THE ROLE OF WATER IN THE ECLOGITE PHASE TRANSITION AND CRUSTAL RECYCLING ON VENUS

S. G. Herzog and P. C. Hess, Dept. of Geological Sciences, Brown University, Providence RI 02912

Introduction: Basaltic crust on Venus has apparently been vertically accreted, and may be vertically recycled by the phase transformation to eclogite. The solid state reaction to eclogite requires the presence of water to permit the phase change to occur on geologically reasonable time scales. Field evidence from Earth indicates that high concentrations of water may be required to allow the reaction to proceed past the granulite stability field. The quantity of water required to yield a certain reaction rate is unknown. The crust of Venus is probably not devoid of water because dehydration of vertically accreted crust is inefficient. Eclogite likely played a role in Venus' crustal evolution, but may not be relevant to crustal dynamics at present.

One principle result of the analysis of data from the recent Magellan mission is that the evolution of the crust of Venus has not followed a uniformitarian history. Rather, the cratering record suggests that Venus has undergone a catastrophic resurfacing approximately 300 - 500 Myr ago, followed by a low level of activity manifested at the surface [1, 2]. An important question at present is whether this catastrophic activity is episodic or monotonic [3, 4, 5], and thus, what is the nature and fate of the crust before and after such an event. The need for recycling of accumulated basaltic crust on Venus is uncertain; crust is apparently not recycled by Earth-like Wilson-cycle plate tectonics. Is the thickness of the crust dynamically limited during and/or after a volcanic resurfacing event? If basaltic crust has accreted vertically, it may be recycled vertically by delamination caused by the pressure-induced transformation to eclogite.

Eclogite is denser than the presumably peridotitic mantle (by about 15%), and so if the phase change occurred, it could result in crustal subsidence or delamination. The thermal gradient of Venus' lithosphere is uncertain. The high surface temperature may be restricted to the near-surface, a result of the greenhouse atmosphere, and a low-temperature crust would help to explain the apparent strength of the crust. However, if crustal production and recycling are not as efficient as on Earth, due to the absence of plate tectonics, incompatible radioactive heat sources would remain at depth and contribute to longer-term internal heating [5]. It is unclear whether Venus' lithospheric temperature gradient is significantly different than Earth's. For a conductive geotherm of about 15 K km^{-1}, which might be expected for a thickened lithosphere, the eclogite phase change will occur at about 50 km depth for a tholeiitic basalt composition [6]. The phase transformation is gradual, through the production of granulite, but may cause sufficient instability to induce gravitational instability of the crust [3]. Gravity data indicate a relatively uniform (except in the tessera highlands) crustal thickness between 20 and 50 km, which could be a product of periodic removal of eclogite from the base [7].

The Role of Water: The transformation of a basaltic mineralogy to an eclogitic one occurs through a series of solid state reactions whose kinetics are dependent on the rate of diffusion of the reacting components. The determination of reaction rate has been approached theoretically [8, 9], but quantitative experimental investigation has not followed, primarily because of the complexity of the reaction mechanisms, especially considering the role of varying basalt composition, and because of the slow rate of reaction. Observations of natural terrestrial eclogite settings may provide some insight. Terrestrial eclogite samples yield information about conditions of equilibration through equilibrium mineral compositions, and information about reaction mechanisms can be gleaned if textural features indicating partial reaction can be identified, which is not common. Eclogite-forming reactions in natural rocks equilibrated at temperatures greater than 750 C usually do not show evidence for fluid infiltration [10]. This may indicate lack of free fluid during reaction, or more likely, expulsion of fluid during the early stages of reaction. Some field evidence suggests that eclogites are formed on Earth only where kinetics are enhanced by fluids and/or deformation. Terrestrial granulites in several terrestrial localities are found to persist metastably in the eclogite facies in the absence of fluid in eclogite-bearing shear zones which alternate on a scale of meters with the dry, unsheared granulites [11, 12, 13]. Granulite production may be kinetically easier than eclogite, even on water-saturated Earth, because hydrous fluids, which facilitate rapid reaction, may be removed from the rock during metamorphism of basalt to granulite. Granulite is denser than basalt, and so may have a similar (but weaker) negative buoyancy effect on the crust as eclogite, but reaction to granulite on reasonable time scales probably also requires some amount of water. The role of deformation may also be important, because styles and depths of deformation will be different for a vertically accreting crust than for the lateral movement of Earth's lithospheric plates.

