



# Experimental constraints on the fate of subducted upper continental crust beyond the “depth of no return”

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## Abstract

The subducted continental crust material will be gravitationally trapped in the deep mantle after having been transported to depths of greater than ~250–300 km (the “depth of no return”). However, little is known about the status of this trapped continental material as well as its contribution to the mantle heterogeneity after achieving thermal equilibrium with the surrounding mantle. Here, we conduct an experimental study over pressure and temperature ranges of 9–16 GPa and 1300–1800 °C to constrain the fate of these trapped upper continental crust (UCC). The experimental results show that partial melting will occur in the subducted UCC along normal mantle geotherm to produce K-rich melt. The residual phases composed of coesite/stishovite + clinopyroxene + kyanite in the upper mantle, and stishovite + clinopyroxene + K-hollandite + garnet + CAS-phase in the mantle transition zone (MTZ), respectively. The residual phases achieve densities greater than the surrounding mantle, which provides a driving force for descent across the 410-km seismic discontinuity into the MTZ. However, this density relationship is reversed at the base of the MTZ, leaving the descended residues to be accumulated above the 660-km seismic discontinuity and may contribute to the “second continent”. The melt is ~0.6–0.7 g/cm<sup>3</sup> less dense than the surrounding mantle, which provides a buoyancy force for ascent of melt to shallow depths. The ascending melt, which preserves a significant portion of the bulk-rock rare earth elements (REEs), large ion lithophile elements (LILEs), and high-field strength elements (HFSEs), may react with the surrounding mantle. Re-melting of the metasomatized mantle may contribute to the origin of the “enriched mantle sources” (EM-sources). Therefore, the deep subducted continental crust may create geochemical/geophysical heterogeneity in Earth’s interior through subduction, stagnation, partial melting and melt segregation.

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## 1. INTRODUCTION

Continental crust materials can be transported into the deep mantle through continental subduction, oceanic (sediment) subduction and tectonic erosion (Yamamoto et al., 2009). Investigations of ultra-high pressure metamorphic (UHPM) rocks from continental subduction zones have

suggested that continental crust rocks can be subducted to depths of ~200–300 km, as indicated by the discovery of former “majoritic-garnet” and “stishovite” (Van Roermund and Drury, 1998; Ye et al., 2000; Liu et al., 2007). Experimental studies and theoretical calculations have demonstrated that the density of subducted UCC is no longer buoyant with respect to the surrounding mantle when it has been transported to a depth greater than ~250–300 km (Irifune et al., 1994; Dobrzhinetskaya and Green, 2007; Liu et al., 2007; Wu et al., 2009; Kawai et al., 2013), which defines the “depth of no return” or “point of no return”. Consequently, continental crust mate-

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rials subducted to depths of less than the “depth of no return” can return to Earth’s surface as a result of the effects of buoyancy, whereas materials subducted beyond the critical depth cannot return to the surface through buoyancy alone (Irifune et al., 1994; Wu et al., 2009; Kawai et al., 2013). The issue of what happens to materials subducted beyond the “depth of no return” is currently enigmatic: it is not known whether the materials stagnate in the deep mantle or falls into the MTZ as a result of gravitational instability. It is also currently uncertain whether convection in the deep mantle stirs the materials around so that they lose their physical and chemical signatures, or whether at least some reappear in the deep mantle and cause geophysical and geochemical heterogeneities.

Recent geochemical studies have detected isotopic and trace element signatures (e.g.,  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{176}\text{Hf}/^{177}\text{Hf}$ ) of subducted UCC in the near surface lavas (e.g., Jackson et al., 2007; Chauvel et al., 2008; Workman et al., 2008). But little geophysical evidence is available about the presence of UCC in the deep mantle (Schneider et al., 2013) because of the complex structure of the upper mantle and the limited supply of continental crust materials to the mantle relative to that of oceanic slabs (Helffrich and Wood, 2001).

