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Pham Dieu Linh

GEOCHEMICAL CHARACTERIZATION OF THERMAL WATER FROM CENTRAL VIETNAM AND BORGARFJÖRDUR, W-ICELAND

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MSc thesis
School of Engineering and Natural Sciences
Faculty of Earth Sciences
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by

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INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six-month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2019, 718 scientists and engineers from 63 developing countries have completed the six month courses, or similar. They have come from Africa (39%), Asia (35%), Latin America (14%), Europe (11%), and Oceania (1%). There is a steady flow of requests from all over the world for the six-month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the Government of Iceland.

Candidates for the six-month specialized training must have at least a BSc degree and a minimum of one-year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but many excellent students with only BSc degrees have made requests to come again to Iceland for a higher academic degree. From 1999, UNU Fellows have also been given the chance to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. A similar agreement was also signed with Reykjavik University in 2013. The six-month studies at the UNU Geothermal Training Programme form a part of the graduate programme.

It is a pleasure to introduce the 65th UNU Fellow to complete MSc studies under a UNU-GTP Fellowship. Pham Dieu Linh, Geologist by education, from Vietnam Institute of Geosciences and Mineral Resources (VIGMR), completed the six-month specialized training in *Chemistry of Thermal Fluids* at UNU Geothermal Training Programme in October 2016. Her research report was entitled: *Chemistry of geothermal fluids in Dienbien and Sonla Provinces, NW-Vietnam.* After one year of geothermal work for VIGMR in Vietnam, she came back to Iceland for MSc studies at the School of Engineering and Natural Sciences, Faculty of Earth Sciences, University of Iceland in August 2017. In June 2019, she defended her *MSc thesis* in *Chemistry,* presented here, entitled: *Geochemical characterization of thermal water from Central Vietnam and Borgarfjördur, W-Iceland*. Her studies in Iceland were financed by the Government of Iceland through a UNU-GTP Fellowship from the UNU Geothermal Training Programme. We congratulate Dieu Linh on the achievements and wish her all the best for the future. We thank the School of Engineering and Natural Sciences, Faculty of Earth Sciences, at University of Iceland for the co-operation, and her supervisors for the dedication.

Finally, I would like to mention that Dieu Linh's MSc thesis with the figures in colour is available for downloading on our website *www.unugtp.is* (to change to *www.grogtp.org* by January 2020) under publications.

With warmest greetings from Iceland,

Lúdvík S. Georgsson, Director
United Nations University
Geothermal Training Programme

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I would like to express my sincere gratitude to the Government of Iceland for granting me a scholarship through the United Nations University Geothermal Training Programme.

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My thanks to my employer, Vietnam Institute of Geosciences and Mineral Resources for granting me leave to attend this course.

To my friends and colleagues, I enjoyed all of the time spending with you either on study or activities during my two years in Iceland. You showed me how beautiful the world is when we have friends. I wish to thank you all for your enthusiasm.

To all members of my family, thank for your patience and unconditional love. I am almost ready for reunion with you all.

DEDICATION

This work is dedicated to my dear mum, husband and kids for their encouragement, patience and love during my long absence of study.

ABSTRACT

The geochemistry of low-temperature geothermal water in Central Vietnam and Borgarfjördur (W-Iceland) was studied as well as its potential utilization possibilities.

Twenty samples of geothermal water were collected in Central Vietnam and twelve samples in Borgarfjördur in the summer of 2018. The water temperature, pH, DIC and H_2S concentrations were measured on site and major elemental composition analysed using ICP-OES and IC at the University of Iceland. Stable isotopes of hydrogen and oxygen (δD and $\delta^{18}O$) were also determined at the University of Iceland, by IRMS. The surface temperatures of the geothermal waters in Vietnam were 42- 96°C and in Borgarfjördur they were 40-98°C.

The stable water isotope ratios, Cl and B concentrations were used to assess the water origin, mixing and water-rock interaction. Based on the results of this analysis it was concluded that geothermal waters in Vietnam and Borgarfjördur are of meteoric origin affected by rock leaching and mixing with non-thermal water and with possible seawater or salt evaporaties in the case of geothermal water in Vietnam.

The SiO_2 concentrations of the geothermal fluids in Vietnam and Borgarfjördur were 38-138 ppm and 54-178 ppm, respectively. Using these concentrations and assuming equilibrium with chalcedony the reservoir geothermal temperatures in Vietnam and Borgarfjördur were found to be as high as ~120°C and ~135°, respectively. The geographical projection of the major elemental concentrations and geothermometer temperatures revealed three geothermal anomalies in Vietnam: Le Thuy, Quang Binh; Mo Duc, Quang Ngai; Hoi Van, Quang Binh and the highest temperatures at Haegindi in Borgarfjördur.

Following the utilization of low-temperature waters in Borgarfjördur and elsewhere in Iceland, the Líndal diagram suggests several utilization possibilities for the geothermal resources in Vietnam including house heating and cooling, greenhouse farming, fish farming, swimming pools and bathing, drying and food processing, and even electricity production for the waters with the highest temperatures. The utilization options will, however, largely depend on accessibility and the quantity of geothermal water for each location.

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1. INTRODUCTION

Low-temperature geothermal activity is widespread worldwide and associated with variable geological settings (e.g., Arnórsson, 1995; Hawkins, 2016; Lund and Boyd, 2016; Reyes, 2015). The heat source of most low-temperature geothermal systems is the surrounding warm rocks and commonly they are associated with active tectonics and permeable rock formations (e.g. Arnórsson, 1995). Low-temperature geothermal systems have been classified based on temperatures being less than 150°C at 1000 m depth (Bödvarsson, 1961; Fridleifsson, 1979). Low-temperature water has a wide range of utilization options from direct use to electricity generation. In 2015, the total installed capacity of direct low-temperature geothermal energy in the world was ~70 GWth (Lund and Boyd, 2015). In addition to direct utilization of low-temperature natural resources, geothermal heat pumps have gained popularity worldwide in recent years.

Among the key questions arising when discussing utilization and low-temperature geothermal resources and their nature is the origin of the water itself. Stable isotopes and conservative elements have been applied to address these questions in the past. The pioneering work by Craig (1961, 1963), Friedman et al. (1964) and Árnason (1976, 1977) led to extensive work on stable water isotopes of cold and geothermal waters and precipitation. The relationship between δD and $\delta^{18}O$ values for most low-temperature water closely follows the global meteoric water line (GMWL) suggesting meteoric sources and sometimes also seawater. In most cases, the δD and $\delta^{18}O$ ratios of the geothermal water resemble those of a local meteoric source but sometimes they differ suggesting water transport, for example from high to low ground or water originating from when climate conditions in the area were different (Árnason, 1977; Arnórsson and Andrésdóttir, 1995). Conservative elements like B, Cl and SO_4 have also been applied to trace water sources and mixing of two or more water types as well as water-rock interaction (Arnórsson and Andrésdóttir, 1995; Gunnarsson-Robin et al., 2017). In precipitation, their concentrations are usually low, and upon water-rock interaction and mixing with for example seawater, their relative ratios show changes that can, in turn, be used to quantify the various sources of elements.

Water-rock interaction has been considered one of the major processes affecting low-temperature geothermal water composition. Based on inspections of temperature related equilibria between the waters and the geothermal minerals observed in the systems it has been concluded that a close approach to mineral-water equilibria is often attained, which in turns controls the solute concentrations in the water (e.g. D'Amore and Arnórsson, 2000). Such mineral-water equilibria have been applied in order to estimate subsurface water temperatures based on single or multi ion concentration relations, i.e. makes the theoretical background for geothermal geothermometry (e.g. D'Amore and Arnórsson, 2000).

The aim of the current study was to use the chemical and isotope composition of low-temperature geothermal water in central Vietnam and Borgarfjördur (W-Iceland) to investigate the origin of the water, assess mixing between two or more water sources and quantify water-rock interaction including the application of solute geothermometry for estimation of the reservoir temperatures.

2. STUDY AREAS

2.1 Central Vietnam

Vietnam and South East Asian countries such as Laos, Cambodia, Thailand, Malaysia, The Philippines and Indonesia are located at the boundary of the Eurasian, Indian-Australian and Philippine tectonic plates which contain some complex combinations of allochthonous continental terrane and islands and tributaries with the origin being derived from Gondwana (Gatinski et al., 1984; Hutchison, 1989; Tri et al., 2009). The crust was formed in the Precambrian, Palaeozoic and Mesozoic ages, it then migrated to the north during the Palaeozoic and was accreted to pre-Tethyan Eurasia.

The study area is located in the central part of Vietnam extending from Ha Tinh to Khanh Hoa provinces (Figure 1). The area has undergone many geological events since the Palaeozoic to form the land. According to Tri et al. (2009), the area experienced four main geological setting periods. Firstly, the Pre-Cambrian continental basin was re-transformed in Phanerozoa, in which mostly metamorphic sites, such as the KanNack, Ngoc Linh, and Nam-Ngai complexes in the central part of Vietnam, were a part of the Indosinia craton. The Ngoc Linh complex is expanding from North to South by the Tra Bong and Ba To faults, respectively. It includes metatexites and biotite-garnet-sillimanite gneiss and mafic rocks, such as garnet amphibolite, eclogites, and biotite-hornblende orthogneiss, (Michel et al., 2018). The KanNack complex consists of meta-greywacke, metapelite, quartzite, marble, and mafic rocks metamorphosed under granulite facies conditions. Secondly, between these sites is the poly-episodic orogenic system formed in the Middle Palaeozoic - Early Mesozoic of Indochina including the Da Nang - Se Kong mountain belt in the Middle Palaeozoic and Truong Son mountain belt in the Late Palaeozoic - Early Mesozoic ages. The Da Nang - Se Kong mountain belt was curved and bounded by the Truong Son mountain belt in the north and the Kon Tum massif in the south via the Hue – Huong Hoa and Tam Ky - Phuoc Son faults respectively. This mountain belt consists of formations of Cambrian to Ordovician and Silurian age. These formations are composed of weakly metamorphosed quartz-sericite schist, sandstone and siltstone and terrigenous deposits and felsic and mafic volcanites. Being a part of the Da Nang - Se Kong mountain belt also includes the alkaline lime intrusive rock, granite gneiss, granite batholite distributed sparsely in the centre of Vietnam. Also observed is the limestone formed in C-P in the Hoi An and ThuaThien Hue provinces. The Truong Son mountain belt is distributed widely in central Vietnam. This area is limited by the Song Ma suture in the north and the Hue - HuongHoa fault zone in the south. Limestone, sandstone, siltstone, sericite schist, terrigenous deposits and andesitic, felsic and mafic volcanites of Middle Ordovician-Silurian, Devon-Carboniferous, and Carboniferous-Permian ages cover most of the area. The magmatic activity in this area consists of the dioritoid intrusive located in QuangBinh and a batholite granite mass distributed along Truong Son Mountain. Thirdly, overlapping the above-mentioned structures are the basins of the late Palaeozoic Cainozoic, which formed from a different origin at a different time. They were internal rift systems post Mesozoic such as Sam Nua - Hoanh Son and Song Bung - An Khe. In the south of the study area the continental margin was active. These basins are composed of sedimentary rocks of Triassic – Jurassic ages including the materials from volcanoes as mafic volcanites, tuff, or sericite schist, sandstone and siltstone and terrigenous deposits or anthracite deposits. In this period, some granite intrusive masses were observed in Quang Ngai, BinhDinh and Phu Yen provinces. Finally, Cainozoic basins lie on top of multi-source bases. In the mainland, most of them are the small basins located along the faults as pull-aparts. These basins consist of the Neogene diffuse basalt that covers much of southern Indochina and parts of the sea and Quaternary sediments. According to Nguyen and Flower (1998) the age data of these basalts reflect spatial-temporal patterns consistent with a rotating stress field rather than supra-hotspot lithosphere migration.

