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Time-lapse characterization of hydrothermal seawater and microbial interactions with basaltic tephra at Surtsey Volcano

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Abstract. A new International Continental Drilling Program (ICDP) project will drill through the 50-year-old edifice of Surtsey Volcano, the youngest of the Vestmannaeyjar Islands along the south coast of Iceland, to perform interdisciplinary time-lapse investigations of hydrothermal and microbial interactions with basaltic tephra. The volcano, created in 1963–1967 by submarine and subaerial basaltic eruptions, was first drilled in 1979. In October 2014, a workshop funded by the ICDP convened 24 scientists from 10 countries for 3 and a half days on Heimaey Island to develop scientific objectives, site the drill holes, and organize logistical support. Representatives of the Surtsey Research Society and Environment Agency of Iceland also participated. Scientific themes focus on further determinations of the structure and eruptive processes of the type locality of Surtseyan volcanism, descriptions of changes in fluid geochemistry and microbial colonization of the subterrestrial deposits since drilling 35 years ago, and monitoring the evolution of hydrothermal and biological processes within the tephra deposits far into the future through the installation of a Surtsey subsurface observatory. The tephra deposits provide a geologic analog for developing specialty concretes with pyroclastic rock and evaluating their long-term performance under diverse hydrothermal conditions. Abstracts of research projects are posted at http://surtsey.icdp-online.org.

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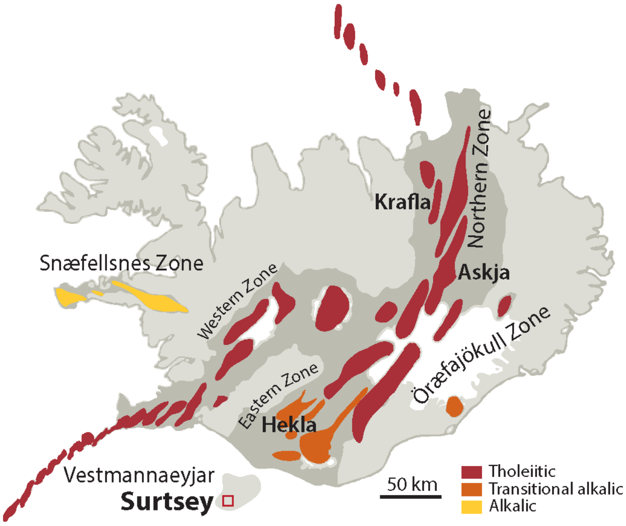

Figure 1. The location of Surtsey Volcano within the southernmost extension of the Eastern Icelandic rift zone (scale bar of 50 km; after Trønnes, 2002). Colors refer to compositional trends in basaltic rocks (Jakobsson et al., 2008).

Figure 2. Surtsey Volcano in eruption, 30 November 1963 (Terry Mann, courtesy of Robert Carson).

1 Introduction

The very young volcanic island of Surtsey, which formed over a 3.5-year episode of eruptions along the southern offshore extension of the SE Icelandic volcanic rift zone (Figs. 1, 2), represents a world-class example of a rift zone volcano that has grown from the seafloor in historic time. The Surtsey eruption was thoroughly documented beginning in November 1963, when a plume of ash first broke the sea surface, until the termination of subaerial lava flow activity in June 1967. Surtsey was designated a UNESCO World Heritage site in 2008 and "has been protected since its birth, providing the world with a pristine natural laboratory" for study of earth and biological processes (Baldursson and Ingadóttir, 2007). An International Continental Drilling Program (ICDP) workshop on Heimaey Island in October 2014 convened 24 scientists from 10 countries and representatives from the Surtsey Research Society, who developed the scientific objectives of the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and INnovative Concretes (SUSTAIN) drilling project (Jackson, 2014). The project will include the eventual installation of an in situ Surtsey subsurface observatory for monitoring hydrothermal microbial life and changes in the physical and compositional properties of associated hydrothermal fluids, which will complement the 50 years of observations of plant and animal life on the surface of Surtsey.

