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How irreversible heat transport processes drive Earth's interdependent thermal, structural, and chemical evolution

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ABSTRACT

Because magmatism conveys radioactive isotopes plus latent heat rapidly upwards while advecting heat, this process, not convection, links and controls Earth's thermal and chemical evolution. On this basis, we present an alternative view of Earth's internal workings. Earth's beginning involved cooling via explosive outgassing of substantial ice (mainly CO) buried with dust during accretion. High carbon content is expected from Solar abundances and ice in comets. Reaction of CO with metal provided a carbide-rich core while converting $MgSiO_3$ to olivine via oxidizing reactions. Because thermodynamic law indicates that primordial heat from gravitational segregation is neither large, nor carried downwards, whereas differentiation forced radioactive elements upwards, formation of the core and lower mantle greatly cooled the Earth. Reference conductive geotherms, calculated by using accurate thermal diffusivity data, require that heat-producing elements are sequestered above 670 km which limits convection to the upper mantle.

These irreversible beginnings limit secular cooling to radioactive wind-down, permitting deduction of Earth's inventory of heat-producing elements from today's heat flux. Coupling this estimate with meteoritic data indicates that Earth's oxide content has been underestimated. Density sorting segregated a Si-rich, peridotitic upper mantle from a refractory lower mantle with high Ca, Al and Ti contents, consistent with diamond inclusion mineralogy. Early and rapid differentiation means that internal temperatures have long been buffered by freezing of the inner core, allowing survival of crust as old as ~4 Ga. Magmatism remains important. Melt escaping through stress-induced fractures in the rigid lithosphere imparts a lateral component and preferred direction to upper mantle circulation. Mid-ocean magma production over 4.5 Ga has deposited a slab volume at 670 km that is equivalent to the transition zone, thereby continuing differentiation by creating a late-stage chemical discontinuity near 400 km.

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1. Introduction

Planetary thermal history depends on several factors: (1) initial conditions; (2) the amounts, types, and distribution of heat sources; (3) material heat transport properties; and (4) magmatism and degassing, which overshadow convection and conduction because latent heat is immense and the phases involved are rapidly buoyed upwards. That cooling is strongly affected by locations of heat-emitting elements and magma generation, which in turn create compositional layers, means that Earth's thermal, physical, and chemical evolution are inseparable. However, the current view of Earth's evolution is based on cooling models which omit magmatic and volatile transport while incorporating heat transport properties with systematic errors, and on a chemical model grossly deficient in carbon and refractory oxides. The popular view that Earth has retained much internal heat while vigorously convecting, which sheds heat faster than conduction, seems inconsistent. The perceived vigor rests on diverse assumptions, such as core formation producing large amounts of heat, and the view that 1-dimensional cooling models better represent oceanic heat flux than measurements. The present paper revisits flow of heat in planets, based on a new and accurate thermal diffusivity database for minerals, associated revisions in our understanding of heat flow, and other recent discoveries.

The goals of the present paper are to (1) show how heat transport processes, particularly magmatism and degassing, control Earth's internal layers and workings, (2) describe Earth's thermal state to 1st order using new and accurate transport data, (3) set limits on secular cooling, (4) infer Earth's chemical composition via the tie of chemical and physical processes during cooling, while (5) explaining the observations. We argue that Earth is currently governed by radioactivity slowly winding down, due to early magmatism and degassing that made the core, lower mantle, and upper mantle chemically distinct.

2. The physics of heat flow and cooling of large bodies

The oft quoted statement that three mechanisms exist for heat transport (conduction, radiation, and convection) incorrectly represents planetary transport. Convection is not a mechanism, but rather a large-scale response of the system, which combines microscopic mechanisms and furthermore can be overprinted by additional, macroscopic processes. In response to a thermal gradient, heat-energy in large, planetary bodies moves via conduction, radiation, advection, magmatism, and outgassing. Fig. 1 schematically illustrates the various processes and key physical parameters, which are described below.

2.1. Microscopic mechanisms for heat transport

2.1.1. Lattice conduction

The smallest scale process (conduction) involves diffusive motion of *phonons* over distances as small as atomic, and is quantified in experiments. Historically, conduction has been attributed to scattering of acoustic phonons after Debye (Fig. 1a). However, laser-flash analysis (LFA) measurements, which avoid systematic errors of contact losses and spurious, ballistic radiative transfer gains (Parker et al., 1961; Mehling et al., 1998), shows that infrared (IR) modes participate in conduction (Branlund and Hofmeister, 2012). Based on observations and theory, Hofmeister et al. (in preparation) propose a second mechanism, namely, sequential emission and absorption of IR photons down the temperature

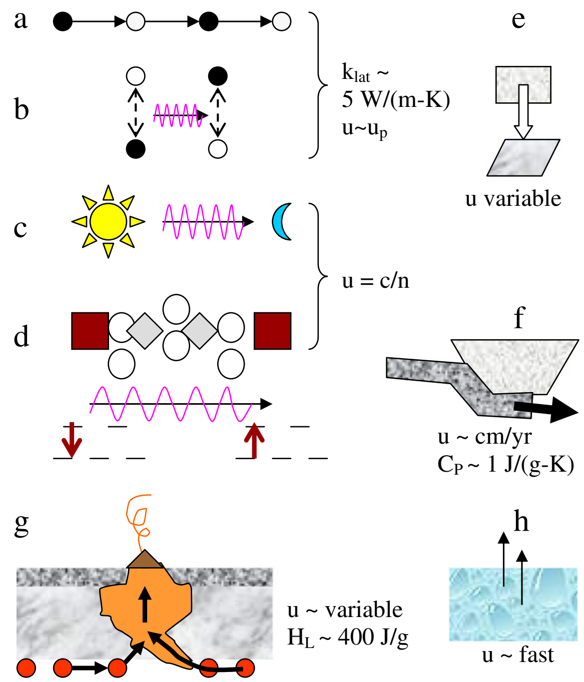

Fig. 1. Schematic of processes transferring heat with key physical properties regarding the Earth. Circles indicate atoms, arrows provide direction of flow. Pink sine wave indicates photons. Speeds are for the shortest distance. (a) Scattering of acoustic phonons. (b) Absorption and reemission of IR light, which sum with phonons to give thermal conductivity of the lattice. (c) Ballistic radiative transfer. (d) Diffusive radiative transfer, which is as fast as ballistic over the smallest distance. (e) Deformation in the laboratory, which occurs at a predetermined rate. (f) Advection in the lithosphere. (g) Magma generation and motion. (h) Degassing.