Most of the main faults in central Vietnam are in a NW-SE direction such as the Nao Ray, Bach Ma faults. They play a very important role in the division of geological structures. There are also fault zones running in the NE-SW, N-S or even W-E directions. These faults intersect with the main faults and formed the pull-apart basins, which were filled by Cainozoic sediment.

There are two main types of groundwater systems in the region, one is the porous aquifer which exists in the Holocene, Pleistocene and Pliocene sediments with respective depths from 10 to 50 m; and the

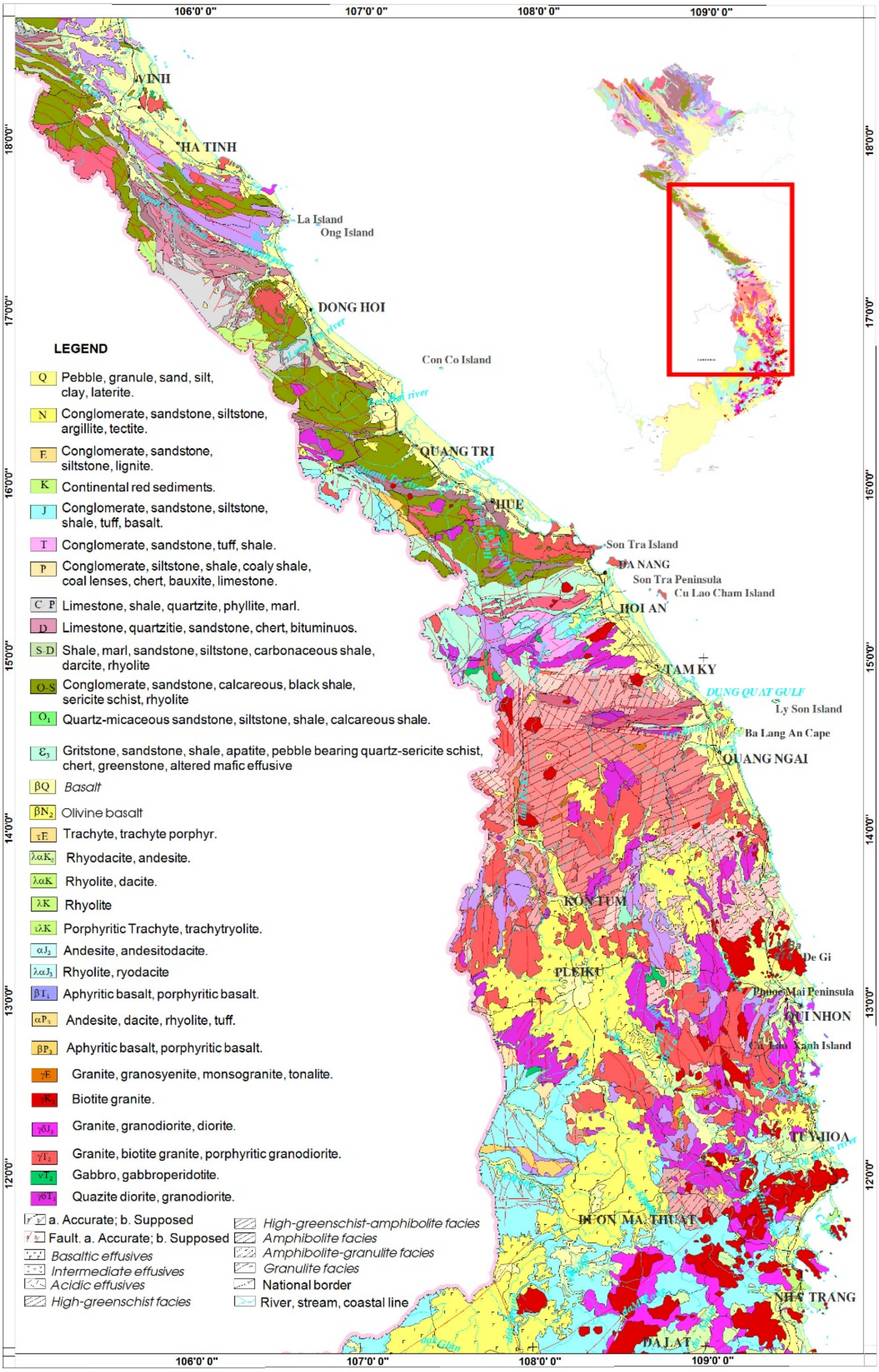


FIGURE 1: Geological map of the study area in Central Vietnam
(modifed from Vietnam-Laos-Cambodia geological map, scale 1:1000000, Phan, 2013)

other is a fractured aquifer located in the Carboniferous, Permian sediments and Palaeozoic and Mesozoic formations (Vietnam Institute of Geosciences and Mineral Resources VIGMR, 1995; 1998).

Hot springs are mostly located along the fault zones or pull apart basins. Most of the hot springs were explored during the French colonization period and during the geological mapping of the last century. After that, several geothermal studies have been explored with the aim of investigating and estimating the geothermal potential in the country (Koenig, 1981; Vo et al., 1998). The geothermal potential in parts of the study area were studied in more detail and reported in two internal reports from VIGMR (Vietnam Institute of Geosciences and Mineral Resources) (VIGMR, 1995; 1998). Geochemical and geophysical methods were applied to determine the temperature of the reservoirs and their potential for heating and other possible utilization. Two reservoirs were considered to have a higher potential than others including Le Thuy and Mo Duc. The chemical composition of the low-temperature geothermal waters was characterized by neutral to alkaline pH values and low to moderate Cl concentrations (VIGMR, 1995; 1998).

2.2 Borgarfjördur

The Borgarfjördur area is among the largest low-temperature fields in Iceland (Georgsson et al., 1984). It is located adjacent to the Reykjanes-Langjökull axial rift zone and is commonly divided into five thermal systems based on the resistivity and the chemical composition of the thermal water (Jóhannesson et al., 1980; Gunnlaugsson, 1980). The systems are referred to as Reykholt, Baer, Brautartunga, England and Húsafell.

The basement of the Borgarfjördur area consists mainly of Late Tertiary basaltic lava flows (Figure 2). According to Saemundsson (1977) the Borgarnes anticline has a NE-SW direction and lies between the Snaefellsnes syncline to the west and the active Reykjanes-Langjökull rift zone to the east. The lavas east of the anticline dip in to the rift zone. The axis is plunged towards the northeast and evanesces under the Hredavatn unconformity. There is a major gap in the lava succession near Hredavatn. Jóhannesson et al. (1980) found that the flows beneath the unconformity are about 13 million year old and have been overlain by older ones before the younger sediment layers covered it, subsequently. The lava layers reach the rift zone by younger layers. The Borgarfjördur region is divided into two fault systems based on the origins and character of the faults (Jóhannesson et al., 1980). The first one runs NE-SW like the fissure swarms of the active rift zone which have been derived from the crustal tension inside the rift zone. The second one is faults formed by lateral shear forces in different directions, located in the Snaefellsnes Fracture Zone.

The geothermal geochemistry of low-temperature waters in Borgarfjördur has been studied to some details previously (e.g., Gunnlaugsson, 1980; Arnórsson and Ólafsson, 1986; Kristmannsdóttir et al., 2005). Several projects have entailed geochemical studies of the geothermal fields in Borgarfjördur. Based on these studies, the waters are of meteoric origin, display alkaline pH values and low Cl concentrations (<50 ppm). Based on geothermometer temperature estimations, reservoir temperatures may be as high as ~150°C in the area.

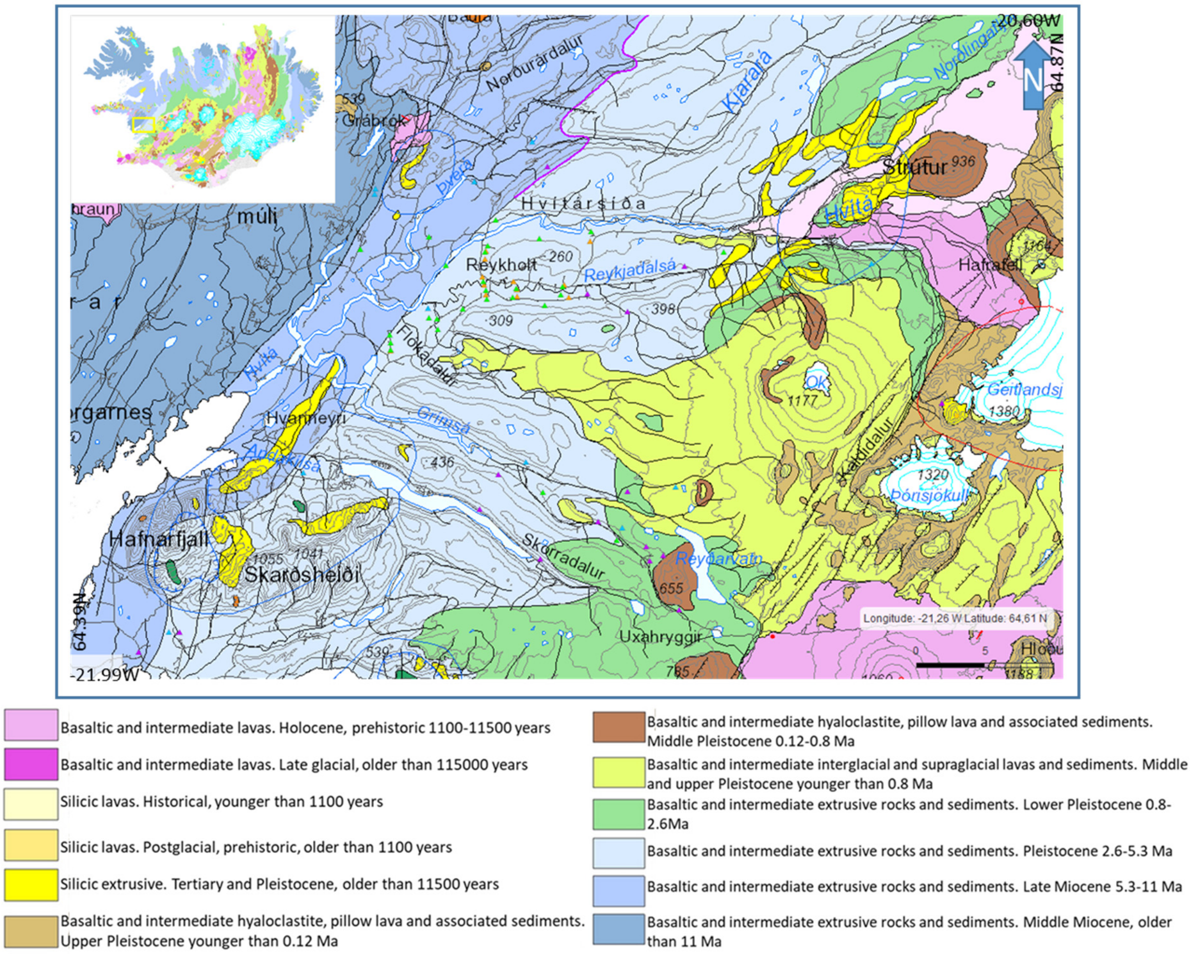


FIGURE 2: Geological map of Borgarfjördur, Iceland (extracted from Geological map of Iceland, scale 1:600,000, ISOR (Hjartarson and Saemundsson, 2014)

3. METHODS

3.1 Sampling

In Central Vietnam 20 samples and in Borgarfjördur 12 samples of cold and low-temperature geothermal water were collected in the summer of 2018, or in total 32 samples. Sample locations are shown in Figure 3.

