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Physical properties of fresh or hydrothermalized volcanic rocks from the west coast of Basse-Terre and Terre-de-Haut (Guadeloupe archipelago)

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ABSTRACT

The physical rock properties (solid phase and bulk densities, porosity, permeability, thermal conductivity and P-wave velocity) of 64 samples from outcrops of the Guadeloupe archipelago and more especially from the Basal Complex (2.79 ± 0.04 Myr - 2.68 ± 0.04 Myr), the Vieux-Habitants-Bouillante area (1.023 ± 0.025 Myr - 0.435 ± 0.008 Myr) and Terre-de-Haut (2.98 ± 0.04 Myr to 2.00 ± 0.03 Myr) were measured and analyzed. Samples were classified according to their lithotypes and hydrothermal alteration, considering the Basal Complex exhibits proofs of hydrothermal activity and the central part of Terre-de-Haut as an exhumed geothermal palaeo-system.

Lithotypes are lava flows and dikes, debris flows, volcanic breccias and pyroclastites including scoria, pumice and ashes.

Even if the solid phase density is relatively uniform for all lithotypes 2.57-2.75 g.cm^{-3} reflecting a constant mineralogical composition, physical properties obtained on these volcanic rocks display high variability. Porosity varies from 26 % to 42 % for volcaniclastic deposits and 7 % to 11 % for andesite lava. Permeability of lava is lower than 10^{-15} m^2, while it is higher than 10^{-14} m^2 and can reach 10^{-9} m^2 in the volcaniclastics due to a well-connected porosity and open fractures. Both porosity and permeability increase with hydrothermal alteration in andesite lava. Average thermal conductivities are almost divided by two in volcaniclastic deposits 0.51-0.99 W.m^{-1}.K^{-1} compare to lava's values, 1.60 W.m^{-1}.K^{-1}. Thermal conductivity slightly increases in hydrothermalized lava due to pyrite crystallization. P-wave velocities are often hardly measurable in pyroclastic rocks because of the low cohesion and fractures. However average P-waves velocity measures display values twice lower in volcaniclastics 2045 m.s^{-1} than in lava 4122 m.s^{-1}.

1 INTRODUCTION

The Lesser Antilles arc is located at the convergent boundary between North American and Caribbean plates Figure 1). This convergence is accommodated by the subduction of the North American lithosphere under the Caribbean plate at a relatively low velocity of 2 cm.yr^{-1} (DeMets et al., 2000). The Guadeloupe archipelago is a part of two subparallel volcanic arcs (Bouysse et al., 1990). Marie Galante and Grande-Terre of Guadeloupe are a part of the eastern older inactive arc. Basse-Terre of Guadeloupe and Les Saintes (Terre-de-Haut and Terre-de-Bas) are a part of the western recent volcanic arc. The volcanic activity of Les Saintes Islands ranged between 2.98 ± 0.04 Myr to 0.888 ± 0.009 Myr (Zami et al., 2014) whereas volcanism on Basse-Terre Island began 2.79 ± 0.04 Myr ago and is still active (Samper, 2007).

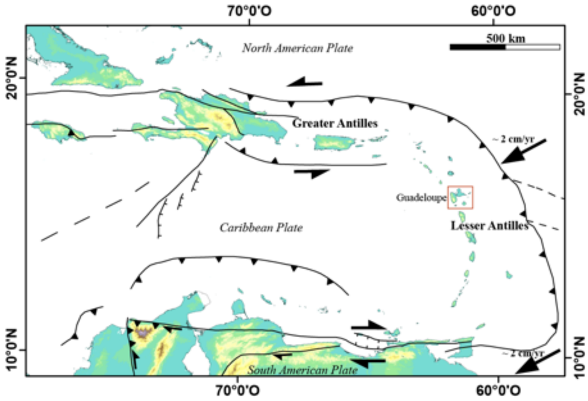

Figure 1: Geodynamic setting of the Lesser Antilles arc (after Feuillet et al., 2002).

Since the 1970's the geology of Guadeloupe archipelago is extensively studied in particular for its geothermal resource (Bouchot et al., 2011, 2010; Calcagno et al., 2012; Patrier et al., 2003; Sanjuan and Brach, 2015, 1998). Indeed a high-temperature (250-260°C) geothermal field has been identified in Bouillante (Figure 3) in the 1970's (Bouchot et al., 2010). This geothermal field is exploited since 1985 for electricity generation. Now, the geothermal plant covers approximately 7% of the electrical needs of La Guadeloupe.