The crucial question now is a familiar one: how much water is contained in Venus' crust? Venus is generally considered dry because the atmosphere is dry. This reasoning is not sufficient to constrain water content in the crust.

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Other lines of reasoning for a dry Venus include the apparent strength of the crust, and the tempting argument that because Earth has plate tectonics, continental crust, and water, then water may be required for the first two; but because Venus (and the other terrestrial planets) has no plate tectonics or continents, therefore it has no water.

A more relevant question may concern Venus' earlier history. Did Venus contain much more water in the past, and how has its internal water budget changed? The high atmospheric D:H ratio indicates that Venus' atmosphere contained water before the presumed runaway greenhouse effect, possibly initially similar to the water content of Earth [14]. Several episodes of global resurfacing may have helped deplete Venus' interior of water [9]. Removal of water by basaltic eruptions is dependent on the ratio of intrusive to extrusive magmatism, which is not well constrained. Earth has a volcanic to plutonic ratio of about 1:10. There is little or no evidence of erosional removal of rock which would expose plutons to the atmosphere on Venus. Once a pluton is emplaced, its fate is to remain in the crust or be recycled into the interior. Vertical accretion and recycling of crust is thus an inefficient means of dehydrating a planet.

It is difficult to conclude that Venus' crust is completely devoid of water, or dehydrated to the extent required for behavior in accordance with the rheology of the dry diabase reported by Mackwell [15]. This is because, although water behaves incompatibly during basalt petrogenesis [16], even the nominally anhydrous minerals contain a finite amount of structurally bound water, ranging from 1 to 1000 ppm, with olivines generally containing up to 100 ppm water [17]. Contaminants such as water are mineral structural defects whose presence in some finite amount is required by energetic considerations. Water may be removed during eruption of basalt, but bubble formation is hindered by the higher atmospheric pressure on Venus. Trapped water could recrystallize the basalt to produce greenschist facies rocks. Water may be trapped in glass as well; silicate glasses can contain up to several weight percent water [18, 19]. Heat exchange between crust and atmosphere may be more rapid due to the higher temperature and greater atmospheric density, promoting rapid cooling and quench rind formation, which would serve to restrict diffusive loss of water to the atmosphere. The crust is thus unlikely to be in equilibrium with the atmosphere with respect to volatiles [20, 21, 6].

Conclusions: Although Venus may be drier than Earth, the mantle and crust may well have contained appreciable amounts of water in the past, and is probably heterogeneous with respect to water content; therefore eclogite may have played a significant role in crustal recycling in the past. Evidence for the eclogite phase change may be present on the surface in the form of lava-filled basins in the relatively ancient tessera terrain, which may represent sites of crustal downwelling or delamination [7, 20,]. Although the presence of significant concentrations of water in the crust cannot be ruled out, eclogite may not be relevant to crustal dynamics beneath most of Venus' crust at present. Terrestrial field evidence indicates that high concentrations of water may be required to promote the reaction. In addition, recent Magellan gravity data analysis suggests the mean thickness of the Venusian crust is 20 to 50 km, which approaches but is generally shallower than the eclogite stability field for most basalt compositions. Accumulated crust may only be recycled during periodic gravitational instability of the crust and depleted mantle, although it is possible that the basalt-eclogite phase transition provided an impetus for this overturn, particularly if the crust contained more water prior to resurfacing [3]. If the water content of the crust were sufficiently high, it is also possible that the thickness of basalt could have been limited by the depth of the eclogite phase change immediately following the resurfacing. This could explain the apparent relatively uniform depth of crust.

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