The 181 m deep hole drilled within the eastern tephra cone in 1979 (Fig. 3a) was sponsored by the US Geological Survey and the Icelandic Institute of Natural History. It has provided well-constrained information about the substructure and stratigraphy of the volcano, as well as the nature of its hydrothermal system, which continues to be manifested by steam vents at the surface (Jakobsson and Moore, 1986, 1992; Jakobsson et al., 2013). Investigations of the core and downhole temperature measurements described the petrologic characteristics of the basaltic tephra, partially altered to palagonite tuff, the thermal conditions and nature of hydrothermal alteration, and the authigenic mineral growth of a rare aluminous calcium-silicate-hydrate and zeolite mineral assemblage above and below sea level (Fig. 3b). These minerals, Al-tobermorite and phillipsite, have cation exchange capabilities for certain radionuclides and heavy metals and have been the focus of laboratory syntheses of concretes for hazardous waste encapsulations (Komarneni and Roy, 1983; Komarneni, 1985; Trotignon et al., 2007; Cappelletti et al., 2011; Coleman et al., 2014). In the SUSTAIN drilling project, time-lapse investigations of dynamic secondary mineral assemblages in the altered tephra deposits will yield information from a geological analog for the long-term performance behavior of specialty concretes formulated with pyroclastic rock. The results of these investigations will advance technological developments initiated by ancient Roman engineers, who developed pozzolanic concretes with this same mineral assemblage that have maintained their integrity despite centuries-long exposure to seawater (Brandon et al., 2014). A recent study of hot fluids in the 1979 drill hole (Fig. 3b) has identified for the first time potentially indigenous thermophilic bacteria and archaea deep in the center of an isolated Neogene volcanic island (Marteinsson et al., 2015). In the SUSTAIN project, studies of microbial colonization of the altered subterrestrial tephra and hydrothermal fluids could provide new insights into archaeal lineages in the very young biosphere and, possibly, contribute to understanding the nature of the archaeal ancestor of eukaryote organisms (Spang et al., 2015).

Two holes through the 50-year-old deposits, designed in collaboration with the Icelandic National Planning and Environment Agencies to protect the sensitive habitats of the Surtsey Natural Reserve, will be drilled at a site within ∼5 m of the 1979 hole (Fig. 3a). A vertical drill hole, ∼210 m deep, will explore pore water chemistry, microbiology, and microbiological–water–rock interactions and compare the present state of hydrothermal alteration with that in the 35-year-old drill core. The hole will be cased with anodized aluminum for future Surtsey subsurface observatory studies. A ∼300 m long inclined hole with steel casing will intersect tephra deposits, dikes and other vent facies beneath the crater; provide additional information on deep stratigraphy and submarine structure below the 181 m depth of the 1979 hole; and investigate the changing temperatures and the compositions of whole-rock, glass and mineral assemblages of the hydrothermal system. Slim-hole logging sondes will be deployed from a motorized winch to the base of the holes at 200–300 m depth. Sensors will acquire equilibrated temperature measurements, total natural gamma to log lithological variations; electrical resistivity and self-potential to show variations in fluid salinity and influences of alteration processes; and sonic P-wave velocity and magnetic susceptibility to show possible variations in compaction, alteration, and authigenic mineralogy. Core segments from the inclined hole will be oriented to ±1° of azimuthal accuracy to further evaluate the internal structure, stratigraphy, composition and mineralogy of the volcanic edifice.

