General Report:
Lewis & Clark Fund Grant *and* Early Career Collaboration Award
to
Dr. Roy Price, currently at SUNY Stony Brook, SoMAS, New York; formerly at University of Southern California, Los Angeles, California (at time of L&C grant only).

[This report is a summary of activity relating to the Lewis and Clark Fund Grant, and subsequently the Early Career Collaboration Award, received by Dr. Roy Price in order to investigate alkaline *shallow-sea* hydrothermal vents as analogs to early Earth environments important for origin of life.]

Background and Objectives

On June 4th, 2012, Price received grant approval for his proposal "*Expanding frontiers for origin of life research: Serpentinite-hosted shallow-sea hydrothermal vents*". The goal of this research was to travel to New Caledonia (South Pacific) to collect samples from the Prony Hydrothermal Field (PHF), a shallow-sea vent site with a 38 m carbonate hydrothermal edifice and active alkaline venting, similar to the Lost City Hydrothermal Field (LCHF), off-axis mid-ocean ridge. As pointed out in the proposal, the PHF and LCHF may be analogous to early-Earth serpentinizing environments where abiogenesis – the long ago switch from abiotic to biotic processes – may have occurred. Research of submarine, alkaline, serpentinizing hydrothermal systems has thus far been limited to the Lost City, and thus there is a fundamental lack of information for these important environments. Unfortunately, after receiving the funds, Price had difficulties in obtaining a sampling permit for collecting samples from the New Caledonia site. Unknown to him, a group of French scientists had started similar work to what was proposed. Due to overlap with thier research objectives, the permit was denied, and Price began negotiations with them to collaborate on another NASA-funded New Caledonia project focusing on aspects not being considered. At this point Price asked permission to switch the L&C funding to another, similar and perhaps more important, field site – the Strytan Hydrothermal Field (SHF), located in Eyjafjord, northern Iceland. Due to similarities between the two shallow-sea vent sites, we anticipated no significant changes in our sampling/analysis objectives, only a change in the location of the field site. For example, both sites exhibit very similar geochemical characteristics when compared to the Lost City, such as the discharge of a reduced, alkaline (pH ~10-11), warm (30-75 ºC) hydrothermal fluid, which mixes with surrounding seawater to precipitate 35-55 m high porous mineral towers. Permission was granted, and the funds from the Lewis and Clark research grant were combined with funds already received from the National Science Foundation (CDEBI), and an expedition took place in July 2013.

Subsequently, progress was made with the French research team (called "HydroProny"), and Price submitted an Early Career Collaboration award proposal, which would allow him to travel to New Caledonia and begin the collaborative efforts with the HydroProny group. That proposal was granted, and an expedition took place in April/May 2014.

The objectives for each of these expeditions were to collect and analyze hydrothermal fluids and precipitates for geochemical characteristics in the context of the NASA Astrobiology roadmap, particularly the first three major Science Goals: (1)

understanding the nature and distribution of habitable environments in the universe, (2) exploring for habitable environments and life in our own Solar System, (3) understanding the emergence of life.

Progress update for the Lewis and Clark Award

[The following text is from a manuscript in prep. All methods, tables, figures and most interpretations have been left out of this summary report. It is anticipated that the manuscript, currently entitled, "Low temperature alteration of basalt and H_2 / CH_4 production in a ridge-flank hydrothermal system: the shallow-sea, alkaline, Strytan Hydrothermal Field (SHF), Eyjafjördur, Iceland" will be submitted by the end of 2014.]

Sampling

An expedition to the Strytan Hydrothermal Field took place July 2013. The primary purpose of this study was to evaluate the geochemical signatures at the site that may result from low temperature 'serpentinization' of basalts, particularly H_2 and CH_4 concentrations and an evaluation of $\delta^{13}C$ of the CH_4 to evaluate biogenic vs. abiogenic production of CH_4. Preliminary samples for microbiology were also taken. Funding from the L&C were used entirely for supporting the SCUBA diving operations through the Strytan Diving Center. Additional logistical and scientific funds were obtained from the NSF Center for Deep Biosphere Interactions (CDEBI).

