Artículo de Investigación. Revista Ciencia e Ingeniería. Vol. 46, No. 3 pp. 353-360, agosto-noviembre, 2025.
ISSN 1316-7081. ISSN Elect. 2244-8780 Universidad de los Andes (ULA)

Petrogenetic study of the El Verdalito Granodiorite through petrologic and petrographic analysis

Estudio petrogenético de la Granodiorita El Verdalito mediante análisis petrológico y petrográfico

Rosales, Rafael[1*]; Andara, Ángel[1]; Torres, Gusbel[1]; Gómez, Jessica[2]; Maldonado, Maricarmen[3]; Caraballo, José[3]; Lujano, José[3]; Uzcátegui, Francyret[3];
[1]Grupo de Investigaciones TERRA. Escuela de Ingeniería Geológica. Universidad de Los Andes. Venezuela.
[2]Laboratorio de Palinoestratigrafía y Paleobotánica, Centro de Investigaciones Científicas, Argentina.
[3]Escuela de Ingeniería Geológica - Universidad de los Andes-Venezuela, Venezuela.
* rafaeljrosales@ula.ve

Abstract

Outcropping along the Rafael Caldera Highway in Mérida, Venezuela, the El Verdalito granodiorite stands out as a prominent igneous body due to its geological and petrographic characteristics. This study aims to deepen its understanding through petrological and petrographic analyses of its mineralogy to comprehend its petrogenesis and evolution. U/Pb zircon dating estimates a crystallization age of approximately 440 ± 19 million years. Regarding its petrographic characteristics, the El Verdalito granodiorite displays a range of primary textures with variable grain sizes, showing a dominance of plagioclase phenocrysts with normal zoning, along with quartz and alkali feldspars, and accessory minerals such as biotite, muscovite, epidote, sericite, and chlorite. Analyses reveal primary textures resulting from recrystallization, as well as secondary alterations from hydrothermal fluids. The presence of immobile elements determines the tectonic setting of formation and evolution, suggesting magma generated in a pre-collisional subduction zone.

Keywords: Granodiorite, Petrogenesis, Petrography, Geochemistry, Andes Cordillera, Tectonics.

Resumen

Aflorando a lo largo de la autopista Rafael Caldera en Mérida, Venezuela, la granodiorita de El Verdalito simboliza un cuerpo ígneo muy llamativo debido a sus características tanto geológicas como petrográficas, por ello, se busca profundizar su estudio a través de análisis petrológicos y petrográficos de su mineralogía, con el fin de comprender su petrogénesis y evolución. Mediante la datación U/Pb en circones, se estima una edad de cristalización de aproximadamente 440 ± 19 millones de años. En cuanto a sus características petrográficas, la granodiorita de El Verdalito muestra una serie de texturas primarias con variedad de tamaños de granos. Presenta dominancia de fenocristales de plagioclasa con zonación normal, como también cuarzo y feldespatos alcalinos, así como también minerales accesorios como lo pueden ser las micas biotita, moscovita, epidota, sericita y clorita. Los análisis revelan texturas primarias producto de la recristalización, asimismo, alteraciones secundarias provenientes de fluidos hidrotermales. La presencia de elementos inmóviles determina el ambiente tectónico de formación y evolución, sugiriendo un magma generado en una zona de subducción pre-placa.

Palabra clave: Granodiorita, Petrogénesis, Petrografía, Geoquímica, Cordillera de los Andes, Tectónica.

1 Introduction

Between 1974 and 1976, the Ministry of Energy and Mines documented for the first time the El Verdalito Granodiorite, located on the geological map of Tovar–Guaraque–Mesa Bolívar–Bailadores, Mérida State, Venezuela. This igneous body crops out in the Chama Canyon within the Venezuelan Andes and spans approximately 1.7 kilometers in a North–South direction and 1.5 kilometers East–West.

Classified as a granodiorite by Van der Lelij in 2013 and corroborated by Professor Rafael J. Rosales R. in 2020, it is found in discordant contact with Cretaceous rocks and is presumed to have intruded formations belonging to the Tostós Association. Sample 08VDL03, located at latitude N 8°28'49" and longitude W 71°34'13", yielded a U–Pb zircon age of 449.3 ± 2.5 Ma (Van der Lelij, 2013), suggesting it is contemporaneous with the Estanques Granite and other similarly aged plutonic bodies in the region.

This study employs analytical techniques such as thin section petrography and geochemical analysis to characterize in detail the mineralogical composition of this igneous body. Additionally, a petrological and petrographic assessment is conducted with the aim of contributing to the understanding of the petrogenesis of the El Verdalito Granodiorite.

