Natural H_2 Potential of West Colombia

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Synopsis :

Western Colombia is a promising region for natural hydrogen (H_2) generation owing to its geological and geodynamic context. The main potential sources of H_2 include ophiolites, through the process of serpentinization of ultramafic rocks, organic-rich sedimentary facies via late maturation processes, and oxidation of igneous intrusions. However, the area is highly heterogeneous due to the complex succession of extensional and compressional tectonic phases. This tectonic complexity has led to the isolation of geological units within accreted terranes. The aim of this study was to provide a comprehensive overview of the various H_2 origins across western Colombia. The study area spans from the Planeta Rica iron-nickel mine in the north (8°N) to El Tambo in the south (1.4°N).

Soil gas analyses confirm the presence of H_2, especially in the fault zones bordering the Western and Central Cordilleras. Furthermore, petrography analysis confirms a high Iron content as well as a highly variable degree of serpentinization within the studied formations. Two areas systematically display the highest H_2 soil content values: the Cauca-Patía zone and the Planeta Rica mining area. The most likely source of H_2 in these regions is the oxidoreduction of iron-rich formations, which are characteristic of both accreted oceanic lithosphere and, in certain instances, mineralization associated with granitic intrusions.

Introduction

The exploration of natural H_2 has commenced in various countries, such as Australia, France, and the United States. This exploration has accelerated over the past five years driven by the demand for low-carbon and low-cost energy. In South America, no country has yet adapted its mining legislation for H_2. As of mid-2025 Colombia is no exception despite the regulation being nearly finalized. Nevertheless, data confirming the presence of H_2 have already been published: in the Cauca-Patía Basin (Carrillo et al., 2023), in the foreland basins (Llanos and Putumayo) (Patiño et al., 2024) and in the Central Cordillera (Vargas et al., 2025). Additionally, coal from various Colombian mines has demonstrated excellent H_2-generating potential (Moretti et al., 2024). Surveys aimed at defining the most promising areas of

Colombia are currently underway. Here we present new data acquired in Western Colombia, focusing on: (1) soil gas measurements, (2) analyses of the H_2 generating potential of the sampled rocks.

H_2 generating rocks

The classification of natural H_2 generation processes generally adheres to two distinct methodologies: one focusing on the specific geochemical reactions responsible for production, and the other on the geological contexts of occurrence. Both have advantages and disadvantages, as they can lead to conceptual overlaps or oversimplification. Given that this paper focuses on the potential of Western Colombia, we will adopt the second approach, that is, a classification based on geological context.

Accordingly, we adopt the nomenclature established by (Lévy et al., 2023), which categorizes H_2 provinces by the dominant H_2-Generating rocks:
H_2_GR1: Oceanic lithosphere and the mantle.
H_2_GR2: Iron-rich sedimentary rocks and intrusive rocks that can be oxidized.
H_2_GR3: Radioactive rocks.
H_2_GR4: Organic matter (OM) rich source rocks.

Natural H_2 generation originates from multiple geochemical processes. Among the most significant and long-studied mechanisms are water reduction (notably through serpentinization but also via other reactions) and radiolysis. These two mechanisms have been extensively investigated for decades (Klein et al., 2009; Lollar et al., 2014), and demonstrate a substantial capacity to daily generate H_2 (Worman et al., 2016). More recently, late thermal maturation of organic-rich source rocks has been shown to generate H_2 (above 200 °C), especially from coals (Horsfield et al., 2022; Moretti et al., 2024b).

Water reduction by redox reaction is not restricted to olivine oxidation. Other iron-bearing minerals, such as iron oxides or iron carbonates, are equally capable of generating H_2 when their ferrous iron (Fe^{2+}) is oxidized (Geymond et al., 2023; Milesi et al., 2015). Furthermore, rocks like granites can contribute to H_2 production through hydrothermal alteration, a mechanism supported by the presence of H_2 within fluid inclusions in these lithologies(Murray et al., 2020; Truche et al., 2021).

H_2_GR1 (in Cauca-Patía) and H_2_GR4 (coal mines) have already been proposed as categories of natural hydrogen generation in Colombia. Recently the siderite oxidation H_2_GR2 has been also proposed as origin for the H_2 measured in the Llanos Basin (Moretti et al., 2025). H_2_GR1 is mainly associated with the alteration of oceanic and mantle rocks, such as ophiolites, we will take a closer look at how Colombia's complex geological context, marked by its tectonic activity and lithological diversity (Figure 1), determines the presence of H_2 and its potential.

