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Rheological and petrological implications for a stagnant lid regime on Venus

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ABSTRACT

Venus is physically similar to Earth but with no oceans and a hot dense atmosphere. Its near-random distribution of impact craters led to the inferences of episodic global resurfacing and a stagnant lid regime, and imply that it is not currently able to lose proportionately as much heat as Earth. This paper shows that a CO_2-induced asthenosphere and decoupling of the mantle lid from the crust, caused by the elevated surface temperature, enables lid rejuvenation. Global hypsography implies a rate of $4\cdot0\pm0\cdot5$ km² a^{-1} and an implied heat loss rate of $32\cdot8\pm3\cdot6$ TW, ~90% of a scaled Earth-like rate of heat loss of 36 TW. Estimates of the rate of lid rejuvenation by plume activity – $0\cdot07$ to $0\cdot09$ km² a^{-1}– imply that ten times the number of observed plumes are required to equal this rate of heat loss. However, lid rejuvenation by convection allows Venus to maintain a stable tectonic regime, with subcrustal horizontal extension (half-spreading) rates of between 25 and 50 mm a^{-1} determined from fits to topographic profiles across the principal rift systems. While the surface is largely detached from these processes, the association of rifting and other processes does imply that Venus is geologically active at the present day.

1. Introduction

How Venus loses its internal heat has been uncertain since the realisation that its high surface temperature inhibits plate recycling that is so an effective heat loss mechanism on Earth (Anderson, 1981). The observation of a near-random distribution of impact craters (Phillips et al., 1992; Strom et al., 1994) led to the hypothesis of catastrophic, or episodic, global resurfacing (Turcotte, 1993), which proposes that for long periods (500 to 1000 Ma) the lithosphere cools and thickens whilst the interior heats up, the system eventually becoming unstable. In a geologically short period (~50 Ma) the whole lithosphere overturns and is replaced with new thin, buoyant lithosphere, whereupon subduction stops, and the cycle begins again.

Whether or not this happened, Venus is considered to now be in a stagnant lid regime (Solomatov and Moresi, 1996), in which the absence of an asthenosphere means that the lithospheric lid is coupled to a high viscosity mantle that convects slowly enough for conductive cooling to be the dominant heat transport mechanism. Some authors regard this regime as either complementary to episodic global resurfacing (Fowler and O'Brien, 1996; Sleep, 2000) or as a change in convective regime following the last global resurfacing event (Reese et al., 1999). Whilst some lateral movements are expected in response to large-scale convection of the mantle (Grimm, 1994), such a lithosphere is not mobile in the terrestrial sense and is instead dominated by discrete small-scale plumes (Nimmo and McKenzie, 1998; Ogawa, 2000).

1.1. Global heat budget

Almost nothing is known about the internal properties of Venus; its moment of inertia is unknown and no seismic data have been obtained from which to constrain its internal structure. The lack of an intrinsic magnetic field and its k_2 love number indicate that its core may be entirely liquid (Konopliv and Yoder, 1996) but there is little to constrain the core mass. Cosmochemical models (Basaltic Volcanism Study Project, 1981; Morgan and Anders, 1980) suggest core mass fractions between $23\cdot6$ and $32\cdot0$%–implying a mantle mass proportionately similar to or greater than Earth's. The Venera landers returned a number of K, U and Th measurements that imply bulk ratios, and hence internal radiogenic heating rates, comparable with Earth (Namiki and Solomon, 1998). While the Urey ratio may be different for Venus, the simplest assumption is to scale Earth's heat flux to Venus.

Earth's global heat flux, 44 TW (Pollack et al., 1993) scaled to Venus is 36 TW, or 76 mW m^{-2}. Turcotte et al. (1999) calculate that the hypothesis of episodic global resurfacing can remove only

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4·5 to 7·5 TW; their suggested mechanism for removing the remaining 28·5–31·5 TW is 'a very vigorous episode of tectonics and volcanism, following a global subduction event but prior to the subsequent stabilisation of a global lithosphere'. There are two problems with this reasoning: first, the global resurfacing event is the process that stabilises the lithosphere, by replacing unstable ($>$250 km thick) lithosphere with thin, warm, buoyant new lithosphere; and second, the 'very vigorous' process is given no plausible physical explanation that can be tested either numerically or geologically. Thus more than three-quarters of the global heat budget is unaccounted for in this hypothesis.

A stagnant lid regime is able to remove 8–20 mW m^{-2} (3·7–9·2 TW) depending on the model assumptions made (Reese et al., 1998; Solomatov and Moresi, 1996). Armann and Tackley (2012) explore the combination of magmatic heat pipes with stagnant lid regimes and conclude that while good fits may be obtained to observed topography, geoid and admittance ratios, the crustal production (magmatic resurfacing) rate is much too high, by about 2 orders of magnitude. Combining all three processes – episodic global resurfacing, magmatic heat pipes, and a stagnant lid regime – improves matters but still requires a magmatic flux at least an order of magnitude too high. However, the authors note that the inclusion of magmatic intrusion and a more realistic crustal rheology may be significant in reducing this discrepancy. This paper investigates the effect of realistic rheologies and the influence of mantle volatiles on a stagnant lid regime.

