B-VALUE MAPPING FOR VOLCANIC-RELATED GEOTHERMAL SYSTEM: A CASE STUDY OF NEVADO DEL RUIZ VOLCANO, COLOMBIA

Pablo Aguilera[1,3], Ludmila Adam[1] and Geremew Lamessa[2]

[1] School of Environment, University of Auckland, Auckland, New Zealand

[2] School of Earth Sciences, Wollega University, Nekemte, Ethiopia

[3]Colombian Geothermal Association, Bogotá, Colombia

pablo.aguilera@auckland.ac.nz

Keywords: *Microseismicity, Magnitude of completeness, b-values, Nevado del Ruiz volcano.*

ABSTRACT

The Nevado del Ruiz Volcano (NRV) (Colombia) has two areas with geothermal potential located to the north and north-west of its crater which are highly seismically active. In the period of 2000 - 2018 thousands of volcano-tectonic events have been recorded beneath the volcano and within the two geothermal areas, with most earthquakes occuring at depths of 2-9 km and Md magnitudes up to 4.4.

Physical interpretations of subsurface processes related to volcano-geothermal activity can be performed by analyzing microseismicity information (hypocenters and magnitudes). The frequency-magnitude distribution of earthquakes in any region on Earth can be described by the Gutenberg-Ritcher relationship. This relationship is linear and from the slope, a common seismological parameter is estimated: the b-value. In the literature, high b-values have been associated with the presence of magmatic bodies, fluids migration, changes in fluid pressure, and high fracture density. Hence, the quantification of b-value and its uncertainty can be associated with the physics of subsurface mechanisms for earthquakes triggering. The aim of our study is to map b-values (2D and 3D) and delimit its anomalies with implications on the prospective geothermal areas of Nevado del Ruiz volcano. Potential mechanisms in the area are associated with fluid recharge from rainfall, variable stresses and changes in fluid pressures due to magma injection and fluid-phase transition (liquid water-to-vapor transitions).

1. INTRODUCTION

NRV is located close to the city Manizales (Caldas department) in the middle of the Cordillera Central and 150 km west of Bogotá, the Colombian capital city. The volcano reaches an elevation of 5327 metres above sea level (Figure 1). It is one of the most active volcanoes in Colombia and most dangerous in the world. NRV caused the death of 25,000 due to an eruption that triggered a large lahar recorded as the deadliest one in human history (Vargas et al., 2017).

NRV is the most studied volcano for geothermal purposes in Colombia. The geology of NRV is highly influenced by a thick layer of rocks and deposits of volcanic origin that are in a discordant contact with the Cajamarca Complex, a metamorphic rock formation comprised mainly of schists. Geochemical geothermometer calculations on surface hot springs and fumaroles indicate that reservoir temperature can reach up to 260 ºC (Alfaro et al., 2002; Alfaro et al., 2005). Additionally, 2D numerical modeling of heat transfer and rock thermal conductivity at reservoir scale suggests a geothermal potential range between 54 MWt and 130 MWt (Velez et al., 2018).

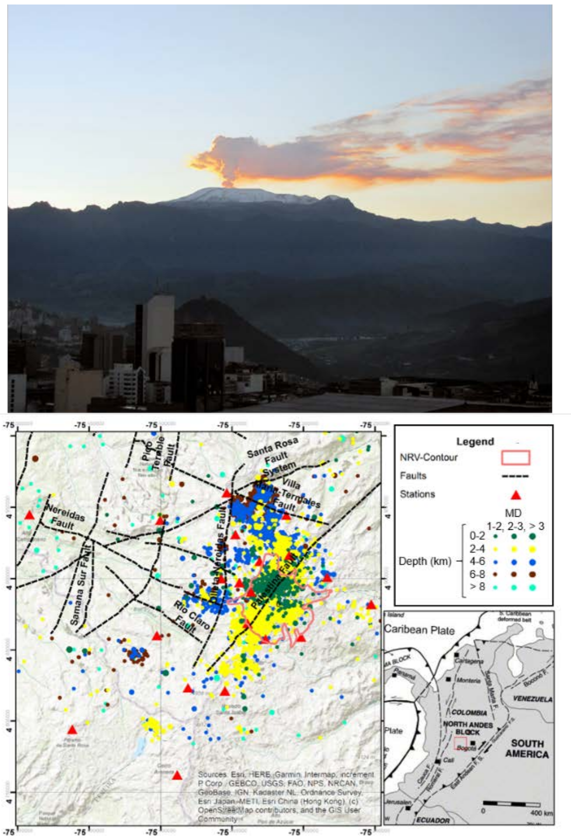

Figure 1: Top: Picture with NRV in the background taken from Manizales City. Bottom: NRV seismotectonics map. The red box is the location of the study area. Seismic network are indicated with red triangles. Microseismic events with M_d magnitudes greater than 1 are plotted, and local faults are also shown. A-A' and B-B' are cross-sections analyzed for the b-value.