The methodology employed to assess the H_2 generation potential in Western Colombia was based on fieldwork, gas analysis and detailed laboratory rock characterization. We adopted the methodology outlined by (Lévy et al., 2023). This methodology integrates surface acquisition but also rock characterization using optical petrography, X-ray diffraction, Mössbauer spectroscopy, electron microprobe analysis and magnetic susceptibility measurements (Carrillo et al., 2025 in prep)

Western Colombia geological context

The tectonic evolution of Colombia is the result of accretionary orogenesis with extension and compression phases in a subduction system that has been active since the Jurassic period (Zapata et al., 2019). The west coast is bordered by the W-E Pacific subduction and the Caribbean coast by north-south subduction of the Caribbean Plate below South America. The Colombian Andes are formed by three N-S mountain ranges: the Eastern, Central, and Western cordilleras, separated by the inter- Andean valleys of the Cauca and Magdalena rivers. The Eastern cordillera is a former cretaceous back arc basin, now inverted and the Central and Western Cordillera contain accreted material from Jurassic and cretaceous oceanic lithospheres. In the western part, southward the Nazca Plate plunges at a steep angle while northward of approximately 5.5°N, that subduction becomes almost horizontal, slowing down recent volcanism (Vargas et al., 2019). The Caldas Tear, a plate rupture zone linked to the Sandra Ridge, separates the tilted (south) and flat (north) subduction segments (Syracuse et al., 2016).

Zone A: Northern Region

The Romeral Fault System in the north constitutes the eastern boundary of the San Jacinto Folded Belt (SJBF). The SJFB is overlain by a marine and continental sedimentary cover deposited in the Late Cretaceous and Quaternary. Peridotite units parallel to the Romeral Fault System are also reported (Ramírez-Cárdenas et al., 2024). In addition, a primitive intra-oceanic arc, active 88-73 Ma ago, exists in the basement of the SJBF (Cardona et al., 2012).

Zone B: Central Cordillera

The Central Cordillera marks the boundary between the South America Plate and accreted terranes, featuring strong inhomogeneity enhanced by some Upper Cretaceous pluton intrusions. The key geological complexes and faults include:

- The Romeral Fault System (RFS), a major feature in northwestern Colombia.
- The San Jerónimo Fault which divides the continental Cajamarca Complex from the deformed volcanic/sedimentary Quebradagrande Complex.
- The Silvia-Pijao Fault which separates the Quebradagrande Complex from the Arquía Complex, which consists of varied metamorphic rocks, including low- to medium-pressure rocks, high-pressure rocks (e.g., eclogite), and serpentinized ultramafic rocks.
- The Cauca-Almaguer Fault marks the boundary between the Arquía Complex and the Western Cordillera (Nivia et al., 2006).

And the potential H_2 generating rocks are the mafic-ultramafic rocks and/or the basement

- Mafic-ultramafic bodies are found on both sides of the Cauca-Almaguer Fault: those to the west have a Plateau-like affinity (e.g., Bolívar Ultramafic Complex), while those to the east are part of an ophiolitic sequence (e.g., Medellín meta-Harzburgite).
- The region's basement composed of a Permian-Triassic-Jurassic metamorphic basement (Cajamarca Complex), and unconformably overlain by Early Cretaceous siliciclastic units.
- The Quebradagrande Complex on the western flank consists of volcanic-sedimentary rocks associated with a younger extensional back-arc to arc setting.
- Late Cretaceous plutons (98 Ma to 60 Ma) related to the back-arc setting, intrude the basement (Villagómez et al., 2011).

Zone C: Western Cordillera

The Western Cordillera is characterized by the remnants of the oceanic Caribbean Plateau accreted to the continental margin between 75-65 Ma (Villagómez et al., 2011; Zapata et al., 2019). The main facies include massive pillowed basalts, gabbros, diorites, dolerites, tonalites and pyroclastic rocks with plateau-like signatures, overlaid by siliciclastic sequences (Pardo-Trujillo et al., 2020) sourced from both continental and oceanic basements. The volcanic rocks of the Western Cordillera intrude these oceanic domains, such as for instance the Bolivar Ultramafic Complex, dated from 100 to 70 Ma (Weber et al., 2015). In the Valle del Cauca region, the Ophiolitic Complex is associated with the RFS. This region is characterized by thick-skinned deformation with west-verging thrusts, where the Mesozoic ophiolitic basement and its Cenozoic sedimentary cover are involved in the structural configuration.