2 Materials and methods

The study was conducted at the Optical Mineralogy and Petrography Laboratory of the Universidad de Los Andes. Following the standard cutting and polishing protocols established by MacKenzie et al. (1997), thin sections were prepared and examined using a Nikon ECLIPSE E200 POL polarizing light microscope. This enabled the detailed identification and description of crystallinity, grain size, textural patterns (both primary and secondary textures), and modal mineralogical composition (primary and secondary minerals, expressed as volume percentages).

Rock classification was performed using the classification triangles of Le Bas et al. (1991). The normative and relative modal percentages of the major minerals observed in the thin sections were calculated and plotted on the diagram to determine the appropriate rock nomenclature.

For the geochemical analysis of the granodiorite, the geochemical dataset for the Venezuelan Andes provided by Van der Lelij (2013) was used. Several classification and tectonic discrimination diagrams were applied, including the TAS (Total Alkali-Silica) diagram by Le Maitre (1982), the AFM (Al_2O_3–FeO–MgO) diagram, and the alkalinity and aluminosity diagrams by Maniar and Piccoli (1989). Additionally, the tectonic discrimination diagram by Pearce (1976), the immobile element ratio diagram by Winchester and Floyd (1976), and the R1–R2 diagrams proposed by De la Roche (1980) and Batchelor et al. (1984) were employed. Trace element relationships such as Th–Ta–Hf/3 (Wood, 1980) and Th vs. Co (Hastie et al., 2007) were also analyzed to gain insights into the magmatic evolution and geodynamic setting of formation.

3 Results and Discussion

3.1 Petrography of the El Verdalito Granodiorites

Through petrographic examination of thin sections from samples GVM-101, GVM-102, GVM-103, and GVM-104 under the microscope, it has been determined that all samples exhibit minerals with slight variations in the modal percentages of quartz, orthoclase, and plagioclase. See Table 1. The samples contain 22.5% or less of mafic (dark colored) minerals, classifying them as felsic. The average Color Index (CI) is estimated to be below 25%, thus the rock is inferred to be leucocratic. According to the classification of Le Bas et al. (1991), the samples classify the rock as a granodiorite (Fig. 1).

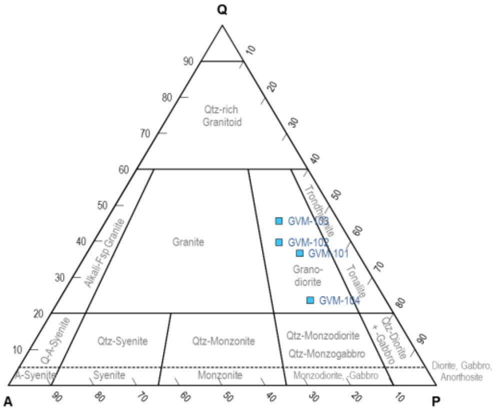

Figure 1. Modal APQ ternary classification diagram for plutonic rocks (Le Bas et al., 1991).

The observed modal variations indicate that the igneous body exhibits mineralogical—and possibly chemical—heterogeneities at different spatial scales within its emplacement. These differences could be related to local fluctuations in crystallization conditions, such as temperature, pressure, and magma chemistry, as well as to subsequent processes involving fluid interaction and magmatic differentiation.

Table 1. Modal percentages of thin sections taken from the El Verdalito Granodiorite.

Sample	GVM-101	GVM-102	GVM-103	GVM-104
Quartz (Qtz)	28.50	33.40	39.30	20.80
Orthoclase (Or)	10.50	12.30	8.60	12.20
Microcline (Mc)	0	1.80	3.30	3.30
Plagioclase (Pl)	38.50	36.40	34.80	51.60
Muscovite (Ms)	9.50	10.30	3.60	5.90
Biotite (Bt)	5.0	1.50	3.50	1.20
Zircon (Zr)	0	0	0	0.50
Chlorite (Chl)	2.50	0	1.70	1.0
Sericite (Se)	1.0	0.30	0	1.60
Epidote (Ep)	4.0	3.50	3.40	2.30
Hornblende (Hb)	0	0	0	2.0
Opaques (Op)	0.50	0.50	1.80	0.60

Regarding the observed textures, perthites (Fig. 2a) and antiperthites were identified. According to Winter (2001), the characteristic texture of granitic rocks is indicative of exsolution and suggests fluctuations in magma crystallization temperature— a typical feature of rocks formed through slow cooling under plutonic conditions. Along the same lines, myrmekites (Fig. 2b) were identified by their vermicular intergrowth of quartz within acidic plagioclase crystals. Additionally, Castro (2015) infers that changes in temperature, pressure, and/or magma composition during crystallization and progressive undercooling result in variations in the proportions of albite and anorthite as the crystal grows, leading to zoning in plagioclase (Fig. 2c).

