Universidad de Investigación de Tecnología Experimental Yachay

ESCUELA DE CIENCIAS DE LA TIERRA ENERGÍA Y AMBIENTE

BIBLIOGRAPHIC REVIEW WESTERN CORDILLERA

Trabajo de integración curricular presentado como requisito para la obtención del título de Geólogo

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Urcuquí, Julio de 2023

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DEDICATORY

I want to dedicate this work to my mother, Maria Carmen Simbaña Gómez, and my father, Juan Manuel Paillacho Lema †. *They believe that education is the better inheritance that I can obtain.*

Bladimir Robinson Paillacho Simbaña

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RESUMEN

La cordillera occidental de Ecuador es un cinturón orogénico complejo y dinámico que ha sido moldeado por la interacción de las placas de Nazca y Sudamericana y la subducción de la dorsal Carnegie. La geología de esta región es poco conocida debido a la dificultad de acceder a áreas remotas. Algunos de los principales desafíos y limitaciones del estudio de la cordillera occidental son: falta de exposición de las rocas del basamento, el metamorfismo que afectó a los terrenos y la escasez de datos geocronológicos y geoquímicos confiables. Sin embargo, se han logrado algunos avances en los últimos años mediante la aplicación de nuevos métodos, como la datación con circón, la datación isotópica. Estos enfoques han ayudado a delimitar la naturaleza, origen y evolución de las diferentes formaciones.

Esta revisión bibliográfica consiste en recopilar una serie de fuentes bibliográficas relevantes relacionadas con la geología y tectónica de Ecuador. Estas fuentes incluyen artículos científicos, mapas y libros que abarcan un amplio rango de temas, desde la evolución tectónica de la región hasta la geología de formaciones específicas y la geoquímica de las rocas. Se ha realizado una exhaustiva búsqueda y selección de estas fuentes para proporcionar una visión completa y actualizada del tema en cuestión. Además, se ha prestado atención a la cronología de las publicaciones, tomando en cuenta los trabajos más antiguos hasta los más recientes, lo que permite observar la evolución del conocimiento y las investigaciones en el campo de la geología en Ecuador a lo largo del tiempo. Esta revisión bibliográfica constituye una herramienta valiosa para comprender los enfoques utilizados en los estudios geológicos y tectónicos en el Ecuador, y sienta las bases para investigaciones futuras en esta área.

Palabras clave: Acreción, Colisión, Mineral, Orogenia, Meseta y Cordillera Occidental

ABSTRACT

The western cordillera of Ecuador is a complex and dynamic orogenic belt that has been shaped by the interaction of the Nazca and South American plates and the subduction of the Carnegie Ridge. The geology of this region is poorly understood due to the difficulty of accessing remote areas. Some of the main challenges and limitations of the study of the western cordillera are: lack of exposure of the basement rocks, the metamorphism that affected the terrain, and the scarcity of reliable geochronological and geochemical data. However, some progress has been made in recent years by applying new methods such as zircon dating, isotopic dating. These approaches have helped to define the nature, origin and evolution of the different formations.

This bibliographic review consists of compiling a series of relevant bibliographic sources related to the geology and tectonics of Ecuador. These sources include scientific articles, maps, and books that cover a wide range of topics, from the tectonic evolution of the region to the geology of specific formations and the geochemistry of rocks. An exhaustive search and selection of these sources has been carried out to provide a complete and up-to-date vision of the subject in question. In addition, attention has been paid to the chronology of the publications, taking into account the oldest works to the most recent, which allows observing the evolution of knowledge and research in the field of geology in Ecuador over time. This bibliographical review constitutes a valuable tool to understand the approaches used in geological and tectonic studies in Ecuador, and lays the foundations for future research in this area.

Key Words: Accretion, Collision, Mineral, Orogeny, Plateau and Western Cordillera

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CHAPTER 1: Introduction

1.1 Conceptualization of the theme.

The Western Cordillera of Ecuador is a complex orogenic belt that resulted from the accretion of several allochthonous terranes to the South American margin during the Late Cretaceous and Early Tertiary (Vallejo et al., 2005). These terranes are composed of mafic oceanic basement rocks, overlain sedimentary sequences (Vallejo et al., 2005). The Western Cordillera has experienced significant deformation and transcurrent displacements along major N-S trending faults, resulting in variable clockwise rotations of the tectono-stratigraphic units (Margirier et al., 2023). This bibliographic review summarizes the main findings and challenges in studying the Western Cordillera of Ecuador. It focuses on its geomorphological and geochronological aspects, looking for information from the oldest to the most recent articles research.

