# Subsurface hydrothermal processes and the bioenergetics of chemolithoautotrophy at the shallow-sea vents off Panarea Island (Italy)

***Authors***

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***Abstract***

The subsurface evolution of shallow-sea hydrothermal fluids is a function of many factors including fluid-mineral equilibria, phase separation, magmatic inputs, and mineral precipitation, all of which influence discharging fluid chemistry and consequently associated seafloor microbial communities. Shallow-sea vent systems, however, are understudied in this regard. In order to investigate subsurface processes in a shallow-sea hydrothermal vent, and determine how these physical and chemical parameters influence the metabolic potential of the microbial communities, three shallow-sea hydrothermal vents associated with Panarea Island (Italy) were characterized. Vent fluids, pore fluids and gases at the three sites were sampled and analyzed for major and minor elements, redox-sensitive compounds, free gas compositions, and strontium isotopes. The corresponding data were used to 1) describe the subsurface geochemical evolution of the fluids and 2) to evaluate the catabolic potential of 61 inorganic redox reactions for *in situ* microbial communities. Generally, the vent fluids can be hot (up to 135 °C), acidic (pH 1.9-5.7), and sulfidic (up to 2.5 mM $H_2S$). Three distinct types of hydrothermal fluids were identified, each with higher temperatures and lower pH, $Mg^{2+}$ and $SO_4^{2-}$, relative to seawater. Type 1 was consistently more saline than Type 2, and both were more saline than seawater. Type 3 fluids were similar to or slightly depleted in most major ions relative to seawater. End-member calculations of conservative elements indicate that Type 1 and Type 2 fluids are derived from two different sources, most likely 1) a deeper, higher salinity reservoir and 2) a shallower, lower salinity reservoir, respectively, in a layered hydrothermal system. The deeper reservoir records some of the highest end-member Cl concentrations to date, and developed as a result of recirculation

of brine fluids with long term loss of steam and volatiles due to past phase separation. No strong evidence for ongoing phase separation is observed. Type 3 fluids are suggested to be mostly influenced by degassing of volatiles and subsequently dissolution of $CO_2$, $H_2S$, and other gases into the aqueous phase. Gibbs energies ($\Delta G_r$) of redox reactions that couple potential terminal electron acceptors ($O_2$, $NO_3^-$, $Mn^{IV}$, $Fe^{III}$, $SO_4^{2-}$, $S^0$, $CO_2$,) with potential electron donors ($H_2$, $NH_4^+$, $Fe^{2+}$, $Mn^{2+}$, $H_2S$, $CH_4$) were evaluated at *in situ* temperatures and compositions for each site and by fluid type. When Gibbs energies of reaction are normalized *per kilogram of hydrothermal fluid*, sulfur oxidation reactions are the most exergonic, while the oxidation of $Fe^{2+}$, $NH_4^+$, $CH_4$, and $Mn^{2+}$ are moderately energy yielding. The energetics calculations indicate that the most robust microbial communities in the Panarea hot springs combine $H_2S$ from deep water-rock-gas interactions with $O_2$ that is entrained via seawater mixing to fuel their activities, regardless of site location or fluid type.

**Key Words:** Shallow-sea, hydrothermal, subsurface processes, bioenergetics, microbial metabolism, thermodynamics, biogeochemistry

## 1. Introduction

Marine hydrothermal vent fluids are often highly enriched in reducing inorganic chemical species (electron donors) which, when mixed with oxidized seawater, can generate aqueous solutions with multiple redox disequilibria. In deep-sea vent environments, microbial communities take advantage of these energy sources and comprise the base of the food web for some of the most diverse ecosystems on the planet (Felbeck and Somero, 1982; Imhoff and Hügler, 2009; Lutz and Kennish, 1993). However, these hydrothermal mixing regimes are not limited to the deep sea. Shallow-sea vent fluids also mix with seawater to establish redox gradients (Akerman et al., 2011; Amend et al., 2003a; Dando et al., 1999; Fitzsimons et al., 1997; Meyer-Dombard et al., 2011; Price and Pichler, 2005). Shallow-sea hydrothermal vents are generally defined as occurring at a water depth < 200 m, a depth which marks the deepest extent of the photic zone and coincides with a large change in the slope of the seawater boiling curve (Tarasov et al., 2005). They are often accompanied by abundant free gas discharges. As a result, shallow-sea hydrothermal systems are often referred to as ‘gasohydrothermal’ vents, and have been documented on the summits of seamounts, on the flanks of volcanic islands, and in other near-shore environments characterized by high heat flow (Italiano and Nuccio, 1991; Pichler, 2005; Price et al., 2013a; Tarasov et al., 2005). Their easy accessibility, relative to deep-sea hydrothermal systems, makes them excellent natural laboratories to study a wide range of chemical, physical, and biological processes (Pichler et al., 2006).

The subsurface geochemical processes controlling the composition of discharging hydrothermal fluids at deep-sea vents are manifold, and have been investigated and

reviewed extensively (e.g., see Alt, 1995; Berndt et al., 1988; Bischoff and Rosenbauer, 1985; Fournier, 2007; Foustoukos and Seyfried, 2007; German and Von Damm, 2003; Hannington et al., 2005; Hedenquist and Lowenstern, 1994; Heinrich et al., 2004; Henley and Ellis, 1983; Seyfried and Mottl, 1982; Tivey, 2007). The final compositions are a function of many factors including fluid-mineral equilibrium, phase separation, magmatic inputs, mineral precipitation, and mixing. While these processes have been well defined for deep-sea systems along mid-ocean ridges, and more recently at back-arc basins (Reeves et al., 2011), much less is known about the subsurface processes taking place at shallow-sea hydrothermal vents. They are most often associated with island arc volcanoes, and thus silicic magmas more similar to back-arc basins rather than mid-ocean ridges. Shallow-sea vents occur within the photic zone, and can have meteorically derived groundwater as a potential source fluid. These characteristics, combined with their occurrence in lower pressure environments, begs the question of what consequences this has for the evolution of fluid chemistry and how this in turn influences the related seafloor microbial communities.

The quest for energy is a key function of all living systems (Schroedinger, 1944), and the potential metabolic activities of microorganisms in shallow-sea hydrothermal systems can be determined by calculating the Gibbs energy of reactions between the electron donors and acceptors present in discharging fluids. This type of thermodynamic analysis of potential microbial metabolisms has been successfully conducted in many environments, including several submarine (Amend et al., 2011; Amend and Shock, 2001; Hernandez-Sanchez et al., 2014; LaRowe and Amend, 2014; LaRowe et al., 2008; McCollom, 2000; McCollom, 2007; McCollom and Shock, 1997; Shock and Holland,

2004; Shock et al., 1995; Teske et al., 2014), and terrestrial hydrothermal systems (Inskeep et al., 2005; Inskeep and McDermott, 2005; Shock et al., 2010; Spear et al., 2005; Vick et al., 2010; Windman, 2010). Unfortunately, energetic profiles of shallow-sea hydrothermal systems are rare, despite the fact that their diverse geochemistry accounts for a large number of potential catabolic strategies.

In this communication, geochemical data are presented for vent and pore fluids collected from 2008 to 2010 from three distinct sites in the shallow-sea hydrothermal system off Panarea Island (Italy). The main purpose of this paper is to describe the variability of vent fluid chemistry between sites, and understand how this variability evolved as a result of subsurface hydrothermal processes. As a secondary but logical extension of this analysis, geochemical data are then used to calculate *in situ* redox reaction energetics in order to link subsurface geochemical processes and the resulting differences in vent chemistry, as understood through our geochemical data, to potential microbial metabolisms.

## 2. Site Characteristics

### *2.1. Bedrock Lithology*

Panarea Island is part of the Aeolian arc, a string of islands and several seamounts just north of Sicily (Italiano & Nuccio, 1991; Fig. 1a and 1b). Panarea and the associated islets were emplaced on ~15–20 km thick continental crust (Neri et al., 2002), and are located between the active volcanoes of Vulcano and Lipari in the southwest and Stromboli in the northwest part of the arc (Fig. 1a). Several investigations have suggested that the western and eastern islands along the arc are structurally and compositionally

distinct (Calanchi et al., 2002; De Astis et al., 2000; Peccerillo, 2001; Peccerillo and Panza, 1999). Rocks from the western arc are calc-alkaline and have compositions that suggest a genesis within a MORB-type mantle with modification by fluids and melts released from an oceanic slab (Ellam et al., 1989; Francalanci et al., 1993). However, to the east, Stromboli shows calc-alkaline to potassic-alkaline rocks with lower large ion lithophile element (LILE)/high field strength element (HFSE) ratios along with more radiogenic isotopic Sr composition than rocks from the western arc (Calanchi et al., 2002; De Astis et al., 2000; Ellam et al., 1989). Thus, the source rocks beneath Panarea are a mixture of these two sources, i.e., partially western arc mantle and partially Stromboli mantle (Calanchi et al., 2002), and hydrothermal fluids could be reacting with either or both of these bedrock lithologies.

*2.2. Hydrothermal Activity and Sampling*

Free gas bubbles and aqueous fluids vent at ~20 m below sea level depth near La Calcara beach (~50 to 200 m offshore; Fig. 1b). More intense hydrothermal activity with focused and diffuse venting occurs at several sites ~2 km offshore in 18 to 25 m water depth, inside a submerged caldera (Fig. 1b). In both areas, emissions are marked by white deposits of colloidal sulfur associated with microbial activity (Gugliandolo et al., 1999; Italiano and Nuccio, 1991; Maugeri et al., 2009).

Sampling efforts in this study focused on three distinct sites near Panarea Island: Hot Lake, Black Point, and La Calcara (see Fig. 1b). Hot Lake, located in the main submerged caldera (Latitude 38°38'19.3032", Longitude 15°06'32.7511"), is an oval-shaped (~ 4 by 6 m), ~2.5 m deep depression in the seafloor partially filled with thick

white mats of elemental sulfur and associated microorganisms (Fig. 2a). Diffuse venting of a warm (up to 80 °C) hydrothermal brine appears to fill the small depression from below, but very little free gas (i.e., as venting gas bubbles) is visible. Black Point, also located within the main caldera (Latitude 38°38'13.9961", Longitude 15°06'18.0177"), is a large (~20 by 25 m) sediment-filled basin with vigorous gas and fluid venting (Fig. 2b), and is named for a ~0.5 m tall smoker-type chimney located within the basin (noted in Fig. 2b). The vent fluids and outer-most mineralized zone of the chimney are enriched in Fe and Mn, consisting of metal sulfides and oxides, including galena, pyrite, marcasite, sphalerite, as well as the barium sulfate mineral barite (Becke et al., 2009). The La Calcara site is an expansive area of sediments several hundred square meters in size characterized by diffuse hydrothermal gas and water venting, located outside the main caldera and just offshore Panarea (Fig. 2c; Latitude 38°38'40.7129", Longitude 15°04'32.6926"). Sediment ripples are commonly crested with white mats; orange-red sediments (presumably Fe- and Mn-oxides) occur along the periphery. In some areas at La Calcara, gas venting is very intense, similar to that occurring at Black Point, but fluid flow rates never approach what would be considered a typical “focused” hydrothermal vent (Fig. 2c). Fluids collected from one of these intense gas venting areas at La Calcara are referred to as “gas-rich fluids” (GRF) for the remainder of the manuscript.

## 3. Methods

### *3.1 Sampling and geochemical analyses*

Three types of fluids were collected by SCUBA divers: 1) focused vent fluids, VF (only at Black Point), 2) fluids associated with free gas emissions (only at La Calcara;

GRF = gas-rich fluids), and 3) pore fluids (from all 3 sites; SPF and RPF, see below). VF and GRF were both collected with BD® sterile 60 mL syringes from the outlet of an inverted funnel placed over the vent after the temperatures of the exiting fluids stabilized. Pore fluids were collected in 2 different ways: syringe pore fluids (SPF) were collected from ~10 cm sediment depth by inserting a small (~1 cm diameter) polycarbonate tube with a pipette tip attached, and slowly drawing fluids into BD® sterile 60 mL syringes. To minimize seawater contamination, the first 20 ml of each sample were discarded through a 3-way valve. Rhizon pore fluids (RPF) were obtained from sediment cores collected with polycarbonate tubes and rubber end caps (Seeberg-Elverfeldt et al., 2005). Background seawater was sampled ~1 km from the area of hydrothermal venting.

Temperatures were measured *in situ* with probes in a custom-built underwater housing (Max Planck Institute for Marine Microbiology, Bremen, Germany). Onshore, a WTW pH meter 3210 and a Mic-D electrode with temperature compensation was used to measure the pH of each sample. Aliquots for $H_2S$ concentration measurements were preserved in the field by the addition of 1 ml of a 50 mM zinc acetate solution to 3 ml of sample to precipitate zinc sulfide. The preserved sample aliquots were then frozen. Once back in the laboratory, aliquots were thawed and analyzed for decreased light intensity caused by the ZnS precipitate with a Merck photometer at a wavelength of 670 nm (Cline, 1969; Moest, 1975). Alkalinity titrations were performed following the methods of Grasshoff et al. (1983). Analytical uncertainties were approximately ± 0.1 ºC for temperature, ± 0.1 for pH, and ± 5 % for $H_2S$ and alkalinity measurements.

Samples for anion (Br, Cl, $SO_4$) analyses were filtered in the field (using a 0.2 μm mesh) and then frozen until measurement by ion chromatography (Dionex IC system

housed at the University of Bremen). No salt precipitation was observed after thawing. Samples for elemental analyses (Na, Ca, K, B, Sr, Si, Ba, Mn, and Fe) were filtered in the field (0.2 μm) and acidified using ultrapure double distilled $HNO_3$ to 1 % by volume (note: for all vent samples, Si exists as $H_4SiO_4$ (Gunnarsson and Arnorsson, 2000), but will be referred to as Si for the remainder of this paper). The preserved sample elemental concentrations were then measured by inductively coupled plasma – optical emission spectrometry (Perkin-Elmer Optima 3300 ICP-OES housed at the University of Bremen). Li, Rb, and Cs were measured by high-resolution double-focusing inductively coupled plasma – mass spectrometry (Thermo Finnigan Element 2 ICP-MS housed at the University of Bremen). The instrument limit of detection (LOD; in □g/L unless otherwise noted) for each element analyzed, calculated by multiplying 3 by the standard deviation of a blank sample, was: Na (3), Ca (0.01), K (0.27), B (0.05), Sr (0.19 μg/L), Si (0.42 μg/L), Ba (0.21 μg/L), Mn (0.32 μg/L), Fe (2.4 μg/L), Li (20.7 ng/L), Rb (10.0 ng/L), Cs (4.6 ng/L), Cl (0.2), Br (0.1), and $SO_4$ (0.2). The analytical uncertainty, determined by averaging the uncertainties of field duplicates, was consistently better than 2 % for Na, Ca, K, B, Sr, Si, Ba, and Mn, and better than 3% for Fe. Chloride, Br, and $SO_4$ uncertainties were consistently better than 0.5%, while uncertainties for Li, Rb, and Cs were consistently better than 3, 2, and 1 %, respectively. Dilution was necessary in order to account for the high salt content in the fluid samples, and all data are blank and dilution corrected.

Gas sampling was carried out by first placing a stainless steel funnel, with the large opening in the sediments, over an area of gas bubble venting (Müller, 2011). Glass sampling tubes with valves on each end were filled with seawater before the dive, then

connected to the top of the funnel. Once the gas had completely replaced the seawater and flushed through for approximately 1 minute, the valves were closed. Samples were then transferred to the National Institute of Geophysics and Volcanology (INGV) for analysis. The dissolved gases were extracted from water samples after the attainment of equilibrium (at constant temperature) between the water sample and a known volume of high purity argon, which was injected inside the sampling bottle (Müller, 2011). Analyses were carried out by a Perkin Elmer 8500 gas chromatograph equipped with a double-detector (TCD-FID) using argon as carrier gas.

Samples for Sr isotope analysis were selected across the range of temperature and Mg concentrations, and prepared following the method described in Price et al. (2013b). Briefly, sample splits (0.2 to 1 mL) were transferred into 15 mL Teflon beakers and dried down on a hotplate at <80 °C. The solid, pure white residue was then dissolved in a 4 ml mixture of ultrapure double distilled concentrated HF and $HNO_3$ (proportion of 3:1 by volume). The sealed Teflon beakers were left on a hotplate for 48 h at ~90 °C to ensure complete digestion. The samples were dried and subsequently re-dissolved first in ultrapure concentrated $HNO_3$ and then in ultrapure concentrated HCl acid. Finally, the dried solid residues were re-dissolved in 2.5 M ultrapure HCl, centrifuged, and passed through a cation exchange column to purify the Sr. The same procedure is used for routine rock analysis and ensures that all mineral phases are effectively dissolved, which provides a high degree of confidence that our analyses are representative of the entire sample. The purified Sr splits (14 ml) were dried on a hotplate, re-dissolved in 2 M HCl and then ~1/6 to ~1/8 of the sample was loaded onto outgassed W filaments coated in a $TaCl_5$ solution.

Strontium isotope ratios were measured on a Thermo Scientific TRITON-series multi-collector thermal ionization mass spectrometer (MC-TIMS, Univ. Leeds) running in static mode. The $^{87}Sr/^{86}Sr$ ratios were normalized to an $^{86}Sr/^{88}Sr$ ratio of 0.1194 to account for mass fractionation. The reported $^{87}Sr/^{86}Sr$ values were normalized to NIST SRM-987 standard values of $^{87}Sr/^{86}Sr = 0.710248$ (McArthur et al., 2000). The instrumental errors were always better than $6 \times 10^{-6}$ of the mean of 180 single determinations. The total blank concentrations for Sr were negligible (<100 pg) compared to the Sr concentration of the samples analyzed.

The saturation index of anhydrite, $\Omega_{anhydrite}$, was calculated as a function of temperature using

$$\Omega_{anhydrite} = IAP/K_{sp} \quad (1)$$

where IAP and $K_{sp}$ stand for the ion activity product and saturation product of anhydrite, respectively. Values of IAP are calculated using

$$IAP = a_{Ca^{2+}} \cdot a_{SO_4^{2-}} \quad (2)$$

and the activities of $Ca^{2+}$ and $SO_4^{2-}$, $a_{Ca^{2+}}$ and $a_{SO_4^{2-}}$, respectively, are calculated using the concentrations of these species in seawater, 11 m*m* and 28 m*m*, and

$$a_i = \gamma_i \left( \frac{C_i}{C_i^{\theta}} \right) \quad (3)$$

$\gamma_i$ stands for the activity coefficient of the *i*th species and $C_i$ and $C_i^{\theta}$ denote the concentrations of the *i*th species in seawater and under standard state conditions, respectively. Standard state conditions for aqueous species stipulate that the concentrations of a species is taken to be equal to one molal referenced to infinite dilution. Values of $\gamma_i$ were in turn computed as a function of temperature and ionic strength using an extended version of the Debye-Hückel equation (Helgeson, 1969). Values of $K_{sp}$ were calculated as a function of temperature and pressure in the same manner as the other equilibrium constants (see below).

End-member concentrations were calculated using the 'zero-Mg' method, which assumes all magnesium has been removed from the hydrothermal reservoir fluids prior to any mixing with seawater. In this case, the end-member compositions were calculated according to the following formula:

$$X_{hf} = \frac{Xm - Xsw\ (Mgm/Mgsw)}{1 - (Mgm/Mgsw)} \qquad (4)$$

where $X_{hf}$ is the calculated end-member concentration, $X_m$ is the measured concentration and $X_{sw}$ is the concentration in seawater (Pichler et al., 1999).

*3.2 Bioenergetic computations*

The amount of Gibbs energy available from a given chemical reaction ($\Delta G_r$) can be calculated using

$$\Delta G_r = -RT \ln \frac{K_r}{Q_r}, \qquad (5)$$

where $K_r$ and $Q_r$ refer to the equilibrium constant and reaction quotient of the reaction, respectively, $R$ represents the gas constant, and $T$ denotes temperature in Kelvin. $\Delta G_r$ is then divided by the number of electrons in each metabolic reaction to give moles per electron transferred. Values of $K_r$ were calculated using the revised-HKF equations of state (Helgeson et al., 1981; Shock et al., 1992; Tanger and Helgeson, 1988), the SUPCRT92 software package (Johnson et al., 1992), and thermodynamic data taken from (Schulte et al., 2001; Shock and Helgeson, 1988; Shock and Helgeson, 1990; Shock et al., 1989; Sverjensky et al., 1997). Values of $Q_r$ were calculated using

$$Q_r = \prod_i a_i^{\nu_i}, \qquad (6)$$

where $a_i$ stands for the activity of the $i$th species and $\nu_i$ corresponds to the stoichiometric coefficient of the $i$th species in the reaction of interest. Molalities of the $i$th species, $m_i$, were converted into activities using individual activity coefficients of the $i$th species ($\gamma_i$),

$$a_i = m_i \gamma_i . \qquad (7)$$

Values of $\gamma_i$ were in turn computed as a function of temperature and ionic strength using an extended version of the Debye-Hückel equation (Helgeson, 1969).

Values were also normalized to energy per kg of $H_2O$, $E_{H_2O}$, and were calculated using (LaRowe and Amend, 2014):

$$E_{H_2O} = \frac{-\Delta G_r}{v_i} * [i] \quad (8)$$

where $\Delta G_r$ refers to the Gibbs energy of reaction per reaction turnover, $v_i$ stands for the stoichiometric coefficient of the *i*th species and [*i*] represents the molal concentration of the *i*th electron donor or acceptor per kg of seawater.

## 4. Results

Field and laboratory geochemical data for three hydrothermal sites at Panarea are presented in Table 1. Data are arranged by site (Hot Lake, Black Point, and La Calcara), then by sample type (RPF, SPF, VF or GRF) within each site grouping, and finally with RPF fluids arranged subsequently by depth. *In situ* pore fluid temperatures were generally 35 to 80 °C at Hot Lake, 40-100 °C at Black Point, and 45-80 °C at La Calcara (Figs. 3a and 3b). The zone with the most vigorous gas venting measured up to 135 °C at ~10 cm into the sediments at La Calcara. Vent fluids at Black Point also reached 134 °C, which is consistent with more than 2 decades of measurements from these sites (Italiano & Nuccio, 1991). The pH of pore fluid at the three sites was commonly circumneutral to slightly acidic (5-7), with a few measurements at Hot Lake and Black point more acidic (~3; Table 1; Figs. 3a and 3c). Pore fluid $H_2S$ concentrations were higher at Hot Lake (up to 2.5 mM) than at Black Point (up to 0.61 mM) and La Calcara (consistently

indistinguishable from the detection limit (0.01 mM); Figs. 3b and 3c). For comparison, ambient seawater temperature was ~20 °C, pH 8.0, and $H_2S$ concentrations were below detection.

