BASIC MINERALOGICAL MODELS FOR SILICATE- AND CARBON-RICH MEGA-EARTHS CONSIDERING COMPOSITIONAL AND GEOPHYSICAL CONSTRAINTS.

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Introduction

In the last decade, hundreds of terrestrial-type had been discovered by the sensitive observation techniques. Most terrestrial planets (TPs) are super-Earths with masses between 1 and 10 Earth-masses (M⊕), but dozens of low-mass rocky planets are also known. A small fraction of TPs have masses over 10 M⊕ and relatively high mean densities, which are consistent with a terrestrial-like composition. They are the so-called mega-Earths. It is supposed that the mineralogical composition of mega-Earths may be similar to that of super-Earths. Accordingly, they are composed mostly of silicates, metals and carbon-rich compounds for the case of C/O ratio is higher than 1 or it is between 0.8-1.

Model

Theoretical models of twenty-earth-mass planets with Earth-like structural properties (for the case of cored planets) have been made focusing on basic bulk compositions of two silicate-dominated and a carbon-rich planetary bodies. The one of the theoretical basic types of mega-Earths is a silicate-rich planet with a mantle composition consisted of terrestrial analog materials in the upper mantle (olivine, ol; wadsleyite , wd; plus ringwoodite, rw; post-perovskite, pv and postpost-perovskite, ppv) and ultrahigh-pressure (UHP) mineral phases of MgSiO₃ in the deepest mantle region. For the case of two-stage dissociation,ppv phase of MgSiO₃ dissociates into CsCl (B2)- type MgO plus P₂1/C -type MgSiO₃ at 0.9 TPa and the further transition yields CsCl-type MgO plus FeP-type SiO₂ at 2.1 TPa. In terms of the studies of Umemoto et al. 2017 and Wu et al. 2014 [1,2] three-stage dissociation occurs for MgSiO₃ in multi-megabar pressure conditions. MgSiO₃ ppv dissociates into Γ42d-type MgSiO₃ + P₂1/c-type MgSiO₂-0.75 TPa (UHP1). UHP1 transform into Γ42d-type MgSiO₃ + FeP-type SiO₂-1.31 TPa- (UHP2). The final-stage of the dissociation is UHP2 dissociated into CsCl-type MgO + FeP-type SiO₂-3.09 TPa- (UHP3). The highly-oxidized MgSiO₁₂ may consisted of the lowermost of mantle in mega-Earths with masses above 20 M⊕. In the mantles of O-rich silicate-dominated planets, MgO, SiO2, MgSiO₁₂ and possibly MgSiO₃ can be the essential planet-forming minerals [3]. In the multi-tetrapascal pressure range, iron-rich cores built up from high-pressure iron phases. Hexagonal-close-packed (hcp) iron is the stable form of iron from 0.1 TPa to multi-TPa pressures, between 7-21 TPa the face-centred-cubic (fcc) phase is slightly more stable than the hcp-iron. Pickard and R J Needs have found a transition to a fcc-centred-tetragonal (bct) phase at 34 TPa and the bcc-phase also becomes more stable than the hcp above 35 TPa [4].

The other basic mineralogical type of mega-Earths is the carbon-rich planets. Two compositional types have been suggested with belonging to the carbon-rich planets, based upon the C/O ratio: carbon-planets (CP) (C/O >1) (silicon-carbide mantle and iron-dominated core with high carbon-content) and carbon-silicate planets (CSP). The mantle of carbon-planets is made of silicon-carbide. SiC with cubic symmetry (3C-SiC, β-SiC) transforms from the ZnS-structure (B3) to the rock salt-structure (B1) at 90 GPa. The metallic core has been built up from Fe, iron-carbides and C. SiC, silicates and silicon oxycarbides (SiOₓCₓ₋₉) [5] can also be found in the mantles of carbon-silicate planets.

UHP phases of MgSiO₃ constitute the lowermost region of the silicate-mantle of mega-Earths over ~20 M⊕. The metallic core composed of high-pressure phases of Fe (hcp-Fe and fcc-Fe at given conditions) or Fe-alloys. For carbon-rich massive solid planets, the mantle is consisted of the phases of SiC and the core built up from Fe and iron-carbides containing of elementary C. The main mineralogical type of silicate-rich mega-Earths is divided into two subtypes, which are the O-rich and the Si-rich terrestrial planets. The mineralogical subtype of the carbon-planets is the Si-rich carbon-planet. It is likely that large population of the supermassive terrestrial bodies are need to have been cored, as opposed to being coreless.

<table>
<thead>
<tr>
<th>Planet</th>
<th>C/O&lt;0.8</th>
<th>C/O=0.8-0.1</th>
<th>C/O&gt;0.8</th>
</tr>
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<tr>
<td>O-rich terrestrial planet</td>
<td>TP</td>
<td>Si-rich terrestrial planet</td>
<td>CSP</td>
</tr>
<tr>
<td>Mantle</td>
<td>MgO, SiO₂, MgSiO₃</td>
<td>Silicates, Silicon-carbide</td>
<td>C,SiC, TiC</td>
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<td>Core</td>
<td>Fe,Fe-Ni alloy, FeO</td>
<td>Fe, Fe-Ni alloy, Fe-C₃</td>
<td>Fe, C₃</td>
</tr>
</tbody>
</table>

Table 1. Basic mineral compositions for the main planetary spheres of the massive solid planets. The core of TPs contains O, Si in several percent [6] and C in several ppt [7].

Summary: The basic mineral compositions of mega-Earths are consistent with the cosmochemical element abundances. At the same time, it is likely that solid planets may exist in wide chemical and mineralogical diversity.


Figure 1. Schematic compositional models for twenty-Earth-mass planets with two-(a) and three-stage (b) dissociations of MgSiO₃ and a carbon composition (c), respectively.