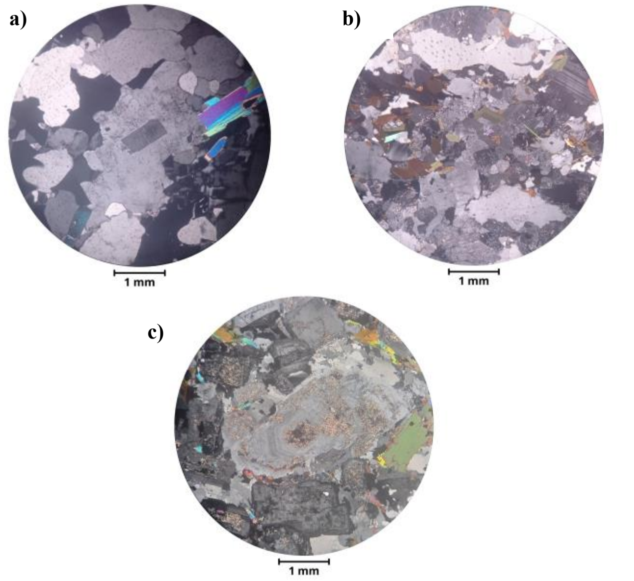

Figure 2. Microphotographs of the El Verdalito Granodiorite. 4x objective. a) Sample GVM-101. Perthitic texture, resulting from cooling below the solvus curve. Poikiloblastic texture, indicating recrystallization processes either metamorphic in nature or related to the crystallization sequence of phenocrysts. b) Sample GVM-103. Myrmekitic texture, generated by the intergrowth of quartz and plagioclase, associated with post-magmatic reactions. c) Sample GVM-103. Zoned plagioclase texture, resulting from variations in albite and anorthite proportions during crystallization. Secondary sericitization texture affecting both alkali feldspars and plagioclase.

In most of the thin sections examined, a prominent poikilitic texture (Fig. 2a) was observed. This texture results from varying nucleation and growth rates of crystal nuclei, which dictate the order of crystallization. It is established that if one mineral species encapsulates another, it must have crystallized first. This term is also associated with metamorphic processes related to mineral adjustments in a recrystallization environment influenced by pressure and temperature fluctuations.

Moreover, the analyzed samples display a holocrystalline degree of crystallinity, indicating complete crystallization, with no residual glass material present. This characteristic suggests progressive cooling without significant interruptions, aligning with the phaneritic texture noted in the medium- to coarse-grained crystals. The serial inequigranularity, wherein grains of varying sizes coexist, indicates non-uniform crystallization, potentially arising from fluctuations in magmatic input or environmental conditions during cooling. Consequently, phenocrysts exhibit a hypidiomorphic form, developing subhedral habits, a typical feature of magmas that experience multiple stages of crystallization, indicating that certain crystals had extended growth periods prior to final solidification.

Additionally, the rock has undergone substantial hydrothermal alterations, evidenced by secondary textures such as chloritization, saussuritization, and sericitization (Fig. 2c) within the plagioclase, orthoclase, and microcline. Best (2003) suggests that during post-magmatic stages, the granodiorite was subjected to hydrothermal fluids enriched in volatile elements, likely sourced from the crystallization process of the magma or from adjacent intrusions. This alteration has not only transformed the primary mineralogy but has also enhanced the diversity of mineral phases present, including sericite, chlorite, and epidote.

Furthermore, the photomicrograph in Fig. 3 illustrates a hornblende crystal with scalloped edges, indicative of an incomplete habit, suggesting a peritectic replacement process. This edge morphology is characteristic of the partial dissolution of the original mineral under unstable conditions within the system, possibly due to variations in pressure, temperature, or the chemical composition of the magma.

The hornblende mineral is surrounded by biotite, muscovite, and plagioclase, indicative of environments where magmatic differentiation processes or interactions with residual fluids occur. This phenomenon contributes to the mineralogical diversification of the igneous body and reflects changes in crystallization conditions during the emplacement of the pluton.