A dense seismic network deployed by The Colombian Geological Survey (SGC by its Spanish acronym) is permanently monitoring NRV. Londono et al. (2018) detailed the seismic activity of NRV in two main periods: 2000-2006 as part of a low to high phreatic activity starting in 1993 and, 2007-2016 as magmatic activity kept developing until 2018. What distinguishes these two periods is the considerable increasing of volcano-tectonic (VT) seismic events (Figure 2), frequent ash emissions, high deformation and SO_2 flux reported by SGC (Londono,

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275

2016). These activities are interpreted as related to the rise of pulses of magma from depths of ~10 km during the periods of 2007-2009 and 2011-2013 (Lundgren et al., 2015; Londono et al., 2018). The magmatic input was also suggested by the seismic tomography carried out by Vargas et al. (2017) who obtained a high anomalous Vp/Vs values at depth between 2 and 5 km, and extending to the west, of NRV's summit. This Vp/Vs anomaly suffered a temporary and gradual decrease in value between 2011 and 2014 interpreted as due to degassing and crystallization of the magma reservoir. However, by 2015 this reservoir was enriched with new portions of volatile-rich magma. The dynamic magmatic system of NRV suggests that this volcano is having a frequent input/output of magma and gas mainly through the Palestina fault system.

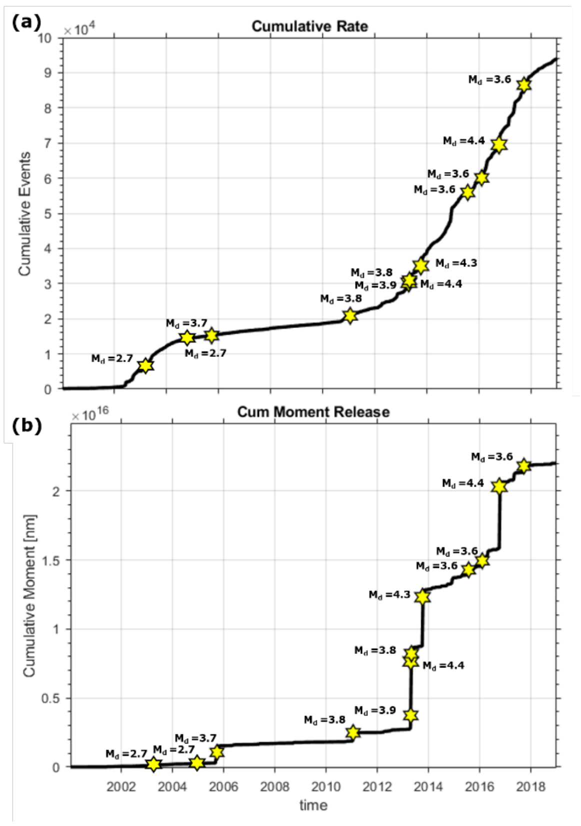

Figure 2: Seismicity catalog of VT events between 2000 and 2018. a) Cumulative events, b) Cumulative moment release. Stars highlight some of the relatively high events of the catalog.

Similarly, a 2D magnetotelluric (MT) inversion at NRV carried out by Gonzalez-Garcia et al. (2015) shows relatively good agreement with the aforementioned Vp/Vs anomalies. The MT anomaly suggests a tripartite magma chamber at a depth of ~10 km that consists of a main reservoir possibly composed of basaltic magma which feeds an intermediate reservoir of possible dacitic composition at ~6 km in depth. This latter reservoir is connected to a shallow andesitic chamber at approximately 2 km depth. The MT inversion also suggests a convective hydrothermal system with an outflow of chloride waters channeled to the north and northwest by the fault systems of NRV. This hydrothermal system interacts with the magmatic flow that ascends through the tripartite magmatic system. Additionally, a vapour-dominated region is interpreted from the MT inversion and related to the shallow magma chamber sulphate waters.

The frequency-magnitude distribution (FMD) of an earthquakes catalogue can be described by the empirical Gutenberg-Ritcher relationship "G-R power law" (Gutenberg et al., 1944) given by:

$$logN = a - bM \quad (1)$$

where N is the total number of events with magnitudes higher than or equal to M, a refers to the overall seismicity rate and b describes the relative size distribution of FMD. Estimation of a and b-values using a maximum likelihood method for magnitudes of completeness M_C has demonstrated a perfect fit to the G-R power law (Aki, 1965; Bender, 1983). M_C is the lowest magnitude at which a seismic network can detect an earthquake (Rydelek et al., 1989). A correct choice of M_C is crucial for the estimation of a and b and their uncertainties. Woessner et al. (2005) detailed four methods of assessing M_C; Entire-magnitude-range method (EMR), Maximum curvature (MAXC), Goodness of-fit test (GFT) and M_C by b-value stability. Between these methods, MAXC is recommended for a fast computation of M_C

The parameter b helps better understand the physics of subsurface mechanisms for earthquakes triggering (Wyss et al. 2000; Wyss, 1973). An overview of physical causes associated with b-value variations has been compiled by El-Isa et al. (2014) For instance, b-value variations over time and space have been associated with:

- Intrusions and magma chambers: high b-value anomalies are related to magma bodies (Wyss, 1997; Wiemer et al., 1997; Murru et al., 1999; Wyss et al., 2001; Wiemer et al., 2002; Murru et al., 2005; Murru et al., 2007; Lamessa et al., 2019),
- Geothermal activities (high b-values) (Lin et al., 2007; Wiemer et al., 2002),
- Increase of pore pressure (high b-values) (Murru et al., 2007),
- Thermal stresses (high b-values) (Warren et al., 1970; Wiemer et al., 1997),
- Increase of shallow crustal heterogeneities (high b-value) (Enescu et al. 2011),
- Differential stress (inversely proportional) (Schorlemmer et al., 2005; Wu et al., 2005),
- P-wave velocities (inversely proportional) (Ogata et al., 1991; Wiemer et al., 1997).
- Dynamic failure and large earthquakes (decrease of b-value). (Schorlemmer et al., 2005).

2. METHODOLOGY

The parameters M_C and b value are determined by using the Zmap code developed by Wiemer (2001). The earthquake catalogue of duration magnitudes (M_d)from NRV during the time period of 2000 and 2018 is analyzed. From this analysis, horizontal slices and 3D b-value distribution maps are obtained.

2.1 Earthquake Catalogue

The whole seismicity catalog comprise an area defined by the coordinates {4.78 < latitude < 5.03; -75.11 < longitude < -75.55}. This catalog was acquired by the seismic network of the Colombian Geological Survey. It contains the information of date, epicentral coordinates (longitude and latitude), magnitude (M_d) and depth relative to the reference elevation of 5.1 km. The catalog comprises a total of 94.022 events for duration magnitudes M_d ranging from -2.59 to 4.4 and depths up to 35.5 km. For the analysis, only microseismic events with depths up to 10 km were chosen (93776 events) as the events located deeper are few and probably the result of other processes (Figure 3).

Between 2000 and 2018 the basic configuration of the seismic network at NRV has not varied significantly. Londono (2016) reported some changes until 2015 which relate to changing seismic stations from short-period to broad-band, as well as increasing the number of near-field stations to improve the earthquake coverage and location calculations. Londono (2016) also demonstrated that these changes in the basic configuration of the seismic network do not have a significant effect on the spatial distributions of seismicity, meaning that the main changes in the seismic activity are due to volcanic activity.

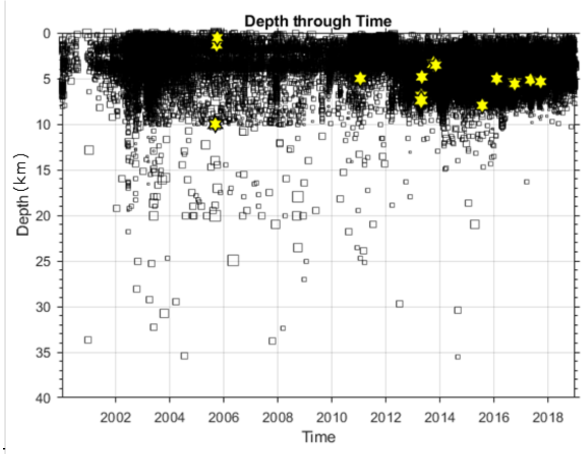

Figure 3: VT seismicity and depths. Most of the microseismic events occur at depths up to 10 km. Yellow stars refer to events with $M_d > 3.5$. Square size represents relative magnitude of an event.

2.2 Magnitude of Completeness M_c

The changes in the seismic network results in the variation of the magnitude of completeness M_C over time. M_C is computed by using the MAXC method which consists of computing the maximum value of the first derivative of FMD which matches the magnitude with the highest amounts of events in the non-cumulative frequency distribution (Wiemer et al., 2000).

2.2 b-value Mapping

The estimation of b-value using a maximum-likelihood technique is given by:

$$b = \frac{log_{10}(e)}{\left[\langle M\rangle - \left(M_c - {}^{\Delta M_{bin}}/_{2}\right)\right]} \qquad (2)$$

where $\langle M\rangle$ refers to the mean value of the magnitudes equal and higher than M_C of the sample and ΔM_{bin} is the binning width of the catalogue.

The mapping of b-values is carried out by using a grid of 0.01° x 0.01° based on the high-density hypocenter distribution. One hundred and fifty earthquakes were used per grid cell with a minimum of fifty events with M_d higher that M_C required to compute a b value in each cell. Instead of assuming a unique M_C value, M_C is automatically calculated according to the FMD in each grid cell sample. The b-values estimations are finally obtained by using maximum likelihood using Zmap MATLAB code.

