Impact-generated hydrothermal systems that can promote organic synthesis: Implications for the origin of life

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Understanding of geological processes responsible for prebiotic organic synthesis on Hadean Earth is critical for the origin of life. Hydrothermal systems are suggested to be a promising emergence place of life given both of the presences of early chemoautotrophs in current hydrothermal vents and chemical gradients (e.g., Martin et al., 2008). However, organic synthesis, such as CH_4 formation, through reduction of CO_2 are considered to be inhibited even high abundances of H_2 without metallic catalysts (e.g., Shibuya et al., 2013, McCollom, 2016). On the other hand, life would have emerged on Earth at least in 3.95 billion years ago, which is coincident with the end of the late heavy bombardment period. Recent studies suggest that impacts of differentiated bodies (e.g., metallic small bodies) would have provided Fe-Ni alloy into the impact craters (e.g., Kendall and Melosh, 2016), where hydrothermal systems could have been subsequently induced due to impact heating (e.g., Osinski et al., 2013). Here, we perform both hydrological modelling and hydrothermal experiments to examine the possibilities of prebiotic organic synthesis within an impact crater of differentiated bodies on early Earth.

Using the hydrological model, we reproduce hydrothermal groundwater circulations emerged within an impact crater with diameter of ~200 km. Our model results show that a large-scale hydrothermal circulation occurs within whole of the crater when the heat source is 200ºC beneath the crater. In this large-scale circulation, upwelling of hydrothermal groundwater occurs mainly at the crater floors where the altitudes are lowest. In contrast, our results also indicate that multiple circulation cells appear within the crater when the heat source is 300ºC. In the small-scale circulations, groundwater experiences temperatures up to ~200ºC and, then, rapidly upwells into the crater cavity. Our results suggest that hydrothermal circulations would be closed within the crater cavity if the heat source is 200ºC or greater. The experienced temperature would be ~200ºC in the hydrothermal circulations.

We conducted hydrothermal experiments using a $^{13}CO_2$-containing (99.99 % ^{13}C), NaCl solution and a powder mixture of synthesized basaltic rocks and Fe-Ni alloy at temperatures of 200ºC and 300ºC and a pressure of 300 bars. Although almost initial CO_2 (~ 90 %) is fixed as carbonate mineral, we find the formation of $^{13}CH_4$, $^{13}C_2H_6$, and HCOOH (or $HCOO^-$) from CO_2 in fluid samples collected during the experiments. C_3H_8 is also found in the experiment of temperature of 200ºC. Hydrothermal alterations of basaltic rocks control fluid pH as alkaline (pH ~8–9) (Shibuya et al., 2013), where reactive HCO_3^- is stable and is reduced to form $HCOO^-$ using H_2 in fluids. Metallic Fe-Ni alloy would be a catalyst to hydrogenate $HCOO^-$ to CH_4. Based on the low H_2 concentrations in the fluids, the rate limiting reaction of CH_4 formation is highly likely H_2 production due to oxidation of metallic Fe. Given the low activation energy of oxidation of metallic Fe (30 kJ/mol: Grosvenor et al., 2005), CH_4 formation proceeds effectively even at low temperatures, such as 200ºC.

Combining these results, we suggest that impacts of differentiated bodies would have provided hydrothermal environments, where reduced organic molecules are effectively provided. Produced CH_4 and other hydrocarbons could be converted to prebiotic organics, such as HCN or HCHO, through

photochemical reactions. The formation process of CH_4 from CO_2 is similar to the carbon fixation of anaerobic chemoautotrophs, such as methanogen; namely, methyl branch of acetyl CoA pathway. Our results imply that impact-generated hydrothermal systems could provide a promising place where early life could have acquired metabolic pathways on Earth.

Keywords: Early Earth, Organic synthesis, Hydrological modelling, Hydrothermal experiment, Origin of life