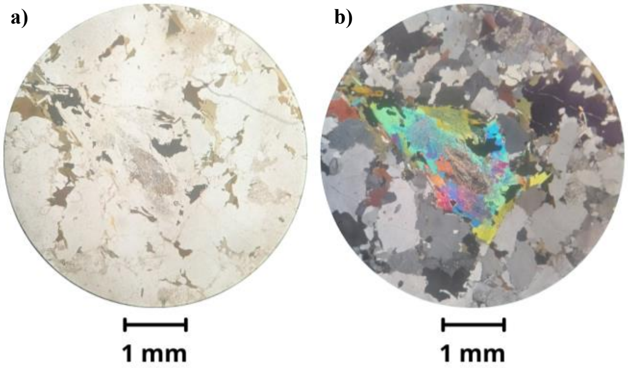

Figure 3. Microphotograph of the El Verdalito Granodiorite. 4x objective. Sample GVM-104. Evidence of peritectic replacement of hornblende by biotite due to partial system instability

As previously stated, this type of reaction is common under metamorphic conditions or during the later stages of magmatic crystallization. This may indicate modifications in the physical and chemical conditions as temperature decreases or changes in the chemical composition of the system that favor the formation of micas over hornblende. Furthermore, hornblende may react with a water-rich fluid phase to produce micas under the moderate temperature conditions characteristic of metamorphism.

3.2 Geochemistry of the El Verdalito Granodiorite

According to the geochemical data from the Andes in Mérida provided by Van der Lelij (2013), the El Verdalito granodiorite, coded as 08VDL03, contains 64.89 wt% SiO_2, classifying it as an intermediate-composition rock with a low to moderate content of mafic minerals and a slightly felsic character.

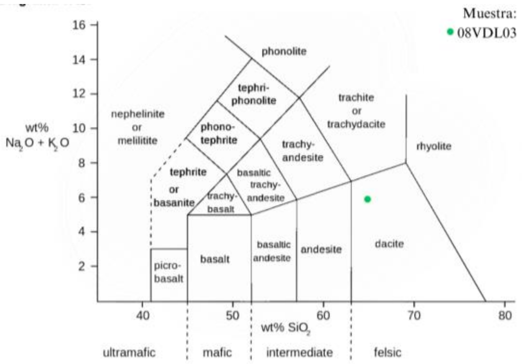

Figure 4. TAS diagram (Le Maitre, R. W., 2002). Sample source: Van der Lelij (2013).

Initially, the TAS (Total Alkali-Silica) diagram by Le Maitre (1982) places the sample within the dacite field, with a tendency toward andesitic composition (Fig. 4), suggesting magmatic evolution from a more mafic parental source. The silica enrichment observed in the sample is indicative of advanced differentiation, consistent with a subduction-related environment, where magmas typically follow a calc-alkaline trend, as further confirmed by analysis using the AFM (Al_2O_3–FeO–MgO) diagram.

The AFM diagram, used to discriminate between calc-alkaline and tholeiitic magmas, reinforces the calc-alkaline classification of the granodiorite (Fig. 5), which is typical of volcanic arc magmas generated in subduction zones. This process involves the early crystallization of mafic minerals, which increases the silica content in the residual magma and promotes the formation of intermediate to felsic rocks, such as the igneous body in question.

Continuing with the classification, the alkalinity and aluminosity indices were analyzed, yielding values of A/NK = 1.75 and A/CNK = 1 (Fig. 6), placing the rock in the metaluminous field with a trend toward peraluminous composition. This indicates a balanced relationship between aluminum oxides and alkalis. A metaluminous composition is common in subduction-related magmas that have undergone slight crustal enrichment, suggesting that the parental magma interacted with crustal materials during its ascent.

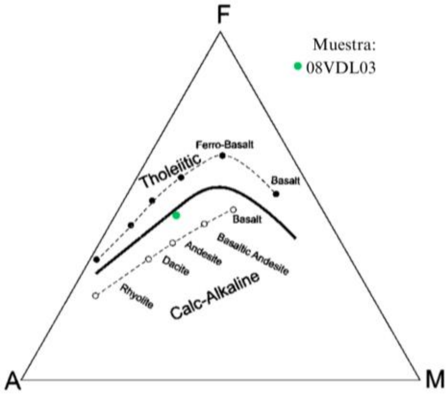

Figure 5. AFM diagram showing the line separating tholeiitic and calc-alkaline fields (Irving et al., 1971). Sample source: Van der Lelij (2013).

