Earth and Planetary Science Letters 474 (2017) 13–19

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Heat-pipe planets

William B. Moore [a,b,*], Justin I. Simon [c], A. Alexander G. Webb [d]

[a] Department of Atmospheric and Planetary Sciences, Hampton University, Hampton, VA 23668, USA
[b] National Institute of Aerospace, Hampton, VA 23666, USA
[c] Center for Isotope Cosmochemistry and Geochronology, Astromaterials Research and Exploration Science, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058-3696, USA
[d] Department of Earth Sciences and Laboratory for Space Research, University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 5 June 2017
Accepted 7 June 2017
Available online 29 June 2017
Editor: A. Yin

Keywords:
planetary thermal evolution
volcanism
terrestrial planet lithosphere
terrestrial planet surface

ABSTRACT

Observations of the surfaces of all terrestrial bodies other than Earth reveal remarkable but unexplained similarities: endogenic resurfacing is dominated by plains-forming volcanism with few identifiable centers, magma compositions are highly magnesian (mafic to ultra-mafic), tectonic structures are dominantly contractional, and ancient topographic and gravity anomalies are preserved to the present. Here we show that cooling via volcanic heat pipes may explain these observations and provide a universal model of the way terrestrial bodies transition from a magma-ocean state into subsequent single-plate, stagnant-lid convection or plate tectonic phases. In the heat-pipe cooling mode, magma moves from a high melt-fraction asthenosphere through the lithosphere to erupt and cool at the surface via narrow channels. Despite high surface heat flow, the rapid volcanic resurfacing produces a thick, cold, and strong lithosphere which undergoes contractional strain forced by downward advection of the surface toward smaller radii. We hypothesize that heat-pipe cooling is the last significant endogenic resurfacing process experienced by most terrestrial bodies in the solar system, because subsequent stagnant-lid convection produces only weak tectonic deformation. Terrestrial exoplanets appreciably larger than Earth may remain in heat-pipe mode for much of the lifespan of a Sun-like star.

1. Introduction

There is currently great interest in exploring other terrestrial planets, for a broad range of reasons – e.g., to learn more about the nature of solar systems; to seek other possible environments in which life may be sustainable, or have arisen; to provide perspective and insight for our understanding of our own planet. Our exploration of terrestrial bodies in our own solar system has largely emphasized the different geologic histories experienced by the different bodies: Mercury's early contraction, Venus's desiccated, relatively young surface, Earth's plate tectonics, the Moon's bimodal crustal composition, Mars' hemispheric dichotomy and isolated volcanic edifices, Io's exceptionally rapid volcanic resurfacing. In the face of such diversity and the likely discovery of still different planetary surfaces in exoplanetary solar systems, it is necessary to explore what aspects of geological history may be held in common by all of these terrestrial bodies, in order to address the larger question of what features may be shared by terrestrial planets across the galaxy.

It is generally agreed that the terrestrial planets have initial evolutionary phases in common: accretion of planetesimals led to heating, differentiation into metallic cores and silicate mantles. The immense early heat input – potentially augmented by short-lived radionuclides or tidal heating – required that significant fractions of their mantles were molten (magma oceans), even for objects as small as Vesta. In contrast, the subsequent path from magma oceans to the generation of relatively rigid outer lithospheres and convecting mantles is largely thought to be distinct for each of our solar systems' terrestrial planets: At Mercury, a rapidly developed lithosphere is generally thought to have experienced global contraction due to bulk cooling of the interior (Solomon, 1977; Byrne et al., 2014). Venus is widely thought to have experienced catastrophic global resurfacing, possibly multiple times, due to formation of a stagnant lid that inhibits heat flow. Earth developed plate tectonics, but the pathway is unclear: some interpretations posit plate tectonics from nearly the initial development of lithosphere, or at least as far back as 4.3–4.1 Ga (e.g. Harrison, 2009), whereas others suggest formation of a single-plate lithosphere akin to Venus' that gradually or catastrophically transitioned to a plate tectonic lid system (e.g. Debaille et al., 2013). The Moon's evolution remains puzzling. Many workers argue that its dominantly plagio-

* Corresponding author.
E-mail address: william.moore@hamptonu.edu (W.B. Moore).

http://dx.doi.org/10.1016/j.epsl.2017.06.015

clase crust must have floated up and crystallized at the top of the magma ocean (Warren, 1985), but generating nearly pure plagioclase compositions by this mechanism requires extremely efficient melt drainage (Piskorz and Stevenson, 2014). Mars' early evolution may have involved whole mantle overturn (Elkins-Tanton et al., 2005) or a proto-plate tectonic regime, potentially generated by early impacts (Yin, 2012), that later seized up isolating long-lived chemically distinct lithospheric reservoirs (Borg and Draper, 2003).

These five terrestrial bodies may have experienced divergent evolutions, but they likely have all been continually cooling since initial accretion and differentiation. Jupiter's moon Io, however, diverges from that pattern: it has been kept above its solidus temperature for the majority of its evolution because its dominant heat source is frictional heating caused by its gravitational (tidal) interactions with Jupiter and the other Galilean moons (O'Reilly and Davies, 1981). With a surface heat flux forty times that of Earth, Io is dominated by volcanic heat advection. The rapid cooling and subsequent burial of volcanic rocks at the surface leads to a downward advection of cold surface material, chilling the lithosphere. Perhaps counter-intuitively, the terrestrial body with the highest known heat flux exhibits a thick, cold single-plate mechanical lithosphere which is the consequence of rapid crustal/lithospheric formation from the top by addition of new flows. Recently, based on a survey of geological and geochemical observations, heat-pipe cooling has been suggested as a possible mechanism for the early cooling and lithospheric generation of Earth, for as much as the first third of Earth history (Moore and Webb, 2013).