Terre-de-Haut Island is a part of Les Saintes Islands. It is entirely composed of medium-K calc-alkaline volcanic rocks (Jacques and Maury, 1988). This composition is typical of the central part of the recent active arc in the Lesser Antilles. According to Zami et al. (2014), Terre-de-Haut was built in three volcanic phases between 2.98 ± 0.04 Myr and 2.00 ± 0.03 Myr: (i) Phase I at 2.98 ± 0.04 Myr, (ii) Phase II at 2.40 ± 0.04 Myr and (iii) Phase III from 2.08 ± 0.03 Myr to 2.00 ± 0.03 Myr. Phase I consists of dacitic lava flows and explosive breccia from Napoléon dome. The second phase built up the Morne Morel starting with explosive phreato-magmatic activity and continuing with the emplacement of pyroclastic flows. The third phase achieved the build up of the island with the development of the Pointe Morel basic andesitic flows, the dark andesite lava flow in the central part of Terre-de-Haut and the Chameau dome. Dark andesites of this phase present a high hydrothermal alteration in the central part of the island (Figure 2). It consists in the development of smectite, kaolinite, veins of quartz, pyrite and gypsum (Jacques and Maury, 1988). Verati et al. (2016) precisely described the high temperature association of this hydrothermal mineralogy. They concluded that this central part of Terre-de-Haut is an exhumed geothermal palaeo-system.

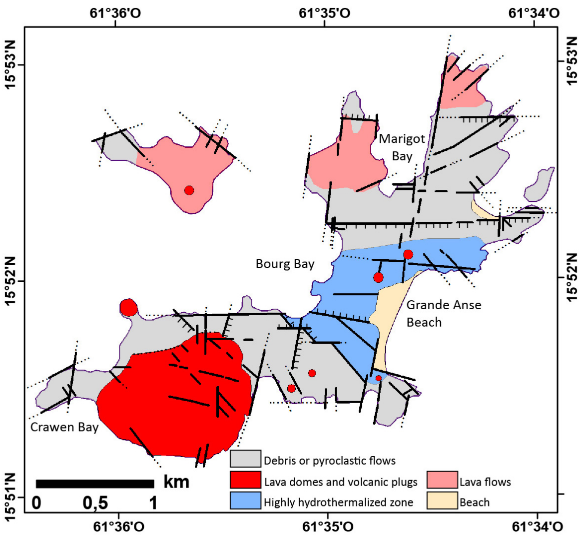

Figure 2: Main structures and geology of Terre-de-Haut Island (after Verati et al., 2016).

The volcanism activity in Terre-de-Haut began approximately at the same time as the volcanism of Basse-Terre (Samper, 2007). Basse-Terre is a late Tertiary to Quaternary still active volcanic island that belongs to the Inner Arc of the Lesser Antilles. It consists in six major eruptive complexes that are successively emplaced from north to south according to a NNW-SSE direction (Figure 3). The Basal Complex active between 2.79 ± 0.04 Myr and 2.68 ± 0.04 Myr forms the substratum of Basse-Terre. It is made of sub-aerial lava flows eroded volcanic edifices (Mathieu, 2010). The calc-alkaline Northern Chain 1.81 ± 0.03 Myr - 1.15 ± 0.02 Myr consists of voluminous lava flows and domes of andesitic and dacitic compositions (Komorowski et al., 2005). The Axial and Bouillante Chains composed of Piton Bouillante, Icaque, Capesterre and Sans Toucher volcanoes formed between 1.023 ± 0.025 Myr and 0.435 ± 0.008 Myr. These chains are characterized by voluminous hyaloclastites covered by lava flows. On the west coast the volcanism activity is essentially phreatomagmatic and there is a wide range of magma compositions: olivine basalts, andesites, dacites and quartz-bearing rhyolites (Komorowski et al., 2005). The Monts Caraïbes were active from 0.555 Myr to 0.445 Myr. The onland part results from explosive subaerial eruptions including plinian deposits of dacitic compositions and lava flows. The inactive Trois-Rivières-Madeleine and still active Grande Découverte-Soufrière Complexes are younger than 0.25 Myr. They are characterized by an effusive activity, which produced voluminous domes, lava flows and a more limited volume of pyroclastites (block-and-ash flows, ash and scoria flows).

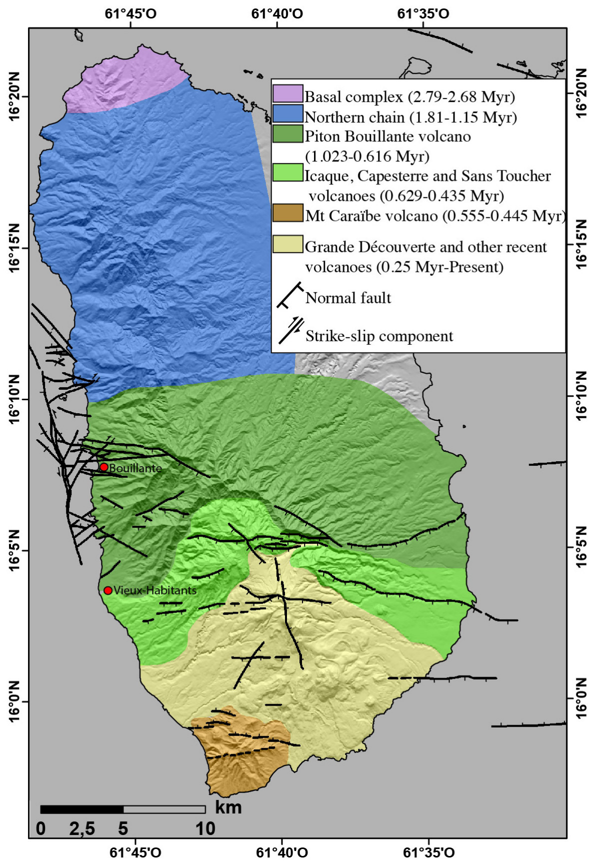

Figure 3: Main structures and geology of Basse-Terre Island (after Calcagno et al., 2012; Feuillet et al., 2002; Mathieu, 2010; Mathieu et al., 2011; Samper, 2007). The background digital elevation model is provided by IGN. Its resolution is 25 m.

