Magellan+ Workshop Report "Drilling an active hydrothermal system associated with a submarine intraoceanic arc volcano"

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ECORD European Consortium for Ocean Research Drilling

IODP INTEGRATED OCEAN DRILLING PROGRAM

CREMINER Centro de Recursos Minerais, Mineralogia e Cristalografia
Fac Ciências Univ Lisboa LARSyS (Lab Associado)

Fig. 1: Facilities provided by the University of Lisbon were convenient, comfortable, and well resourced with projection equipment

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1) Rationale

Recent discoveries have shown that hydrothermal processes associated with intraoceanic arcs play a major role in the exchange budgets of the global oceans and seafloor crust. Seafloor hydrothermal systems along arcs are host to diverse animal and microbial communities together with large polymetallic sulfide deposits, making them a primary target for deep-sea mineral exploration and an important analogue for fossil Cu-Au deposits mined on land. Investigations of the distribution of subseafloor mineralization and alteration styles are critical in further assessing the potential of intraoceanic arc hydrothermal systems as a tectonic environment for seafloor resources and a supplier of important metals and nutrients to the oceans. Seafloor hydrothermal systems along intraoceanic arcs are also some of the most hostile environments for life, owing to the extraordinary high concentrations of toxic metals and metalloids in very acidic (and gas-rich) fluids. Brothers volcano of the Kermadec arc is an outstanding example of this type of environment.

With a total length of ~7,000 km and typically several vent sites per 100 km, intraoceanic arcs rival mid-ocean ridges (MORs) in terms of frequency of venting and overall hydrothermal mass transfer from the crust to the oceans. However, the high concentrations of S species gases, CO_2, and metals such as Fe, means that arc hydrothermal systems have the potential to form mineral deposits of a different style/type to those typically found along MORs. In addition, these systems are more likely to host previously unknown microbes. The 50 or more known submarine arc magmatic-hydrothermal systems worldwide have in common hydrothermal vents driven by the crystallization of magmas produced by melting of mantle that is fluxed by volatiles released from the subducting slab. These magmas are very rich in volatiles, as witnessed by extraordinary sights such as the discharge of liquid CO_2 and the formation of liquid 'lakes' of sulfur on the seafloor. Magmatic degassing of fluids with highly variable salt and gas contents is therefore common in this setting. Buoyant fluxing of magmatic fluids is so great that they leave a distinct, and commonly unique, geochemical signature in the hydrothermal fluids venting at the seafloor. At a MOR hydrothermal vent, hot water discharged on the seafloor is almost entirely derived from the circulation of modified seawater. By contrast, at an intraoceanic arc volcano a significant fraction of the vent fluid is derived from the magma degassing process. This means that the addition of magmatic vapors and brines will affect the very type and style of subseafloor mineralization that could form in fundamentally different ways to those found at MORs. Moreover, these vapors also heavily influence the composition of the expelled vent fluids, the vent biota, and transfer of metals and nutrients into the oceans. Arc volcano-hosted hydrothermal systems are also known to undergo dynamic changes as a consequence of changes in magma degassing flux. Magma degassing is invariably dominated by H_2O, CO_2, H_2S and/or SO_2 (± HCl, ± HF), which leads to drastic differences in fluid compositions, commonly within a single volcanic edifice, such as witnessed at Brothers volcano (de Ronde et al., 2011).

While recent exploration of arc hydrothermal vents has provided first insights into the variable magma-hydrothermal-biological feedbacks within these systems, very little is known about the subseafloor distribution of mineralization and microbial habitats. It is also not clear what governs fluid flow in the vent-hosting volcanoes, which have a subseafloor architecture very different from that of ocean crust formed at a spreading ridges. Economic geologists have developed conceptual models for magma-fluid-rock interactions in pluton-related porphyry Cu and epithermal Au systems, which are believed to represent ore forming environments above magma chambers in hydrologically active arc volcanoes. Indeed, some of the world's largest Cu-Au deposits fall in this category. While advances have been made on understanding the seafloor environments of submarine arc hydrothermal systems, knowledge on the potential for these volcanoes to form subseafloor Cu deposits is entirely lacking. Indeed, the whole transition from a magmatic vapor-dominated system to one of a circulating hydrothermal cell is unknown. So too are the mechanisms for the transfer of metals from the underlying, fractionating magma to the overlying hydrothermal system, and the capacity for arc-related magmas of andesitic to dacitic composition to concentrate metals. Thus, drilling of Brothers volcano would provide the missing link (i.e., the 3^{rd} dimension) in our understanding of mineral deposit formation along arcs, the subseafloor architecture of these volcanoes and their related permeability, and the relationship between the discharge of magmatic fluids and the deep biosphere.

