Possible Tectonic Impact of Biosphere

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Key Points:

- Biochemical energy in the subsurface biomes is enough to produce the strongest earthquakes;
- The estimates of maximal depth where life can exist should be at least 75 km;
- Ultra-deep subsurface microorganisms might produce earthquakes.

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Abstract

This paper explores the possibility of existence of ultra-deep biosphere (deeper than 10 km under the surface) and the biogenic earthquake hypothesis – the idea that subsurface microorganisms might be directly related to earthquake activity. The importance of electroautotrophic type of metabolism is underlined, and the role of telluric currents in this process is explored in some detail, as well as the role of subsurface and atmospheric microorganisms in the global electric circuit.

It seems that the existing estimates of the adaptability of biological organisms are inconsistent with empirical evidence, and theoretical concepts predict key biochemical processes to fail long before the onset of the temperatures and pressures, at which microorganisms are actually observed. This implies that life might exist much deeper beneath the surface than previously assumed. At the same time the estimates of energy radiated during the strongest earthquakes are consistent with the biochemical energy available to the subsurface biosphere.

Some additional evidence is examined. It is proposed that the ultra-deep biosphere might represent an important factor in resolving the debate on the nature of hydrocarbons. At the same time the deep subsurface microorganisms might play a significant evolutionary role, not only providing seismically induced genetic variation and a "seed bank" for quick recovery after a mass extinction, but also by modulating longer climatic cycles through planetary-wide bio-geo-electrochemistry.

Plain Language Summary

The depths of the Earth's crust and layers beneath it are hostile to living organisms due to high temperatures and pressures. Previous estimates have been suggesting that life (even tiny microorganisms) cannot exist in the Earth's crust deeper than about 10 km. Yet recent findings have shown that the limits of heat and pressure that microorganisms can withstand have been underestimated. It is logical to assume that life can exist at greater depths – up to 75 km at least.

The energies produced by microbes under the surface (combined) is enough to produce an earthquake (shaking of the ground). Perhaps it is this previously unrecognized deep microbial collective that is causing the earthquakes. Earthquakes might release the nutrients and other necessary chemical elements from the surrounding rocks, as well as cause exchange of genes between microbial cells, which might drive their evolution.

Most of the earthquakes occur at the edges of the Pacific Ocean at large trenches in the Earth's crust. These trenches allow microorganisms to get deeper into the crust, where they might produce an earthquake. It might also explain the presence of hydrocarbons (oil and gas) deep beneath the surface – they might be produced by the same microorganisms.

1 Introduction

So far, Earth has been the only known celestial body to demonstrate signs of tectonic activity (Taylor & McLennan, 2008). One of the manifestations of this activity, as it is currently assumed, is the earthquake phenomena – a sudden release of energy in the Earth's crust that produces seismic waves. At the same time Earth is also the only celestial body known to harbor biological life (Graham, 1990). In the recent years, the evidence has been presented that tectonic activity on our planet might have not existed before Archean Eon (which is supposed to correspond to the formation of life on Earth) (McCall, 2010). Therefore, it seems, one might assume that the very appearance of the tectonic activity correlates with the appearance of life on Earth.

This paper follows the said conjecture (though is not necessarily limited by it) and explores the possibility that perhaps it's not the tectonic activity that has driven the appearance of early life, but *vice versa* – that this activity was (and perhaps still is) produced or at least enhanced by life. In doing that I would mostly focus on the issue of earthquakes and not the other phenomena frequently attributed to tectonic activity (e.g. relative motions of the continents).

I propose what might be tentatively called *biogenic earthquake hypothesis* and explore its possible implications and evidence that might support it. In particular, Section 2 is devoted to explicitly formulating the hypothesis and estimating its feasibility in terms of energy. Section 3 goes one level deeper and explores the observable limitations of living organisms, existing possibilities for nutrient acquisition and energy generation. Section 4 analyzes the existing secondary evidence of feasibility of the hypothesis (related to methane emissions, induced earthquakes, volcanic eruptions and post-earthquake infections).

Section 5 expands the scope of discussion and introduces a wide array of additional conjectures and assumptions that might be feasible in the light of the proposed hypothesis – in particular, I duscuss: additional possibilities for adaptation, the origins of hydrocarbons, deep-focus earthquakes, global electric circuit of Earth, implications for extraterrestrial life, evolutionary implications and a few uncategorized ideas as well.

2 Biogenic earthquake hypothesis

2.1 Formulation and initial analysis

The hypothesis I propose might be formulated as follows: *living organisms play an active role in the earthquake phenomena.*

It seems logical to subdivide the separate scenarios that might follow from that, depending on their answer to two questions:

- 1) are living organisms the primary *cause* (trigger) of an earthquake?
- 2) are living organisms the primary *source of energy* for an earthquake?

For simplicity we shall encode them as such: if the answer to one of those questions is "yes", we denote that with a letter "Y", and if "no" – the letter "N". So if answer to both questions is "yes", that particular scenario would be denoted as YY. If the answer to the first question is "no", and to the second is "yes", we denote this scenario as NY, if vice versa – YN, etc.

So these separate scenarios might be formulated as:

- YY: "Living organisms are the primary cause of an earthquake and they provide most of the energy released in the event";
- YN: "Living organisms are the primary cause of an earthquake, but most of the energy released in the event comes from somewhere else";
- NY: "Living organisms are not the primary cause of an earthquake, but provide most of the energy released in the event";
- NN: "Living organisms are not the primary cause of an earthquake, and most of the energy released in the event comes from somewhere else".

At first glance the NN scenario leaves no room for the hypothesis to exist in the first place. But even if biogenic component in the energy release is not the main one, it still might contribute a certain fraction to it. And at the same time perhaps not all the effects of an earthquake might be reduced to the mechanical energy release (see discussion in the following sections – e.g. 4.4, 5.4, 5.6, 5.7). Note: for simplicity we shall at the moment ignore a potentially important case where different earthquakes (or perhaps different types of earthquakes) might be caused by different factors. I would return to this idea in Section 5.3.

2.2 Energy estimates

In order to evaluate the possibility of YY and NY scenarios (see Section 2.1) let us compare the energies that might be released during an earthquake to the energies typically produced by living organisms.

At present, the most powerful earthquake recorded by instrumentation is the 1960 Valdivia earthquake (Chile) with a seismic moment of the main event estimated as $M_0 = 3.2\times10^{23}$ N·m (Lomnitz, 2004). In fact (to put it in some context), the seismic moment of that earthquake alone accounts for perhaps about 30% of the cumulative seismic moment (and thus, the energy) of all the earthquakes in the whole XX century combined (Bufe & Perkins, 2005).

According to the current models of stress release, the energy of an earthquake might be evaluated from its seismic moment as (Hanks & Kanamori, 1979)

$$E = \frac{1}{2 \times 10^4} M_0. \tag{1}$$

In the case of 1960 Valdivia earthquake this relation yields the energy of 1.6×10^{19} J.

For the initial approach I would assume that the living organisms mentioned in the hypothesis consist of cells. (Some alternatives are only briefly mentioned in Section 5.7). Thus, this energy estimate might be directly compared to the amounts of energy produced by a single cell to evaluate the necessary number of such cells needed to produce the total energy.

For a crude preliminary estimate we shall use a typical biochemical reaction of adenosine triphosphate (ATP) hydrolisis. This reaction yields about 3×10^4 J·mol^{-1} of energy (Rosing & Slater, 1972) (with a caveat that it has been measured in a standard state). At the same time a typical living cell might produce about 10^9 ATP molecules per second (Flamholz et al., 2014), that is, about 10^{-14} mol. So overall we might expect one cell to be able to provide the power of the order of 3×10^{-10} W.

Effectively, this result means that in order to generate equivalent amount of energy as was radiated during 1960 Valdivia earthquake by regular biochemical means of energy production we'd need the amount of cells of the order of 10^{29}, if we assume a momentary (time window ~ 1 s) production of all the required energy. Although incredibly large at first sight, this amount of cells fits well into even [rather conservative (see Section 5.7)] recent estimates of the abundance of microbial cells in the oceanic sediments alone, which is also of the order of 10^{29} (Kallmeyer et al., 2012). To put this in context, according to the cited estimate, this corresponds to only 0.6% of the total biomass on the planet.

Therefore, we might conclude that the conservative estimates indicate the biosphere of the planet *en masse* having 2 to 3 orders of magnitude larger biochemical power production than the energy needed to cause the strongest earthquake recorded so far in just 1 second. Thus, even scenarios YY and NY (as proposed in Section 2.1) seem energetically viable.

3 Detailed analysis

3.1 Energy localization

Although, as indicated in Section 2.2, the amount of biomass on the planet is more than enough to produce the needed amounts of radiated energy for even the strongest of earthquakes, it is far from being clear how this energy might be localized in the crust through known biological processes. If we abstain from invoking some unknown type of long-range interaction between living cells in the biosphere, it seems that the only option would be *in situ* energy production (or triggering of its release, as e.g. in YN scenario in Section 2.1).

Therefore, in order for the hypothesis to work, we must also assume the presence of biological organisms in the crust and, perhaps, in the layers below. It is currently assumed that the conditions in the Earth's interior are unfavorable for life, mostly because the current models imply high temperature and pressure gradients in these areas (Anderson, 1989). At the same time it is known that the absolute majority of earthquakes happen at fault lines (C. H. Scholz, 1969).