Samples were collected from both hot springs and non-thermal water according to standard methods (e.g., Arnórsson et al., 2006). When more than one discharge point was available, the one with highest temperature and flow rate was chosen for sampling. The apparatus used for collecting the water samples included a kit for H_2S titration, pH meter, conductivity meter, thermometer, pipette and tips, GPS and camera, cooling spiral, pump and hoses, filter holder and filter paper and various reagents. The components analysed for were pH, DIC, H_2S, B, Si, F, Cl, Br, SO_4, Al, Ca, Fe, K, Mg, Na, δD and $\delta^{18}O$.

For major cation and anion determination, the samples were collected by pumping the water from the sample source though a PTFE filter holder containing a 0.2 µm cellulose acetate filter. During sampling in Vietnam a hand operated pump was used whereas for the Icelandic sampling a battery driven peristaltic pump was used. The sample collection method and sample treatment on site were adjusted for the sample type and the components that were to be analysed. Samples for B, Si and cations (Al, Ca, Fe, K, Mg, Na) were filtered and collected into 60 mL high-density polyethylene (HDPE) bottles and acidified to 1% with HNO_3 (Merck Suprapur®). Samples for anion (F, Cl, Br, SO_4) determinations were filtered and collected into 100 mL HDPE bottles and not further treated. Samples for stable water isotope (δD and $\delta^{18}O$) analysis were filtered and collected into 30 mL HDPE bottles without further treatment. Samples for determining the total dissolved inorganic carbon (DIC) were not filtered but were collected into 250 mL amber glass bottles with an air-tight cap to prevent contact with air. pH, conductivity and H_2S concentration were determined on site.

3.2 Chemical analysis

Major cations (Na, K, Ca, Mg, Fe, and Al), B and Si were analysed for by inductively coupled optimal emission spectrometry (ICP-OES) and major anions (F, Cl, Br and SO_4) were analysed for using ion chromatography (IC). pH was measured on-site after cooling of the samples to close to room temperature using a pH electrode calibrated against commercial buffer solutions. H_2S was analysed for on-site using an Hg-precipitation titration and dithizone as an indicator (Arnórsson et al., 2006). The dissolved inorganic carbon (DIC) concentrations were analysed for within 1-2 days of sampling using a modified alkalinity titration (Stefánsson et al., 2007). The analytical precision for all major element analysis was based on duplicate analysis of the samples, and was found to be <3% at the 95% confidence level in all cases and ±0.05 units for pH.

Stable water isotope ratios (δD and $\delta^{18}O$) were determined using a Delta V Advantage IRMS (Isotope Ratio Mass Spectrometer) system with a gas-bench device and the results reported relative to the VSMOW reference material. The analytical precision was found by repeated determinations of δD and $\delta^{18}O$ and are <1.0‰ and <0.1‰ respectively.

3.3 Geochemical calculations

The processing of the data involved three steps: (1) estimation of fluid origin and mixing using conservative element behaviour and isotope ratios in water; (2) calculation of reservoir fluid composition and estimation of reservoir temperature; (3) calculation of aqueous speciation and mineral saturation indices.

Geothermal fluid origin and fluid mixing were assessed using stable water isotopes (δD and $\delta^{18}O$) and B and Cl concentration relations. For these calculations, the Cl concentration in precipitation was

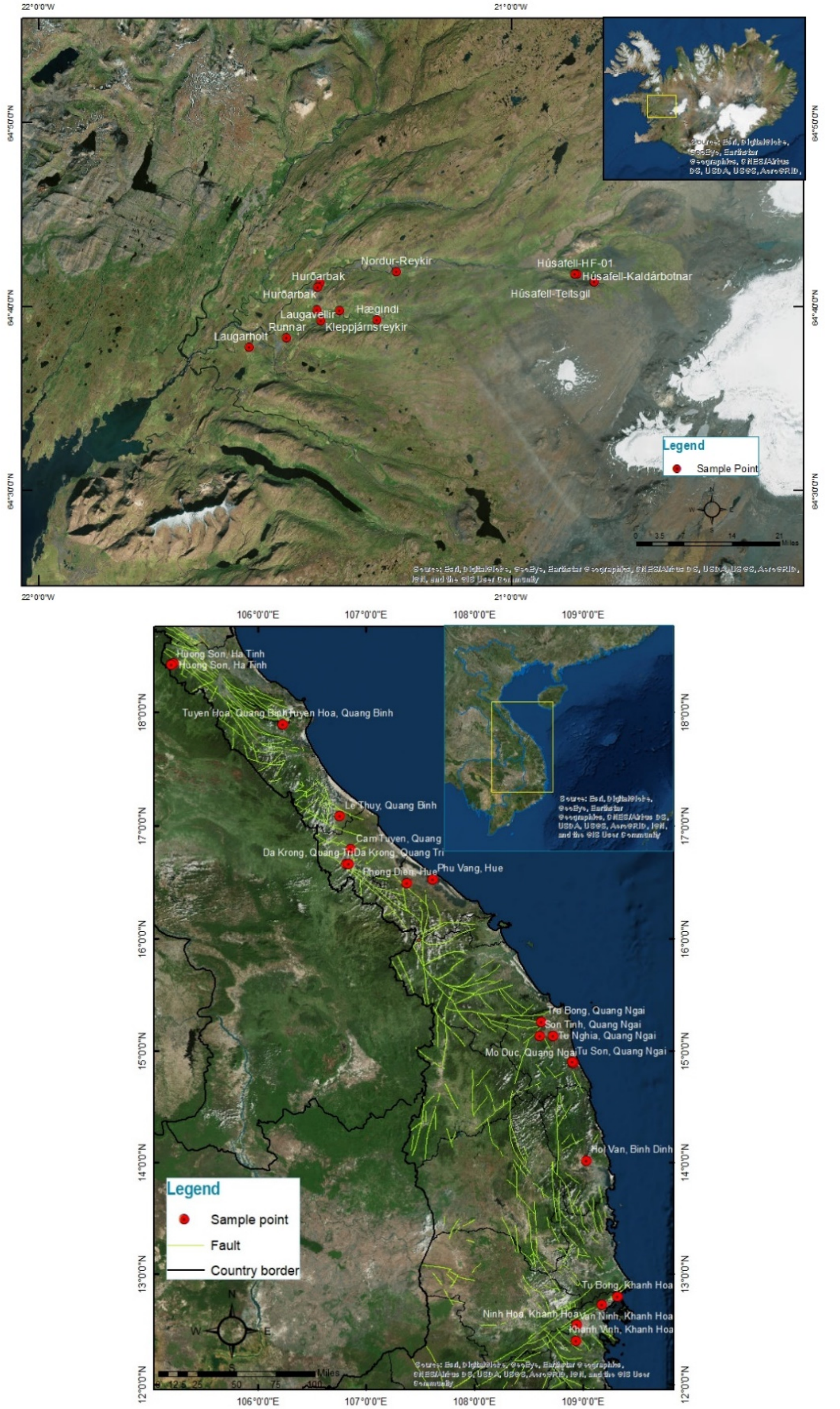


FIGURE 3: Sample locations at Borgarfjördur, Iceland (above) and Central Vietnam (below)

assumed to be 1-10 ppm (Sigurdsson and Einarsson, 1988). For basalts in Iceland, the Cl and B concentrations were taken to be 170 ppm and 1.2 ppm, respectively (Arnórsson and Andrésdóttir, 1995). The corresponding Cl and B concentrations for basalts, sandstone and carbonates in Vietnam were taken to be 60 ppm and 5 ppm, 10 ppm and 35 ppm and 150 ppm and 20 ppm, respectively (Turekian and Wedepohl, 1961).

The calculations of reservoir temperatures, reservoir fluid composition, aqueous speciation and mineral saturation indices were carried out using the WATCH program (Arnórsson et al., 1982; Bjarnason, 2010). For these calculations, the quartz (Fournier and Potter, 1982), chalcedony (Fournier, 1977) and Na/K (Arnórsson et al., 1983) as well as the multiple geothermometry approach (Reed and Spycher, 1984) were applied. For boiling hot springs which are subject to possible steam and gas loss, the boiling hot spring model of the WATCH program was applied for reconstruction of the reservoir fluid composition. For these calculations, equilibrium degassing was assumed. Using the resulting reservoir fluid composition, the aqueous speciation and mineral saturation states were computed.

4. RESULTS

The chemical composition of non-thermal and geothermal waters from central Vietnam and Borgarfjördur, Iceland is reported in Table 1 and shown in Figure 4.

4.1 Chemical composition of waters from Vietnam

The measured surface temperatures of geothermal water in central Vietnam were 42-96°C and the pH was 6.24-9.29 measured in the field after cooling. There were indications that H_2S was present in many samples from Vietnam but technical problems prevented it from being determined. The concentrations of SiO_2 were 38-138 ppm, B were 0.03-3.5 ppm and Cl concentrations were variable ranging from 3.36 to 2999 ppm with most waters sampled displaying low Cl concentrations except for Phu Vang, Mo Duc, and Tu Son thermal waters. Dissolved inorganic carbon concentrations were also elevated in some thermal fluids for example up to 277 ppm in Cam Tuyen and 866 ppm in Phu Vang. The $\delta^{18}O$ and δD ratios were -8.92 to -5.84‰ and -57.56 to -32.64‰, respectively.

Based on the major elemental composition and geographical location (Figure 3), the water samples were divided into four groups: (1) ground water, (2) highland geothermal water, (3) lowland geothermal water and (4) coastal geothermal water. The coastal geothermal waters displayed high Cl and SO_4 concentration and most lowland geothermal waters were high in DIC concentration. Most of the samples were elevated in Na and concentrations.

4.2 Chemical composition of waters from Borgarfjördur

The temperature of geothermal waters sampled in Borgarfjördur (Iceland) was 40-98°C and the pH measured in the field at ambient temperature was 6.24-9.29. The concentrations of SiO_2 were 54-178 ppm, those of B were 0.20-0.43 ppm and the Cl concentrations were 23.4-103 ppm. The DIC concentrations displayed a narrow concentration range of 23.2 to 44.3 ppm. The $\delta^{18}O$ and δD ratios were -12.05 to -9.32‰ and -88.76 to -68.37‰, respectively.

Based on the major constituent composition and geographical location of the waters (Figure 3) five groups were distinguished for the Borgarfjördur area: non-thermal water, Húsafell water, Runnar water, Laugarholt water, and 30-40 ppm Cl water. In all cases, the waters were relatively dilute, with DIC, SO_4 and Cl all being important anions and Na being the dominant cation.