Overall, major element concentrations (that is, the elements typically found in highest concentrations in seawater) were highly variable. Magnesium concentrations ranged from 35 to 60.4 mM in the vent fluids, while seawater was 58.3 mM (note: salinity of Mediterranean seawater is generally higher (~38‰) than 'typical' seawater (~35‰) as a result of evaporation without sufficient rainfall to balance outputs). Sulfate concentrations in vent fluids ranged from 5.4 to 32.1 mM, less than the seawater concentration of 32.9 mM. On a site-by-site comparison, Hot Lake fluids are generally more depleted in Mg and $SO_4$, and more enriched in all of the other major and trace elements, compared to the other two sites (Table 1). The other major cations, Na, Ca, K, B, and Sr had mM concentrations ranging from 452 to 740, 9.1 to 390.0, 8.5 to 86.7, 0.3 to 20.2, and 0.08 to 2.0, respectively. This is compared to seawater values of 547, 11.1, 11.0, 0.46, and 0.09 mM, respectively. Bromine and Cl ranged from 0.3 to 2.2 and 510 to 1410 mM, which compared to seawater values of 0.94 and 618 mM, respectively.

Trace element concentrations were highly variable. Like the major elements (except Mg and $SO_4$), they typically showed enrichment over seawater values. Silica ranged from 0.01 to 3.5 mM, with seawater concentration of 0.04. Iron, Mn, Ba, Li and Rb were all in the μM range, with concentrations ranging from below detection to 354, 0.1 to 9050, 0.1 to 21.5, 8.3 to 6180, and 1.0 to 275, respectively. Seawater concentrations of Fe and Mn were below detection by our analysis method, and we have reported published values of 0.017 μM (Achterberg et al., 2001) and 0.0055 μM (Lan and

Alfassi, 1994), respectively. Cesium concentrations showed orders of magnitude variability, ranging from the seawater value of 2.0 to as high as 47090 nM.

Strontium isotopic ratios for selected samples ranged 0.709208 to 0.706642. Seawater $^{87}Sr/^{86}Sr$ was 0.709160. Although sparse, the $^{87}Sr/^{86}Sr$ data seem to reflect the special character of Hot Lake fluids, having the least radiogenic value (0.706642).

## 5.0 Discussion

The location in a hydrothermal system where hydrothermal processes take place can be divided into three main areas - the recharge, subseafloor reaction, and discharge zones - which in reality cover a continuum of processes occurring in a dynamic system (Alt, 1995). In a simplified model, the major processes affecting hydrothermal vent fluid chemistry take place as follows: Heating up of the cold, entrained seawater which has entered the crust in the recharge zone, and the onset of low temperature water-rock reactions (Berndt and Seyfried, 1993; Berndt et al., 1988). This includes oxidation/alteration of the crust, and fixation of Mg, alkalis and B (Alt, 1995). This process forms smectite at lower temperatures and chlorite at higher temperatures, and can be generally described by the following reaction (Tivey, 2007):

$$4(NaSi)_{0.5}(CaAl)_{0.5}AlSi_2O_8 + 15Mg^{2+} + 24H_2O \Rightarrow$$
$$3Mg_5Al_2Si_3O_{10}(OH)_8 + SiO_2 + 2Na^+ + 2Ca^{2+} + 24H^+ \qquad (9)$$

where $4(NaSi)_{0.5}(CaAl)_{0.5}AlSi_2O_8$ represents anorthite+albite making up the basement rocks, and $3Mg_5Al_2Si_3O_{10}(OH)_8$ is chlorite. Note that abundant Na and Ca is mobilized,

along with $SiO_2$ and concomitant acidification. However, experimental results suggest that uptake of Mg by rock is more or less balanced by mobilization of Ca to the fluids (Bischoff and Rosenbauer, 1989; Mottl, 1983). Most of this Ca will combine with $SO_4$ and be removed by subsequent precipitation of anhydrite ($CaSO_4$; Alt, 1995). Continued heating in the "subsurface reaction zone" of the hydrothermal system causes high temperature reactions that include mobilization of alkalis, Fe and Mn (Alt, 1995; Alt et al., 1986; German and Von Damm, 2003). Deeper in the system, anorthite is altered to albite, a process called albitization, with Na and Si being added to the crust in exchange for Ca, which is released from the rock into the fluid (Alt, 1995; Berndt, 1987; Berndt et al., 1989; Mottl et al., 1974; Seyfried et al., 1988; Seyfried et al., 1991; Tivey, 2007; Wolery and Sleep, 1976). This reaction can be stated generally as:

$$CaAl_2Si_2O_8 + 2Na^+ + 4SiO_{2(aq)} \Rightarrow 2NaAlSi_3O_8 + Ca^{2+} \qquad (10)$$

Note the removal of Na and addition of Ca during the formation of albite. Near the magma chamber, acidic magmatic fluids and magmatic volatiles ($H_2O$, $CO_2$, $SO_2$, $H_2S$, $H_2$, He), can be introduced to the newly evolved hydrothermal fluids, along with very high temperature reactions of the new fluid with host rocks, including deposition of magma-derived $SO_4$ as anhydrite, titration of acidity, and further metal mobilization (Craig and Lupton, 1981; Gamo et al., 1997; German and Von Damm, 2003; Hannington et al., 2005; Lupton et al., 2008; Reeves et al., 2011). Subsequently, both "supercritical" and "subcritical" phase separation can occur. Above the critical point, "supercritical" phase separation can occur and create a high-salinity vapor (≥3.2 wt% NaCl) by

*condensation* of a small amount of liquid (Alt, 1995; Bischoff and Rosenbauer, 1985; Foustoukos and Seyfried, 2007; German and Von Damm, 2003). Recent evidence suggests that supercritical fluids occurring near a magma chamber can ‘compact’ without crossing the two-phase solvus (i.e., do not boil), thus creating very high salinity fluids crucial for development of high sulfide epithermal mineral deposits (Hedenquist and Lowenstern, 1994; Heinrich et al., 2004). However, *subcritical* phase separation below the critical point of seawater occurs as a result of decompression during upflow, wherever the 2-phase boundary is intercepted, producing ~3.2 wt% NaCl liquid coexisting with a low-salinity vapor (Berndt et al., 2001; Foustoukos and Seyfried, 2007; Seyfried et al., 2003). This process is essentially boiling, creating a gas-rich vapor phase and residual brine. Phase segregation, or separation of the low salinity vapor from the high salinity brine, can occur, which plays a crucial role in creating the large range of chlorinities often observed in hydrothermal fluids (Butterfield et al., 1990; Edmonds and Edmonds, 1995; German and Von Damm, 2003; Ishibashi, 1995; Tivey, 2007; Von Damm et al., 2003). Resulting brine phases are sometimes not able to ascend due to their high density (Alt, 1995), ultimately leading to a ‘layered’ hydrothermal system ("double-diffusive convection"; Bischoff and Rosenbauer, 1989; Butterfield and Massoth, 1994; Nehlig, 1993). In this case, fluids in the lower, denser layer recirculate and become more concentrated, while the upper layer has a ‘single-pass’ mixing with seawater (Bischoff and Rosenbauer, 1989). Rapid upflow of hydrothermal fluids occurs in the upflow zone, and can create both focused or diffuse discharge (note: ‘diffuse’ in this sense indicates vent fluids are not sufficiently channeled or focused to reach the seafloor directly while focused fluids indicate direct discharge of fluids from the subsurface reservoir; Alt,

1995). Focused flow is often accompanied by formation of epidosite (Alt, 1994; Nehlig, 1993). Secondary acidity can be generated by Fe sulfide deposition in both diffuse and focused upflow zones, and quartz precipitation is abundant (Alt, 1995; German and Von Damm, 2003; Hanningtion et al., 2005). During diffusive upflow, more mixing with overlying seawater occurs. Heating of this entrained seawater can cause deposition of admixed seawater $SO_4$ as anhydrite. If fluids fall below anhydrite stability temperatures, dissolution of previously formed anhydrite deposits can occur (Tivey, 2007). Additional low temperature water/rock reactions, such as boron fixation, may also occur prior to venting at the seafloor (Alt, 1995; Reeves et al., 2010). Mineral precipitation can occur upon cooling and due to redox reactions, which further removes some ions such as Si, Fe, and Mn very near the seafloor.

The identification and description of these processes are primarily from deep-sea hydrothermal vents. Much less is known about the subsurface processes taking place at shallow-sea hydrothermal vents. Although many of the processes occurring at deep-sea vents also occur in shallow-sea hydrothermal environments (Price et al., 2012), shallow-sea vents are by their very nature discharging at substantially lower pressures than those commonly found in deep-sea environments (Fig. 4). As a result, free gas phases are common in shallow-sea vent systems (Dando et al., 1995). This may lead to enhanced gas exsolution (formation of free gas bubbles or degassing)(e.g., Caracausi et al., 2005; Lupton et al., 2008), and may therefore substantially alter fluid chemistry by mass transfer from gas to aqueous phase (e.g., $CO_2$, $H_2S$ scrubbing). Finally, it is important to note that most shallow-sea vent systems, including Panarea, are associated with arc volcanoes. These felsic-hosted magmatic hydrothermal systems contain more degassed

volatiles than their mid-ocean ridge counterparts. This can lead to much more acidic fluids, and subsequent leaching of Mg from host rocks (Reeves et al., 2011; Yang and Scott, 1996). These characteristics make shallow-sea hydrothermal venting distinctly different from their deep sea counterparts. Here we evaluate the potential subsurface processes taking place at Panarea, leading to an improved model for the evolution of the hydrothermal fluids. As a reference, we illustrate the main processes outlined above in Fig. 5.

*5.1 General observations and mixing trends*

The major element chemistry of vent fluids at Panarea suggests that a variety of subsurface processes may contribute to the geochemistry of each of the investigated sites. The Mg and $SO_4$ concentration for all samples are shown in Fig. 6a. For reference, horizontal and vertical lines indicate seawater concentrations of $SO_4$ and Mg, respectively. These data indicate that many, but not all, hydrothermal fluids analyzed during this study are depleted in Mg and $SO_4$ relative to seawater. Furthermore, the covariation between Mg and other major elements indicates a ‘triple trend’ mixing pattern (Figs. 6b and 6h). Enrichment of most major cations and anions occurs within (1) the Hot Lake pore fluids, (2) the focused vent fluids from Black Point, and (3) the gas-rich fluids from La Calcara, while La Calcara and Black Point pore fluids do not follow this pattern of enrichment (Table 1). Furthermore, mixing between seawater and the Hot Lake fluids is different when compared to Black Point vent fluids and La Calcara gas-rich fluids (Figs. 6b-6h). The regression line connecting the seawater value and Hot Lake fluid data points is much steeper when compared to the other two sites, and as such

suggests the possibility for a much higher salt content as a source fluid. Thus, there must be more than one hydrothermal end-member for the vent fluids, and the pore fluids collected from Black Point and La Calcara, although high temperature and low pH, evolved in a different manner than the other fluids.

As defined by the disparate mixing trends, all the fluids measured during the course of this study can be categorized into three major groups. The fluids most enriched in major elements relative to seawater (i.e., the Hot Lake pore fluids), are regularly referred to as 'Type 1' fluids. The vent fluids from Black Point, along with gas-rich fluids from La Calcara, follow similar compositional trends and are therefore labeled as 'Type 2' fluids. In contrast, pore fluids from Black Point and La Calcara, which do not generally show enrichments of major cations and anions, will be referred as 'Type 3' fluids. These distinctions allow for the identification of mixing trends with seawater and separate hydrothermal end-members.

### *5.2 Subsurface evolution of hydrothermal fluids*

#### *5.2.1. The End-members*

The subsurface evolution of the hydrothermal fluids at Panarea can be investigated by calculating the end-member hydrothermal reservoir composition(s), which is often carried out assuming a Mg concentration of zero in the hydrothermal end-member (the "zero-Mg" extrapolation method; Bischoff and Disckson, 1975; Mottl et al., 1974). This assumption is made on the understanding that Mg should be almost entirely removed from the hydrothermal fluids as a result of water-rock interactions above ~150 °C. Unlike most deep-sea submarine hydrothermal vent fluids, Mg and $SO_4$ do not

extrapolate to zero concentration for the Panarea fluids (see projected intercept on Fig. 6a). Vent fluids have sulfate concentrations below what would be expected for simple seawater mixing. This may be due either to sulfate reduction or precipitation of anhydrite below the seafloor (Butterfield and Massoth, 1994). Most fluids extrapolate to $SO_4$ = zero at ~30 mM Mg (Fig. 6a), although two Type 2 vent fluids extrapolate to zero-$SO_4$ at zero-Mg. The negative sulfate intercepts are most likely due to some seawater entrainment into the near-seafloor plumbing system resulting in sulfate removal as anhydrite, while Mg remains in solution and is vented (i.e., seawater entrainment at temperatures high enough for anhydrite to precipitate but not high enough for water-rock interactions to remove all Mg (Butterfield and Massoth, 1994)). Given the abundant anhydrite present within Panarea sediments (see later discussion), this is a likely scenario. This would furthermore explain why only the very high temperature fluids have $SO_4$ depletion relative to Ca (Table 1). Following this line of thinking, using Mg = 0 is still a valid assumption.

*5.2.2. Subsurface Processes*

In Table 2, we report the calculated hydrothermal end-members based on Mg = 0 mM in the deep hydrothermal reservoir fluid. In the case of most pore fluids for Black Point and La Calcara, concentrations are too close to seawater in composition to accurately determine the end-member, and thus mostly only Type 1 and Type 2 fluids are reported. Our calculations confirm that the hydrothermal reservoir fluid feeding Hot Lake has a much higher salt content overall after removing the seawater component (Table 2). For example, Hot Lake Na concentrations ranged from 471-1113 mM (mean 960; n = 20), compared to 444-463 (mean 452; n = 3) and 306-317 (mean 312; n =2) mM for

Black Point and La Calcara vent fluids, respectively (Fig. 7a). Calcium concentrations were a mean of 570 mM at Hot Lake, compared to a mean of 150 and 112 mM for Black Point and La Calcara, respectively (Fig. 7b). The higher salt content of the reservoir feeding Hot Lake is also reflected in K, B, Sr, and Br end-member data (Table 2). Chloride concentrations are exceptionally elevated in concentration (Tables 1 and 2; Figs. 7a-7b), and chloride end-member concentrations reach a mean value of 2220 mM for Hot Lake fluids, and 847 and 532 for Black Point and La Calcara, respectively. In comparison to other systems (e.g., mid-ocean ridge and back-arcs), the Panarea concentrations are much higher. For example, in Figs. 7a-7b, typical end-member concentrations of Na and Ca in various hydrothermal systems are plotted. Not only do Na values for Hot Lake (Type 1) fluids reach higher values, but Cl concentrations are more than double that typically calculated for any other deep-sea hydrothermal system.

As described at the beginning of the discussion and illustrated in Fig. 5, several processes can contribute to these compositions. Experiments have shown that often the observed salinities in hydrothermal vent fluids cannot solely be explained by phase separation (Bischoff and Rosenbauer, 1987), and it was suggested that the observed variations in mid-ocean ridge hydrothermal fluids could only be explained if seafloor geothermal systems consist of two vertically nested convection cells (Bischoff and Rosenbauer, 1989). The lower cell, composed of highly saline brine, circulates at depth within the cracking front and transfers heat and some salt to the overlying seawater (single pass) cell during double-diffusive convection (this is illustrated in detail in Fig. 5). If the hypothesis of a double-diffusive deep recirculating brine is true, then one could

imagine all elements in this zone could be further enriched through distillation over time. This could explain the ‘extreme’ concentrations of major elements in Type 1 fluids.

For most mid-ocean ridge fluids, the Na/Cl ratios for vents with elevated chlorinity are not scattered but define a reasonably straight line that departs from the seawater evaporation trend with lower Na, and the relative Na deficiency with increasing Cl is made up primarily by increasing Ca (Bischoff and Rosenbauer, 1989). We observe a similar trend for the Panarea data (Table 2 and Figs. 6a-6b). These data indicate two co-occurring phenomena: first, Cl enrichment as a result of the concentrating effect of the phase separation (see below) and the formation of a double-diffusive, recirculating brine deep reservoir, and second, Na/Ca variation as a result of water-rock interactions (Fig. 5). Sodium can be removed from the fluids as a result of Na–Ca replacement reactions in plagioclase feldspars, i.e., albitization. On a chloride-normalized basis, Na is decreased in hydrothermal fluids relative to seawater, suggesting Na removal (Table 2). On the other hand, Ca, K, and Sr are higher relative to seawater (again, on a Cl-normalized basis), suggesting enrichment of these elements. Low Na/Cl and high Ca/Cl fluid ratios relative to seawater can be inferred to be caused by albitization (Gallant and Von Damm, 2006). The observed Na/Cl and Ca/Cl ratios in the Panarea fluids follow this trend, although they plot separately from most deep-sea systems, particularly for Type 1 fluids (Fig. 7c). This suggests that significant replacement of Na with Ca is occurring, particularly for Type 1 (Hot Lake) fluids (Figs. 7a-7c). However, because the ratios fall on more or less the same trend as other vents, it is likely that these elements are concomitantly enriched in the brine reservoir. Furthermore, the deviation of the data for Panarea (more Ca, less Na), is most similar to that observed for other arc- and back-arc related hydrothermal

systems, relative to mid-ocean ridge systems (Figs. 7a-c). Strontium is, like Na and Ca, solubility controlled (Berndt et al., 1988), and the Sr/Cl ratios reflect similar trends in the Type 1 fluids (Fig. 7d). High Ca concentrations and low Sr/Ca also provide evidence for albitization because Sr is partitioned strongly into albite; fluids which have formed Na-rich plagioclase should have a lower Sr/Ca ratios (Butterfield and Massoth, 1994).

The co-variation between the Sr concentrations and the $^{87}Sr/^{86}Sr$ for selected fluid samples from this study and Panarea volcanic rocks (igneous rocks from the surrounding islands; Calanchi et al., 2002), are displayed in Figure 7c. Also included for comparison are values from a locally deposited volcanic ash layer, which can reach up to 9.5 m thick on Panarea Island (Calanchi et al., 2002; Calanchi et al., 1999), and vent precipitates associated with the Black Point chimney edifice (unidentified but possibly "strontiobarite" or related metal sulfides; Becke et al., 2009; Sieland, 2009). As pointed out above, the basement rocks of Panarea are actually somewhat heterogeneous, having transitional compositions between the western and eastern arc (Calanchi et al., 2002). We've highlighted the $^{87}Sr/^{86}Sr$ and 1/Sr fields for these rocks, noted as "Stromboli Affinity" and "Western Arc Affinity" in Figure 7e. This suggests that the hydrothermal fluids at Panarea are equilibrated more with the rocks of Stromboli affinity. The ash layer is reported to consist of glassy calc-alkaline basalt to basaltic-andesite, plus a thin interbedded trachytic ash with potassic-alkaline character, possibly sourced from nearby Stromboli volcano (Calanchi et al., 1999).

The $^{87}Sr/^{86}Sr$ ratio and Sr concentrations depend on the extent of water/rock interaction as function of temperature and bedrock lithology (Berndt et al., 1988). Laboratory experiments consisting of diabase and seawater at 375-425°C and 375-400

bars produced dissolved Sr/Ca ratios in close agreement with those observed in ridge crest hot springs, while basalt alteration produced ratios that were much lower. This suggests that interaction of hydrothermal fluids with diabase deeper in the hydrothermal system – not basalt in the shallower areas – at high temperatures is a good analog to subsurface processes responsible for production of ridge crest fluids (Berndt et al., 1988). This suggests that most hydrothermal fluids in mid-ocean ridge environments are obtaining their compositions deep in the ridge system. The general trends observed for Panarea fluids suggest a similar trend, and therefore deep-seated reactions may dominate the overall evolution of the fluids.

*5.2.3. Phase separation vs. Degassing*

Previous investigators have suggested the possibility of phase separation at Panarea (e.g., Sieland, 2009; Tassi et al., 2009). Most of the Type 3 fluids have Cl values less than seawater (Table 1), and a plot of Cl vs. Na suggests that (subcritical) phase separation and phase segregation may have occurred (Fig. 8a). We note in this figure also that the fluids with Na and Cl less that seawater concentrations trend towards a zero concentration, and that above seawater concentrations the decrease in Na is again obvious, suggesting Na removal. Chloride and Br are typically thought to be little affected by water-rock interactions. Figure 8b indicates that these two elements linearly correlate ($r^2$ = 0.99 for all data points), but that concentrations for both can be below seawater values, and extend to zero. Bromide, as viewed through the Br/Cl ratio, can be fractionated from chloride whenever halite is formed or dissolves, because bromide is preferentially excluded from the halite structure (the ratio increases during halite

precipitation, but decreases halite dissolution; (Oosting and Von Damm, 1996; Von Damm, 2000). Fluids that have precipitated halite will therefore have high Br/Cl ratios, while fluids that have dissolved halite will have low Br/Cl ratios, relative to seawater. Measured values for Cl vs. Br/Cl indeed show significant deviation of the Br/Cl relative to seawater (Fig. 8c). However, organic matter degradation has been shown to increase Br concentrations to as much as 2.9 times seawater value, which can thus change the Br/Cl concentration relative to seawater (Martin et al., 1993). Alteration of volcaniclastic sediments can also alter the Br/Cl ratio (Martin, 1999). End-member Cl vs. Br/Cl ratios suggest that departures from the Br/Cl ratio of seawater can occur for Panarea hydrothermal fluids, although not significantly (Fig. 8d). This occurs for one Hot Lake fluid, and most of the La Calara and Black Point fluids. It is important to note that most Type 3 fluids calculated to negative values for Cl and Br (i.e. Cl and Br = 0). For these fluids the Br/Cl ratio would be zero, although for several of the Black Point Type 3 fluids, the bromide concentrations ranged from 0.1 to 0.4 mM. The Br/Cl ratio for these fluids would be above that for seawater, suggesting that, although we cannot plot these values, phase separation cannot be discounted.

Finally, if phase separation is occurring, the vapor phase should be enriched in neutral aqueous species reflecting the low-ionic strength of the solution and the associated salting-out effects in the highly ionic brine phase (Foustoukos and Seyfried, 2007). In this case, B/Cl ratios will tend to increase with Cl decrease due to the vapor enrichment in $B(OH)_{3(aq)}$. If the fluids from Black Point and La Calcara (Type 3) reflect the input of a low-salinity vapor phase, then the B/Cl molar ratios in these samples should

be larger than others. We only see evidence for this in one sample (Fig. 8e). Again, this suggests that phase separation is not a major process in the subsurface at Panarea.