Thus, following the initial hypothesis I shall focus on the idea that biological organisms connected to earthquake activity might be present beneath the surface in these areas in especially large numbers and/or be more active there for some reason. One obvious reason might lie on the surface (both literally and figuratively): as fault lines are frequently associated with significant deformations in the crust – often with extremely high elevation gradients, – these would be the areas, where the crustal interior is most easily accessible for biological organisms from the surface (e.g. subduction zones or mid-oceanic ridges). In particular, about 90% of all earthquakes on the planet occur at the "Ring of Fire" (Circum-Pacific belt) (Kious & Tilling, 1996), which topographically represents a ribbon of very deep trenches. It is quite natural to assume that the subsurface in this area would be the most accessible for microorganisms.

What kind of organisms they might be? It seems reasonable to assume that most likely they would be unicellular – due to the mentioned extreme conditions in the crust and below, not favoring complex multicellular organisms. But beyond that I would not state any hypotheses on their particular taxonomy: they might be represented by one or many species of archaea, bacteria, protozoa, algae, yeasts, fungi or other types of yet unknown organisms (perhaps even of non-cellular nature, such as viruses (also see a comment in Section 5.1), or some symbiotic arrangement of those. For the purpose of further discussion, in the following sections I shall refer to them simply as "microorganisms" (unless the type of the organism would be known).

It is quite obvious that in order to be able to operate in these deep habitats, microorganisms would have to overcome at least three significant challenges:

- Hostile environmental conditions;
- Lack of nutrients;
- Lack of energy sources.

In Section 3.2 we shall consider the potential for solving the first problem (see also Section 5.1), in Section 3.3 we shall concentrate on the second, and in Section 3.4 we shall analyze the third.

3.2 Adaptive strength

Let us discuss the environmental conditions that life can withstand, according to the observations. In the recent decades a range of studies has been made on the ability of microorganisms to adapt to the most extreme habitats. It is now known that bacteria, for example, might survive and even thrive in the environments with high pressures (barophiles or piezophiles) and high temperatures (thermophiles), and often both. These would be most relevant for us, according to the current models of Earth's crust and layers beneath it with their supposedly significant pressure and temperature gradients.

In particular, evidence has been found that significant prokaryotic populations are present below the sea floor at least down to the depths of 1.6 km (and temperatures of 100°C) (Roussel et al., 2008). What is perhaps the most interesting is that in this study contrary to all expectations in the deepest examined sample the percentage of dividing cells was more than twice higher than in the layers above. At the same time, methane- and sulfur-cycling chemoautotrophes have been found at depths up to 600 m below the mid-ocean ridge, also demonstrating peculiar discrete layering intervals in cycling intensity (Lever et al., 2013).

Barophilic bacteria have been found in the sediment at Mariana Trench at pressures of 100 MPa (C. Kato et al., 1998). Moreover, even non-barophilic organisms that are much better fit for regular atmospheric pressure (0.1 MPa) were found there (*Pseudomonas bathycetes*), as well as barophiles that are best fit for pressures of 70 and 80 MPa (of genus *Shewanella* and *Moritella* correspondingly). At least one of the iron-reducing organisms taken from "black smokers" at mid-ocean ridge was able to survive at 130°C (the possibility of growth at this temperature was not determined) and then still grow after lowering the temperature to 103°C (Kashefi & Lovley, 2003). At temperatures below 85°C the cells were alive, but did not divide anymore.

Analysis of a sulfide chimney, recovered from the ocean floor at >2 km depth, has revealed presence of microorganisms in the areas, where the temperature range must have been about 150–300°C (Schrenk et al., 2003) and similar other detections have been reported previously with temperatures around 300°C (Harmsen et al., 1997; Takai et al., 2001). Signs of presence of microorganisms (lipid fatty acids) were found in the interior of the flange of a black smoker right next to a fluid with a temperature of 350°C (Hedrick et al., 1992). More recently, bacteria *Bacillus amyloliquefaciens* have been shown to survive an exposure to the dry heat at temperatures of 420°C and be able to successfully replicate afterwards (Beladjal et al., 2018).

If we just directly assume a moderate temperature gradient of, say, 25°C (Gholamrezaie et al., 2018) (note that it is considered to be lower for continental crust and higher for oceanic crust), we'd arrive at possible depths for microorganisms to exist of about 16 km beneath the surface. At the same time it is assumed in the current models, that the geothermal gradient in the mantle should be two orders of magnitude lower, otherwise the temperature would rise too quickly for the rock to remain solid (Monnereau & Yuen, 2002).

However, regardless of that the real gradient for most of the planet's surface is unknown (except for measurements during isolated drilling operations, which barely got below 12 km beneath the surface (Carr et al., 1996)), and some of the models show that in fact temperatures of only 430°C (along with pressures of 3 GPa) would exist at depths of 75 km (E. G. Jones & Lineweaver, 2010). Curiously enough, according to the same model this is also the bottommost point where liquid water might still exist.

The estimated pressure of 3 GPa is order of magnitude higher than the pressures at which microorganisms have been observed in the examples given above. But laboratory studies have shown that microorganisms in fact might survive at pressures of tens of GPa (Hazael et al., 2016), despite all the evidence which indicates that the stability and functioning of key biomolecular components should fail above few hundreds of MPa. It appears that our current understanding of key factors making life possible is far from being complete, and the limits of biological adaptability are in general underestimated. As an example, some recent theoretical studies have indicated that life cannot exist at temperatures higher than 150-180°C (Bains et al., 2015), which directly contradicts the observational evidence given above, some of which has been available for more than a decade prior.

Thus, we might conclude that at least some models indicate that the existence of the already known microorganisms (as well as liquid water) might be possible down to the depths of 75 km below the surface of the planet. However, one cannot at the moment rule out the existence of some yet unknown microorganisms that might be present even deeper. Additionally, we might suppose that the lack of readily available liquid water at greater depths (if the cited model is correct) can be compensated by the presence of confined water and/or water in the hydrated minerals, assumed to be abundant in the mantle (Schmandt et al., 2014; Fei et al., 2017; Liu et al., 2018; Tschauner et al., 2018). In fact, there are indications that these minerals are the primary source of water on the surface in the first place (Pearson et al., 2014), so an assumption of water-depleted mantle does not seem to hold merit at the moment.

3.3 Possible nutrient sources

The analysis given in Section 3.2 shows that microorganisms might tolerate the conditions present at depths of tens of kilometers beneath the surface or possibly even more. Yet, as noted in Section 3.1, it is not enough to make their existence possible: some sources of nutrients and energy would also be required.

With regards to nutrient production and consumption, I deem reasonable to consider two possible sources (which are not mutually exclusive):

- Conversion of the surrounding minerals;
- Recycling of the previous generations of microorganisms.

The second option seems self-evident, and is not going to be discussed here in much detail. We might simply assume that the previous generations have penetrated the lower layers from upper layers, perhaps more favorable for nutrition, and thus provided a certain stack of nutrients for next generations; theoretically this process might have continued iteratively for many generations, thus bringing the microorganisms lower and lower into the mantle. On the other hand, considering that the origin of life is still unknown[1], the process might have actually went in reverse. It is considered currently, for example, that hydrothermal vent precipitates represent the oldest known fossils (Dodd et al., 2017), so based on that assumption one might actually think that life did arise in the deep underground in the first place and emerged to the surface only in later epochs (see also Section 5.6).

With regards to the first option, the current models indicate, for example, that noticeable amounts of carbon should be present in the mantle (Wood et al., 1996; Armstrong et al., 2019), though it is assumed that its distribution is not homogeneous (Le Voyer et al., 2017). And at the same time it is known that some bacteria have adapted to environments with long-term carbon deficiency by improving their carbon-concentrating mechanisms (Dobrinski et al., 2005). So we might assume that the minerals below the surface might provide enough carbon for life to exist – given that there are mechanisms to extract and use it.

Oxygen, according to the present models of Earth's interior, should also be abundant in mantle minerals (Y. D. Chen et al., 1991) – notably, among others, in iron-rich compounds (Bykova et al., 2016; C. Xu et al., 2017). Hydrogen seems to also be available in mantle minerals, according to the current models (Yang et al., 2016). There is even the evidence of hydrocarbons present in minerals, assumed to be originating from

[1] and even the very fact of the existence of origin is not proven

the mantle (Sugisaki & Mimura, 1994), which might also serve as an additional source of these elements (see Section 5.2 for additional discussion). And, finally, some studies indicate that nitrogen should be available in the mantle too (Mallik et al., 2018). So it seems that according to the current models of Earth's interior the key elements are readily present in the surrounding minerals.

3.4 Possible energy sources

Let us consider now the possibilities for energy acquisition for microorganisms in the hypothetical ultra-deep biosphere. It seems at first glance that the most obvious option would be the well-known chemotrophic processes – the oxidation of reduced compounds. It would seem from the considerations given in Section 3.3 that in order for the hypothesis to work, there should be at least some types of microorganisms of chemoautotrophic type (being able to process environmental carbon into organic molecules), since chemoheterotrophs (organisms that consume biogenic carbon compounds) alone would not produce a steady increase in biomass over time.