TABLE 1: Chemical composition of geothermal water from Vietnam and Iceland

#	Location	Water type	T°C	pH / °C	SiO_2 ppm	B ppm	Na ppm	K ppm	Ca ppm	Mg ppm	Fe ppm	Al ppm	F ppm	Cl ppm	DIC [a] ppm	SO_4 ppm	H_2S ppm	δD ‰	$\delta^{18}O$ ‰
Vietnam																			
LV1	Huong Son	Highland	78	9.20 / 33	101	0.31	66.3	2.68	1.62	0.008	< 0.005	0.040	4.85	3.36	80.5	49.6		-57.6	-8.92
LV2	Huong Son	Ground	23	5.97 / 23	19.2	<0.01	2.08	1.10	1.21	2.90	< 0.005	< 0.0075	0.07	1.39		4.94		-49.9	-8.18
LV3	Tuyen Hoa	Lowland	62	8.62 / 40	71.0	0.21	102	7.84	2.43	0.069	< 0.005	0.012	9.02	11.0	156	9.80		-54.6	-8.62
LV-3-1	Tuyen Hoa	Ground	25	/	10.7	<0.01	3.93	< 0.4	5.60	2.21	0.180	< 0.0075	0.11	4.47	0.0	1.65		-50.0	-7.63
LV4	Le Thuy	Lowland	96	8.50 / 51	138	0.66	170	11.0	1.82	0.061	0.010	0.074	5.42	27.4	228	30.7		-48.8	-7.60
LV5	Cam Tuyen	Highland	42	7.30 / 31	38.0	0.36	75.3	2.18	63.9	16.2	0.081	< 0.0075	1.28	5.50	277	97.0		-43.8	-6.99
LV6	Da Krong	Highland	55	8.39 / 32	65.8	0.37	92.8	2.22	3.96	0.062	< 0.005	0.010	5.04	26.1	97.8	21.5		-49.0	-7.76
LV7	Da Krong	Highland	56	7.61 / 33	69.8	0.42	99.7	5.37	18.6	2.17	0.016	< 0.0075	7.27	27.7	80.8	97.9		-45.9	-7.42
LV8	Phong Dien	Lowland	64	6.82 / 30	58.3	0.24	46.5	6.75	160	15.3	0.072	< 0.0075	1.23	29.6	202	349		-32.6	-5.84
LV9	Phu Vang	Coastal	50	6.24 / 30	26.9	3.50	1003	55.6	97.1	20.2	0.224	< 0.0075	2.63	1188	866	207		-45.4	-6.75
LV10	Khanh Vinh	Lowland	44	9.29 / 44	76.4	0.054	76.2	1.61	1.46	0.028	< 0.005	< 0.0075	7.54	11.8	90.4	15.0		-54.1	-8.68
LV11	Ninh Hoa	Lowland	66	9.14 / 38	74.2	0.049	78.7	2.03	1.76	0.042	0.043	0.044	8.55	16.0	74.0	30.2		-54.3	-8.58
LV12	Van Ninh	Coastal	66	8.65 / 59	70.5	0.029	131	3.73	10.6	0.033	< 0.005	0.017	3.72	170	38.4	18.8		-43.9	-7.42
LV13	Tu Bong	Coastal	75	8.54 / 63	94.8	0.059	181	6.55	10.2	0.033	< 0.005	0.010	3.72	240	43.6	32.7		-39.4	-6.64
LV14	Hoi Van	Coastal	79	8.70 / 33	91.8	0.094	154	5.74	4.67	0.031	< 0.005	0.022	14.5	126	90.4	33.4		-50.4	-7.85
LV15	Mo Duc	Coastal	80	7.30 / 32	105	0.41	1393	71.9	368	3.70	< 0.005	< 0.0075	4.02	2666	57.5	156		-39.4	-6.32
LV16	Tu Son	Coastal	53	6.83 / 53	115	0.41	1510	95.5	391	4.12	< 0.005	< 0.0075	3.87	2976	73.9	145		-41.4	-6.43
LV17	Tu Nghia	Coastal	80	8.20 / 80	92.7	0.23	159	6.14	6.77	0.046	< 0.005	0.019	8.70	167	76.8	31.0		-46.1	-7.37
LV18	Son Tinh	Lowland	68	8.61 / 44	98.1	0.21	102	3.39	3.45	0.017	< 0.005	0.014	10.4	28.2	109	42.9		-48.6	-7.72
LV19	Tra Bong	Lowland	64	8.95 / 54	65.3	0.14	94.6	2.67	2.22	0.008	< 0.005	0.021	6.76	53.2	78.1	19.8		-44.0	-7.14
Iceland																			
L001	Húsafell-Teitsgil	Húsafell	40	8.98 / 40	54.2	0.24	58.4	1.04	5.58	0.11	< 0.005	0.017	8.35	23.4	35.6	45.1	0.015	-80.1	-10.29
L002	Húsafell-Kaldár	Cold water	4	7.68 / 4	15.3	<0.01	8.06	0.51	4.32	1.66	< 0.005	< 0.0075	0.15	5.90	30.3	2.51		-74.1	-9.80
L003	Húsafell-HF-01	Húsafell	76	9.34 / 25	86.0	0.43	90.9	1.64	4.56	< 0.005	< 0.005	0.060	14.5	35.4	40.5	71.5	0.15	-88.8	-12.05
L004	Nordur-Reykir	30-40ppm Cl	91	9.34 / 29	146	0.38	82.9	2.42	2.35	< 0.005	< 0.005	0.219	2.08	33.4	37.3	61.8	0.50	-74.8	-9.91
L005	Hægindi	30-40ppm Cl	98	9.24 / 22	178	0.30	85.4	3.69	2.65	0.007	< 0.005	0.076	2.63	32.7	50.8	62.7	2.48	-72.5	-9.88
L006	Laugavellir	30-40ppm Cl	92	9.21 / 29	153	0.27	81.7	2.67	2.49	0.122	< 0.005	0.082	3.19	33.9	44.3	57.5	2.30	-73.1	-10.44
L007	Deildartunguhver	30-40ppm Cl	97	9.30 / 31	143	0.25	78.9	2.28	2.76	< 0.005	< 0.005	0.126	2.74	34.2	37.3	52.9	1.57	-71.7	-10.23
L008	Kleppjárnsreykir	30-40ppm Cl	89	9.40 / 27	139	0.22	78.7	2.25	2.96	< 0.005	< 0.005	0.157	2.53	35.2	34.4	53.2	1.15	-72.9	-10.15
L009	Runnar	Runnar	56	9.51 / 18	110	0.21	82.6	1.91	3.11	0.006	< 0.005	0.078	2.20	46.9	30.9	54.4	0.020	-68.4	-9.32
L010	Hurðarbak	30-40ppm Cl	98	9.31 / 26	146	0.29	79.8	2.28	2.79	< 0.005	0.007	0.109	2.63	33.3	40.0	55.9	1.25	-74.6	-10.31
L011	Hurðarbak	Cold water	7	8.22 / 10	18.8	<0.01	14.5	1.39	7.94	4.28	0.026	< 0.0075	0.080	16.4	43.7	3.60		-67.0	-9.35
L012	Laugarholt	Laugarholt	77	8.93 / 38	120	0.20	103	2.47	12.7	0.018	< 0.005	0.017	2.04	103	23.2	71.1	0.16	-73.3	-10.45

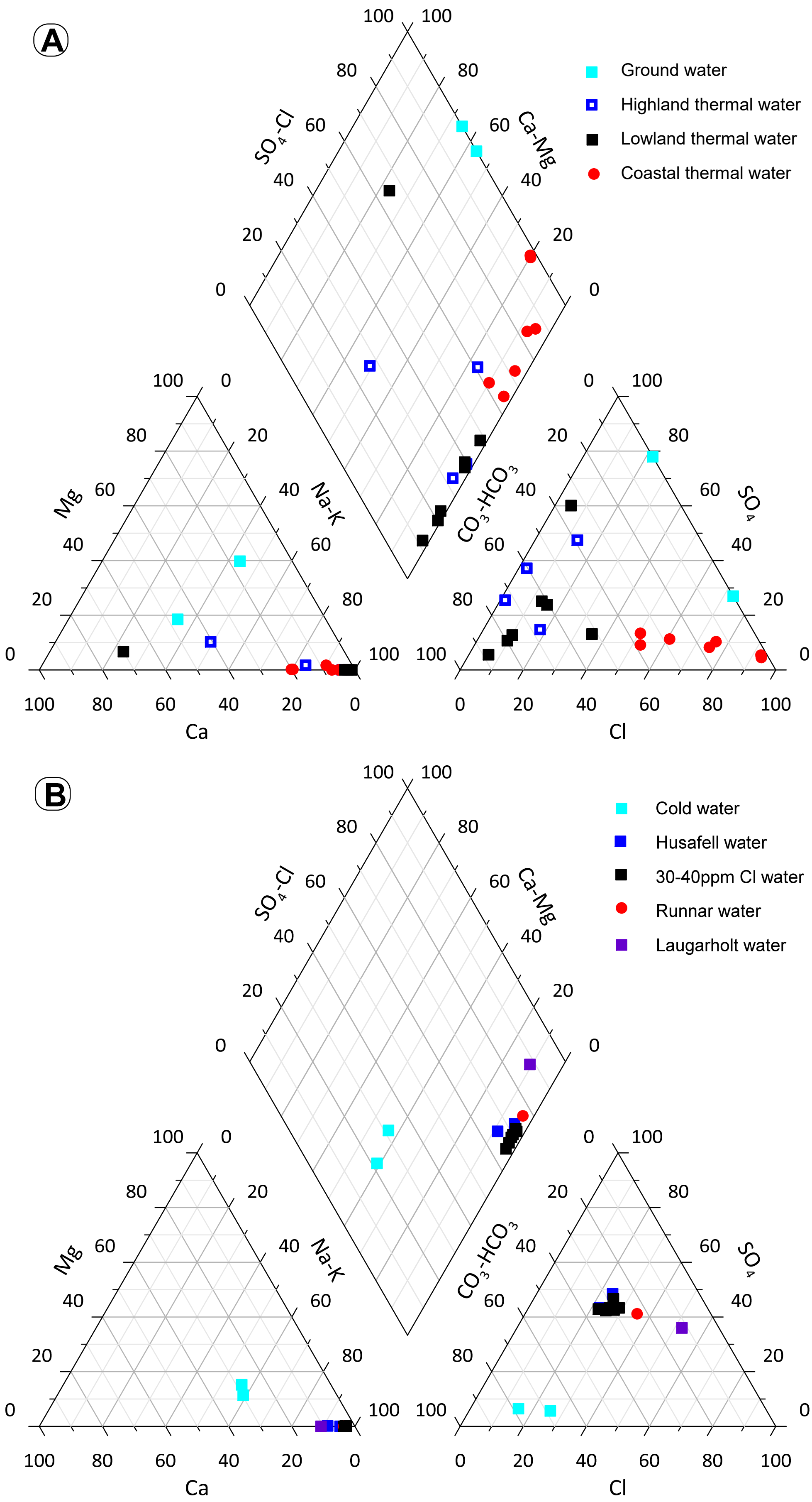


FIGURE 4: The chemical composition of non-thermal and geothermal waters in Central Vietnam (A) and Borgarfjördur, Iceland (B) shown on a Piper diagram

5. DISCUSSION

5.1 Water origin traced by δD and $\delta^{18}O$

Isotope ratios in water (δD and $\delta^{18}O$) are commonly applied to trace the origin of geothermal water (Craig, 1963; Árnason, 1976; Stefánsson et al., 2017). The relationship between δD and $\delta^{18}O$ values for most low-temperature geothermal water closely follows the global meteoric water line (GMWL) suggesting meteoric sources and sometimes seawater (e.g. Árnason, 1976). In many cases, the δD and $\delta^{18}O$ ratios of the geothermal water resemble a local meteoric source but sometimes they differ suggesting water transport, for example from high to low ground or water originating from when climate conditions in the area were different.

In the Vietnam samples, the δD and $\delta^{18}O$ ratios ranged between -57.56 and -32.64‰, and between -8.92 and -5.84‰, respectively, whereas the corresponding values at Borgarfjördur, Iceland ranged from -88.76 to -68.37‰ and from -12.05 to -9.45‰, respectively. The δD of local precipitation in Vietnam was taken from the Atlas of Isotope Hydrology – Asia and the Pacific (IAEA, 2008) with values between -44 and -31.6‰. The δD of precipitation in Borgarfjördur Iceland was taken from Árnason (1976), with values ranging from -82 to -62‰ for the region.

As seen in Figure 5 the δD and $\delta^{18}O$ of geothermal waters in Vietnam and Borgarfjördur closely follow the global meteoric water line indicating meteoric sources. The values for δD and $\delta^{18}O$ in Vietnam cover a wide range and show that the geothermal waters are likely from different reservoirs whilst the δD and $\delta^{18}O$ values in Borgarfjördur are quite clustered indicating a similar and local source. All the water samples with 30-40 ppm Cl and waters at Laugarholt formed one group in terms of isotope ratios. In contrast waters at Runnar displayed higher values and waters at Húsafell displayed lower values. According to Árnason (1976) the origin of geothermal water in Borgarfjördur is traced to the glacier ice melt and local precipitation with a general groundwater flow from east towards west. The higher δD values at Runnar and lower values at Húsafell are in good agreement with the geographical distribution of deuterium in local groundwater and precipitation. The geothermal waters are generally more depleted than non-thermal waters sampled near-by.