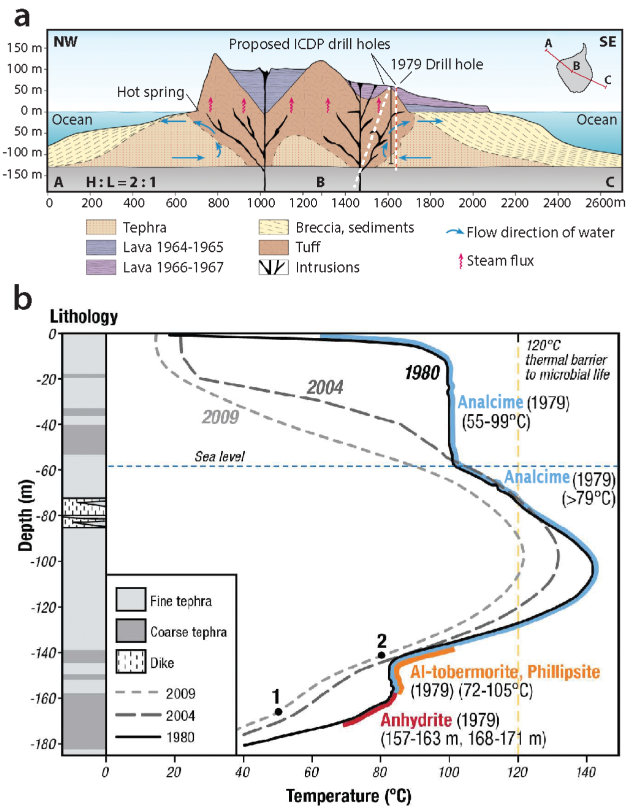

Figure 3. Hydrothermal alteration of Surtsey deposits (after Jackson, 2014). **(a)** Schematic cross section (Jakobsson et al., 2009) shows inferred feeder dikes, palagonitization of basaltic tuff in 2004, the 1979 drill hole, and the two planned ICDP drill holes. **(b)** Temperatures in the 1979 hole. Lines adjacent to the 1980 curve show greatest abundance of authigenic analcite (blue), Al-tobermorite and phillipsite (orange), and anhydrite (red). Downhole water sampling in 2009 and microbiological analyses reveal diverse subterrestrial bacterial sequences and *Methanobacteriales*blackbox[CE]Please note that when written individually only the "genus" devision names withing the taxonomic clasification system are italicized, it seems that Methanobacteriales refers to an "order" of the system. For future reference, does Methanobacteriales fall under a different set of taxonomy and nomenclature rules?-like archaeal sequences at 172 m (54 °C) (site 1) and an archaeal community dominated by *Archaeoglobus*-like 16S rRNA sequences at 145 m (80 °C) (site 2) (Jakobsson and Moore, 1986; Olafsson and Jakobsson, 2009; Marteinsson et al., 2015).

2 Workshop goals

The SUSTAIN drilling project will use the natural laboratory of the Surtsey tephra above and below sea level, and interdisciplinary volcanological, microbial, geochemical, mineralogical, and geoarchaeological research programs to undertake scientific investigations situated within the larger ICDP research themes of the evolution of hydrothermal seawater–rock interactions in rift zone volcanism, the succession of early microbial life, and the development of industrial resources, using the alteration processes of palagonitized tuff as models for creating sustainable, high-performance concretes with pyroclastic rocks.

2.1 Subaerial and submarine structures of the type locality of Surtseyan volcanism

Descriptions of the episodic eruptions at Surtsey from 1963 to 1967 provide the most comprehensive record of Surtseyan-style emergent volcanic activity and island rift zone volcanism in the world (Thórarinsson, 1967). Questions remain,