Among the most notable known examples of such organisms are iron-reducing bacteria (e.g. of the genus *Geobacter*) (Luef et al., 2013) and sulfur-reducing bacteria (e.g. of the genus *Shewanella*) (Moser & Nealson, 1996). For the production of energy these organisms use electron acceptors other than oxygen, thereby performing anaerobic respiration (J. R. Lloyd, 2003). As both iron and sulfur (Savage et al., 2015) are present in the deeper environments of Earth, it seems reasonable to accept that type of metabolism as a possible source of energy (most likely in conjunction with other biochemical processes, involving processing of the surrounding minerals). This possibility is further reinforced by observations: chemoautotrophic sulfur-reducing bacteria have already been found at the depths of 2.4 km (Lollar et al., 2019) and 2.8 km (Chivian et al., 2008). Quite often these microbes are also extremophiles – for example, one of the bacteria mentioned in Section 3.2 is also an anaerobic iron-reducing species, which is able to grow at 122°C (Kashefi & Lovley, 2003).

One potentially important property of some of these organisms is the ability to perform extracellular electron transfer (necessary for reduction and – ultimately – anaerobic respiration) through highly conductive nanowires (Reguera et al., 2005; Gorby et al., 2006; Creasey et al., 2018). It allows these microbes to "breathe rock" at a distance, while not having to actually digest it. Similar processes occur at the seafloor, where some bacteria are able to connect together and form long conductive filaments, delivering electrons from few centimeters down into the soil up to the surface, where oxygen receives them (Pfeffer et al., 2012), thus performing "distributed breathing" at distances, 4 orders of magnitude greater than the size of each individual bacterium. Even aerobic iron-oxidizing bacteria have been shown to be able to grow just by feeding on the electric current (Summers et al., 2013).

Thus not only we potentially have an alternative energy source for the deep subsurface biosphere, but we also arrive at an intriguing possibility that the energy release during an earthquake might be a purely electrical phenomenon in the first place. Indeed, such hypotheses have been made previously (e.g. in (Davidson et al., 2015; Trenkin, 2015)), as in the recent decades extensive observations and analyses of pre-earthquake very low frequency or ultra low frequency radioemissions (VLF, ULF) have been made (Petraki et al., 2015).

Most of the studies usually assume that these observations could be explained by magneto-hydrodynamic, piezomagnetic and electrokinetic effects or crustal asperity in fault zones etc., yet none (to my knowledge) have previously considered a potential role of biological organisms in this process. It would seem that the "byproduct" of the mechanisms of operation of these microorganisms (electric current) have the potential to be the energy source for the production of an earthquake. At the same time it might represent a previously unrecognized (Helman, 2013) source of telluric currents in general. In fact, it has been found that electrical properties of bacterial cells and the charge transfer process during their attachment to mineral surfaces impacts the bulk electrical properties of the subsurface environment – its conductivity in changing electromagnetic fields in particular (Abdel Aal et al., 2019).

At the moment it is not clear whether the fault line regions would have lower or higher electrical conductivity (thus having an enhanced or inhibited telluric currents along the fault lines), as electrical conductivity of minerals depends on temperature, pressure, water content and other parameters, which are currently poorly constrained due to the lack of observations (X. Guo et al., 2016). There exist some models, yet there is no proven theory on that subject, and even the whole issue of electrical conductivity of fault line structures is often ignored (Kawakatsu & Utada, 2017), although some practical studies in electromagnetic observations of these structures have been successfully made (Bologna et al., 2014) – notably, detecting a subsurface layer of biogenic material. Some of the research seems to indicate a higher conductivity of fault lines (Jiracek et al., 2007), which might be a sign of the presence of biogenic conductive tissue akin to the mentioned nanowires.

It is not entirely clear, how exactly these ultra-deep microorganisms, telluric currents and earthquakes might be related. Returning to my initial classification (see Section 2.1), perhaps we might map these entities onto the proposed scenarios in the following way:

- YY: "Microorganisms in their metabolic dynamics produce both an earthquake and the telluric currents associated with it";
- YN: "Microorganisms in their metabolic dynamics produce the telluric currents, which in their turn trigger an earthquake";
- NY: "Metabolic dynamics of microorganisms is enhanced by [external] telluric currents, which leads to an earthquake";
- NN: "Metabolic dynamics of microorganisms might cause telluric currents and contribute some of the energy to an earthquake, but the main source of energy and the main trigger of an earthquake is non-biogenic".

Unfortunately, at the current stage of the development of the hypothesis it is impossible to rule any of these options out. Yet I believe that the possibility of the connection between ultra-deep biosphere, telluric currents and earthquakes (and tectonic processes in general) is viable and should be researched further.

4 Secondary evidence

In this section I examine some of the additional evidence that might support the idea of a connection between microorganisms deep in the Earth's crust (or below it) and earthquakes.

4.1 Methane emissions

As one of the possible sings of microbial activity is the emission of biogenic methane (e.g. produced by methanogenic archaea (Gao & Gupta, 2007)), perhaps the detection of this gas assiciated with earthquakes and fault line structures in general would be a hint towards the biogenic nature of tectonic activity in the first place. And such emissions indeed have been observed, even though the mechanisms that drive this release remain poorly understood (Bonini, 2019).

In particular, a noticeable release of methane has been observed after the 2010 Maule earthquake (Chile, $M_W 8.8$) (Geersen et al., 2016). Another study conducted a few years ago has found evidence of a significant (a conservative estimate of mass shows about 10^6

kg) release of methane during the strong (M_W8.1) earthquake at the Makran Trench (Arabian Sea) in 1945 (Fischer et al., 2013). At the same time even in seismically calm periods at least some fault lines demonstrate noticeable methane degassing: for example, recently a narrow band of methane plumes was found west of the North America coast – at Cascadia fault (Johnson et al., 2019). Methane emissions have also been found at the fault in the Sea of Marmara (Dupré et al., 2015) etc.

Several hundred-meter tall plumes of increased water opacity have been observed at the ocean floor near the fault line even months after the 2011 Tōhoku earthquake (Japan), as well as heavy methane emissions (Kawagucci et al., 2012). In fact, it seems that after the earthquake methane emissions have been prominent even at Japanese islands themselves, as evidenced by multiple unexplained fires, preceded by some misty white vapours and bubbling in the offshore area – very similar to the analogous events after 1993 Hokkaidō earthquake (Enomoto et al., 2018).

A recent survey done in the UK has found that there is an elevated methane emission from local faults, but interestingly enough it does not correlate with the presence or absence of known hydrocarbon deposits (Boothroyd et al., 2017), which might serve as an additional evidence of the hypothesized ultra-deep biosphere that produces this gas independently. It is worth noting that many studies (e.g. (Etiope et al., 2019; Howarth, 2019)) attempt to distinguish between biogenic and non-biogenic sources of methane depending on the isotope ratio of ^{13}C.

Yet this might not be conclusive at all, given that laboratory experiments have shown that certain methanogenic chemolithoautotrophs change isotope ratios in biogenic methane depending on the environmental conditions (Takai et al., 2008). This flexibility in biogenic methane isotope composition might explain the observed problematic character of separation of biogenic and abiogenic CH_4 in continental bedrock environments in spite of a similar spatial distribution of methanogenic microbes among the different sites (Kietäväinen & Purkamo, 2015). Interestingly, certain methanogenic chemolithoautotrophs at higher pressures are also able to withstand higher temperatures – in the given particular case up to 130°C for 3 hours at 30 MPa (Takai et al., 2008).

4.2 Induced earthquakes

It is now known that hydrocarbon mining operations using the hydraulic fracturing techniques can lead to earthquakes (Council, 2013). It is generally assumed that the earthquakes produced during these activities are caused by two different reasons: 1) fracking itself (fluid injection intended to fracture the hydrocarbon bearing rock) – these are rare and weak earthquakes; 2) disposal of wastewater via injection into the deep storage wells – this is the primary cause of stronger earthquakes and increased seismicity due to fracking in general (Rubinstein, 2019).

We shall not focus our discussion on the earthquakes produced in the first way – it is after all understandable that the mechanical shocks, associated with hydraulic fracturing, might produce seismic signals. The second pathway of generation of earthquakes represents higher interest with regards to the proposed hypothesis. In particular, the injection of salt water (one of the main components of the wastewater which is injected underground (Rubinstein, 2019)) clearly might provoke a response in metabolism of microorganisms. Not only does it provide them with water itself, but it is highly conductive water, which might play a significant role in the enhancement of extracellular electron transport processes and/or telluric currents (see Section 3.4).

So we might assume that the fracking related induced earthquakes might also be subject to the same mechanisms of biogenic earthquake production. It should be noted here that most of the current models of induced seismicity during wastewater injection are not consistent with observations (Eyre et al., 2019), and the exact mechanisms of their generation are not yet clear. On the other hand, a widespread presence of microorganisms in deep oil and gas fields is not a subject of doubt – e.g. sulfur-reducing bacteria are in fact so prominent there that they cause a well known and serious problem of rapid corrosion of the objects of infrastructure of hydrocarbon production (steel tanks etc.) (Enning & Garrelfs, 2014).