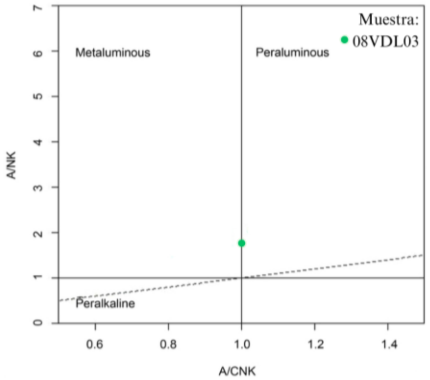

Figure 6. A/CNK–A/NK. Shand's Alumina Saturation Index (molecular Al/(Ca+Na+K)) versus the Alkali Saturation Index (molecular Al/(Na+K)) (Maniar, P. D., et al., 1989). Sample source: Van der Lelij (2013).

Additionally, in the Winchester and Floyd (1976) diagram—based on immobile element ratios such as Nb/Y versus SiO_2—the sample plots at the transition between dacite and rhyodacite, see Fig. 7. This positioning suggests that the El Verdalito granodiorite represents a magma that has undergone significant evolution from an andesitic composition, accumulating silica and transitioning toward felsic compositions.

To refine the tectonic interpretation, FeO, MgO, and CaO–Al_2O_3 ratios were analyzed using the Jensen (1976) diagram, which places the El Verdalito granodiorite in the calc-alkaline field, specifically within the andesite zone. This supports the intermediate nature of the rock and confirms its association with a subduction-related environment, where calc-alkaline magmas are predominant.

To better constrain the tectonic setting, the Pearce (1976) and Wood (1980) diagrams—focused on immobile element ratios such as Th–Ta and Th–Hf/3 (see Fig. 8)—confirm that the origin of the igneous body is associated with a volcanic arc. According to Polat (2006), these immobile elements are not significantly altered by post-magmatic processes, thus preserving the original geochemical signature of the tectonic environment, validating the association with magmas generated in subduction zones.

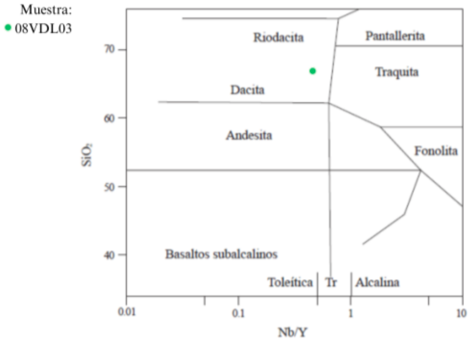

Figure 7. Winchester and Floyd diagram (1976). Immobile element ratios (Rb, Zr, Ti, Y) versus SiO_2. Sample source: Van der Lelij (2013).

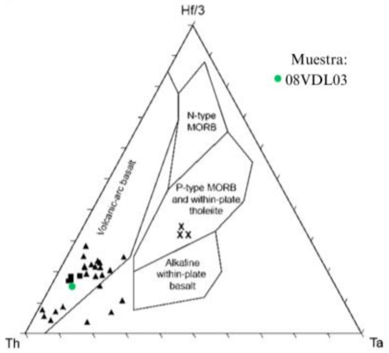

Figure 8. Th–Hf/3–Ta ternary diagram for tectonomagmatic classification (Wood, D. A., 1980). Sample source: Van der Lelij (2013).

Finally, the R1–R2 diagram used to determine the tectonic setting, following De la Roche (1980) and Batchelor et al. (1984), places the granodiorite in a pre-collisional tectonic context. Fig. 9. This result suggests that the parental magma originated during an early stage of tectonic convergence, prior to full plate collision. This phase of high tectonic compression allowed magma ascent and facilitated deep cooling and crystallization, as noted by Best (2003).

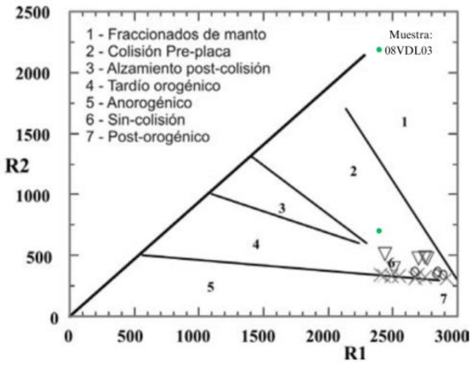

Figure 9. Diagram for tectonic setting discrimination (Batchelor et al., 1984). Sample source: Van der Lelij (2013).