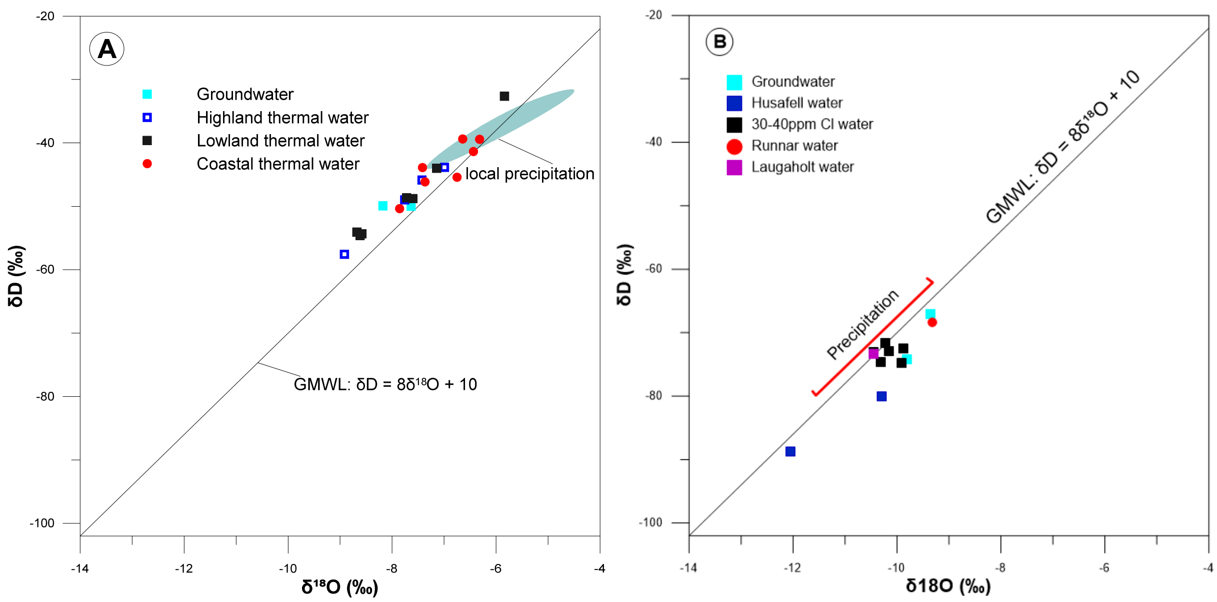


FIGURE 5: The relationship between δD and $\delta^{18}O$ in waters in Vietnam (A) and Borgarfjördur (B); also shown is the range of values for local precipitation and the global meteoric water line (GWML)

5.2 Water origin, mixing and progressive water-rock interaction

The Cl and B components of geothermal water have been used to gain information on the origin of the geothermal water and assess possible mixing of two or more water components of different composition (Arnórsson and Andrésdóttir, 1995; Stefánsson et al., 2017). Chloride and B are considered to be conservative in geothermal systems and are not incorporated into secondary minerals upon water-rock interaction. Non-thermal waters generally have low Cl and B concentrations, between <0.001 ppm and a few ppm and <1 ppb to several tens of ppb, respectively (e.g. Arnórsson and Andrésdóttir, 1995). In contrast, seawater has high Cl and B concentrations of 19400 ppm and 4.45 (Bruland, 1983). Upon water-rock interaction, Cl and B are dissolved from the primary rocks and glasses, the rock typically having a different Cl/B ratio than the meteoric and seawater sources. It follows, that Cl and B may be ideal to trace water origin (meteoric or seawater) and progressive rock leaching. It can further be used to assess mixing between two or more water sources given that their Cl/B ratios and concentrations are different.

The relationship of the Cl and B concentrations in the geothermal waters in Vietnam and Borgarfjördur are shown in Figures 6. The values for precipitation are also shown as well as the seawater ratio and trends corresponding to progressive rock leaching.

Most of the waters in Borgarfjördur were observed to be enriched in B relative to the local meteoric water and have approached the Cl/B ratio of basaltic rock. The geothermal waters in Runnar and Laugarholt were enriched in Cl relative to B and the Cl/B basalt ratio thus raised. Mixing with old seawater or interaction with rocks having different Cl/B ratios could explain these discrepancies. Inspection of the relationship between δD and Cl/B ratio reveals the waters to be of modern and meteoric origin supporting the latter explanation. Moreover, the two samples from Húsafell displayed different δD values from deep well water having lower δD compared to the surface spring water sample. These findings suggest a slightly different water source depending on depth possibly suggesting a deep groundwater flow from Langjökull towards the west and more local meteoric water at shallow depths or there might be a mixture of the deep geothermal water (as the sample from the HF-well) and cold groundwater in the surface (Húsafell spring sample).

The relationship between Cl and B for the geothermal waters in Vietnam is shown in Figure 6 together with the corresponding values for precipitation and seawater and rock ratios. As the geothermal waters in Vietnam were located in systems of variable host rock composition (basalts, sandstone and carbonates) several trends upon rock leaching are shown. As observed, the geothermal waters in the highland areas indicate a meteoric origin affected by progressive water-rock interaction whereas waters in coastal and lowland areas indicate seawater mixing. However, an inspection of the relationship between δD and Cl/B (Figure 7) suggests that the source of the salts is not in all cases directly seawater input but rather meteoric water affected by dissolution of salt deposits of seawater origin or having similar Cl/B ratio as seawater, possibly indicative of old evaporites.

From the δD, $\delta^{18}O$, Cl and B relationships it can be concluded that all these low-temperature geothermal waters are predominantly of meteoric origin that have later been modified by progressive water-rock interaction. In Borgarfjördur, most of geothermal waters are from a similar reservoir with the exception of waters in Húsafell whereas the geothermal waters in Vietnam differ with respect to their geographical location.

5.3 Reservoir fluid composition and temperature

Geothermometers have been applied to estimate geothermal reservoir temperatures at depth (e.g. Fournier and Truesdell, 1973; Fournier and Potter, 1979, 1982; Arnórsson et al, 1983; Giggenbach, 1988). These are based on temperature-dependent equilibria between aqueous species and secondary minerals and assuming the reservoir be thermodynamically isolated from to surface, i.e. negligible effects of secondary processes upon fluid ascent such as mixing with non-thermal water, secondary mineral formation and open system boiling and phase separation or vapor condensation.

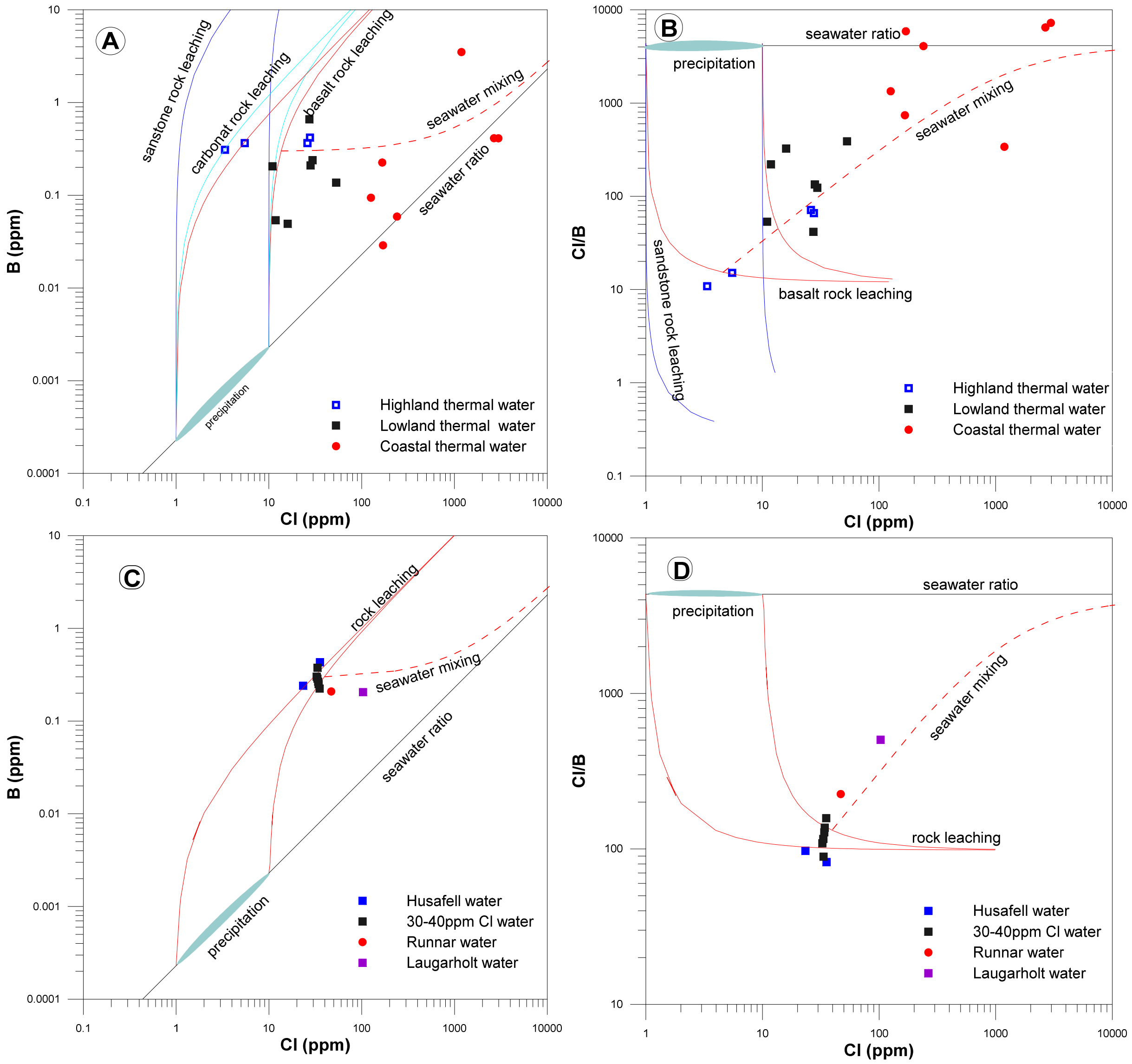


FIGURE 6: The relationship between Cl and B (A, C) and Cl/B and Cl (B, D) for geothermal waters in Borgarfjördur (C, D) and Central Vietnam (A, B). The Cl/B ratio of seawater was taken from Bruland (1983) and the corresponding rock ratios were taken from Arnórsson and Andrésdóttir (1995) and Turekian and Wedepohl (1961). The Cl concentration of local precipitation for both areas was assumed to be 1-10 ppm but may vary to greater degree, the limitation of assessing the exact value is the lack of data on precipitation chemical composition (in Vietnam data)

These primary and secondary processes can be visualised on a silica-enthalpy diagram (Figure 8). Assuming silica equilibrium at reservoir conditions, the silica concentration in the geothermal water is expected to reflect the temperature-dependent solubility of quartz or chalcedony. If the reservoir fluids have temperatures higher than the boiling point of water, they may boil upon ascent to the surface resulting in loss of H_2O to the vapour phase and increased silica concentration in the boiled liquid phase as SiO_2 does not partition into the vapor phase at these temperatures. Non-reactive mixing with non-thermal water may then be indicated by a linear trend between the reservoir water and non-thermal water. As seen in Figure 8, such trends are observed at Borgafjördur with reservoir temperatures close to ~120-140°C and mixing with non-thermal water for example at Húsafell, Runnar and Laugarholt. For geothermal waters in Vietnam, such mixing trends can be seen for all waters within a given region (highland, lowland and coastal waters) with possible maximum temperatures being ~110-125°C depending on location. Alternatively, the shift to lower enthalpies relative to SiO_2 concentrations of the waters and SiO_2 mineral equilibrium saturation may indicate fluid ascent and conductive cooling.

