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PCAS 2014-2015 Critical Literature Review

Delving into the deep: uncovering the ecology of subglacial lakes in Antarctica

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Abstract

Beneath the Antarctic ice sheets there is an aquatic subglacial ecosystem which consists of a complex network of subglacial lakes and interconnecting water courses. The possibility of microbial life surviving in extreme environments has led to the direct sampling of several subglacial lakes. To ensure the validity and integrity of results, rigorous risk management planning and clean methods of sampling must be adopted to prevent the risk of contaminating both the samples and the natural biodiversity of these isolated ecosystems. Following the Code of Conduct for the environmental stewardship of these environments and the application of clean sampling methods such as hot water drilling are the safest option currently available. All current and future research projects should be undertaken only after undertaking a detailed risk analysis, and research operators should practise their methodologies on small scale lakes so that they can learn from this baseline information and thus reduce the environmental impacts of their exploration methods.

Introduction

Although water bodies were identified underneath the ice sheets in Antarctica over 40 years ago, it has only been since the 1990s that the use of ice penetrating radar and seismic mapping of the East and West Antarctic ice sheet has revealed a complex network of approximately 400 subglacial lakes and interconnecting watercourses (Christner et al., 2014; Fox, 2014; Kennicutt II and Siegert, 2011, pp. 1; Pearce, 2009; Skidmore, 2011, pp.1). This vast subglacial aquatic ecosystem is thought to be the world's largest wetland ecosystem, making up 9% of the world's land area (Fox, 2014; Meduna, 2014). Subglacial lakes are formed when the bottom of the thick (3-4 km) overlying ice sheet is warmed by the background geothermal heat from the Earth's interior (approximately ~40-70 mW m^{-2}); (Siegert et al., 2012). This, combined with pressure from the weight of the ice sheet, and the inherent insulating properties of the ice, reduces the basal ice melting point despite the extremely cold conditions at the ice surface. Subglacial melt water then collects in subglacial topographic hollows which dictate the size and depth of the lakes (Siegert et al., 2012). Gravitational forces and pressure from the ice sheet may cause subglacial lakes to drain into subglacial streams or rivers, which form an interconnecting aquatic ecosystem beneath the ice sheets (Meduna, 2014; Pearce, 2009; Popov et al., 2011, pp. 46; Siegert et al., 2012; Skidmore, 2011, pp.76).

The largest subglacial lake in Antarctica, and the first to be formally identified in 1996, was Lake Vostok (Bulat and Lukin, 2011, pp, 187; Kennicutt II and Siegert, 2011, pp, 1; Pearce, 2009; Popov et al., 2011, pp, 45; Siegert et al., 2007; Vasiliev et al., 2007). It is situated 4 km below the East Antarctic ice sheet and is approximately 250 km in length; in excess of 500 m deep; and with an estimated volume of 1800 km^3 (Bulat et al., 2011; Kennicutt II and Siegert, 2011, pp, 2; Popov et al., 2011, pp, 45; Siegert et al., 2012). The discovery of the deep nature of Lake Vostok caused scientists to consider the possibility that microbial life could exist there, and marked the beginning of subglacial aquatic environment research (Kennicutt II and Siegert, 2011, pp, 1; Popov et al., 2011, pp, 46; Siegert et al., 2007; Siegert et al., 2012). Antarctic subglacial lake ecosystems are characterised by high pressure; low temperature; permanent darkness; low nutrient availability; and low oxygen concentrations (Bulat et al., 2011; Pearce, 2013). They are therefore considered to be one of the world's most extreme environments (Pearce, 2009).

Recent scientific interest in extremophiles (microorganisms which are found to exist in extreme environments e.g. ice, hydrothermal vents; acids; salt crystals; and nuclear reactors) and the possibility of life surviving in extreme environments, has led scientists to hypothesise that Antarctic subglacial lakes may provide a viable habitat for microbial life to exist, and therefore allow novel phylogenies and physiologies to evolve over time due to the unusual selection pressures and long isolation from the rest of the biosphere (Brito et al., 2012; Christner et al., 2014; Kennicutt II and Siegert, 2011, pp, 1; Meduna, 2014; Pearce, 2009; Pearce, 2013; Popov et al., 2011, pp, 45; Ross et al., 2011, pp, 222; Siegert et al., 2007; Siegert et al., 2012). Thus, subglacial lakes may contain unique assemblages of microbial life that have not been seen before, or they may harbour relic populations of species that have become extinct elsewhere on Earth (Pearce, 2013).