However, invoking a lack of phase separation is problematic because it does not help explain the occurrence of the deep recirculating brine (the source of Type 1 fluids). It could be hypothesized that this brine may have been created by phase separation, followed by distillation and a continuing increase in salt content, but the Br/Cl and B/Cl ratios do not support this hypothesis. It is possible that this deep brine was generated by 'compaction' of supercritical fluids without crossing the two-phase solvus (i.e., does not boil; Hedenquist and Lowenstern, 1994; Heinrich et al., 2004). This, theoretically, could create the Type 1 fluids without deviations from the Br/Cl and B/Cl ratios. However, without more data we can only speculate at this time.

Type 3 fluids are hot and acidic, but have salinities that are near to that observed for seawater. One possible explanation is that seawater is being altered by the abundant free gas present in the system. Dissolved gases ($CO_2$, $H_2S$, etc.) are primarily present in vent fluids from magmatic volatile inputs. These dissolved gases can come out of solution to form free gas bubbles in two ways, both of which occur as a result of depressurization. The processes are: 1) boiling (i.e., sub-critical phase separation), and 2) exsolution, or phase transition from an aqueous to a gas phase (e.g., $CO_{2(aq)} \Rightarrow CO_{2(g)}$). Exsolution is a chemical process that occurs during (subcritical) phase separation (including boiling), while phase separation is caused by changes in physical conditions. Dissolved volatile species ($H_2$, $H_2S$) have a strong tendency to partition in the vapor phase during subcritical phase separation, but phase separation need not occur for free volatiles to form. While phase separation will always be accompanied by exsolution if the

parent fluid contains dissolved magmatic gases, exsolution does not require phase separation, only depressurization. As we have noted above, shallow-sea vent systems allow for depressurization without phase separation (Fig. 5). Exsolution, with or without phase separation, can result in scrubbing of those gases (e.g., $CO_2$ to create carbonic acid, $SO_2$ to create sulfide and sulfuric acid), delivering heat and other dissolved constituents which alter the fluid composition. Gas absorption or scrubbing involves the re-distribution of solutes between the gas and the liquid phase when the 2 phases come into close contact with each other (Delalande et al., 2011; Kenig and Górak, 2005; Rouwet and Tassi, 2011). However, some steam condensation must be involved to obtain the observed dilutions. Most likely, these processes co-occur. We therefore suggest that this phenomenon plays a key role in influencing the composition of Type 3 fluids. They are sediment pore fluids (i.e., buried and entrained seawater) which have been altered by mass transfer from free gas bubbles derived from depressurization release from the dissolved phase.

Although less common in deep-sea hydrothermal systems, free gas bubbles are nearly always present in shallow-sea hydrothermal systems due to lower pressures. Note that the P-T conditions for shallow-sea vents in Fig. 4 suggest this will be controlled primarily by changes in pressure, rather than temperature. The gases in the Panarea hydrothermal system are predominantly $CO_2$, $H_2S$, and trace $O_2$, $N_2$, CO, and $CH_4$ (Italiano and Nuccio, 1991). This is within typical values for shallow sea vent gases investigated to date (Dando et al., 1995; Italiano and Nuccio, 1991; Pichler et al., 1999). Thus, this phenomenon may be ubiqutious in shallow-sea vents, and evolution of Type 3 fluids may therefore be common in shallow-sea hydrothermal systems. Continuous gas-

liquid exchange in shallow-sea vents can create a new type of hydrothermal fluid, which is hot and acidic due to exchange of heat, $CO_2$ and $H_2S$, but which has close to seawater major ion concentrations. Small amounts of water vapor condensation will create slight dilutions in major ion chemistry of the sediment pore fluids. Furthermore, if the heat from these gases bubbling through seawater raise the temperatures to above ~130 °C (e.g., as observed for the shallow sediments at La Calcara and Black Point), anhydrite precipitation can occur, removing $SO_4$ but not Mg.

*5.2.4. Secondary Processes*

We note that some Mg values are higher than seawater, although concentrations are only slightly higher (<2 mM), and only for some of the Type 3 fluids (Fig. 5a). It has been suggested that higher than seawater Mg in hydrothermal fluids may possibly occur as a result of acid leaching of Mg from host rocks in arc/back-arc systems where the pH is exceedingly low (Gamo et al., 1997; Reeves et al., 2011; Resing et al., 2007). We hypothesize that acid alteration is causing the Mg enrichments in Panarea fluids. Argillic alteration occurs in highly acidic, often high sulfide conditions characteristic of near-seafloor (or near-surface) hydrothermal environments where oxidation $H_2S$ (or $SO_2$) produces sulfuric acid (Shanks III, 2012). Magnesium is often depleted in rocks from these zones, while K is enriched (Lowell and Guilbert, 1970; Pirajno, 2009; Shanks III, 2012; Tivey, 2007), suggesting the Mg enrichment should occur in resulting fluids. Alunite ($KAl_3(SO_4)_2(OH)_6$), a common product of argillic alteration, is common in Panarea sediments (Dekov et al., 2013; Prautsch et al., 2013), and during sampling abundant white clay materials were often observed in the lower portions of cores (~10-30

cm depth). As high temperature gases (primarily $CO_2$ and $H_2S$) move through sediment pore fluids, carbonic and sulfuric acid is produced. Thus, Mg is replaced by K in these shallow rocks and sediments, and Mg enrichment occurs. This furthermore helps explain lower K values in these fluids (Table 1).

Anhydrite precipitation may be a major influence on the composition of discharging fluids. Preliminary scanning electron microscopy (SEM) combined with energy dispersive X-ray analyses were carried out on hard precipitates found at the La Calcara gas-rich area. The results, shown in Figure 9a, reveal the first discovery of massive anhydrite deposits at the sediment/seawater interface in a shallow-sea hydrothermal system. Measured Ca vs. SO4 for Type 3 fluids trend from seawater values to zero concentration for each, suggesting complete removal of these elements (Fig. 9b). The first step in the formation of a deep-sea black smoker chimney is precipitation of an anhydrite framework caused by the heating of seawater as hydrothermal fluids first begin to discharge (Haymon, 1983). Anhydrite solubility (Ω), as a function of temperature using seawater as the starting fluid, was calculated by dividing the ion activity product (IAP) by the solubility product (Ksp) for the reaction of $Ca^{2+}$ with $SO_4^{2-}$ to produce $CaSO_4$. Data indicate that above ~100 °C (at saturation pressure), anhydrite becomes insoluble (Fig. 9c). Because the hydrothermal vent fluids observed at both Black Point and La Calcara were approximately 135 °C, anhydrite precipitation is expected in the shallow subsurface environments, although Ca appears to still be present in these fluids (Fig. 9b). This scenario could have led to the current “chimney” at Black Point. The high temperature site at La Calcara was not observed prior to 2009, but was present during both the 2009 and 2010 expeditions, suggesting that a chimney-type structure may be

forming there. Widespread anhydrite precipitation in the subsurface sediments surrounding the submerged caldera off Panarea was observed during drilling at the site, which revealed abundant massive anhydrite/gypsum as well as native sulfur. These precipitates were interpreted to represent a cap forming at the interface between seawater and geothermal fluids ascending towards the seafloor (Petersen et al., 2007).

Minor or trace elements, such as Si, Fe, Mn, Ba, Li, Rb, and Cs are also useful tracers of hydrothermal input because their concentrations are even lower in seawater. Concentrations of these elements compared to that of Mg illustrate the differences between each site investigated for this study. For example, several of the trace elements follow similar patterns as observed for K, Na, B, Sr, and Br vs. Mg and $SO_4$ (specifically, Mn, Ba, Li, Rb, and Cs are enriched only in Type 1 and 2 but not Type 3 fluids; Figs. 10a-10e). This suggests solubility controls on these elements. Silica is most elevated in the lowest Mg samples, particularly for Hot Lake (Fig. 10e). Furthermore, Black Point vent and pore fluid concentrations are elevated in dissolved silica, despite having near seawater Mg concentrations. Elevated silica concentrations in hydrothermal fluids are common, as silica is readily leached from the rocks hosting the hydrothermal fluids, and will only be removed upon cooling and precipitation (typically as silica sinter). Iron, in contrast to silica, is relatively low in all Black Point and Hot Lake fluids, while La Calcara Fe concentrations are much more elevated (Fig. 10f). Elevated Fe concentrations at La Calcara are not unexpected, as precipitates of Fe-(oxy)hydroxides are abundant.

### *5.3. Hypothetical Model*

A model of subsurface processes at Panarea was first proposed by Italiano and Nuccio (1991), and has since been suggested by others (Caracausi et al., 2005; Tassi et al., 2009; Sieland, 2009). Fluids were hypothesized to be derived from a high-Cl reservoir recharged from very deep in the system, and an overlying shallower, medium salinity reservoir (higher salinity relative to seawater but considerably lower salinity compared to the deeper high-Cl portion). We suggest here that the deeper high Cl reservoir could have been created by 1) direct condensation of a supercritical phase, and/or 2) double-layered convection, and the development of a closed, recirculating brine cell. Our data suggest that the Type 1 (Hot Lake) fluids are discharging from the deeper high-Cl reservoir directly to the seafloor. Overlying the deep brine cell, seawater is circulating through in a 'single-pass' system, thus diluting the higher element concentrations found in the deeper reservoir. Type 2 (Black Point vent and La Calcara gas-rich) fluids are being fed by this shallower reservoir. Finally, Type 3 fluids develop as dissolved gases exsolve at depth and rise rapidly to the surface, bringing heat, $CO_2$ and $H_2S$. This heat and gas is then transferred to sediment pore fluids near the composition of seawater. Each of these processes are illustrated in Fig. 5, which shows the special character of shallow-sea hydrothermal venting.

*5.4 Catabolic potential*

*5.4.1 Overview and Approach*

As illustrated by the trends outlined and discussed in the preceding sections, variability in the geochemistry of discharging fluids exists as a function of the mixing of seawater with different types of hydrothermal end-member fluids. This will ultimately

influence the microbial communities at each specific site through the availability of potential electron donors derived from each fluid type, and electron acceptors mainly derived from seawater.

In order to evaluate the theoretical spectrum of potential metabolic energies encountered at the Panarea sites, we selected data from two samples from each of the vent sites which represent both a high and moderate temperature for our energetics calculations. These samples also represent variability in fluid types encountered in the system. Temperature, along with Mg concentration, is one of the best ways to track hydrothermal fluid mixing with seawater. In this case, one fluid contained low levels of Mg (35 to 41.5 mM) and therefore represented fluids characterized by a relatively large hydrothermal fluid component (i.e., higher T), and the other was characterized by mid-range Mg levels (46.7 to 55.5 mM), more similar to seawater (lower T). The samples selected are highlighted in grey in Table 1, and indicated by a star in Figure 5a.

In order to quantify the potential metabolic activity of the hydrothermal system off Panarea Island, the Gibbs energies of the 61 reactions listed in Table 4 were calculated. These reactions contain all of the electron donors and acceptors that were measured during field expeditions during 2008-2010. However, in order to be able to calculate the potential metabolic activity at the site, we also included values not measured in this study (e.g., $H_2$, $CH_4$, $O_2$, $CO_2$, CO, $NH_4^+$), but that have been reported in other studies that were sampled from the same exact sites (Luther and Tsamakis, 1989; Müller, 2011; Sieland, 2009; Tassi et al., 2009; and the National Institute of Geophysics and Volcanology, Palermo (INGV)). For example, values for seawater concentration of Mn are from Klinkhammer et al. (1985). The iron concentration in seawater is taken to be the

equilibrium value calculated using Geochemist's workbench. In order to accurately calculate the Gibbs energies of these reactions, the *in situ* activities of the species in them were determined by carrying out speciation calculations at the temperature of interest using the concentration data given in Tables 1 and 3 and Geochemist's Workbench using the thermo.dat dataset. Seawater values for aqueous $H_2S$ are from Luther and Tsamakis (1989). Aqueous seawater values for $CH_4$, $H_2$, CO, and $N_2$ are from Charlou et al. (2002). $NO_3^-$ values at Hot Lake and La Calcara is an average of values from Tassi et al. (2009). Because dissolved $O_2$ at La Calcara was not reported, the equilibrium value for $O_2$ free gas concentrations were used. $NO_2^-$ at La Calcara is an average of the other sites. Available data for Hot Lake, Black Point, and La Calcara (e.g., $HCO_3$, $O_2$, $NO_3$, $NO_2$, $NH_4$, Fe, and Mn) are from Sieland (2009), Müller (2011), and Tassi et al. (2009).

Ideally, the concentration of all the reactants and products in the metabolic reactions would have been taken from the exact same samples in order to characterize the energetic potential of a particular fluid at a precise moment in time. However, these data were not collected, and excluding reactions containing these species would not accurately represent the metabolic potential of Panarea hydrothermal vents since they are known to exist there. Our first assumption is that some of these species (e.g., free gas phases, $CO_2$, $H_2S$, etc.), do not have significant temporal and/or spatial differences relative to the sampling. These data have been consistently similar, with very little difference in the gas compositions, over the past several decades (Italiano and Nuccio, 1991; Italiano, pers. comm), and we therefore consider this to be a safe assumption. It is clear that some dissolved species (e.g., $HCO_3$, $NH_4^+$, etc.) will change with mixing ratio between seawater and hydrothermal end member. For these data, we matched the fluid

temperatures and Mg concentrations reported in the literature with the measured temperature and Mg concentration for the sample chosen for the calculations. Despite these shortcomings, we consider the data set is adequate enough to allow us to estimate the potential metabolic activity at each site.

*5.4.2. Energetics per electron transferred*

The Gibbs energies of the 61 reactions listed in Table 4 are shown in order of exergonicity in Figures 11a and 11b. Each horizontal bar in these figures represents the calculated range of $\Delta G_r$ available from the indicated reaction for the temperature and chemical composition conditions of all six of the sample sites listed in Table 3. The color of the lines in Figures 11a and 11b indicates the type of electron acceptor (oxidant) and donor, respectively, in each reaction (as shown in the legend). The variable lengths of the bars are due to the stoichiometry of the reactions under consideration and the variable temperatures and compositions of the six study sites. As has been shown in similar energetic profiles (Amend et al., 2003b; Rogers and Amend, 2005; Rogers and Amend, 2006; Rogers et al., 2007; Shock et al., 2005; Shock et al., 2010), the range of $\Delta G_r$ spans from approximately 0 to -120 kJ (mol e-)$^{-1}$. Disproportionation reactions and those in which $S^0$, $SO_4^{2-}$, CO and $CO_2$ serve as oxidants are among the least exergonic reactions, typically less exergonic than -20 kJ (mol e-)$^{-1}$. However, it is worth noting that some of the reactions in which $O_2$, $NO_2^-$, $NO_3^-$, $N_2$, Fe(III), and Mn(IV) serve as electron acceptors also fall into the low end of the energy spectrum, despite their reputation for being highly exergonic oxidants (LaRowe and Van Cappellen, 2011). In fact, the energetics of those reactions in which these species are oxidants are found throughout the

range of Gibbs energies shown. Therefore, knowledge of the electron acceptor does not necessarily indicate the energetics, and thus the likelihood, of a given metabolic strategy being utilized in a particular setting.

*5.4.3. Energy density*

The exergonicity of potential catabolic strategies shown in Figures 11a and 11b can give a somewhat misleading impression of which reactions are most energetically relevant to microorganisms in a particular environment. For instance, the three most exergonic reactions shown in Figures 11a and 11b all have nitrite as an oxidant. However, the concentration of nitrite at the six samples sites is micromolal or less (and is expected to be so regardless of the data source). A more considered approach is to normalize the potential energy *per kilogram of $H_2O$* (e.g., (McCollom, 2000; LaRowe and Amend, 2014). The result of using this method is illustrated in Figures 11c and 11d, where the range of energy available per kilogram of $H_2O$ for the 61 reactions shown in Table 4 at the temperature and chemical composition conditions of all six of the sample sites are plotted. The horizontal bars refer to the energetics of reactions in the same order as those shown in Figures 11a and 11b. It can be clearly seen that the most exergonic reactions reported per mole of electron transferred in Figures 11a and 11b are not the most energy-rich reactions when presented as per kilogram of $H_2O$. Metabolisms that rely on nitrite as an electron acceptor are not substantial sources of energy. Additionally, some of the least exergonic reactions in Figures 11a and 11b, e.g., those in which Fe(III) and Mn(IV) are the oxidants, provide far more energy per kilogram of $H_2O$ than those that appear to be the most exergonic per mole of electron transferred. The values of $E_{H_2O}$

with the lowest energy yield for each reaction were used to generate Figures 11c and 11d, since in most cases either the electron donor or acceptor will be a limiting reactant. In order to carry out these calculations the activities of all reactants and products were held constant, simulating a steady state condition. The energetics of the disproportionation of $S^0$ (Reaction 37) was not included in this analysis since there is no limiting species other than the presence of $S^0$.

The amount of energy available varies by several orders of magnitude, as indicated by the length of the bars in Figures 11c and 11d. This is due to the broad range of methane concentrations at the sample sites. It is noteworthy that the amount of energy available from the oxidation of methane by $O_2$, $NO_3^-$, $NO_2^-$, goethite, pyrolusite, $S^0$ and $SO_4^{2-}$, per kg of $H_2O$, can all generate equivalent amounts of energy, depending on the site. In fact, in terms of oxidants, only $SO_4^{2-}$, (Reactions 9 and 10) is not capable of producing more energy than $O_2$ through the oxidation of $CH_4$. Per kg of $H_2O$, there is somewhat less energy available from reactions in which $H_2$ is an electron donor than that for $CH_4$. Also, there is a narrower range of energies derived from $H_2$ at the study sites than from methane. However, all of the $H_2$ oxidation reactions (except Reaction 23) can supply as much energy as $O_2$ (Reaction 12), which is similar to $CH_4$. Because the abiotic rate of the knallgas reaction is faster at higher temperatures (Foustoukos et al., 2011), we might expect that in the hottest hydrothermal systems, microorganisms would have to be able to catalyze the knallgas reaction (Reaction 12) faster than it happens abiotically. However, the concentrations of $H_2$ and $O_2$ used in this study are measured values of these species in this system and therefore the resulting energetics calculations are a direct reflection of the energetic potential of this system, which is our goal. The knallgas

reaction is not anywhere close to being a major supplier of energy when normalized to J / kg of $H_2O$, so we have opted to leave out further discussion of the biotic vs. abiotic rates of the knallgas reaction.

The most consistently energetic class of reactions per kg of $H_2O$ is those involving the oxidation of $H_2S$ and $S^0$, shown in Figures 11c and 11d. That is, Reactions 24-37 supply nearly 1 J / kg $H_2O$ or more at one or more of the sample sites. Furthermore, Reactions 24-27 and 31-34 supply > 10 J / kg $H_2O$ at one or more of the sample sites. By presenting the energetics of these reactions per kg of $H_2O$, it can be seen that sulfur oxidation ($H_2S$ and $S^0$) is likely a major source of energy for microorganisms living in the hydrothermal systems at Panarea.

The energetics of $Mn^{2+}$, $NH_4^+$ and $Fe^{2+}$ oxidation by various electron acceptors, Reactions 38-50, are also shown in Figures 11c and 11d. Ferrous iron oxidation provides a moderate range of energies at the six sample sites, between about 0.01 and 0.5 J / kg $H_2O$. Interestingly, the oxidation of $NH_4^+$ by $MnO_2$, Reactions 43 and 44, are the most energy yielding reactions considered in this study per kg $H_2O$, due mostly to the high concentrations of ammonium at some of the sites. For the same reason, the oxidation of $Mn^{2+}$, Reactions 38-40, could be moderate sources of catabolic potential, although they are not as rich in energy.

Oxidation of CO is generally a highly exergonic reaction per mole of electron transferred. However, when considered per kg of $H_2O$, it is among the least energy rich electron donors in Panarea hydrothermal fluids due to its low concentration, regardless of the oxidant (Reactions 51-59, see Figures 11c and 11d).

$NH_4^+$ oxidation provides more energy than $H_2S$ and $S^0$ (Figures 11c and 11d) at most sites. The highly exergonic $NH_4^+$ oxidation reactions are with $MnO_2$ as the oxidant (Reactions 43 and 44). These reactions are highly exergonic primarily due to the fact that, because $MnO_2$ is a mineral, it does not have a limiting concentration (i.e., the activity is taken to be 1). However, when the same calculations are conducted for $H_2S$, which also has high concentrations, the lower-concentration oxidants become the limiting reactants, resulting in less energy per kg $H_2O$. Thus, while $NH_4^+$ oxidation by $MnO_2$ appears to be a dominant metabolism, this is unlikely. This is because this bioenergetic calculation *assumes* the presence of $MnO_2$, but this mineral is clearly not present in, for example, the Hot Lake fluids. Thus, it is unlikely that Reactions 43 and 44 are a dominant metabolism utilized by the microorganisms at Panarea (i.e., the reactions of Mn-reduction should not occur because of the absence of $MnO_2$ minerals).

*5.4.4 Energetics comparison by fluid type*

Figure 12 summarizes the energy available from the same groups of reactions containing the same electron donors but has the $MnO_2$ oxidation reactions removed from the figure. This indicates that reactions containing $H_2S$ and $S^0$ are most likely to be the dominant metabolisms at each of the sites and fluid types investigated (note: reactions with very little available energy are omitted from this figure). $Mn^{2+}$ oxidation provides some energy at each of the sites investigated. $CH_4$ oxidation could also be a potential source of metabolic energy for the La Calcara gas-rich fluids due to the elevated concentrations of this electron donor at this site (Table 3). Although iron concentrations

were elevated at La Calcara relative to the other sites, oxidation of $Fe^{2+}$ does not provide a significant amount of energy (Fig. 12).

While $H_2S$ and $S^0$ oxidation by $O_2$ is similar between Hot Lake and La Calcara sites (e.g., each produces ~40 J per kg of $H_2O$), these reactions for Black Point vents yield much more energy. This is due to higher $O_2$ concentrations in the Black Point fluids, which is likely the result of the hydrology of the shallow subsurface at Black Point (i.e., more seawater entrainment occurs in the shallow seafloor sediments at Black Point, and thus more $O_2$ exists in these fluids; Italiano and Nuccio, 1991). This may be the key controlling factor when comparing the bioenergetics of this system: seawater entrainment provides more $O_2$ at Black Point, which causes the electron acceptor to no longer be limiting. Thus, as noted, shallow, near seafloor seawater entrainment may be a crucially important phenomenon. Shallow-sea hydrothermal systems, with large fluxes of free gas, may enhance this seawater entrainment (Dando et al., 2000; Haeckel et al., 2007).