Within the GEOTREF project (mutlidisciplinary platform for innovation and demonstration activities for the exploration and development of high geothermal energy in fractured reservoirs), one of the main goals is to discover a sustainable geothermal resource in the Vieux-Habitants area located ten kilometers south of Bouillante. The fieldwork has become faster since 2015 to complete previous knowledge of local geology. Geochemical, geological and geophysical surveys on the surface have recently begun. In this paper, the study aims at characterizing physical properties of volcanic rocks to build a database, improve the interpretation of forthcoming borehole logging and provide parameters for 3D modeling of the reservoir. These properties have been measured both on fresh rocks coming from Vieux-Habitants-Bouillante area and hydrothermalized rocks from exhumed geothermal reservoirs of the Basal Complex and Terre-de-Haut.

2 MATERIAL AND METHODS

2.1 Samples

In this case study physical rock properties and the influence of hydrothermal alteration on these properties were analyzed. Samples were collected in Terre-de-Haut (Les Saintes) and on the west coast of Basse-Terre. More precisely, samples were taken in the Basal Complex where evidence of hydrothermal activity have been showed and in the Vieux-Habitants-Bouillante area where we prospect the geothermal resource and a lot of hydrothermal manifestations have been indexed (Bézèlgues-Courtade and Bes-de-Berc, 2007). On Terre-de-Haut, samples were collected both in the geothermal paleo-system and in the other parts of the island without hydrothermal alteration.

The sampling was done on outcrops taking either blocks or drilling plugs. Sixty-four samples were selected to cover an exhaustive panel of lithotypes outcropping (20 fresh andesite lava or dikes, 15 moderately to highly hydrothermalized andesite lava flows, 9 debris flows, 14 pyroclastites and 6 highly hydrothermalized volcanic breccia). Blocks and plugs were oriented on the fields. For sufficiently cohesive samples, cubes were cut and plugs were drilled to perform all physical properties measurements. For fragile ones block surfaces were flattened and porosimetry was done on pieces of rocks.

2.2 Density and porosity

A lot of methods allows to characterize the porosity of a material (Haffen, 2012; Rosener, 2007; Zinsner and Pellerin, 2007). As some volcanic materials are insufficiently cohesive or contain clays, three methods have been selected to treat every sample.

Triple weighing method

The triple weighing method is defined by the norm RILEM (try n°I.1, 1978). It consists in weighing the sample in three conditions. Firstly the dry sample was weighed m_d after 48 h in an oven at 50 °C. The sample was placed in a vacuum chamber for 24h. Then distilled water (density of 1) was injected in the vacuum chamber to soak sample by capillarity. After a 48 h immersion two masses were measured: the saturated mass m_s and the hydrostatic mass m_h. Finally, effective porosity Φ was calculated using the equation:

$$\Phi = \frac{\text{Volume of pores}}{\text{Volume of the sample}} \times 100 = \frac{m_s - m_d}{m_s - m_h} \times 100 \quad [1]$$

The volume of the sample V_{sample} could be deduced from equation [2]:

$$V_{sample} = \frac{m_s - m_h}{\text{density of water}} \quad [2]$$

Helium pycnometry

Solid phase density ρ_s measurements of core samples or pieces of blocks have been performed with a gas pycnometer using helium as a measuring fluid. It allows a fast and non-destructive measurement on a lot of samples. The solid phase density of each dry sample was determined five times thanks to the Boyle-Mariotte law. The bulk density ρ_b was calculated by dividing the dry sample weight by the gross volume.

Therefore, connected porosity value is calculated using equation:

$$\Phi = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100 \quad [3]$$

So called the gas-effective porosity.

Mercury porosimetry

The mercury porosimetry is a useful characterization technique to investigate pore diameters from 330 µm to 6 nm. It provides a lot of information like the pore size distribution, the total pore volume, the skeletal and apparent density (Belghoul, 2007; Giesche, 2006).

2.3 Matrix permeability

Intrinsic permeability K measurements were performed thanks to two methods based on Darcy's law. A portable air permeameter was used for high permeable low cohesive samples such as pyroclastites and highly hydrothermalized or fractured samples because it was almost impossible to drill some plugs. For sufficiently cohesive samples, the permeability was obtained using a nitrogen laboratory permeameter. The field permeameter allows fast and reliable measurements (several tens per day) ranging from 10^{-10} to 10^{-15} m^2 (Tiny Perm II User's Manual, Farquharson et al., 2015; Haffen et al., 2013). Whereas the analysis time of the more accurate nitrogen permeameter permits only three or four measures per day covering a wide range of permeabilities (10^{-9} m^2 to 10^{-19} m^2). Permeabilities measured on the same samples with the two permeameters have been compared to verify the values given by the field permeameter.