4 Conclusion

4.1 Petrogenesis and tectonic context of the El Verdalito Granodiorite

The El Verdalito granodiorite is the result of a complex magmatic evolution in a subduction setting influenced by the tectonic interaction between the Caribbean and South American plates. Petrographic analyses have revealed characteristic textures indicative of crystallization processes under fluctuating thermal and chemical conditions. These textures suggest solidification in a dynamic context, likely due to the injection of new magmatic pulses and interaction with metasomatic fluids, which altered the original conditions of the magma.

From a geochemical perspective, the parental magma displays an intermediate, calc-alkaline composition, having evolved through fractional crystallization and prolonged differentiation during its ascent through the continental crust. This process led to the formation of a high-potassium, metaluminous rock, typical of arc magmatic environments associated with subduction zones.

The pre-collisional tectonic setting provides a comprehensive explanation for both the magmatic and tectonic evolution of this granodiorite, which exhibits affinity with other igneous bodies in the Venezuelan Andes that display similar evolutionary patterns. In this regard, the El Verdalito granodiorite can be interpreted as part of a regional magmatic cycle, where subduction processes and subsequent tectonic collision have played a fundamental role in generating differentiated magmas and shaping the crust in this region.

4.2 Magma–crust interaction during the ascent and emplacement of the El Verdalito Granodiorite

During the ascent of the El Verdalito granodiorite, a complex interaction occurred between the magma and the Earth's crust. Throughout its magmatic evolution, beginning in a subduction setting, the body underwent chemical and mineralogical changes due to the incorporation of crustal materials, resulting in compositional enrichment and the development of distinct textures. Some of these petrographic features, such as poikilitic texture, reflect modifications in magma composition, leading to the assimilation of crustal elements that, upon partial melting, contributed to its differentiation and textural complexity.

The magma–crust interaction enabled sequential crystallization of minerals, consistent with a prolonged process of fractional differentiation, evidenced by plagioclase zoning and the late-stage appearance of mineral phases such as hornblende and micas. These findings underscore how the dynamic interaction between magma and crust played a crucial role in the chemical and textural evolution of this igneous body, closely tied to the long-standing tectonic subduction activity in the region.

4.3 Post-magmatic alteration stage of the El Verdalito Granodiorite

The post-magmatic alteration stage of the El Verdalito granodiorite is characterized by a series of mineralogical transformations reflecting the interaction of the rock with hydrothermal fluids under cooling conditions. These alterations include processes such as sericitization of plagioclase, chloritization of biotite, and saussuritization of plagioclase, which indicate a history of exposure to fluids rich in volatile elements. Sericitization reflects potassium incorporation during late-stage alteration, while chloritization suggests the progressive replacement of mafic minerals by more stable phases in a decreasing-temperature environment.

These post-magmatic alterations, in addition to modifying the original mineralogy, also provide insights into the cooling environment and geotectonic processes that affected the igneous body after its emplacing. The diversity of secondary mineral phases, such as sericite, chlorite, and epidote, reinforces the notion of an active hydrothermal environment, possibly associated with a fracture system that enabled fluid ingress. Thus, the post-magmatic alteration stage adds an important layer of complexity to the evolution of the granodiorite, linking its history to the prolonged tectonic activity in the Venezuelan Andes region.

References

Audemard, F.E., Audemard F.A. (2002). Structure of the Mérida Andes, Venezuela: relations with the South America-Caribbean geodynamic interaction. Tectonophysics, 345,1-4, 299-327.

Bailey, J.C., (1981). Geochemical criteria for a refined tectonic discrimination of orogenic andesites. Chemical Geology, 32. 139-154.

Bass M., Shagam R. (1959). Edades Rb-Sr de las rocas cristalinas de Los Andes merideños, Venezuela. En III Congreso Geológico Venezolano, Caracas, 1, 377-381.

Batchelor, R., Bowden, P. (1984). Petrogenetic interpretation of granitoid rock series using multicationic parameters. Chemical Geology, 48, 43-55.

Bellizzia A., Pimentel N. (1994). Terreno Mérida: Un cinturón alóctono herciniano en la Cordillera de Los Andes de Venezuela. En V Simposio Bolivariano Exploración Petrolera, Caracas, 5, 271-290.

Best, M. G. (2003). Igneous and metamorphic petrology (2nd ed.). Blackwell Publishing.

Burkley, J. (1976). Geochronology and Geochemistry of the Estanques Granite, Venezuela. Journal of the Geological Society of Venezuela, 31, 42-58.

