When circulation gets tough, the TOUGH gets going. Modeling of hydrothermal fluid circulation in active volcanic areas

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Numerical modeling of hydrothermal fluid circulation has been prompted by a wide variety of industrial needs, ranging from nuclear waste disposal and geothermal energy exploitation, to the more recent applications devised for environmental remediation and carbon sequestration. Volcanological applications had a later start, hindered by the formidable challenges posed by poorly-constrained and extreme system conditions, joined with a chronic lack of founding and good-quality, modeling-oriented data sets. Nevertheless, as the volcanological implications of hydrothermal activity are important, modeling of fluid circulation in active volcanic system has become more popular in recent times. Modeling results provided useful hints on the evolution of active volcanic systems, by illustrating the role of an evolving source of volcanic gases and showing the diversity of the geochemical and geophysical signals that can be generated by fluid circulation. Numerical simulations also showed how these signals can be modulated by the properties of the rocks, and by their temporal and spatial evolution. This talk will provide an overview of the volcanological applications of hydrothermal circulation models, highlighting the strength and weaknesses of this approach, and discussing future developments. In particular, a promising research direction is the application of inverse modeling of hydrothermal fluid circulation as a tool for the assessment of volcanic system conditions. Preliminary results from the first application to the well known Campi Flegrei caldera will provide an opportunity to discuss potential and problems of the inverse approach to the interpretation of monitoring signals.

Estimation of carbon dioxide emission from Kuju Volcano, Japan, and its numerical modeling

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Kuju Volcano is located in Kyushu and one of the active volcanoes in Japan. In order to infer the mass balance and energy balance of the hydrothermal system in the Kuju volcanic area, we tried to estimate volcanic CO_2 emission and to construct a numerical model of the hydrothermal system of Kuju Volcano.

We considered four forms of volcanic CO_2 emission; from the fumaroles, the bare area around the fumaroles, the flank by the soil gas, and some hot springs at the foot of the volcano. We adopted the value of about 166 t/day from the plumes of Kuju Volcano estimated by Ehara et at. (1981). On the other hand, Itoi (1993) shows the distribution of soil gas CO_2 concentration in the bare area around the fumaroles. In our previous study (Araragi et al., 2008), the relationship between soil gas CO_2 concentration measured by the Kitagawa Gas Detector Tube System and CO_2 flux measured by a CO_2 flux meter in Kuju Volcano was found. Therefore, the CO_2 concentration values shown by Itoi (1993) were converted into the CO_2 flux values, and about 0.8 t/day of the volcanic CO_2 emission was estimated. We measured soil gas CO_2 concentration at 60 points on the flank of the volcano by the Kitagawa Gas Detector Tube System and collected 15 soil gas samples to conduct the carbon isotope analysis to identify the origin of the CO_2. As a result, we concluded that the volcanic CO_2 emission from the flank was 0 t/day. And for the CO_2 emission from the hot springs at the foot of the volcano, the hot water discharge rate and the average CO_2 concentration in the carbonated water of the Nagayu Hot Springs area was adopted. Then about 5.0 t/day of the volcanic CO_2 emission from Nagayu Hot Springs was estimated. These results show that the volcanic CO_2 emissions by the plumes from the fumaroles and by the carbonated water from a hot springs area are dominant in Kuju Volcano.

In order to construct a numerical model of the hydrothermal system of Kuju Volcano, we used a geothermal simulator STAR Version 9 (Pritchett, 1989) that can treat the components of H_2O and CO_2 but has the limitations of temperature from 0 to 350 deg. C and pressure from 1 to 600 bars. The modeling area has a horizontal extension of 25 km (E-W) and 15 km (N-S), and a vertical extension from -500 m asl to the ground surface. Finally, we constructed a numerical model, which explains the heat discharge rate and CO_2 emission rate by the plumes from the fumaroles and the CO_2 emission rate from the Nagayu Hot Springs area, by trial and error. This numerical model also indicates that the volcanic CO_2 emission is dominated by the gas from the fumaroles and hot water from Nagayu Hot Springs.

The bolsena-torre alfina geothermal field (Italy): a case of caldera-related blind geothermal resource

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The Torre Alfina geothermal field is located about 10 km north of the Quaternary Bolsena caldera. The reservoir is a buried structural high made of Mesozoic-Cenozoic carbonatic sequences characterised by discontinuous secondary permeability and sealed by clay-rich alloctonous syn-orogenic flysch successions and Pliocene neo-authoctonous marine clays. The reservoir is locally highly productive, water-dominated and CO2-rich, with T at its top of 120 degrees C. The origin of the heat source was not investigated in detail but generally attributed to some unidentified deep magmatic body. Our field structural data document fracturing and faulting that affect both the reservoir and the seal units with dominant NE-SW and a subordinate E-W as maximum extension directions. The surface pattern and kinematics indicate that fault systems are part of the Pliocene-Quaternary tectonic episode in Central Italy, where strike-slip kinematics transfers deformation between main extensional shear zones. The fault network controls intense hydrothermal manifestations and travertine deposition north of the Torre Alfina area. 230Th/234U dating allows distinguishing three different stages of hydrothermal pulses bracketed between 200 and 90 ka. To improve the current understanding of the geometry and density of subsurface fracture system we applied the Shear Wave Splitting (SWS) technique studying the waveforms from local microearthquakes recorded in the area from 2008 to 2011. The analysis of SWS provides parameters directly related to the strike of the subsurface fluid-filled fractures and their density. According to the extensive-dilatancy anisotropy hypothesis (Crampin, 1984) SWS is generated by propagation through distributions of fluid-filled cracks, microcracks, and preferentially oriented pore space aligned according to the active stress field in the area.

The analysis was made using the software ANISOMAT and gives a major direction NW-SE. The results agree both with structural data and with the focal mechanism of the earthquakes collected in the area between years 1977 and 1992. From the analysis on the crack density our data gives as result a good index of fracture for the reservoir's rocks. Based on the updated conceptual model we performed numerical simulations in TOUGH2 code. Results indicate that deep circulation is forced by the geometry of the reservoir and by T and P gradients. We interpret the Torre Alfina field as a "blind" system, formed dominantly by lateral advection of heat and mass from the Bolsena caldera deep system driven both by high T and by the greater depth at which reservoir rocks are downthrown by the volcano-tectonic collapse. Preferential fracture fabric in the deep carbonates allows the lateral heat transfer. The cap-rocks have excellent sealing characteristics allowing the preservation of heat in correspondence with positive structural traps.

U-Pb dating of zircon as an aid in interpretation of geothermal systems: a case study from the Kawerau Geothermal Field, New Zealand

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Exploration and development of geothermal resources for electrical power generation and direct heat use requires an understanding of the geology that hosts the geothermal system. Key to this understanding is being able to date and correlate marker horizons to link permeable formations, constrain displacement history of faults and time the presence of local heat sources.

The Kawerau Geothermal Field is the most northeasterly of high-temperature geothermal systems in the Taupo Volcanic Zone (TVZ, New Zealand), an active Quaternary arc locus of rhyolitic volcanism and thermal output. The reservoir rocks are a 1 km thick pile of lava, pyroclastic rocks and sediments, supplied with fluid circulating through faulted Mesozoic basement greywacke. Here, where correlation solely by petrographic and textural observations was ambiguous due to hydrothermal alteration, we show the value of U-Pb age information on interpreting geothermal systems. U-Pb age determinations on zircons from extensively altered lithologies provide estimates of crystallisation and eruption ages that allow depositional and faulting histories of rocks hosting the geothermal system to be reconstructed. These histories may be linked to evidence for episodic local magmatism beneath the field and to changes in regional tectonic stress patterns.

Prior to the 0.32 Ma Matahina ignimbrite (a regional marker plane), deposition of ignimbrites occurred in short-lived episodes around 1.45, 1.0, and 0.55-0.6 Ma, separated by thin sediment-dominated intervals which accumulated at average rates of 0.06 mm/yr. The ignimbrites represent marker horizons from other volcanic centres and do not reflect the presence of local magmatic heat sources. Net subsidence rates inferred from depths to these marker planes do not reflect the present-day situation. Modern rates of subsidence (2+/-1 mm/yr) associated with TVZ rifting processes can have been active for no more than 50,000 years in the area of the field, based on elevation differences of the Matahina ignimbrite top surface.

Bodies of coherent rhyolite (i.e., lava or intrusive material) occur at multiple intervals in the volcanic/sedimentary cover and basement greywacke. Age dating resolves these multiple bodies as either domes or intrusions: two petrographically contrasting magma types with associated tuffs were emplaced as domes and sills at 0.36+/-0.03 Ma, and a third type at 0.138+/-0.007 Ma as dikes, and domes exposed at surface. Heat sources beneath the field resulted from these local magma intrusions, together with that feeding the Holocene eruptive activity of Putauaki andesite/dacite volcano. Of these, the last is responsible for the thermal and alteration characteristics of the modern field. We infer that only at long-spaced intervals is there evidence of magma at shallow enough crustal levels beneath the field to generate vigorous hydrothermal activity (as at the present day); at other times no Kawerau geothermal system’ existed.

Concept of the Japan Beyond-Brittle Project (JBBP) for new forntier of geothermal power generation

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New conventional geothermal energy projects have not been actively promoted in Japan for the last decade because of perceptions of high relative cost, limited electricity generating potential and the high degrees of uncertainties and associated risks of subsurface development. More recently however, EGS (Enhanced Geothermal System) geothermal has been identified as a most promising method of geothermal development because of its potential applicability to a much wider range of sites, many of which have previously been considered to be unsuitable for geothermal development. Meanwhile, some critical problems with EGS technologies have been experimentally identified, such as low recovery of injected water, difficulties in establishing universal design/development methodologies, and the occurrence of induced seismicity, suggesting that there may be limitations in realizing EGS in earthquake-prone compression tectonic zones.