2.4 Thermal conductivity

Thermal conductivity λ_{sample} was measured using a Thermal Conductivity Scanner (TCS). The technique is based on the change in surface temperature after a known and set heat input (Boulanouar et al., 2013). The measuring instrument includes a mobile plate composed of two thermal sensors and a heat source. A cold sensor measures the temperature of the thermal conductivity known standard and the dry sample before the crossing of the heat source. The hot sensor measures standard and sample temperatures after the heat input. λ_{sample} is calculated thanks to temperature variations of the standard $\Delta T_{standard}$ and sample ΔT_{sample} and the comparison with thermal conductivity of the standard according to equation:

$$\lambda_{sample} = \lambda_{standard} \times \left(\frac{\Delta T_{\text{standard}}}{\Delta T_{\text{sample}}} \right) \quad [4]$$

2.5 P-wave velocity

The measurement of compression waves (P-waves) was performed using ultrasonic velocity method. It is a non-destructive testing based on the transmission of a pulse. The instrument is composed of two 54 kHz piezoelectric transducers P (a transmitter and a receiver) and a pulse generator. The acoustic emission that arrives to the receiver is converted in an electrical signal acquired with a computer-controlled oscilloscope. The velocity of P-waves V_p was then calculated dividing the travel distance of the wave by its arrival time.

3 RESULTS

Physical properties of volcanic rocks were measured for outcrop samples from the West coast of Basse-Terre and Terre-de-Haut. As the most of physical properties are controlled by lithology, whole samples were classified by rock type. A summary of these measures is presented in Table 1 including median and the range of values.

Average bulk density is highly variable. Lava flows are clearly denser than volcaniclastic deposits (fresh andesite lava 2.59 $g.cm^{-3}$, pyroclastites 1.46 $g.cm^{-3}$), while solid phase density is relatively uniform due to a constant mineralogy (fresh andesite lava 2.75 $g.cm^{-3}$, pyroclastites 2.57 $g.cm^{-3}$). Bulk density directly reflects porosity. For volcaniclastic deposits, average porosity is about 33.7 % and it exhibits a large variability according to the lithotype. The low porosity 11.89 % was measured for a silicified volcanic breccia with high hydrothermal alteration but the porosity for fresh samples varies between 17.47 % for a debris flow matrix and 52.74 % for a pumiceous block. The higher dispersion is observed in pyroclastite group with a 30 % difference between the lowest and the highest porosity. This difference is assigned to the diversity of grain size and nature of material (ash, pumice, scoria). Fresh andesite lava flows and dikes have generally porosity lower than 5 % (median equal to 4.54 %) at the exception of few porous vesiculous lava blocks reaching a porosity of 10-20 % due to large open vesicles. But generally lava flows are clearly less porous than volcanic sediments. Lava flows with hydrothermal alteration exhibit two very different trends. For andesites coming from the Basal Complex of Basse-Terre, the porosity is lower than 3 % for samples with a pressure dissolution schistosity while samples without schistosity have porosities higher than 20 %. Hydrothermalized samples from the central part of Terre-de-Haut Island (e.g. Grande Anse beach), where the alteration totally transforms the initial andesite, have higher average skeletal density (2.76 $g.cm^{-3}$) and porosities ranging from 20 % to 30 %.

Matrix permeability is very dependent from lithology and ranges over nine orders of magnitude. Pyroclastites exhibit the highest permeability (median $1.15.10^{-13}$ m^2) and especially thin-grained pumices. Permeabilities for ashes sampled in Plinian deposits were impossible to measure with the air permeameter due to the lack of cohesion of the material and the roughness of the surface. Permeability is generally high in debris flow matrix (median $3.65.10^{-14}$ m^2). The cohesion of these samples is better than pyroclastites. It permitted to cut cubes with flat surfaces to have reliable measurements with the air permeameter. In this lithology, thin-grained samples with 20-30 % of centimeter clasts and 70-80 % of matrix were the most permeable. Permeability of hydrothermalized volcanic breccia is close to that of debris flow matrix with a median of $4.3.10^{-14}$ m^2. It displays a lower dispersion with only three orders of magnitude. Andesites are significantly less permeable with medians of $1.06.10^{-16}$ m^2 and $1.48.10^{-15}$ m^2 for fresh and hydrothermalized andesites respectively. The comparison of permeability and porosity Figure 4 displays a strong correlation between these two physical properties. Indeed, a strong correlation coefficient of 0.67 is calculated thanks to an exponential regression.