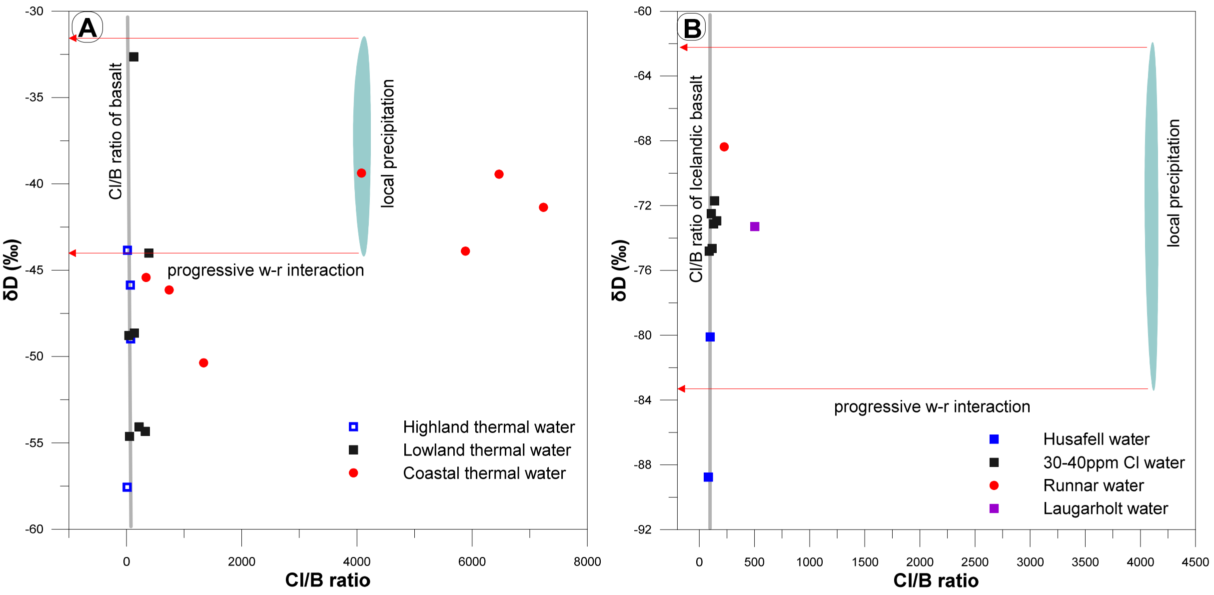


FIGURE 7: The relationship between δD and Cl/B in geothermal water from Vietnam (A) and Borgarfjördur, Iceland (B). The Cl/B ratio of the various rock types were taken from Turekian and Wedepohl (1961) and Arnórsson and Andrésdóttir (1995), and the seawater composition is taken from Bruland (1983)

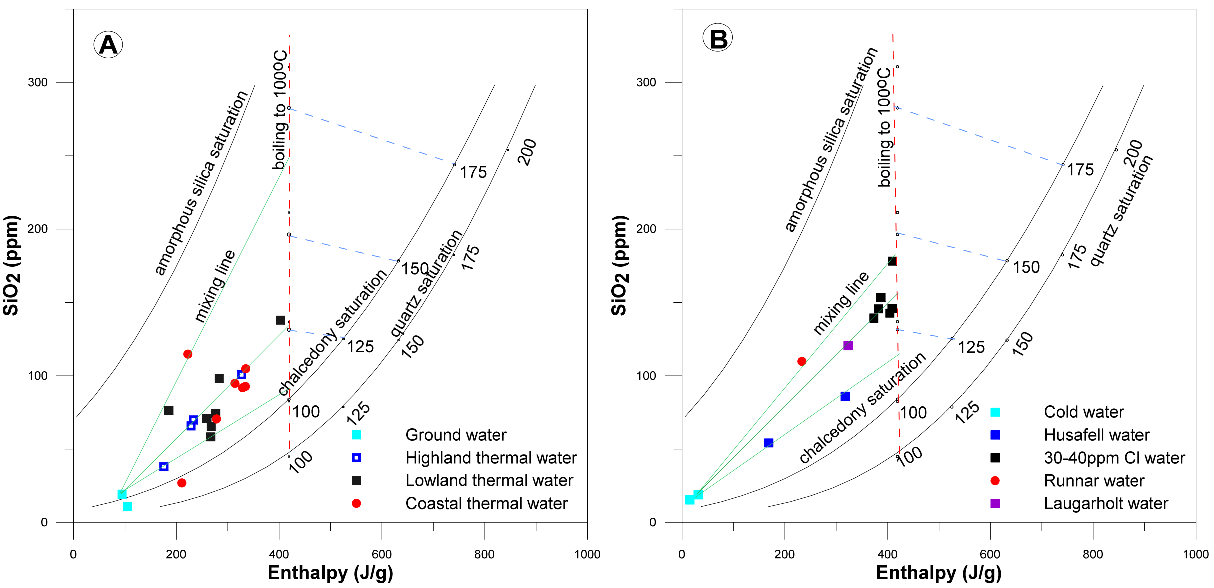


FIGURE 8: SiO_2-enthalpy diagram (Truesdell and Fournier, 1977; Fournier, 1977; Arnórsson, 1985) showing the solubility of SiO_2 solid phases (amorphous silica, chalcedony and quartz), the effect of adiabatic boiling and mixing with non-thermal waters

The geothermometer temperatures were further calculated for individual samples based on the quartz (Fournier and Potter, 1982), chalcedony (Fournier, 1977) and Na/K (Arnórsson et al., 1983) geothermometers and multiple mineral-solute equilibria (Reed and Spycher, 1984). The calculations were conducted with the aid of the WATCH program (Arnórsson et al., 1982; Bjarnason, 2010). The results are reported in Table 2 and examples of the multiple mineral-solute equilibria calculations are also shown in Figure 9.

TABLE 2: The results of geothermometers for reservoir water in Vietnam and Borgarfjördur.

Sample	Location	Water type	Quartz	Chalcedony	Na/K	Temp from SI	Selected Temp
			°C	°C	°C	°C	°C
Vietnam							
LV1	Huong Son	Highland	122	94	118	70-95	94
LV3	Tuyen Hoa	Lowland	113	84	175	75-90	84
LV4	Le Thuy	Lowland	147	121	158	110-130	125
LV5	Cam Tuyen	Highland	90	58	94	55-65	58
LV6	Da Krong	Highland	113	83	83	65-80	83
LV7	Da Krong	Highland	118	89	141	60-80	89
LV8	Phong Dien	Lowland	109	80	241	65-85	80
LV9	Phu Vang	Coastal	75	43	142	65-80	43
LV10	Khanh Vinh	Lowland	101	70	76	65	70
LV11	Ninh Hoa	Lowland	106	76	87	70-85	76
LV12	Van Ninh	Coastal	109	79	93	70-85	79
LV13	Tu Bong	Coastal	125	97	109	75-90	97
LV14	Hoi Van	Coastal	139	112	136	85-105	112
LV15	Mo Duc	Coastal	139	112	136	85-110	112
LV16	Tu Son	Coastal	145	119	154	90-115	119
LV17	Tu Nghia	Coastal	126	98	114	80-100	98
LV18	Son Tinh	Lowland	129	102	103	70-95	102
LV19	Tra Bong	Lowland	100	69	93	65-80	69
Iceland							
L001	Húsafell-Teitsgil	Húsafell	96	65	67	55-65	65
L003	Húsafell-HF-01	Húsafell	115	86	68	85-95	86
L004	Nordur-Reykir	30-40ppm Cl	142	116	95	110-140	116
L005	Hægindi	30-40ppm Cl	160	136	123	110-135	140
L006	Laugavellir	30-40ppm Cl	148	123	102	110-120	123
L007	Deildartunguhver	30-40ppm Cl	141	115	94	110-125	130
L008	Kleppjárnsreykir	30-40ppm Cl	139	112	94	110-135	112
L009	Runnar	Runnar	127	99	81	95-110	99
L010	Hurðarbak	30-40ppm Cl	145	119	94	110-125	135
L012	Laugarholt	Laugarholt	138	111	83	85-95	111

In Borgarfjördur, the calculated geothermometer temperatures were in reasonable agreement with chalcedony temperatures of ~65-135°C, the Na/K temperatures of ~65-125°C and multi-equilibrium temperatures of ~55-140°C. Calculated quartz temperatures were higher, however, as pointed out previously, equilibrium with chalcedony rather than quartz is observed at low-temperatures (e.g., Arnórsson et al., 1983). In Vietnam the calculated reservoir temperatures agreed in most cases, with chalcedony temperatures of ~70-120°C, Na/K of ~75-175°C and multi-equilibrium temperatures of ~55-130°C. The Na/K temperatures were often higher than the others indicating a lack of equilibrium between the water and alkali-feldspars, and possible mixing with non-thermal waters.

Using the above calculated reservoir temperatures, the reservoir composition was calculated taking into account possible steam loss and degassing due to boiling. Of the water samples collected in Vietnam only one sample was boiling (LV4) whereas three samples in Borgarfjördur were boiling (L005, L007 and L010). For these samples, the geothermometry temperatures were used for the calculation and the effects of degassing and boiling considered, by use of the boiling springs model of the WATCH code. For sub-boiling samples, it is not possible to assess whether the waters have undergone conductive cooling from reservoir temperatures and/or mixing with non-thermal water. The reservoir temperatures obtained were then used for calculations of the reservoir fluid composition. The results are reported in Table 3.

TABLE 3: The reservoir geothermal water compostion reconstructed with the aid of the WATCH program