We propose a new concept of engineered geothermal development where reservoirs are created in ductile basement. This potentially has a number of advantages including: (a) simpler design and control of the reservoir, (b) nearly full recovery of injected water, (c) sustainable production, (d) lower cost when developed in relatively shallower ductile zones in compression tectonic settings, (e) large potential quantities of energy extraction from widely distributed ductile zones, (f) the establishment of a universal design/development methodology, and (g) suppression of felt earthquakes from/around the reservoirs.

To further assess the potential of EGS reservoir development in ductile zones we have initiated the "Japan Beyond-Brittle Project (JBBP)". It is intended that the first few years of the JBBP will be spent in basic scientific investigation and necessary technology development, including studies on rock mechanics in the brittle/ductile regime, characterization of ductile rock masses, development of modeling methodologies/technologies, and investigations of induced/triggered earthquakes. We expect to drill a deep experimental borehole that will penetrate the ductile zone in northeast Japan after basic studies are completed.

The preliminary conceptual model of Tolehu geothermal resource based on geology, geochemistry and MT data

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The Tolehu Geothermal area Ambon (70 m asl.), which had initially been studied more than fifteen years ago was resurveyed by additionalMT-TDEM method and an exploration well in 2010 and 2011 to constrain a conceptual model for the prospect area. Based on those conceptual model that integrated the 1D and 2D MT inversion images with data from existing wells and geochemistry, six gradient thermal wells with the maximum depth 150 m and one exploration well of about 930 m depth had indicated over 200 degree Celsius resource. The deep well was drilled to confirm the elements of the model and extended the proven geothermal reservoir 1.5 km to 2.5 km to the south an old volcanic complex. Shallow cores and deeper cuttings were analyzed by using petrography and x-ray methods. They had confirmed that the low resistivity detected by MT and TDEM surveys closely correlated with the distribution of low temperature smectite and high temperature of illite and chlorite clay alteration. Due to the greater tendency of clay minerals (smectite, illite, phyrophlite, chlorite clay) to inhibit the formation of fracture permeability relative to more brittle clays, the top of the permeable reservoir generally conformed to the geometry of the base of the low resistivity clay alteration. The rough correlation of the 200 degree Celsius geothermometry with the 5 and 10 ohm-m contours below the transition from smectite,illite, illite to chlorite clay were used to predict the depth of cap rocks.The extreme temperature of thermal gradient is 123 degree Celsius at the depth of 150 m and the water dominated system with Chloride concentration lower than 5000 ppm at 930 m depth, indicate sea water uninvolved to the geothermal system.

A business model of hot spring power generation and its current progress in Japan

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A business model of hot spring power generation was proposed by Muraoka (2007) and Osato and Muraoka (2008) to efficiently utilize low-temperature hydrothermal resources such as the numerous hot springs in Japan. About 28,000 hot spring sources are distributed all over Japan and their pre-existence is one of the serious barriers to develop new geothermal power plants in Japan. However, current binary cycle technology enables power generation by hot spring water even less than 100℃. Most of high-temperature hot springs are mainly used for bathing in Japan until the present where they have to be cooled down to the adequate bath temperature 42℃ without any serious dilution of balneological constituents. It means that high-temperature hot springs need more works in terms of the bath use compared to the moderate-temperature hot springs. Then, we proposed to introduce a very small binary cycle in the upper reach of high-temperature hot springs. If we do that, we could make power generation with the high-temperature range above the bath-use temperature and we could make the cooling down to the adequate bath use temperature without any serious dilution of balneological constituents at the same time. This is our business model of hot spring power generation. This business model gives a further merit, that is, if hot spring owners adopt the business model of hot spring power generation, the conflict between hot spring owners and geothermal power development will be gradually reduced, because the hot spring power generation itself is some sort of geothermal power development. At the time of the proposal, we did not have any small binary cycle power generation systems suitable for the small discharge rate of hot springs and therefore we made our efforts to develop a 50 kW class Kalina cycle hot spring power generation system. This system was almost completed and is now under the operation experiment in the Matsunoyama hot spring field, Niigata Prefecture. In addition to this, many makers recently manufactured small-scale binary cycle power generation systems such as 70 kW, 50 kW, 20 kW and 3 kW classes in Japan. The feasibility studies of hot spring power generation are recently made in Niigata, Shizuoka, Nagasaki, Oita, Nagano, Toyama and Aomori Prefectures. The profitability of hot spring power generation is still marginal even by the new Feed-in Tariff system at 42 Yen/kWh introduced in July 2012, but the hot spring power generation market will be established within the coming ten years.

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Magmatic and Hydrothermal Activity in the East African Rift

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The caldera volcanoes of the East African Rift are among some of the most dangerous volcanoes in the world (Aspinall et al, 2011), since they have had eruptions within the very recent past, are close to densely populated areas and are un-monitored. However, they also contain significant geothermal resources and are therefore subject of large infrastructure investment. There is a critical lack of understanding of the current activity of the magmatic and hydrothermal system, and the potential volcanic hazards. To address this we are engaged in active research projects on two young volcanoes, Alutu, Ethiopia and Longonot, Kenya. Both of these volcanoes are currently undergoing active deformation, identified by InSAR during the period 1997-2010 (Biggs et al, 2011). Alutu is currently the location of the only major geothermal power plant in Ethiopia and drilling is about to start at Longonot, Kenya. Naturally occurring changes in the volcano affect the operation of the plant while the production itself may change the state of stress in the reservoir and surroundings, influencing the seismic and volcanic hazard. This project involves seismic monitoring, MT and geodetic measurements and well as airborne imagery , field mapping and sampling. The opportunity to obtain such a multi-disciplinary dataset offers the potential to transform our understanding of the status of ongoing magmatic and hydrothermal activity associated with these active volcanic systems and their current and future volcanic hazards.

Magmatic vapor plumes in active volcanoes: dynamics, discharge and disasters

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Magmatic gas mixtures released by crystallizing intrusives expand across permeability discontinuities from lithostatic to near-hydrostatic pressure within volcanic systems. In arc volcanoes they provide most of the heat energy that is widely dispersed as extensive geothermal systems or released directly through the surface as high temperature, high enthalpy fumaroles and extensive solfatara and as gas plumes.Modeling of their expansion to the surface and their interaction with groundwater to form magmatic vapor plumes is compromised by the difficulties of dealing with compressible fluids. Data from fossil plumes (for example, porphyry and high sulfidation copper-gold deposits) however provide evidence of their scale and internal structure that may then be used to constrain modeling (Henley and McNabb, 1978).

A general approach to analysis of the dynamics of magmatic vapor plumes is outlined here based on simple phase relations and Markov principles and shows that one of the principle controls on plume architecture is the ratio,Kp, of vertical to horizontal permeability (Hurwitz et al., 2003). In low Kp systems, phase separation to form envelopes on the margins of plumes is a consequence of the net decrease in enthalpy due to groundwater mixing and has implications for hydrothermal alteration and mineralisation, and the evolution of geothermal systems. Where Kp is large, high energy discharges are maintained. In addition to input power, their periodicity is related primarily to changes in fracture permeability due to mineral deposition and depletion of the source magmatic gas reservoir.

Understanding of the behavior of magmatic vapor plumes may contribute to the analysis of the history of volcanic systems and their energy flux. It may also provide a basis for forecasting and tracking Plinean eruptions and their linkage to major seismic events in tectonically-challenged crust.

Understanding phreatic & hydrothermal explosion dynamics: insights into the energy conversion based on lab experiments

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Phreatic eruptions are amongst the most common and most diverse eruption types on earth. Often they are precursory to another type of volcanic activity but they can stand as well on their one. Phreatic explosions occur for instance when subsurface water or water on the surface is heated by magma, lava, hot rocks, or fresh volcanic deposits and result in craters, tuff rings and debris avalanches. Another wide and important field affected by steam explosions are hydrothermal areas; here hydrothermal explosions might occur every few months creating explosion craters and resemble a significant hazard to hydrothermal power plants as well as visitor parks. Despite of their hazard potential, phreatic explosions have so far been overlooked by the field of experimental volcanology. A part of their hazard potential in owned by the fact that phreatic explosions are hardly predictable in occurrence time and size as they have manifold triggers. The diversity of phreatic and hydrothermal eruptions arises from the variety of host rocks, ways to seal possible degassing pathways, and to alter this material depending on the composition of volcanic gases and the hydrothermal fluids.

We conduct rapid decompression experiments on a variety of natural samples from igneous rocks to sedimentary rocks; consolidated and unconsolidated. The setup used can be operated with gas and/or vapour overpressure of up to 20 MPa and in a temperature range from range from 20℃ to 400℃, further we vary the degree of water saturation of the samples. The experiments are monitored with a set of pressure and temperature sensors, synchronized to high-speed video recording of the particle ejection. The resulting particles are recovered and their grain size distribution are analysed. This together allows us to constrain the fragmentation behaviour and the efficiency of the fragmentation in phreatic explosions. We observe that the threshold for fragmentation is slightly lowered whereas the propagation speed of the fragmentation process through the sample is comparable to dry magmatic experiments. A clear contrast is seen for the ejection speed of the clasts: phreatic clasts can be ejected at almost double the speed as their magmatic counterparts under similar overpressure conditions. Further the ejection speed depends on the ratio of superheated water to vapour and argon gas. This ratio controls also the efficiency of fragmentation as well as the grain shapes.

Our experiments and results enable us to better understand the dynamics of phreatic and hydrothermal explosions and associated risks. Here we present insights into the energy conversion during phreatic eruptions, based on various starting scenarios. This will provide vital information for the hazard assessment of hydrothermally active areas.

New Insights on the structure and dynamics of geysers

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Recent experiments performed at Lone Star Geyser and the reprocessing of seismic ambient noise data collected at Old Faithful Geyser (OFG), both at Yellowstone Nat. Park (USA) provide new insights on the structure and eruption dynamics of these geysers.