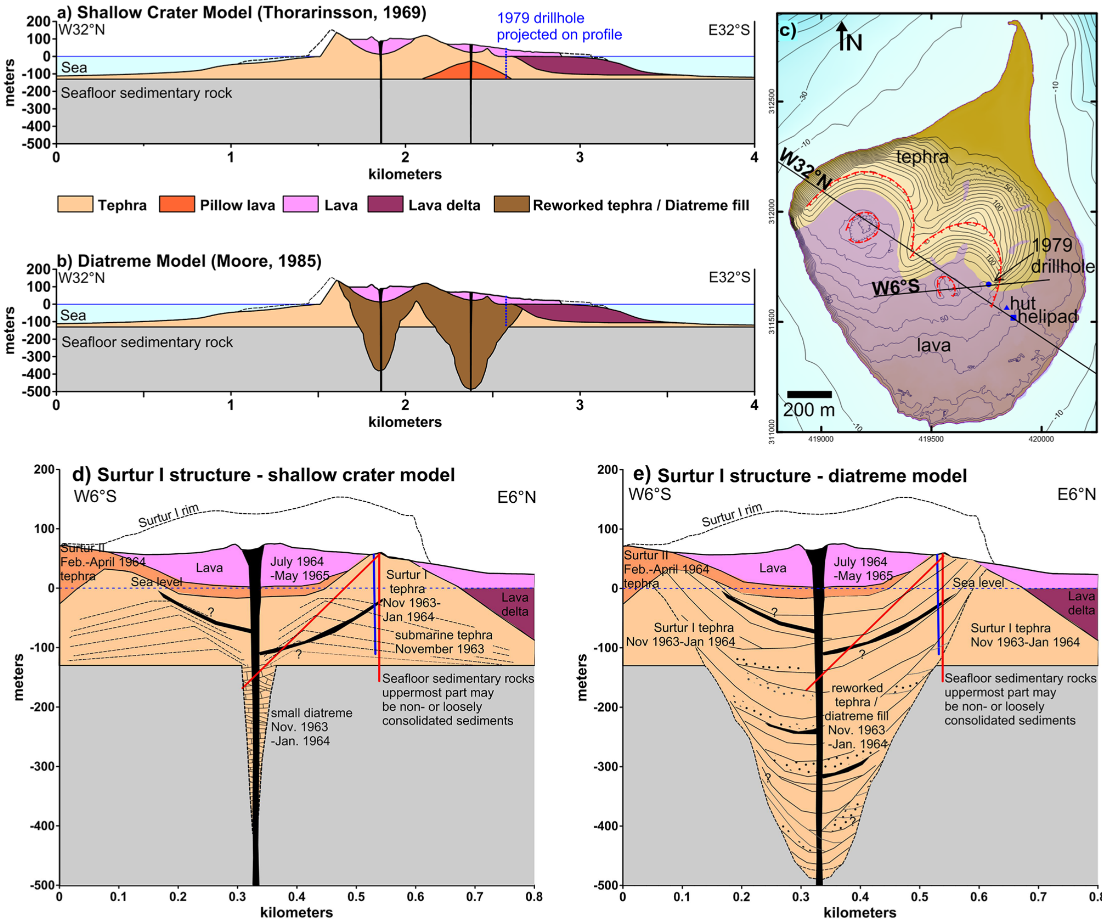

Figure 4. Structural models of Surtsey, showing the shallow crater hypothesis **(a, d)** (Thórarinsson, 1969) and the diatreme hypothesis **(b, e)** (Moore, 1985). Red lines on **(d)** and **(e)** show the planned drill holes. Although the occurrence of a layer of pillow at the bottom of the formation cannot be ruled out (model shown in **a**), no pillow mound is included in **(d)** as neither was it detected in the 1979 drill hole nor in gravity modeling (Thorsteinsson and Gudmundsson, 1999). The geological map of Surtsey **(c)** shows the helipad, the Pálsbær II hut, and 1979 drill site.

however, about the earliest submarine part of the edifice, which was not observed during initial studies of the volcano (Fig. 4). The role of seawater interaction with hot magma and temporal variations in magmatic volatile content in driving subaerial explosive eruptions will also be investigated. New drilling will clarify Surtsey's early history and submarine structural anatomy and provide interdisciplinary perspectives into explosive eruptive processes and how volcanic facies, structural discontinuities, pyroclast size and vesicularity provide a template for hydrothermal fluid flow, heat transfer, diagenetic and biogenetic alteration processes, and temporal changes in porosity and rock physics properties.