There are two main areas where cones and hydrothermal venting are present in Eyjafjord, and are referred to as "Arnarnesstrytan" and "Big Strytan" (Figure 1). Big Strytan was the first to be discovered, and is so called because of the presence of a very large cone, reaching up to 55 m height from the seafloor. There are series of other cones in the area of the Big Strytan, but our sampling only took place on the largest cone. Arnarnesstrytan is located north of Arnarnes, a small spit on the west side of the fjord. The system is comprised of several hydrothermal chimneys or clay-stacks forming a 500 m long line trending approximately north-south. Many individual and overlapping chimneys rise up to 10 m above the seafloor (Gautason et al., 2005). Another site, off of the island of Hrisey, which consists of hydrothermal fluid venting through horizontal cracks in basalt rocks with no cone development, was also sampled (Figure 2A). Abundant microbial mats were present where the hydrothermal fluids came into contact with overlying rocks.

During the second dive on July 9th at Arnarnesstrytan, Scuba divers noticed that, for unknown reasons, a small (~70 x 30 cm) cone was broken off, at approximately 20m water depth. Two days before, the cone was intact (Erlendur Bogason, pers. comm). We collected the cone for both microbiological and geochemical analyses, and this site was designated "A1". Subsequently, fluids were collected from the broken off area where the cone once existed. Site A2 was on a near-by large cone with significant fluid venting, and at a shallower depth (~12 m). Sites S1 and S2 were located on the biggest cone at Big Strytan (Figure 3B). S1 was located at ~24 m depth, on the rope side of the cone, to right of a blue rope used as a guide, and was a "big" vent, which has a focused vent opening of ~2" diameter. S2 was located above S1, at ~19 m depth. A single dive took place off the northeast point of the island Hrisey, and samples were taken for geochemistry using syringes. Seawater was sampled for background geochemistry directly out from the Strytan Dive Center.

Results

Geochemistry

In total 5 sites were sampled for hydrothermal fluids during the expedition. Two from the Big Strytan area (S1 and S2), two from the Arnarnesstrytan area (A1 and A2), and one from Hrisey Island (H1). Temperatures ranged from 66.6 to 78.1°C, with the highest temperature measured at the A2 site. Hrisey temperatures measured 67.4°C, while the A1 and A2 sites were 66.6 and 78.1 °C, and the S1 and S2 sites were 72.1 and 73.4 °C, respectively. Various other temperature measurements where fluid samples were not taken fall within this range. The pH of the fluids at Hrisey ranged from 9.16 to 9.37, while the range for A1 (9.6 to 9.86), A2 (9.83 to 10.08), S1 (10.14 to 9.79), and S2 (9.91 to 10.22), all fall within a narrow range of values. The ambient seawater temperature was approximately 7 °C, and the pH was 8.12, and variability in both temperature and pH should be affected by seawater entrainment during sampling (i.e., a decrease in temperature and increase in pH should accompany seawater mixing). Thus, these values should be taken as minimum, relative to the deeper hydrothermal reservoir fluids.

Oxidation-reduction potential (ORP), which is the activity of all oxidizers and reducers in the solution relative to a platinum electrode (Myron-L meter), were always negative for samples from Arnarnesstrytan and Big Strytan (-76 (A2) to -160 (S1)), and positive for Hrisey (+103 to +156). A negative ORP indicates the ability to donate electrons; the higher the negative charge, the greater the ability to provide electrons and the more reducing the fluids. Thus, hydrothermal fluids from the SHS in general are highly reducing. Seawater ORP measured +217, and thus it is possible that the Hrisey site has mixed with oxidized seawater, either during or prior to sampling, or that the shallow-circulating source fluids are more oxygen-rich compared to the cone systems. Hrisey Island is very small, and it is thus likely that the fluids circulating through the system have not had adequate time to become reducing, and are still oxygen-rich.

Using TDS as an estimate of salinity, it is clear that the hydrothermal fluids from all sites, including the Hrisey site, were very dilute compared to seawater. For example, seawater TDS was 36450 ppm, while the range for the hydrothermal fluids were as follows, also in ppm: A1 (527 to 5758), A2 (305 to 3367), S1 (464 to 3781), S2 (300 to 2430), and Hrisey (1990 to 5106). Previously, Marteinsson et al. (2001) indicated that the Big Strytan fluids were primarily derived from meteoric water with low concentrations of major seawater salts and $\delta^{18}O$ and $\delta^{2}H$ ratios nearly identical to local precipitation. Our data agree with this evaluation, and it is likely that not only the Big Strytan site, but also the Arnarnesstrytan and Hrisey sites are derived from local meteoric water which penetrates through the ground, is heated up, and discharges into the fjord.