1.2. Mantle volatiles

A compositionally Earth-like Venus would have volatiles, particularly H_2O and CO_2, in its mantle and consequently a weak low-viscosity asthenosphere. However, even from Pioneer Venus data it was clear that the 4 to 31 m km^{-1} geoid–topography ratio is much higher than the terrestrial value of – 1–5 m km^{-1} (Kucinskas et al., 1996; Smrekar and Phillips, 1991) implying the lack of an asthenosphere on Venus and a more-or-less constant viscosity mantle. Since a low-viscosity asthenosphere is considered to be essential for terrestrial plate tectonics (Richards et al., 2001), which Venus lacks, the absence of an asthenosphere is perhaps not surprising.

The extremely dry atmosphere, which contains only 30 ± 10 ppm H_2O below the clouds (de Bergh et al., 2006), is consistent with the inference of a dry interior. Kaula (1999) argues that the deficiency of ^{40}Ar in the atmosphere implies that the mantle must have been fully degassed very early in its history, before the accumulation of significant volumes of radiogenic ^{40}Ar in the mantle. It is usually assumed that Venus lost its water through evaporation and hydrodynamic escape but given that even the Moon-forming impact did not fully devolatilise the terrestrial mantle and that extensive hydrodynamic erosion of a water-rich atmosphere is precluded by its noble gas inventory (Albarede, 2009), it seems more likely that Venus simply accreted less water than Earth.

New evidence for pyroclastic volcanism (Ghail and Wilson, 2013) raises questions about whether the mantle is dry at all. However, water is not the only possible volatile: CO_2 is abundant in the atmosphere and perhaps the interior too, while the variability in atmospheric SO_2 (Esposito, 1984; Marcq et al., 2013) may require a volcanic source. Pauer et al. (2006) have shown that an Earthlike mantle with a 20 to 200 km thick high viscosity lid (lithosphere) above a 100 km thick low viscosity channel (asthenosphere), albeit less pronounced than on Earth, and a gradually increasing viscosity with depth below that, is at least equally consistent with the geoid–topography data. Armann and Tackley (2012) also find a mantle viscosity structure similar to Earth.

Like water, CO_2 is known to depress the pyrolite solidus at depth (Falloon and Green, 1989) and induce minor melting to form an asthenosphere. The depression of the solidus by water in the mantle of Earth and CO_2 in the mantle of Venus is similar (Fig. 1) until an abrupt increase in magnitude at 1·85 GPa on Venus caused by the breakdown of diopside to give dolomite. The equivalent increase in magnitude of solidus depression at 3·0 GPa on Earth is more abrupt but less severe and results from the breakdown of pargasite. The magnitude of the solidus depression in both cases reduces gradually above 4·5 GPa (deeper than

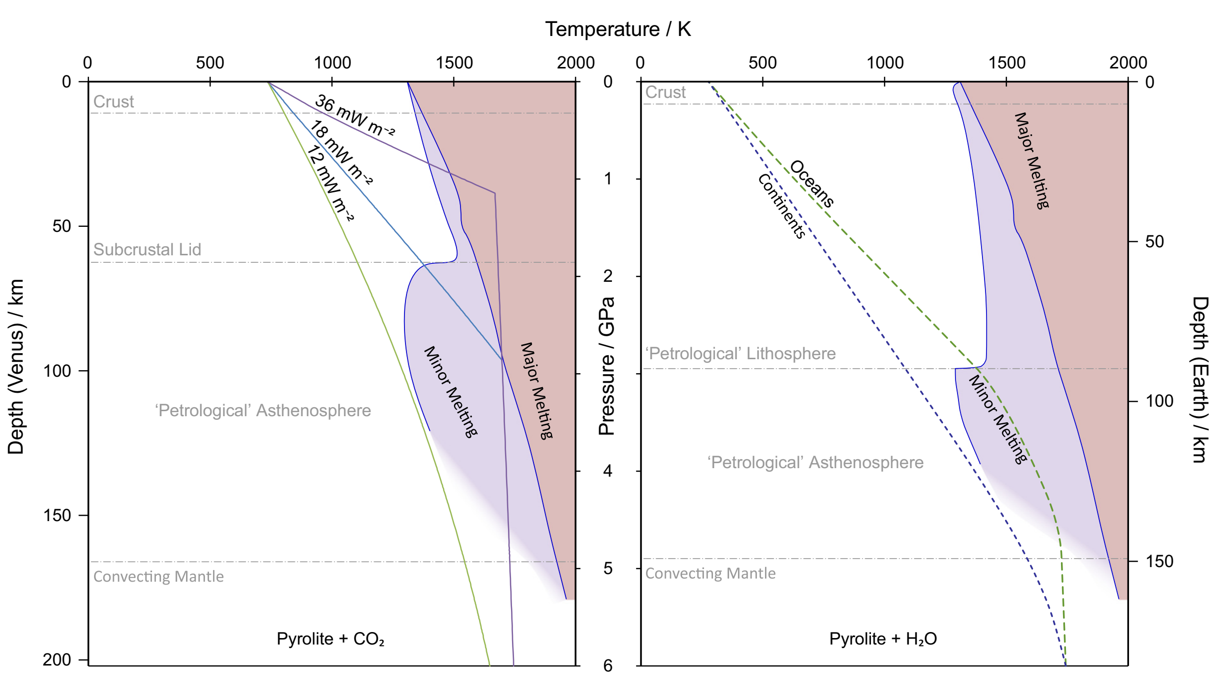

Fig. 1. Possible Venus geotherms (left) compared with Earth (right). The 'petrological' asthenosphere is produced by ~1% partial melting in the presence of CO_2 on Venus or H_2O on Earth (Falloon and Green, 1989). Major Melting curves approximate those for a 1650 K adiabat. All data are plotted against pressure; depths in Venus and Earth are approximate.