### *5.5 Comparison of available energy to microbial diversity and other sites*

Several lines of evidence suggest that sulfur should be the predominant metabolized element in this system. For example, sedimentary sulfur isotope data indicate the presence and activity of different sulfur utilizing bacteria (Peters et al., 2011). Furthermore, chemolithoautotrophic, sulfur-oxidizing rod-shaped bacteria isolated from vent samples are "*Thiobacillus*-like" (Gugliandolo et al., 1999). *Thiobacillus spp*. display a wide range of metabolisms primarily associated with oxidation by $O_2$ of S or Fe (oxidation of $H_2S$ by $O_2$ is common). Microscopic observation of a subsample from a whitish mat revealed a variety of morphologically distinct filamentous forms resembling

the *Thiothrix* genus, a filamentous sulfur-oxidizing bacteria (Gugliandolo et al., 2006). Those authors demonstrated that several of these strains deposited sulfur externally, and produced sulfate in liquid medium.

Recent molecular investigations at Hot Lake suggest that microorganisms making up the white filaments at the site are a highly diverse community of bacteria dominated by sequences of Epsilonproteobacteria (Berg, 2011). This is similar to deep-sea vent sites where, due to their ability to carry out different types of metabolism using a variety of alternate electron donors (e.g. $H_2$, formate, elemental sulfur, sulfide, thiosulfate) and acceptors (e.g. sulphite, elemental sulfur, nitrate), Epsilonproteobacteria play an important role in carbon, nitrogen and sulfur cycles. Members of the Thiotrichales order were not detected, which was surprising since they are commonly observed in marine sulfur mats. The archaeal clone library was less diverse: most of the archaeal sequences were related to thermophilic and hyperthermophilic organisms but no Crenarchaeota were found. Overall, the data suggest it is likely that elemental sulfur filaments in the white mats are biologically precipitated as part of a microbially-mediated sulfur cycle. Further evidence for S metabolism at the site is provided by cultured relatives of the detected species, which are mostly able to catalyze sulfur related metabolisms, including sulfide oxidation, sulfur reduction or sulfate reduction (Huang, 2012). Metagenome analysis supports the relevance of sulfur metabolism and of the rTCA cycle for autotropic life at Hot Lake (Huang, 2012). Maugeri et al. (2009), suggested that sulfur-oxidizing bacteria were detected by both culture-dependent and -independent methods at two nearby sites within the Panarea submerged caldera.

Thus, microbiological and genomic data support our interpretation that $H_2S$ and $S^0$ oxidation seem to be the dominant metabolisms at each of the Panarea sites. This observation is similar to that for deep-sea vents where, in both the basalt-hosted and felsic rock-hosted systems, sulfide oxidation is the predominant catabolic energy source at all temperatures (and SW:HF ratios) considered (Amend et al., 2011). Differences in temperature do not influence the potential energy much at each site, but rather it is the concentrations of electron donors and/or acceptors, which play a larger role. Amend et al., (2003b) also made a similar observation for hydrothermal vent fluids collected from Volcano Island (Italy).

Most of the studies that have quantified the amount of energy available to microorganisms in natural settings only present results in units of energy per mole of substrate or electron transferred. As noted in the Introduction, the range of exergonic energy yields, for inorganic and organic redox reactions alike, fall between approximately 0 to -120 kJ per mole of electrons transferred. However, it is illustrated in Fig. 11 and elsewhere (LaRowe and Amend, 2014; Osburn et al., 2014) that energetic yields normalized per mole of electrons transferred can predict a very different set of reactions that are likely being catalyzed than energetics calculations that take into account the concentrations of limiting reactants as well. In order to put the results of this study into context, the energy density calculations summarized in Fig. 11c and 11d are compared to other published studies that also consider the energetic impact of limiting substrate concentrations.

The number of Joules available to microorganisms per kg of fluid due to the disequilibrium created by the mixing of hydrothermal fluids and seawater can vary by

many orders of magnitude depending on the mixing ratio and the original compositions of the end-member fluids. This is clearly illustrated in a recent study in which the maximum amount of energy available from seawater mixing with fluids coming from 12 different hydrothermal systems has been calculated (Amend et al., 2011). In this study it is shown that reactions such as $H_2S$, $CH_4$ , $H_2$ and Fe(II) oxidation can provide more than 1000 J/kg $H_2O$ while sulfate reduction, methanogenesis and the anaerobic oxidation of methane (AOM) can provide hundreds of J / kg $H_2O$. However, the amount that each reaction provides varies considerably from one system to the next depending on the types of rocks that the hydrothermal fluids circulate through. Other studies have shown similar results. For instance, hydrothermal fluids from ultramafic systems that mix with seawater can provide up to 3700 J /kg $H_2O$ for $H_2$ oxidation (McCollom, 2007), but in fluid mixing from a basalt-hosted mid-ocean ridge system (East Pacific Rise, EPR, $21^o$ N OBS vent) only ~35 J/kg $H_2O$ (Shock and Holland, 2004). Similarly, the ultramafic mixtures tend to supply much more energy per kg $H_2O$ than other types of hydrothermal systems for methane oxidation (2100 J /kg $H_2O$) and Fe(II) oxidation (1300 J /kg $H_2O$) as compared to EPR fluids, 30-150 J /kg $H_2O$ (McCollom and Shock, 1997). In an analysis of the energy available in a hydrothermal plume, the energy available from a similar set of chemolithoautotrophic reactions are more similar to the EPR fluids (McCollom, 2000).

In terms of sulfur-based metabolisms, ultramafic hydrothermal systems can provide up to 900 J / kg $H_2O$ ($S^0$ oxidation and sulfate reduction) (McCollom, 2007) whereas the maximum amount of energy from sulfide oxidation at EPR-type systems can generate up to 3200 J /kg $H_2O$,but sulfate reduction only yields tens of J / kg $H_2O$ (McCollom and Shock, 1997). A more recent assessment of fluids from EPR shows that

elemental sulfur oxidation and $H_2S$ oxidation to sulfate and $S^0$ all provide ~ 30 J / kg $H_2O$, with $S^0$ and sulfate reduction below about 20 J / kg $H_2O$. The amount of energy available from S-based reactions at the 6 sites considered in this study are more similar to these latter values. It should be noted that typically, the most exergonic reactions for a particular ratio of hydrothermal fluids : seawater are the ones that are reported in the studies mentioned above. However, under unfavorable mixing ratios, the amount of energy available from these reactions is orders of magnitude lower than the most optimal conditions. This is clearly shown in the current study and one carried out by (Houghton and Seyfried Jr., 2010).

## 6. Concluding remarks

While subsurface processes associated with deep-sea hydrothermal vent fluids are fairly well understood, shallow-sea venting has received much less attention. It has been suggested that there is a definable link between subsurface hydrothermal processes and the associated microbial communities (Flores et al., 2011; Meyer-Dombard et al., 2011; Nakagawa et al., 2005; Nunoura and Takai, 2009; Price et al., 2013b). Shallow-sea vents provide excellent opportunities to investigate this link.

Evaluation of geochemistry from three shallow-sea vent sites located off shore Panarea Island indicate that, although trends were similar for pH, temperature, Mg, and $SO_4$, each site displayed distinct differences in major and trace element composition. As such, at least 3 end-member solutions are plausible, each of which mixes with ambient seawater upon discharge. Type 1 fluids, which discharge from “Hot Lake”, have the highest salinities, and seem to be direct discharge of the deepest part of the hydrothermal

reservoir underlying the island. Based on Cl/Br ratios, these fluids do not seem to have undergone phase separation, and are mostly influenced by water-rock reactions. Extreme salinities may result from long term distillation. Type 2 fluids, which are present as vent and gas-rich fluids from the Black Point and La Calcara sites, respectively, are lower in salinity relative to Type 1 fluids, yet higher salinity compared to seawater. These fluids seem to be derived from a shallower low-salinity reservoir, which may have lower salinity due to entrainment of seawater. This indicates that the Panarea system maintains a layered reservoir with double-diffusive circulation. Type 3 fluids, which are represented by pore fluids from Black Point and La Calcara, develop as a result of gas scrubbing as exsolved gases percolate through sediment pore fluids.

Thermodynamic calculations indicate that sulfur ($H_2S$ and $S^0$) oxidation by $O_2$ should be the dominant metabolic activity at each site and fluid type investigated. Differences are primarily a function of the abundance of $H_2S$ and $S^0$ as electron donors, and the $O_2$ provided, e.g., in Black Point pore fluids as a result of shallow, near-seafloor seawater entrainment. $CH_4$ oxidation is much more prevalent at the La Calcara site, and $Mn^{2+}$ oxidation is likely at the Black Point site, reflecting elevated concentrations of these electron donors.

The combined approach of describing both subsurface hydrothermal processes and thermodynamic calculation of catabolic potential allows us to evaluate the related importance of both abiotic and biotic influences as agents of global element cycling. Future research on shallow-sea hydrothermal venting should focus more on the influence that abundant free gas discharge has on the evolution of hydrothermal vent fluid

chemistry, particularly its role in providing electron donors through gas scrubbing, and its role in providing electron acceptors ($O_2$) by seawater entrainment.

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Figure Captions:

Fig. 1. (a) Location of the island of Panarea and the submarine hydrothermal vents selected for this investigation. Sampling sites are indicated in (b) for La Calcara, Hot Lake and Black Point.

Fig. 2. (a-left) Underwater photographs of the Hot Lake area. Depression in the surrounding rocks is approximately 4 m by 6 m, and is filled with hydrothermal brine (see diver for scale). (a-right) close-up of microbial filaments in Hot Lake. (b-left) General area around Black Point (see diver for scale) and (b-right) close-up of white smoker and 'chimney'. (c-left) General area picture of La Calcara (see diver for scale) and (c-right) close-up of 135 °C gas-rich vents where anhydrite precipitation occurs.

Fig. 3. Measured field geochemistry data for Panarea fluids, (a) temperature versus pH. (b) temperature versus $H_2S$, and (c) $H_2S$ versus pH. Note that Black Point vent and La Calcara gas-rich fluids often have the most extreme values, although Hot Lake fluids have the highest $H_2S$ concentrations. Symbols in 3a are the same for 3b and 3c.

Fig. 4. Two-phase curve for seawater, including the critical point (c.p.) of seawater (c.p.= 407 °C, 298 bars), and the maximum vent temperatures for hydrothermal systems in different volcanic and tectonic settings (data from Hannington et al., 2005; curve from Bischoff and Rosenbauer, 1987; c.p. from Bischoff and Rosenbauer, 1984). Note slope of curve shallows significantly at >200 m, indicating that changes in pressure will dominate over changes in temperature. Grey area in upper left designates the pressure and temperature conditions encountered in shallow-sea hydrothermal vent systems.

Fig. 5. Hypothetical model of subsurface processes occurring in many hydrothermal systems. See text for details. (a) Low temperature water-rock reactions, (b) high temperature water-rock reactions, (c) magmatic volatile inputs, (d) phase separation, (e) continued water-rock reactions, and (f) degassing of dissolved volatiles. Note: 1) Panarea Type 1 fluids are directly fed by deep recirculating brine reservoir and form a brine pool due to extremely high salinity, 2) Type 2 fluids are focused upflow from the shallower brine which has been diluted by seawater, and 3) Type 3 fluids are derived from volatile degassing at lower pressures, followed by gas scrubbing to seawater-like pore fluids.

Fig. 6. (a) Measured concentrations of $Mg^{2+}$ vs. $SO_4^{2-}$ for Panarea fluids, with two possible projected intercepts. Horizontal and vertical lines in (a) indicate equivalent seawater concentrations. (b), $Mg^{2+}$ vs. K (c) and $Mg^{2+}$ vs. Na (c) for all hydrothermal fluids analyzed in this study. Note "triple-trend" mixing, and designation of Type 1, Type 2, and Type 3 fluids in (b) and (c). Starred data points indicate samples used in bioenergetics calculations, (b) and (c) include data previously collected by the National Institute of Geophysics and Volcanology (INGV, as noted) and confirms different mixing trends for Type 1, Type 2, and Type 3 fluids. (d) Mg vs. Ca, (e) Mg vs. Sr, (f) Mg vs. B, (g) Mg vs. Cl, and (h) Mg vs Br. Triple trends and 3 fluid types are present but not marked in (d) through (h). Symbols in 6a the same for other plots.

Fig. 7. End-member plots for Cl vs. Na (a), Cl vs Ca (b) concentrations, and end-member element rations for Na/Cl vs. Ca/Cl (c), and Na/Cl vs. Sr/Cl (d). (e) shows $^{87}Sr/^{86}Sr$ isotopic ratios for selected vent fluids from this study, plotted along with ratios for surrounding rock samples (Ash layer and * from Calanchi et al. (2002); ** from INGV database). Data trend towards subsurface rocks with a "Stromboli affinity". (note: the precision and accuracy of the data used for the mixing end-members is much smaller than the size of the symbols used, and so even the most conservative deviations from the considered mixing end-member are largely ignorable as they will bear no impact on the discussion or have minimal, if any, impact on the calculations). Symbols in 7a the same for 7b-7d. MOR = mid-ocean ridge systems; R-HS = ridge – hot spot intersections; Sed. = sedimented; IBABs = intraoceanic back-arc basins; IHS = intraplate hot spot; UM = ultramafic; Arc – BAB = transitional arc and back-arc. Other vent data from Hannington et al. (2005).

Fig. 8. Data plots used for evaluation of phase separation. Measured Cl vs. Na (a) Cl vs. Br (b), and Cl vs. Br/Cl (c) for hydrothermal fluids from each location. End-member Cl vs. Br/Cl (d) and (c) Cl vs. B/Cl (e) for Panarea hydrothermal fluids analyzed in this study. Symbols in 8a the same for other plots.

Fig. 9. (a) SEM image of hydrothermal precipitates occurring at the sediment / water interface where ~135 °C gas-rich fluids discharge at La Calcara. EDX analysis results, indicating the precipitates are anhydrite ($CaSO_4$), are shown upper right. (b) Ca vs. SO4 plot indicating removal of these elements in pore fluids, and (c) anhydrite solubility (□), as a function of temperature using seawater as the starting fluid.

Fig. 10. Trace element plots: (a) Mg vs. Mn, (b) Mg vs Ba, (c) Mg vs Li, (d) Mg vs Rb, (e) Mg vs. Cs, (f) Mg vs Si, and (g) Mg vs. Fe concentrations for the Panarea hydrothermal fluids. Symbols in 10a the same for other plots.

Fig. 11. Gibbs energies, $\Delta G_r$, of the 61 catabolic reactions listed in Table 1 per mole of electron transferred colored by (a) oxidant and (b) electron donor (ED). (c) and (d) represent energy per kilogram of $H_2O$ colored by oxidant and electron donor, respectively. The temperatures and compositions used to calculate these values are those describing the six samples locations summarized in Table 3. The horizontal bars in each panel denote the range of Gibbs energies for the indicated reaction for all sample locations. The colors of the bars refer to the types of electron acceptors and donors in each of the reactions, respectively.

Fig. 12. Comparison of energy available on a per site basis after removal of Reactions 43 and 44, the oxidation of $NH_4^+$ by $MnO_2$.

Fig. 1.

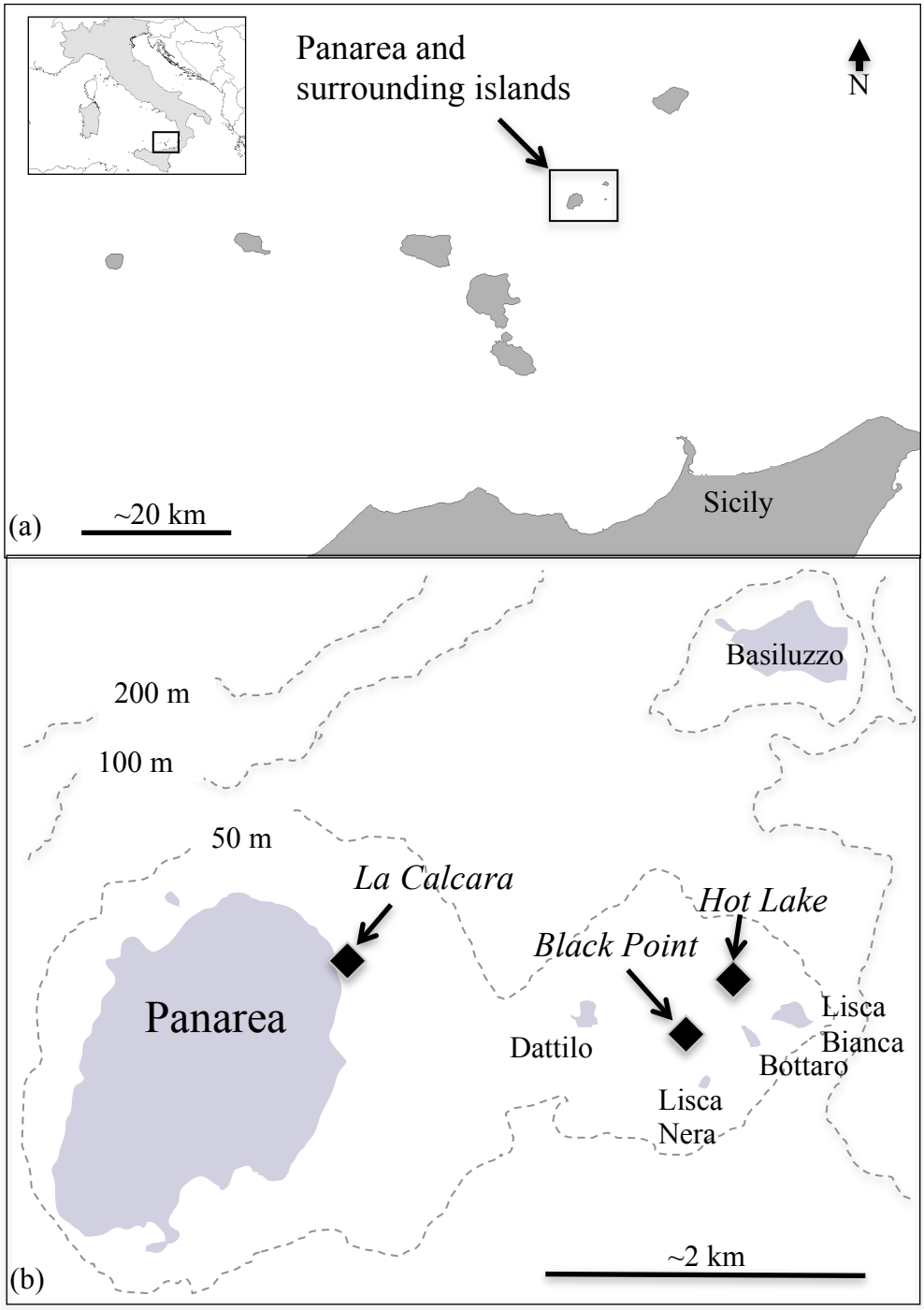
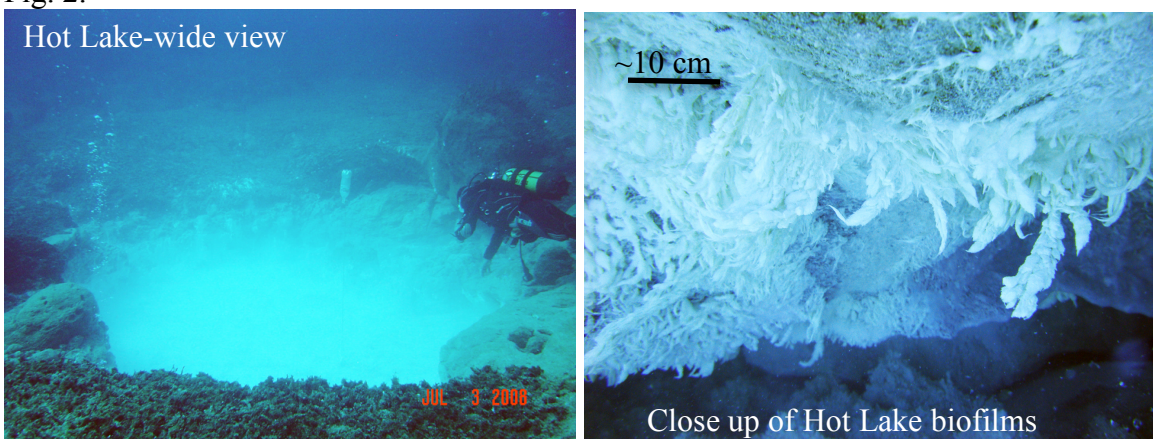
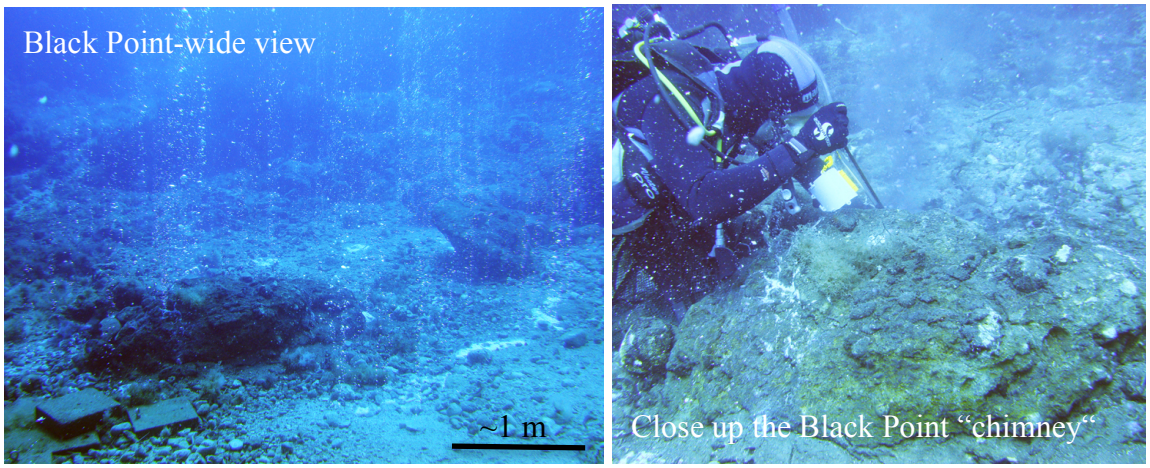

Panarea and
surrounding islands
N
Sicily
(a)
~20 km
Basiluzzo
200 m
100 m
50 m
La Calcara
Hot Lake
Black Point
Panarea
Dattilo
Lisca
Bianca
Bottaro
Lisca
Nera
~2 km
(b)

Fig. 2.