2.2 Fluid geochemistry and microbial colonization of subsurface deposits

Surtsey is an isolated oceanic island that has provided an exceptionally well-monitored laboratory of world-wide significance for the investigation of biological colonization and succession on and in basaltic tephra deposits. Furthermore, the temperature range recorded in the 1979 hole (Fig. 3b) is ideal for studying the extreme temperature conditions of chemosynthetic life. A subsurface biome comprising bacteria and archaea has recently been observed in fluids extracted from the 1979 hole below 145 m depth (Fig. 3b). This subsurface microbial community is quite possibly indigenous, since it occurs below a >120 °C thermal barrier at 100 m depth that prevents the downward dissemination of surface organisms (Marteinsson et al., 2015). Microbial colonization has been recognized as one of the primary drivers of alteration in ridge crest seafloor basalts and has important implications for global element budgets, seafloor and seawater exchange, and biogeochemical cycles (Thorseth et al., 2001; Furnes et al., 2007; Santelli et al., 2008; Edwards et al., 2012). Investigating the nature and extent of the subseafloor biosphere has become an important scientific goal of research programs, including the International Ocean Discovery Program (IODP). It is, however, exceedingly difficult and costly to investigate these processes through drilling at depths of oceanic ridge systems. Drilling into Surtsey's active hydrothermal system will provide a new window into the subterrestrial biome at relatively low cost and in an exceptionally well-constrained drill site that already has a proven record of success. The subseafloor pressure at the Surtsey subsurface observatory at < 0.2 km depth will be lower than that typical of the neovolcanic zone of mid-ocean ridges at ~ 2.5 km depth. This means that more phase separation (boiling) can occur in this shallow environment at temperatures relevant to microbial metabolism. Because many of the energy-rich substances capable of supporting autotrophic life (e.g., H_2, H_2S, CH_4) partition into the vapor phase, we may expect to see higher redox gradients and more spatial diversity in microhabitats in this environment compared to those that could be investigated on the ridge crest.

2.3 Evolving hydrothermal processes and tephra alteration

Comparisons of new cores with the 1979 core and original samples of the newly erupted deposits will give precise information about the time-integrated evolution of fluid–rock interactions. These include the alteration of basaltic glass to form palagonite, at variable temperature and fluid chemistry, and associated secondary mineral nucleation and growth (Fig. 3a). Palagonite is a metastable alteration product of fresh basaltic glass that has interacted with aqueous solutions and lost Si, Al, Mg, Ca, Na and K, gained H_2O, and become preferentially enriched in Ti and Fe (Stroncik and Schmincke, 2002). Recent compositional analyses of the Surtsey magma series provide a reference for the original compositions of these deposits (Schipper et al., 2015). The ongoing hydrothermal alteration and lithification of tephra has great relevance to the longevity of the island since it is the progressive formation of palagonitized tuff, rather than capping lavas, that provides resistance to incessant marine erosion (Moore et al., 1992; Jakobsson et al., 2013). The Surtsey hydrothermal system is one of the few localities worldwide that is actively producing an authigenic Al-tobermorite and zeolite assemblage (Jakobsson and Moore, 1986). Tobermorite, $Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$, with 11 Å c axis interlayer spacing is formed by the action of hydrous fluids on basic igneous rocks, such as the amygdules in Paleogene lavas in contact with hydrothermal fluids on the Island of Skye, Scotland (Livingstone, 1988). It also occurs among the alteration products at the cement–rock interface of toxic and nuclear waste repositories (Gaucher and Blanc, 2006). It is a candidate sorbent for nuclear and hazardous waste encapsulation owing to its ion-exchange behavior which arises from the facile replacement of labile interlayer cations (Coleman et al., 2014). Al-tobermorite and phillipsite also occur as the principal cementitious mineral phases in the volcanic ash–lime mortar of ancient Roman concrete harbor structures. These mortars bind zeolitic tuff and carbonate rock coarse aggregate in piers, breakwaters, and fish ponds that have remained stable in Mediterranean seawater for 2000 years (Jackson et al., 2013a, b). Little is known, however, about how hydrothermal chemistry and phase-stability relationships in Al-tobermorite and zeolite mineral assemblages evolve as a function of time, temperature, fluid interactions, and microbial activity. The new cores will therefore provide a real-time geologic analog for understanding the evolving microstructures and macroscopic physical properties of tuff and sustainable concrete prototypes with pozzolanic pyroclastic rocks under the variable hydrothermal conditions of the engineered barriers of waste repositories.