Seismic data obtained in 1992 with a dense array around Old Faithful Geyser have been re-processed using acoustic localization techniques (beamforming) to characterize the spatial and temporal patterns of seismic sources inside the geyser conduit. The remarkably energetic, seismo-acoustic activity at OFG is induced by the continuous cavitation of steam bubbles, which occurs in the upper one meter of the water column. Time-dependent localization of this powerful acoustic source during the eruption cycle allows us to track water level and phase separation in the conduit, which in turn provides new insights on the dynamics of the geyser. The distribution of the dominant noise sources at OFG highlights two distinct structures in the geyser subsurface where water boiling is concentrated: the cylindrical geyser conduit, and a previously unknown lateral reservoir. This reservoir is activated during the recharge period at the beginning of each geyser eruption cycle and plays a major role in the oscillatory behavior of the water level in the conduit before each eruption.

Geophysical experiments have been carried out during one week in 2011 at Lone Star geyser, during which seismic ambient noise, ground deformation, acoustic, Infra-red and water flow data from 30 eruptions were collected. We focus here on the dynamics of the pre-play preceding the eruption, in which the conditions required to initiate the eruption are slowly reached. During the pre-play, thermal expansion and oscillation of the fluid into the conduit induces several episodes of water overflow, which are followed after some delay by a very energetic pulse of seismic noise indicating boiling at depth. Eruption starts when these two processes are synchronous.

Eruptions at Lone Star Geyser, Yellowstone National Park, USA: Energetics and Eruption Dynamics

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Geysers provide a unique natural laboratory to study multiphase eruptive processes. We present results from a four day experiment at Lone Star geyser in Yellowstone National Park, USA. We measured simultaneously water discharge, acoustic emissions, infrared intensity, and visible and infrared video to quantify the energetics and dynamics of eruptions, occurring approximately every three hours. We define four phases in the eruption cycle: 1) a 28 ± 3 minute phase with liquid and steam fountaining, maximum jet velocities of 16–28 m/s, steam mass fraction of 0.5–2.5$\%$, intermittently choked flow, and unsteady flow oscillations with periods increasing from 20 to 40 s, coincident with a decrease in jet velocity and an increase of steam fraction, 2) a 26 ± 8 minute post-eruption relaxation phase with no fluid discharge from the vent, infrared (IR) and acoustic power oscillations gliding between 30 and 40 s, and ~ 8 s lag between the peak in acoustic and IR signals, 3) a 59 ± 13 minute recharge period during which the geyser reservoir progressively refills, and 4) a 69 ± 14 minute pre-play period characterized by a series of 5–10 minute–long steam puffs, small volumes of liquid water discharge, 50–70 s oscillations, and no lag between IR and acoustic signals. The erupted waters ascend from a $163 \pm 5°$C – $186 \pm 2°$C reservoir and the volume discharged during the entire eruptive cycles is 20.8 ± 4.1 m^3. Assuming isentropic expansion, we calculate a heat output of 1.5–1.7 MW, which is $< 0.1\%$ of the total heat output from Yellowstone Caldera.

Imaging seismic source variations throughout the eruptive sequences of volcanoes and geysers using back-projection methods

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Our understanding of the mechanisms, dynamics, and plumbing networks that characterize volcanic and hydrothermal systems is limited by our ability to remotely observe weak motions related to dynamic processes at depth. Seismic records from these systems are typically extremely noisy, making it difficult to utilize traditional seismic methods to resolve 3D subsurface structures. High-amplitude bursts within the noise (i.e. eruptions), which might be suitable for use with traditional seismic methods, occur infrequently compared to the length of the entire eruption cycle. Therefore, while these events may help us understand the dynamics of a particular eruption, they shed little insight into the mechanisms and dynamics that occur throughout the entire eruption sequence. Without a continuous temporal sampling we cannot characterize the system as a whole. However, it has been shown that much more abundant low-amplitude “noise” in these records actually represents a series of overlapping low-magnitude displacements that can be directly linked to magma and fluid movement at depth. This data, ignored by most prior studies, contains valuable information about the processes occurring in the volcanic or hydrothermal system before, during and after eruptions. New array processing has the potential to provide crucial insight into the overall behavior of the volcanic or hydrothermal system.

In this study, we present a new method that seeks to comprehensively study how the seismic source distribution of all events - - including micro-events - - evolves through a volcanic or hydrothermal systems entire eruption cycle. We apply a back-projection search algorithm to image sources of seismic “noise” at different stages in the eruptive cycle of a volcano (Sierra Negra, Galapagos) and hydrothermal system (El Tatio Geyser Field, northern Chile). By analyzing coherent seismic energy from all possible events to all available receivers, we determine how the seismic source location changes through time. This approach utilizes data from the entire seismic record before, during and after eruptions and thus allows for a more complete understanding of how seismic sources change throughout an eruptive sequence rather than only during a particular high-magnitude event or eruption. This information will help 1) answer fundamental geologic questions about volcano-tectonic processes, 2) make more accurate assessments of volcanic and hydrothermal hazards, and 3) improve our understanding of how geothermal reservoirs evolve.

First results from the broadband seismological network at Wayang Windu geothermal area, West Java, Indonesia

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The understanding of structure and dynamics of geothermal reservoirs for geothermal exploration and a sustainable use of the resource requires assessment using multidisciplinary approach. We deployed a temporary network of 30 broadband and 4 short-period seismic stations with Güralp and Trillium sensors (0.008 - 100 Hz) since October 2012 which is still recording in West Java, Indonesia. The two phase liquid/vapor geothermal field is situated inside the volcanic zone in the center of West Java. The presence of a complex tectonic setting may explain the co-existence of a large variety of intense surface manifestations like geysers, hot-steaming grounds, hot water pools, and active volcanoes (including Papandayan volcano). These co-existent features around the two phase geothermal field suggest an intimate coupling between volcanic, tectonic and hydrothermal processes in this area. We describe the set-up of the broadband network and discuss first observations and results.

Reconstructing the volcanological and paleoenvironmental setting of an Archean Hollandaire Cu-Au volcanic hosted massive sulphide deposit, Murchison Domain, Yilgarn Craton, Western Australia

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Discovered in late 2011, Hollandaire is a Cu-Au VMS deposit situated near the town of Cue within the Archean Murchison Domain of the Youanmi Terrane, Western Australia, and occurs within the Greensleeves Formation of the Polelle Group (2820-2735 Ma). Host rocks are variably silicified, chloritised and sericitised, have been metamorphosed to upper greenschist facies, and have a pervasive foliation (S1) that is crenulated (S2) in places. As a result, primary textures are obscured. From stratigraphic logging of 31 diamond drill holes, geochemistry (major and trace elements), petrography and geochronology, we reconstruct the paleo volcano-sedimentary setting. Host rocks consist dominantly of either quartz-chlorite-muscovite schists (andesitic to dacitic in composition) or quartz-chlorite-muscovite schists with larger blue quartz crystals (rhyolitic). The former lithofacies, where least deformed and altered, consists of thin interbedded fine and coarse layers up to 100 m thick, as well as intervals of fine-grained carbonaceous black material. This lithofacies is interpreted as a metasedimentary, below wave-base, deep water, distal turbidite succession. The rhyolitic schist lithofacies, with evenly dispersed quartz crystals, ranges up to 300 m thick, and even within less deformed domains is massive and uniform. Fragmentation is absent at the margins of this lithofacies, indicating it is a high-level intrusion. The lone breccia interval (1 m), consisting of cobble-size clasts of coherent rhyolite in a metasedimentary matrix, is interpreted as reworked autoclastic volcanic debris. Undeformed dacite porphyries cross-cut the stratigraphy and clearly post-date deformation, and based on our preliminary geochronological work, are 2780 Ma. Sulphide mineralisation ranges from massive intervals of mainly pyrite and chalcopyrite (up to 14 m thick) to stringers and disseminated styles. Massive intervals are restricted to the metasedimentary lithofacies, while disseminated sulphides are found within both the metasediments and high-level rhyolite intrusion and rarely within the younger dacite porphyries. We interpret much of this as remobilisation but are uncertain to what extent the primary mineralisation reflected seafloor vs sub-seafloor emplacement. We interpret the setting as a rhyolitic cryptodome with VMS mineralisation in a deep-water setting that was pervasively deformed by both S1 and S2 and subsequently intruded by dacitic porphyries. We know of no clear evidence for an arc, however, the tectonic setting remains unclear. Voluminous volcanic events contemporaneous with Hollandaire include the nearby Eelya plutonic complex (2750 Ma), which has similar geochemistry to the high-level rhyolitic intrusion, and the mafic-ultramafic Gnanagooragoo Igneous Complex. This study highlights some of the difficulties in working with Archean deposits and adds to the small database of VMS deposits within the Yilgarn Craton.

Understanding the volcanic processes, stratigraphy and mineralization of the archean teutonic bore, jaguar and bentley volcanic massive sulphide deposits, yilgarn craton, western australia.

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Teutonic Bore, Jaguar and Bentley volcanic hosted massive sulphide deposits are situated in the Eastern Goldfields of the Archean Yilgarn Craton, Western Australia. The VMS complex is situated in the Gindalbie Terrane which is a linear belt (2695-2680 Ma). This bimodal rhyolite-basalt volcanic belt enriched in high field strength elements, consists of felsic calc-alkaline volcanic rocks, quartz rich sedimentary rocks, layered mafic complexes and mafic sills, formed during a period of regional extension in a back arc setting. The VMS deposits are hosted by a bimodal mafic and felsic volcanic succession with associated volcaniclastics and mudstones, and are located along strike over a 12 km distance. The rocks are metamorphosed to lower greenschist facies and have undergone moderate deformation.