#	Location	Water type	Temp. °C	pH	SiO_2 ppm	B ppm	Na ppm	K ppm	Ca ppm	Mg ppm	Fe ppm	Al ppm	F ppm	Cl ppm	DIC ppm	SO_4 ppm	H_2S ppm
Vietnam																	
LV1	Huong Son	Highland	94	8.49	101	0.31	66.3	2.68	1.62	0.008	< 0.005	0.040	4.85	3.36	80.5	49.6	
LV3	Tuyen Hoa	Lowland	84	8.23	71.0	0.21	102	7.84	2.43	0.069	< 0.005	0.012	9.02	11.0	156	9.80	
LV4	Le Thuy	Lowland	125	5.84	131	0.62	161	10.4	1.72	0.058	0.010	0.070	5.13	25.9	1266	29.0	
LV5	Cam Tuyen	Highland	58	7.24	38.0	0.36	75.3	2.18	63.9	16.2	0.081	< 0.0075	1.28	5.50	277	97.0	
LV6	Da Krong	Highland	83	7.94	65.8	0.37	92.8	2.22	3.96	0.062	< 0.005	0.010	5.04	26.1	97.8	21.5	
LV7	Da Krong	Highland	89	7.46	69.8	0.42	99.7	5.37	18.6	2.17	0.016	< 0.0075	7.27	27.7	80.8	97.9	
LV8	Phong Dien	Lowland	80	6.77	58.3	0.24	46.5	6.75	160	15.31	0.072	< 0.0075	1.23	29.6	202	349	
LV9	Phu Vang	Coastal	43	6.20	26.9	3.50	1003	55.6	97.1	20.2	0.224	< 0.0075	2.63	1188	866	207	
LV10	Khanh Vinh	Lowland	70	9.00	76.4	0.05	76.2	1.61	1.46	0.028	< 0.005	< 0.0075	7.54	11.8	90.4	15.0	
LV11	Ninh Hoa	Lowland	76	8.67	74.2	0.05	78.7	2.03	1.76	0.042	0.043	0.044	8.55	16.0	74.0	30.2	
LV12	Van Ninh	Coastal	79	8.40	70.5	0.03	131	3.73	10.6	0.033	< 0.005	0.017	3.72	170	38.4	18.8	
LV13	Tu Bong	Coastal	97	8.18	94.8	0.06	181	6.55	10.2	0.033	< 0.005	0.010	3.72	240	43.6	32.7	
LV14	Hoi Van	Coastal	112	8.02	91.8	0.09	154	5.74	4.67	0.031	< 0.005	0.022	14.5	126	90.4	33.4	
LV15	Mo Duc	Coastal	112	7.06	105	0.41	1393	71.9	368	3.70	< 0.005	< 0.0075	4.02	2666	57.5	156	
LV16	Tu Son	Coastal	119	6.83	115	0.41	1510	95.5	391	4.12	< 0.005	< 0.0075	3.87	2976	73.9	145	
LV17	Tu Nghia	Coastal	98	8.05	92.7	0.23	159	6.14	6.77	0.046	< 0.005	0.019	8.70	167	76.8	31.0	
LV18	Son Tinh	Lowland	102	8.07	98.1	0.21	102	3.39	3.45	0.017	< 0.005	0.014	10.4	28.2	109	42.9	
LV19	Tra Bong	Lowland	69	8.77	65.3	0.14	94.6	2.67	2.22	0.008	< 0.005	0.021	6.76	53.2	78.1	19.8	
Iceland																	
L001	Húsafell-Teitsgil	Húsafell	65	8.63	54.2	0.24	58.4	1.04	5.58	0.109	< 0.005	0.017	8.35	23.4	35.6	45.1	0.01
L003	Húsafell-HF-01	Húsafell	86	8.51	86.0	0.43	90.9	1.64	4.56	< 0.005	< 0.005	0.060	14.5	35.4	40.5	71.5	0.15
L004	Nordur-Reykir	30-40ppm Cl	116	8.30	146	0.38	82.9	2.42	2.35	< 0.005	< 0.005	0.219	2.08	33.4	37.3	61.8	0.50
L005	Hægindi	30-40ppm Cl	140	6.11	164	0.28	78.7	3.40	2.44	0.006	< 0.005	0.070	2.42	30.1	298.7	57.8	6.78
L006	Laugavellir	30-40ppm Cl	123	8.15	153	0.27	81.7	2.67	2.49	0.122	< 0.005	0.082	3.19	33.9	44.3	57.5	2.30
L007	Deildartunguhver	30-40ppm Cl	130	6.55	134	0.23	74.0	2.14	2.59	< 0.005	< 0.005	0.118	2.57	32.1	129.0	49.6	2.96
L008	Kleppjárnsreykir	30-40ppm Cl	112	8.34	139	0.22	78.7	2.25	2.96	< 0.005	< 0.005	0.157	2.53	35.2	34.4	53.2	1.15
L009	Runnar	Runnar	99	8.38	110	0.21	82.6	1.91	3.11	0.006	< 0.005	0.078	2.20	46.9	30.9	54.4	0.020
L010	Hurðarbak	30-40ppm Cl	135	6.36	136	0.27	74.3	2.12	2.60	< 0.005	0.007	0.101	2.45	31.0	170.1	52.0	2.69
L012	Laugarholt	Laugarholt	111	8.07	120	0.20	103	2.47	12.7	0.018	< 0.005	0.017	2.04	103	23.2	71.1	0.16

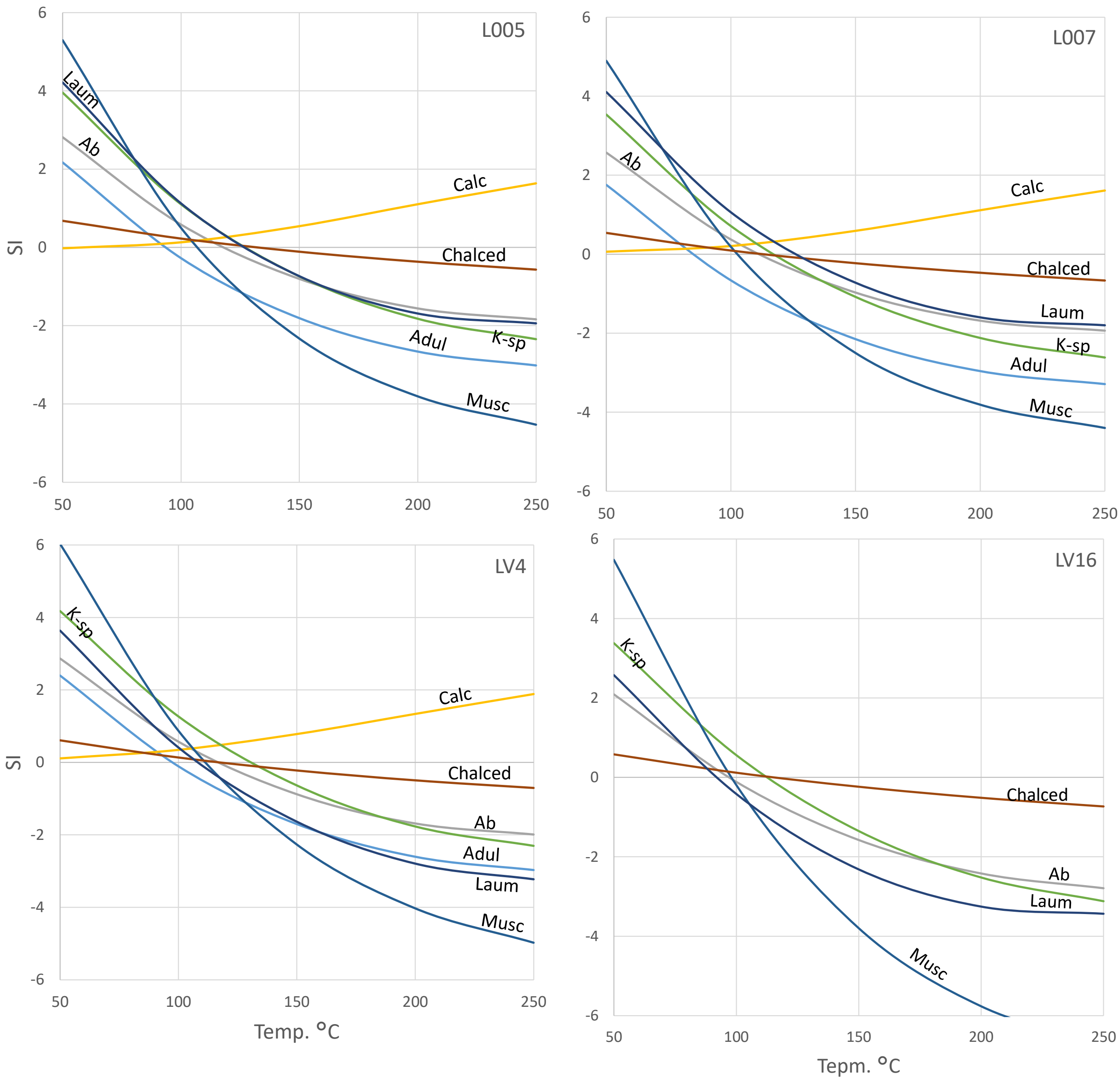


FIGURE 9: Example of multiple equilibria mineral-solute geothermometry calculations carried out using the WATCH program (Arnórsson et al., 1982; Bjarnason, 2010). adularia – Adul, albite low – Ab, calcite – Calc, microcline – K-sp, muscovite – Musc, chalcedony – Chalced, laumontite – Laum

5.4 Geographical distribution of geothermal activity

To study the distribution of geothermal activity in Borgarfjördur and Vietnam the geographical distribution of the δD, Cl and reservoir temperature was projected. The representative maps are shown in Figures 10 and 11.

For the geothermal waters in Vietnam, the δD values were found to decrease inland and from south to north, consistent with isotope fractionation and isotope values decreasing with increasing altitude and increasing distance from the sea. Similarly, the Cl concentration were found to increase from the highlands towards the coast indicating progressive seawater input. Three areas of geothermal anomalies can a be identified: Le Thuy, Quang Binh; Mo Duc, Quang Ngai; Hoi Van, Quang Binh. Within this central area of geothermal activity, the Cl concentrations are often also elevated indicative of seawater or salt input to the geothermal water. According to VIGMR (1998) there were some other hot springs close to hot spring in Le Thuy, Quang Binh (6-8 km away) and surface temperature was from 50-60°C.

