-tRNA or EF-Tu participating in ternary complex formation have led to the formulation of possible models for the ternary complex (*5–7*). However, none of these models is in agreement with the x-ray model described in this article.

The crystal structure of yeast tRNA^{Phe} revealed the structural organization of tRNA as two double-helical segments almost perpendicular to each other (*8, 9*). Each helical segment contains two base-

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