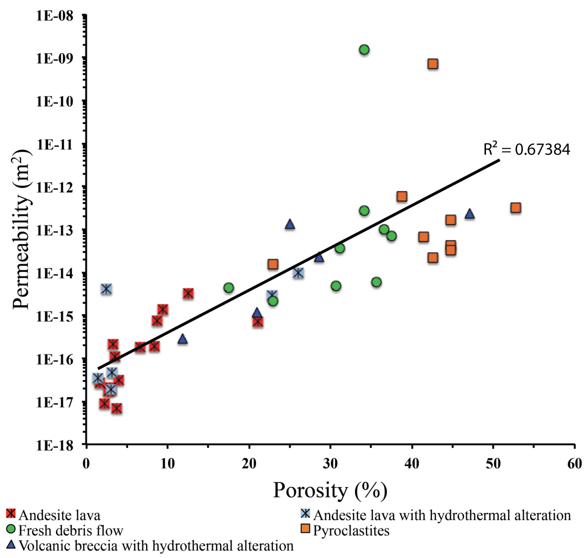

Figure 4: Cross plot of permeability versus porosity of the investigated volcanic rocks. The exponential trend is drawn for all samples.

Thermal conductivity as well as porosity and permeability are highly dependent of the lithotype.

Hydrothermalized andesites have the highest thermal conductivities up to 2.08 $W.m^{-1}.K^{-1}$ for samples from Terre-de-Haut with cristallizations of pyrite and chalcopyrite. Fresh andesites, mainly composed of plagioclases, pyroxenes and amphiboles, have generally thermal conductivity values around 1.6-1.7 $W.m^{-1}.K^{-1}$. The lowest values 0.77 $W.m^{-1}.K^{-1}$ is measured for highly weathered samples. Pyroclastites have an average thermal conductivity three times lower 0.51 $W.m^{-1}.K^{-1}$ than andesites. Debris flows have slightly higher values around 0.8 $W.m^{-1}.K^{-1}$ certainly due to a lower porosity. Altered volcanic breccias have intermediary thermal values 0.99 $W.m^{-1}.K^{-1}$. The general trend of the thermal conductivity and porosity plot is a decrease of porosity when thermal conductivity increases (Figure 5). Strong correlations between these two properties are displayed especially for volcanic breccias and debris flows with correlation coefficients of about 0.84 and 0.82 respectively. The correlation is also good for pyroclastites with r^2 equal to 0.62. Andesite lava flows and dikes have lower correlation coefficients but may not be negligible.

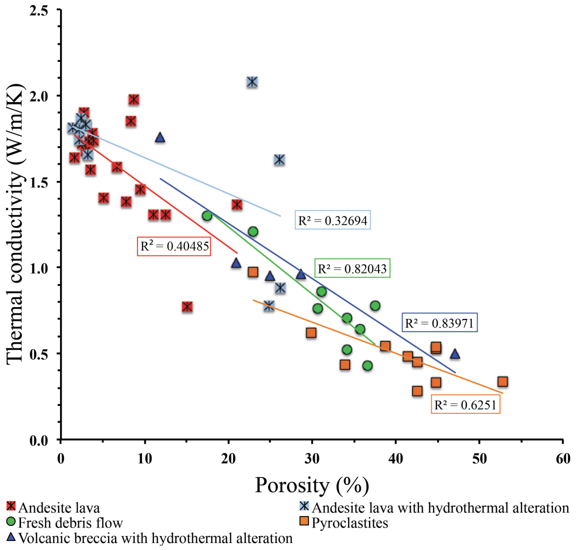

Figure 5: Cross plot of thermal conductivity versus porosity of the investigated volcanic rocks. Linear trend lines are drawn for each lithotype.

A clear correlation appears between permeability and thermal conductivity (Figure 6) with $r^2 \approx 0.64$. The general trend is an increase of thermal conductivity when permeability decreases.

P-wave velocity measurements reveal large differences between volcaniclastic deposits and lavas. The P-wave velocity of hydrothermalized andesites is approximately 800 $m.s^{-1}$ lower to those of the fresh ones. Fresh andesites have an average velocity of 4512 $m.s^{-1}$. This velocity is more than twice the velocity of pyroclastites, debris flows and volcanic breccias. Debris flows and volcanic breccias have almost the same median velocities 2071 $m.s^{-1}$ and 2028 $m.s^{-1}$ respectively. Pyroclastites have lower values due to their low cohesion.

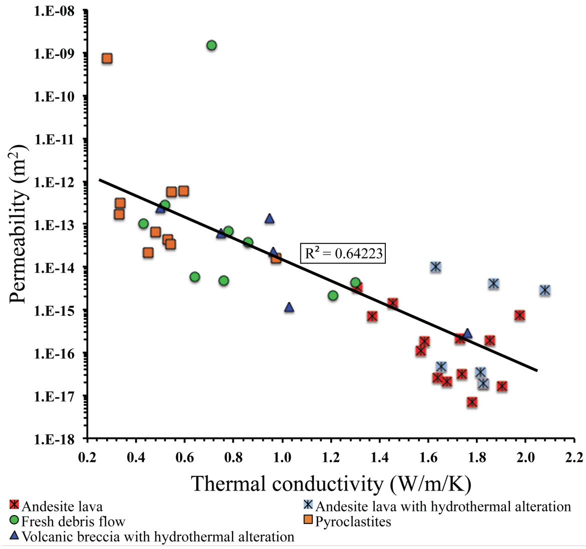

Figure 6: Cross plot of permeability versus thermal conductivity of the investigated volcanic rocks. The exponential trend is drawn for all samples.