Drilling into an intraoceanic arc volcano with diverse hydrothermal vents would provide critical new insights into the following interrelated processes:

• Mechanisms and extent of fluid-rock interaction and consequences for mass transfer of S and C species, and some metals and metalloids, into the oceans,

• Distribution of metals and associated formation of mineral deposits in the subseafloor,

• Diversity and extent of microbial life in a hostile volcanic environment.

These issues are closely related to major themes of the current and future IODP science plan, as they directly address plate tectonics and the accretion of crust, and the distribution and functioning of a deep biopshere in hostile, high pressure and high temperature environments.

2) Meeting Structure

The purpose of the workshop was to bring together an international group of geologists, petrologists, geochemists, geophysicsists, and microbiologists to discuss and plan an IODP proposal to drill into a hydrothermal system hosted by the submarine Brothers volcano of the Kermadec intraoceanic arc. The group included specialists in volcanic processes, fluid geochemistry, fluid-rock interaction, ore deposit formation, petrology and geochemistry, geophysical exploration, and microbiology of extremophiles. Scientists who have played lead roles in past hydrothermal drilling expeditions were on hand to guide those with less IODP drilling experience and to impart their wisdom gained from previous drilling of seafloor hydrothermal systems. The meeting was planned by a group of scientists with extensive experience in hydrothermal system research, in addition to profound knowledge of submarine arc hydrothermal systems and ODP/IODP drilling.

The meeting was co-funded by ECORD-EMA and IODP-MI. The three-day workshop took place in a building of the Faculty of Sciences, University of Lisbon, and was hosted by Dr. Fernando Barriga. The CREMINER center of the University of Lisbon co-sponsored the meeting by providing free access to the meeting facility. Ms. Celia Lee and Ana Sousa of the University of Lisbon helped organize and run the meeting.

A field trip to the Neves Corvo mine on Nov. 14 was attended by many of the participants. This is one of two large, operating mines in Portugal, and is the western-most mine along the famed, ~E-W trending, Iberian Pyrite Belt (IPB). The belt is part of a tectono-stratigraphic sequence that is host to numerous massive sulfide deposits that have, over the years, relinquished 100s of millions of tonnes of ore. The underground workings at Neves Corvo are accessed via an incline. Several stops were made to view contact relationships, and to examine various types of ore, including massive and stockwork. The deposit, like many along the IPB, is strongly deformed, with the majority of contacts between geological units and ore horizons distinctly tectonized. The visit provided the workshop participants with some insight into the 3rd dimension of these submarine deposits, and the visit was capped off with a very pleasant meal in a nearby village that is host to 11th century buildings.

Lectures in the mornings of Days 1 and 2 covered the following topics:

- Global distribution and significance of arc hydrothermal systems,
- Insights from geochemical studies of hydrothermal vents,
- Life in, on, and at active volcanoes,
- Lessons from past scientific drilling in hydrothermal systems,
- Lessons from drilling the Iheya hydrothermal system (IODP Exp. 331)

• Geology of Brothers volcano and its hydrothermal systems,

• Geophysical site survey data of Brothers volcano, and

• Opportunities using wireline borehole logging.

Discussion sessions took place in the afternoons of Days 1 and 2 and all of Day 3, and covered the following topics:

• What do we know about arc hydrothermal systems and what do we not know?

• How do we close crucial gaps in our knowledge base by drilling these systems?

• What outstanding science questions can best be addressed by drilling?

• What measurements are required to maximize the amount of information gathered from recovered drill core?

• What additional site survey work would be needed, if any, to drill at Brothers?

• What should the drilling and logging strategies be?

• What are the likely technical difficulties with drilling Brothers volcano?

• Outline a drilling proposal and assign writing assignments

3) Discussion results and recommendations

3a) Big science questions

Understanding the different mass transfers in a subduction system is crucial for understanding the evolution and couplings of the mantle-crust-hydrosphere-atmosphere. Drilling at Brothers would be complementary to scheduled Izu-Bonin (I-B) drilling, as Brothers represents an end-member (i.e., an arc volcano) not represented by the I-B drill sites. Some of the most pressing questions in arc research were reiterated at the workshop:

What is the element cycling occurring within the subduction factory? In particular, what are the mechanisms and efficiencies of volatile recycling into the mantle wedge, where do melts first form, and how do the magmas evolve? Where do magmas reside and what are the processes and pathways of melt degassing during cooling and crystallization of the magma? How does magmatic degassing impact the transport of metals to the seafloor? And what is the role of arc volcanoes in terms of hydrothermal fluxes of carbon, sulfur, and metals into the oceans?