The stratigraphy is divided into a hanging wall facies association and a footwall facies association, which are commonly separated by sulphide mineralization. The dominant lithofacies are coherent basalt, rhyolite, andesite and dolerite, which form concordant, tabular bodies black mudstone, with minor graded bedded sandstones (turbidites) and rare polymictic conglomerates, represent the ambient deep water facies that are intercalated with the volcanic units. The basalt is present in both the hanging wall and footwall and contains both massive and pillow basalt facies, indicating that at least some basalts were seafloor lavas. However, monomictic volcanic breccia, commonly with peperitic textures, occurs at the tops and bottoms of many basalt units, indicating that they intruded into unconsolidated sediments. The rhyolite is mainly present in the footwall and is highly altered. Dolerite occurs as late intrusions with coarse crystalline textures.

The Teutonic Bore consists of one steeply dipping lens of massive polymetallic sulphide underlain by stringer mineralization. The Jaguar and Bentley deposit consists of three lenses of massive sulphide that are split by a late dolerite intrusion. The massive sulphide consists of pyrite, sphalerite and chalcopyrite. The mineralization is mainly hosted by black mudstone but also occurs in pillowed basalt above the rhyolites. The sulphide lens occurs as: 1. massive bodies without any dominant fabric; 2. banded bodies of pyrite and sphalerite and chalcopyrite replacing the pyrite at places; and 3. stringer and disseminated patches. The sulphide shows replacement textures with basalt and black mudstone, and therefore represents sub-seafloor mineralization that postdates sedimentation and basalt emplacement. The disseminated sulphide occurs both in the hanging wall and footwall as patches and blebs. Hydrothermal alteration extends into the hanging wall, which also supports a late mineralizing event.

Magma-related hydrothermal system in volcanic terrain: An example of the alteration in Unzen USDP-4 scientific drilling

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Magmatic heat sources form hydrothermal systems in volcanic areas. Magmatic fluids transport various elements and produce secondary minerals as a result of reactions with surrounding rocks. For describing the hydrothermal system inside volcanic terrain, this study examines the characteristics of the hydrothermal alteration undergone by sample drilled cores and cuttings. The samples were taken from a site located about 840 m above sea level on the northern side of Mt. Heisei-shinzan. The conduit drilling USDP-4, International Cooperative Research with Scientific Drilling, began here in 2003. In July 2004, the drilling head reached the conduit zone corresponding to the 1990-1995 eruption (Nakada et al., 2005). The total length of the USDP-4 drilling hole is 1995.75 m. Cuttings were sampled every 2 m along the drilled hole, and sixteen cores named C1 to C16 were sampled at depths exceeding 1582 m. The drilled cores consist of hornblende-bearing andesite to dacite lavas or pyroclastic rocks.

According to the cutting samples, fresh volcanic rocks can be found at depths less than 200 m. Smectite and pyrite occur at depths of more than 1100 m and 1400 m, respectively. Smectite disappears at a depth of 1600 m in both cuttings and core samples. Chlorite appears at depths more than 1700 m in the core samples. The occurrence of these alteration minerals shows generally good correlation with those expected at these depth. On the other hand, some minerals such as kaolinite occur along fractures or faults. Therefore, it is considered that a relatively high temperature solution rose along the fractures or faults, which provided good pathways for hydrothermal fluids. In addition, hydrothermal breccia-bearing veins up to 1 m wide can be observed, indicating that some hydrothermal solution rose explosively. Tuffisite veins are chlorite-altered with green color, which suggests that these veins made good pathways for the migration of volcano-related fluids. Calcites occur as veinlets at depths of less than 1900 m in the drilled cores. The calcite veins often cut through the tuffisite veins, suggesting that the calcite was precipitated at the latest hydrothermal period.

Inside the Unzen volcanic terrain, the hydrothermal alteration is very similar to those of epithermal vein-type gold deposits or geothermal fields. According to the alteration minerals, it can be estimated that the smectite zone shallower than 1600 m was formed at 100 to 150℃, while the chlorite zone deeper than 1700 m was formed at temperatures higher than 190℃. These mineral assemblages correspond to II to IV zones (Izawa et al., 1990) in the hydrothermal systems such as Hishikari, Kushikino gold deposits, and Ogiri geothermal field in Kyushu.

Age dating volcanic springs in the Western Highlands of Cameroon, along the Cameroon Volcanic Line: a multi-tracer approach

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The Western Highlands of Cameroon (WHC) is located mid-way along a chain of volcanoes (ca. 1600 km), cutting diagonally across Cameroon, called the Cameroon Volcanic Line (CVL). The area forms the main watershed in the country and consists of mineralised springs (MS) and numerous less mineralised springs (LMS). Despite the significance of such subsurface waters in volcanic processes, little hydrological data is available on the origin and age of these fluids along the CVL. Such data can provide information on the interaction of subsurface fluids along the CVL. In this study, a preliminary multi-tracer technique has been conducted on 18 LMS (mean TDS of 1542 mg/l) and 6 MS (TDS of 45 mg/l) in the WHC to determine their origin and time of circulation in the upper crust. Except for one MS (hot spring, T >33oC), all other springs are cold (T <27oC). Field observations revealed emanations of an unknown gas at the MS, which may be CO2 based on related studies along the CVL. Regardless of their discharge at relatively low altitudes, all MS are isotopically depleted (mean delta O-18 of -5.67 per-mille) in relation to high altitude discharging LMS (mean delta O-18 of -4.04 per- mille) suggesting recharge of MS under relatively cold climatic conditions. However, both plot along the Local Meteoric Water Line, suggesting their meteoric origin. Tritium values in MS are low, ranging from >0.3 TU (4 samples) to 2.3 TU, compared to 2.4 to 3.1 TU in LMS, mainly indicating pre-1957 recharge of the former and post-1957 recharge of the later. The CFC-12 (like CFC-11 and CFC-113) and SF6 in MS are low, ranging from 6 to 85 pk/kg and from 0 to 0.34 fmol/lg, respectively. On the contrary, LMS show high values in CFC-12 and SF6, ranging from 28 to 239 pk/kg and 1.01 to 7.23 fmol/lg, respectively. Based on the known concentrations of CFCs and SF6 in the atmosphere, CFC-12 versus CFC-11, CFC-113 and SF6 plots of samples show a binary mixing model in MS and mainly an exponential mixing model, of uniform areal recharge, in LMS. CFC-12 versus 3H and delta O-18 versus delta-D plots show different degrees of binary mixtures of old MS and young LMS. Thus, based on the multi-tracer approach, the estimated ages of MS and LMS range from 51 to 35, and 45 to 19 years, respectively, indicating the long residence time and deep circulation of MS which may explain their enriched mineralization. Conclusively, the MS may represent a portion of magmatic fluid that mixes with old deep circulating groundwater, upon its upward movement it further mixes with shallow and cold young groundwater.

Key words: spring water origin, residence time, subsurface circulation, The Cameroon Volcanic Line

Chemical evolution within a hydrothermal fluid circulation system at the Aira caldera, Kyushu, Japan

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A caldera structure provides a geological setting suitable for development of a hydrothermal fluid circulation system, since it is equipped with a heat source magma and fluid conduit of fault networks. The Aira caldera is one of Quaternary calderas which formed within the Kagoshima graben in south Kyushu. At present, most part of the Aira caldera (30 km x 20 km in size) is submerged to be a part of Kagoshima Bay.

The Wakamiko submarine crater is considered as the volcanic center of the past giant eruption that formed the Aira caldera. On the seafloor of 200 meters water depth at the Wakamiko submarine crater, venting of high temperature fluid (around 200 degC) was observed during dive expeditions using ROV (Remote Operation Vehicle). On the other hand, along the shoreline at northern part of the Kagoshima Bay where corresponds to the rim of the Aira caldera, some hot springs are pumped up from the aquifers situated at 650-1100 m depth. The hot spring waters showed temperature of 40-80 degC and NaCl-rich chemistry. In order to reveal similarities in these fluids, geochemical studies were conducted for submarine hydrothermal fluid and onshore hot spring waters.

Relationships among delta-D and chloride concentration of these fluids are commonly explained by around 1:1 mixing of the meteoric water and seawater. This result implies they share the same fluid reservoir that may distribute across subbasement of the caldera floor. Comparison of water chemistry would provide important keys to understand how fluid chemistry evolves during fluid circulation from a recharge zone to discharge zone.

Geochemistry of geothermal fluids in the active Liquiñe-Ofqui Fault System (Southern Andes Volcanic Zone, Chile).

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The nature of the interplay between tectonics and the chemical composition and circulation of geothermal fluids is a major question in active continental margins (Cox, 2010; Rowland and Simmons, 2012). The intra-arc, strike-slip Liquiñe-Ofqui Fault System (LOFS) in the Southern Andes Volcanic Zone (SAVZ) of Chile offers a unique opportunity to address this question because of evident changes in tectonic style related with changes in geochemical signature of volcanic products (Lopez Escobar, 1995; Lara et al., 2006). Two main volcano–tectonic features have been recognized by Cembrano and Lara (2009): 1) kinematically coupled systems directly related to the current dextral transpressional tectonic regime, including NE–trending volcanic alignments of stratovolcanoes and monogenetic cones of primitive, basaltic compositions; 2) kinematically uncoupled systems, including NW–trending of stratovolcanoes associated with ancient reverse faults of the volcanic arc basement. Within this context, one lesser known but relevant aspect of the evolution of geothermal systems associated to the LOFZ is the relation between these volcano–tectonic features and fluid geochemistry.

This study focus on the chemical and isotopic composition of gases and waters in selected volcanoes in the SAVZ. The NE–trending volcanic alignment Callaqui–Copahue is investigated at the northern termination of the LOFS, where the spatial distribution of the hydrothermal discharges is controlled by a NW–trending faults (Nakanishi et al., 1995). South of this area, two additional systems are studied: the Tolhuaca volcano, whose geothermal system seems to be related to an active NW–trending fault, and the NE–trending systems that control the active Lonquimay volcano.