3 Characterization of the 50-year-old deposits

The collaborative research investigations to be undertaken by the scientific team of the SUSTAIN drilling program focus on three ICDP research themes: volcanic systems and geothermal regimes, the geobiosphere, and natural resources as applied to pyroclastic rock concretes in the sustainable built environment.

3.1 Anatomy of 1963–1967 Surtsey deposits and eruptive processes

The subaerial tuff cones of Surtsey are constructed from deposits produced by intermittent tephra-finger jets and from continuous uprush eruptions. Continuous uprush lasted for several minutes to several hours and produced eruption jets 100–250 m in diameter and 500–2000 m in height forming up to 9 km high eruption columns (Thórarinsson, 1967). The new drill holes should clarify whether the lower part of the edifice contains a mound of submarine pillow lavas (Fig. 4a) (Thórarinsson, 1967) or tephra (White and Houghton, 2000) that preserves the initial submarine depositional phase of the eruption, or a deep funnel filled with slumped and downfaulted subaerial deposits (Fig. 4b) (Moore, 1985). We can therefore test which of two contrasting models best represents the true structure of the island: the shallow crater model (Fig. 4a) (Thórarinsson, 1967; Jakobsson and Moore, 1992; Jakobsson et al., 2013) where any diatreme that may have formed is narrow, leaving the pre-eruption seafloor relatively intact underneath the volcanic edifice, or the diatreme model (Fig. 4b) (Moore, 1985) that has wide, funnel shaped, tephra-filled diatremes that extend a few hundred meters into the pre-eruption seafloor. The new oriented cores should help us define these volcanic structures. For example, do the primary layering and pre-solidification slump planes dip steeply inward toward the vent of the volcano (Fig. 4e) as observed in unoriented cores from the 1979 drill hole (Moore, 1985) or do beds dip gently outward away from the vent (Fig. 4d) as suggested by a shallow crater model? Deepening of the inclined hole may resolve the disparity in the two models regarding the width of the subseafloor diatreme structure and may possibly intersect the outer wall of the diatreme if it is sufficiently narrow. Analyses of core from the inclined hole should also provide information about how the onset of fragmentation, submarine transport of tephra, and deposition in the submarine environment differs from what is represented in subaerial deposits. The extent to which Surtsey's activity was predominantly phreatomagmatic, versus the degree to which it involved substantial volatile-driven magmatic explosivity has important implications for predicting potential hazards to air traffic from future Surtseyan-type eruptions. These processes can be clarified with rigorous analysis of deposits (e.g., Schipper et al., 2010, 2015) combined with experiments using remelted material from the island (Büttner et al., 2002).