Drilling Brothers volcano offers a unique opportunity for tackling a number of these questions. Brothers volcano is a typical, mid-sized caldera volcano in the re-building stage that includes a more recent, larger, volcanic cone, and a smaller, older cone inside the caldera. Many of these arc volcanoes, of which there are known to be at least 200, have highly evolved dacitic to rhyolitic compositions (e.g., Haase et al., 2006). Why evolved magmas are so common along these arcs is unclear.

Within the extreme change in forcing parameters of subduction along the Tonga-Kermadec Trench, such as subduction rate, Brothers provides the possibility for examining specific structural/magmatic/volcanic co-evolution patterns. Temporal changes in hydrothermal fluxes, known to occur at Brothers, are controlled by both transients in degassing and hydrology-dominated variations in subseafloor mixing. The basics of the critical subseafloor gas-water-rock interaction processes, however, remain essentially unknown.

Brothers is at the leading edge of the subducting Hikurangi Plateau to the south, and forms the northern boundary of a length of arc characterized by extremely high degrees of hydrothermal activity. The subduction of this thicker lithosphere at Brothers may be key to the increased hydrothermal activity along the southern part of the Kermadec arc.

A question central to hydrothermal deposit research over the past several decades, is the role of leaching of metals by circulating external waters, relative to metal input from degassing magmatic fluids (supercritical fluids, brines, and vapors). The question of how much metal transport is due to magmatic-degassing flux versus water-rock dominated hydrothermal circulation can be investigated at Brothers volcano as it is host to hydrothermal systems derived by both these mechanisms.

Arc volcanoes would present an excellent opportunity to study volatile element loss during magma degassing when reconstructing subduction factory output fluxes. Any degassing-related loss of elements in the deep magmatic system will affect the composition of magmas feeding arc volcanoes, and hence the output archive that would include tephra deposits. The inventory of volatile metals and metalloids in tephra glasses relative to that of similarly incompatible, but refractory metals, will yield new insights into magma degassing and its control on element transport. Specifically, it will address the questions: how does metal input work in these systems, and what is the role of oxidation state, fractional crystallization, and magma mixing in mediating metal transport? Drilling will provide a long time-record of tephra glasses, which would enable the investigation of relationships between degassing and metal transport in the evolution of an arc volcano. In this context, the ecosystems inhabiting the vent sites and immediately subseafloor during the evolution of the volcano-hydrothermal system would also be of great interest to microbiologists.

Subseafloor hydrological patterns at volcanoes like Brothers are closely related to caldera and cone formation. Thus, drilling will aid in our understanding of how volcano architecture influences the distribution of large-scale permeability. Like other arc volcanoes, magma degassing and hydrothermal processes at Brothers results in significant fluxes of elements into the oceans. The transport of reduced components to the seafloor provides the foundation of VMS-type ore deposits and microbial ecosystems harnessing the energy stored in kinetically inhibited redox reactions in the mixing zones of hydrothermal fluids and seawater at, below, and above the seafloor. Drilling provides a unique means for investigating the linked volcanologic-hydrological-geochemical-microbial processes and constitutes a primary tool for assessing these interactions.

To accomplish progress in this multidisciplinary scientific frontier, both shallow and deep coring is vital. Both approaches are needed to make full use of opportunities to look at the evolution from juvenile (magmatic) to more mature (seawater-dominated) fluids. Deep, non-riser drilling will provide access to critical zones dominated by magma degassing and high-temperature hydrothermal circulation. The desired drill cores should contain valuable information on the influence of magmatic degassing on metal transport and allow us to distinguish between two principal sources: (i) directly from the magma; (ii) via acid-promoted dissolution or leaching of rock. The cores will also help in the examination of the upflow zones away from areas of shallow entrainment of seawater (e.g., by studying the distribution of isotopic signatures for magma vs. seawater sources from $\delta^{34}S$ values). Fluid inclusion studies of deep core material will provide insight into brine-vapor partitioning of metals and unique opportunities to study the co-evolution of volcanic and hydrothermal processes.

The drilling technology currently available on the *JOIDES Resolution (JR)*, however, has a poor record of achieving high core recovery for the 10s m immediately below the seafloor. Any JR-style drilling expedition to recover deep samples will have to be complemented by seabed drill-rig sampling, which will provide core from shallow intervals most useful for microbiological studies. These shallow holes will also address some of the geochemical questions pertinent to the role of shallow seawater incursion/entrainment in mediating metal fluxes to the seafloor.