Unfortunately, to my knowledge no significant electromagnetic detection studies exist yet in relation to fracking-induced earthquakes. Only recently some electromagnetic measuring suites have started to be deployed in the field. For the most part, the sensitivity of the instruments is barely enough to detect any changes, yet there is already evidence that the real surface-based monitoring examples do not replicate the expected magnitude of change derived from modeling – for example, the surface change in electrical resistivity is larger than expected (Thiel, 2017). Perhaps future studies would show whether electric currents (potentially biogenic in nature) might be related to these earthquakes.

4.3 Volcanic eruptions

As volcanic activity seems to be related to seismicity, we might also assume that the hypothetical ultra-deep biosphere might play a role in these processes as well. This possibility is reinforced by contemporary models, which show that the depth of typical volcanic magma reservoirs is quite modest – barely surpassing 10 km mark (Huber et al., 2019), which should be easily accessible for microorganisms. The only possible problem is high temperature that magmas typically have. At the same time a recent study of Borgarhraun eruption in Iceland has provided a direct estimate of magma residence time in basaltic systems of the deep crust, which turned out to be of the order of 1000 years (Mutch et al., 2019), which is exactly the estimated time scale of crustal biomass turnover (Shoemaker & Lennon, 2018).

Yet microorganisms are quite frequently found in and around volcanic rocks and lava flows (Byloos, 2017; Byloos et al., 2018). For example, samples of lava taken from Eyjafjallajökull volcano outflows (Iceland) a few months after the eruption in 2010 show a prominent presence of bacteria (Kelly et al., 2014), and the most interesting detail is that the samples of this fresh lava were dominated by non-phototrophic species, whereas older lavas of the same mineralogic structure are usually dominated by phototrophs. It might indicate that some of these organisms were not introduced into the cooling lava, but might have been present there intially.

Interesting cases of populational changes have also been seen after underwater volcano eruptions, where suddenly the old species disappear, and the new ones are introduced, as if they've migrated hundreds of kilometers to get to the site (Mullineaux et al., 2010). Just as well, over the span of 2 years unexplained large shifts in the dominant taxonomic groups of microbial community has been observed at the flanks of the Mid-Atlantic Ridge (Tully et al., 2018), where, despite oxic conditions, members of the microbial community were poised to exploit hypoxic or anoxic conditions and showed a functional redundancy that did not correlate with the shifting microbial community membership.

A peculiar case is represented by an eruption of Tagoro submarine volcano (Atlantic Ocean), where multiple curious filaments a few centimeters long (dubbed "Venus's hair" by researchers) made of bacterial cells and covered together by a protective sheath were observed (Danovaro et al., 2017). Genetic analysis has also shown that these organisms do not belong to the local ecosystem.

I would also hypothesize that the source of sulfur compounds in volcanic eruptions might be biogenic in the first place. Perhaps e.g. volcanic sulfur oxides might be produced through the secondary oxidation in the atmosphere or upper layers of the crust of sulfur, reduced by ultra-deep crustal microorganisms tens or hundreds of kilometers below the given volcano.

4.4 Post-earthquake infections

One additional hypothesis we might conjure is that the ultra-deep biosphere (connected to earthquake activity, according to my initial hypothesis) might be partially released closer to the surface (e.g. in the groundwater or even the atmosphere) during or after an earthquake. These microorganisms potentially might be pathogenic on their own. But more importantly, they might modify the other microorganisms through horizontal gene transfer (as does happen e.g. with genes responsible for arsenic resistance (Dunivin et al., 2018); see also Section 5.6), which might enhance the pathogenic character of the already present microorganisms.

Therefore, we might look at the data concerning post-earthquake infections and try to find some patterns that might be present in it. Or course, an earthquake on its own might introduce conditions that would increase the number of infections even by regular means – e.g. by compromising sanitation (Uprety et al., 2017) – so this type of evidence could not be considered conclusive even if present. Yet perhaps one might still expect a strong earthquake causing the emergence of rapid shifts in many microbial, phylogenetic and functional gene abundances and pathways, as happens, for example, during permafrost thawing (Mackelprang et al., 2011). One of the examples of this process might be the rapid spreading of pathogenic microorganisms near the epicenter of an earthquake (Potera, 2005).

An interesting case is represented by simultaneous emergence of clonal strains of fungus *Candida auris* on three continents from 2012 to 2015 (Lockhart et al., 2017), most notably having a higher tolerance for elevated temperatures (Casadevall et al., 2019). Under consideration given in the present study we might assume that this enigmatic occasion might have been caused by 2011 Tōhoku earthquake (Japan) – the fourth strongest earthquake in recorded history. The idea being, that some microorganisms could have been released from the crust as a consequence of an earthquake and interacted with the fungus, whereas a temperature susceptibility pattern would be explained by the possible relation to the crustal thermophiles.

Curiously, the majority of the post-earthquake pathogenic organisms are represented by Gram-negative bacteria or fungi (Y. Wang et al., 2010; J. Xu et al., 2010; Ran et al., 2010; Daito et al., 2013; Mishra et al., 2016), which is an oddity, since at least up to 2010 the standard medical guidelines proposed by the Centers for Disease Control and Prevention and the World Health Organization for treatment in these situations specifically targeted Gram-positive bacteria (Miskin et al., 2010; Bekçibaşı et al., 2017). In my opinion, this might serve as an indication of some previously unnoticed change in microbial communities caused by strong earthquakes. At the same time we should acknowledge the occasions of post-earthquake outbreaks of (for example) tetanus (Sutiono et al., 2009), which is caused by Gram-positive bacteria.

Another potentially important case is represented by catastrophic cholera outbreak in Haiti after a strong earthquake in 2010 (Orata et al., 2014), causing a largest national cholera epidemic in recent history. Before that occasion, cholera (also caused by Gram-negative bacteria) have never been observed on the island. Even though it was concluded that most likely the infection was spread by transmission from United Nations relieve teams, arriving from Asia, the more recent research seems to indicate that the biotype of the infection was different after all (Kirpich et al., 2017).

Perhaps Gram-negativity might be linked to the extracellular electron transfer (most likely connected to telluric currents), which I assume to be present in hypothetical ultra-deep biosphere. It is generally considered that Gram-positive bacteria do not participate well in this process due to their thick non-conductive cell walls. However, recently it was demonstrated that the artificial addition of conductive polymers might change the situation (Pankratova et al., 2019).

It is interesting to note that cold plasma inactivation shows a different response in Gram-positive and Gram-negative bacteria, though it seems that the difference is mostly caused by variations in cell membrane thickness: the thicker, the less effective (Mai-Prochnow et al., 2016). At the same time the very mechanism of action of cold plasma on bacteria is not clear (Šimončicová et al., 2019). If extracellular electron transfer plays a significant role in the proposed ultra-deep biosphere, perhaps we might expect a different response to plasma too in any related organisms.

It is also known that bacteria respond to piezoelectric stimulation, and Gram-positive and Gram-negative species behave differently (Carvalho et al., 2019). Recent study has also shown that the sensitivity of microorganisms to pulsed electric fields might be reduced if previously they had to adapt to some other external influence by modifying their cell membranes (L.-H. Wang et al., 2019). Overall, I envision a possible connection of earthquakes to the spreading of new pathogenic microorganisms as an interesting avenue of research.

5 Discussion

In this strictly secondary section I discuss some additional considerations, as well as potential implications of the hypothesis, also giving a glance at a broader scope of more controversial assumptions that might be built around it in case it would turn out to be true.

5.1 Additional tools for survival

The following considerations are meant to reinforce the points made in Section 3.2 – in particular, explore the tools that ultra-deep biosphere members might use in order to withstand the (hypothetically) extremely hostile environment of deep Earth's crust and below.

We might assume that in order to better counteract the high pressures and temperatures that supposedly exist deep within Earth's crust, microorganisms might form some type of protective shell. Known examples of similar behavior are many: *Nostoc* bacteria colonies, which form an extracellular matrix of high viscosity polysaccharides and might reach 0.17 m in size and perhaps even bigger (Sand-Jensen, 2014); colonies of *Pseudopediastrum boryanum*, as well as some other organisms, which surround themselves with sporopollenin – a tough polymer, providing good protection from the environment (Sutkowy & Kłosowski, 2018); colonial algae of the genus *Synura*, which produce durable silicate scales and spines for protection (Leadbeater, 1990).

Some microscopic animals (like rotifers) are also known to grow a protective exoskeleton (Hamre, 2016). Similar type of exoskeleton is represented by silica-rich external shells (frustules) of diatoms (Parker & Townley, 2007), and even bacteria possess some exoskeletons of their own (sacculi) (Koch, 2000) etc. As all the materials required to build a durable external shell seem to be available in the crust, it's natural to assume this might be a viable option for the enhancement of survivability of endoterrestrial microorganisms.

Another frequently observed tool (e.g. emerging during the attachment of bacterial collectives to interfaces) is the formation of biofilms that enhance protection and make recycling of the surrounding minerals easier (Beveridge et al., 1997). Interestingly, it is known that biofilms noticeably reduce the effectiveness of high pressure inactivation of pathogenic microorganisms (Dommerich et al., 2012). Also, Gram-negative microorganisms (see discussion in Section 4.4) are less susceptible to this process in the first place. It seems to indicate that the formation of a biofilm might be a natural response of microorganisms in the deep subterranean environments to the surrounding conditions.