Sulfide measurements indicate low but significant concentrations, which at pH 9-10 is probably in the form HS^{-} and/or the completely deprotonated form S^{2-}. Hrisey concentrations were lowest, ranging from 0.1 to 0.5 μM, while A1 and A2 (6.5 to 7.6 and 7.2 to 9.8 μM, respectively) and S1 and S2 (11.9 to 12.5 and 11.9 to 12.4, respectively) were much higher. Note that concentrations at Arnarnesstrytan versus Big Strytan were consistently lower.

Typically, all major seawater elements correlate along a mixing line between seawater and the hypothetical hydrothermal end-member, close to a zero-salt meteoric water. Calcium is the only element among this suite that seems to be slightly different for the Hrisey samples. Even though the TDS measurement of our seawater values were near what is expected for typical seawater (e.g., ~35000 ppm), our major element concentrations are consistently approximately 40% lower than the IAPSO seawater standard. This could be due to 1) analytical error, and/or 2) groundwater discharge at the site of collection. Given the wet conditions in the area, the latter is certainly possible. Thus, seawater major chemistry from our sample should be taken with caution.

Of the elements analyzed in this study, Na, Mg, K, Ca, Cl, Br, B, and Sr all more or less correlate with one another, falling on a mixing line with seawater concentrations of these elements. Another trend, however, is observed in most of the trace elements (e.g., Si, Al, As, V, Mo, W, and although less clear, Cr, Cu, and Zn). These relationships are almost certainly controlled by the solubility of minerals contained within the Icelandic basalts. For example, predicted (quartz) silica solubility at ~75 °C is around 1.5 mM. Our samples are slightly higher than this value, suggesting a higher reservoir temperature. These data are currently undergoing a more in-depth synthesis.

Organic acid analyses included lactate, acetate, formate, propionate, butyrate, and valerate. Of all these, propionate was the only one consistently elevated in concentration in hydrothermal fluids. All measurements of these organic acids in seawater were below detection. No patterns were observed versus site and/or other geochemical parameters, although the highest concentrations of propionate were in the lowest TDS samples, suggested a deeper, hydrothermal source. DIC concentrations ranged from 0.2 to 0.8 mM, while seawater values were greater than 1.4 mM. This suggests that DIC is quite low in the hydrothermal fluids.

Dissolved gases CH_4, H_2, and CO were measured in hydrothermal fluids. While low, generally the concentrations of CH_4 and H_2 were elevated compared to normal seawater values. The carbon isotopic signature of the CH_4 as a function of CH_4 concentration suggests the possibility that some of the CH_4 has an abiotic origin. The abiotic production of CH_4 (and H_2) in this basalt-hosted system is intriguing, as it broadens the range of potential origin of life environments significantly.

Microbiology

There are two sets of microbiological data: 1) 16s rRNA clone library classifications, and 2) intact polar lipid analysis results. Lipids indicated both Archaea and Bacteria were present, although Bacteria dominated all samples (excluding H1) with the exception of S1. Up to 50% of the lipids at S1 site were archaeal. This site was the most focused vent, and therefore could be bringing up deeper subsurface Archaea. Abundant lipids included "PC" and tetraethers (GDGTs). The lipid 'PC' is found in many alpha- and gamma-proteobacteria, as well as in some gram positive and Bacteroides-Flavobacteria. Tetraethers (GDGTs) are abundantly present in different archaeal kingdoms.