3. RESULTS AND DISCUSSION

The available seismic catalog was prepared by declustering (i.e. removing) foreshock and aftershock events using the Reasenberg algorithm (Reasenberg, 1985). This process found 836 clusters of earthquakes, removing a total of 89779 events so that 3997 events are left. Out of the 3997 events, 3628 are contained inside the study area (red box in figure 1) and were used for b value mapping. Figure 4 shows the cumulative events and cumulative moment release associated with these events. This results in a homogenized and complete catalog in time and M_d magnitude (Figure 4a). Figure 4b shows that the main periods of abrupt increments in the cumulative moment release are also preserved when comparing with figure 2b influence by a few larger events.

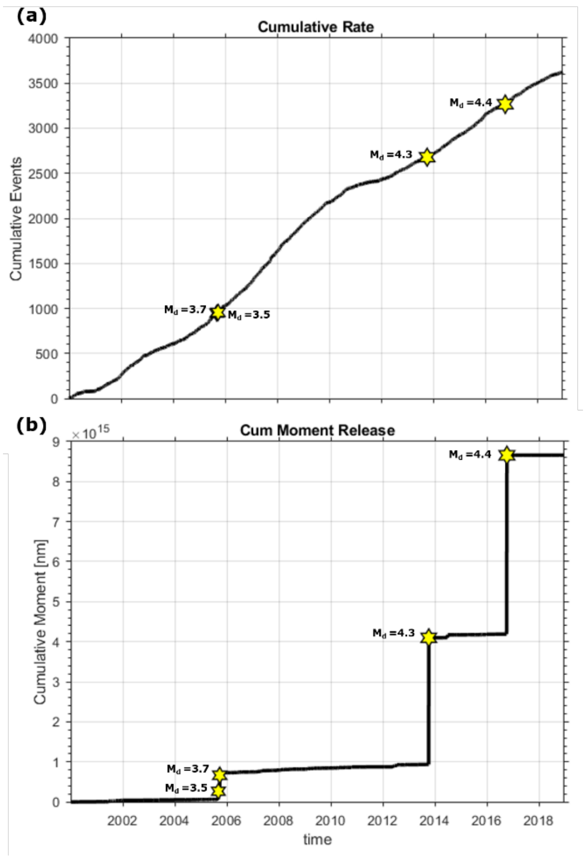

Figure 4: Declustered catalog of the study area. a) Cumulative events; b) Cumulative moment release.

For the declustered catalog, M_C is computed over time (Figure 5). During the study period this parameter dropped from 0.8 to 0.2, which reflects the improved coverage of the seismic network increase during recent years. The main drops are associated with changes of stations from short-period to broadband as it is reported by Londono (2016).

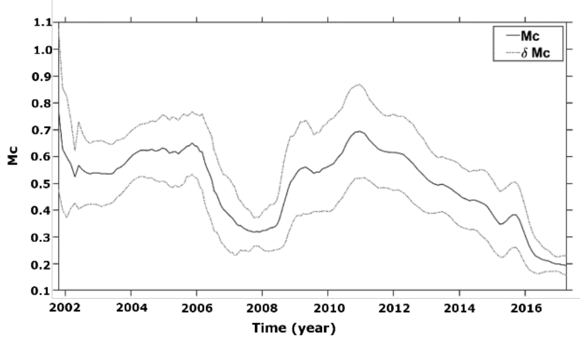

Figure 5: M_c over time using a sample window size of 500 events with an overlap of 4.

Also, the average M_C and b values for the entire period of the declustered catalog were computed, resulting in $M_C = 0.41 \pm 0.31$ and $b = 0.82 \pm 0.02$ (Figure 6a). To determine uncertainties, bootstrapped distributions of M_C and b values are obtained by doing sampling with replacement from the whole catalog. In addition, a general trend of increase of b value with depth is obtained (Figure 6b). These results could be associated with magma activity, the locations and connectivity of magma chambers suggested by Londono et al. (2018), Vargas et al. (2017), Gonzalez-García et al. (2015) and other related studies. Additionally, b value is increasing with time, reflecting the high magmatic activity happening in NRV mainly since 2007 (Londono, 2016; Vargas et al., 2017). The partial drops of this parameter over time could be related with degassing and the release of energy caused by the large earthquakes as it is also mentioned by the aforementioned studies.

Figure 7 shows slices of b-value at different depths for the NRV area in the red box in Figure 1. The slight increase of b-value on the western and northern parts of NRV at depths between 2 and 4 km (from the surface) coincide with potential geothermal areas. The high anomalies of b-values in the deeper slices between 8 and 10 km could be associated with the magma chambers. The alignment SW-NE of the b-value anomaly at 10 km in depth coincidences with the strike of the Palestina fault, the main fault that favoured the existence of NRV and the volcanoes associated with the volcanic complex known as Cerro Bravo-Cerro Machin (Londono, 2016). See also Figure 8.