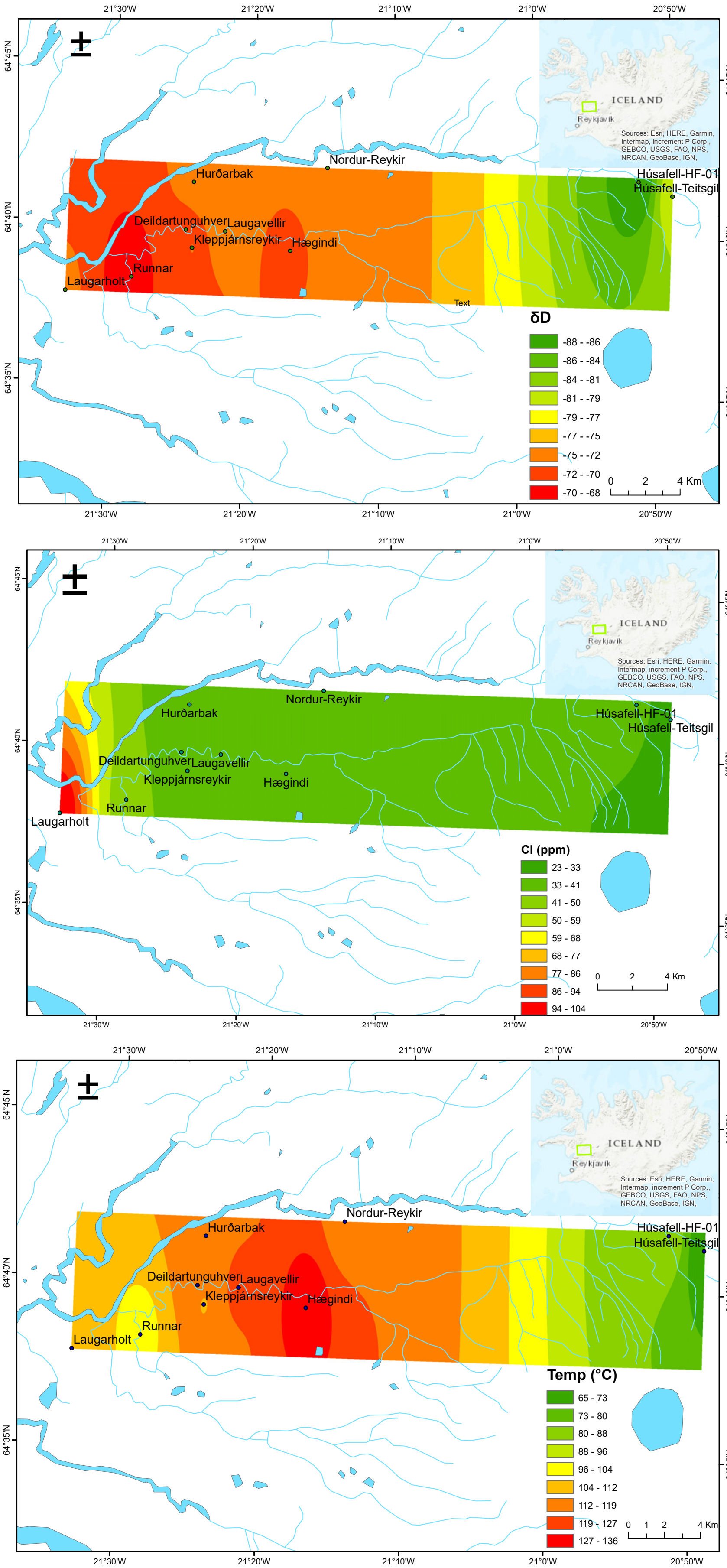
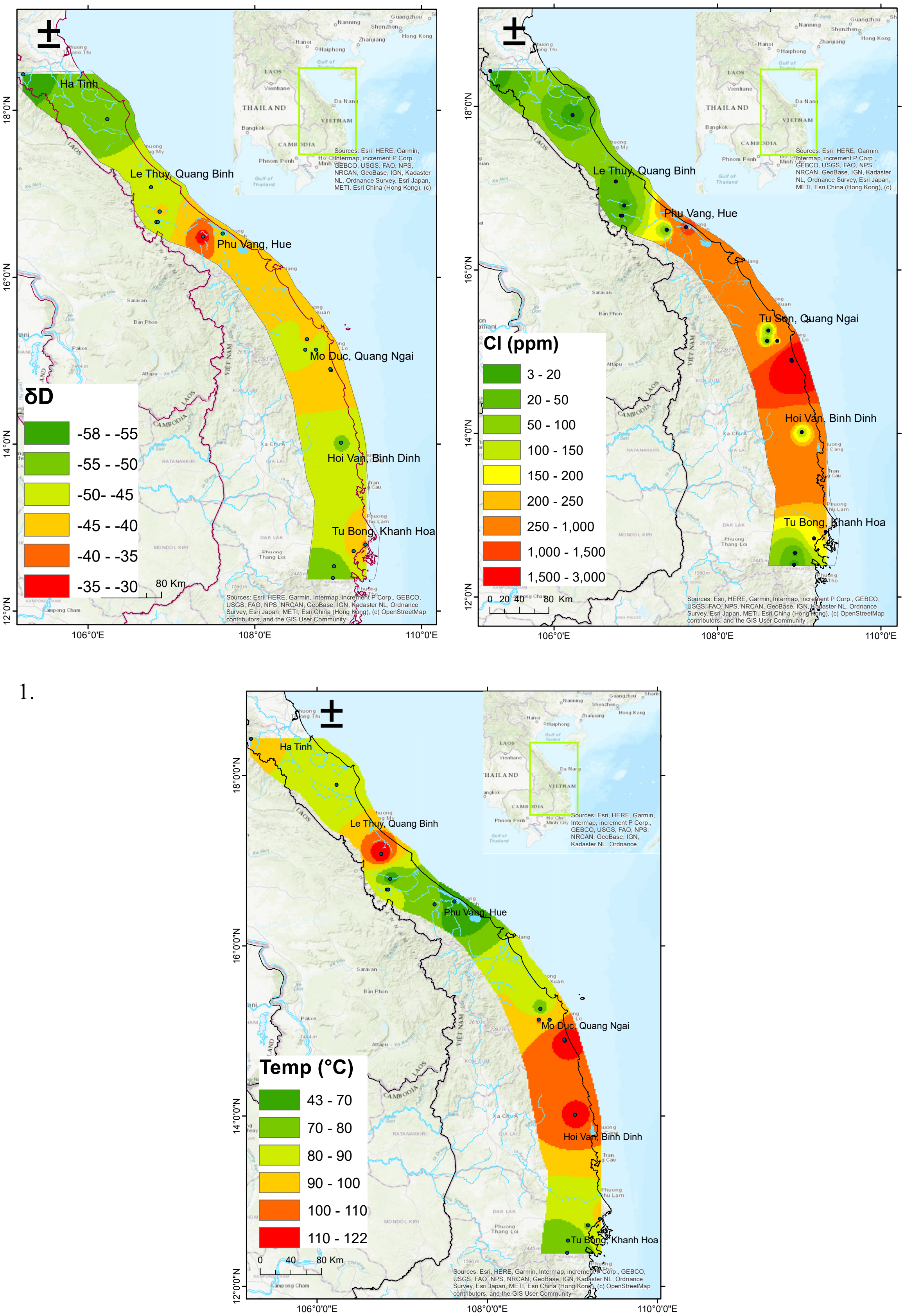


FIGURE 10: Geographical distribution of deuterium, chloride concentration and calculated reservoir temperature in Borgarfjördur, Iceland



1.

FIGURE 11: Geographical distribution of deuterium, chloride concentration and calculated reservoir temperature in central Vietnam

Similarly, there are some other hot springs around Mo Duc, Quang Ngai such as Tu Nghia (LV17), Tu Son (LV16), Son Tinh (LV18) or Tra Bong (LV19) but all have surface temperatures lower than the Mo Duc hot spring. These observations show that the heat centres are located below the Le Thuy, Quang Binh and Mo Duc, Quang Ngai and the heat decreases from the central area to the surroundings and likely towards the North-East direction.

The maps of the Icelandic data show a similar trend. The δD value decrease from the coast to inland as expected. The Cl concentrations remain quite uniform within the region, but nonetheless a trend towards lower Cl concentrations is observed further inland. The temperature distribution shows the highest reservoir temperatures at Haegindi. Borgarfjördur is located in the active Reykjanes-Langjökull rift zone, the heat source presumably being hot rocks near the volcanic centres within the area. The water origin is presumably local meteoric water and a regional groundwater flow from the highland and Langjökull glacier area in the east towards the lowlands in the west.

5.5 Utilization potential of geothermal water in Borgarfjördur and Vietnam based on temperature and chemical composition

Both Central Vietnam and Borgarfjördur share some characteristics of low-temperature geothermal fields although the geothermal temperatures in Borgarfjördur are somewhat higher than in Central Vietnam. The bedrock composition is different, however the chemical composition with regard to most major elements is remarkably similar indicating temperature dependent water-rock equilibria as a major control factor.

Therefore, the potential utilization possibilities for the geothermal water in Vietnam are likely to be similar to those developed in Borgarfjördur and other locations in Iceland. These are shown according by the Líndal diagram (Figure 12).

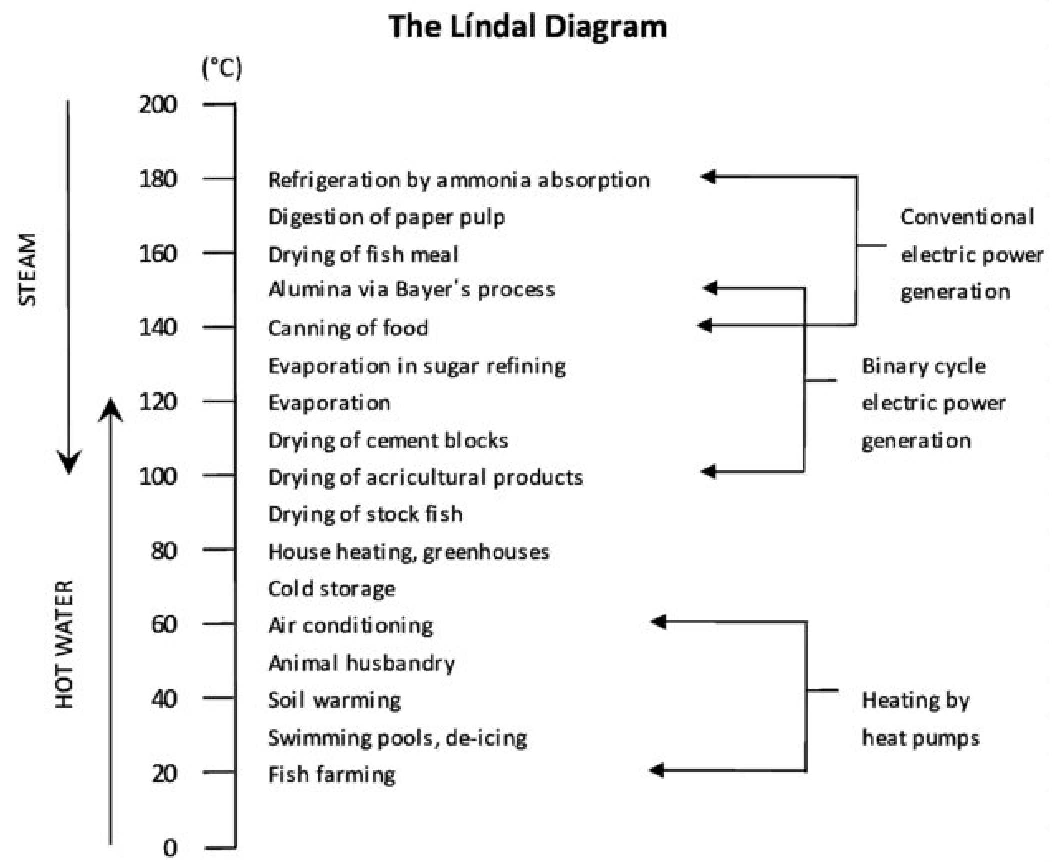


FIGURE 12: Líndal diagram showing different applications of geothermal resources based on temperature (redrawn from Gudmundsson, et al., 1985)

In Borgarfjördur and elsewhere in Iceland, the low-temperature geothermal waters are used for example for house heating, swimming pools and bathing, agriculture and greenhouse farming, fish farming, and more recently electricity production using binary stations where temperatures are high enough. In Vietnam, there is similar potential for the utilization of geothermal water including house heating and cooling, bathing, agriculture, fish farming and possibly also electricity generation especially associated with the highest temperature waters (Table 4).

TABLE 4: A list of utilization options for the different waters

	Temp.°C	Utilization possibilities
Iceland		
Borgarfjörður	~65-135	House heating, greenhouse farming, fish farming, swimming pools and bathing, drying and food processing, electricity production
Vietnam		
Phu Vang, Cam Tuyen	~40-60°C	House warming and cooling, bathing, fish farming, greenhouse farming, food production
Tra Bong, Khanh Vinh, Ninh Hoa, Van Ninh, Phong Dien, Da Krong, Tuyen Hoa, Da Krong, Huong Son, Tu Bong, Tu Nghia, Son Tinh, Hoi Van, Mo Duc, Tu Son, Le Thuy	~70-120°C	House heating, greenhouse farming, fish farming, swimming pools and bathing, drying and food processing, electricity production

6. CONCLUSIONS

The geochemistry of low-temperature geothermal water in Central Vietnam and Borgarfjördur (W-Iceland) was studied as well as its potential utilization possibilities.

Twenty samples of geothermal water were collected in Central Vietnam and twelve samples in Borgarfjördur in the summer of 2018. The water temperature, pH, DIC and H_2S concentrations were determined on site and major elemental composition analysed using ICP-OES and IC at the University of Iceland. The surface temperatures of the geothermal waters in Vietnam were 42-96°C and in Borgarfjördur they were 40-98°C.

The water isotope ratios (δD and $\delta^{18}O$), and Cl and B concentrations were used to assess the water origin, mixing and water-rock interaction. Based on this analysis is was concluded that geothermal waters in Vietnam and Borgarfjördur are of meteoric origin, affected by rock leaching and mixing with non-thermal water and possibly with seawater or salt evaporaties in the case of geothermal water in Vietnam.

The SiO_2 concentrations of the geothermal fluids in Vietnam and Borgarfjördur were 38-138 ppm and 54-178 ppm, respectively. Using these concentrations and assuming equilibrium with chalcedony the geothermal reservoir temperatures in Vietnam and Borgarfjördur were found to be as high as ~120°C and ~135°, respectively. The geographical projection of the major elemental and geotermomometer temperatures revealed three geothermal anomalies in Vietnam: Le Thuy, Quang Binh; Mo Duc, Quang Ngai; Hoi Van, Quang Binh and the highest temperatures at Haegindi in Borgarfjördur.
Following the utilization of low-temperature waters in Borgarfjördur and elsewhere in Iceland, the Líndal diagram suggests several utilization possibilities for the geothermal resources in Vietnam including house heating and cooling, greenhouse farming, fish farming, swimming pools and bathing, drying and food processing, and even electricity production for the waters with the highest temperatures. The utilization options will, however, largely depend on accessibility and the quantity of geothermal water in each location.

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