Perhaps one other tool might be represented by symbiotic interaction of multiple species, each one specializing on solving a part of the hot pressing issues[2]. Symbiosis is indeed observed in unicellular organisms, as, for example, in *Stentor polymorphus*, keeping *Chlorella* algae inside its cell to provide protection for them and receive maltose in exchange (Reisser, 1981). Perhaps a relevant example including relatvely large animals would be a giant shipworm that burrows under the surface of the seafloor, while being covered by its protective shell, and consuming the energy provided by symbiotic sulfur-oxidizing chemoautotrophs in its gut (Distel et al., 2017).

I would hypothesize that a mixed-species collective might form such symbiotic relationship in the ultra-deep subsurface of the Earth, forming something akin to a microbial mat. Curiously, research has already shown that even different species of microbes are capable of coordinating extracellular transfer of electric current together and performing external symbiotic catabolism (S. Kato et al., 2012).

Another viable tool of protection might be represented by dormancy. Many microorganisms are capable of temporarily "shutting down" their metabolism in order to protect themselves from the harsh external conditions. Even multicellular organisms are capable of that – e.g. tardigrades produce trehalose (Hengherr et al., 2008) and intrinsically disordered proteins (Boothby et al., 2017), in effect vitrifying themselves to facilitate survival during severe dehydration and other undesirable conditions (cryptobiotic state referred to as tun).

As some research suggests that biochemical processing of ATP might become unstable at high temperatures and pressures (Leibrock et al., 1995), one might assume that the hypothetical microorganisms lie dormant most of the time, and only occasionally and suddenly wake up, significantly increasing intensity of their metabolism, and produce an earthquake (see discussion in sections 3.4 and 5.7). In a recent study a modeling of overlap between protein efficiency of metabolism and ATP production has been analyzed, with the conclusion that they should anticorrelate, i.e. the lower ATP yield corresponds to higher protein efficiency (Y. Chen & Nielsen, 2019). I suppose it is worth investigating in this regard, how would an electrotrophic type of metabolism change this picture. There is data that suggests that extreme conditions tend to suppress dormancy, provoking higher activity due to increase in competition (Aanderud et al., 2016), but perhaps if the conditions are beyond extreme, these bursts of activity would still alternate with periods of dormancy.

Another related instrument of survival is the formation of bacterial endospores. These formations allow bacteria to survive in the most extreme conditions and for staggeringly large amounts of time – tens to hundreds of millions of years, as studies show (Cano & Borucki, 1995). Some estimates also show that in the sub-seafloor environments bacterial endospores might be as abundant as vegetative cells (Lomstein et al., 2012). Dormant endospores of thermophilic bacteria in particular are present in marine sediments worldwide (Hanson et al., 2019). Furthermore, their genetic stability might be used to track oceanic circulation (Müller et al., 2014), even though their origin might not be clear (de Rezende et al., 2013). Perhaps their origin is exactly the hypothetical ultra-deep subsurface biosphere, which they for some reason left by lifting up from an oceanic trench or a volcanic eruption.

I might also propose some more exotic ways of dealing with extreme environments. Perhaps the hypothetical exoskeleton might be enhanced by some phase transitions of

[2] Pun intended

water (Pollack, 2013), carbon or carbon based polymers (Grumbach & Martina, 1996; Gross & Jaenicke, 1994; W. Guo et al., 2007). And, as some carbon-based materials demonstrate incredibly high proximity to perfect black bodies, we might assume that thermal emission might be one of the instruments of reducing the heat load on the ultra-deep biosphere microorganisms. Since thermal radiance rises as the fourth power of temperature, at higher temperatures it might be an effective tool of thermoregulation. One of these materials – VANTABLACK – might be created at temperatures accessible to life (400°C) (South China Morning Post, 2014). And recently even darker material was synthesized at the same temperature (Cui & Wardle, 2019).

On the other hand, perhaps environmental heat might actually be utilized as an energy source. Since the collectives of microorganisms might perform distributed electron transport, forming long chains (see Section 3.4), we might assume that they can utilize the thermal gradients in the crust in order to drive their metabolic processes (and/or the currents associated with them) - in effect, operating as a "biological thermocouple".

I would also hypothesize that the ultra-deep subsurface might be rich in viruses. It seems that at least in the oceans the abundance of viruses is comparable to the abundance of microbial cells, though it decreases with increase in microbial cell density (Wigington et al., 2016).

5.2 Origin of hydrocarbons

Perhaps the hypothesis proposed in this paper might provide a new perspective on the origin of hydrocarbons. In particular, if we assume the existence of ultra-deep biosphere (tens to perhaps hundreds of kilometers deep beneath the surface), then these microorganisms might represent an additional, previously unrecognized biogenic source of hydrocarbons. This might explain, for example, problematic observations of hydrocarbons at even geologically young formations (Galant, 2017), which cannot be adequately explained by the present biogenic models.

One of the hints towards the viability of such perspective is the similarity between bacteria found in warm subsurface petroleum reservoirs and bacteria in oceanic crust (Hubert et al., 2009). So perhaps the ultra-deep biosphere microorganisms might be responsible for both the production of methane (see Section 4.1) and the synthesis of more complex organic molecules. Recently the possibility of generation of spongelike crystalline materials called metal-organic frameworks (Service, 2019) has been shown, and it was demonstrated that they are capable of capturing gases (including water vapor and carbon dioxide) and actually producing hydrocarbons in the process. I would assume that the collectives of microorganisms might be capable of performing similar processes in the ultra-deep subsurface.

In this case all the problematic observations in favor of the hypotheses of abiogenic hydrocarbon production (Höök et al., 2010) and the presence of deep hydrocarbon reservoir in the Earth's interior (Gold & Soter, 1980) might be explained by the presence of the ultra-deep biosphere. Perhaps in this case we might also hypothesize that the hydrocarbon deposits might play a role of energy/nutrient reserves for these microorganisms, as the reverse processes – production of methane from hydrocarbons – have been observed in archaea (Laso-Pérez et al., 2019) and other so-called hydrocarbon degraders (Mason et al., 2010). There is, for example, evidence of methane inclusions in the serpentine rocks (Klein et al., 2019), yet somehow it is assumed that it is abiotic – even though the temperatures at which serpentinization occurs are accessible to living organisms (see Section 3.2). Even the shallower deposits of shale oil and gas might be produced by microorganisms themselves, as evidenced by their widespread presence there (see Section 4.2).

5.3 Deep-focus earthquakes

Some of the recent estimates for the maximum depth where life can exist correspond to about 10 km (Plümper et al., 2017). However, they were obtained using outdated figure for maximal temperature that life can withstand (122°C), which is now known to be at least 3.5 times higher. In Section 3.2 I have proposed a revised maximal depth for the existence of life, which seems to lie in the region of 75 km – at least at our current level of observational knowledge about the limitations of biological organisms.

Yet the current models of propagation of seismic signals imply that earthquakes might happen much deeper than that – at the depths of hundreds of kilometers at least (Frohlich, 1989). These are so-called deep focus earthquakes. So their existence seems to be problematic to explain from the standpoint of the hypothesis considered in this paper. Yet I can see at least four possibilities that would still allow it to be viable:

- The mechanism of deep-focus earthquakes is different (non-biogenic);
- The adaptational limits of biosphere are still underestimated;
- The temperatures and pressures in Earth's interior are overestimated;
- The depth estimates of earthquakes need to be revised.

The first option would imply that the shallower earthquakes and deep-focus earthquakes are produced through different mechanisms. The depth distribution of earthquakes mostly follows a relatively clear exponential curve until about 400 km (Frohlich, 1989), which might be expected in case of biogenic origin, as the number of cells e.g. in oceanic sediments also drops exponentially with depth (Jørgensen, 2012). But after 400 km the frequency of earthquakes starts to rise, potentially indicating on another mechanism in action.

The second option is self-evident. As we don't fully understand how even the observed organisms might withstand theoretically impossible conditions, we cannot say for sure what their ultimate limitations are. Additionally, potential secondary means of enhancement of adaptability for extreme environmental conditions have been discussed in Section 5.1. The third option implies that we might not understand the real conditions deep in the Earth's crust and below, as direct observational data below 12 km (Carr et al., 1996) is simply non-existent. The existing models have to deal with a system with too many unknowns and invoke many hypotheses simultaneously to get a coherent picture – which might not be correct.

The fourth option would imply that perhaps a reevaluation of models estimating the depth of earthquake focus is needed. It is worth noting that some debate on this topic has already been going on, indicating serious uncertainties (of about 100 km) in the estimation of depth of certain earthquakes (Rees & Okal, 1987). In absence of real data on the mechanical properties of rock below 12 km the amount of possibilities obviously increases, and constraints on models are virtually absent. A few other examples of the same problem might be represented by inconsistencies and lack of acceptable interpretation of seismic signals, seemingly related to the hypothetical inner core (Vidale, 2019), placing of the very deep earthquake focuses where they should not occur, according to models (Furumura & Kennett, 2017), long-standing problems with deriving an adequate explanation of the existence of low-velocity layers (Magnitsky, 1971) and some other essential problems of plate tectonic theory (McCall, 2010). It has been demonstrated, for example, that the seismic data might be consistently and coherently explained in the model of the Earth without a core (Lamprecht, 1999).