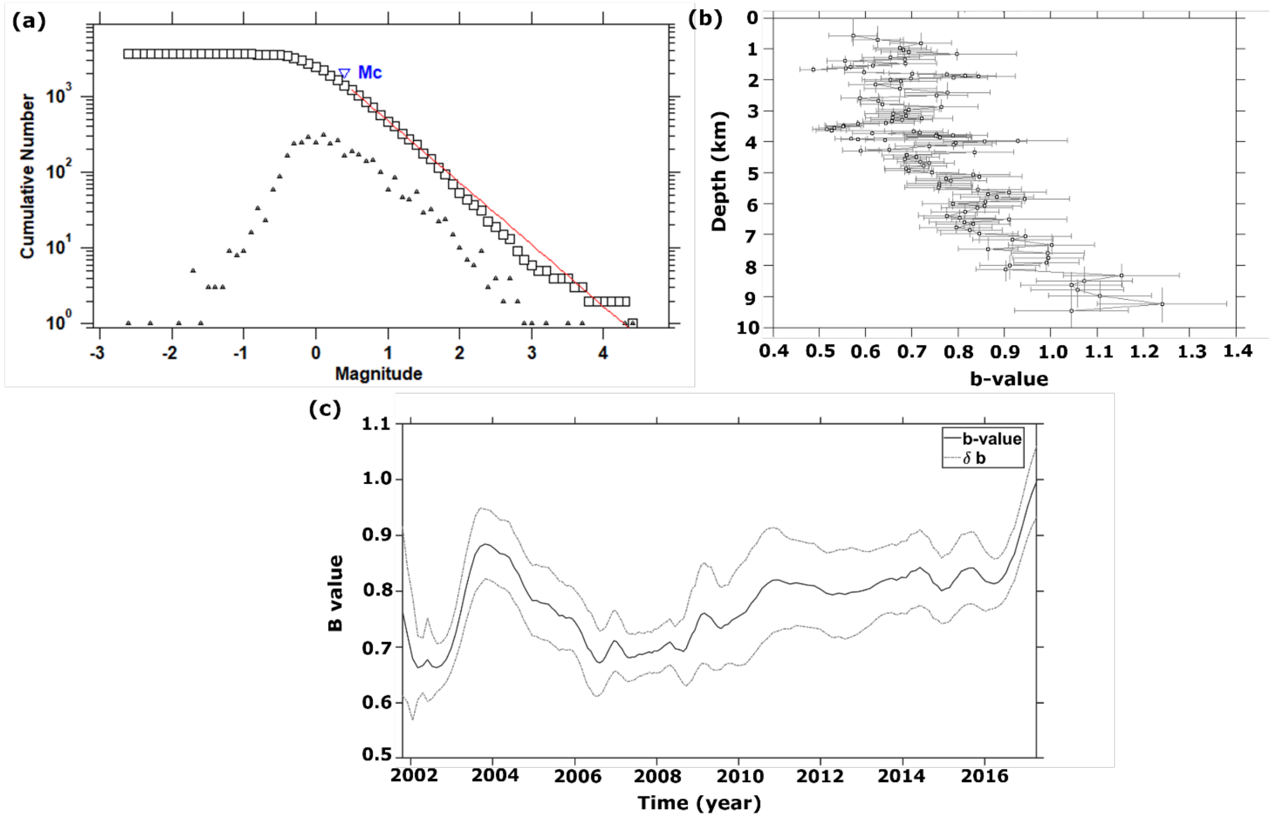

Figure 6: b-value for declustered catalog. a) FMD using maximum likelihood solution and uncertainty by bootstrapping: b value = 0.82 +/- 0.09, M_C = 0.41 +/- 0.31; b) b value vs depth; c) b value over time. The results are computed using a minimum number of earthquakes for each grid cell ni = 150.

