EFFECT OF PLANETESIMAL IMPACTS ON MANTLE DIFFERENTIATION:  
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During the period of heavy bombardment [1], mantle differentiation would be induced 
by two processes. One is the extraction of melt formed at the ascending region of mantle 
convection due to adiabatic decompression (endogenic process). The other is the differentiation 
induced by impact melting (exogenic process). We estimate the volume production rate of melt 
by each process to clarify quantitative importance of the exogenic processes on the early Earth.

To estimate the volume production rate of melt at the ascending region, we use a simple 
two dimension model of steady state convection heated from within. It is based on the thermal 
boundary layer theory [2, 3] with fixed flow pattern. Thickness and density of melt (crust) are 
both dependent upon mantle temperature [4]. We obtain the volume production rate of melt, \( \dot{V}_c \) 
(\( \dot{V}_c = h u_s / L \); \( h \), \( u_s \), and \( L \) are the thickness of melt, surface velocity, and width of the cell, 
respectively) as a function of mantle potential temperature (Figure 1). We use \( 10^{21} \) Pas case as 
a representative case of the endogenic process.

We have to distinguish two effects of impact on mantle differentiation: 1) impact-induced 
melting, and 2) impact brecciation. The former may enhance mantle differentiation, but the 
latter homogenizes the near surface layers. We estimate both the volume production rate of 
melt produced by impact and the volume production rate of ejecta. To estimate melt volume 
we use a simple shock wave model based on the planar impact approximation [5]. We assume 
that the particle velocity is constant at the near field (isobaric core) and that it decays outside 
the isobaric core with distance. Using Rankine-Hugoniot equations with the first law of 
thermodynamics, we calculate three dimensional distribution of residual temperature rise after 
release of shock pressure for given impact velocity, impactor size and initial temperature 
profile of the Earth (mantle potential temperature). Figure 2 shows the example (impactor 
velocity, size, and the mantle potential temperature are 15km/s, \( 10^6 \) Earth mass (about 80km in 
radius) and 1500 K, respectively). The contour line expresses the isothermal line, and nearly 
hemispherical region is the total melt region. The melt volume almost linearly depends on 
impact velocity and impactor size, but it is almost independent of geotherm. The volume 
production rate of melt, \( \dot{V}_e \) is given by \( \dot{V}_e = \phi_f / S_p \), where \( \phi_f \) is impact flux and \( S_p \) is the total 
surface area of the planet. We estimate the impact flux assuming that the size distribution of 
planetesimals follows a power law approximation [7]. In the similar manner, we define the 
production rate of ejecta, \( \dot{V}_e = \phi_f / S_p \), where \( \phi_f \) is volume of ejected material by single 
impact, which is estimated by Maxwell’s Z-model [8, 9].

The dominant mode of mantle differentiation is obtained by comparing \( \dot{V}_c \) and/or \( \dot{V}_e \) 
with \( \dot{V}_c \) as a function of mass accretion rate, \( \phi_f \), and the maximum planetesimal mass, \( M_{\text{max}} \) 
(Figure 3). To be conservative, we define the gray zone by the parameter range where two of 
\( \dot{V}_c \), \( \dot{V}_e \), or \( \dot{V}_c \) are on the same order. The exogenic process is dominant when mass accretion rate 
is large (\( > 10^{13} \sim 10^{14} \) kg/yr). Impact-induced melting dominates differentiation, when both mass 
accretion rate and the maximum planetesimal mass are large (\( > 10^{5} \) Earth mass).

Although it is very difficult to estimate the mass accretion rate, it can be obtained from 
cumulative lunar crater density [10]. The time evolution of mass accretion rate estimated by 
previous workers [10, 11, 12] are also shown as three arrows. As shown in Figure 3, the 
impact-induced melting dominates differentiation in quantity before 4.2Ga. Before 4.0Ga, the 
exogenic process has comparable effect with the endogenic process. Though we have not yet 
found any traces of old crust before 3.96Ga on the Earth [13], it is possible to find differentiation 
products on the other terrestrial planets (Mars, the Moon etc.). Moreover, it is interesting to
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note that the period while the impact-induced melting surpasses the endogenic melting overlaps the period while no crustal material is preserved (Figure 4).

In this study, we neglect melt production during isostatic rebound during cooling of magma pond. This process probably increases the volume of melt. On the other hand, total melt produced by impact may not contribute differentiation, because it might solidify without chemical differentiation. The most important problem is the difference between exogenic and endogenic processes in 'quality.' Namely, we have to investigate the difference in chemical signature of differentiation products.

Reference