(a)


Hot Lake-wide view
JUL 3 2006
~10 cm
Close up of Hot Lake biofilms

(b)


Black Point-wide view
~1 m
Close up the Black Point "chimney"

(c)

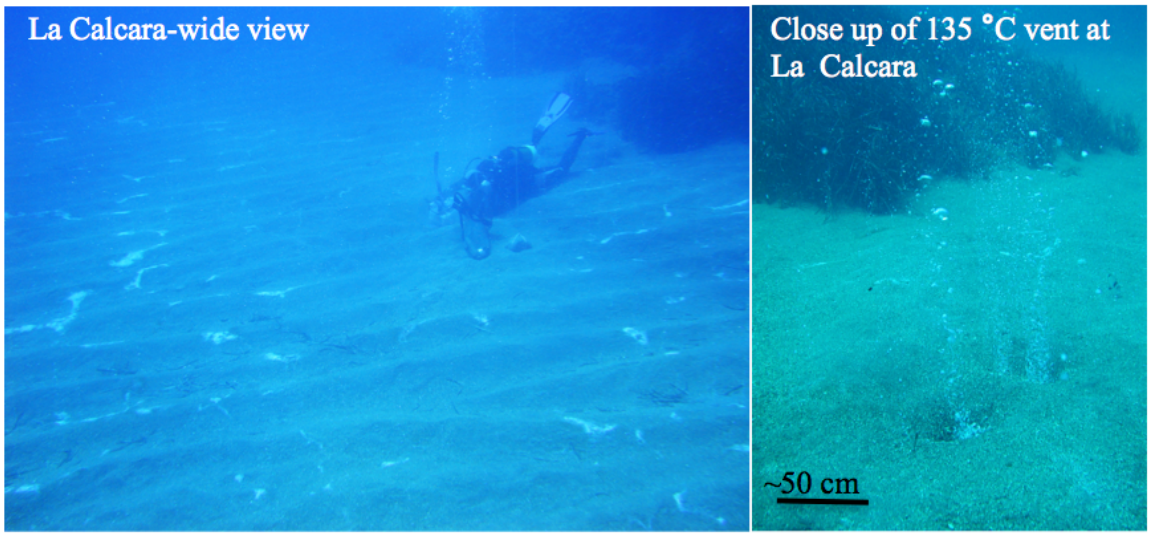

La Calcara-wide view
Close up of 135 °C vent at La Calcara
~50 cm

Fig. 3.

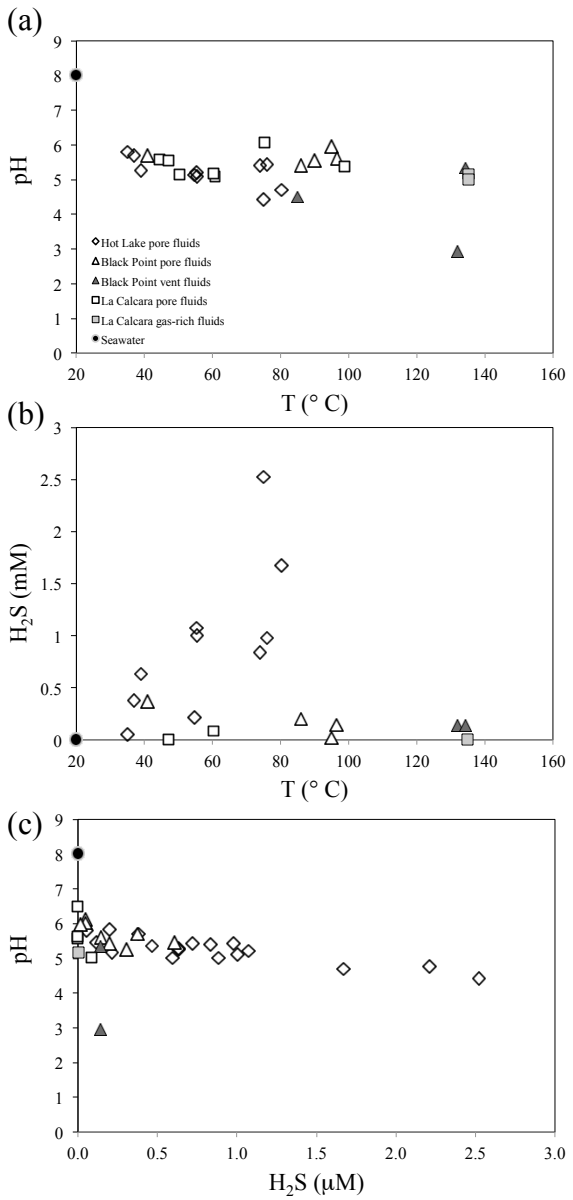

(a)
pH
T (° C)
Hot Lake pore fluids
Black Point pore fluids
Black Point vent fluids
La Calcara pore fluids
La Calcara gas-rich fluids
Seawater
(b)
H2S (mM)
T (° C)
(c)
pH
H2S (μM)

Fig. 4.

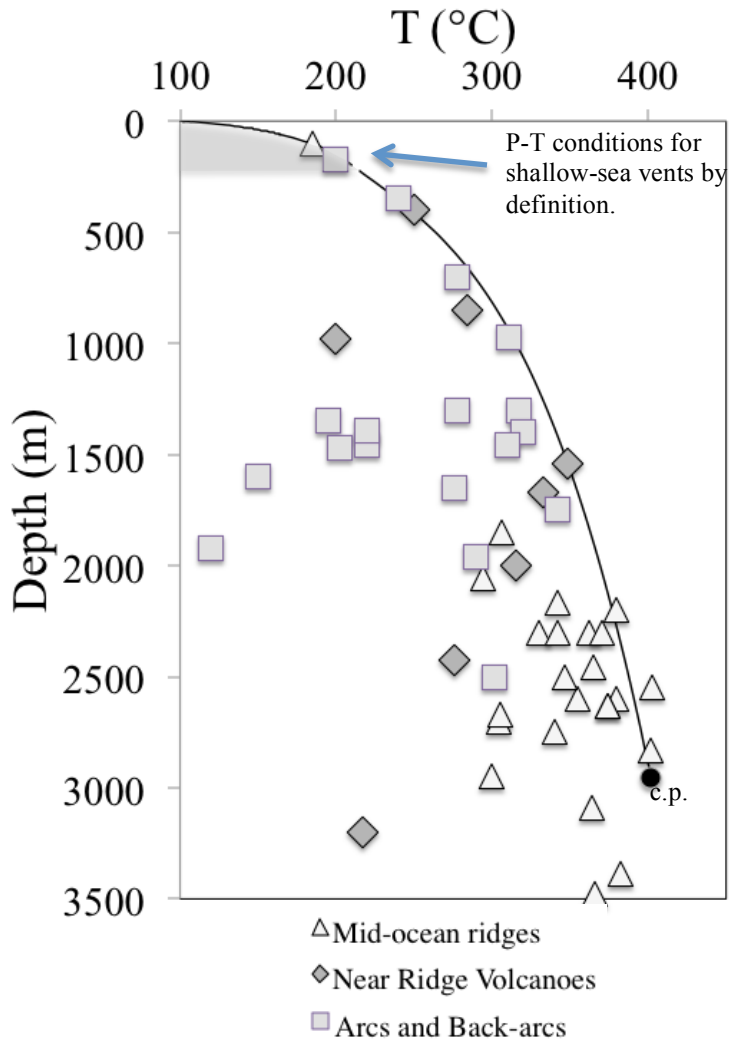

T (°C)
100
200
300
400
0
500
1000
1500
2000
2500
3000
3500
Depth (m)
P-T conditions for shallow-sea vents by definition.
c.p.
Mid-ocean ridges
Near Ridge Volcanoes
Arcs and Back-arcs

Fig. 5.

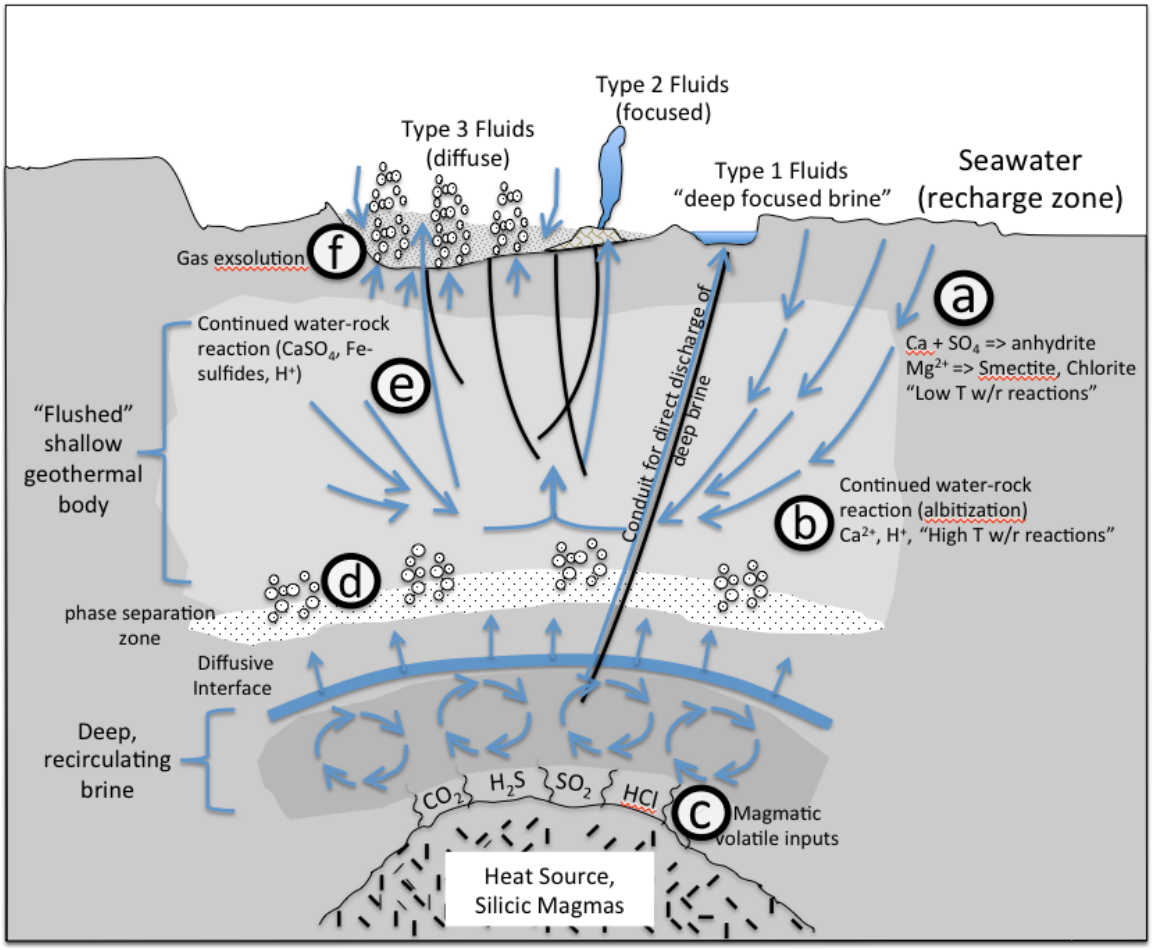

Type 2 Fluids
(focused)
Type 3 Fluids
(diffuse)
Type 1 Fluids
"deep focused brine"
Seawater
(recharge zone)
Gas exsolution
f
a
Ca + SO4 => anhydrite
Mg2+ => Smectite, Chlorite
"Low T w/r reactions"
Continued water-rock
reaction (CaSO4, Fe-
sulfides, H+)
e
"Flushed"
shallow
geothermal
body
Conduit for direct discharge of
deep brine
Continued water-rock
reaction (albitization)
Ca2+, H+, "High T w/r reactions"
b
d
phase separation
zone
Diffusive
Interface
Deep,
recirculating
brine
CO2
H2S
SO2
HCl
c
Magmatic
volatile inputs
Heat Source,
Silicic Magmas

Fig. 6.

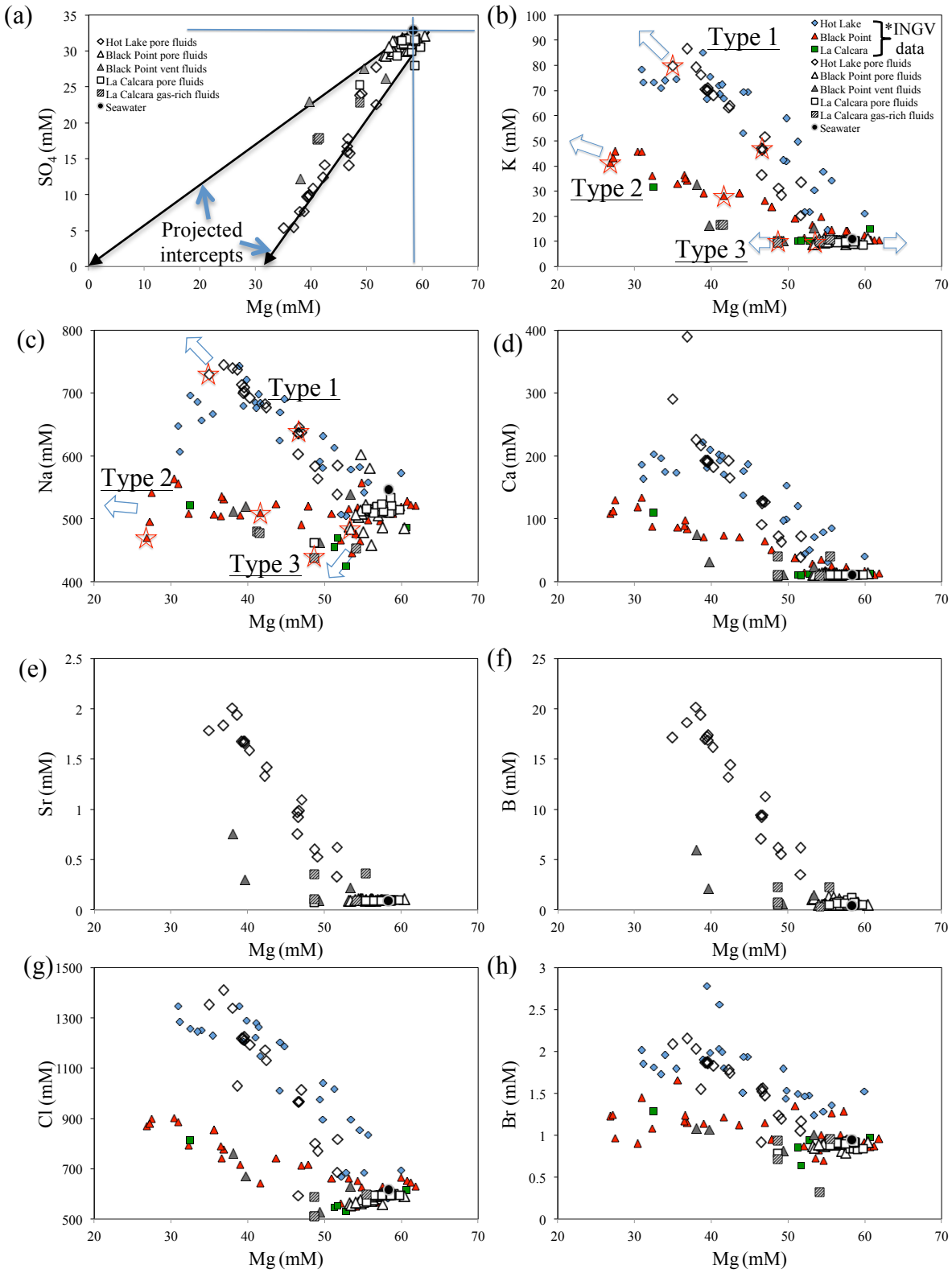

(a)
Hot Lake pore fluids
Black Point pore fluids
Black Point vent fluids
La Calcara pore fluids
La Calcara gas-rich fluids
Seawater
Projected intercepts
SO4 (mM)
Mg (mM)
(b)
Type 1
Type 2
Type 3
Hot Lake
Black Point
La Calcara
*INGV data
Hot Lake pore fluids
Black Point pore fluids
Black Point vent fluids
La Calcara pore fluids
La Calcara gas-rich fluids
Seawater
K (mM)
Mg (mM)
(c)
Type 1
Type 2
Type 3
Na (mM)
Mg (mM)
(d)
Ca (mM)
Mg (mM)
(e)
Sr (mM)
Mg (mM)
(f)
B (mM)
Mg (mM)
(g)
Cl (mM)
Mg (mM)
(h)
Br (mM)
Mg (mM)

Fig. 7.

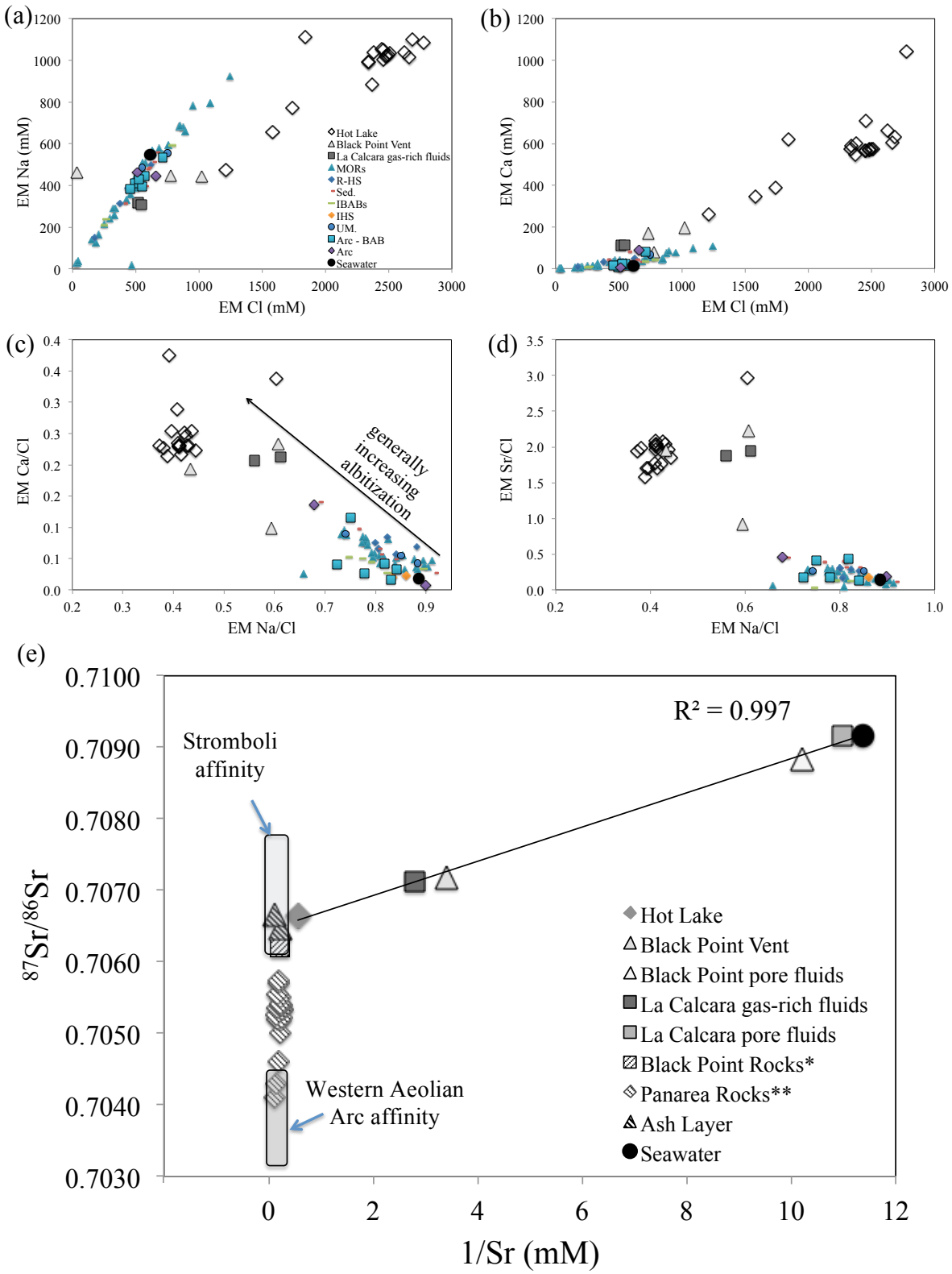

(a)
EM Na (mM)
EM Cl (mM)
Hot Lake
Black Point Vent
La Calcara gas-rich fluids
MORs
R-HS
Sed.
IBABs
IHS
UM.
Arc - BAB
Arc
Seawater
(b)
EM Ca (mM)
EM Cl (mM)
(c)
EM Ca/Cl
EM Na/Cl
generally increasing albitization
(d)
EM Sr/Cl
EM Na/Cl
(e)
R² = 0.997
Stromboli affinity
Western Aeolian Arc affinity
Hot Lake
Black Point Vent
Black Point pore fluids
La Calcara gas-rich fluids
La Calcara pore fluids
Black Point Rocks*
Panarea Rocks**
Ash Layer
Seawater
87Sr/86Sr
1/Sr (mM)

Fig. 8.