3b) Site selection

Brothers volcano features two types of active hydrothermal systems: (i) high-temperature (up to 302°C) venting of relatively gas-poor, moderately acidic fluids along the western and NW walls of the caldera, where Cu-Au-rich sulfide chimneys are common, and (ii) lower-temperature (≤120°C) venting of gassy, very low-pH fluids (to 1.9) at the summits of the two cone sites, where native sulfur chimneys and expansive Fe-oxyhydroxide crusts occur (de Ronde et al., 2011). These hydrothermal fields are closely correlated to areas of magnetic 'lows', consistent with hydrothermal upflow zones (Caratori Tontini et al., 2012). Other areas of low-magnetic intensity were also identified inside the caldera, such as the extinct SE caldera site. All of the sites can be related to the local tectonic fabric where caldera-bounding faults intersect with more regional NW-SE oriented lineaments (de Ronde et al., 2005; Embley et al., 2012).

Highest priority should be given to a drill site on top of the caldera rim in the NW sector of the volcano, where flat ground (and evidence for hydrothermal activity) is present. Given that the caldera-bounding faults are likely outbound (Embley et al., 2012), and incorporating the observation of progressively younger mineralization ages from the caldera rim to the base of the caldera (de Ronde et al., 2011), drilling in this area would provide the opportunity for spudding into a fossil hydrothermal upflow zone of the Type I variety mentioned above.

The cone site offers a number of flat areas suitable for drilling the Type II system. The Lower Cone is more weathered and degraded than the Upper Cone, which is younger. Both have acidic and gas-rich hydrothermal discharge, with more Fe venting from the older (Lower) cone. The Upper Cone is hosted by dacite with patchy advanced argillic alteration, which would make for a good drilling target. The best-suited target for drilling is an area of maximum surface expression of advanced argillic alteration in the ~40 m diameter pit crater atop of the Upper Cone, as the likelihood for successful penetration is highest there, as is the possibility of sampling deep rocks influenced mainly by magma degassing and possibly unaffected by seawater recharge.
A third major drilling target is the caldera floor in the area of a significant magnetic low that extends eastwards from the West caldera site and onlaps the main cone in the southern part of the caldera. Areas between the cone and the western border of the caldera are suitable for that objective. Another, equally good target, would be downslope and south of the numerous high-temperature vents of the NW caldera field where a distinct magnetic low extends onto the caldera floor. Here, we have a good opportunity to drill into an upwelling zone within the volcano. Also, tremor data collected from hydrophones on the caldera floor appear to indicate the presence of a two-phase zone in this region at a depth of about 800 m below the caldera floor (Dziak et al., 2008), thus making the caldera floor site an interesting target for deep drilling. It was noted that, given the relatively shallow depth of the magma plumbing system of Brothers, exsolution of magmatic volatiles would be two-phase. The vapor-rich phase likely discharges in the cone sites of sulfate-acid venting, but the corresponding brine phase is likely trapped in inclusions at depth, which makes the cone site a high-priority site for tackling questions on metal partitioning in an active magma-hydrothermal system.

3c) Implementation/technology/site survey data

A lot of discussion time was focused on possible difficulties associated with drilling into Brothers at any of these sites. The cone site is relatively young, so predominantly glassy and perhaps rubbly lithologies there may impose a serious problem to drilling. The caldera wall site may encounter problems if the upflow zone is not heavily veined and altered. Based on experience from previous drilling in similar environments (e.g., ODP

Leg 193; IODP Exp. 331), it was concluded that basement hosted by felsic rocks is easily penetrated by the drill, whereas fresh volcanic flows and deposits of hard sulfide intercalated with soft clay and gangue may impose severe problems. The three sites mentioned above were selected to circumvent these issues as much as possible and to maximize the scientific information that could be gleaned from the drill core recovered. It was also noted that a conservative approach to deep drilling should be imperative, which would include having casing installed, once spudded in for about 100 m. Moreover, it was suggested that the use of non-RCB type of bits should be looked into.

Understanding volcano permeability and seawater entrainment, and their effects on microbial colonization, requires high core recovery from the shallow basement. Seabed drill rigs such as MeBo (Freudenthal and Wefer, 2007) are designed for mud drilling and yield core suitable for pore water geochemical work. Other lander-type drills (e.g., the BGS rock drill) have been successful in seafloor sulfide deposits before (e.g., Petersen et al., 2005). The top-of-the-line of this type of platform yields cores 63 mm in diameter to depths of up to 75 mbsf. Shallow seabed drill core would provide information useful for determining the best approach to be used in deep drilling with the *JR*. Thus, it would be preferred (but not required) that shallow drilling be done prior to the deep drilling.