Relatively good correlations can be observed between thermal conductivity and P-wave velocity (Figure 7). The correlation coefficient for hydrothermalized volcanic breccias is almost 0.86. Fresh andesites and debris flows exhibits also a high correlation coefficient, 0.66 and 0.65 respectively. However hydrothermalized andesites do not display any correlation.

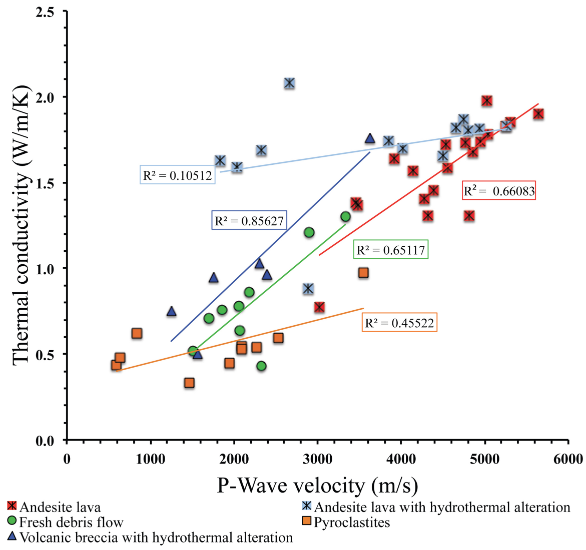

Figure 7: Cross plot of thermal conductivity versus P-wave velocity of the investigated volcanic rocks. Linear trend lines are drawn for each lithotype.

Table 1: Summary of measured physical properties

Rock type	Hydrothermal alteration		ρ_b [g.cm^{-3}]	ρ_s [g.cm^{-3}]	Φ [%]	K [m^2]	λ [W.m^{-1}.K^{-1}]	V_P [m.s^{-1}]
Andesite lava	Fresh	Average	2.59	2.75	6.78	$4.66.10^{-16}$	1.58	4512
		Median	2.61	2.75	4.54	$1.09.10^{-16}$	1.64	4560
		Min - Max	2.37-2.73	2.61-2.84	1.64-21.04	$6.92.10^{-18}$-$3.29.10^{-15}$	0.77-1.98	3021-5638
	Moderate-high	Average	2.37	2.64	11.44	$2.84.10^{-15}$	1.62	3732
		Median	2.56	2.63	3.11	$1.48.10^{-15}$	1.7	4020
		Min - Max	1.89-2.6	2.54-2.77	1.39-26.2	$1.92.10^{-17}$-$9.94.10^{-15}$	0.78-2.08	1838-5259
Pyroclastites (pumices, ash, scoria)	Fresh	Average	1.46	2.57	38.62	$7.26.10^{-11}$	0.51	1801
		Median	1.455	2.61	42	$1.15E^{-13}$	0.51	2018
		Min - Max	1.01-2.13	2.32-2.72	22.98-52.74	$1.56.10^{-14}$-$7.24.10^{-10}$	0.28-0.975	594-3546
Debris flow	Fresh	Average	1.75	2.57	31.15	$1.68.10^{-10}$	0.8	2214
		Median	1.65	2.54	34.16	$3.65E^{-14}$	0.76	2071
		Min - Max	1.51-2.71	2.44-2.71	17.47-37.5	$2.15.10^{-15}$-$1.51.10^{-09}$	0.43-1.3	1513-3330
Volcanic breccia	Moderate-high	Average	1.78	2.58	26.72	$7.72.10^{-14}$	0.99	2148
		Median	1.85	2.61	25.01	$4.30.10^{-14}$	0.96	2028
		Min - Max	1.26-2.3	2.45-2.67	11.89-47.09	$2.81.10^{-16}$-$2.39.10^{-13}$	0.5-1.76	1247-3623

4 DISCUSSION

In this part measured physical properties are discussed and compared to other published data.

Porosity and matrix permeability of fresh andesites are highly heterogeneous. Besides permeability displays a variation of three orders of magnitude. The most porous samples have large open vesicles, which are partially connected at the sample and the thin section scales. Moreover, this connectivity of vesicles is improved by cracks, which are preferential pathways increasing fluid permeability. The proportion of vesicles can vary widely in the same lava flow or dyke. This is the case for two samples located at a two meters distance in the same lava flow. The first sample has a porosity of 10 % and a permeability of $1.4.10^{-15}$ m^2, whereas the second sample has only a porosity of 3 % and a permeability of 2.10^{-16} m^2. Even if lava flows have approximately the same chemical and mineralogical compositions, their physical properties are locally highly variable. Macroscopic and microscopic observations indicate that porosity of fresh andesite is almost totally acquired when the lava sets and vesicles form. These vesicles have different shapes either millimeter spheres or centimeter elongated planes with an infra millimeter opening. For the same connected porosity, samples with elongated vesicles have higher permeability. Some fresh lava flows with fractures show a beginning of spheroidal weathering (Jamtveit et al., 2011, 2009). The central part of the sphere has similar physical properties to fresh lavas (Φ = 1.6 % and K = $2.7.10^{-17}$ m^2) but as spheroidal alteration increase, physical properties of matrix varie from fracture surfaces to the internal parts of the rock. This change in physical properties is attributed to an increase of fracture density and replacement processes.