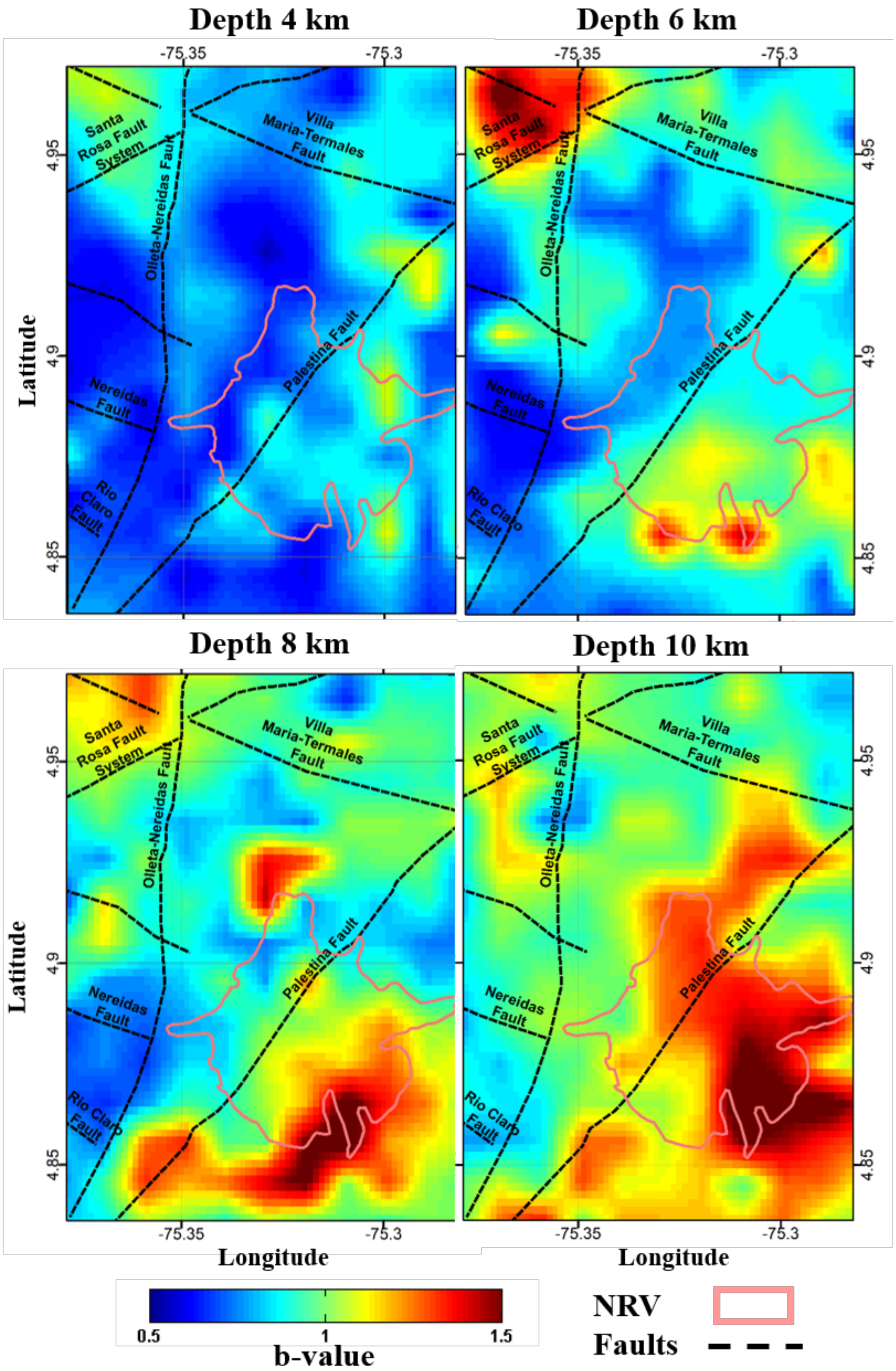

Figure 7: Depth slices of b-value. Surface faults and NRV contour are superimposed. The high b-values in red could be associated with the magma chambers of NRV controlled by the Palestina fault. Intermediate b-values in green at 4 km and 6 km depth on the northwestern and northern part could be suggested as possible high pore pressure associated with hydrothermal activity controlled by the faults Nereidas, Olleta-Nereidas and Villa Maria-Termiales. The depths of the slices are relative to the peak of NRV.

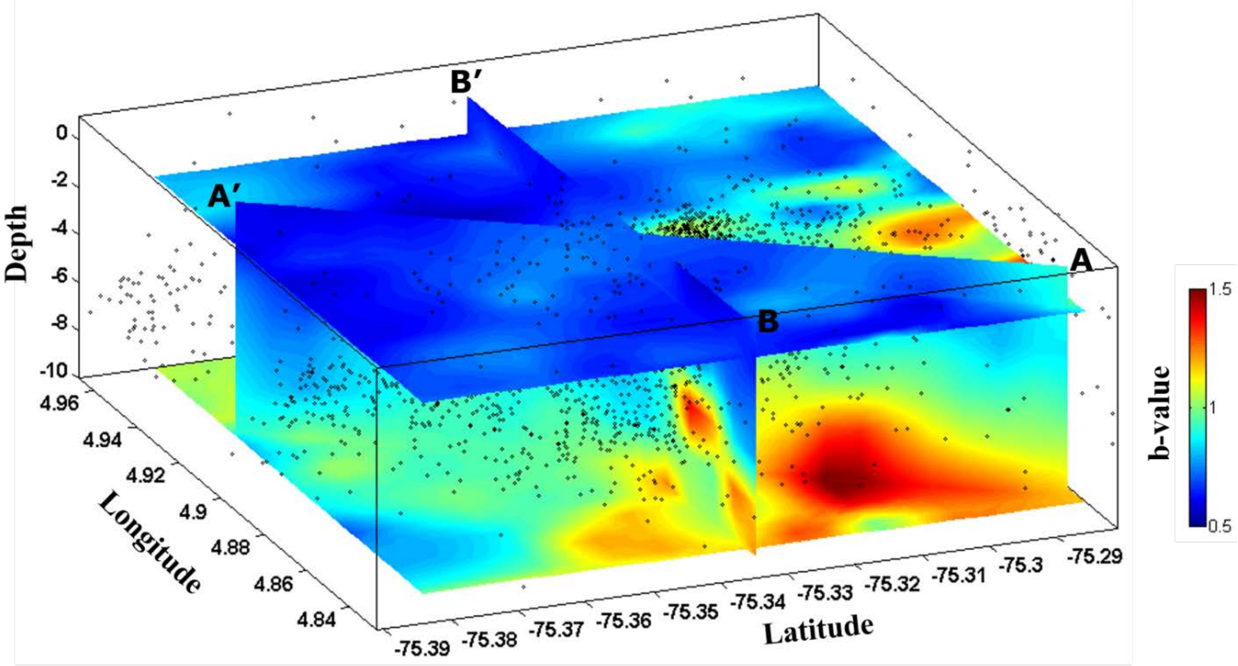

Figure 8: b value volume. Black dots are the earthquakes of the declustered catalog. Horizontal slices are 2 km and 10 km depth. Vertical slices are the cross-sections indicated in Figure 1.

