The mass impacts on chemosynthetic primary producers: potential implications on anammox communities and their consequences

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Introduction

The Chicxulub impact is considered one of the most devastating episodes in the recent Earth’s history (Alvarez et al., 1980). The event that took place at the Cretaceous–Paleogene boundary caused a global catastrophe on Earth. Due to the impact, a large cloud of ashes and dust was released to the atmosphere, shielding the solar radiation from reaching the surface of the planet (Pope et al., 1994; Pierazzo et al., 2003). Cold and darkness covered the surface of Earth during several years after the impact.

The biosphere was particularly affected during this episode. As a consequence of darkness, photosynthesis collapsed during the first 2 years. More than 75% of the species became extinct, including the end of the dinosaur’s reign (Alvarez et al., 1980). The structure of the biosphere was also sensibly altered after the impact. While the biggest organisms practically disappeared, others like detritivores and mushrooms were remarkably favoured during this period, due to the large amount of organic matter and cadavers of dead animals (Pope et al., 1994; Vellekoop et al., 2014).

During the present work, we continue exploring the potential influences on the biosphere induced by an impact like Chicxulub’s. However, in this particular case, we discuss a practically unexplored issue in the literature. How would a mass impact like Chicxulub’s affect the chemosynthesis done by anammox communities? What implications would these affectations bring to the biosphere, or how do they affect the dynamics of our planet at global scale. The potential answers to these questions are discussed in the next sections.

Anammox communities: peculiarities and transcendence

For a long time, chemosynthetic (chemoautotrophic) organisms were considered species confined or restricted to very small habitats. Before 1990, most of the chemosynthetic species were found in rather extreme habitats, such as submerged caves or in the surrounding of fumaroles and hydrothermal vents. Accordingly, opposite to the role conferred to photosynthesis, chemosynthesis was considered a marginal process with little contribution to the biogeochemistry of our planet at global scale.

However, the discovery of anammox in 1995 completely changed this picture (Mulder et al., 1995). With an ample variety of species, anammox appears as one of the most extended organisms in our planet (Dalsgaard et al., 2005). Showing an amazing capability of adapting to a wide range of environmental conditions, anammox habitats include the seas (Smith et al.,

Abstract

The potential of a mass asteroid impact on Earth to disturb the chemosynthetic communities at global scale is discussed. Special emphasis is made on the potential influence on anammox communities and their implications in the nitrogen biogeochemical cycle. According to our preliminary estimates, anammox communities could be seriously affected as a consequence of global cooling and the large process of acidification usually associated with the occurrence of this kind of event. The scale of affectations could vary in a scenario like the Chicxulub as a function of the amount of soot, depth of the water column and the deposition rate for sulphates assumed in each case. The most severe affectations take place where the amount of soot and sulphates produced during the event is higher and the scale of time of settlements for sulphates is short, of the order of 10 h. In this extreme case, the activity of anammox is considerably reduced, a condition that may persist for several years after the impact. Furthermore, the impact of high levels of other chemical compounds like sulphates and nitrates associated with the occurrence of this kind of event are also discussed.
The impact of global cooling

After the impact of Chicxulub, the thick layer of material expelled into the atmosphere caused a remarkable reduction in the levels of solar radiation on the surface of our planet. It is considered that the drastic luminous attenuation was mainly due to the large amount of soot and sulphur compounds from the atmosphere to the ocean. In both cases, the selection of the environmental variables responds, on one hand, to the availability of plausible estimations about the real impact of Chicxulub on the climate of the Earth; on the other hand, due to the high sensitivity reported in the literature for the anammox species under variations of temperature and pH.

The impact of acidification

Acidification is recognized as another of the most important collateral effects associated with the occurrence of a mass impact on Earth (Tyrrell et al., 2015). The deposition of a large amount of chemical compounds, mainly in the form of aerosol sulphates, are responsible for a decrease of pH values affecting both the ocean and freshwater ecosystems. In the case of Chicxulub, this effect was particularly enhanced by the peculiarities of the target rock, mostly a mixture of carbonate- and sulphate-rich rocks (Pope et al., 1994; Pierazzo et al., 2003; Ohno et al., 2014). Other chemical species like carbon dioxide and nitrates may have contributed, but in a lower extent, to the acidification process in the ocean (Tyrrell et al., 2015).

The drop of pH may have caused a noticeable impact in many communities of microorganisms. For instance, according to the results of Carvajal-Arroyo et al. (2013), there is a drastic inhibition of suspended anammox cultures if the pH of the medium is below 6.5 or above 8.0. According to that, and taking into account that many species of anammox show high sensitivity to pH variations, let us estimate how the productivity of these communities was affected by the fall of the typical pH values in the oceanic surface after the impact. As the severity of this process depends not only on the net amount of material deposited, but also on how fast this material is delivered to the ocean, two rather extreme scenarios were considered. In both cases, our analyses were based in the pH behaviour for sulphate additions reported previously by Tyrrell et al. (2015).

In the first case, we study the induced affectations considering 15, 30, 60 PMol of sulphates where the e-folding time for the deposition was set to 6 months. In the second case, the same
procedure was repeated but the scale of time considered was remarkably reduced to only 10 h, in accordance with the more recent estimates suggested by Ohno et al. (2014). As it is stressed by Tyrrell et al. (2015), such rapid additions exacerbate the influence in the pH values if we compare them with the behaviour displayed by the former case.