5.4 Global electric circuit

As I have assumed that telluric currents might play an essential role in the biogenic earthquake production (see Section 3.4), it is reasonable to consider other key electric systems of the planet – the global electric circuit in particular. It is considered to be mostly limited to the atmosphere of the Earth, and the role of the underlying layers (below the immediate surface of the crust) is seldomly, if ever, discussed (Rycroft et al., 2008). Let us firstly consider the biogenic effects on the atmosphere, and then I'll make a few assumptions regarding the hypothetical ultra-deep biosphere in relation to the global electric circuit.

Recent studies have indicated a significant impact of microorganisms on sea spray aerosol properties (Cochran et al., 2017). It seems that these types of effects might influence evaporation processes in a noticeable way, and potentially modulate e.g. cyclonic activity, which might have serious implications for thunderstorm activity, ionospheric potential and vertical electric current density in the atmosphere. Some interesting experiments on transfer of microorganisms from the ocean to the atmosphere have been conducted (J. M. Michaud et al., 2018). It seems that the enhancement of the cell membrane by hydrophobic envelope increases chances of aerosolization.

Even the low temperatures in the stratosphere do not seem to represent an impenetrable barrier for microorganisms. Extremophiles adapted to cold environments (psychrophiles) have been observed to grow at temperatures of at least $-15°$C (Mykytczuk et al., 2013). At the same time theoretically it is assumed that in the presence of ice in the range of temperatures between $-10°$C and $-26°$C microbial cells undergo vitrification (transition to glassified state), after which they might sustain much lower temperatures, while not being metabolically active, but at the same time still being alive (Clarke et al., 2013).

Some decades ago the concept of bioprecipitation (Morris et al., 2014) was introduced – the idea that biological organisms might noticeably enhance cloud condensation and related phenomena. It is now known that biological ice nucleators are actually the most active and thus some bacteria might promote quick ice nucleation in the atmosphere, which, perhaps, helps them spread to other habitats with precipitation, as they are ubiquitously found in snowfall all around the world (Christner et al., 2008). In fact, INA (ice-nucleation active) bacterial proteins (mostly produced by *Pseudomonas syringae*) have been used for decades for the creation of artificial snow – e.g. at winter sports resorts (Lagriffoul et al., 2010).

This indicates that perhaps the role of microorganisms in atmospheric chemistry and global weather and climatic patterns is underestimated. Even the known mechanisms of relationship between strong volcanic eruptions (providing additional sulfur dioxide and other sulfur compounds into the atmosphere) and cloud condensation nuclei (e.g. see (Berresheim et al., 1993)) might be questioned in that regard – is it not possible that it's the sulfur-reducing bacteria being activated by additional "nutrient" influx that causes these changes in cloud condensation microphysics? Recent studies, after all, indicate on a significant abundance of bacteria in the upper troposphere (DeLeon-Rodriguez et al., 2013) and the stratosphere (Bryan et al., 2013). And biogenic ice nucleating particles originating from underwater organisms have been observed even in the Arctic atmosphere (Creamean et al., 2019).

It has been recently shown that water microdroplets spontaneously lose electron, producing hydrogen peroxide (Lee et al., 2019). I would hypothesize that this process might be used by aerobic bacteria in the atmosphere for energy acquisition. As it seems that on the empirical level the cloud microphysics and associated weather and climate responses are mostly governed by the change in vertical electric current density in the atmosphere (Lam & Tinsley, 2016), perhaps even the airborne microorganisms and biogenic ice nucleating particles should be considered a crucial part of Earth's global electric circuit? I might hypothesize even that the mysterious noctilucent clouds (Thomas & Olivero, 2001) have something to do with presence of microorganisms in the atmosphere.

Next, I would assume that the hypothetical ultra-deep biosphere might be at least partly responsible for the electrical polarization of the crust. Conventional models (Rycroft & Odzimek, 2010) certainly show how the potential difference between the crust and the ionosphere can be maintained (namely, owing to the upward current in thunderstorms and downward current in fair weather), yet the question of the generation of this potential difference still remains open (what causes the upward current in thunderstorms in the first place). If the microorganisms in the ultra-deep environments possess the same negative electric potential as any regular cell (or perhaps the negatively charged exotic water phases are somehow involved in their operation (Pollack, 2013)), it would induce positive charges on the interfaces in their immediate vicinity, which would in its turn negatively polarize the surface of the crust, so the correct charge sign would be observed.

It is known that the propagation of positive charges from underground depths to the surface frequently precedes major earthquakes, increasing air ionization (which leads to various atmospheric phenomena – e.g. "earthquake lights", corona discharges, increase in infrared radiation, ionospheric disturbances etc.) and causing detectable changes in the groundwater chemistry, which alters animal behavior (Grant et al., 2011; F. Freund & Stolc, 2013). This also indicates that the electrical processes (possibly initiated or enhanced by the hypothetical ultra-deep biosphere) initiate at least days before the moment of the earthquake. Laboratory studies indicate that this process might have a piezoelectric nature (F. T. Freund et al., 2006), i.e. the currents might be generated in the rock as a consequence of applied mechanical stress, ultimately related to the transport of dislocations and defects in the crystal lattices (F. T. Freund, 2011).

This might be the case, however we might also assume that these currents might be a result of metabolic processes of the hypothetical ultra-deep biosphere microorganisms – meaning that the physical mechanism of charge transfer in the rock is secondary, while the primary process is the biogenic electrochemistry in the ultra-deep subsurface (perhaps involving partial cell depolarization – e.g. due to motility, – which would exactly correspond to the upward current, since it would tend to reduce the induced charges in the crust). Or perhaps both processes act together in this case, as an increase in metabolism of microorganisms might cause additional mechanical stresses in the surrounding rock (see Section 3.4). I would also hypothesize that motility of microorganisms might introduce static electricity which might be used for metabolic purposes or be related to earthquakes themselves.

As an additional curiosity, it has been found that the temporal distribution of deepest earthquakes (see Section 5.3 for general discussion) demostrates noticeable seasonal inhomogeneity (Zhan & Shearer, 2015), which, following my hypothesis, might imply the integration of the metabolism of ultra-deep endoterrestrial organisms into other global cycles – perhaps through the global electric circuit or by some other cosmophysical mechanisms that seem to regulate stochastic processes in general (Shnoll, 2012).

5.5 Extraterrestrial life

Given the ever widening range of environmental conditions that biological organisms are known to be able to tolerate, the logical next step would be to look at the other celestial bodies and potential for life existing there.

Seismic events of uncertain nature has been detected on the Moon (Oberst, 1987) ("moonquakes") and Mars (Voosen, 2019) ("marsquakes"). In my opinion, there is not enough evidence yet to definitely claim that the nature of these phenomena is the same as the nature of seismicity on Earth. But in case we assume that these events indeed genuinely represent the shaking of planetary crust due to internal forces, we might as well hypothesize that these forces might be biogenic.

Not only we might assume the existence of ”native” life on these bodies, but even life from Earth might have been able to colonize them. One of the hypothetical scenarios might look like that: endospores of crustal bacteria get to the ocean (as discussed in Section 5.1, they are indeed present there), from the surface of which they undergo aerosolization (as discussed in Section 5.4, this process is observed) and lift high up into the atmosphere with the cyclonic updraft and the associated upwards electric current, from there they might get to the upper ionosphere e.g. via equatorial ion fountain or similar plasma structures (Bilitza, 2015; Loi et al., 2015), after which they might get to the magnetosphere via current systems connecting it to the ionosphere (Borovsky & Valdivia, 2018).

As Earth’s magnetotail is known to extend all the way to the Moon (causing there significant electromagnetic disturbances in the regolith (Jordan et al., 2014)), we might assume that the endospores might get to its surface too. Furthermore: as the Earth’s magnetosphere is directly coupled to the solar wind plasma with its electric and magnetic fields, it represents a possibility for the endospores to escape into interplanetary space and – eventually – reach other celestial bodies, including Mars. Then these endospores would simply wait for the appropriate conditions to arise and resume into vegetative state again when the time is right. In this light one might assume that the the mysterious seasonal emissions of methane on Mars (Safi et al., 2019) could be of biogenic nature after all, perhaps associated to some electrical changes in Mars’ environment (see Section 3.4). E.g. some research has proposed the possibility of seismically produced hydrogen to be a source of metabolic energy on extraterrestrial worlds (McMahon et al., 2016) (which is relevant in case seismicity on these worlds might be driven by other reasons too).

At least the first part of this scenario seems viable, as microorganisms from Earth have been observed growing on the surface of International Space Station more than 400 km above the planetary surface (TASS, 2014). Indeed, microorganisms show incredible potential of adaptation to low pressures. It has been shown that bacteria might be successfully trained to tolerate such conditions (Nicholson et al., 2010) – even though it is assumed that the adaptive potential of archaea is even higher in the most general case (Albers et al., 2000; Koga, 2012; Siliakus et al., 2017), despite the evidence that in the subseafloor environments they are represented in similar abundances (K. G. Lloyd et al., 2013). The other set of experiments has also shown that at least some organisms might survive the long-term exposure to the conditions in outer space (Cockell et al., 2011; Onofri et al., 2012).