Previous works in Copahue volcano shows a variability in He concentration between the two, NW and NE, structural lineation that control the geothermal system (Agusto 2011). We are using He, O, H and N isotopes able to provide insights about fluid sources, gas–water–rock interactions and their relation with the volcano–tectonic structures, mentioned above.

The Source to Surface Project: what are geochemical proxies really telling us about magmatic-hydrothermal systems in the Taupo Volcanic Zone, New Zealand?

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The uses of geochemical proxies both to describe and quantify heat and mass fluxes are important tools in understanding hydrothermal systems globally. Information derived from these proxies is crucial for geothermal resource characterization and management, studying ore-forming processes, understanding geochemical cycling, and the assessment for both hydrothermal and volcanogenic hazards. Over the past half-century, hydrothermal systems in the Taupo Volcanic Zone, New Zealand (TVZ) have been extensively studied to which numerous inferences have been presented describing the origin, flow paths, and heat and mass flux through fluid geochemistry. In this study, we have compiled and compared published, unpublished, and our own data for liquid, gas, and soil-gas surveys in the TVZ hydrothermal systems. We describe here an updated model for the origin, flow paths, and heat and mass transport for fluids in the TVZ. Numerous relationships between elements and compounds show evidence for a geochemically distinct single-parent fluid. However, the ultimate origin(s) or end-member(s) for the elements and compounds comprising this fluid is not known. New interpretations are presented regarding three unique groupings based on B/Cl relationships. Where these groupings occur, they do not spatially correlate with any particular tectonomagmatic setting, as inferred by previous authors. We propose these relationships to be the result of water-rock interaction and phase separation and not from multiple fluid sources. We also show from soil-gas surveys, that 'blind' structural components are a significant factor in detecting upflow zones that are not readily apparent from either structural mapping or temperature profiles. Spatial correlations also exist between geophysical data and our soil-gas surveys demonstrating a powerful new combined method in the identification of upflow. Finally, from our soil CO_2 studies we demonstrate that for high-resolution surveys, a CO_2-based method incorporating the carbon isotopic signature of CO2 may provide a more accurate heat flux value than existing chloride models which may not always be reliable throughout the TVZ (Bibby et al., 1995). This has implications for reassessing the heat flux for the entire TVZ (currently accepted to be 4500 MW) and ultimately the scale of modern crustal magmatism. Our findings are of particular interest for similar arc- and rift-type systems alike and our methods are likely applicable outside the TVZ for both assessment and monitoring of magmatic-geothermal systems.

Eruption due to depressurization: Numerical simulation by VERA code

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Magma and hydrothermal systems are more or less stable under lithostatic and hydrostatic circumstance, however, in case of some pressure condition, the system becomes unstable and even a tiny perturbation can trigger a catastrophic instability, which may lead to an eruption. In a hydrothermal system and shallow volcanic fluid system, the gas-liquid interaction controls the activities, and the instability of two-phase flow dynamics is essential to recognize the eruption mechanism.

There are several candidates as "tiny perturbation", for example, new magma intrusion from deeper part, magma mixing, etc. One of the important triggering mechanisms is depressurization, which occurs in many situations: the opening of a "plug" which is keeping a pressurized gas-water system would disturb a hydrothermal system. For magma plumbing system, magma ascends and reduces the pressure itself, then the bubbling is promoted. Once the volume fraction of gas component overcomes a threshold, the fragmentation occurs and we can detect as an explosive eruption. This series of phenomena from depressurization to fragmentation is controlled by many factors. We developed a numerical simulation code "VERA", by which volcanic eruption is simply simulated as a phenomenon triggered by pressure release due to an opening of a conduit cap at the top. In VERA code, we formulate gas-liquid flow by the expanded two-phase flow model and adopt VOF scheme for free surface evaluation. The subsurface plumbing system is modeled to consist of cylindrical conduit and spherical reservoir with an adequate length and/or diameter. As an initial condition, we assume an initial radius of a bubble in the magma reservoir, bubble number density, and excess pressure in reservoir. Opening of the conduit cap releases fluid pressure and enhances the growth of bubbles. When the void ratio exceeds a threshold, fluid is fragmented. The fluid viscosity is also an important factor, and in case of large viscosity, the fluid is very hard to be fragmented, since the bubbles cannot expand easily. This model is also applied to the Mount Fuji magma system depressed as large as 1MPa due to the enormous ground deformation by Tohoku megathrust earthquake. Our simulation code VERA reveals the details of the fragmentation phenomena, significant heterogeneous distribution of gas and liquid components as well as pressure perturbation in the conduit and reservoir.

Features of geyser's eruptive activity in broadband seismic records (Valley of Geysers, Kamchatka)

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Valley of Geysers on Kamchatka Peninsula is one of the world's major geyser areas, in a league with Yellowstone, El Tatio in Chile, Waiotapu on New Zealand's North Island, and Iceland. We use seismic method for detection of possible hidden feature of geyser's eruptive activity in Valley of Geysers in Kamchatka.

A geyser is a spring characterized by intermittent discharge of water ejected turbulently and accompanied by a vapor phase (steam). The reasons of geyser periodicity and specifics of the activity for every particular geyser are not completely clear yet. So almost for all known geysers it is necessary to develop the personal model.

We obtained broadband seismic records of geyser generated signals in Valley of Geysers hydrothermal field by 24-bit digital output broadband seismometers GURALP CMG-6TD (0.033-50 Hz). Three geysers were surveyed: the fountain type Big and Giant geysers and the cone type Pearl geyser. Seismometers were set as close as possible to the geyser's surface vent (usually at the distance near 3 m).

For the large Big and Pearl geysers low-frequency seismic response on geyser's eruption was detected. Seismometers showed surface deformation caused by water-steam burst from the vent (or geyser eruption) with the period about 10-12 min. It was shown, that eruptions of the Big geyser are not constant at different frequency bands. Some eruptions are weaker than other in low-frequency band (lesser then 0.01 Hz), but approximately similar for the range 20-50 Hz. It means possible deep variations of thermal supply.

The most important result is the detection of hidden underground geyser in the area of the Giant geyser. Its deep activity is recorded by seismic and mass position channels as very stable quasi-periodic oscillations with period 16-18 min. It caused quasi-harmonic displacements of surface with amplitude about 5-6 mm. Earlier the existents of the underground geyser was assumed due to observation of intense bursts with such periodicity during boiling-effusion mode before every eruption. So the supposed underground geyser was accounted as the main heat provider and the principal cause of the Giant geyser eruptions. We named this deep quasi-periodic source of seismic signal (underground geyser) Heart of Giant.

Characterization and quantification of geyser eruptions: insights from infrasound monitoring at Yellowstone National Park

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This study investigates the infrasound emissions from geysers in Yellowstone National Park to characterize and quantify eruption parameters. Geysers are hot springs, which intermittently erupt hot water and steam. Their eruption phenomena include bubble bursts and two-phase fluid jets, which are strong emitters of near-infrasound (1-20 Hz) and low frequency audible airwaves.

During a field campaign in August 2011, a 2-element and two 4-element MEMS transducer arrays were installed to continuously record the infrasound generated by three distinctive geysers: Sawmill Geyser, Great Fountain Geyser and Lone Star Geyser. The infrasound waveforms are diverse and distinct. We highlight the comparison of their spectral content and acoustic power. Time-synched video observations reveal how the geysers' eruptive behaviors relate to their waveform characteristics.

Great Fountain Geyser (GFG) typically produces episodic bi-modal pressure pulses (compression-rarefaction), which we interpret as bubble or gas slug bursts leading to two-phase fluid ejections. Characterizing GFG as a monopole source, we calculate that the largest excess pressures recorded correspond to cumulative fluid ejections on the order of 50 m^3. In contrast to GFG, the periodic (0.7 s) pressure pulses of Sawmill Geyser (SMG) commence with a rarefaction, which we interpret as the collapse or implosion of steam bubbles. Lone Star Geyser (LSG) eruptions consist of ~30-minute episodes of continuous broadband tremor. We observe from the recorded signals that LSG displays a distinct change in behavior from a relatively low frequency water-dominated phase (20-60 Hz) to a higher frequency pure steam-jet-dominated phase (40-85 Hz).

The two-phase (water and steam) eruptions of geysers provide a useful intermediary in the comparison of analogue laboratory experiments and silicic magmatic eruptions. Geysers are easily accessible for observation, erupt often, and display a wide range of behaviors. Hence, despite differences in scaling and materials erupted, we conclude that geysers and their eruption dynamics could be useful analogues for the interpretation of infrasound generated by volcanoes.