De la Roche H., (1964). Sur l'expression graphique des relations entre la composition chimique et la composition minéralogique quantitative des roches cristallines. Présentation d'un diagramme destiné à l'étude chimico-minéralogique des massifs granitiques ou granodioritiques. Application aux Vosges cristallines. Sciences de la Terre, 9(3), 293-337.

Castro Dorado, A. (2012). Petrografía de rocas ígneas y metamórficas. Servicio de Publicaciones de la Universidad de Huelva.

De la Roche H. (1976). Sur la contribution des données chimiques à une systématique générale des roches ignées, avec, en appendice, "A diagram for a chemical classification of igneous rocks referred to their mineral contents". Sciences de la Terre, 23, 17-35.

De la Roche H. (1978). La chimie des roches présentée et interprétée d'après la structure de leur faciès minéral dans l'espace des variables chimiques. Fonctions spécifiques et diagrammes qui s'en déduisent. Application aux roches ignée. Chemical Geology, 21, 63-87.

De La Roche H., Grandclaude P., Marchal M. (1980). A Classification of Volcanic and Plutonic Rocks Using R1-R2 Diagram and Major Element Analyses Its Relationships with Current Nomenclature. Chemical Geology, 29, 183-210.

González de J. C. (1980). Geología de Venezuela y de sus Cuencas Petrolíferas. Caracas: Foninves.

Grauch R. L. (1972). Preliminary report of a Late (?) Paleozoic metamorphic event in the Venezuelan Andes. Geological Society of America, 132, 465-473.

Irving, T. N. y Baragar, W. R. (1971). A guide to the Chemical classification of the common volcanic rocks. Earth Science, 8, 523-548.

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., & Zanettin, B. (1991). A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram. Journal of Petrology, 27(3), 745-750. https://doi:10.1093/petrology/27.3.745

Le Bas M.J., Streckeisen A. (1991). The IUGS Systematic of Igneous Rocks. Geological Society London, 148, 825-833.

Le Maitre R. W. (2002). Igneous rocks a classification and glossary of terms. Recommendations of the IUGS subcommission on the Systematics of Igneous Rocks. Cambridge: Cambridge University Press.

Le Maitre, R. W. (1982). Numerical Petrology: Statistical Interpretation of Geochemical Data. Elsevier, 281 pp.

MacKenzie, W. S., Donaldson, C. H., & Guilford, C. (1997). Atlas of Igneous Rocks and Their Textures. Pearson Education, 148 pp.

Maniar, P. D., Piccoli, P. M. (1989). Tectonic discrimination of granitoids. Geological Society of America, 101, 635-643.

Pearce J. A. (1976). Statistical analysis of major element patterns in basalts. Mineral Petrology, 17, 15-43.

Pearce J. A., Norry M. J. (1979). Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Mineral Petrology, 69, 33-47.

Pearce J. A., Harris N. B. W., Tindle A. G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Petrololy, 25, 956-983.

Polat A., Kerrich R. (2006). Reading the Geochemical Fingerprints of Archean Hot Subduction Volcanic Rocks: Evidence for Accretion and Crustal Recycling in a Mobile Tectonic Regime. American Geophysical Union Monograph Series, 164, 189-213.

Schubert C. (1969). Geologic structure of a part of the Barinas Mountain front, Venezuelan Andes. Geological Society of America, 80, 3, 443-548.

Streckeisen A. (1967). Classification and nomenclature of igneous rocks. Final report of an inquiry. Mineral, 107, 144-240.

Streckeisen, A. (1976). Classification of the common igneous rocks by means of their chemical composition. Mineral, 1, 1-15.

Streckeisen A., Le Maître R.W. (1979). A chemical approximation to the modal QAPF classification of the igneous rocks. Mineral, Abh., 136, 169-206.

Van der Lelij R., Spikings R., Ulianov A. (2011). From the Rheic Ocean to the Proto-Caribbean Sea in Venezuela: 300 Ma of Magmatism in the Northern Andes. Geophysical Research, 13.

Van der Lelij, R., Spikings, R.A., Gerdes, A., Chiaradia, M., Vennemann T., Mora, A. (2019). Multi-proxy isotopic tracing of magmatic sources and crustal recycling in the Palaeozoic to early Jurassic active margin of NorthWestern Gondwana. Gondwana Research, 66, 227-245.

Van der Lelij, R., Spikings, R.A., Ulianov, A., Chiaradia, M., Mora, A. (2016). Palaeozoic to Early Jurassic history of the northwestern corner of Gondwana, and implications for the evolution of the Iapetus, Rheic and Pacific Oceans. Gondwana Research, 31, 271-294.