These microbial communities are hypothesised to be chemoautotrophic due to the absence of sunlight and low nutrient availability in subglacial lake environments, and are thought to play a significant role on a global scale through the mobilization of elements from the lithosphere via biogeochemical cycling (Skidmore, 2011, pp, 1). Results from a study of subglacial Lake Whillans suggest that microbial communities might supply iron, for example, to subglacial waters which may eventually reach the ocean (Fox, 2014). This process could provide an important source of nutrients to the iron deficient Southern Ocean ecosystem and thus influence the biological systems there (Christner et al., 2014; Fox, 2014; Pearce, 2013).

Understanding how life functions in Antarctic subglacial lakes will be of direct relevance to our knowledge of the development, limitations on, and evolution of life in other extreme environments on Earth, both in the past and the present, and elsewhere in the solar system (Siegert et al., 2012). An example might be Jupiter's moon Europa, which has a liquid ocean beneath a crust of ice (Siegert et al., 2012).

An additional hypothesis that drives subglacial lake exploration is that some subglacial lake bed sediments may contain valuable paleoclimatic information to be found nowhere else on the continent (Siegert et al., 2012). Such information could enhance the understanding of past changes in the climate and the glacial history of the ice sheets in Antarctica (Bentley et al., 2011, pp, 83; Brito et al., 2012; Kennicutt II and Siegert, 2011, pp, 1; Popov et al., 2011, pp, 45; Ross et al., 2011, pp, 222; Siegert et al., 2007; Siegert et al., 2012). This is particularly important with regard to the West Antarctic ice sheet, the glacial history of which is poorly understood (Siegert et al., 2012). Understanding how current climate change may impact ice sheet stability is critical to assessing the present-day risk of ice sheet collapse and consequent rises in sea level (Siegert et al., 2012). In order to elucidate these hypothesises, and to validate them with sound scientific data, direct in- situ measurement and sampling of subglacial lake environments is required (Siegert et al., 2012). To ensure the validity and integrity of such sampling results, and to preserve the pristine nature of these aquatic habitats, clean methods of exploration and sampling must be adopted in order to minimise environmental impacts, and to prevent the risk of contaminating both the samples and the natural microbial biodiversity of these isolated ecosystems (Christner et al., 2014; Siegert et al., 2012).

The issue of how to protect and conserve the ecological integrity of these systems while exploring them, is of paramount importance, and guidelines on the environmental stewardship and a code of conduct on Antarctic subglacial lake explorations have been established by the U.S. National Academy of Sciences and the Scientific Committee on Antarctic Research (Alekhina et al., 2011). These guidelines and code of conduct aim to encourage researchers to develop methodologies which enable maximum scientific return whilst causing very little impact on the environment (Siegert et al., 2012). I will investigate the current and potential future environmental impacts of subglacial lake exploration through in-situ sampling; the current guidelines/protection measures in place to safeguard subglacial lake environments; and how well these have been adopted and applied during past and current exploration projects. I will make recommendations based on my findings on how undesirable or negative environmental impacts on subglacial lake environments may be mitigated in order to eliminate any risk of damaging these ecosystems, and to preserve the ecological integrity of the microbiological diversity contained within them for now and in the future.

Environmental impacts of Antarctic subglacial lake exploration

Due to their long isolation, subglacial lakes are considered to be pristine ecosystems and therefore opening these systems up for scientific exploration poses a considerable risk of potential contamination to both the habitat, and most significantly, the microbiological diversity contained within them Kennicutt II and Siegert, 2011, pp, 1). The issue of contamination is at the forefront of subglacial lake exploration and is a main driver in determining how sampling is conducted (Brito et al., 2012). In order to access and sample Antarctic subglacial lakes, the overlying ice sheet must first be penetrated and this is achieved through drilling a bore hole. Maintaining a clean drilling operation is vital to preventing contamination of the potential microbial communities that exist below. In order to prevent contamination, boreholes must be drilled using clean drilling methods. This requires that the probe and all its components must be cleaned and sterilised prior to accessing the lake (Brito et al., 2012).