The most favorable zones for fluid flow in fresh andesites are located in dyke walls or in certain parts of lava flows, which are richer in open vesicles. However the majority of the investigated samples of fresh lavas represent bad reservoirs with porosity and matrix permeability lower than 5 % and 10^{-16} m^2 respectively.

Hydrothermalized andesites do not have noticeable vesicles. Their porosity is mainly due to a significant dissolution of original phenocrysts, their ghost forms are still identifiable (plagioclases, pyroxenes, amphiboles) and they are partially replaced by secondary mineralogies such as clays. Two groups are clearly defined. The first group is composed of samples coming from the geothermal palaeo-system of Terre-de-Haut. Samples have isotropic permeability ranging between 10^{-15} m^2 and 10^{-14} m^2. P-wave velocities are half the fresh andesite values, porosities are higher than 20 % and thermal conductivities have higher values than fresh andesites because of crystallization of quartz, pyrite and chalcopyrite. Physical properties of the most altered parts could not be measured because samples were too fragile. The second group comes from the Basal Complex. With the exception of one sample, all samples are anisotropic. This anisotropy is supported by pressure dissolution schistosity. A few samples have also a patchy alteration pattern with large iron oxide aureoles. These samples have porosities lower than 4 % and intermediary thermal conductivities between fresh andesites and highly hydrothermalized andesites from Terre-de-Haut. Their permeability is one order of magnitude higher when the measure is performed parallel to the schistosity plane. This anisotropy is confirmed by the decrease of P-wave velocity perpendicular to the schistosity plane. Therefore, the schistosity plane is a preferential pathway for fluid flow.

Volcaniclastic deposits (pyroclastites and debris flows) have great storage properties. Indeed porosities range between 17 % and 53 % and permeability vary between 2.10^{-15} m^2 and 1.10^{-9} m^2. However their averaged thermal conductivities are very weak since they are strongly porous, fractured and composed of minerals with low thermal conductivities. Volcaniclastic deposits are anisotropic because of sedimentary processes they derive from and their heterogeneous grain size. Despite this anisotropy, they exhibit good correlations between physical properties. As these samples are composed of lava clasts and thin-grained matrix, their pores have variable forms and sizes. That is the reason why the distribution of pore diameters obtained thanks to mercury porosimetry do not exhibit clearly defined families. Permeabilities higher than 10^{-13} m^2 confirm that the porous network is well connected and with larger thresholds.

Only six samples form the group of highly hydrothermalized volcanic breccia. One of these hydrothermal breccia was used to constrain the beginning of the activity of the geothermal system of Bouillante thanks to adularia datation (Verati et al., 2013). They have nearly exclusively more than 20 % of porosity. Thin section observations reveal this porosity comes from fractures and the dissolution of original phenocrysts. Breccias are oxide rich samples like some hydrothermalized lava samples of the Basal Complex. They have intermediary permeability between hydrothermalized andesite and volcaniclastic deposits. Regularly spaced parallel fractures seem to be responsible of the well-connected porous network and therefore high permeability values.

Comparisons to other published data

Only few data in similar geological settings are available. Bernard (1999) and Bernard et al. (2007) published physical properties of fresh andesitic rocks from Montagne Pelée volcano (Martinique, French Lesser Antilles). They measured a lot of physical properties like porosity, permeability or thermal conductivity on a wide range of materials. Table 2 is a summary of the average values measured by these authors. Doing a comparison between our data and theirs has benefits. They work in the same geological context on an active volcano, just 150 km south of our study zone with approximately the same measurements methods. The main difference is that we consider hydrothermal alteration. The comparison with our physical properties Table 1 reveals no significant difference. Porosities and permeabilities of Montagne Pelée vesicular lava blocks are higher certainly due to a stronger proportion of gas in the magma. Properties measured on volcaniclastic deposits (pumice, scoriaceous blocks and block-and-ash flows) are almost the same. Bernard et al. (2007) demonstrated that pumices have high-unconnected porosity responsible to a low permeability compared to their high total porosity. Unfortunately, we could not confirm this assertion in the present study because our pumice sample was not big enough to do both porosity and permeability measurements.

Farquharson et al. (2015) and Heap et al. (2015) both worked on andesites from Volcán de Colima in Mexico. They studied either permeability and porosity relationships of edifice-forming andesites or fracture and compaction of andesite. The geological context is different but according to them Volcán de Colima is representative of andesitic stratovolcanoes worldwide. They provided values of porosity and permeability for lava blocks and volcaniclastic deposits (lahar, block-and-ash flows, pumiceous and scoriaceous blocks). Porosity and permeability values are higher than ours especially for the permeability of lava blocks that is approximately equal to our volcaniclastic deposits. This highlights the significance of the mechanisms of degassing and vesiculation, which depend of the type of eruption (Bernard et al., 2007).