Due to the patterns represented by the lipids (e.g., S1 dominated by Archaea), clone library synthesis has to date focused on sites S1 and A2 due to their similar temperature regimes. No clear differences in clone libraries could be made, however, between sites. Bacterial sequences were dominated by betaproteobacteria, particularly the genus *Dechloromonas sp.* This organism is a soil microbe known to conduct dissimilatory perchlorate reduction as well as denitrification ((i.e. the reduction of nitrate to N2) combined with the oxidization of aromatic compounds (NCBI Blast results). Deltaproteobacteria were the second most dominant group, particularly the genus *Desulfovibrio sp.* a sulfate reducer commonly found in aquatic environments with high levels of organic material, and which are major community members of extreme oligotrophic habitats such as deep granitic fractured rock aquifers. Archaeal results indicate a dominance of Crenarchaeota. Particularly, Thermoproteales, which are typical acidophiles found in Icelandic sulfataras that form H_2S and CO_2 from elemental sulfur and organic substrates. The second most dominant archaeal group was Desulfurococcales, which are Ignicocci with optimum growth temperatures of 90°C. This group can reduce elemental sulfur to hydrogen sulfide using molecular hydrogen as the electron donor (Huber et al., 2002). A unique symbiosis with (or parasitism by) nanoarchaea has also been reported (Huber et al., 2002).

For comparison, both preliminary cultivation- and molecular-based microbiology were conducted by Marteinsson et al. (2001). Among 50 thermophilic isolates, most identified with *Bacillus sp.,* although often <97% identification (ID<97% is generally taken to define a new species. One member of the Archaea, *Desulfurococcus mobilis*, was also identified from the interior of the chimney, which agrees with our results. On the outside of the chimney *Thermonema sp.* were identified. 16S rRNA genes PCR amplified and cloned directly from environmental DNA showed that 41 out of 45 bacterial sequences belonged to members of the Aquificales, whereas all of the 10 Archaea sequences belonged, intriguingly, to the Korarchaeota. Relatives of many of the *Bacillus* species are found in Icelandic on-land hot springs, but some new, unidentified species with a low G-C content were also isolated, which were most similar to the microbial flora from the deepest sea muds from the Mariana Trench (Marteinsson et al., 2001; Takami et al., 1997).

Future Objectives

The future objectives for this L&C funded work include completion of the geochemistry manuscript, and further data gathering for the microbiological characterization of the system. The microbiological data are currently being collected and synthesized by colleagues Jan Amend and Brandi Kiel Reese at the University of Southern California. It is anticipated that data collection will be completed by the end of the year, with submission of a microbiology manuscript early in 2015. It is absolutely clear that this Lewis and Clark grant will provide significant publishable results, along with seed data for submission of a larger proposal.

Progress update for the Early Career Collaboration Award

As stated previously, funding was received from the ECC award for geochemical sampling at the Prony Hydrothermal Field (PHF), New Caledonia (Figure 2). Shortly after returning from the expedition, which took place in April/May 2014, Price was contacted by Michael Schirber, a writer for Astrobiology Magazine. Price's experiences and objectives for sampling at the PHF are summarized in a subsequent article published in June 2014, "Hydrothermal Vents Could Explain Chemical Precursors to Life". Much of the following text is taken from this article, which can be found at: http://www.astrobio.net/topic/origins/extreme-life/hydrothermal-vents-explain-chemical-precursors-life/. Furthermore, as noted earlier, significant efforts were made to collaborate with the HydroProny research group. Any future research at the site will require their permission. Any reproduction/publication of the following text must be cleared through Price.

Background

The Prony site resembles the Lost City in many ways, as recently documented in pioneering work by the "HYDROPRONY" group, an interdisciplinary research team affiliated with the Mediterranean Institute of Oceanography (MIO) and the French Institute of Research and Development (IRD). In a recent article in the journal *Biogeochemistry*, Christophe Monnin (GET, University of Toulouse), and other HYDROPONY members showed that, like the Lost City, the water that bubbles out of the Prony vents has an extremely basic, or alkaline, pH of around 11. Temperatures reach up to 40°C in some places, and fluids are highly enriched in dissolved hydrogen (H_2) and methane (CH_4). Calcium dissolved in the fluids reacts with bicarbonate in seawater, which leads to the formation of tall, monolithic calcite chimneys that look like ruins from an ancient civilization. Recent work by Marianne Quéméneur, Anne Postec, Gaël Erauso, and others on the HYDROPRONY team indicated that microbial communities at Prony are dominated by methanogenic Archaea (*Methanosarcinales*) similar to those found in the Lost City, as reported in the journal *Environmental Microbiology Reports*.
One big difference, however, between the two sites is that the Lost City is nearly a kilometer underwater, whereas the main Prony chimney, called "the Needle of Prony" or "l'Aiguille" in French, nearly breaches the water surface, making the site accessible to divers.