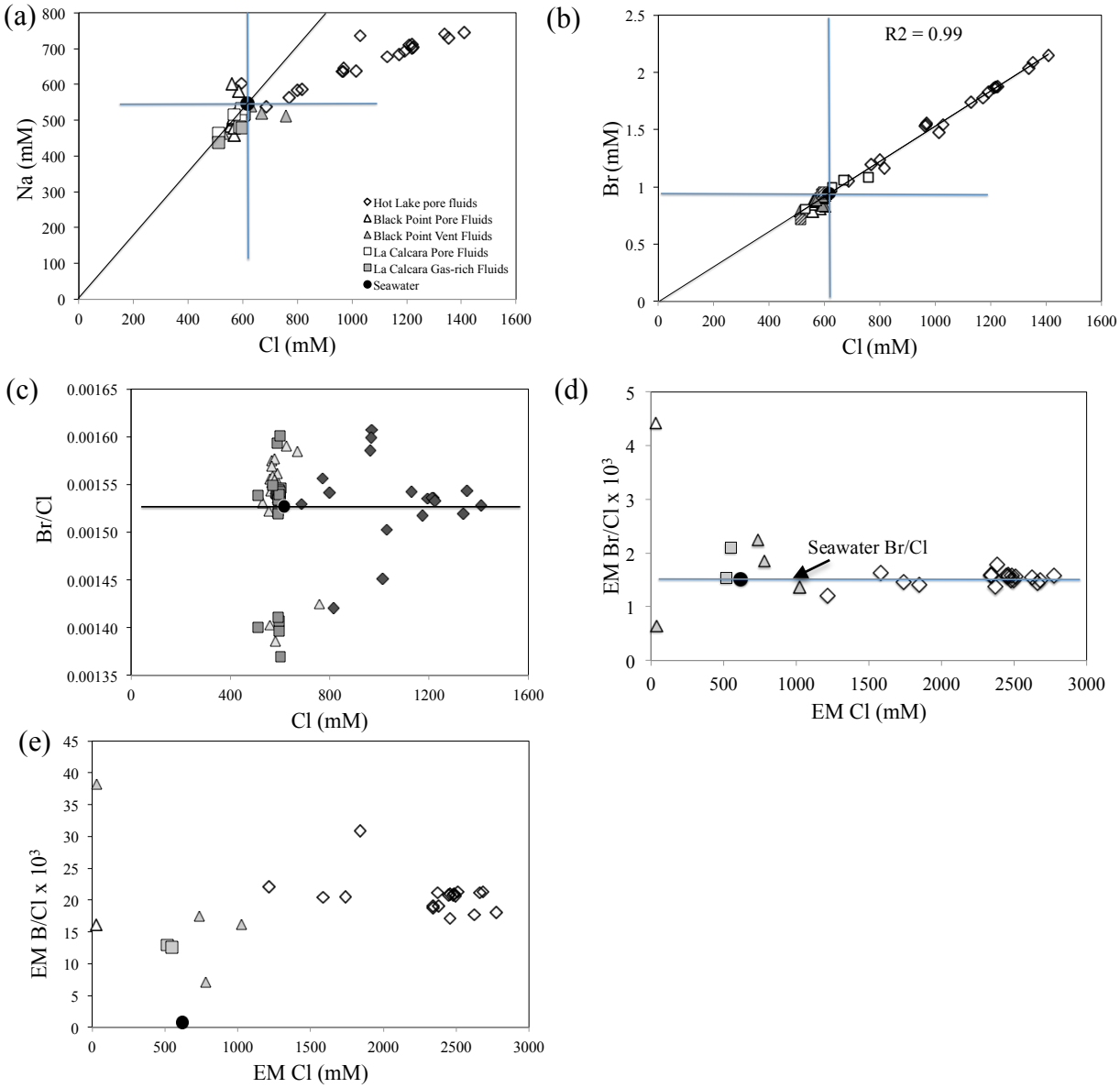
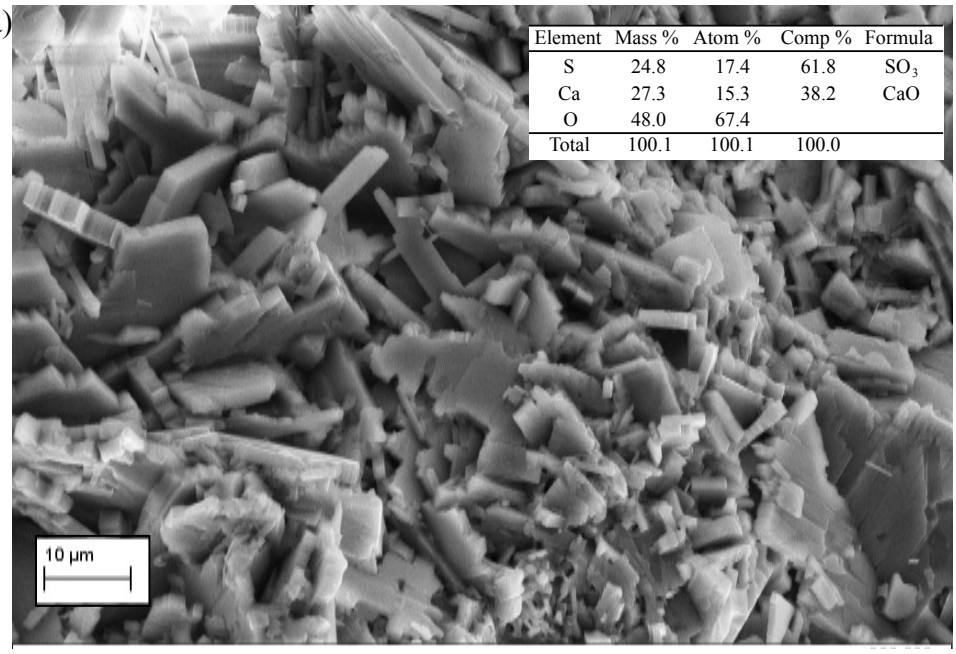
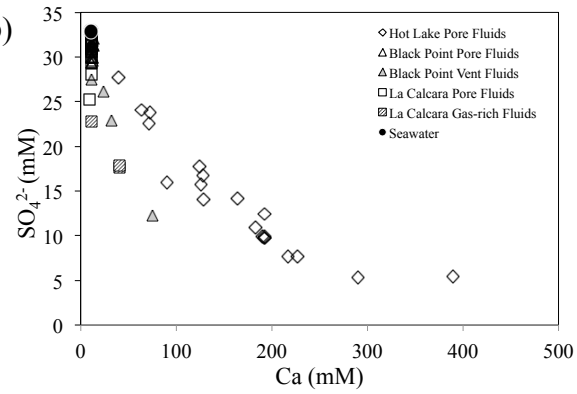

(a)
Na (mM)
Cl (mM)
Hot Lake pore fluids
Black Point Pore Fluids
Black Point Vent Fluids
La Calcara Pore Fluids
La Calcara Gas-rich Fluids
Seawater
(b)
R2 = 0.99
Br (mM)
Cl (mM)
(c)
Br/Cl
Cl (mM)
(d)
EM Br/Cl x 10³
Seawater Br/Cl
EM Cl (mM)
(e)
EM B/Cl x 10³
EM Cl (mM)

Fig. 9. (a)




| Element | Mass % | Atom % | Comp % | Formula |
|---|---|---|---|---|
| S | 24.8 | 17.4 | 61.8 | $SO_3$ |
| Ca | 27.3 | 15.3 | 38.2 | CaO |
| O | 48.0 | 67.4 | | |
| Total | 100.1 | 100.1 | 100.0 | |

(b)




(c)

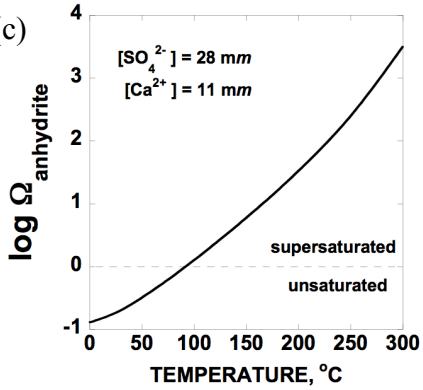


Fig. 10.

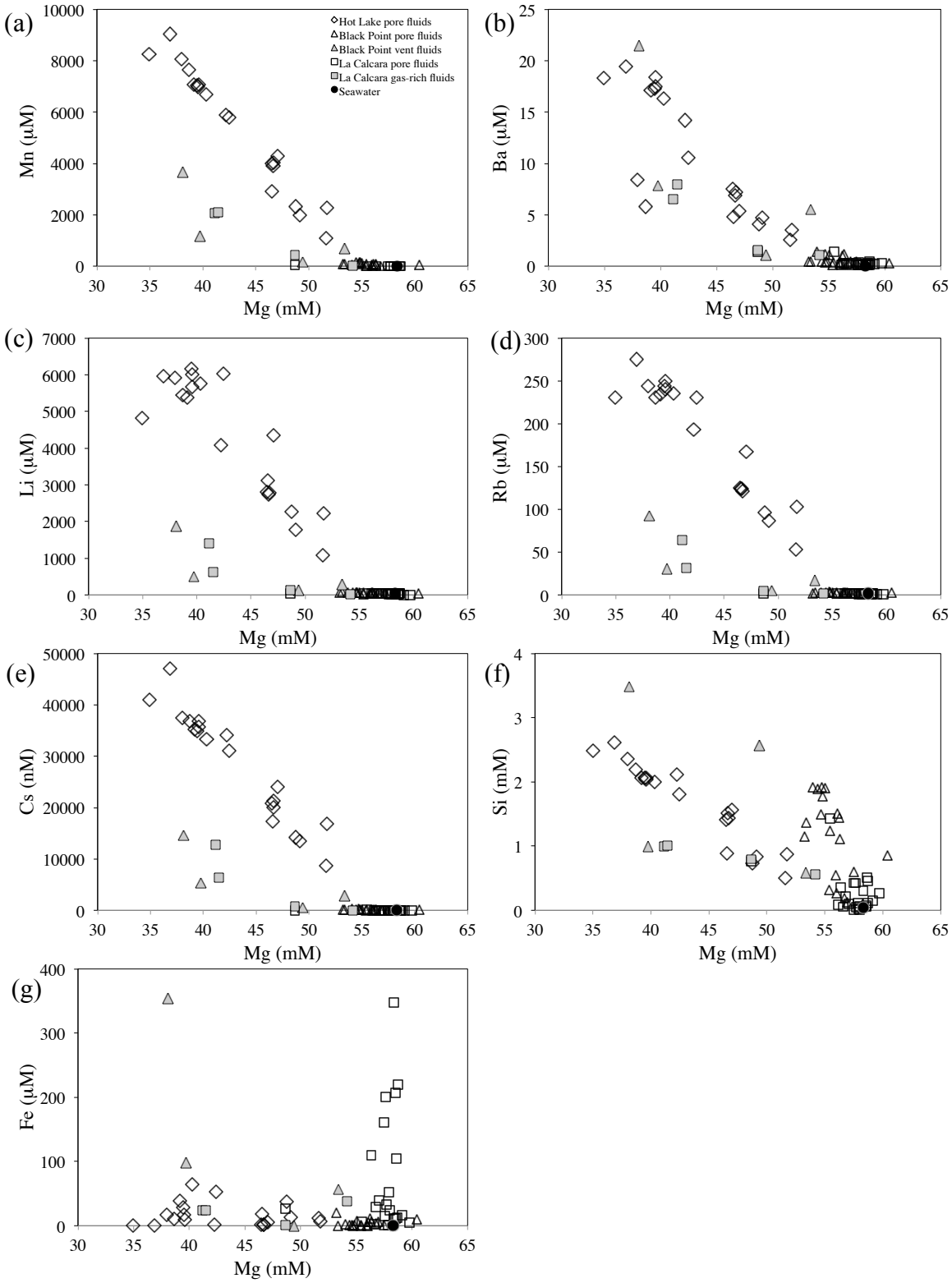

(a)
Hot Lake pore fluids
Black Point pore fluids
Black Point vent fluids
La Calcara pore fluids
La Calcara gas-rich fluids
Seawater
Mn (μM)
Mg (mM)
(b)
Ba (μM)
Mg (mM)
(c)
Li (μM)
Mg (mM)
(d)
Rb (μM)
Mg (mM)
(e)
Cs (nM)
Mg (mM)
(f)
Si (mM)
Mg (mM)
(g)
Fe (μM)
Mg (mM)

Fig. 11.

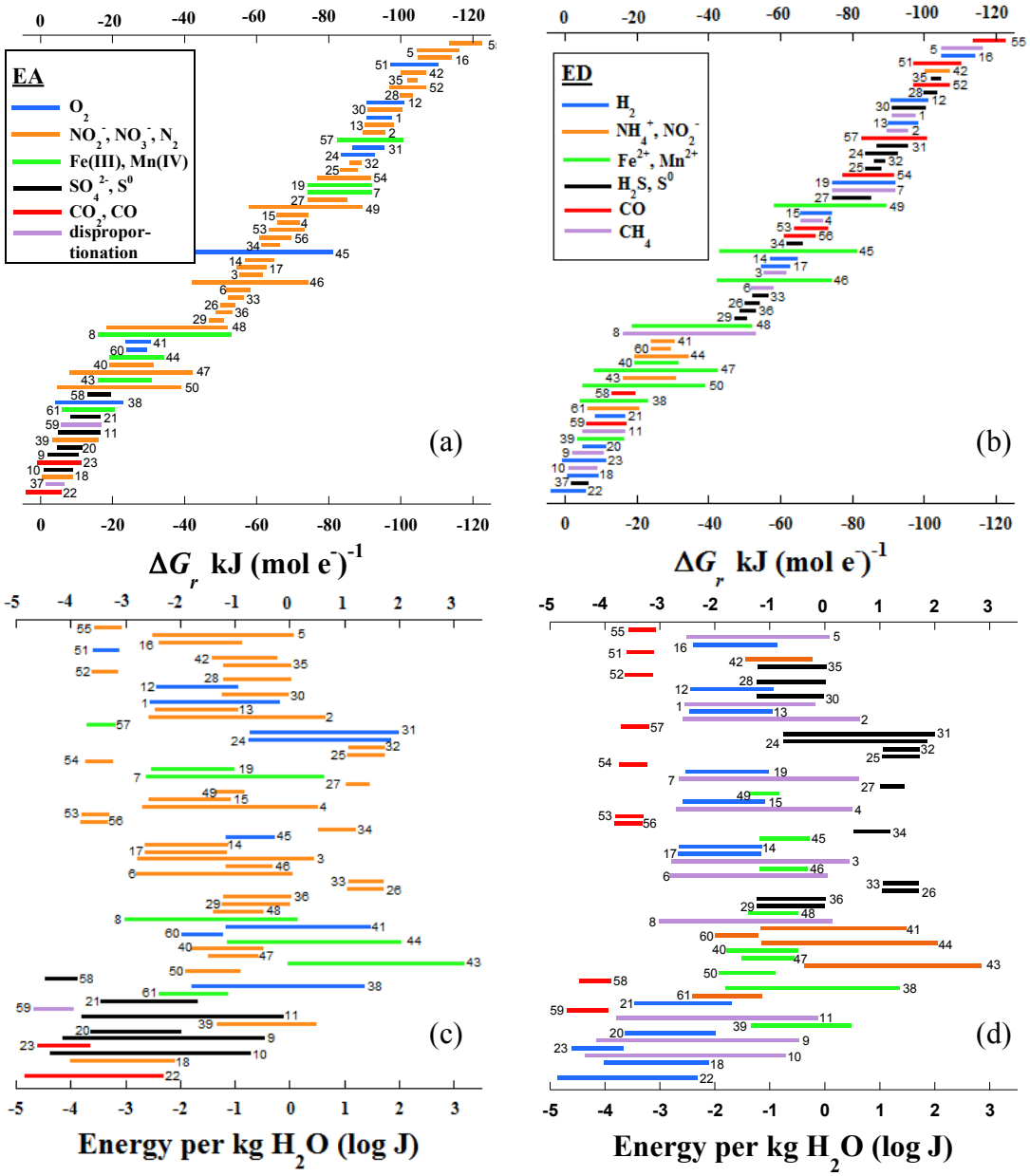

EA
$O_2$
$NO_2^-$, $NO_3^-$, $N_2$
Fe(III), Mn(IV)
$SO_4^{2-}$, $S^0$
$CO_2$, CO
disproportionation
(a)
ED
$H_2$
$NH_4^+$, $NO_2^-$
$Fe^{2+}$, $Mn^{2+}$
$H_2S$, $S^0$
CO
$CH_4$
(b)
$\Delta G_r$ kJ (mol e$^-$)$^{-1}$
(c)
(d)
Energy per kg $H_2O$ (log J)

Fig. 12.

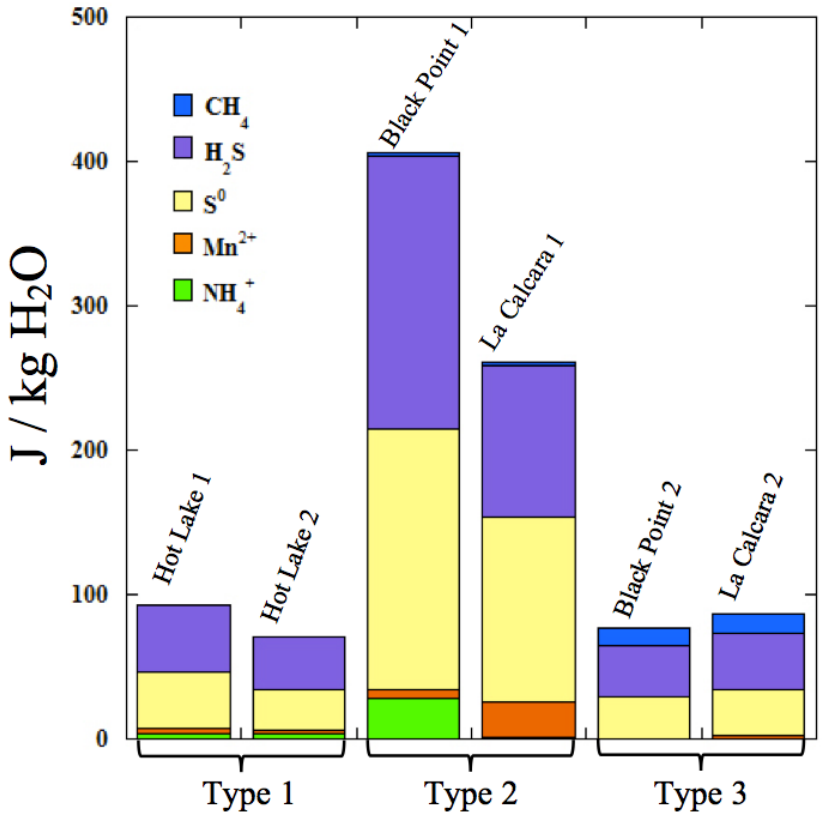

500
400
300
200
100
0
J / kg H2O
CH4
H2S
S0
Mn2+
NH4+
Hot Lake 1
Hot Lake 2
Black Point 1
La Calcara 1
Black Point 2
La Calcara 2
Type 1
Type 2
Type 3

**Table 1**

Table 1

Major physicochemical parameters, major, and minor elements in hydrothermal fluids from three shallow-sea vents offshore Panarea.