Estimates of Heat output from the Yellowstone Plateau Volcanic Field using different approaches

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Yellowstone is one of the largest and most restless calderas on Earth and its magmatic system is one of the most focused heat sources on Earth. The most recent caldera-forming eruption occurred around 0.64 Ma ago, though smaller explosive and lava-effusing eruptions have continued up until approximately 70 ka. The magmatic system remains active as manifested by abundant seismicity, deformation and the presence of more than 10,000 thermal features. Quantifying heat flux through the ground surface can provide insight into magma intrusion rates and hydrothermal flow, but is a daunting task because of the vast extent of thermal areas in and around the Yellowstone Caldera. Nevertheless, obtaining such data could provide an improved understanding of magmatic processes, which in turn, allows for a better estimate of hazards. Heat is transported to the surface by conduction and by advection of liquid water and steam. Heat is transported away from the surface by evaporation from lakes, pools, and rivers, conduction to the atmosphere, and radiation. Diverse methods are used to quantify heat discharged through these various modes. Estimates in the early 20th century that were based on the integration of discharge and temperature measurements of individual thermal features throughout Yellowstone yielded a total heat output of about 1 GW [Allen and Day, Carnegie Inst. Publication, 1935]. The chloride-inventory method, which was initially applied to Yellowstone in the 1970s, assumes that all the chloride discharged by rivers draining Yellowstone is derived from a single deep parent fluid [Fournier, AREPS, 1989]. With this method and a set of plausible parameter values, estimates of heat output vary by a factor of two. A minimum output of 4 GW corresponds to a chloride concentration of 450 mg/L, a temperature of 320 C, and a chloride flux of 45 kt/yr, and a maximum output of 8 GW corresponds to a Cl concentration of 350 mg/L, 360 C, a flux of 55 kt/yr Shallow conductive temperature gradient measurements and evaporation from thermal pools are restricted to very small areas [Morgan et al., JGR, 1977; Hurwitz et al., JGR, 2012] and the extrapolation of these data to the entire Yellowstone Plateau incorporates many assumptions. Extrapolation of the average heat flux from two small vapor dominated areas to the approximately 35 km2 of vapor dominated areas in Yellowstone yields more than 3.6 GW [Hurwitz et al., JGR, 2012]. Satellite-based thermal infrared (TIR) remote sensing methods provide estimates for the entire Yellowstone thermal anomaly, but measure only the radiative component of heat output. For example, nighttime ASTER TIR data were used to estimate a radiative heat output of about 2.0 GW [Vaughan et al., JVGR, 2012]. Future studies aimed at integrating these disparate approaches and characterizing temporal variations will require a combination of ground-based methods, airborne infrared, and improved satellite radiometers.

The response of geysers to stress and weather perturbations

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Geysers are rare with less than 1,000 worldwide, of which between 200 and 500 occur in the geyser basins of Yellowstone National Park. Their rarity reflects a delicate balance between supply of water, a large supply of heat, and a unique geometry of fractures and porous rocks. Because of the delicate balance between these controlling parameters, only a few geysers display relatively constant intervals between eruptions. Analyzing the sensitivity of geysers to stress perturbations from earthquakes and Earth tide and weather variations, including barometric pressure, precipitation, and wind can yield significant information on cause and effect relationships in these systems, and on the threshold stress perturbation amplitude required to trigger eruptions. Previous studies that examined geyser response to external forcing were based either on sub annual or discontinuous geyser eruption records, and therefore have resulted in conflicting interpretations. To overcome these shortfalls, we analyzed nearly continuous records of eruption patterns of Daisy and Old Faithful geysers in the Upper Geyser Basin of Yellowstone National Park for the period between 2001 and 2011 available from the Geyser Observation Society of America. Geyser eruption times are determined from continuously recording temperature sensors in the geysers outflow channels, and are compared with data on regional and remote earthquakes, barometric pressure, precipitation, wind storms, and calculated theoretical Earth tides. Daisy and Old Faithful geysers were selected for the analysis because they have relatively uniform eruption intervals and long-term records are available. Preliminary results indicate that eruption intervals at Old Faithful slightly shortened in response to the passage of surface waves from only a few large global earthquakes. Daisy Geyser eruption intervals were only modulated after the passage of surface waves from the November 2002 Denali earthquake. Eruption intervals of both geysers are not modulated by earth tides. The results of this study have implications for studying the triggering of volcanic eruptions by external forces. As with volcanoes, stress perturbations in hydrothermal systems can either perturb the nearly saturated fluid, and thus enhance or suppress phase separation and bubble formation, or perturb the surrounding rocks and fractures, both of which may lead to, or delay an eruption. Because geyser eruptions are more frequent and uniform than volcanic eruptions, statistical analysis linking external forces with geyser eruptions rely on much larger datasets, and thus may provide more robust insight on the sensitivity of multiphase erupting systems.

Filling geyser conduits between eruptions, as revealed by acoustic measurements in the El Tatio Geyser Field, Chile

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We performed the acoustic and temperature measurements, correlated with visual observations, at the El Tatio Geyser Field, at an elevation of ca.4300 m in the Northern Chilean Andes. We focused on two geyser systems, named El Jefe and El Cobreloa.

El Jefe Geyser erupts every 2 minutes lasting for 15 seconds. We confirmed that acoustic measurements are useful for monitoring the sequence of eruptions during at night. When eruptions occur, documented by rising temperatures in the conduit, high frequency sound is recorded. Sound may be generated by water droplets landing on the ground surface. Between eruptions, sounds with a characteristic frequency approximately 100 Hz are recorded. This may be originated from the air column resonance within the conduit. During the day time it was windy, and acoustic measurements do not show a correlation with eruption activity. We also confirmed that measurements of ground temperature can detect the flowing hot water associated with eruptions.

We applied these methods to the other target, El Cobreloa Geyser, which erupts in two ways: vigorous major eruptions, and less energetic minor eruptions. We monitor major eruptions measuring ground temperature and minor eruptions acoustically. We found that major eruptions occur at regular intervals of approximately 4 hours and 40 minutes. During the inter eruption period, minor eruptions also occur regularly, with an interval of approximately 13 minutes. The observations suggest that filling of the conduit is a complex process.

A physical model for the phreatic explosion on July 15, 1888 at Bandai volcano, northeastern Japan

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The 1888 eruption at Bandai volcano, Japan, has been well known as one of the most gigantic historical phreatic explosions. The precise nature of the explosion mechanism, however, has not been quantitatively clarified until now. It is due to the statements and interpretations in the leading article of Sekiya and Kikuchi (1890) were mainly based on the various circumstantial evidences that were collected by seeing of authors' selves and local habitants. They inferred that the hydrothermal fluid triggering the explosion and rock avalanche might have been located beneath the exploded peak called Kobandai-san and that the depths of the earthquakes immediately preceding the eruption might be very shallow in the volcano. These naive inferences have been left without any quantitative examination for more than one century. We re-examined their ambiguous inferences about the explosion source and the earthquakes preceding the eruption. We analyzed primarily the following two observational data: The one is the shallow bulge structure beneath the old crater that is recently deduced from the seismic tomography and the other is the isoseismal map drawn from questionnaire by Sekiya and Kikuchi. The map showed that the perceptible area of the biggest preceding earthquake had a shape of an ellipsoid elongated in the direction of N25E and its intensity at the boundary was assigned to 1 on the JMA scale which was equivalent to ca. 2 gal. The characteristics of the observed isoseismal were compared with those calculated as a function of source depth and directivity under several reasonable assumptions. Referring to the observed 3D bulge structure beneath the old crater, an explosion source was modeled by a pressurized spherical cavity with a radius of 0.5 km located at a depth of 1.0 km. The numerical analysis revealed that the fluid pressure would escape from the cavity through two tensile fractures oriented in different directions; one is oriented upward from the apex of the cavity and the other is at an oblique angle of 30 degrees with the ground surface at a horizontal distance of about 1.8 km from the apex. We concluded that the explosion source with a radius of 0.5 km was located beneath Numanotaira (the old crater) at a shallow depth of 1.0 km but not beneath Kobandai-san (the collapsed mountain) and that two tensile fractures in directions of N20W and N100E were simultaneously opened due to an excess pressure, resulting the dynamic collapse with large rock avalanche into the north and the steam-jet burst with mud flow into the south-east. The seismic moment and magnitude of the biggest earthquake immediately preceding the explosion were estimated to be 10**16 Nm and M4.6, respectively. These results provided a counter-evidence for the traditional inference by Sekiya and Kikuchi.

Experimental constraints of phreatic eruptions at Solfatara volcano, Campi Flegrei

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The Phlegraean Fields caldera, a nested and resurgent structure, is amongst the most dangerous volcanic areas in the world, enclosing part of the city of Naples, the town of Pozzuoli and numerous densely inhabited villages. The relationship between resurgence and volcanism in the past 15 ka is manifested by an intense volcanic activity preceded and accompanied by important phases of ground deformation [Orsi et al., 2004]. A complex interaction between the deep magmatic source and the shallow hydrothermal system seems to have driven most of the recent unrest episodes, during which ground uplift and seismic activity affected Pozzuoli City and the near fumarolic field of Solfatara. The latter represents the most active hydrothermal site of Phlegraean Fields; here historical chronicles report the occurrence of a phreatic event in the 12th century. Phreatic eruptions usually occur with little or no warning and are able to create substantial explosion craters. Additionally they are often precursory to a new cycle of volcanic activity as was the case during the 1538 Monte Nuovo eruption.

We present an experimental approach based on a shock-tube apparatus [Alidibirov and Dingwell, 1996, Spieler et al. 2004, Scheu et al. 2008] to investigate different scenarios likely for phreatic eruptions in the Solfatara area. This technique allows producing fragmentation from a combination of Argon gas overpressure and steam flashing within the connected pore space of the tested samples at varying PT conditions. Neapolitan Yellow Tuff is used as sample material for the study as it is the stratigraphic unit of the expected source region for phreatic explosions [Orsi et al. 1996].

The hydrothermal system below Solfatara is thought as a gas plume with a shallow single phase gas zone and a deeper mixing zone. The latter occur at depth between 1000 and 1500 m (20-25 MPa), where temperature conditions are close to the critical point of water (>360℃) [Caliro et al., 2007].

We focused in a first case study on the deeper system, therefore a pressure and temperature range of 15-20 MPa and 300-350℃ were chosen mimicking the natural conditions. The entire experiments were monitored with temperature and pressure sensors, the latter were also used to determine the speed of fragmentation. The generated fragments were fully recovered and the grain-size distribution and thus the efficiency of fragmentation were determined. Further different degrees of water saturation and variably tempered samples have been used in order to investigate strength reduction due to both water weakening effects and the zeolite dissolution.

The study's aim is to raise awareness of the hazard potential of phreatic explosions in Solfatara area. It also represents the first part of an experimental data base we are aiming to construct and that will enable us to constrain the phreatic eruption scenarios in Solfatara area as well as other sites in Phlegraean Fields.