Contamination of a subglacial lake via an ice drilling operation has the potential to introduce exotic species into the pre-existing microbial community, either from the surface or from the ice sheet itself as the drill moves down (Pearce, 2009; Priscu et al., 2013). Introduction of exotic microbial species could significantly alter the community structure; assemblage diversity; and (potentially) the functional role of these communities in the ecosystem (Siegert et al., 2012). The hydrological interconnectivity of the Antarctic subglacial aquatic ecosystem means that any contamination, if it does occur, may not be limited to the one lake (Pearce, 2009). Contamination could have a wide reaching effect on a large geographical scale, with the ecology of many lakes becoming altered as a result. As mentioned previously, this could have wider reaching impacts, especially with regard to the hypothesised contribution these communities are thought to have on biogeochemical cycling and the supply of vital nutrients to the oligotrophic system of the Southern Ocean ecosystem (Fox, 2014). Subglacial lake exploration, therefore, has the potential to cause disturbances to the subglacial habitat which in turn may have the potential to alter the environmental variables, and thus could impact on the survival of microbial communities due to conditions becoming unfavourable for a sustained growth and existence in their present form. Another risk posed by drilling methods is that a blowout might occur, and the resulting depressurisation could lead to high-speed ejection of water and gas from a borehole (Brito et al., 2013). Such an occurrence might cause catastrophic damage to a lake ecosystem by allowing contaminates from the surface to mix with subglacial water (Brito et al, 2013).

Guidelines for the environmental protection of Antarctic subglacial lake ecosystems

Environmental stewardship is the guiding principle of the Antarctic Treaty System (Doran and Vincent, 2011, pp, 149). The recent attempts and future planning of the sampling of Antarctic subglacial lakes has generated a need for stewardship guidelines. Such guidelines are essential for their environmental protection (Doran and Vincent, 2011, pp, 149). In response to a request from the U.S. National Science Foundation, the National Research Council of the National Academies of Sciences (NAS) has created the Committee on the Principles of Environmental and Scientific Stewardship for the Exploration and Study of Subglacial Environments (Doran and Vincent, 2011, pp, 149). The committee produced a report detailing specific recommendations, and also a decision tree and a flow chart to provide a framework for environmental impact assessments with regard to subglacial lake exploration (Doran and Vincent, 2011, pp, 149). This report was based mainly on the Code of Conduct (CoC) for the exploration of subglacial aquatic environments which was formulated by the Scientific Committee on Antarctic Research Action Group (SCAR) (Doran and Vincent, 2011, pp, 149).

The main guiding principle of the CoC is that all research endeavours that involve in-situ sampling of subglacial lakes are expected to proceed in a manner that is consistent with the Protocol on Environmental Protection to the Antarctic Treaty. This protocol, if adhered to, will minimize the risk of possible damage and contamination of existing ecosystems, and will protect their value for future generations, not only in terms of their scientific value, but also in terms of conserving and protecting these pristine environments in perpetuity (Alekhina et al., 2011). Accordingly, prior to any research activity, scientists are required to submit an environmental impact assessment, and if they intend to drill they are required also to fill out an Initial Environmental Evaluation (IEE), and a subsequent comprehensive Environmental Evaluation (CEE) (Alekhina et al., 2011). The CoC also encourages a stepwise approach in which the data, and lessons learned from experience, are documented and used as a guide for future stewardship. This information is made available to all parties involved in subglacial research so that future scientific investigation methods and technological development can be improved (Alekhina et al., 2011).

Methods for clean exploration of Antarctic subglacial lake ecosystems

So far, several international teams have attempted to drill into three of Antarctica's subglacial lakes for the purposes of obtaining direct samples (Meduna, 2014). In order to achieve the aims and objectives of the environmental guidelines for the environmental stewardship of subglacial lake ecosystems, and to ensure the validity and integrity of in-situ sampling results, clean methods of sampling and rigorous risk management planning must be adopted to prevent the risk of contaminating both the samples and the natural biodiversity of these isolated ecosystems (Brito et al., 2012; Christner et al., 2014). The issue of how to protect and conserve the ecological integrity of these systems is paramount and the use of clean sampling methods such as hot water drilling are strongly encouraged. Hot water drilling works by utilising filtered water which is UV treated, and then heated via a heat exchanger before being pumped, at high pressure, through the drill hose. This jets the hot water which then melts the ice in its path (Siegert et al., 2012). This method is currently thought to be the safest and most effective means of obtaining rapid, accurate, and sterile access to subglacial lakes (Siegert et al., 2012).