On the other hand, as a prototype of the pH influence on anammox communities, we considered the data published by Carvajal-Arroyo et al. (2013). In this case, data were taken directly from the plot and conveniently interpolated to facilitate computations. The results derived in each case are shown in Figs. 4 and 5.

According to Figs. 4 and 5, anammox communities could be seriously affected as a result of the decrease in pH values. The magnitude of such affectations can vary according to the net quantity of sulphate produced during the event and the timescale that governs the process of atmospheric deposition. The greater and faster are the additions of $H_2SO_4$, the more marked and abrupt are the changes in the pH of the ocean, and consequently, a more devastating and inhibitory effect on anammox bacteria is seen.

On the other hand, Fig. 6 shows that if the addition of $H_2SO_4$ is slower, the adverse effects on the relative activity of anammox will be less drastic but more lasting over time. The above corresponds to a longer acidification period caused by a low deposition rate of sulphuric acid on the ocean. It can be inferred from Fig. 6 that anammox shows good recovery capacities once the sea pH conditions return to normal.

In our analyses, we also considered the potential influence of nitrates on the anammox relative activity. We must take into account that $NO_3^-$ has an inhibitory effect on anammox if its
concentration is higher than 50 Mm (Carvajal-Arroyo et al., 2013). However, according to our estimates, the influence of this particular chemical species was negligible on the RAA due to its low concentration in the ocean.

**Extrapolating to freshwater and terrestrial ecosystems**

Due to their much smaller volume, freshwater ecosystems would suffer more due to the drastic diminution of surface temperature, reaching up to 26°C in some regions (Bardeen et al., 2017). Due to a similar reason, freshwater ecosystems would be particularly affected by acidification during the Chicxulub impact. With a rather limited volume, the effects of dilution in this kind of system tend to be small. In addition, the entry of substances as a result of rain and evaporation could be more harmful for anammox bacteria and all bacterial communities living in these ecosystems than for those living in the ocean, therefore inhibitory effects would be more intense and lasting. Something similar is expected for the case of groundwater ecosystems.

Several atmospheric modelling of the K/Pg limit used atmospheric residence times of sulphur from several months to a few years (Pierazzo et al., 2003). However, recent studies have proposed an alternative scenario, very different from the one generally accepted for the K/Pg event: it is suggested that immediately after the impact, most of the sulphate aerosols (sulphuric acid aerosols) could have been eliminated by large particles of silicates that fell rapidly back to Earth, delivering the load of H$_2$SO$_4$ in only one or few days (Ohno et al., 2014).

**The net effect of decreasing temperature and pH: a global vision**

According to the results obtained in the previous sections, communities of anammox could be seriously affected during a massive impact by the combined effect of temperature and pH. In both cases, the levels of inhibition could be significant considering the high sensitivity of these species to a combined decrease in temperature and pH. We should bear in mind that most of the anammox species so far studied show greater activity in warm temperature and pH. However, even when the influence of temperature and pH during this study is rather limited to the anammox suspended in the ocean surface, communities in the deep sea sediment could also be affected by the accumulation of ash and other sediments, a well-documented fact in the case of volcanic eruptions (Song et al., 2014). Since the inhibition increases as a function of the ash thickness, it is probable that in a catastrophic scenario like the Chicxulub impact, this effect could be significant. We must take into account that in marine sediments, anammox communities can reach 79% of N$_2$ production (Dalsgaard et al., 2005; Trimmer and Nicholls Joanna, 2009).

On one hand, even when the affectsations on the anammox communities at global scale may reduce the rate of N$_2$ removal in appreciable way, the net impact on the nitrogen biogeochemical cycle remains unclear. Most of the effects considered in our analyses: global cooling, acidification, sulphate deposition combined with a noticeable change in the radiative regime in the surface of the planet, also affect the other components of the nitrogen cycle (Shi et al., 2012; Rees et al., 2017). Probably, many mechanisms for nitrogen fixation were also affected with the reduction of sunlight and the drop of temperature at the surface of the planet. For instance, many nitrogen fixing microorganisms associated with land plants lost their potential during this period. On the other hand, the increases of organic matter from dead organisms favoured the increase of organic nitrogen dissolved in the ocean. In general, even without a full modelling, it can be expected that stagnation of the nitrogen cycle was the most probable condition on Earth, a situation that would persist several years after the impact.

Unravelling the dynamics of the Earth after a mass impact arises as a key element to understand the biogeochemical evolution of our planet. However, a better comprehension of the set of processes that followed an event of this nature implies the integration of photosynthesis and chemosynthesis during these catastrophic episodes. Such kind of modelling also implies a better understanding of the metabolic kinetics of the different microorganisms involved in this complex process (Kartal et al., 2011; Brunner et al., 2013).

**Conclusions**

According to this study, the process of global cooling and ocean acidification as a consequence of an asteroid or comet impact could significantly alter the activity of anammox bacteria and, by extension, other chemosynthetic communities whose metabolism is influenced by changes in temperature and pH. However, even when the influence of temperature and pH during this study is rather limited to the anammox suspended in the ocean surface, communities in the deep sea sediment could also be affected by the accumulation of ash and other sediments, a well-documented fact in the case of volcanic eruptions (Song et al., 2014). Since the inhibition increases as a function of the ash thickness, it is probable that in a catastrophic scenario like the Chicxulub impact, this effect could be significant. We must take into account that in marine sediments, anammox communities can reach 79% of N$_2$ production (Dalsgaard et al., 2005; Trimmer and Nicholls Joanna, 2009).

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**References**