Finally, andesitic samples coming from wells drilled in the Tauhara geothermal field (New Zealand) have been studied by Mielke et al. (2015). These authors did a complete description of physical properties of ash tuff, andesite lava and andesite breccia and their associated hydrothermal alteration. They clearly highlighted the impact of hydrothermal alteration on physical properties. They explained the evolution of porosity according to two opposite processes. The dissolution of primary dense minerals and recrystallization of microcrystalline clays increases porosity, while the precipitation of secondary mineral phases decrease the porosity. Therefore, the evolution of porosity during hydrothermal alteration depends on which is the dominant process. In our case study, hydrothermalized andesites from Terre-de-Haut clearly exhibit the dominance of a first process with a replacement of plagioclases and pyroxenes by clays. For andesites coming from the Basal complex, the two processes seem to be in competition. This would explain the lack of variation in porosity and permeability between these andesites and the fresh ones. Median thermal conductivity values measured for the Tauhara geothermal field are generally lower from those we measured. We measured a median value of 0.96 $W.m^{-1}.K^{-1}$ higher than the andesite breccias of New Zealand 0.72 $W.m^{-1}.K^{-1}$. This difference may be attributed to a lower porosity and a higher quartz and clay content in our samples. The same difference exists between weakly altered andesites. But for those, it may be only explained by the porosity difference. Median values for pyroclastites are approximately the same.

5 CONCLUSIONS

The selected volcanic rocks present similar chemical and mineralogical compositions but their physical properties show a large variability. We observed a wide range of connected porosity (1.39 % - 52.74 %), permeability (nine orders of magnitude), thermal conductivity (0.28 $W.m^{-1}.K^{-1}$ - 2.08 $W.m^{-1}.K^{-1}$) and P-wave velocity (574 $m.s^{-1}$ - 5638 $m.s^{-1}$). Volcaniclastic deposits have clearly the best storage properties but their heterogeneous physical properties make fluid flow modeling very difficult.

Hydrothermalized lavas exhibit two different behaviors according to their type of alteration. Andesites with pressure-dissolution schistosity planes from the Basal Complex have higher bulk density but lower solid phase density. They have low porosities and pronounced permeability anisotropy control by the schistosity plane. Andesites from the Terre-de-Haut geothermal palaeo-system are more porous, conductive and permeable.

The strong correlations between connected porosity, matrix permeability and between thermal conductivity and P-wave velocity for all samples show that the porous volume controls mainly the other physical properties.

Table 2: Physical properties of andesitic rocks from other volcanoes or geothermal fields ([1] Bernard, 1999 & Bernard et al., 2007, [3] Heap et al., 2015, [4] Farquharson et al., 2015, averaged values, samples from outcrops; [2] Mielke et al., 2015, median values, samples from wells)

Rock type	Descrciption - alteration	ρ_s [$g.cm^{-3}$]	Φ [%]	K [m^2]	λ [$W.m^{-1}.K^{-1}$]	V_P [$m.s^{-1}$]	Location
Andesite lava	Dense lava block	2.79	6.80	4.60E-16	1.53	4603	Martinique, Montagne Pelée volcano[1]
	Lava block	2.73	12.43	3.27E-15	1.12	2354	Martinique, Montagne Pelée volcano[1]
	Lava -Weak hydrothermal alteration		9.51	3.88E-17	1.32		Tauhara geothermal field, New Zealand[2]
	Lava block		10.87				Volcán de Colima, Mexico[3]
	Lava block		14.51	1.89E-13			Volcán de Colima, Mexico[4]
	Lava block - High temperature alteration		7.60				Volcán de Colima, Mexico[3]
	Vesicular lava blocks	2.68	23.93	4.15E-12	1.04	2794	Martinique, Montagne Pelée volcano[1]
Andesite breccia	Andesite breccia - High hydrothermal alteration		38.67	1.77E-15	0.72		Tauhara geothermal field, New Zealand[2]
Debris flow	Vesicular lava blocks and indurated ashes	2.71	19.41	7.73E-13	1.09	3362	Martinique, Montagne Pelée volcano[1]
	Block-and-ash flow		17.26				Volcán de Colima, Mexico[3]
	Lahar		24.03				Volcán de Colima, Mexico[3]
Pyroclastites	Ash tuff - Weak-high hydrothermal alteration		40.56	3.22E-14	0.79		Tauhara geothermal field, New Zealand[2]
	Pumice	2.66	57.30	1.95E-12		2033	Martinique, Montagne Pelée volcano[1]
	Pumiceous blocks		58.35	2.22E-12			Volcán de Colima, Mexico[4]
	Scoriaceous blocks	2.84	33.17	2.75E-12	0.61	3296	Martinique, Montagne Pelée volcano[1]
	Scoriaceous blocks		46.60	4.42E-13			Volcán de Colima, Mexico[4]

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