Perhaps the very existence of electrotrophic organisms (Ishii et al., 2015; Zaybak et al., 2018; Trigodet et al., 2019) shows that theoretically Earth-like life is possible anywhere where there exist the necessary elements and the electric currents. Since all the rocky bodies in the Solar System are surrounded by magnetized current-carrying plasma, and the interaction of solar wind protons with oxygen-bearing minerals or atmospheric gases constantly produces water (Stephant & Robert, 2014; Kuhlman et al., 2015), theoretically it means that life might be present anywhere. (See also review of bacterial interactions with rocks in (Byloos, 2017)). Perhaps some remnant of the initial exposure of early organisms to the electromagnetic influences is now resurfacing in the form of positive effects of weak magnetic fields on stem cell proliferation (Van Huizen et al., 2019) and even plant growth (Dhawi, 2014).

Interestingly, small bodies (asteroids and especially comets) seem to hold large abundances of complex organic materials, almost identical to high grade oil shale (kerogen) (Zuppero, 1995). This might indicate on the possible presence of microorganisms even on these bodies, performing ongoing biogenic electrochemical recycling of the rocks. On the other hand, discovery of biogenic materials on small bodies of the Solar System might reinforce the idea that these bodies represent the debris generated during the planetary catastrophies in the past – including the ones involving Earth (Thornhill & Talbott, 2006).

5.6 Evolutionary role

In this section I would examine the possible implications of the presented hypothesis for the evolution of both the hypothetical ultra-deep microorganisms themselves, as well as the evolution of biosphere in general.

Firstly, let us discuss the possible evoltionary advantages of earthquake production. Some studies have hypothesized that the earthquake activity helps to deliver the needed resources to the subterranean biosphere from the surrounding minerals (Sleep & Zoback, 2007). And experiments show that even small earthquakes might provide enough hydrogen for a subsurface lithoautotrophic microbial ecosystem (Hirose et al., 2011). Potentially it might mean that earthquake activity (according to the biogenic hypothesis) might be an evolutionary adaptation mechanism for the deep crustal microorganisms.

And it would seem that earthquake-related mechanical shocks might not be disruptive for their operation, as microorganisms were shown to be able to thrive and reproduce even at extreme accelerations (up to 4×10^5 g), which seems to be facilitated by their small cell size (Deguchi et al., 2011). At the same time, even though the known subsurface microbial communities predominantly assemble by selective survival of taxa able to persist under extreme energy limitation, still the mutation repairs, and therefore gene functions, are maintained in the subsurface sediments despite the extreme energy limitation (Starnawski et al., 2017).

Ultra-deep biosphere potentially might be a source of nutrients and energy for the microorganisms in the upper layers of the crust – e.g. by producing methane or hydrogen. For example, studies of the ecosystems beneath the West Antarctic ice sheet have shown that biogenic methane from underlying layers (produced by reduction of CO_2 with H_2) is then used by other (aerobic) organisms as a source of metabolic energy (A. B. Michaud et al., 2017). It is noted that microbial sulfate reduction in basaltic fluids plays a significant role in the global biogeochemical carbon cycling between the subsurface and the overlying ocean (Robador et al., 2015). At the same time strong earthquakes change the variations in bacteria, phytoplankton and zooplankton in the lakes' ecosystems and cause variations in the sediment, which affect the lakes' chemistry (pH etc.) (Gulakyan & Wilkinson, 2002). These effects might serve as an evolutionary factor for the surface biosphere.

A potentially important question (partly addressed in Section 4.4) is the genetic exchange between the hypothetical ultra-deep biosphere and the biosphere in the upper layers of the crust and on its surface. Horizontal gene exchange might play a significant role in the evolution of the hypothetical ultra-deep biosphere, and that idea is supported by the high frequency of sympatric speciation patterns in subterranean environments (Leijs et al., 2012). In fact, bacterial genetic exchange during earthquakes have been reproduced in laboratory conditions (Yoshida & Fujiura, 2009), so biogenic earthquake production might also be one of the tools of sustaining diversity and adaptation in these environments.

The hypothetical ultra-deep biosphere might represent a unique subsystem of biosphere in evolutionary sense, owing to the assumed extremity of the conditions present there. Experiments show that higher pressure tends to decrease abundance of microorganisms, but increases their diversity (Marietou & Bartlett, 2014), while e.g. barophilic bacteria demonstrate changes in their phenotype when subjected to normal atmospheric pressure (Straube et al., 1990), which is also associated with decrease in sugar uptake (DeLong & Yayanos, 1987). It seems that the exchange of genetic material and biomass between the surface and deep subsurface is bilateral. Even relatively complex eukaryotic organisms such as insects were found underground at depths of about 3.4 km (Borgonie et al., 2019). At the same time symbiotic electron-transferring bacteria are ubiquitously found around (and seem to be highly beneficial for) aquatic plants (V. V. Scholz et al., 2019; Martin et al., 2019).

Dormancy of the ultra-deep microorganisms (see Section 5.1) might modulate the evolutionary processes and interaction between different species (Wisnoski et al., 2019), since it allows to maintain the genetic diversity, altering speciation and extinction (Shoemaker & Lennon, 2018). Perhaps one could think of the hypothetical inhabited channels in and beneath the fault lines as "inverted mountains", "rising" down rather than up, in which case higher diversity there would not be surprising (Rahbek et al., 2019). In general, environmental fluctuations seem to drive temporal variations in population growth that produce long-lived individual organisms, thus promoting multispecies coexistence (Lennon & Jones, 2011). We might assume that crustal biomass and dormant crustal extremophiles, which have migrated to the surface, could play a role of a "seed bank" for the biosphere (S. E. Jones & Lennon, 2010) and e.g. allow a faster recovery after a mass extinction and drive evolutionary innovations (Lowery & Fraass, 2019), filling the newly created ecological niches with new species.

As I've assumed the importance of telluric currents (Section 3.4) and the integration into the global electric circuit (Section 5.4) for the hypothetical ultra-deep biosphere, we might make another logical step and claim that *electroautotrophy* (or at least electrolithoautotrophy (Ishii et al., 2015)) might represent the second most important type of primary energy and nutrient production. After all, there are two main channels of the solar influence on Earth: 1) electromagnetic emission; 2) flux of charged particles (driving or at least modulating the telluric currents). Photoautotrophs on the surface have adapted to utilize the first one and now represent the largest [known] reservoir of biomass (Bar-On et al., 2018). I claim that it would be very strange to assume that no organisms have yet adapted to utilize the second one. And the ultra-deep subsurface (especially associated with fault lines) seems to be the environment where such an autotrophy type would be quite fitting.

I would even go as far as to assume that if life originated on Earth, it might as well have appeared in the crust first. Meaning cracks and crevices of the Earth's crust filled with water and vivified by telluric currents and the associated electrochemistry as primitive "casting molds" for producing the very first alive cells. This idea is even more compelling, considering that the oldest known fossils of microorganisms are found (Dodd et al., 2017) embedded in microscopic haematite tubes and filaments similar to those of microbes from modern hydrothermal vent precipitates and analogous microfossils in younger rocks – crevices, fractures, cracks and serpentinization pores (Früh-Green et al., 2016).

It seems, instead of talking about individual microbiomes, at the current level of our understanding of microbial life it is now more appropriate to talk about a single ecosystem-wide microbiome, serving as an invisible "glue" connecting different habitats, symbiotically aligning with enormous array of other species etc. (Pennisi, 2019). I would suggest applying the same approach on a global scale.

5.7 Concluding remarks

One problem that the proposed hypothesis seem to have is the application of the initial energy estimate (Section 2.2) to the actual ultra-deep subsurface environment. In particular, most if not all of the known microorganisms in deep subsurface have very low metabolic rates (Lever et al., 2015; Solden et al., 2016) – orders of magnitude lower than the ones used in my estimates. I see three possibilities of overcoming this problem (which are not mutually exclusive and might work simultaneously) and still producing an earthquake:

- Possibility of energy accumulation in the ultra-deep subsurface over time;

- High temporal inhomogeneity of metabolism (i.e. spikes of significantly increased metabolism rates);
- Underestimation of the amount of biomass in the ultra-deep subsurface.

The first option might imply that the biogenic currents would slowly charge the [metaphorical or actual] capacitor, which then for some reason discharges, releasing all the accumulated energy and producing an earthquake. The second option was already partly discussed in previous sections, so I won't consider it here in detail. The third option would be discussed in the following paragraphs. Here I wish to note that what seems to be a problem on this level might actually turn out to be a solution for some other observed peculiar effects. For example, if the large metabolic cycles of microorganisms in ultra-deep biosphere are characterized by timescales of, say, 1–100 kyr, we arrive at the intriguing possibility that perhaps it is this biological factor that might explain some other processes occurring on the planet – e.g. the long climatic cycles. This might be applicable even to larger geological timescales – for example, it is assumed in some recent studies that the source of oxygen for the Great Oxygenation Event was in the mantle (Andrault et al., 2018). I might add here that it might have been produced biogenically by sulfur- and iron-reducing microorganisms from the primordial mantle minerals.

