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Chemical evolution on primordial volcanic islands

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1. Introduction

In the late Hadean / early Archean (ca. 4.1–3.5 billion years before present), increasing chemical complexity culminated in the emergence of life. The exact nature of the underlying chemical processes is still unknown. The same is true for the location(s) where these processes took place on the early Earth. It is, however, essential to have an understanding of the local geochemical and geophysical conditions before relevant simulation experiments can be conducted [1]. We think that primordial volcanic islands are promising places for key steps of chemical evolution. Present-day volcanic islands can serve as "field analogues" and guide the design of laboratory experiments.

2. Volcanic islands

As the geothermal heat production on the young Earth was considerably higher than today, it is reasonable to assume that volcanoes were more frequent. It has been suggested that volcanic islands and short-lived protocontinents, but no permanent continents existed [2, 3]. The situation on the early Mars was possibly not too different [1]. On primordial volcanic islands, Earth's original chemical inventory may have been enlarged by a multitude of chemical reactions. Although the islands must have been relatively small, they provided very different environments, such as eruption clouds of ash and gas, lava flows, salty water at the coasts, and rock pools. Therefore, primary abiotic syntheses and their successive reactions, which may have needed different conditions, could have occurred in immediate vicinity (see below).

The chemical reactions may have been effected by fresh volcanic ash and its weathering products (e. g. clay minerals). It is not known whether plate tectonics and the associated type of volcanism already existed before 3.5 Ga. However, the existence of hot-spot volcanism seems probable. Hawai'i and La Réunion are typical examples of present-day hot-spot volcanic islands. Lava flowing into the sea is frequently observed there. Another prebiotically interesting phenomenon is volcanic lightning. For example, in April 2010 intense lightning occurred during the eruption of the volcano under Iceland's Eyjafjallajökull glacier. A combination of field studies and laboratory experiments should be a suitable approach to explore the possible role of volcanic islands in chemical evolution [1].

3. Prebiotic chemistry on volcanic islands

3.1 Primary abiotic syntheses

It can be assumed that volcanic lightning accompanied Hadean and Archean volcanic eruptions, too. The combination of lightning and ejected reducing gases probably produced amino acids in Miller-Urey-type reactions [4]. The amino acids and possibly other organic products reached the coasts of the islands and the ocean by the fallout of ejected material. It is generally accepted that amino acids, for which also other abiotic sources have been discussed [5, 6], were present on the late Hadean / early Archean Earth.

3.2 When lava meets the sea

When lava flows into the ocean large amounts of seawater evaporate and sea salt crusts remain [7]. In this process, dissolved prebiotic compounds such as amino acids became embedded in the salt crusts. Further heating by the hot environment may have led to unusual thermal transformations. We have demonstrated this in laboratory experiments in which salt-embedded α-amino acids were transformed into pyrroles, pyridines, and polycyclic aromatic hydrocarbons (PAHs) [8].

3.3 The next chemical steps

The compounds which had been formed in the eruption clouds and those which resulted from thermolysis reactions at the coast could have accumulated and concentrated in rock pools (tidal pools). A rock pool can be regarded as a natural reaction vessel. Depending on the distance from lava flows and hot basalt, prebiotic rock pools had more or less moderate temperatures. Under these conditions, diverse chemical reactions may have occurred, for example the formation of oligopyrroles from pyrroles and formaldehyde [9]. Volcanic ash and clay minerals such as montmorillonite were potential catalysts and mediators.

4. Conlusions

We suggest that primordial volcanic islands are candidate locations for key steps in chemical evolution. So far the results of pertinent simulation experiments look promising [4, 8, 9]. They indicate that a prebiotic chemical route may have existed that led from inorganic volcanic gases via amino acids to oligopyrrole-type electron-transfer and photoreceptor molecules. The individual chemical steps are simple and make low demands on the reaction conditions. They are not only conceivable on the early Earth but may have occurred and may still occur on other Earth-like planets.

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