As indicated in the ECC proposal, the primary objective for this research was to test whether the Prony vents can produce organic compounds abiotically, without any biological influence. The abiotic production of hydrocarbons and other simple organic compounds in places such as these may have led or at least contributed to abiogenesis — the long-ago switch from abiotic chemical reactions to biologically-mediated reactions probably similar to today's microbial metabolisms. The collaboration with the HydroProny group was crucially important to the success of this expedition.

Sampling and Preliminary Results

The sampling expedition was conducted in April/May 2014. Overall, the sampling expedition was a success. A suite of samples were collected for geochemistry, including *in situ* T, pH, TDS, and ORP, and preservation of samples for subsequent laboratory analysis of major anions, major cations, trace elements, sulfide, dissolved inorganic carbon, organic acids, dissolved and free gases (CH_4, H_2, and CO). Many of the geochemical analyses are still currently underway. Samples for microbiological analyses were collected in parallel, and are currently being analyzed by the HydroProny group.

Three sites were targeted for this work: The main submarine cone known as the "Needle of Prony", and two intertidal sites known as Bain des Japonais Spring and the Rivière des Kaoris Spring. On April 16, Price met the diving leader, Eric Folcher of IRD, who drove him out to the boat launch on the bay. They were joined in the field by two members of the HYDROPRONY group — microbiologists Gaël Erauso of the Mediterranean Institute of Oceanography (University of Marseille) and Mylène Hugoni of the University Blaise Pascal. They are studying the genetic make-up of the microbes and viruses that inhabit the vent environments. Erauso and Hugoni plan to do a thorough DNA survey in order to catalogue the diversity of species, and perhaps cultivate unidentified microorganisms, including *Archaea*, who thrive in these very alkaline environments, and samples collected by Price for geochemistry were conducted in parallel for comparison.

The top of the Needle has no active venting, so the divers swam down the side of the chimney to a depth of about 12 meters (39 feet), where they began to see white-tipped, cone-like structures out of which hydrothermal fluids flow. The water coming out of the vents is fresh, not salty, causing it to shimmer when it mixes with the surrounding seawater. The vent fluid is fresh because it originates from rainwater, which percolates down through the rocks on the island. This water then reacts with the rocks by the serpentinization reactions described earlier, and finally drains down beneath the bay before discharging at the Needle and other areas in and around the bay (Monnin et al., 2013). This freshwater distinguishes the Prony hydrothermal field from other sites such as Lost City, which are fed with saltwater.

A temperature reading showed that the exiting fluids at 16 m were about 33° C (91° F), which is 8 to 9°C higher than the ambient seawater. The venting is very slow, so it took about 10 minutes to fill just one of 50-milliliter syringes with vent fluid while preventing seawater from being sucked in as well. Price measured a pH of 10.1 in the samples, which is one of the highest values obtained for these submarine vents. Full geochemical analysis of these samples will occur later in the lab.

As indicated, the two nearby hot springs, the Bain des Japonais Spring and the Rivière des Kaoris Spring are intertidal, located right on the coast of the Bay of Prony, where they get covered by seawater in high tide (Figure 2). The Japonais site consists of a handful of outcroppings, which are shorter versions of the chimneys found in the middle of bay. At low tide, hydrothermal fluid discharges from the top of these mounds, without much mixing with seawater. The team found that this 'pristine' fluid had a temperature 41° C (106° F) and a pH of 11.2, giving some indication of the geochemical characteristics of the subsurface fluids. The Kaoris Spring is at the mouth of a stream that empties into Prony Bay. It consists of a large terrace, where warm hydrothermal fluid helps to support a variety of microbial biofilms. The researchers collected 40 liters of the fluids along with some slices of these biofilms.

To date, major cations, and dissolved and free gas data have been obtained, and are currently being synthesized. Major cations indicate that the hydrothermal fluids are fresh, with very low TDS concentrations. Dissolved gas concentrations were low relative to those found at the LCHF. This is likely due to the higher pressures at LCHF. At the

PHF, dissolved H_2, CH_4, and CO were generally less than 1%, and ranged from 3.7 to 27.5, 24.5 to 408, and 0.27 to 0.96 μM, respectively. Free gas data were more exciting, with H_2 and CH_4 ranging from 28 to 41, 8.9 to 16, respectively (note free gas were only collected from the intertidal vents). These H_2 concentrations are some of the highest ever reported.