There is a significant problem with conventional methods of detection of these organisms. E.g. samples acquired during the very deep drilling might show lack of microorganisms simply because they were quickly removed from their native environment and couldn't survive the transition. Additionally, as recent analysis shows, most bacterial and archaeal taxa across most biomes on the planet remain uncultured (Steen et al., 2019), which places significant constraint on the estimates of the amount of biomass of microorganisms and even the possibility of their identification in the studied samples in the first place, let alone examining their physiology, metabolism, environmental roles and growth characteristics. Uncultured microbes actually dominate nonhuman environments on Earth, and yet remain almost completely unknown (K. G. Lloyd et al., 2018).

Returning to the question of biomass, earlier estimates (Whitman et al., 1998) have been giving an order of magnitude higher number of prokaryotic cells in the oceanic subsurface. The previously mentioned research (Kallmeyer et al., 2012) – see Section 2.2 – came to the much lower estimate as a result of new observational data, claiming that previous samples were biased in terms of their localization. Indeed, they mostly focused on areas with higher sedimentation rates (most notably, the Pacific Ocean margins), whereas drilling beneath the central gyres of the South and North Pacific yielded a noticeably smaller cell counts (Jørgensen, 2012). The process of biomass estimation still faces significant uncertainties due to the lack of observations and the mathematical procedures used to generalize the known samples (Bar-On et al., 2018). Yet it seems that the samples acquired from underneath the Pacific show a clear inverse correlation of the number of cells and the distance from the continents, which doesn't harm the proposed hypothesis a lot, as the key areas are represented by oceanic trenches at the edges of the Pacific, where the access to the deep subsurface is the easiest.

Artificial active-matter systems of biological or synthetic molecules are capable of spontaneously organizing into structures and generating global flows, yet in order to successfully self-organize they require a boundary-mediated control (Ross et al., 2019). We might assume that the external factors such as the motion of the crust (which produces or fills the cracks and thus determines the space available for microorganisms, perhaps also modulating the availability of certain minerals or water) or telluric currents might serve as such control input. Curiously, coordinated earthquake-like motions have been observed in bacteria – e.g. colonies of *Myxococcus xanthus* (Gibiansky et al., 2013). Additionally, morphology of bacterial cells might experience sudden sharp changes at certain environmental conditions, as, for example, happens during *Escherichia coli* elongating its cells about 10 times under pressures higher than 25 MPa (Kumar & Libchaber, 2013). The stochastic nature of this process somewhat resembles earthquake dynamics. And at the same time similar repeating patterns in earthquake dynamics have been observed, occurring in a span of years or even decades in the localized areas of maybe 100 m in size (Ide, 2019), which might be an evidence of repeating metabolic dynamics of microorganisms.

Of course, one might also assume the existence of some exotic life forms in the ultra-deep subsurface (perhaps not even water-based or not carbon-based). Curiously, simulations show that carbon at high pressures and temperatures might behave as silicon (Grumbach & Martina, 1996). Or perhaps we might think of organisms lacking cellular membranes in the first place, manifesting only as long protein chains. Or maybe cellular microorganisms enveloped by an incredibly large extracellular matrix etc. Perhaps such an extracellular matrix might even stabilize the cellular membranes in the same way as amino acids stabilize fatty acid membranes (Cornell et al., 2019). Proteins themselves might have coevolved in this grid, as they seem to do in bacteria (Cong et al., 2019).

Regardless of whether it is possible, what certainly is possible (in case ultra-deep biosphere exists) is the existence of long-range connectivity of ultra-deep habitats. The network of fault lines enveloping the world gives a good example of how it might look like – perhaps all these areas are actually connected by microorganisms. Interestingly, some recent research has shown that earthquakes might trigger other earthquakes on the other side of the world with a certain lag (O'Malley et al., 2018). We might suppose that this corresponds to the propagation of a certain metabolic signal in the ultra-deep subsurface. Another curious set of evidence for such connectivity is represented by the similarities of seemingly disconnected subterranean bacterial communities (Magnabosco et al., 2014).

We might also hypothesize about the possible role of bacteria in related geological processes, e.g. gold deposition by flash vaporization during an earthquake, which seems to occur at tolerable conditions (see Section 3.2): temperatures (390°C), depths (11 km) and pressures (290 MPa) (Weatherley & Henley, 2013). Such possibility might be reinforced by the evidence that some bacteria can easily tolerate the high concentrations of toxic heavy metal complexes – gold being one of their possible components – and reduce them into a metallic nanoparticle form (Bütof et al., 2018). Interestingly, it has been shown that water might be formed through interaction of quartz with hydrogen (Futera et al., 2017), which is assumed to be connected to deep earthquakes. Perhaps living organisms in the ultra-deep biosphere might utilize this process for their metabolic needs as well.

Interestingly, formation of biogenic magnetite along the bacterial nanowires (see Section 3.4) has been noted (Gorby et al., 2006), which bears a resemblance to the behavior of magnetotactic bacteria that produce and stack crystals of magnetite that allow them to orient in the local geomagnetic field (Blakemore, 1975). In addition to magnetotaxis some microorganisms demonstrate the ability to sense gravity (Fenchel & Finlay, 1986), which, I hypothesize, might be used to sense seismic signals and temporally organize metabolic processes accordingly.

Connected to the geological subject is the much more controversial topic of possible non-chemical and non-electromagnetic (in conventional sense) sources of energy. There is evidence to suggest that biogenic elemental transmutations exist (Biberian, 2019), which might also have important implications for the processing of the crust and lower layers of Earth by hypothetical ultra-deep biosphere, as well as for the energy production in these areas.

And, finally, it is worth mentioning that perhaps the biological activity in the ultra-deep subsurface might be the force behind the observed continental drift in the first place.

6 Conclusions

The primary idea of this research is the exploration of the possibility that biological organisms might be related to the production of seismic signals. Logically the hypothesis rests on two statements: 1) microorganisms might exist much deeper in the Earth's crust (or below) than currently acknowledged; 2) these ultra-deep microorganisms might play a role in earthquake production. We have examined the plausibility of these statements.

In particular, in Section 2 I have formulated the hypothesis explicitly and provided some initial analysis on the exact scenarios (microorganisms acting as a trigger or source of energy for the earthquake, or both), and also shown that the biochemical energy, equivalent to the radiated energy of even the strongest earthquakes is readily available even in the oceanic sediments alone.

In Section 3 I have provided a detailed analysis of the hypothesis. In particular, I have indicated that the most plausible way of delivering the energy is by *in situ* production. As fault lines correspond to the severe deformations of the crust (especially deep trenches of the Pacific "Ring of Fire", where the absolute majority of earthquakes occur), they would also be the most accessible regions for the microorganisms.

I have also shown that the observational data indicates that microorganisms might tolerate much more extreme conditions than even was considered a few years ago, and that the limits of biological adaptability are seriously underestimated, with theoretical reasoning lagging decades behind. I have examined the potential for nutrient and energy production in the crust and the mantle and hypothesized that electrolithoautotrophic type of metabolism, connected to telluric currents might play a significant role in the operation of hypothetical ultra-deep biosphere. Perhaps the ultra-deep biosphere actually represents a previously unrecognized source of telluric currents in the first place.

In Section 4 the existing secondary evidence has been examined. Namely, the emission of (possibly biogenic) methane from fault lines and earthquake epicenters, the widespread presence of bacteria in shale oil and gas, and the earthquakes that are induced in the areas of their mining after wastewater injection (which might provoke increase in bacterial metabolism and produce a biogenic earthquake). I have noted a frequent observation of unique microbiomes in volcanic eruptions and fresh lava, which might indicate that these microorganisms were present there initially. I have examined some cases of post-earthquake pathogen spreading and hypothesized that it might be caused by release of genetic material from the subsurface during the earthquake.

In Section 5 some additional evidence has been provided, as well as various complementary assumptions, which might follow from the initial hypothesis. In particular, I've examined additional tools that microorganisms might utilize for survival in the ultra-deep subsurface (formation of exoskeleton or biofilms, symbiosis, dormancy, phase transitions, thermoregulation through radiative emission).

I have proposed an alternative scenario for the formation of hydrocarbon deposits – by the means of ultra-deep microorganisms alone. I proposed a revised (yet still conservative) maximal depth of the existence of microorganisms of 75 km instead of previously used 10 km and have considered the deep-focus earthquakes in relation to that. I have considered the possible role of microorganisms both in the atmosphere and subsurface in terms of driving the weather and climate cycles, as well as stated that they should represent an important part of the global electric circuit.

I have analyzed the possibility of extraterrestrial life of producing seismicity on other celestial bodies, as well as the possibility of microorganisms from Earth to colonize other planets in the Solar System. I have discussed the possible evolutionary role of the ultra-deep biosphere and potential evolutionary significance of biogenic earthquake production, as it seems to enhance the gene transfer processes and introduce exchange in biomass between the surface of the crust and layers below, as well as serving the metabolic function. I have considered eletroautotrophy to be the second most important type of autotrophy. I have considered the energy constraints of the ultra-deep subsurface and proposed a few options of overcoming it. I have assumed the existence of ultra-deep subsurface connectivity of remote areas of the planet, facilitated by the networks of microorganisms in fault lines. Lastly, I have considered possible geological implications of the hypothesis.

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