Pacific

The Garrapatas-Dabeiba Suture borders the Western Cordillera toward the west, some small ophiolite sequences outcrop near this major fault zone (see Figure 1) but they will not be presented here.

Results: Soil gas analysis

The soil H_2 contents are detailed Figure 2, the average and maximum are on Table 1. The presented maps also include data from a previous campaign published previously (Carrillo et al., 2023, within the zone C Figure 2) and H_2 monitoring results from the Central Cordillera (Vargas et al, 2025).

In the Valley, the methane concentrations were consistently below the detection limit (< 0.1%). CO_2 concentration ranged from 0.1 to 1% with very locally highest values. Elevated CO_2 contents were specifically encountered in the volcanic zone of the Central Cordillera. Along the coast, CH_4 was identified in a bubbling source, and this gas has been then analysed in laboratory. H_2S and CO concentrations were always negligible (<2ppm) in both the Valley and the Northern areas, however few points in the volcanic zone of the Ruiz Volcano show higher H_2S content.

The H_2 content is as usual variable and rather high values (between 100 and 1000 ppm) are numerous. The GA5000 upper threshold is 1000 ppm and has been reached in the fault that borders the ophiolites near Ginebra, zone C. In average, the North (between the Planeta Rica and the Cerro Matoso mines) and the Cauca Valley itself display the higher content, the maximum is also higher in that zones. On the contrary on the Pacific coast the values are very low and it does not suggest an active H_2 system in this area. In the Central Cordillera, some H_2 has been found in the fault zones. Values was not very high between Medellin and Manizales but it is worth noting than Vargas et al who monitored the soil gases in this area (triangle Figure 2) found higher values. The Vargas et al results show a strong daily variation with values around 500 ppm every day during the afternoon but low value by night and the morning. Near Medellin (Figure 2C) the maximum 945ppm. Monitoring was not planned as part of these regional mapping missions, but these temporal variations must always be considered and mean that conclusions about the low potential of an area should not be drawn too quickly.

Results: Serpentinisation level

A first estimation of the remanent potential of the mafic and ultramafic rocks could be deduced from their serpentinization level. In a first bulk approach the density may be used to compute it (Mathur et al., 2025). Correction should be applied using the magnetic signal, but this first approximation presented Figure 3 and on Table 2 already allows us drawing some conclusions.

If all the areas still contain not fully serpentinized rock, the northern area is globally heavily serpentinized, with a mean value around 92%, whereas in the southern zone remains at a low level of serpentinization. None of our samples in the Cauca Patía Basin shows a level of serpentinization above 77%.

Discussion/conclusions

H_2 is present is the soil across the entire studied zones, from Planeta Rica zone in the north to the Cali area in the south, that means over a north-south transect 600 km long. H_2 soil content is variable and the faults that border the cordilleras play a role but H_2 has been also found in the tertiary infilling of the Cauca valley. It confirms and extends the previously findings from the Cali area (Carrillo et al., 2023). The highest values are observed in the south (Figure 2 and Table 1

Given that this portion of Western Colombia comprises accreted Mesozoic oceanic lithosphere, the source of the H_2 is hypothesized to be primarily ongoing serpentinization of the associated mafic and ultramafic rocks. The degree of serpentinization appears to be highly heterogeneous but averaging below 60% in the south, which is consistent with currently active oxidation of these rocks. The data presented here does not allow us to determine whether today's reactions are high-temperature serpentinization, at around 300°C (McCollom and Bach, 2009) or other oxidoreduction reactions involving, for instance, magnetite (Geymond et al., 2025) or siderite (Moretti et al., 2025). This wide heterogeneity in the degree of serpentinization is comparable to observations in other regions such as the Pyrenees (Turon de la Técouere) where values ranging from 3 to 62% have been reported (Loiseau et al., 2024).

It should also be noted that, although this western region of Colombia contains pieces of oceanic lithosphere, it differs fundamentally from classical ophiolite complexes like Oman and New Caledonia. In these latter settings, oceanic lithosphere was obducted beneath continental crust as a relatively simple thrust sheet. There, the ophiolite units outcrop almost continuously over hundreds of kilometers and the full oceanic lithospheric succession could be observed (Deville and Prinzhofer, 2016; Zgonnik et al., 2019). In sharp contrast, Colombia only hosts discontinuous relics of different ages from the multiple oceanic terranes that were accreted during the long history of subduction of the Pacific and Caribbean plates beneath the South American plate.