| | | | Field Data | | | | Major elements in seawater | | | | | | | | | Minor elements | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Year | Sample Type[$] | Depth (cm) | Temp °C | pH | $H_2S$ mM | Mg mM | $SO_4$ mM | Na mM | Ca mM | K mM | B mM | Sr mM | Br mM | Cl mM | Si mM | Fe (total) µM[&] | Mn (total) µM[&] | Ba µM | Li µM | Rb µM | Cs nM | $^{87}Sr/^{86}Sr$ |
| | | Seawater | - | ~20 | 8.0 | 0 | 58.3 | 32.9 | 547 | 11.1 | 11.0 | 0.46 | 0.09 | 0.94 | 618 | 0.04 | 0.017 | 0.0055 | 0.03 | 35.1 | 1.7 | 2.0 | 0.709160 |
| Hot Lake | 2008 | RPF | 10 | | | | 51.7 | 22.5 | 585 | 71.8 | 33.7 | 6.1 | 0.62 | 1.2 | 816 | 0.9 | 7.1 | 2270 | 3.6 | 2219 | 104 | 16790 | |
| | 2008 | RPF | 25 | | | | 47.0 | 15.7 | 637 | 126.0 | 51.7 | 11.3 | 1.09 | 1.5 | 1010 | 1.6 | 5.7 | 4280 | 5.3 | 4363 | 167 | 24100 | |
| | 2009 | RPF-1 | 2 | 35 | 5.8 | 0.05 | 51.6 | 27.8 | 538 | 39.7 | 20.3 | 3.5 | 0.33 | 1.0 | 686 | 0.5 | 11.8 | 1100 | 2.6 | 1098 | 54 | 8773 | |
| | 2009 | RPF-1 | 6 | | 5.8 | 0.20 | 48.8 | 23.8 | 584 | 72.5 | 31.0 | 6.2 | 0.60 | 1.2 | 800 | 0.7 | 37.6 | 2320 | 4.1 | 2267 | 97 | 14260 | |
| | 2009 | RPF-1 | 10 | 37 | 5.7 | 0.38 | 46.5 | 16.0 | 603 | 90.5 | 36.4 | 7.1 | 0.76 | 0.9 | 594 | 0.9 | 18.7 | 2930 | 4.7 | 3110 | 123 | 17290 | |
| | 2009 | RPF-1 | 14 | | 5.4 | 0.47 | 42.4 | 14.1 | 677 | 165.0 | 63.8 | 14.4 | 1.42 | 1.7 | 1130 | 1.8 | 52.9 | 5780 | 10.6 | 6014 | 231 | 31090 | |
| | 2009 | RPF-1 | 18 | | 5.0 | 0.59 | 38.0 | 7.7 | 740 | 227.0 | 79.2 | 20.2 | 2.00 | 2.0 | 1340 | 2.4 | 17.2 | 8050 | 8.4 | 5920 | 244 | 37570 | |
| | 2009 | RPF-1 | 21 | 39 | 5.3 | 0.63 | 38.7 | 7.6 | 737 | 217.0 | 76.1 | 19.4 | 1.94 | 1.5 | 1030 | 2.2 | 10.6 | 7650 | 5.8 | 5439 | 231 | 36800 | |
| | 2009 | RPF-2 | 2 | | 5.5 | 0.12 | 49.1 | 24.1 | 564 | 63.5 | 28.3 | 5.5 | 0.53 | 1.2 | 770 | 0.8 | 13.3 | 1990 | 4.7 | 1772 | 87 | 13460 | |
| | 2009 | RPF-2 | 6 | | 5.3 | 0.63 | 40.3 | 10.9 | 693 | 183.0 | 67.9 | 16.2 | 1.59 | 1.8 | 1190 | 2.0 | 64.2 | 6690 | 16.3 | 5779 | 235 | 33300 | |
| | 2009 | RPF-2 | 10 | 74 | 5.4 | 0.83 | 39.2 | 9.8 | 713 | 192.0 | 70.5 | 17.0 | 1.67 | 1.9 | 1220 | 2.1 | 39.7 | 7070 | 17.1 | 5377 | 234 | 35290 | |
| | 2009 | RPF-2 | 14 | | 5.4 | 0.72 | 39.5 | 9.7 | 700 | 192.0 | 70.0 | 17.2 | 1.67 | 1.9 | 1220 | 2.1 | 28.0 | 7050 | 17.2 | 6182 | 244 | 34980 | |
| | 2009 | RPF-2 | 18 | 76 | 5.4 | 0.98 | 39.5 | 10.0 | 709 | 190.0 | 70.0 | 16.9 | 1.66 | 1.9 | 1210 | 2.1 | 17.0 | 6980 | 17.5 | 5679 | 240 | 35790 | |
| | 2009 | RPF-2 | 22 | | 5.0 | 0.88 | 39.6 | 10.0 | 703 | 192.0 | 70.9 | 17.4 | 1.68 | 1.9 | 1230 | 2.0 | 8.5 | 7060 | 18.4 | 6008 | 249 | 36840 | |
| | 2010 | RPF-1 | 10 | 55 | 5.2 | 0.22 | 46.7 | 14.0 | 645 | 129.0 | 46.8 | 9.4 | 0.98 | 1.6 | 968 | 1.4 | 1.9 | 4040 | 7.2 | 2792 | 122 | 20120 | |
| | 2010 | RPF-1 | 15 | 55 | 5.2 | 1.07 | 46.5 | 16.7 | 636 | 128.0 | 47.0 | 9.4 | 0.97 | 1.5 | 967 | 1.4 | 1.8 | 4020 | 7.5 | 2816 | 125 | 20880 | |
| | 2010 | RPF-1 | 20 | 56 | 5.1 | 1.00 | 46.6 | 17.8 | 636 | 124.0 | 46.1 | 9.2 | 0.92 | 1.5 | 963 | 1.5 | 0.9 | 3910 | 6.9 | 2730 | 124 | 21270 | |
| | 2010 | SPF | 10 | 80 | 4.7 | 1.67 | 35.0 | 5.4 | 729 | 290.0 | 79.8 | 17.1 | 1.78 | 2.1 | 1350 | 2.5 | 0.4 | 8250 | 18.3 | 4821 | 231 | 40980 | 0.706642 |
| | 2010 | SPF | 10 | 75 | 4.4 | 2.52 | 36.9 | 5.5 | 745 | 390.0 | 86.7 | 18.7 | 1.84 | 2.2 | 1410 | 2.6 | 0.4 | 9050 | 19.4 | 5957 | 275 | 47090 | |
| | 2010 | SPF | 10 | | 4.8 | 2.21 | 42.2 | 12.4 | 683 | 192.0 | 63.2 | 13.2 | 1.33 | 1.8 | 1170 | 2.1 | 2.8 | 5800 | 14.2 | 4095 | 193 | 34070 | |
| Black Point | 2008 | RPF | 9 | | | | 57.0 | 30.0 | 505 | 10.7 | 10.2 | 0.5 | 0.10 | 0.8 | 583 | 0.1 | 7.2 | | 0.5 | 31 | 2 | 64 | |
| | 2008 | RPF | 14 | | | | 57.5 | 30.1 | 487 | 11.7 | 8.8 | 0.5 | 0.10 | 0.8 | 558 | 0.6 | 1.0 | | 0.5 | 32 | 1 | 65 | |
| | 2008 | VF | - | 132 | 2.9 | 0.15 | 38.1 | 12.3 | 511 | 75.5 | 32.6 | 6.0 | 0.75 | 1.1 | 758 | 3.5 | 354 | 3650 | 21.5 | 1883 | 93 | 14560 | |
| | 2009 | RPF | 2 | | 6.1 | b.d. | 55.4 | 31.2 | 512 | 10.5 | 10.2 | 1.3 | 0.09 | 0.9 | 589 | 0.3 | b.d. | | 0.2 | 28 | 2 | 18 | |
| | 2009 | RPF | 6 | | 6.0 | b.d. | 56.0 | 31.3 | 514 | 10.7 | 10.2 | 1.2 | 0.09 | 0.9 | 593 | 0.3 | b.d. | | 0.2 | 42 | 2 | 14 | |
| | 2009 | RPF | 10 | 95 | 6.0 | b.d. | 56.7 | 31.1 | 516 | 10.8 | 10.2 | 1.1 | 0.09 | 0.9 | 589 | 0.2 | 3.9 | | 0.3 | 39 | 2 | 12 | |
| | 2009 | RPF | 14 | | 5.6 | 0.05 | 53.2 | 29.4 | 487 | 10.9 | 8.9 | 1.1 | 0.09 | 0.9 | 563 | 1.1 | 21.2 | 76 | 0.5 | 67 | 2 | 107 | |
| | 2009 | RPF | 16 | 97 | 5.6 | 0.05 | 53.4 | 29.3 | 483 | 11.1 | 8.8 | 1.1 | 0.09 | 0.8 | 555 | 1.4 | 10.0 | 91 | 0.5 | 73 | 2 | 112 | |
| | 2009 | VF | - | 134 | 5.3 | 0.15 | 49.4 | 27.5 | 462 | 11.1 | 10.2 | 0.6 | 0.09 | 0.8 | 529 | 2.6 | 0.5 | 161 | 1.1 | 134 | 5 | 588 | |
| | 2010 | RPF-1 | 4 | | | 0.02 | 56.0 | 31.0 | 580 | 11.6 | 10.7 | 0.5 | 0.10 | 0.9 | 586 | 0.5 | 1.0 | 51 | 0.3 | 43 | 2 | 127 | |
| | 2010 | RPF-1 | 6 | | | | 54.4 | 29.6 | 503 | 12.9 | 9.8 | 0.5 | 0.10 | 0.9 | 566 | 1.9 | 0.8 | 138 | 0.4 | 64 | 3 | 133 | |
| | 2010 | RPF-1 | 8 | | | 0.15 | 55.4 | 30.5 | 522 | 12.1 | 10.4 | 0.5 | 0.10 | 0.9 | 581 | 1.2 | 1.4 | 83 | 0.4 | 54 | 3 | 149 | |
| | 2010 | RPF-1 | 12 | | | 0.16 | 54.8 | 30.0 | 508 | 12.9 | 10.2 | 0.5 | 0.10 | 0.9 | 568 | 1.8 | 0.8 | 131 | 0.4 | 59 | 3 | 165 | |
| | 2010 | RPF-1 | 20 | | | 0.03 | 54.7 | 29.9 | 602 | 13.0 | 9.6 | 0.5 | 0.10 | 0.9 | 561 | 1.9 | 0.2 | 138 | 0.4 | 64 | 3 | 124 | |
| | 2010 | RPF-2 | 2 | 41 | 5.7 | 0.11 | 60.4 | 32.1 | 485 | 13.1 | 11.3 | 0.5 | 0.11 | 0.9 | 590 | 0.9 | 10.0 | 62 | 0.3 | 45 | 2 | 86 | |
| | 2010 | RPF-2 | 6 | | 5.3 | 0.39 | 56.1 | 31.4 | 458 | 13.0 | 10.2 | 0.5 | 0.10 | 0.9 | 570 | 1.5 | 5.2 | 79 | 0.4 | 55 | 2 | 123 | |
| | 2010 | RPF-2 | 10 | 86 | 5.4 | 0.33 | 56.3 | 31.8 | 512 | 12.5 | 10.3 | 0.5 | 0.10 | 0.9 | 580 | 1.1 | 6.9 | 60 | 1.1 | 49 | 2 | 125 | |
| | 2010 | RPF-2 | 14 | | 5.5 | 0.37 | 56.2 | 31.5 | 517 | 12.9 | 10.2 | 0.5 | 0.10 | 0.9 | 577 | 1.4 | 10.6 | 82 | 1.0 | 55 | 3 | 148 | |
| | 2010 | RPF-2 | 18 | 90 | 5.6 | 0.30 | 55.0 | 31.3 | 479 | 13.2 | 9.9 | 0.5 | 0.10 | 0.9 | 568 | 1.9 | 7.9 | 112 | 1.1 | 62 | 3 | 134 | |
| | 2010 | SPF | 10 | | | 0.20 | 54.7 | 31.4 | 514 | 12.0 | 11.0 | 0.5 | 0.10 | 0.9 | 576 | 1.5 | 1.4 | 79 | 1.2 | 58 | 3 | 239 | |
| | 2010 | SPF | 10 | | | 0.61 | 54.0 | 30.6 | 507 | 11.7 | 10.9 | 0.5 | 0.10 | 0.9 | 566 | 1.9 | 2.4 | 70 | 1.3 | 61 | 3 | 220 | 0.708836 |
| | 2010 | VF | - | 85 | 4.5 | | 39.7 | 22.9 | 520 | 32.0 | 16.4 | 2.1 | 0.29 | 1.1 | 670 | 1.0 | 98.7 | 1178 | 7.8 | 493 | 30 | 5289 | 0.707190 |
| | 2010 | VF | - | | | | 53.4 | 26.2 | 538 | 24.6 | 15.4 | 1.5 | 0.22 | 1.0 | 628 | 0.6 | 56.8 | 682 | 5.6 | 286 | 18 | 2848 | |
| La Calcara | 2008 | RPF | 5 | | | | 58.0 | 30.0 | 518 | 10.8 | 11.0 | 0.7 | 0.10 | 0.8 | 596 | 0.0 | | | 0.2 | 45 | 2 | 64 | |
| | 2008 | RPF | 15 | | | | 58.5 | 28.0 | 513 | 10.8 | 10.0 | 0.5 | 0.10 | 0.8 | 596 | 0.1 | 10.8 | | 0.2 | 21 | 1 | 62 | |
| | 2008 | RPF | 25 | | | | 59.1 | 31.2 | 515 | 11.0 | 9.0 | 0.5 | 0.10 | 0.8 | 602 | 0.2 | 16.1 | | 0.2 | 10 | 1 | 62 | |
| | 2008 | RPF | 35 | | | | 59.7 | 30.5 | 515 | 11.0 | 8.5 | 0.5 | 0.10 | 0.8 | 593 | 0.3 | 4.5 | | 0.3 | 8 | 1 | 62 | |
| | 2008 | GRF | - | | | | 48.7 | 22.9 | 438 | 10.5 | 10.3 | 0.7 | 0.10 | 0.7 | 511 | 0.8 | 0.8 | 427 | 1.5 | 126 | 5 | 772 | |
| | 2009 | RPF-1 | 2 | | 5.5 | | 57.1 | 31.8 | 511 | 10.9 | 9.8 | 0.8 | 0.09 | 0.9 | 597 | 0.1 | 39.8 | | 0.2 | 36 | 2 | 28 | |
| | 2009 | RPF-1 | 6 | | 5.6 | | 57.9 | 32.1 | 518 | 11.1 | 9.5 | 0.5 | 0.09 | 0.9 | 606 | 0.0 | 52.0 | | 0.1 | 32 | 1 | 12 | |
| | 2009 | RPF-1 | 10 | 44 | 5.6 | | 57.6 | 31.4 | 509 | 11.1 | 9.4 | 0.6 | 0.09 | 0.9 | 594 | 0.0 | 15.8 | | 0.1 | 33 | 1 | 6 | |
| | 2009 | RPF-1 | 14 | | 5.6 | | 58.3 | 31.6 | 522 | 11.3 | 9.4 | 0.4 | 0.10 | 0.9 | 598 | | 11.4 | | 0.2 | 29 | 1 | 3 | |
| | 2009 | RPF-1 | 18 | | 5.5 | 0.001 | 58.0 | 30.9 | 512 | 11.4 | 9.5 | 0.9 | 0.10 | 0.9 | 593 | 0.1 | 23.8 | | 0.2 | 30 | 1 | 4 | |
| | 2009 | RPF-1 | 21 | 47 | 5.6 | 0.001 | 57.7 | 31.4 | 513 | 11.5 | 9.5 | 0.6 | 0.10 | 0.9 | 602 | 0.0 | 32.4 | 1 | 0.2 | 29 | 1 | 3 | |
| | 2009 | RPF-2 | 2 | | 6.5 | | 56.2 | 30.9 | 515 | 10.7 | 10.6 | 0.8 | 0.09 | 0.9 | 585 | 0.1 | | | 0.2 | 42 | 2 | 5 | |
| | 2009 | RPF-2 | 6 | | 6.5 | | 56.6 | 31.0 | 513 | 10.8 | 10.5 | 0.8 | 0.09 | 0.9 | 590 | 0.1 | 2.1 | | 0.2 | 42 | 2 | 5 | |
| | 2009 | RPF-2 | 10 | 75 | 6.1 | | 57.9 | 31.6 | 515 | 11.1 | 10.6 | 1.0 | 0.10 | 0.9 | 595 | 0.1 | 0.9 | | 0.2 | 41 | 2 | 5 | |
| | 2009 | RPF-2 | 14 | | 5.8 | 0.001 | 58.7 | 31.3 | 512 | 11.3 | 10.2 | 0.9 | 0.10 | 0.9 | 593 | 0.1 | 12.0 | | 0.2 | 42 | 2 | 4 | |
| | 2009 | RPF-2 | 18 | 99 | 5.4 | | 58.3 | 31.4 | 509 | 11.1 | 9.6 | 1.2 | 0.09 | 0.9 | 592 | 0.3 | 347 | | 0.2 | 35 | 1 | 4 | |
| | 2009 | RPF-2 | 22 | | 5.4 | | 58.5 | 31.7 | 509 | 11.2 | 9.0 | 0.5 | 0.09 | 0.9 | 596 | 0.1 | 207 | 1 | 0.2 | 18 | 1 | 3 | |
| | 2009 | RPF-3 | 2 | | 5.5 | | 56.8 | 31.4 | 519 | 10.8 | 10.2 | 0.4 | 0.09 | 0.9 | 591 | 0.2 | 29.5 | | 0.3 | 36 | 2 | 6 | |
| | 2009 | RPF-3 | 6 | | 5.2 | | 58.7 | 31.7 | 521 | 11.1 | 10.2 | 0.6 | 0.09 | 0.9 | 598 | 0.5 | 220 | | 0.3 | 37 | 2 | 6 | |
| | 2009 | RPF-3 | 10 | 50 | 5.1 | | 57.7 | 31.8 | 512 | 11.0 | 9.9 | 0.5 | 0.09 | 0.9 | 598 | 0.4 | 201 | | 0.3 | 39 | 2 | 4 | |
| | 2009 | RPF-3 | 14 | | 5.1 | | 57.5 | 31.6 | 524 | 10.9 | 9.7 | 0.7 | 0.09 | 0.9 | 593 | 0.4 | 160 | 1 | 0.3 | 35 | 1 | 6 | |
| | 2009 | RPF-3 | 18 | | 5.0 | | 56.4 | 31.4 | 510 | 10.7 | 9.4 | 0.6 | 0.09 | 0.9 | 593 | 0.4 | 109 | | 0.3 | 37 | 1 | 5 | |
| | 2009 | RPF-3 | 22 | 61 | 5.1 | | 58.6 | 31.5 | 534 | 11.2 | 9.8 | 0.7 | 0.09 | 0.9 | 594 | 0.5 | 105 | | 0.4 | 34 | 1 | 5 | |
| | 2009 | GRF | - | 135 | 5.2 | 0.01 | 54.2 | | 452 | 9.6 | 9.9 | 0.3 | 0.09 | 0.3 | | 0.6 | 38.4 | 19 | 1.1 | 30 | 2 | 12 | 0.709208 |
| | 2010 | SPF | 10 | | | | 48.7 | 25.2 | 462 | 9.1 | 9.7 | 0.5 | 0.08 | 0.8 | 510 | 0.8 | 26.4 | 62 | 1.5 | 36 | 2 | 37 | |
| | 2010 | SPF | 10 | 60 | 5.2 | 0.09 | 55.5 | 29.3 | 516 | 10.9 | 10.8 | 0.5 | 0.09 | 0.9 | 569 | 1.4 | 6.6 | 7 | 1.4 | 47 | 2 | 118 | 0.709157 |
| | 2010 | GRF | - | | | | 41.2 | 17.7 | 480 | 40.2 | 16.6 | 2.3 | 0.36 | 0.9 | 589 | 1.0 | 24.3 | 2090 | 6.5 | 1414 | 64 | 12780 | 0.707119 |
| | 2010 | GRF | - | 135 | 5.0 | | 41.5 | 17.8 | 478 | 40.6 | 16.8 | 2.3 | 0.36 | 1.0 | 597 | 1.0 | 24.3 | 2110 | 8.0 | 618 | 31 | 6468 | |

* n.a. = not analyzed

** b.d. = below detection

[$] SPF = Syringe pore fluids; RPF = Rhizon pore fluids (added number differentiates between multiple cores collected in the same year); VF = vent fluids; and GRF = gas-rich fluids

[&] Seawater Fe concentrations from Achterberg et al., 2001. Seawater Mn concentration from Lan and Alfassi, 1994.

**Table 2**

Table 2.
End-member concentrations based on zero-Mg, and selected element ratios, for Panarea hydrothermal sites investigated in this study compared to other settings.