In 2013 Christner et al. (2014) used hot water drilling methods to penetrate Lake Whillans, which lies beneath 800 m of ice on the Whillans Ice Stream in West Antarctica, and is part of a large and evolving subglacial drainage network (Christner et al., 2014). Christner et al. (2014) followed the guidelines as set forth by the CoC, and as a result obtained the first clean direct samples of subglacial lake water and sediments without contaminating the subglacial lake environment (Christner et al., 2014; Meduna, 2014). This research team discovered a diverse range of microbial life occurring within Lake Whillans (Christner et al., 2014). As these findings were obtained using sterile methods, their scientific validity was sound, thus making these results the first solid evidence to corroborate previous reports suggesting that long periods of isolation have allowed unique assemblages of microorganisms to evolve in subglacial lake ecosystems (Christner et al., 2014). In contrast, the contamination of samples taken from accreted subglacial ice in Lake Vostok which occurred during the drilling, recovery, transportation and analysis of samples, further highlights the importance of clean drilling methods (Christner et al., 2014). Although the subglacial water of Lake Vostok was not penetrated, this outcome raises serious questions over the environmental impacts that a second unaltered drilling operation could have had on the ecological integrity of the microbiological community in the largest subglacial lake on Earth. In order to protect the ecological integrity of Lake Vostok, it would be best to wait until technology associated with access methods is improved and a detailed framework for the evaluation of environmental impact risks is established.

The extreme nature of the Antarctic environment and its relative inaccessibility creates huge logistical challenges for subglacial lake sampling designers and engineers to overcome (Brito et al., 2012). It is therefore logical to expect that, from the outset, designers and engineers should be required to adopt a formal approach for estimating the likelihood of probe failure and contamination (Brito et al., 2012). A study by Brito et al. (2012) proposed that a generic, formal approach should be adopted when managing the operational risks associated with the deployment of probes (if these are required to be used to gain clean access to subglacial lakes during exploration projects). They used the exploration of subglacial Lake Whillans as their case study (Brito et al., 2012). They proposed a novel framework which consisted of integrating a number of techniques. These included the use of a Markvo chain (this being a useful theory for modelling a problem where there is a sequence of events and the probability of an event happening will only depend on the outcome of the preceding trial); fault trees (which are used to determine the probability of faults occurring at different stages of a process and to then assess the potential for such faults to cause the end event to fail); component and subsystem reliability data; and expert judgment (Brito et al., 2012).

Although Markvo chains and fault trees may need to be adapted or refined to meet the specific needs of individual cases, they were still shown to be an effective tool for predicting and managing risks throughout a probing mission (Brito et al., 2012). More studies like this one should be undertaken by all researchers intending to carry out in-situ sampling of subglacial lakes. Such studies will help to refine risk frameworks and thus make them more effective in helping to identify and minimise the potential risk of negative environmental impacts that might arise from intended activities. In addition to screening proposed research projects to identify risk probabilities, another method of reducing the potential environmental impacts on subglacial lakes is to carry out background studies on similar environments in Antarctica. For example, in preparation for the exploration of subglacial Lake Ellsworth, Pearce et al. (2013) first sampled the subglacial sediment from Lake Hodgson, which is a former subglacial lake situated on the fringe of the Antarctic Peninsula Ice Sheet (Pearce et al.,, 2013). This study revealed a high species diversity but low biomass in a biologically active microbiological community (Pearce et al., 2013). Even though Lake Ellsworth has not yet been penetrated successfully, the background preparation and risk management strategies by Pearce et al. (2013) and Brito et al. (2012) respectively, will ensure that when a second probing attempt is made, the mitigation of environmental impacts has been considered carefully and that all proposed procedures comply with the CoC.

Conclusion: *Future recommendations for Antarctic subglacial exploration*

Current understanding of the Antarctic subglacial aquatic ecosystem is incomplete and will only be improved when these environments are entered and sampled in-situ (Kennicutt II and Siegert, 2011, pp, 5). Current and planned projects directed at sampling these environments will inevitably pose a considerable threat to the ecological integrity of the microbial communities within. Advances in technology and improvements to accessibility will mean that more lakes will be exposed to the potential for investigation in the next few years (Kennicutt II and Siegert, 2011, pp, 5). In keeping with the principles outlined by the CoC, it is my recommendation that future studies (where in-situ subglacial sampling is required) should target small subglacial lakes that are close to the edge of the ice sheet. There are several reasons for this:

1) If contamination was to occur, the threat of contaminating other lakes via interconnecting water courses would be significantly reduced;

2) These sites are likely be more accessible and less challenging from a logistical and engineering point of view, and will therefore have lower risks associated with them;

3) Smaller scale studies may provide enough information for scientists to extrapolate the data in order to determine what communities might exist within the larger subglacial lakes (like, for example, Lake Vostok.) This approach might therefore eliminate the need to expose larger ecosystems such as Lake Vostok to the risks of contamination which, if realised, might have the potential to cause irreversible ecological damage to their current functional role in the Antarctic and wider ecosystems.

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