The geomorphology of the Western Cordillera reflects its complex structural history.The Western Cordillera can be divided into three main domains: the Coastal Plain, the Coastal Range, and the Interandean Depression (Vallejo et al., 2005). The Coastal Plain is a low-lying area that extends from the Pacific Ocean to the foothills of the Coastal Range. It is composed of Quaternary alluvial and marine deposits that overlie Cenozoic sedimentary rocks. The Coastal Range is a mountainous belt that reaches elevations up to 1500 m above sea level. It is composed of Paleozoic metamorphic rocks, Jurassic-Cretaceous volcanic rocks, and Cenozoic sedimentary rocks.

Fig 01. Geological and geomorphological structure of Ecuador. (Note. Adapted From: J. Baldock, 1982)

The red rectangle represents Figure 01, the área of the western Cordillera of Ecuador where most units are present, like Macuchi, Mulaute, Pilaton, Naranjal, Angamarca, Yungilla, Natividad, Pallatanga, San Juan and Pujili Units.

The Interandean Depression is a wide valley that separates the Western Cordillera from the Eastern Cordillera. It is filled with Neogene-Quaternary volcanic and sedimentary deposits that overlie Paleozoic-Mesozoic basement rocks, also crossed by several active faults that accommodate part of the deformation related to the subduction of the Carnegie Ridge (Margirier et al., 2023).

The geochronology of the Western Cordillera is based on various radiometric dating techniques applied to different rock types and minerals. The most commonly used methods are U/Pb zircon dating for igneous and metamorphic rocks, $^{40}Ar/^{39}Ar$ dating for mafic basement rocks and volcanic rocks, and fission-track and (U-Th)/He dating for low-temperature thermochronology. These methods have been used to constrain the age, provenance, and thermal history of the basement and clastic cover sequences within the different terranes of the Western Cordillera (Margirier et al., 2023).

1.2 General Objective

- Determine the degree of knowledge about the geomorphological processes and the geochronology of the different units that form the Western Cordillera of Ecuador.

1.3 Specific Objectives

- Analyze the tectonic processes that have intervened in the formation and evolution of the western mountain range, such as subduction, orogeny, and sedimentation.

- Identify the main geochronological units that make up the western Cordillera, from the Late Cretaceous to the Neogene period, and describe their geological characteristics.

- To synthesize current knowledge about the geology of the western Cordillera, highlighting the most relevant aspects and uncertainties for future research

CHAPTER 2: Methodology

The Western Cordillera is a complex tectonic unit that resulted from the accretion of oceanic terranes and island arcs to the South American continental margin during the Mesozoic and Cenozoic (J. A. Aspden & Litherland, 1992).

The methodology used in this bibliographic review process was based on a meticulous and exhaustive search, a detailed and rigorous selection, as well as a critical analysis of relevant sources in the field of geology and tectonics in Ecuador. By organizing the sources in chronological order, it will be adapted to draw a time line that allowed us to observe the evolution of knowledge in this fascinating field. The final result obtained is a complete and updated synthesis that coherently integrates and synthesizes the available information. This approach has provided us with a panoramic and deep vision of the advances and discoveries made to date, providing a solid and reliable base to understand the geology and tectonic dynamics of Ecuador as a whole.

2.1 Identification of the topic

The identification of the main subject of study, the geological evolution of the western cordillera, is fundamental for several reasons. It delimits the scope of the investigation, allowing a deep and detailed analysis of the mountainous region. In addition, it provides a solid basis for structuring the investigation and a coherent presentation of the analyzed information. By focusing on the geological evolution of this mountain range, patterns and processes that have shaped its current configuration are identified, fundamental to understanding its origin and contribution to the geodynamic context.

2.2 Search and selection of sources

The most relevant and up-to-date sources were evaluated and selected to be included in the bibliography review. The scientific quality of the publications, the relevance of the content and the reputation of the authors were taken into account. An exhaustive search was carried out in scientific databases, digital libraries and other academic resources to find relevant sources related to the topic. Scientific articles, maps and books covering different aspects of the geology and tectonics of Ecuador were included.