Experimental approach to constrain phreatic eruption processes on White Island, New Zealand

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White Island is New Zealand's most active volcano and primarily characterised by phreatic and phreatomagmatic eruptions. A phreatic eruption on August 2nd, 2012 ended an eleven year quiescence. More than 100 years of intense hydrothermal activity from magmatic fluids and groundwater has created a weak and unstable volcanic edifice highly susceptible to sector collapses and landslides. Here, we constrain the influence of alteration on phreatic eruption conditions and on the stability of an edifice subjected to an active hydrothermal system. A hydrothermally altered lava flow and four lithified pyroclastic rocks with different grades of alteration, together with unconsolidated material and sulfur- and iron-rich crusts from the crater-fill were sampled and investigated.

The lava flow is primarily composed of plagioclase, K-feldspar and pyroxene, but alteration has also lead to the presence of cristobalite, amorphous silica, gypsum and jarosite. The pyroclastic rocks do not contain any primary minerals or glass and consist instead of amorphous silica, alunite, jarosite, gypsum and kaolinite.

The lava flow with a low porosity (6.6-8%) was found to be moderately strong (110-140 MPa) when deformed in uniaxial compression tests, although we find that the presence of macroscopic fractures can lower the strength to 60 MPa. The altered pyroclastic rocks are more heterogeneous, porous (32-48%) and weaker, with unconfined compressive strengths ranging between 3 and 20 MPa. Our uniaxial experiments also show that the altered pyroclastic rocks are weakened when saturated with water.

Conditions for phreatic eruptions were constrained by fragmentation experiments on dry and water-saturated samples due to rapid decompression (from 9 MPa to atmospheric pressure) at temperatures of up to 300℃. This provided information about the energy threshold, fragmentation efficiency, the maximum speed and evolution of particle ejection velocities. The fragmentation threshold ranges between 5.1 MPa and 3.8 MPa for samples with a connected porosity of 32% to 48% , which is in agreement with the trend for pristine volcanic rocks. The fragmentation efficiency generally increases with higher applied energy but also if the sample is saturated. The particle ejection velocity after fragmentation increases with the applied pressure and porosity. For experiments on dry consolidated samples, where the fragmentation occurs at an argon gas overpressure of 6.5 MPa and 300℃, the ejection speed (45 m/s) is significantly lower than for fully water-saturated samples (145 m/s). Unconsolidated samples with connected porosities of 35% show a similar effect of sample saturation on the ejection.

Our study suggests that hydrothermal alteration and fluid-saturation associated with the presence of a hydrothermal system weakens the rocks (over a range of strain rates), which may result in slope destabilisation, lateral/sector collapse and further phreatic eruptions.

Campi Flegrei Deep Drilling Project and geothermal activities in Campania Region (Southern Italy)

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Recent studies of Campanian volcanic geothermal systems have shown a large geothermal potential (Carlino et al., 2012), similar to the Larderello-Radicondoli-Amiata region, in Tuscany (Central Italy), which has been the first site in the World exploited for electric production. Recently, the Campi Flegrei Deep Drilling Project (CFDDP), sponsored by ICDP and devoted to understand and mitigate the extreme volcanic risk in the area, has also raised new interest for geothermal exploration in several areas of Italy. Following the new Italian regulations which favor and incentivize innovative pilot power plants with zero emission, several geothermal projects have started in the Campania Region, characterized by strict cooperation among large to small industries, Universities and public Research Centers. INGV department of Naples (Osservatorio Vesuviano) has the technical/scientific leadership of such initiatives. We intend to show the present state of art of the researches, new insights and ongoing geothermal projects in Campanian region. Among the most important results of geothermal interest, determined by recent research projects, we also show here new computations of in-situ permeability at Campi Flegrei caldera, obtained during the drilling of CFDDP pilot hole.

Geophysical changes and hydrothermal activity at the early stage of the White Island 2012 unrest episode

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White Island volcano, one of the most active volcanoes in New Zealand, is experiencing an elevated level of unrest at the time of writing, after more than 10 years of relatively low hydrothermal activity. Some sustained periods of volcanic tremor started in June 2012, later accompanied by fluctuations of the crater lake level in July and minor eruptions from August. A small lava dome was first observed in November within the crater and the activity extended to the remnant crater lake location where currently, venting occasionally occurs. This activity is accompanied by rapid variations in the level of volcanic tremor.

The volcano hydrothermal system has most likely been disturbed by this new magmatic activity, potentially before the magma even reached the surface. It is then of paramount importance to better understand the hydrothermal system fingerprint in the early signals of volcanic unrest to better detect future activity at the volcano.

We present results from three magnetic and gravity surveys acquired prior to this unrest episode, between May 2011 and June 2012. Data were collected at the volcano crater floor on 67 magnetic pegs and 10 gravity tiles. We then compare these results with other monitoring datasets and present some preliminary results from numerical modelling (e.g. TOUGH2) in order to assess potential relationships between recorded geophysical signals and the magmatic-hydrothermal processes.

Characteristics of seismicity within proximity to active geothermal and volcanic areas

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Geothermal energy is renewable, clean, and has been utilized worldwide. Exploitation of geothermal energy involves fluid injection for heat circulation purposes and increasing permeability. Increased fluid pore pressure will accelerate the failure process under Coulomb failure criteria. Thus, correlations between seismicity and injection activities are identified at most geothermal reservoirs; one famous example is the Geysers. The triggering front of seismicity due to fluid is controlled by the pore pressure diffusion process in space and time. The hydraulic diffusivity can be obtained from the spatial-temporal pattern of seismicity, which is usually between 0.01 to 10 m2/s, and varies among different regions with generally higher values in geothermal and volcanic areas. California has ample natural resources for geothermal energy. Here, we try to understand the relationship among seismicity, tectonic environments and injection activities. The current study region is the Salton Trough; future analysis will include Coso area. In the Salton Trough, the first-order correlation is strong spatial clustering around injection wells, and temporal correlation between increased seismicity and increased injection. The pore pressure changes likely couple with tectonic applied shear stress, and with affect earthquake stress drop. Some correlation has been identified for hydraulic fracturing experiments. In the Salton Trough, we also find that the stress drop is correlated with distance from injection wells. We will investigate the variation in the Coso geothermal field, and compare seismicity with injection history. In the future, I will apply the analysis method in California to Japan earthquake catalog, to learn about the seismicity pattern in different tectonic environments using high-precision differential time relocation. A comparison of fluid properties will be synthesized based on results in California and Japan.

Stress Distribution in the Rotokawa Geothermal Field, New Zealand and implications for fluid flow through brittle crust

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Quantifying the stress field is a vital tool for mapping and determining how to maintain the pathways that hydrothermal fluids follow in a naturally fractured geothermal system. Permeability in the Rotokawa Geothermal Reservoir, located in the Taupo Volcanic Zone (TVZ), is primarily fracture hosted and is influenced by the activity of large faults. Thus permeability preservation in the reservoir relies on cyclical reactivation of these structures. The magnitude and orientation of the principal stress axes will influence fault mechanics and how fracture-hosted permeability operates in geothermal reservoirs. Slip on faults and fractures can depend heavily on their orientation relative to that of the stress field and the relative magnitude of the principal stresses.

Leak-off Tests (LOTs), density models and borehole images are used to constrain stress magnitudes at depth in the Rotokawa Geothermal Reservoir. In the extensional tectonic setting of the TVZ, the vertical stress axis coincides with the maximum principal stress. As this is dependent on the weight of the overburden, we employed extensive lab-based density measurements that have been performed on core from Rotokawa and other geothermal fields to derive a vertical stress model. Using this data, the vertical stress across the Rotokawa Field has been modeled taking into account the variable lateral thicknesses of different lithologies. Data from LOTs and the observation of drilling induced tensile fractures (DITFs) on borehole acoustic images are used to quantify the minimum and maximum horizontal stresses respectively.

The differential between the vertical and minimum horizontal stresses corresponds to a crust in frictional equilibrium. Results of this study indicate that spatial variation in the vertical stress magnitude due to lateral variation in the thickness of the overlying stratigraphy may be an important factor in maintaining permeable fractures. For example, the presence of a young andesitic cone in the strata causes a local increase in the vertical stress. This may have a local effect on the permeability of the underlying rocks.

Another key outcome of this study is that a portion of the fractures imaged in boreholes is exploiting weaknesses in an otherwise strong rock. The range of fractures observed suggest that the fractures were activated under compressional shear conditions, yet the strength of the rock measured suggest that is difficult to initiate such fractures. It is likely that the rock is weaker due to the presence of primary fractures (i.e., created when the rock was emplaced) or fractures due to subsequent volcanic activity. It is therefore crucial to have a good grasp on the volcano-tectonic history of the region in order to understand the pathways that fluids take to reach the surface.

Geological and geophysical model of cap rock of the Karymshinskaya hydrothermal system (Kamchatka)

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Karymshinskaya hydrothermal system is located to the west of the volcanoes of the Eastern Kamchatka volcanic belt within the valley of the rivers Paratunka and Karymshina and is part of the Upper Paratunka geothermal system, dedicated to the area of the giant caldera of an extinct ancient supervolcano, which lies between the mountains of Berry, Fat Point, Hot, Baby Stone (Leonov and Rogozin, 2007). Structural position of the system is determined by the intersection of the strike slip fault, extends along the axis of the valley with a transverse fault to him. Thermal waters are confined to the tank represented fractured vein zone within the volcanic deposits of miocene-pliocene age (acid tuffs). Results of integrated geophysical studies in the area (Melnikova, Shulzhenkova and others, 2011), in addition to the GPR and well logging GK-5, which is the object of routine observations of the Kamchatka branch of the Geophysical Service RAS (KB GS RAS), allowed us to construct geological and geophysical model of cap rock of the Karymshinskaya hydrothermal system. Cap rock these rocks are massive tuffs, and a violation of these tuffs fractured zones are thermal-water discharge. Discharge zone extends along the fault. In this case, we have a medium-temperature system, dedicated to the same faults.

