Hadean Earth

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The popular conception of a hot Hadean Earth seems to be rooted in a commonsensical understanding of the surface to volume ratio. Planets were born hot, cooled, and died, in proportion to their masses. These ideas received their deepest support from the long-unanswered arguments made by Lord Kelvin regarding the age and evolution of the Earth and Sun. Heat death was at the heart of the cosmogonical speculations of Percival Lowell, and through Lowell and those inspired by Lowell (e.g. H. G. Wells) they reached into every corner of western culture. The Moon, Mercury, and of course Mars provided case studies of planets whose time was passing or had passed. Jupiter and the giant planets were seen as having long still to cool before the rains would fall and the oceans pool, while for Venus one might prophesy a first Edenic moment when the clouds would clear and the Sun would shine on the shores of the world ocean.

Given Kelvin's clocks, the Solar system was less than 50 million years old, and all of this made some sense. But times have changed. Venus, rather than being the next Earth turns out to have sought its own destiny long ago. The Moon has much to do with Earth but not as an analog, while Martian analogies remain evocative but are probably superficial. Meanwhile Earth's Hadean is now known to stretch over a time span longer than the whole of the Phanerozoic.

It is more useful to define the Hadean as the time when impacts ruled the Earth than to define it as the time before the rock record. One cannot help but think that the coincidence between the end of the lunar late bombardment and the appearance of a parsible rock record on Earth is probably not just coincidence. When one imagines the Hadean one usually imagines torrential scalding rains and a lot of volcanos. But one should add enormous ice caps and a great deal more, and one should emphasize the variance in the climate at least as much as one thinks of the average. And one must not forget the impact craters. The biggest ones, more than 1000 km across and several kilometers deep, would last long enough that there were always several of these to be seen at any time in various states of decay. The oceans would have been filled with tens or hundreds of meters of weathered impact ejecta, most of which was ultimately subducted but took with it whatever it reacted with at the time - CO_2 was especially vulnerable to this sort of scouring. The climate, under a faint young sun and with little CO_2 to warm it, might have been extremely cold unless methane (or some other greenhouse gas) were also present. The Hadean as an age of impacts has some stratigraphic value as a horizon shared by other worlds in the solar system, in particular the Moon and Mars. In sum, it seems a better use of the word to use it to describe something specific rather than to restrict its application to a moving target that by definition cannot be observed.

Heat flow and helium and argon degassing in whole mantle convection

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Earth's heat flow is larger than one would expect given the low abundance of radiogenic elements inferred from primitive meteorites, the amount of radiogenic ^{40}Ar in the atmosphere, and the current flux of ^{4}He from the mantle. This seeming paradox has traditionally been resolved by having the mantle convect in layers. The layering impedes both heat flow and degassing, so that the heat is old and the decay products hidden. But seismology does not reveal layering today. Here we ask what is required of Earth if its mantle convects as a whole. We find that self-consistent solutions for argon, helium, CO_2, and the temperature of the Archean upper mantle can be obtained in whole mantle convection only if (i) inert gases are some 4-6 times more compatible with the mantle than is typical of incompatibles such as CO_2; and (ii) heat flow has been roughly constant over geologic history. The sense of paradox stems from (i) the presumption that a rare inert element degasses as agressively as an extremely incompatible element; and (ii) the expectation, based on applying the conventional equations of parameterized convection to plate tectonics, that heat flow decreases rapidly as the mantle cools in order to track radiogenic heating. Neither of these presumptions is founded well enough to rule out whole mantle convection. Newer versions of layered convection, in which the depleted (upper) mantle comprises ~50-70% of the whole, may seem better. These allow higher noble gas degassing efficiencies (although still less than half that of CO_2), and the Th, U, and K partitioning can be chosen to give self-consistent abundances in continent, MORB, and lower mantle. The new layering also requires that heat loss be a weak function of mantle temperature, although the constraints are looser than in whole mantle convection.