Future Objectives

The samples from this expedition are continuing to be analyzed. Major anions, trace elements (and reanalysis of major cations by ICP-MS), H_2S, DIC, organic acids, and the $\delta^{13}C$ and $\delta^{2}H$ isotopic signature of dissolved and free gases will be analyzed hopefully by the end of the year. These data will then be written up into a manuscript for publication early 2015. As for the Lewis and Clark grant, this Early Career Collaboration award has done what it was designed to do: 1) generate collaborative efforts between a US and foreign research group, and 2) generate publishable data, which can also be used as seed data for a larger NASA proposal.

Synopsis:

Alkaline shallow-sea hydrothermal venting as a new target for NASA and origin of life research.

In 2000 researchers discovered an amazing new kind of deep-sea hydrothermal vent, the Lost City Hydrothermal Field (LCHF), located off-axis of the Mid-Atlantic Ridge (Kelley et al., 2001). This system not only displays very different geochemistry and microbiology compared to deep-sea black smokers, but may be crucial to our understanding of the origins of life on Earth and the potential for life on other planets (e.g., Martin et al., 2008; Schulte et al., 2006; Bradley, 2009). At the heart of the hydrothermal activity is the process of serpentinization - the reaction of olivine- and pyroxene-rich rocks with water - which liberates molecular hydrogen, creating a source of energy and electrons at LCHF that can be readily utilized by a broad array of chemosynthetic organisms, and which may have been a critical process at the dawn of life (Schulte et al., 2006; Sleep et al., 2011). Unfortunately, other than recent NASA investigations at the ultra-deep Mid Cayman Rise, no other alkaline submarine hydrothermal sites have been investigated to date. Thus, there is a fundamental lack of information for these important environments where the process of mixing of high pH, high H_2-CH_4 fluids with seawater provides the chemical disequilibrium which drives the microbial communities, and which may mimic the conditions present at the origin of life.

The Prony Hydrothermal Field (PHF) and the Strytan Hydrothermal Field (SHF), display similar characteristics to LCHF, but we argue that they are even more intriguing as a new type of serpentinite-hosted hydrothermal system. Critically important, they create a reduced, alkaline (pH ~11), warm (30 to 78ºC) hydrothermal fluid that mixes with surrounding seawater while precipitating porous mineral towers. Serpentinization of ultramafic rocks give rise to the hydrothermal vents in both Prony Bay and the Lost City, whereas a type of serpentinization (low temperature alteration of iron containing minerals in basalt) is thought to occur at the Strytan Hydrothermal Field. However, unlike the LCHF, fluids at PHF and SHF are created by downward circulating meteoric water. Thus, the discharging fluids are low salinity compared to seawater, which may have important consequences for the microbial communities at the site. Furthermore, the vents occur in a shallow-ocean environment, within the photic zone, thus providing the opportunity for not only chemosynthesis, but also photosynthesis.

All this suggests that both the SHF and PHF are hybrid, perhaps unique, vent systems, with geochemical and microbial characteristics similar to both terrestrial and marine serpentinizing systems. One might imagine that the first precursors to life took advantage of the conditions around these types of hydrothermal vents. Research at alkaline shallow-sea hydrothermal vents such as the SHF and PHF could provide some ground truth for these origin-of-life speculations. If the methane is produced abiotically, then we will have the potential for an early Earth analog which may help us understand the complex sequence of events which led to the origin of life.