The b-values mapping carried out in this work are averages for the 2000-2018 seismic period, and therefore do not show time-variations. Future work will be carried out to choose different time periods in order to map time-dependence anomalies and compare their geometries. Additionally, a sensitivity analysis on cell sizes and declustering would be useful to demonstrate the robustness of the b value distribution. It should be highlighted that the discussion about the location of geothermal reservoirs north-west and north of NRV is still subjected to geoscientific interpretations as no wells have been drilled to prove the geothermal resources in NRV.

4. CONCLUSION

The VT earthquake catalog of NRV reflects the changes and increasing magmatic and hydrothermal activity this volcano is experiencing over the last decade. This information was used to map b-values, a parameter typically computed to describe the abundance of high magnitude earthquakes. It has also demonstrated that the estimation of this parameter offers information of different physical subsurface processes such as fracturing, stress levels, thermal gradients and fluid pressures.

For NRV, the M_C value average variations in time were computed to demonstrate the completeness of the NRV seismic network, which has been improved during the last years. Also, the average of the seismicity parameters b-value = 0.82 ± 0.09, and magnitude of completeness $M_C = 0.41 \pm 0.31$ from 2000 to 2018 were determined after declustering the earthquake catalog. Moreover, the computed average variation of b-values with depth and time agrees with the increase of magmatic activity of NRV deeper and more recently.

The b-values mapping for the period of 2000-2018 shows spatial anomalies that agree with previous descriptions of strong magma activity happening beneath the volcano’s peak, mainly between 6 and 10 km in depth. Additionally, a slight increase of the b-values at shallower depths (2-4 km) on the northwestern and northern parts suggest the existence of potential geothermal areas. A lineament of high b-values is oriented parallel to the Palestina Fault, which is the main path of magma that has favoured the existence of NRV and other discontinuities that allow the upflow of hydrothermal fluids.

ACKNOWLEDGEMENTS

Thanks to The SGC for the information provided for this paper. Ministry of Foreign Affairs and Trade (MFAT) New Zealand development scholarship is acknowledged for the funding offered to the main author for his doctorate studies in New Zealand. The main author as an active member of Colombian Geothermal Association (AGEOCOL by its Spanish acronym) thanks AGEOCOL for facilitating the exchange of knowledge about geothermal in Colombia including NRV. The exercise of this paper is an independent initiative of the authors and the outcomes are not affected, nor are they influenced, by the institutions the authors currently belong to.

REFERENCES

Aki, K. *Maximum likelihood estimate of b in the formula log N = a - bM and its confidence limits.* Bull. Earthq. Res. Inst. Tokyo Univ.43. pp. 237–239. (1965).

Alfaro, C., Aguirre, A., Jaramillo, L.F.: *Inventario de Fuentes Termales Naturales en el Parque Nacional Natural de los Nevados*. Technical Report, INGEOMINAS, Bogotá. pp. 60-67. (2002).

Alfaro, C., Velandia, F., and Cepeda, H.: *Colombian Geothermal Resources*. Proceedings. World Geothermal Congress, Antalya, Turkey. (2005).

Bender, B. *Maximum likelihood estimation of b values for magnitude grouped data.* Bull. seism. Soc. Am. 73. pp. 831–851. (1983).

El-Isa, Z.H. and Eaton, D.: *Spatiotemporal variations in the b-value of earthquake magnitude–frequency distributions: Classification and causes.* Tectonophysics. pp. 615 – 616. (2014).

Enescu, B., Enescu, D. and Ito, K. *Values of b and p: their variations and relation to physical processes for earthquakes in Japan and Romania*. Rom. J. Phys. 56, 590–610. (2011).

González-Garcia, J., Hauser, J., Annetts, D., Franco, J., Vallejo, E., Regenauer-Lieb, K.: *Nevado Del Ruiz Volcano (Colombia): A 3D model combining geological and geophysical information.* Proceedings World Geothermal Congress, Melbourne. (2015).

Gutenberg, B and Richter, C.: *Frequency of earthquakes in California*. Bulletin of the Seismological Society of America. 34 (4). pp. 185 – 188. (1944).

Lamessa, G., Mammo, T. and Raghuvanshi, T. *Homogeneized earthquake catalogue and b-value mapping for Ethiopia and its adjoining regions.* Geoenviromental Disasters. 6:16. (2019).