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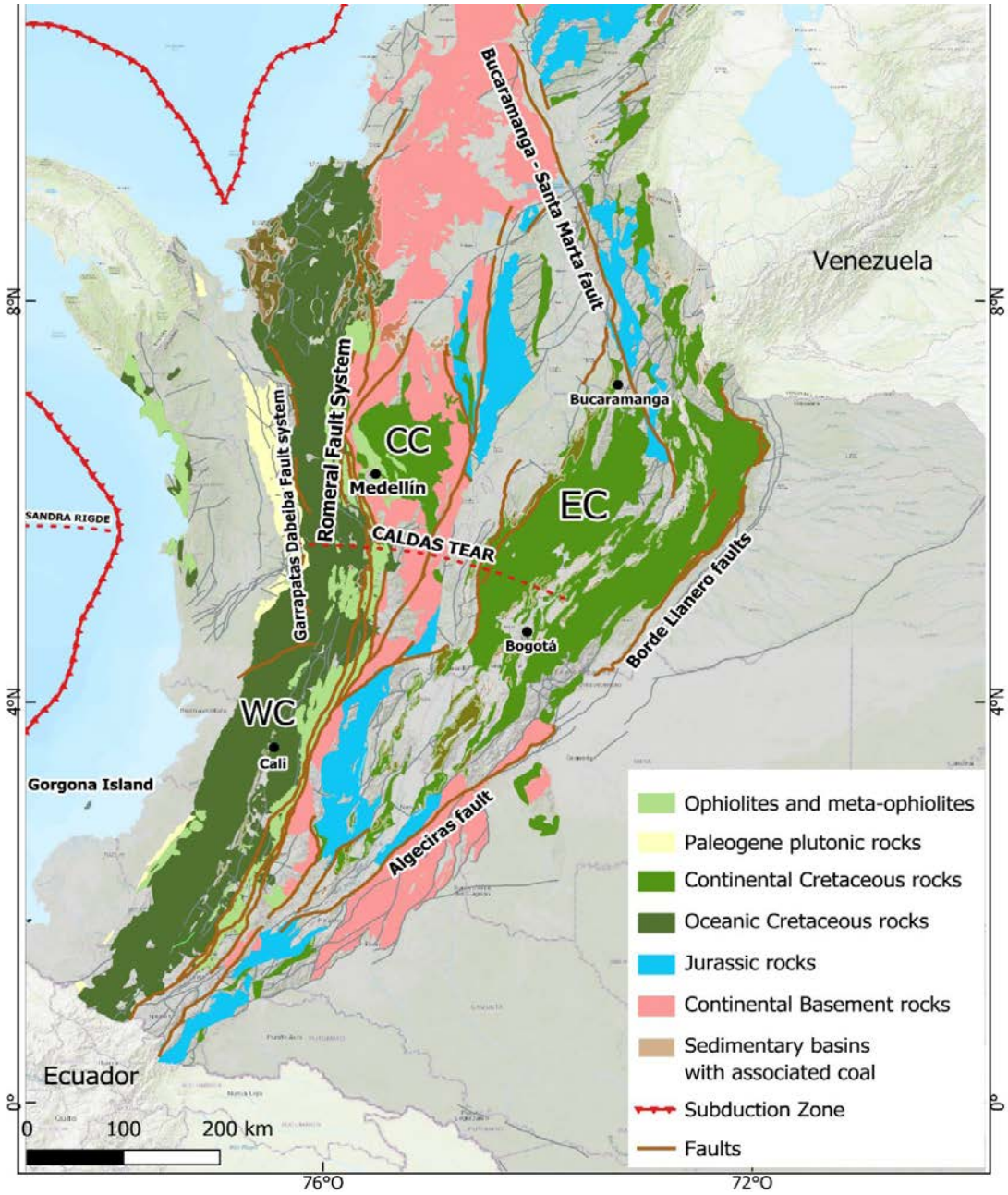

Figure 1. Map of the main geological features of Colombia. WC: Western Cordillera; CC: Central Cordillera; EC: Eastern Cordillera. Data from (Jaramillo-Ríos et al., 2025; Zapata et al., 2019). Modified from Carrillo et al (2025, in prep)