In the bigger picture, we know today that groundwater that reacts with underlying rocks can be seen discharging along the coastlines everywhere around the world. This phenomenon must have occurred on the early Earth, but back then many of the rocks would have been ultramafic. Hybrid, transitional terrestrial-to-marine systems may therefore have been very common during our planet's beginnings. They may also have existed on Mars and other planetary bodies in our solar system. Based on our current understanding of the early Earth, these types of transitional environments could have been highly important for origin of life scenarios

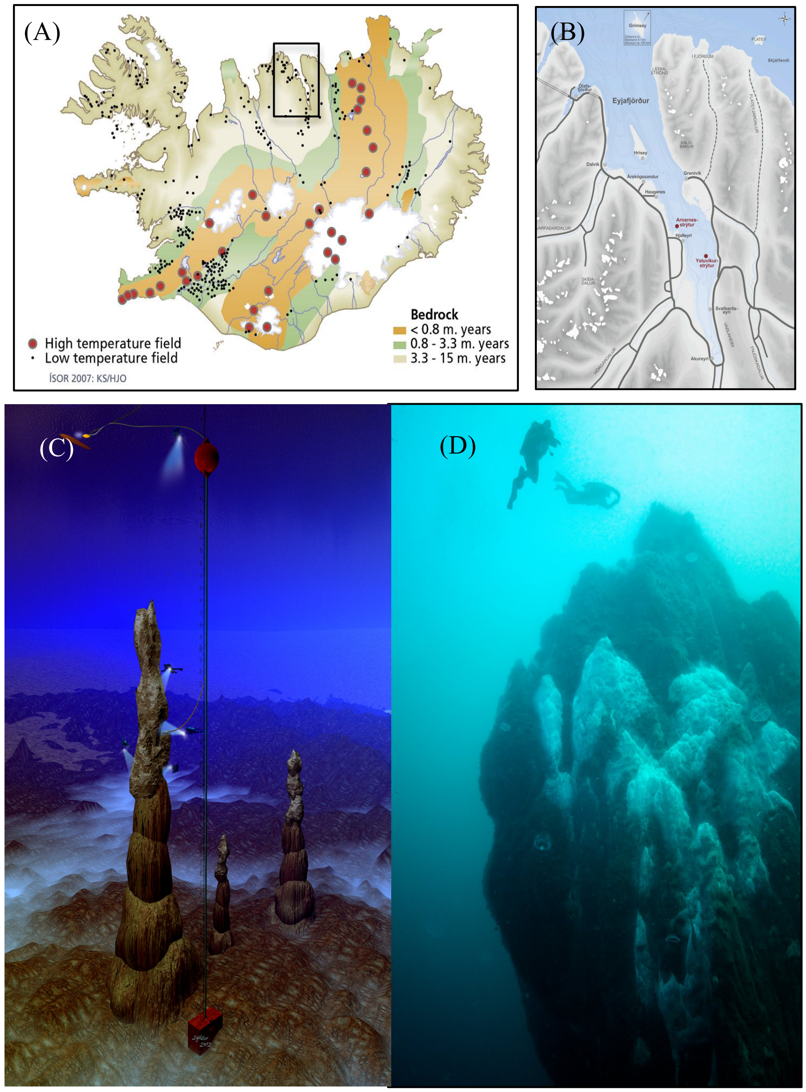
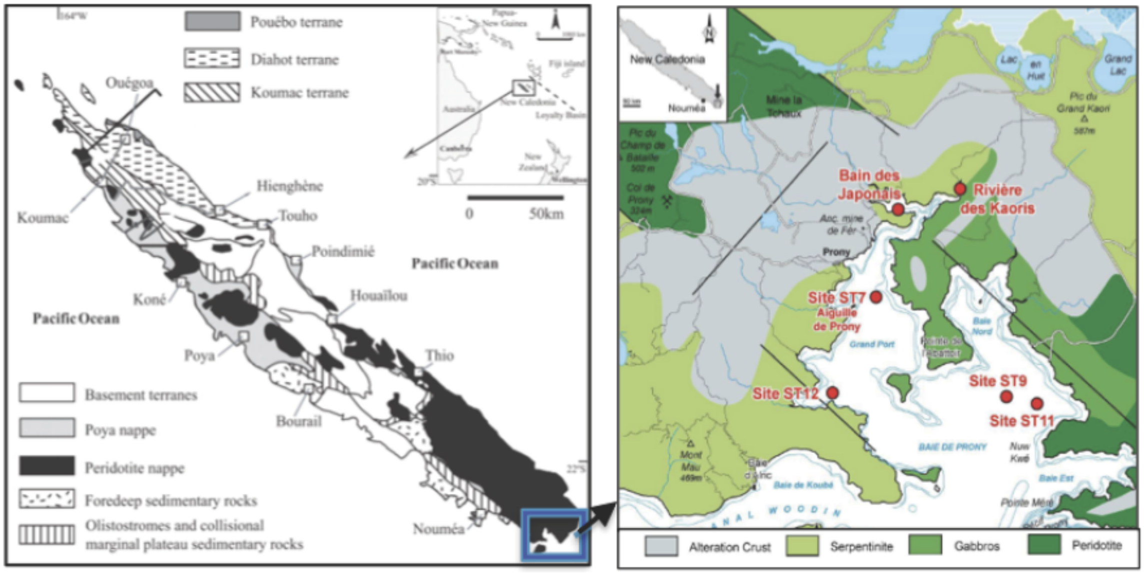