2.3 Chronological organization:

The selected sources were ordered chronologically, type of publication and core focus from the oldest works to the most recent. There are around 50 scientific articles, 1 map and 3 books. This allowed us to observe the evolution of research and knowledge in the field of geology and tectonics in Ecuador over time.

YEAR	Author	Title	Type of publication	Core Focus
1946	Thalmann, H. E.	Micropaleontology of Upper Cretaceous and Paleocene in Western Ecuador	Scientific Article	Paleogeography and stratigraphy
1982	Hall, M. L., & Calle, J.	Geochronological control for the main tectonic-magmatic events of Ecuador	Scientific Article	Volcanism and Volcanic Rocks in Ecuador
1982	Baldock, J. W.	Geología del Ecuador: boletín de la explicación del mapa geológico de la República del Ecuador, escala 1:1,000.000 [Mapa]	Map	Geology of Ecuador
1986	Egüez, A., & Bourgois, J.	La formacion Apagua: Edad y posicion estructural en la Cordillera Occidental del Ecuador	Scientific Article	Metamorphism and Geological Formations
1987	Lebras, M., Mégard, F., Dupuy, C., & Dostal, J.	Geochemistry and tectonic setting of pre-collision Cretaceous and Paleogene volcanic rocks of Ecuador	Scientific Article	Geochemistry and tectonics
1987	Aguirre, L., & Atherton, M. P.	Low-grade metamorphism and geotectonic setting of the Macuchi Formation, Western Cordillera of Ecuador	Scientific Article	Metamorphism and Geological Formations

1987	Roperch, P., Mégard, F., Laj, C., Mourier, T., Clube, T. M., & Noblet, C.	Rotated oceanic blocks in western Ecuador	Scientific Article	tectonics and oceanic plates
1990	Jaillard, E., Soler, P., Carlier, G., & Mourier, T.	Geodynamic evolution of the northern and central Andes during early to middle Mesozoic times: A Tethyan model	Scientific Article	Geodynamic evolution of the Andes
1992	Van Thournout, F., Hertogen, J., & Quevedo, L.	Allochthonous terranes in northwestern Ecuador	Scientific Article	tectonics and oceanic plates
1992	Aspden, J. A., & Litherland, M.	The geology and Mesozoic collisional history of the Cordillera Real, Ecuador	Scientific Article	Geodynamic evolution of the Andes
1995	Romeuf, N., Aguirre, L., Soler, P., Feraud, G., Jaillard, E., & Ruffet, G.	Middle Jurassic volcanism in the Northern and Central Andes	Scientific Article	Volcanism and Volcanic Rocks in Ecuador
1997	Chinner, G. A.	Review of the book The Metamorphic Belts of Ecuador, by M. Litherland, J. A. Aspden, & R. A. Jemielita]	Scientific Article	Metamorphism and Geological Formations
1997	Hughes, R., & Bermudez, R.	Geology of the Cordillera Occidental of Ecuador between 0°00´and 1° 00´S	Scientific Article	Geodynamic evolution of the Andes
1998	Sinton, C. W., Duncan, R. A., Storey, M., Lewis, J., & Estrada, J. J.	An oceanic flood basalt province within the Caribbean plate	Scientific Article	tectonics and oceanic plates
1998	Villamil, T., & Pindell, J. L.	Mesozoic Paleogeographic Evolution of Northern South America: Foundations for Sequence Stratigraphic Studies in Passive Margin Strata Deposited During Non-Glacial Times	Scientific Article	Paleogeography and stratigraphy
1999	Arculus, R. J., Lapierre, H., & Jaillard, É.	Geochemical window into subduction and accretion processes: Raspas metamorphic complex, Ecuador	Scientific Article	Metamorphism and Geological Formations

