Available online at www.sciencedirect.com
ScienceDirect
Russian Geology and Geophysics 58 (2017) 1–11
RUSSIAN GEOLOGY AND GEOPHYSICS
www.elsevier.com/locate/rgg

The evolution of planets. Venus as the Earth's probable future

N.L. Dobretsov [a,b,*]

[a] A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia
[b] Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090, Russia

Received 6 June 2016; accepted 6 July 2016

Abstract

The general evolution of planets in the Solar System is discussed with a focus on the structure and history of Venus compared with the Earth. The history of the planets of the terrestrial group has been similar and included at least six correlated stages. Many common features the terrestrial planets shared in their early and late evolution have been due to their common origin from the protoplanetary gas-and-dust nebula and plume magmatism widespread on all the planets of the terrestrial group. The characteristic features of the structure and evolution of Venus are most brightly manifested in the specific composition of its atmosphere and of plume magmatism. Venus, with its surface as hot as 450 ºC and the near-surface pressure of 92–93 bars, has a hot and dense atmosphere 93 times that of the Earth in mass. Most of its atmospheric mass (99%) belongs to the 65-km thick troposphere consisting of CO_2 (96.5%) and N_2 (3.5%). The upper troposphere includes a 25–30 km thick cloud layer composed mainly of sulfuric acid droplets, water vapor, and SO_2. At a height of 49.58 km, the clouds approach the conditions of the terrestrial surface and might be hospitable to bacterial life. Volcanism, the most active and widespread process of Venusian geology, maintains continuous SO_2 emission. There are diverse volcanic edifices on Venus, which are most often large and are similar to the Earth's plume-related volcanoes. The evolution before 1 Ga, as well as the share and the role of alkaline rocks and carbonatites among its volcanics, are among the most debatable issues about Venus. Being located closer to the Sun, Venus cooled down more slowly and less intensely than the Earth after the primary accretion. In the Proterozoic, it began heating and reached its present state at ~1 or 2 Ga. In the future, as the Sun becomes a red giant, the Earth is predicted to begin heating up in 500–600 Myr to reach the temperature of present Venus in about 1.5 Gyr.

Keywords: volcanism; planet heating; Earth's future; Venus

Instead of Introduction:

This paper was inspired by a discussion after the final lecture at Moscow University on the evolution of the Earth and planets in the Solar System. I kept thinking about the off-hand idea of future heating of the Earth to temperatures that currently exist on Venus and found additional arguments in its favor. The possible scenario of the events is outlined below.

Evolution of planets

The common origin of planets in the Solar System by accretion from a giant protoplanetary nebula of gas and dust suggests that they all, including Venus, have the same age of 4.6 ± 0.03 Ga (Fig. 1) (Ernst, 2014; Mukhin, 2009; Vityazev, 1983; Vityazev and Pechernikova, 2009).

The Earth's accretion lasted 100–120 Myr (Fig. 2), according to the models of Vityazev and Pechernikova (2009) and isotope data (Kleine et al., 2002), and the accretion events may have been equally fast for Venus, Mars, and Mercury (Ernst, 2014; Head, 2014). The origin of the Moon is different; it was presumably separated from the Earth as a result of a megaimpact or changes in a double planet, the separation being about ten times faster than the accretion (see event 3 in Fig. 2). The primordial atmospheres in all the terrestrial planets (except the Moon) formed during the first event but then they all markedly changed. That of the Earth was heavy and dense, without oxygen but with H_2 and CH_4; along with the formation of oceans, it gradually evolved into a modern low-density atmosphere consisting mainly of N_2 and O_2 (Adushkin and Vityazev, 2007; Halliday, 2001; Zharkov, 2013). Nothing is known about the Venusian primordial atmosphere. Its modern dense atmosphere formed after 1 Ga

* Corresponding author.
E-mail address: DobretsovNL@ipgg.sbras.ru (N.L. Dobretsov)

1068-7971/$ - see front matter © 2017, V.S. Sobolev IGM, Siberian Branch of the RAS. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.rgg.2016.12.001

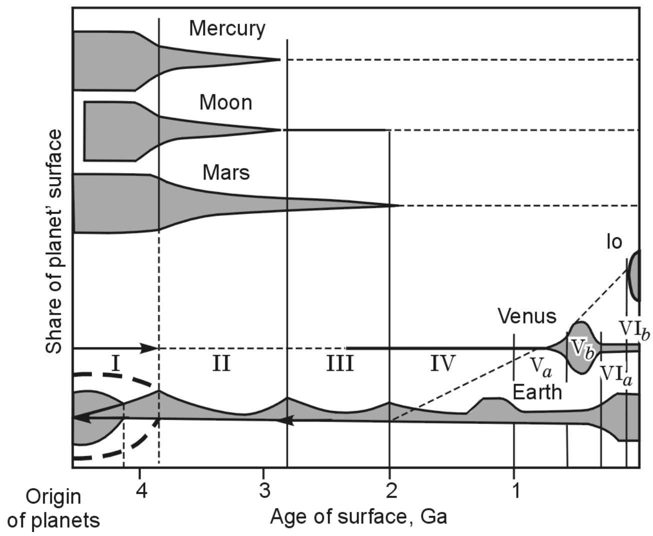

Fig. 1. History of terrestrial planets. Total percentage of surface and near–surface structures that formed in different periods of the planets' history (Head and Coffin, 1997), together with Io (Ernst, 2013), complemented with Earth's data and evolution stages I–VI.