Consensus was reached in that a *JR* expedition early in the first phase of the new IODP would be most beneficial to the overarching goal of arc hydrothermal drilling, and that supplemental shallow drilling might be achieved using non-IODP funding.

While it was considered imperative to have both deep and shallow sampling, the order in which the two are accomplished was not deemed critical to the overall success of the program.

3d) Site survey data

Systematic and detailed ship-borne geophysical data, including high-resolution (AUV derived) bathymetry, seismic line and geomagnetics are available (GNS Science data), as are 1000s of photographs of the seafloor at Brothers, 40+ hours of submersible video tape, and AUV derived water column data that clearly marks all the present-day hydrothermal venting inside the caldera (*Econ. Geol.* special issue, 2012). With the traditional set of site survey data already in hand, questions arose as to what additional site survey data would be beneficial to the selection of drill sites and the choice of drilling strategy.

The wish list of additional ROV- and AUV-based site survey data included:

- Representative survey and systematic rock sampling up the caldera wall,
- Mapping the SE caldera area and recovery of samples,
- Heat flow survey to identify recharge (using thermal blankets in addition to conventional heat flow probes) zones, perhaps best suited for drilling,

- Chirp-sonar survey of the caldera floor,
- Gravity coring the caldera floor,
- Deployment of markers/targets/transponders to help chose drill sites for the *JR*,
- Baseline studies for microbiology, using ROV push cores, and
- Additional vent fluid sampling and pore water sampling from push cores.

While none of these are considered critical in order for IODP drilling to begin, each would be extremely helpful in selecting drilling targets or interpreting the drilling results, especially a dedicated ROV cruise to locate specific drill sites, and perhaps the heat flow and microbial studies.

With proposal deadlines looming for the various parties, US and European participants indicated an eagerness to enquire about options, including the writing of dedicated proposals for an ROV/AUV cruise to the Brothers volcano before the end of 2015. This may be feasible given that US ROVs and AUVs, and US and European ships will be working in the SW Pacific in the next 24 months.

4) References

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5) Agenda MagellanPlus Workshop and Arc Hydrothermal Drilling in Lisbon
Meeting place: Faculty of Sciences building C1 of the University of Lisbon

Nov. 13, 2012 (Tuesday)
16:00 Departure for Castro Verde (Entrance of Hotel NH Campo Grande, Campo Grande 7, Lisbon)
Dinner in Castro Verde
Overnight in Hotel A Esteva, Castro Verde

Nov 14, 2012 (Wednesday)
08:45 Visit to the Neves Corvo Mine, including underground
17:00 Return to Lisbon

Nov. 15, 2012 (Thursday)
8:45 Welcome and introduction
9:00-9:45 Lecture: Global distribution and significance of arc hydrothermal systems (Sven Petersen)
9:45-10:30 Lecture: Insights from geochemical studies of hydrothermal vents (Olivier Rouxel)
10:30-11:00 Coffee break
10:00-11:45 Lecture: Life in active submarine volcanoes (Anna-Louise Reysenbach)
11:45-12:30 Lecture: Lessons from past scientific drilling in hydrothermal systems (Robert Zierenberg)
12:30-13:45 Lunch break
13:45-15:30 Discussion session I "What are the big science questions?"
15:30-16:00 Coffee break
16:00-17:30 Continued discussion session I

Nov 16, 2012 (Friday)
9:00-9:45 Lecture: Brothers, geological overview (Cornel de Ronde)
9:45-10:30 Lecture: Brothers, site survey data (F. Caratori Tontini)
10:30-11:00 Coffee break
11:00-11:45 Lecture: Leg 331 summary (Jun-ichiro Ishibashi)
11:45-12:30 Lecture: Logging / observatory science (Louise Anderson / Brian Glazer)
12:30-13:45 Lunch break
13:45-15:30 Discussion session II: "What particular questions can be addressed at Brothers? How?"
15:30-16:00 Coffee break
16:00-17:30 Continued discussion session II

19:30 Group dinner

Nov. 17, 2012 (Saturday)
9:00-10:30 Discussion session III "where drill, how deep, logging strategy"
10:30-11:00 Coffee break
11:00-12:30 Continued discussion session III
12:30-13:45 Lunch break
13:45-15:30 Discussion session “proposal writing, strategy, assignments”
15:30-16:00 Coffee break
16:00-17:00 Wrap-up and final discussion.

6) List of Participants

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