Lin, J., Sibueti, J., Lee, C., Hsu, S. and Klingelhoefer, F. *Special variations in the frequency–magnitude distribution of earthquakes in the southwestern Okinawa trough*. Earth Planet. Space. 59. pp. 221–225. (2007).

Londono, J. M.: *Evidence of recent deep magmatic activity at Cerro Bravo-Cerro Machín volcanic complex, Central Colombia. implications for future volcanic activity at Nevado del Ruiz, Cerro Machín and other volcanoes.* Journal of Volcanology and Geothermal Research. 324. pp. 156–168. (2016).

Londono, J. M., and Kumagai, H. *4D seismic tomography of Nevado del Ruiz Volcano, Colombia, 2000-2016.* Journal of Volcanology and Geothermal Research. 358. pp. 156–168. (2018).

Lundgren, P., Samsonov, S.V., López Velez, C.M.,and Ordoñez, M. *Deep source model for Nevado del Ruiz Volcano, Colombia, constrained by interferometric synthetic aperture radar observations.* Geophys. Res. Lett. 42.pp. 4816-4823. (2015).

Murru, M., Montouri, C., Wyss, M. and Privetera, E. *The locations of magma chambers at Mt. Etna, Italy, mapped by b-values*. Geophys. Res. Lett. 26. pp. 2553–2556. (1999).

Murru, M., Montouri, C., Console, R., Lisi, A. *Mapping of the b value anomalies beneath Mt. Etna, Italy, during July–August 2001 lateral eruption*. Geophys. Res. Lett. 32. (2005).

Murru, M., Console, R., Falcone, G., Montuori, C., Sgroi, T. *Spatial mapping of the b value at Mount Etna, Italy using earthquake data recorded from 1999 to 2005.* J. Geophys. Res. 112 B12303. (2007).

Ogata, Y., Imoto, M. and Katsura, K. *3-D spatial variation of b-values of magnitude–frequency distribution beneath the Kanto District, Japan*. Geophys. J. Int. 104 (1). pp. 135–146. (1991).

Reasenberg, P. *Second-order moment of central California seismicity. 1969–1982*. J. Geophys. Res. 90. pp. 3–18. (1985).

Rydelek, P. A. and Sacks, I. S. *Testing the completeness of earthquake catalogues and the hypothesis of self-similarity*. Nature. 337. pp. 251–253. (1989).

Schorlemmer, D., Wiemer, S. and Wyss, M. *Variations in earthquake-size distribution across different stress regimes.* Nature. 437(7058). pp. 539–542. (2005).

Vargas, C.A., Koulakov, I., Jaupart, C., Gladkov, V., Gomez, E., Khrepy, S., and Al-Arifi, N. *Breathing of the Nevado del Ruiz Volcano reservoir, Colombia, inferred from repeated seismic tomography*. Sci. Rep. 7:46094. (2017).

Warren, N. and Latham, G. *An experimental study of thermally induced microfracturing and its relation to volcanic seismicity*. Journal of Geophysical Research. 75 (23). pp. 4455-4464. (1970).

Wu, Y-M., Chen, S. K., Huang, T-C., Huang, H-H., Chao W-A. and Koulakov, I. *Relationship between earthquake b-values and crustall stresses in a young orogenic belt.* Geophys. Res. Lett. 45. pp. 1832-1837. (2005).

Wiemer, S. and McNutt, S. *Variations in frequency-magnitude distribution with depth in two volcanic areas: Mount St. Helens, Washington, and Mr. Spurr, Alaska.* Geophys. Res. Lett. 24. 189-192. (1997).

Wiemer, S. and Wyss, M. *Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan*. Bull. Seism. Soc. Am. 90. pp. 859–869. (2000).

Wiemer, S. *A software package to analyze seismicity: ZMAP*. Seismol. Res. Lett. 72. pp. 373–382. (2001).

Wiemer, S. and Wyss, M. Mapping spatial variability of the frequency magnitude distribution of earthquakes, Adv. Geophys. 45. pp. 259–302. (2002).

Wyss, M. *Towards a physical understanding of the earthquake frequency distribution.* Geophyics. J. R. Astr. Soc. 31. pp. 341-359. (1973).

Wyss, M., Shimzaki, K. and Wiemer, S. *Mapping active magma chambers by b values beneath the off-Ito volcano, Japan.* Journal of Geophysical Research. 102. pp. 20.413-20.422. (1997).

Wyss, M., Klein, F., Nagamine, K and Wiemer, S. *Anomalously high b-values in the South Flank of Kilauea volcano, Hawaii: Evidence for the distribution of magma below Kilauea's East rift zone*. J. Volcanol. Geotherm. Res., 106(1–2), 23–37. (2001).

Zuniga, R and Wyss, M.: *Inadvertent changes in magnitude reported in earthquake catalogues*: *Their evaluation through b-value estimates*. Bulletin of the Seismological Society of America. 85 (6). Pp. 1858 – 1866. (1995).