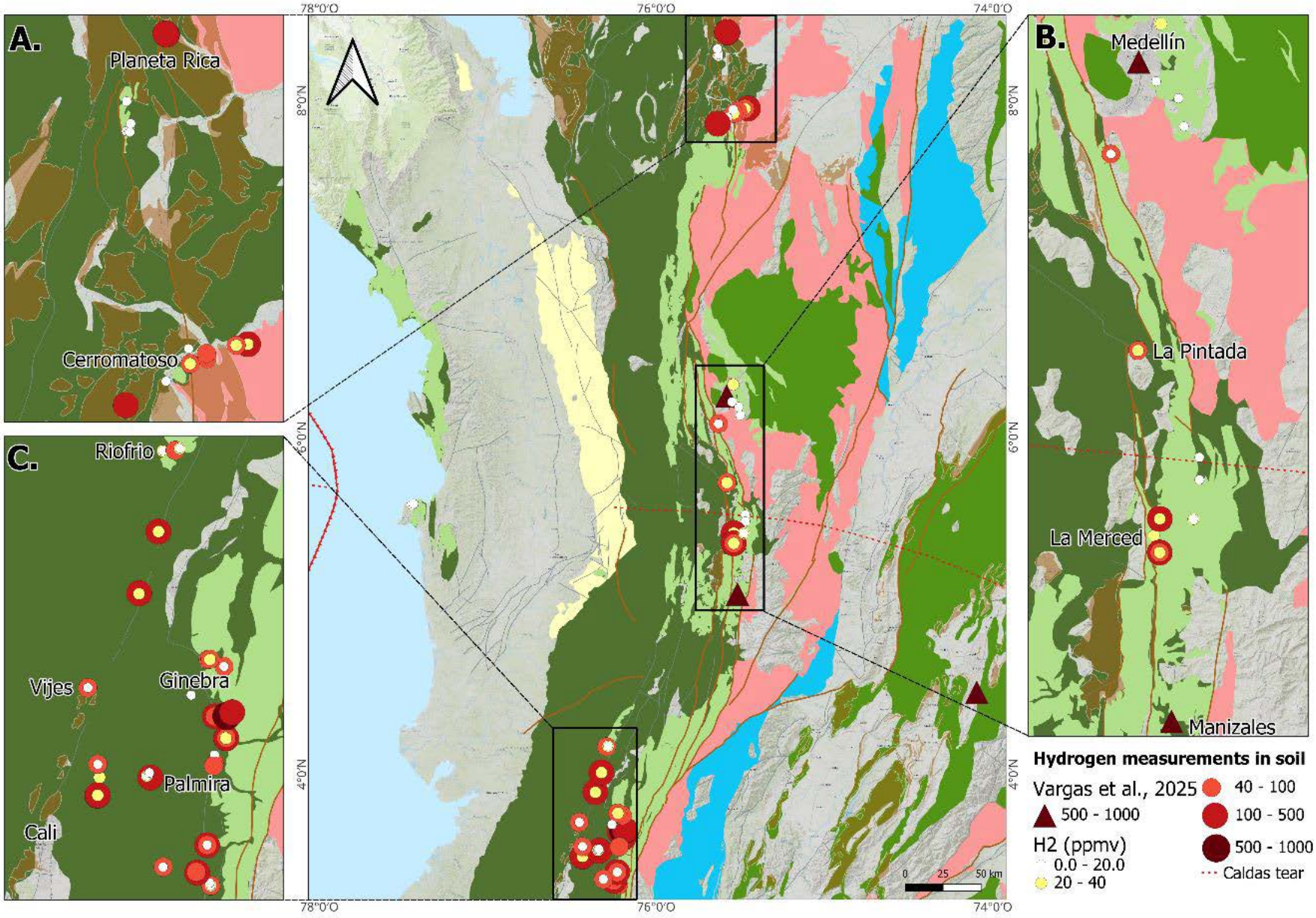

Figure 2. H_2 content in the Soil gas measurements. Geologic units see legend in Figure 1.