3.2 Monitoring hydrothermal processes 50 years after the Surtsey eruptions

The current model for Surtsey's hydrothermal system hypothesizes that cooling of dike intrusions in the eruptive centers of the eastern and western craters (Stefansson et al., 1985) provides the heat to drive hydrothermal convection, which results in palagonitization of the tephra and induration of the core of the island (Fig. 3a). The high heat of vaporization of water means that significant heat transfer occurs isothermally by release of steam through the tephra pile, as indicated by the isothermal (100 °C) portion of the temperature profile measured in 1980 before the well bore filled with water (Fig. 3b). The new cores will further clarify the extent and nature of the intrusive system and how early residual heat in the tephra might have influenced hydrothermal processes. New studies of the cooling hydrothermal system, the roles of meteoric water and tidal flux, salinity, pH, sulfur cycling, and possible microbial oxidation of iron in both new holes will further elucidate water–rock interactions, and the progressive palagonitization and consolidation of glassy basalt deposits through abiotic and/or biotic processes (Walton, 2008; Pauly et al., 2011). Determination of rates of reaction and phase-stability relationships in the evolving Surtsey tuff as a function of time, temperature, and fluid interactions will provide an exceptionally well-constrained geological analog for innovative, pyroclastic rock concrete encapsulations of hazardous wastes that use ancient Roman concrete as a prototype (Jackson et al., 2013b). The formation of Al-tobermorite and phillipsite in massive Roman seawater concrete harbor structures is in part controlled by elevated temperature that arises during formation of poorly crystalline calcium-aluminum-silicate-hydrate (C-A-S-H) cementitious binder due to exothermic reactions, but these processes are poorly understood (Jackson et al., 2013a). The ion-exchange selectivity of the 11 Å tobermorite and zeolitic mineral assemblages for Cs^+ and Sr^{2+} will be determined experimentally on samples of Surtsey tuff at certain critical horizons (Fig. 3b) (Cappelletti et al., 2011; Coleman et al., 2014). The changes in macroscopic rock physics and mechanical properties, such as strength and elastic moduli, that these rock–fluid interactions produced in the pyroclastic deposits will also be investigated (Vanorio and Kanitpanyacharoen, 2015). These processes have implications for the larger-scale stabilization of the Surtseyan-style volcanic edifice against erosion, including subglacial edifices formed in eruptions under ice (Jarosch et al., 2008).

3.3 Active microbial processes and fluid geochemistry

In recent years the deep biosphere has been shown to be an immense habitat for microbial life, and these findings have wide reaching implications for global geochemical cycling (Orcutt et al., 2011). Although there is increasing exploration of the deep biosphere, mainly due to advances in drilling technologies and underwater equipment, one fundamental environment remains unexplored: the "zero age" upper crust. This province is exceptionally interesting since it is here that the first microbial colonization and interaction with basaltic rocks takes place. Exploration of the microbial colonization of Surtsey tephra could therefore give otherwise unavailable insights into the origins of rock-dwelling microorganisms. The diversity, abundance, and function of potentially endemic communities of microorganisms will be analyzed by DNA extraction and next generation sequencing of metagenomes and 16S rRNA genes. The functioning of the microbiome will be investigated by transcriptomic analysis and strain isolations (Marteinsson et al., 2015).

Assessments of the geochemical composition of hydrothermal seawater, reaction progress associated with water–rock–microbiological interaction and inorganic chemical energy available in the hydrothermal system, will be combined with equilibrium reaction models to describe affinities for chemosynthesis and tephra alteration and provide constraints on the potential energy available for microbial metabolism. The design of the Surtsey subsurface observatory is similar to that of observatories installed during recent IODP expeditions (Fisher et al., 2011; Edwards et al., 2012). After drilling, incubation chambers (e.g., Toner et al., 2013) will be deployed inside slotted sections of the aluminum casing to facilitate further microbial, geochemical and hydrological studies in isolated sections of the drill hole above sea level (< 60–70 m below the surface (mbs) at the drill site), in the highest temperature regime (70–140 mbs), and below the high temperature regime (> 140 mbs) (Fig. 3b). The new studies of potentially indigenous subsurface microbial life in the vertical hole will be the first systematic, longitudinal study of microbial colonization of an isolated neovolcanic island at successive depths from the surface to the seafloor.

Participants of the ICDP SUSTAIN workshop

The drilling project collaborators and science team, as well as abstracts describing scientific objectives, are posted at http://surtsey.icdp-online.org.

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