Van Der Lelij, R., (2013). Reconstructing north-western Gondwana with implications for the evolution of the lapetus and Rheic Oceans: a geochronological, thermochronological and geochemical study. Tesis de Doctorado para la obtención del título de Doctor en Ciencias, mención Ciencias de la Tierra, Faculté des sciences de l´Université de Geneve, Ginebra, Suiza.

Van der Lelij R. Spikings R.A. Kerr A.C., Kounov A., Cosca M., Chew D., Villagómez D. (2010). Thermochronology and tectonics of the Leeward Antilles: Evolution of the southern Caribbean Plate boundary zone. Tectonics, 29, 6, 1-30.

Winter J. D. (2001). Igneous and Metamorphic Petrology. New Jersey: Prentice-Hall.

Wood D. A. (1980). The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary Volcanic Province. Earth Planet Sci, 50, 11-30

Received: *March 21th, 2025*

Accepted: *July 26th, 2025*

Rosales, Rafael: *Assistant Professor at the School of Geological Engineering, Universidad de Los Andes. Geological Engineer. PhD candidate in Applied Economics at Universidad de Los Andes. Research interests: Interaction between quantitative and qualitative variables impacting sustained oil production through econometric models. Lecturer in Petrology, Optical Mineralogy, Igneous-Metamorphic Petrography, Mineral Deposits, Basin Analysis, and Field Geology at the School of Geological Engineering, ULA–Mérida.*
https://orcid.org/0009-0007-5988-9421

Andara, Ángel: *Full Professor at Universidad de Los Andes (ULA). PhD in Geology from the University of Oviedo, Spain. Research interests: Crystal growth, thermodynamics of solid solution–aqueous solution systems, analysis and characterization of crystalline materials, and sorption of contaminant metals on mineral surfaces. Collaborating member of the Crystal Growth and Experimental Water Geochemistry group at the Department of Geology, University of Oviedo, Spain. Email: angel.andara@gmail.com*
https://orcid.org/ 0009-0009-2302-6274

Torres, Gusbel: *Instructor Professor at the School of Geological Engineering, Universidad de Los Andes. Master's degree in Renewable Natural Resources and Environmental Management from Universidad de Los Andes, CIDIAT. Research interests include Renewable Resources and Environmental Management, Soil erosion control, and environmental impacts associated with the oil industry. Professor in the areas of Petroleum Geology, Sedimentology, and Well Logging. Email: gusbel@ula.ve*
https://orcid.org/0009-0004-0015-6184

Gómez, Jessica: *Postdoctoral Fellow at the Laboratory of Palynostratigraphy and Paleobotany, Center for Scientific*

Research and Technology Transfer to Production (CICYTTP), affiliated with the National Scientific and Technical Research Council (CONICET). Ph.D. in Geological Sciences from the National University of San Juan, Argentina. Research lines: Late Ordovician palynostratigraphy of western Gondwana; bio-chemostratigraphic correlations in the Late Ordovician; high-resolution stratigraphic analysis of the South American Paleozoic. Member of the Board of Directors (2025–2027) of the Latin American Association of Paleobotany and Palynology. Email: jcgomez@conicet.gov.ar

https://orcid.org/0000-0003-3104-2716

***Maldonado, Maricarmen:** Geological Engineer (Universidad de Los Andes, 2011). Former Wellbore Stability Engineer at PDVSA (Exploration & Production), where she worked on wellbore stability control, well cost analysis, and supervision of well operations (2013–2016). Research interests include wellbore stability and operations, petroleum geology and geochemistry, GIS applications to subsurface studies, and hydrogeochemistry of thermal springs (undergraduate thesis). Email: ing.mcmt@gmail.com*

https://orcid.org/0009-0002-3894-0375

***Caraballo, José Alejandro:** Undergraduate student in Petrography at the professional cycle of the School of Geological Engineering, Universidad de Los Andes. Email: jacaraballog@gmail.com*

https://orcid.org/0009-0004-7226-9380

***Lujano, José:** Undergraduate student in Petrography at the professional cycle of the School of Geological Engineering, Universidad de Los Andes. Email: jlujano21@gmail.com*

https://orcid.org/0009-0001-6117-494X

***Uzcátegui, Francyret:** Undergraduate student in Petrography at the professional cycle of the School of Geological Engineering, Universidad de Los Andes. Email: anakary@ula.ve*

https://orcid.org/0009-0002-2438-2560