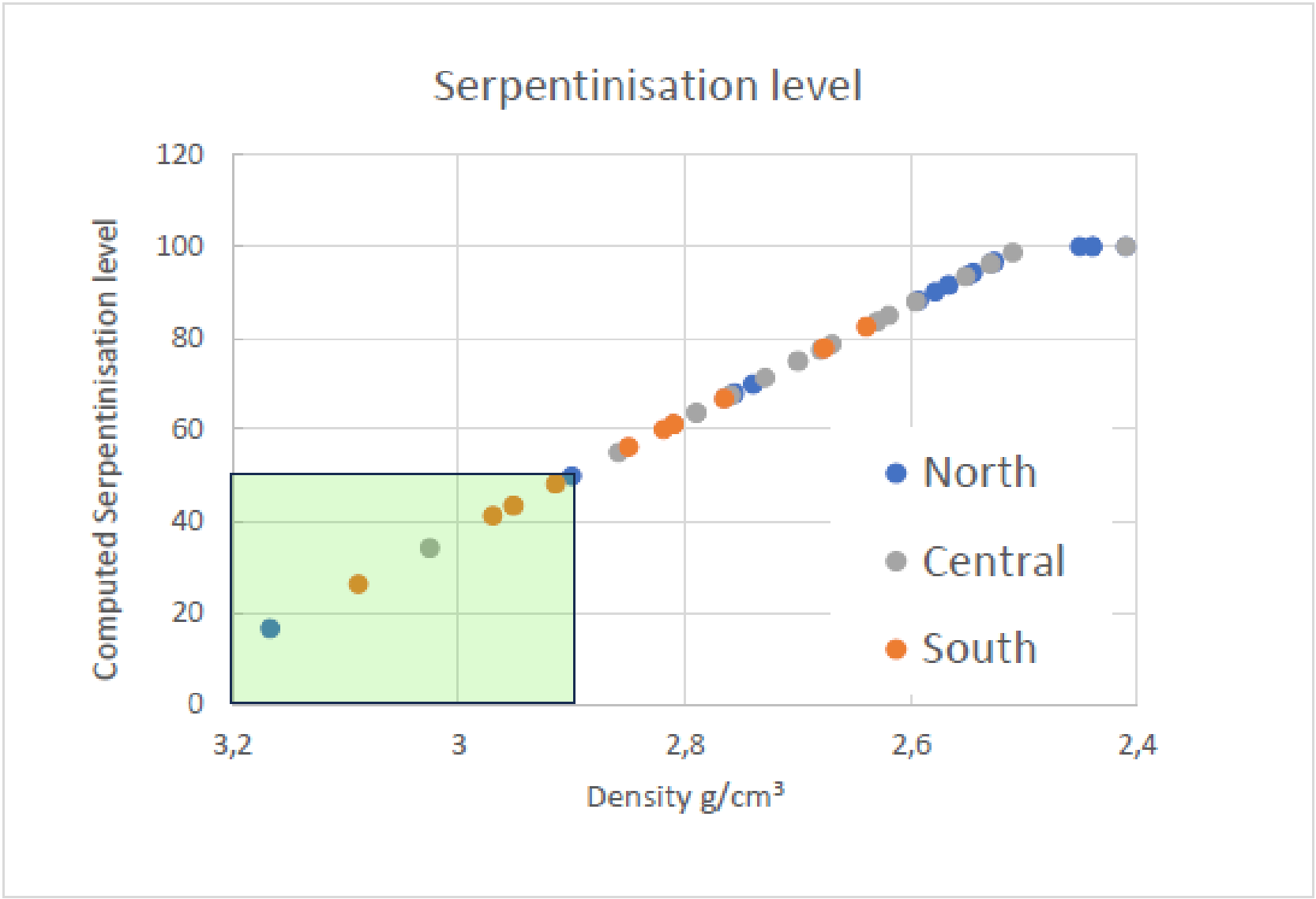

Figure 3. Level of serpentinization deduced from the density using the Miller J. D. & Christensen I. N., 1997) Formula

$S_{\%} = \frac{3.300 - D_c}{0.785} * 100$ Values are not corrected from the magnetic signal and values above 100 have been reduced to 100.

Zone	North	Center	Pacific	South.
Nb of measures	53	77	15	198
Max H_2 (ppm)	277	162	10	> 1000
Average H_2 (ppm)	51	28	3	48

Table 1. Field soil gas measurement. Max and average H_2, content within the different zones.

Zone	Min	Max	Average	Mean
North	16	100	83	92
Central	23	100	77	77
South	34	77	56	60

Table 2. Serpentinization level in %