In this work we explore the possibility that the end of the magma ocean is not the point at which the solar system's rocky bodies diverge in their evolution. Specifically, we review the records of the solar system's stagnant-lid terrestrial bodies to explore whether they too may have experienced an early phase of heat-pipe cooling, as hypothesized for Earth and observed at present on Io. This overview highlights that ancient features common to these terrestrial bodies, e.g., the dominance of low-viscosity, mafic volcanic rocks, commonality of contractional features and scarcity of extensional features, and preservation of ancient topographic signatures, are consistent with the early heat-pipe hypothesis. The tantalizing possibility motivating this exploration is that if heat-pipe cooling may have been experienced by all of our solar system's terrestrial planets, it may be a phase experienced by terrestrial planets universally (Ricard et al., 2014). We begin with a detailed description of the heat-pipe cooling process before discussing the relevant observations of each stagnant-lid planet.

2. Heat pipe cooling

The geological evolution of terrestrial (rocky) planets is driven by the transport of heat from their interiors. Although impacts may obscure endogenic resurfacing processes, everywhere that evidence for such processes is preserved, it is dominated by volcanic landforms (except on Earth, where liquid water, life, and plate tectonics dominate surface evolution). A terrestrial body cooling via heat pipes experiences persistent global volcanic resurfacing by which older layers are progressively buried and advected downward to form a thick, cold, and strong mechanical lithosphere (O'Reilly and Davies, 1981) (Fig. 1, Heat-Pipe inset).

At this point we should note that the mechanical lithosphere of a heat pipe planet is composed almost entirely of the products of melting, that is, it is also the crust. Only when the mantle drops below the solidus can a portion of it adhere to the base of the crust forming what's known as the mantle-lithosphere. While on present-day Earth, the crust is mechanically weaker than the mantle by a significant factor, the products of high-degree, heat-pipe

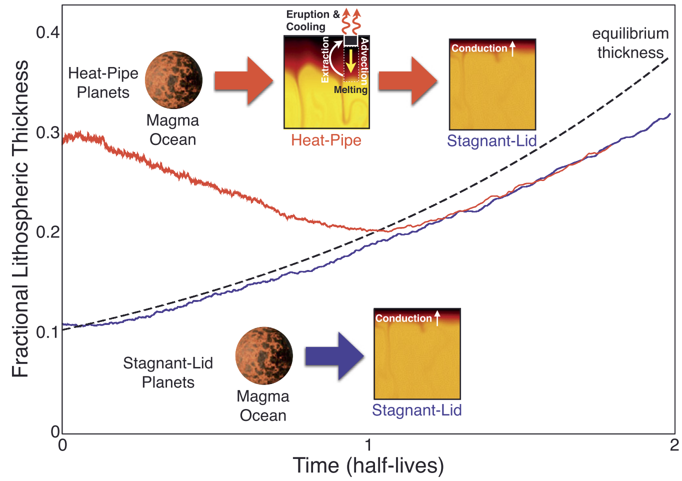

Fig. 1. Modeled evolution of lithospheric thickness (measured as a fraction of the mantle thickness) over time as internal heat production decreases by a factor of four (dashed line shows equilibrium lithospheric thickness increasing). Planets evolving through a heat-pipe phase (red) develop a thick lithosphere early in their history, which thins as volcanism wanes and then thickens as stagnant-lid convection takes over. Planets without melt transport transition directly from the magma ocean to stagnant-lid convection (blue) and begin with thin weak lithospheres that monotonically thicken and strengthen over time.

melting are not as evolved or silica rich and hence tend to be more similar in strength to the mantle. On Earth, this may be responsible for the longevity of cratonic mantle (e.g. the "tectosphere" of Jordan, 1978).

The implications of heat pipes for the tectonic history of terrestrial bodies are illustrated in Fig. 1 by contrasting the modeled evolution of the lithospheric thickness for a planet with a heat-pipe phase of evolution vs. one with a stagnant lid and no melting as heat generation decreases by a factor of four. The models were computed using STAGYY in a 4×1, two-dimensional domain with purely internal heating (decaying exponentially with time), strongly temperature-dependent viscosity (viscosity contrast 10^7), and a linearly pressure-dependent solidus with instantaneous melt extraction (see Kankanamge and Moore, 2016 for model details). Although greatly simplified, our treatment of the melting process captures the first order effects of melting and melt extraction on the heat transport which are that heat and material are advected to the surface on timescales that are rapid with respect to advective or diffusive processes. Unlike the classic stagnant-lid planet (blue) with a monotonically thickening lithosphere that tracks the equilibrium thickness (dashed), the heat-pipe planet (red) develops an early, thick lithosphere that is capable of recording and preserving early deformation events.

Heat-pipe operation leads to: 1) Thick, cold, and strong lithospheres even though heat flow is high, 2) Dominance of compressive stresses as buried layers are forced to smaller radii, 3) Continuous replacement of lithospheric material, 4) High melt-fraction (mafic to ultra-mafic), low-viscosity eruptions and efficient degassing of the interior, and 5) A rapid transition to stagnant-lid or plate tectonic behavior. Heat pipe cooling ends when the internal heat production drops below the rate that can be accommodated by primarily sub-solidus convection (with or without plate tectonics).

In the following sections, we briefly review the observations relevant to the formation of the surfaces of each of the terrestrial planets and current models that have been proposed to explain them. We then discuss any outstanding problems and show how the heat-pipe hypothesis can resolve these in a consistent way across all planets.