Figure 1. (A) Location of the study area in Iceland. (B) Detailed area of the Eyjafjord area, including the location of the Strýtan hydrothermal cones. (C) Schematic of the Strýtan cones (D) Underwater photograph of an actively venting portion of the cones. White areas are sites where hot hydrothermal fluids react with seawater to form mineral precipitates.



Location of New Caledonia, with ultramafic rocks (overthrusted ophiolite) indicated in black. On right is a close up of Prony Bay, where samples were collected for this study.

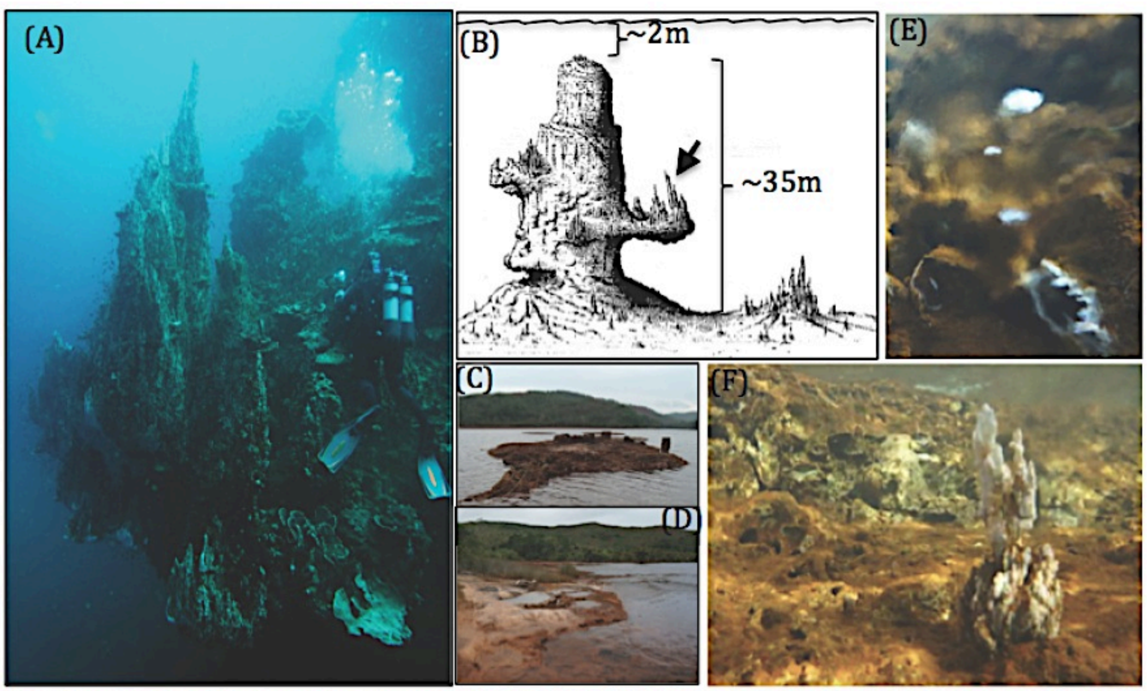


Figure 2. (A) Underwater photograph of an actively venting portion of the Prony Needle (noted by arrow in (B)). (B) Schematic drawing of the Prony Needle (from Launey and Fontes, 1985). (C) Bain des Japonais intertidal site. Four areas of cone 'tops' exist, which are completely submerged at high tide. (D) Kaoris terrestrial/intertidal/submarine site, showing large areas of $CaCO_3$ deposits. (E and F) Underwater photographs of submarine discharge of pH ~11 fluids at Japonais and Kaoris. Note free gas discharge in (E).