The structure of iron-silica rich chimney in shallow marine hydrothermal environment at Iwo-Jima Island, Kikai caldera, southern Japan

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Satsuma Iwo-Jima is a volcanic island in the northwestern rim of Kikai caldera. Two post-caldera volcanoes exist, so one has volcanic and hydrothermal activity at the present. Nagahama bay where the orange-brownish discoloration is taken place is locatd in the southwestern island. The bay is half-closed environment and separated into two parts of East and West-site. The origin of the discoloration is ferrous rich hot spring (pH=5.5, 55-60 degree Celsius) (Shikaura and Tazaki, 2001). Kiyokawa et al. (2012) reported the fast deposition of about 1 m per ten years at West-site which is under control of tide, rain and wind. East-site is distinct because of the presence of chimney mounds, but yet studied in detail.

Samples were the massive chimney (20-30cm) and the floating particle divided from the sea water. We observed the structure of chimney with X-ray CT scan, thin section and FE-SEM, as well as EDS for composition analysis. The massive chimney is classified into two parts: black high-density hard layer and brownish low-density soft layer. The result of X-ray CT scan shows that the chimney is constructed by the aggregation of convex structures (3-4cm). Low-density layer has many pipes (radius of 1mm). Petrographic observations indicate that both high- and low -density layers have the filament-like form, and the form at the low-density layer is vertical to outer rim. In the low-density layer, the number of particles attaching to the filament-like form increases toward the high-density layer. FE-SEM observation shows that the filament-like form at the high-density layer is consists of aggregation of bacillus-like structure that looks the chain of particles (about 2μm). At low-density layer, bacteria-like form attached particles (<1μm) existed and this form is classed into 3 types (helix, ribbon-like, twisted). The floating particles were aggregation of fine particles (<0.5μm) has no bacteria-related form. All particles consist of Fe, Si and O, and those particles are chemically homogeneous by EDS.

According to the observation results above, we present a hypothesis of growth process of a chimney-complex mound in Nagahama bay. The chimney is constructed by aggregation of convex structure with many pipes probably work as the hydrothermal vent. All grains are consist of Fe, Si and O. Bacteria-like form resembles Gallionella spp. as iron-oxidizing bacteria. The bacteria is known as neutrophilic bacteria and prefers to living at redox interface (Weber et al., 2012). The activity of bacteria around hard rim makes high density layer. The chimney is likely to be influenced by activity of microbe.

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Hydrochemical properties of thermal and cold mineral waters of Khnagay Mountain Region, Mongol

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Hydrochemical properties were studied for thermal and cold mineral waters in Khangay mountain region, central Mongolia. The eastern part of Khangay hydro-geothermal system is one of the most energetically powerful on the quality of the fluid heat-carrier (temperatures of the geothermal water at ground surface are up to 92 degree) with the high yield of thermal sources and on the area of deep magma chamber and high activity of Cenozoic volcanism. Chemical ompositions of 14 water samples in which 8 samples were analyzed. The Cl-SO4-HCO3 and Na-K-Mg ternary diagrams and mixing models were used to characterize the water chemistry and estimate their subsurface temperatures. The results show that most of the thermal waters are in partial equilibrium with the surrounding rocks. The hot waters in the study area can be classified into Na-HCO3 and Na-SO4 types.

Geochemical flow model of groundwater in Sho River fan, Toyama Prefecture for heat usage by geothermal heat

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Groundwater flow model is discussed with chemical and isotopic (D, O) compositions of 56 water samples in Sho River fan, Toyama, northern part of central Japan to apply to geothermal heat usage for room air-conditioning and melting of road snow by geothermal heat pump (Geo-HP). Groundwaters are a mixture of two big river waters (Sho and Oyabe) and precipitation. Deep groundwaters from observation wells are characterized to be high pH and enriched in HCO3 compared to the shallow groundwaters. These features may indicate that shallow groundwater originated from a mixture of river water and precipitation moving to the north and becoming confined due to the presence of an impermeable layer. Groundwaters become high pH due to ion exchange reaction with rocks containing clay minerals, where HCO3 concentration also increases.

Geochemical study of hot springs for new geothermal exploration in eastern part of Toyama Prefecture, Japan

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Chemical and H and O isotopic compositions of 13 hot spring waters in eastern part of Toyama Prefecture were analyzed to examine their chemical characteristics and estimate the underground temperature for new geothermal exploration. On the basis of chemical and isotopic compositions, hot spring waters can be divided into two groups; low and high salinities. The low salinity group is of meteoric origin and high one is a mixture of sea water and meteoric water with oxygen isotope shift. The latter may be geopressured fluid, which is characterized by the high delta-D values of ca. -20 permil and medium Cl concentrations of ca. 6,000 mg/L as reported elsewhere. The results of estimated underground temperature support the view that the area along Kurobe River has one of the highest geothermal potential in the studied fields.

GEOCHEMICAL EXPLORATION FOR GEOTHERMAL RESOURCES AT THE SE ZONE OF GRAN CANARIA ISLAND (ATIDAMA MINING GRID), CANARY ISLANDS.

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Very few efforts have been done to date in the Canary Islands to develop the potential geothermal energy resources in the archipelago. Between seventies and nineties, the Geological Survey of Spain performed intense research on geothermal resources in the country due to the oil crisis of the 70s. Later geothermal research declined sharply and only a few projects on geothermal resources were active in Spain from 1994 to 2006, compared with the many projects carried out during the previous two decades. This overall picture has changed dramatically in recent years and geothermal has become a new source of scientific research activity. In 2011 ITER, University of La Laguna, PETRATHERM Spain and the University of Barcelona started a joint research project (GEOTHERCAN), aimed to develop an experimental study of 3D models to characterize geothermal reservoirs in the subsurface of Tenerife, Gran Canaria and La Palma (Canary Islands), which enables further development of geothermal energy in the Archipelago. The multidisciplinary approach of this project, composed by different methodologies and techniques (geochemical, geophysical, and geological) allow us to address the definition of the geothermal potential in the Canary Islands under the framework of this comprehensive and ambitious project.

Under the framework of this project soil gas geochemistry studies will be carried out at different areas of La Palma, Tenerife and Gran Canaria Islands. In recent years soil gas surveys have become increasingly common in geoscientific studies. Among the objectives of these studies are the quantification of gas and heat flux from volcanic and geothermal systems and the identification and delineation of active faults. Both topics are of central importance to investigations of geothermal resources. In this abstract we are presenting the results of a geochemical survey of soil gases and volatiles that was carried out by ITER during summer 2012 in Atidama area (around 100 km2), located at the SE of Gran Canaria island. 600 sampling sites were selected to measured soil CO2 efflux, 222Rn and 220Rn activities, Hg0 and H2S concentrations and soil temperature at 40 cm depth. Soil gas samples were collected at same depth for chemical analysis (He, H2, N2, CO2, CH4 and Ar). Relatively low CO2 efflux values were measured, ranging from non-detected up to 52.9 g m-2 day-1, with an average value of 1.9 g m-2 day-1. The total diffuse CO2 output was estimated in 144 +- 3 t/d. Significant trends observed in the concentration of other chemical components, suggest the presence of vertical permeability structures in the studied area.

Fluid geochemistry of the vicano-cimino hydrothermal reservoir (central italy): implications for geothermal exploration

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The Vicano-Cimino Volcanic District (VCVD), located in the peri-Tyrrhenian sector of central Italy, is characterized by Pleistocenic volcanic products derived from two different magmatic cycles: i) the acid cycle, consisting of a SiO2-rich magma of the Tuscan Magmatic Province, encompassing the Cimino Volcanic District, and ii) the K-alkaline cycle of the Roman Magmatic Province, encompassing the Vicano Volcanic District. The volcanic products overlie a sedimentary sequence constituted by Plio-Pleistocene clays, Cretaceous-Oligocene flyschoid sediments and a thick Mesozoic carbonate-evaporite formation containing a pressurized hydrothermal reservoir.

Extensive exploration surveys were carried out in this area in the seventies to nineties for geothermal purpose although the VCVD is presently not exploited. The presence of thermal waters and of anomalous heat flow, together with demographical growing in the last years, makes this site a suitable location for applications of the geothermal resource.

On the whole, 333 fluid discharges (cold waters, thermal waters and bubbling pools) and 25 gas emissions were collected for chemical and isotopic compositions. Water chemistry points out the presence of two main reservoirs at different depths. The deepest one is hosted in the Mesozoic formation and shows a Ca-SO4(HCO3) composition, likely produced by high temperature fluid-rock interaction involving Triassic anhydrite layers at the base of the carbonates. The shallow aquifer is hosted within the volcanic domain and has a Ca-HCO3 composition. deltaD and delta18O values suggest that both reservoirs are fed by meteoric waters.

Carbon dioxide, largely dominating the free gas phase associated to both cold and thermal springs, has a twofold origin, being related to i) mantle degassing and ii) thermo-metamorphic reactions occurring in the carbonate reservoir. The R/Ra values range from 0.41 to 1.14 and suggest relatively low contribution of mantle-derived fluids with respect to those gases produced in the crust. The 13C/12C ratios of CH4 and 34S/32S ratios of H2S are likely indicating an origin for these two gas species mainly controlled by high temperature reactions occurring within the Mesozoic reservoir and involving the reduction of CO2 and that of the Triassic anhydrites, respectively. Furthermore, delta15N-N2 isotopic data point out to a non-atmospheric source for N2 likely related to high-temperature alteration of organic-rich meta-sedimentary rocks of the Palaeozoic basement below the Mesozoic reservoir.

Gravimetric and structural data suggest that the spatial distribution of the deep-originated fluid discharges corresponds to the boundaries between positive and negative gravity zones, which are interpreted as extensional faults bordering buried structural highs of the carbonate basement.

Gas geothermometric calculations have allowed to estimate reservoir temperature in a range between 250 and 300 degrees.