| Site | Year | Sample Type | $SO_4$ | Na | Ca | K | B | Sr | Br | Cl | Si | Ba | Li | Rb | Cs | Na/Cl | Ca/Cl | K/Cl | B/Cl | Sr/Cl | Br/Cl | Sr/Ca |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mM | mM | mM | mM | mM | mM | mM | mM | mM | µM | µM | µM | nM | | | | x10$^3$ | x10$^3$ | x10$^3$ | x10$^3$ |
| Hot Lake | 2008 | RPF | ** | 883 | 547 | 212 | 50.3 | 4.6 | 3.2 | 2373 | 7.4 | 31.6 | 19330 | 902 | 148300 | 0.37 | 0.23 | 0.09 | 21.2 | 1.94 | 1.36 | 8.4 |
| | 2008 | RPF | | 1013 | 605 | 221 | 56.4 | 5.3 | 3.8 | 2663 | 7.9 | 27.2 | 22370 | 856 | 124300 | 0.38 | 0.23 | 0.08 | 21.2 | 1.99 | 1.44 | 8.8 |
| | 2009 | RPF-1 | | 471 | 260 | 92 | 26.9 | 1.9 | 1.5 | 1214 | 4.0 | 22.4 | 9286 | 454 | 76320 | 0.39 | 0.21 | 0.08 | 22.2 | 1.58 | 1.20 | 7.4 |
| | 2009 | RPF-1 | | 772 | 388 | 134 | 35.7 | 3.2 | 2.5 | 1739 | 4.3 | 25.0 | 13730 | 584 | 87490 | 0.44 | 0.22 | 0.08 | 20.5 | 1.85 | 1.46 | 8.3 |
| | 2009 | RPF-1 | | 824 | 403 | 136 | 33.3 | 3.6 | 0.7 | | 4.2 | 23.1 | 15230 | 603 | 85390 | | | | | | | 8.9 |
| | 2009 | RPF-1 | | 1026 | 575 | 205 | 51.6 | 4.9 | 3.7 | 2497 | 6.5 | 38.8 | 21960 | 841 | 114000 | 0.41 | 0.23 | 0.08 | 20.7 | 1.96 | 1.49 | 8.5 |
| | 2009 | RPF-1 | | 1101 | 630 | 207 | 57.2 | 5.6 | 4.0 | 2684 | 6.7 | 24.1 | 16940 | 698 | 107900 | 0.41 | 0.23 | 0.08 | 21.3 | 2.08 | 1.48 | 8.8 |
| | 2009 | RPF-1 | | 1113 | 623 | 205 | 56.8 | 5.5 | 2.6 | 1843 | 6.5 | 17.2 | 16110 | 682 | 109400 | 0.60 | 0.34 | 0.11 | 30.8 | 2.97 | 1.41 | 8.8 |
| | 2009 | RPF-2 | | 656 | 343 | 121 | 32.4 | 2.7 | 2.6 | 1582 | 5.2 | 29.6 | 11040 | 542 | 85280 | 0.41 | 0.22 | 0.08 | 20.5 | 1.70 | 1.64 | 7.8 |
| | 2009 | RPF-2 | | 1020 | 568 | 195 | 51.4 | 5.0 | 3.7 | 2479 | 6.4 | 52.7 | 18640 | 757 | 107800 | 0.41 | 0.23 | 0.08 | 20.7 | 2.01 | 1.50 | 8.8 |
| | 2009 | RPF-2 | | 1054 | 564 | 193 | 50.9 | 5.0 | 3.9 | 2449 | 6.2 | 52.1 | 16340 | 712 | 107700 | 0.43 | 0.23 | 0.08 | 20.8 | 2.04 | 1.58 | 8.9 |
| | 2009 | RPF-2 | | 1023 | 572 | 194 | 52.4 | 5.1 | 3.9 | 2484 | 6.3 | 53.3 | 19100 | 753 | 108500 | 0.41 | 0.23 | 0.08 | 21.1 | 2.05 | 1.58 | 8.9 |
| | 2009 | RPF-2 | | 1049 | 566 | 194 | 51.4 | 5.1 | 3.9 | 2458 | 6.3 | 54.2 | 17540 | 740 | 111000 | 0.43 | 0.23 | 0.08 | 20.9 | 2.07 | 1.59 | 9.0 |
| | 2009 | RPF-2 | | 1033 | 575 | 198 | 53.3 | 5.1 | 3.9 | 2510 | 6.3 | 57.3 | 18660 | 774 | 114800 | 0.41 | 0.23 | 0.08 | 21.2 | 2.04 | 1.57 | 8.9 |
| | 2010 | RPF-1 | | 1041 | 602 | 191 | 45.4 | 4.7 | 4.3 | 2380 | 7.1 | 36.1 | 13890 | 604 | 101100 | 0.44 | 0.25 | 0.08 | 19.1 | 1.96 | 1.79 | 7.7 |
| | 2010 | RPF-1 | | 989 | 587 | 189 | 44.6 | 4.6 | 3.7 | 2342 | 6.8 | 36.9 | 13770 | 613 | 103100 | 0.42 | 0.25 | 0.08 | 19.1 | 1.96 | 1.58 | 7.8 |
| | 2010 | RPF-1 | | 991 | 575 | 186 | 44.0 | 4.1 | 3.7 | 2339 | 7.4 | 34.3 | 13460 | 610 | 106000 | 0.42 | 0.25 | 0.08 | 18.8 | 1.76 | 1.60 | 7.2 |
| | 2010 | SPF | | 1004 | 709 | 183 | 42.1 | 4.4 | 3.8 | 2457 | 6.2 | 45.7 | 12010 | 574 | 102500 | 0.41 | 0.29 | 0.07 | 17.1 | 1.78 | 1.56 | 6.2 |
| | 2010 | SPF | | 1086 | 1042 | 217 | 50.2 | 4.7 | 4.4 | 2776 | 7.0 | 52.8 | 16170 | 747 | 128300 | 0.39 | 0.38 | 0.08 | 18.1 | 1.71 | 1.58 | 4.6 |
| | 2010 | SPF | | 1039 | 665 | 200 | 46.6 | 4.5 | 4.1 | 2626 | 7.6 | 51.3 | 14740 | 696 | 123300 | 0.40 | 0.25 | 0.08 | 17.7 | 1.70 | 1.54 | 6.7 |
| Black Point | 2008 | RPF | | | | | 2.3 | 0.5 | | | 4.1 | 21.1 | | | 2787 | | | | | | | |
| | 2008 | RPF | | | 55 | | 3.4 | 0.8 | | | 41.6 | 34.3 | | | 4615 | | | | | | | 14.9 |
| | 2008 | VF | | 444 | 197 | 73 | 16.4 | 2.0 | 1.4 | 1024 | 10.0 | 62.0 | 5370 | 264 | 42030 | 0.43 | 0.19 | 0.07 | 16.1 | 1.95 | 1.37 | 10.1 |
| | 2009 | RPF | | | | | 17.3 | 0.1 | 0.1 | 31 | 5.5 | 3.4 | | 4 | 318 | | | | 565.4 | 2.93 | 4.43 | |
| | 2009 | RPF | | | 1 | | 19.2 | 0.1 | | | 5.6 | 4.3 | 210 | 4 | 306 | | | | | | | 93.7 |
| | 2009 | RPF | | | | | 23.8 | 0.1 | | | 5.5 | 9.9 | 170 | 2 | 348 | | | | | | | |
| | 2009 | RPF | | | 9 | | 7.8 | 0.1 | 0.5 | | 12.7 | 5.4 | 402 | 6 | 1203 | | | | | | | 10.2 |
| | 2009 | RPF | | | 11 | | 8.1 | 0.1 | | | 15.7 | 5.6 | 487 | 8 | 1308 | | | | | | | 8.1 |
| | 2009 | VF | | | 11 | 6 | 1.4 | 0.1 | | 36 | 16.6 | 7.0 | 682 | 21 | 3837 | | 0.31 | 0.16 | 38.2 | 2.50 | | 8.1 |
| | 2010 | RPF-1 | | | 24 | 3 | 1.5 | 0.3 | | | 13.0 | 6.9 | 230 | 19 | 3183 | | | | | | | 14.4 |
| | 2010 | RPF-1 | | | 38 | | 1.1 | 0.2 | 0.3 | | 27.7 | 5.6 | 467 | 17 | 1963 | | | | | | | 6.3 |
| | 2010 | RPF-1 | | 52 | 31 | | 1.3 | 0.3 | 0.1 | | 24.2 | 7.5 | 407 | 20 | 2955 | | | | | | | 9.3 |
| | 2010 | RPF-1 | | | 41 | | 1.1 | 0.3 | 0.3 | | 29.0 | 6.2 | 427 | 22 | 2710 | | | | | | | 6.2 |
| | 2010 | RPF-1 | | | 42 | | 1.1 | 0.3 | 0.3 | | 30.5 | 6.0 | 500 | 16 | 1978 | | | | | | | 6.0 |
| | 2010 | RPF-2 | | | 1177 | 186 | 23.8 | 11.8 | | | 472.0 | 157.0 | 5690 | 235 | 48860 | | | | | | | 10.0 |
| | 2010 | RPF-2 | | | 61 | | 1.5 | 0.4 | | | 39.0 | 9.8 | 562 | 20 | 3201 | | | | | | | 5.8 |
| | 2010 | RPF-2 | 0.8 | | 52 | | 1.6 | 0.4 | | | 31.5 | 31.2 | 446 | 19 | 3582 | | | | | | | 7.3 |
| | 2010 | RPF-2 | | | 61 | | 1.6 | 0.4 | | | 38.9 | 27.0 | 599 | 24 | 4069 | | | | | | | 6.0 |
| | 2010 | RPF-2 | 4.6 | | 48 | | 1.2 | 0.3 | 0.2 | | 32.9 | 18.9 | 509 | 16 | 2327 | | | | | | | 5.5 |
| | 2010 | SPF | 8.6 | 16 | 26 | 11 | 1.1 | 0.3 | 0.3 | | 23.7 | 19.0 | 406 | 23 | 3834 | | | | | | | 9.8 |
| | 2010 | SPF | 1.7 | 1 | 19 | 10 | 1.0 | 0.2 | 0.4 | | 25.4 | 17.2 | 382 | 18 | 2964 | | | | | | | 11.7 |
| | 2010 | VF | 1.6 | 464 | 77 | 28 | 5.6 | 0.7 | 1.4 | 780 | 3.0 | 24.4 | 1471 | 91 | 16570 | 0.59 | 0.10 | 0.04 | 7.2 | 0.92 | 1.85 | 9.4 |
| | 2010 | VF | | 447 | 172 | 63 | 12.8 | 1.6 | 1.7 | 735 | 6.6 | 66.3 | 3018 | 191 | 33860 | 0.61 | 0.23 | 0.09 | 17.4 | 2.23 | 2.25 | 9.5 |
| La Calcara | 2008 | RPF | | | | 11 | 47.1 | 2.0 | | | | 33.1 | 1998 | 21 | 12130 | | | | | | | |
| | 2008 | RPF | | | | | 23.8 | 5.9 | | | 11.7 | 99.1 | | | 35160 | | | | | | | |
| | 2008 | RPF | | | | | 23.8 | 5.9 | | | 70.0 | 99.1 | | | 34810 | | | | | | | |
| | 2008 | RPF | | | | | 23.8 | 5.9 | | | 134.0 | 157.0 | | | 34691 | | | | | | | |
| | 2008 | GRF | | | 7 | 7 | 1.9 | 0.2 | | | 4.7 | 9.0 | 589 | 21 | 4681 | | | | | | | 20.2 |
| | 2009 | RPF-1 | | | 1 | | 17.0 | 0.1 | | | 3.0 | 8.3 | 84 | | 1270 | | | | | | | 65.1 |
| | 2009 | RPF-1 | | | 11 | | 6.3 | 0.1 | | | | 10.2 | | | 1430 | | | | | | | 8.1 |
| | 2009 | RPF-1 | | | 11 | | 12.1 | 0.1 | | | | 5.9 | | | 302 | | | | | | | 8.1 |
| | 2009 | RPF-1 | | | 128 | | | 5.9 | | | | 99.1 | | | 760 | | | | | | | 46.4 |
| | 2009 | RPF-1 | | | 69 | | 86.0 | 2.0 | | | 3.9 | 33.1 | | | 294 | | | | | | | 29.3 |
| | 2009 | RPF-1 | | | 50 | | 14.1 | 1.1 | | | 0.0 | 16.5 | | | 138 | | | | | | | 21.2 |
| | 2009 | RPF-2 | | | | | 9.9 | 0.1 | | | 1.4 | 4.7 | 232 | 7 | 80 | | | | | | | |
| | 2009 | RPF-2 | | | 1 | | 12.1 | 0.1 | | | 0.4 | 5.9 | 275 | 5 | 95 | | | | | | | 110.9 |
| | 2009 | RPF-2 | | | 11 | | 79.2 | 1.5 | | | 10.2 | 24.8 | 910 | 16 | 381 | | | | | | | 139.4 |
| | 2009 | RPF-2 | | | 128 | | 257.0 | 5.9 | | | 35.0 | 99.1 | 4291 | | 993 | | | | | | | 46.4 |
| | 2009 | RPF-2 | | | 11 | | 432.0 | 0.1 | | | 152.0 | 99.1 | 93 | | 1343 | | | | | | | 8.1 |
| | 2009 | RPF-2 | | | 69 | | 23.8 | 0.1 | | | 23.4 | 99.1 | | | 352 | | | | | | | 1.3 |
| | 2009 | RPF-3 | | | | | | 0.1 | | | 7.0 | 10.5 | 58 | 2 | 161 | | | | | | | |
| | 2009 | RPF-3 | | | 11 | | 82.1 | 0.1 | | | 245.0 | 157.0 | 1201 | | 2509 | | | | | | | 8.1 |
| | 2009 | RPF-3 | | | 1 | | 4.3 | 0.1 | | | 37.9 | 26.3 | 375 | | 206 | | | | | | | 65.1 |
| | 2009 | RPF-3 | | | | | 18.0 | 0.1 | | | 27.7 | 19.7 | 35 | | 286 | | | | | | | |
| | 2009 | RPF-3 | | | | | 4.8 | 0.1 | | | 10.2 | 8.3 | 84 | | 88 | | | | | | | |
| | 2009 | RPF-3 | | | 69 | | 140.0 | 0.1 | | | 274.0 | 216.0 | | | 1518 | | | | | | | 1.3 |
| | 2009 | GRF | | | | | | 0.1 | | | 7.3 | 15.2 | | 0 | 144 | | | | | | | |
| | 2010 | SPF | | 33 | | 3 | 0.7 | 0.0 | 0.1 | | 4.4 | 9.0 | 40 | 2 | 216 | | | | | | | |
| | 2010 | SPF | | | 7 | 7 | 1.3 | 0.1 | 0.1 | | 29.0 | 28.6 | 283 | 10 | 2424 | | | | | | | 13.0 |
| | 2010 | GRF | | 317 | 110 | 30 | 6.7 | 1.0 | 0.8 | 518 | 3.3 | 22.1 | 4736 | 213 | 43560 | 0.61 | 0.21 | 0.06 | 13.0 | 1.95 | 1.55 | 9.2 |
| | 2010 | GRF | | 306 | 113 | 31 | 6.8 | 1.0 | 1.1 | 547 | 3.4 | 27.7 | 2056 | 104 | 22440 | 0.56 | 0.21 | 0.06 | 12.5 | 1.88 | 2.10 | 9.1 |
| Mid-ocean ridges | | | 0.4 | 417 | 35 | 23 | | 0.1 | | 531 | 15.1 | 79.7 | 668 | | | 0.79 | 0.06 | 0.04 | | 0.19 | | 3.3 |
| Ridge-hot spot intersections | | | 0.4 | 355 | 31 | 21 | | 0.1 | | 431 | 14.0 | 29.8 | 350 | | | 0.83 | 0.07 | 0.05 | | 0.24 | | 3.5 |
| Ultramafic hosted | | | 4.3 | 493 | 39 | 21 | | 0.2 | | 605 | 7.5 | 34.5 | 292 | | | 0.83 | 0.06 | 0.03 | | 0.27 | | 3.9 |
| Sedimented ridges | | | 0.2 | 458 | 43 | 33 | | 0.2 | | 581 | 11.6 | 26.0 | 784 | | | 0.79 | 0.08 | 0.05 | | 0.37 | | 5.4 |
| Intraoceanic back-arc basins | | | 4.6 | 419 | 30 | 34 | | 0.1 | | 534 | 12.1 | 34.8 | 1159 | | | 0.80 | 0.05 | 0.06 | | 0.18 | | 6.1 |
| Volcanic arcs | | | 16.0 | 455 | 47 | 20 | | 0.2 | | 587 | 7.4 | 100.0 | 314 | | | 0.79 | 0.07 | 0.03 | | 0.32 | | 13.7 |
| Transitional arc - back-arc basins | | | 5.3 | 434 | 27 | 49 | | 0.2 | | 552 | 11.3 | 47.0 | 2163 | | | 0.79 | 0.05 | 0.09 | | 0.26 | | 5.7 |
| Intraplate hot spot volcanoes | | | 26.0 | 437 | 11 | 11 | | 0.1 | | 515 | 1.2 | | 39 | | | 0.85 | 0.02 | 0.02 | | 0.17 | | 7.7 |

Note: Representative Major Element Composition of End-Member Fluids from Selected Sea-Floor Hydrothermal Vents from Hannington et al. (2005)

** blank cells calculated to negative values

**Table 3**

Table 3
Summary of geochemical parameters used for calculating the theoretical bioenergetics for inferred site and fluid type compositions investigated at Panarea.

| Sample/site | Fluid Type | Temp °C | pH | $Na^+$ mM | $K^+$ mM | $Mg^{2+}$ mM | $Ca^{2+}$ mM | $Cl^-$ mM | $Br^-$ mM | $SO_4^{2-}$ mM | $SiO_1$ mM | $B^{3+}$ mM | $Sr^{2+}$ mM | $Mn^{2+}$ mM | $Fe^{2+}$ mM | $Ba^{2+}$ mM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seawater | n.a. | 20 | 8.02 | 546.9 | 11.0 | 58.3 | 11.1 | 617.7 | 0.9 | 32.9 | 0.04 | 0.46 | 0.10 | 5.E-06 | 1.00E-16* | 0.034 |
| Hot Lake 1 | 1 | 80.1 | 4.7 | 729.5 | 79.8 | 35.0 | 290.1 | 1352.6 | 2.1 | 5.4 | 2.5 | 17.1 | 1.78 | 6.37[x] | 0.0145[x] | 0.018 |
| Hot Lake 2 | 1 | 54.7 | 5.2 | 645.2 | 46.8 | 46.7 | 128.7 | 968.3 | 1.6 | 14.0 | 1.4 | 9.4 | 0.98 | 6.14[x] | 0.009[x] | 0.017 |
| Black Point 1 | 2 | 135.0 | 2.9 | 511.4 | 32.6 | 38.1 | 75.5 | 758.4 | 1.1 | 12.3 | 3.5 | 6.0 | 0.75 | 4.15[x] | 0.19[x] | 0.022 |
| Black Point 2 | 3 | 96.6 | 5.6 | 483.4 | 8.8 | 53.4 | 11.1 | 554.9 | 0.8 | 29.3 | 1.4 | 1.1 | 0.09 | 1.38[x] | 0.035[x] | 0.504 |
| La Calcara 2 | 2 | 135.0 | 5.0 | 477.6 | 16.8 | 41.5 | 40.6 | 597.4 | 1.0 | 17.8 | 1.0 | 2.3 | 0.36 | 2.1* | 0.024* | 0.008 |
| La Calcara 1 | 3 | 60.3 | 5.2 | 515.7 | 10.8 | 55.5 | 10.9 | 568.5 | 0.9 | 29.3 | 1.4 | 0.5 | 0.09 | 0.007* | 0.007* | 0.001 |

| | | $HCO_3^-$ mM | $H_2S$ mM | $O_2$ mM | $NO_3^-$ mM | $NO_2^-$ mM | $NH_4^+$ mM | $CO_{2(g)}$ % | $H_2S_{(g)}$ vol % | $O_{2(g)}$ % | $N_{2(g)}$ % | $CO_{(g)}$ ppm | $CH_{4(g)}$ ppm | $H_{2(g)}$ ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seawater | n.a. | 2.3 | 2 nM | 0.24 | 0.0081 | 0.0002 | 0.0005 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Hot Lake 1 | 1 | 1.04[$] | 1.67 | 0.025[x] | 0.027[&] | 0.0002[$] | 3.39[$] | 96.4 | 2.7 | 0.02 | 0.5 | 4.0 | 5.0 | 35.0 |
| Hot Lake 2 | 1 | 1.48[$] | 0.22 | 0.04[$] | 0.027[&] | 0.0002[$] | 1.69[$] | 96.4 | 2.7 | 0.02 | 0.5 | 4.0 | 5.0 | 35.0 |
| Black Point Vent 1 | 2 | 0.8[&] | 0.15 | 0.194[x] | 0.11[&] | 0.0005[$] | 1.69[$] | 98.7 | 0.3 | 0.03 | 0.4 | 3.2 | 817.3 | 91.3 |
| Black Point Vent 2 | 3 | 2.4[$] | 0.05 | 0.24[$] | 0.034[&] | 0.0005[$] | 0.003[$] | 98.7 | 0.3 | 0.03 | 0.4 | 3.2 | 817.3 | 91.3 |
| La Calcara 1 | 2 | n.a.[#] | n.a. | n.a. | 0.027[&] | 0.0003 | 0.18[&] | 97.2 | 0.2 | 0.08 | 0.9 | 3.0 | 5306.5 | 694.8 |
| La Calcara 2 | 3 | n.a. | 0.086 | n.a. | 0.027[&] | 0.0003 | 0.18[&] | 97.2 | 0.2 | 0.08 | 0.9 | 3.0 | 5306.5 | 694.8 |

notes: Seawater values for aqueous $H_2S$ from Luther and Tsamakis (1989). Aqueous seawater values for $CH_4$, $H_2$, CO, and $N_2$ are from Charlou et al. (2002). Seawater $Mn^{2+}$ from Klinknhammer et al. (1985). $NO_3^-$ values at Hot lake and La Calcara is an average of values from Tassi et al. (2009). Because dissolved $O_2$ at La Calcara was not reported the equilibrium value for $O_2$ free gas concentrations were used. $NO_2^-$ at La Calcara is an average of the other sites. #n.a. = not available.

* = equilibrium value calculated using Geochemist's workbench.

$ = from Sieland, 2009 sample with matching Mg concentration.

x = these data points and all dissolved gas data from Müller, 2011.

& = from Tassi et al., 2009

**Table 4**

Table 4.

Summary of metabolic reactions consider in the present study

| | | | |
|---|---|---|---|
| | **$CH_4$ oxidation** | 32 | $5S^0 + 6NO_3^- + 2H_2O \rightarrow 5SO_4^{2-} + 3N_2 + 4H^+$ |
| 1 | $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ | 33 | $4S^0 + 3NO_3^- + 7H_2O \rightarrow 4SO_4^{2-} + 3NH_4^+ + 2H^+$ |
| 2 | $5CH_4 + 8NO_3^- + 8H^+ \rightarrow 5CO_2 + 4N_2 + 14H_2O$ | 34 | $S^0 + 3NO_3^- + H_2O \rightarrow SO_4^{2-} + 3NO_2^- + 2H^+$ |
| 3 | $CH_4 + NO_3^- + 2H^+ \rightarrow CO_2 + NH_4^+ + H_2O$ | 35 | $S^0 + 2NO_2^- \rightarrow SO_4^{2-} + N_2$ |
| 4 | $CH_4 + 4NO_3^- \rightarrow CO_2 + 4NO_2^- + 2H_2O$ | 36 | $S^0 + NO_2^- + 2H_2O \rightarrow SO_4^{2-} + NH_4^+$ |
| 5 | $3CH_4 + 8NO_2^- + 8H^+ \rightarrow 3CO_2 + 4N_2 + 10H_2O$ | 37 | $4S^0 + 4H_2O \rightarrow SO_4^{2-} + 3H_2S + 2H^+$ |
| 6 | $3CH_4 + 4NO_2^- + 8H^+ \rightarrow 3CO_2 + 4NH_4^+ + 2H_2O$ | | **$Mn^{2+}$ oxidation** |
| 7 | $CH_4 + 4MnO_2 + 8H^+ \rightarrow CO_2 + 4Mn^{2+} + 6H_2O$ | 38 | $2Mn^{2+} + O_2 + 2H_2O \rightarrow 2MnO_2 + 4H^+$ |
| 8 | $CH_4 + 8FeOOH + 16H^+ \rightarrow CO_2 + 8Fe^{2+} + 14H_2O$ | 39 | $5Mn^{2+} + 2NO_3^- + 4H_2O \rightarrow 5MnO_2 + N_2 + 8H^+$ |
| 9 | $CH_4 + SO_4^{2-} + 2H^+ \rightarrow CO_2 + H_2S + 2H_2O$ | 40 | $3Mn^{2+} + 2NO_2^- + 2H_2O \rightarrow 3MnO_2 + N_2 + 4H^+$ |
| 10 | $3CH_4 + 4SO_4^{2-} + 8H^+ \rightarrow 3CO_2 + 4S^0 + 10H_2O$ | | **$NH_4^+$ oxidation** |
| 11 | $CH_4 + 4S^0 + 2H_2O \rightarrow CO_2 + 4H_2S$ | 41 | $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+$ |
| | **$H_2$ oxidation** | 42 | $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$ |
| 12 | $H_2 + 1/2O_2 \rightarrow H_2O$ | 43 | $NH_4^+ + 4MnO_2 + 6H^+ \rightarrow NO_3^- + 4Mn^{2+} + 5H_2O$ |
| 13 | $5H_2 + 2NO_3^- + 2H^+ \rightarrow N_2 + 6H_2O$ | 44 | $NH_4^+ + 3MnO_2 + 4H^+ \rightarrow NO_2^- + 3Mn^{2+} + 4H_2O$ |
| 14 | $4H_2 + NO_3^- + 2H^+ \rightarrow NH_4^+ + 3H_2O$ | | **$Fe^{2+}$ oxidation** |
| 15 | $H_2 + NO_3^- \rightarrow NO_2^- + H_2O$ | 45 | $4Fe^{2+} + O_2 + 6H_2O \rightarrow 4FeOOH + 8H^+$ |
| 16 | $3H_2 + 2NO_2^- + 2H^+ \rightarrow N_2 + 4H_2O$ | 46 | $5Fe^{2+} + NO_3^- + 7H_2O \rightarrow 5FeOOH + 0.5N_2 + 9H^+$ |
| 17 | $3H_2 + NO_2^- + 2H^+ \rightarrow NH_4^+ + 2H_2O$ | 47 | $8Fe^{2+} + NO_3^- + 13H_2O \rightarrow 8FeOOH + NH_4^+ + 14H^+$ |
| 18 | $3H_2 + N_2 + 2H^+ \rightarrow 2NH_4^+$ | 48 | $2Fe^{2+} + NO_3^- + 3H_2O \rightarrow 2FeOOH + NO_2^- + 4H^+$ |
| 19 | $H_2 + MnO_2 + 2H^+ \rightarrow Mn^{2+} + 2H_2O$ | 49 | $3Fe^{2+} + NO_2^- + 4H_2O \rightarrow 3FeOOH + 0.5N_2 + 5H^+$ |
| 20 | $4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O$ | 50 | $6Fe^{2+} + NO_2^- + 10H_2O \rightarrow 6FeOOH + NH_4^+ + 10H^+$ |
| 21 | $H_2 + S^0 \rightarrow H_2S$ | | **CO oxidation/disproportionation** |
| 22 | $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ | 51 | $2CO + O_2 \rightarrow 2CO_2$ |
| 23 | $3H_2 + CO \rightarrow CH_4 + H_2O$ | 52 | $5CO + 2NO_3^- + 2H^+ \rightarrow 5CO_2 + N_2 + H_2O$ |
| | **$H_2S$ oxidation** | 53 | $4CO + NO_3^- + H_2O + 2H^+ \rightarrow 4CO_2 + NH_4^+$ |
| 24 | $H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+$ | 54 | $CO + NO_3^- \rightarrow CO_2 + NO_2^-$ |
| 25 | $5H_2S + 8NO_3^- \rightarrow 5SO_4^{2-} + 4N_2 + 2H^+ + 4H_2O$ | 55 | $3CO + 2NO_2^- + 2H^+ \rightarrow 3CO_2 + N_2 + H_2O$ |
| 26 | $H_2S + NO_3^- + H_2O \rightarrow SO_4^{2-} + NH_4^+$ | 56 | $3CO + NO_2^- + H_2O + 2H^+ \rightarrow 3CO_2 + NH_4^+$ |
| 27 | $5H_2S + 2NO_3^- + 2H^+ \rightarrow 5S^0 + N_2 + 6H_2O$ | 57 | $CO + MnO_2 + 2H^+ \rightarrow CO_2 + Mn^{2+} + H_2O$ |
| 28 | $3H_2S + 8NO_2^- + 2H^+ \rightarrow 3SO_4^{2-} + 4N_2 + 4H_2O$ | 58 | $4CO + SO_4^{2-} + 2H^+ \rightarrow 4CO_2 + H_2S$ |
| 29 | $3H_2S + 4NO_2^- + 4H_2O + 2H^+ \rightarrow 3SO_4^{2-} + 4NH_4^+$ | 59 | $4CO + 2H_2O \rightarrow 3CO_2 + CH_4$ |
| 30 | $3H_2S + 2NO_2^- + 2H^+ \rightarrow 3S^0 + N_2 + 4H_2O$ | | **$NO_2^-$ oxidation** |
| | **$S^0$ oxidation/disproportionation** | 60 | $2NO_2^- + O_2 \rightarrow 2NO_3^-$ |
| 31 | $S^o + 1.5O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+$ | 61 | $NO_2^- + MnO_2 + 2H^+ \rightarrow NO_3^- + Mn^{2+} + H_2O$ |

All species are taken to be aqueous except elemental sulfur ($S^0$), pyrolusite ($MnO_2$) and goethite (FeOOH), which are all crystalline phases.