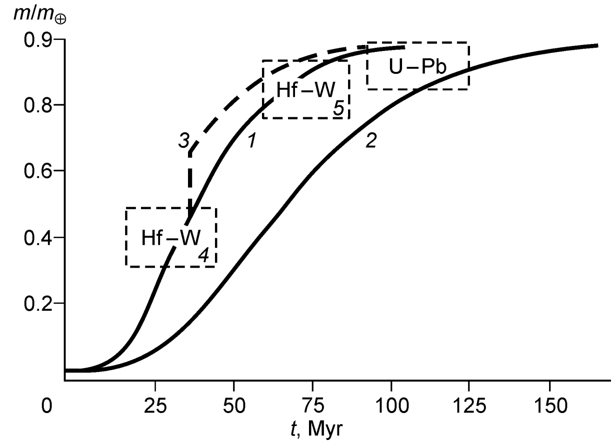

Fig. 2. Time and stages of Earth accretion (Vityazev and Pechernikova, 2009). Curves 13 correspond to different models: large bodies (*1*); expanding feeding zones (*2*); megaimpact (*3*); possible core formation, according to isotopes (*4*); same for late Moon formation (*5*).

(Fig. 1), at the time of active volcanism which, together with heavy clouds, obscures its earlier history. Event I ended about 3.8 Ga on all the planets (except Venus), which is confirmed by isotopic data for the Earth and the Moon (Fig. 3). It coincided with the end of heavy meteorite bombardment of the Moon, the Earth, and possibly also Mars, according to astronomical observations and modeling (Bottke et al., 2012).

Approximate synchronicity of events I–III for Mercury, Mars, the Moon, and the Earth is evident from Fig. 1 and is confirmed by isotope data for the Earth and the Moon (Figs. 3 and 4). Event II was the time when the meteorite bombardment ended on the Moon, the Earth, and Mars. The event is especially well constrained for the Moon (Fig. 3), with the main peak of impact events at 4.0–3.3 Ga, secondary peaks at 3.3–2.8 Ga, and sporadic impacts till 1.3 Ga (Hiesinger et al., 2011). Knowledge of event III (2.8–2.0 Ga) is available only for the Earth and Mars and a little for the Moon.

Events II and III on the Earth (Fig. 4) correspond to tectonics of small plates and paleoplate tectonics, respectively (Dobretsov, 2009; Dobretsov and Turkina, 2015; Stern, 2008), which record the evolution of oceans parallel to the formation of asthenospheric flows and their changes. Nothing like plate tectonics has been known to exist on other planets. Tectonics of small plates may have existed on Mars during event II (Ernst, 2014; Halliday et al., 2001) and plume magmatism ended at event III, while the Moon and Mercury have experienced no activity since event II.

The activity of event IV was restricted to the Earth, though was possible on Venus as well. Events V_a, V_b, VI_a, and VI_b took place both on the Earth and on Venus, but only a record of two latter events was found on Venus, while the traces of older events may be buried under younger lavas and/or remain invisible behind dense clouds (Ernst, 2014; Head, 2014). The modern dense atmosphere on Venus began forming during event V_a (1.0–1.8 Ga), the time of relative quiescence on the Earth. Event V_b (0.8–0.5 Ga) on Venus was the main period of atmosphere formation and active plume magmatism, while the oceans, continents, and the biosphere were forming on the Earth (Dobretsov, 2010, 2011). During event VI, stable atmospheric circulation and plume magmatism continued on Venus (Ernst, 2014) while oceans were opening on the Earth. In the time of event VI_b (past 200 Myr), when the oceans formed on the Earth, Jupiter's largest satellite Io (Fig. 1) underwent active magmatism and convection associated with high concentration of sulfur and periodic contraction and expansion pulses as its distance to Jupiter changed (Ernst, 2014).

Thus, it was an evolution of the whole planetary system: activity stopped on one planet and began (or increased) on another (Fig. 1). However, there is correlation of events (Fig. 1) on different planets (e.g., on the Earth, Venus, Moon, and Mars), due to (i) their common origin; (ii) heavy meteorite bombardment during the early event, which can be interpreted as the end of two–stage accretion; (iii) plume magmatism (throughout the Earth's geological history and restricted to 2 Gyr on Mars). The past 1 Gyr were a new stage of the Earth's plume magmatism and the main stage of that on Venus (see in Fig. 1 the stepwise decay of activity during events I–II on Mercury and Mars (rather I–III on Mars), some decrease on the Earth during event IV, and greater activity on the Earth and on Venus at V and VI).

The superplume activity on the Earth correlated with growth of supercontinents (Condie, 2004) and major atmospheric and biospheric crises (Ernst, 2014; Wignall, 2005). Note that Figs. 1, 3, and 4 are based on different sources of knowledge and criteria but show similar milestones of the planetary evolution associated with plumes, accretion, and postaccretion events.

Our further discussion focuses on Venus, specifically, on the conditions of its atmosphere and magmatism, as well as on the probability that the Earth would undergo similar changes in the future.