A number of experimental studies have been conducted on the phase relations and partial melting of continental crust materials under high pressure (mostly above the “depth of no return”) and relatively low temperature (subduction geotherm) conditions (e.g., Gardien et al., 2000; Hermann and Green, 2001; Vielzeuf and Schmidt, 2001; Hermann, 2002; Auzanneau et al., 2006; Massonne, 2009; Spandler et al., 2010). The main purpose of these experiments was to interpret the observed microstructures and mineral assemblages of typical continental crust rocks in UHPM zones. Thus far, only a few reports are available on the phase relations (especially partial melting relationships) of UCC materials beyond the “depth of no return”. Irifune et al. (1994) investigated the phase relations of an average UCC composition in the pressure range from the upper mantle to the bottom of the MTZ. Their experimental results suggested that UCC is mainly composed of stishovite, K-hollandite, garnet, clinopyroxene, kyanite/CAS-phase and minor Ca-perovskite; however, these results are inconsistent with the experiments conducted by Wu et al. (2009) using a natural rock powder. Recently, Ishii et al. (2012) examined the phase relations of UCC from the middle part of MTZ to about 800 km depth. They concluded that the discrepancies between the results of Irifune et al. (1994) and of Wu et al. (2009) in the lower part of the MTZ might result from differences in the chemical compositions of the starting materials, or sluggish reaction of the natural rock powder. However, the discrepancies from the upper mantle to the middle part of MTZ are still a matter of under debate.

In this study, we carried out a series of experiments to examine the phase relations of subducted continental crust in the pressure ranges from 9 GPa (roughly equivalent to the “depth of no return”) to the middle part of the MTZ (16 GPa). The model explored here assumes that the recycled continental crust has been heated to approach the nor-

mal mantle geotherm. The main purpose of the present study is to investigate the fate of subducted continental crust in the deep mantle and its implications for the origin of the observed chemical/physical heterogeneity in Earth’s deep mantle.

## 2. EXPERIMENTAL DETAILS

### 2.1. Starting materials

A natural paragneiss sample from Sanjiang, China, was used as the starting material (Table 1). The rock is composed of plagioclase ( $\text{An}_{32}$ , 49 wt%), quartz (27 wt%), biotite (21 wt%), and traces of K-feldspar (3 wt%). The chemical composition of the starting material is similar to the average bulk composition of UCC (Rudnick and Gao, 2003), and has relatively higher FeO and lower CaO content than the material used by Irifune et al. (1994). Details of the starting materials used by Wu et al. (2009) and Ishii et al. (2012) are also listed in Table 1 for comparison. The water content of the starting material was estimated from loss on ignition, yielding to be  $\sim 0.83$  wt%. In a previous study, our experimental results demonstrated that subducted UCC can transport  $\sim 0.5$  wt% of water to a depth of  $\sim 9$  GPa under cold conditions (Wu et al., 2009). In another study, Hermann (2002) reported that subducted UCC can transports  $\sim >1$  wt% of water to depth of greater than 100 km. In this study, the water content is slightly higher than that reported by Wu et al. (2009), but is slightly lower than that reported by Hermann (2002). Therefore, the water content used in this study is reasonable to represent deep subducted UCC. The starting material was prepared by repeated grinding into very fine powder (less than 5  $\mu\text{m}$ ) in alcohol, and kept in a desiccator and dried at 120 °C for at least 24 h before loading into an  $\text{Au}_{75}\text{-Pd}_{25}$  capsule. Then, the capsule was laser-sealed at both ends to prevent the release of water during the experiments.

### 2.2. Experimental and analytical techniques

High-pressure and high-temperature (HPHT) experiments were conducted on a 1000-ton Walker type multi-anvil press at the Laboratory for Study of the Earth’s Deep Interior (SEDI-Lab), China University of Geosciences (Wuhan). Cell assemblies (10/5), with 10 mm octahedral edge length and 5 mm truncation edge length (Fig. 1) were used on 25.4 mm edge length WC cubes. A  $\text{LaCrO}_3$  sleeve was placed inside a ceramic octahedron ( $\sim 45$  wt%  $\text{MgAl}_2\text{O}_4 + \sim 55$  wt%  $\text{MgO}$ ) for thermal insulation (Leinenweber et al., 2012). A rhenium furnace was used for heating. The sample, which was contained in an  $\text{Au}_{75}\text{-Pd}_{25}$  capsule, was insulated from the furnace by an alumina tube. Type C W–Re thermocouple was used to measure the temperature at the center of furnace. The pressure calibration of the cell assembly was reported in Wu et al. (2012) and Zhang et al. (2013). To minimize thermal gradients during the experiments, sample capsules were kept of less than 1.5 mm. Two-pyroxene (diopside and enstatite) thermometry experiments were performed at 1200 °C in the  $\text{CaO-MgO-SiO}_2$

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