1999	Reynaud, C., Jaillard, É., Lapierre, H., Mamberti, M., & Mascle, G. H.	Oceanic plateau and island arcs of southwestern Ecuador: their place in the geodynamic evolution of northwestern South America	Scientific Article	Geodynamic evolution of the Andes
2000	Boland, M. L., Pilatasig, L. F., Ibadango, C. E., McCourt, W. J., Aspden, J. A., Hughes, R. A., & Beate, B.	Geology of the Cordillera Occidental of Ecuador between 0° and 1° N (Informe No. 10). CODIGEM-BGS; Proyecto de Desarrollo Minero y Control Ambiental	Book	Geology of Ecuador
2000	Lapierre, H., Bosch, D., Dupuis, V., Polvé, M., Maury, R. C., Hernandez, J., Monié, P., Yeghicheyan, D., Jaillard, E., Tardy, M., De Lépinay, B. M., Mamberti, M., Desmet, A., Keller, F., & Sénebier, F.	Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau province	Scientific Article	tectonics and oceanic plates
2001	Spikings, R. A., Winkler, W., Seward, D., & Handler, R.	Along-strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust	Scientific Article	Geodynamic evolution of the Andes
2002	Kerr, A. C., Aspden, J. A., Tarney, J., & Pilatasig, L. F.	The nature and provenance of accreted oceanic terranes in western Ecuador: Geochemical and tectonic constraints	Scientific Article	Geochemistry and tectonics

2003	Hansen, B. C. S., Rodbell, D. T., Seltzer, G. O., León, B., Young, K. R., & Abbott, M.	Late-glacial and Holocene vegetational history from two sites in the western Cordillera of southwestern Ecuador	Scientific Article	Metamorphism and Geological Formations
2003	Alava, J. T., & Jaillard, E.	The Rumi Cruz formation: A clastic sedimentary response to an upper Eocene accretion in the Western Cordillera of Ecuador	Scientific Article	Metamorphism and Geological Formations
2004	Chiaradia, M., Fontboté, L., & Beate, B.	Cenozoic continental arc magmatism and associated mineralization in Ecuador	Scientific Article	
2004	Jaillard, E., Ordoñez, M., Suárez, J., Toro, J., Iza, D., & Lugo, W.	Stratigraphy of the late Cretaceous-Paleogene deposits of the cordillera occidental of central Ecuador: Geodynamic implications	Scientific Article	Metamorphism and Geological Formations
2004	Mamberti, M., Lapierre, H., Bosch, D., Jaillard, E., Hernandez, J., & Polvé, M.	The Early Cretaceous San Juan Plutonic Suite, Ecuador: a magma chamber in an oceanic plateau	Scientific Article	Volcanism and Volcanic Rocks in Ecuador
2005	Vallejo, C., Winkler, W., Spikings, R., Hochuli, P., & Luzieux, L.	Geochronology and provenance analyses of allochthonous terranes of the Western Cordillera, Ecuador	Scientific Article	Metamorphism and Geological Formations
2005	Toro Álava, J., & Jaillard, E.	Provenance of the Upper Cretaceous to upper Eocene clastic sediments of the Western Cordillera of Ecuador: Geodynamic implications	Scientific Article	Metamorphism and Geological Formations
2006	Luzieux, L. D. A., Heller, F., Spikings, R., Vallejo, C. F., & Winkler, W.	Origin and Cretaceous tectonic history of the coastal Ecuadorian forearc between 1°N and 3°S: Paleomagnetic, radiometric and fossil evidence	Scientific Article	Geodynamic evolution of the Andes
2006	Vallejo, C. G., Spikings, R. A., Luzieux, L. D. A., Winkler, W., Chew, D. M., & Page, L.	The early interaction between the Caribbean Plateau and the NW South American Plate	Scientific Article	tectonics and oceanic plates

2007	Vallejo, C.	Evolution of the Western Cordillera (Late Cretaceous-Paleogene)	Scientific Article	Geodynamic evolution of the Andes
2009	Vallejo, C., Winkler, W., Spikings, R., Heller, F., & Bussy, F.	Mode and timing of terrane accretion in the forearc of the Andes in Ecuador	Book	Geodynamic evolution of the Andes
2010	Cordani, U. G., Fraga, L. M., Reis, N., Tassinari, C. C. G., & Brito-Neves, B. B.	On the origin and tectonic significance of the intra-plate events of Grenvillian-type age in South America	Scientific Article	Geochemistry and tectonics
2011	Chew, D. M., Cardona, A., & Mišković, A.	Tectonic evolution of western Amazonia from the assembly of Rodinia to its break-up	Scientific Article	Geodynamic evolution of the Andes
2013	Chiaradia, M.	Copper enrichment in arc magmas controlled by overriding plate thickness	Scientific Article	Geochemistry and tectonics
2014	Alvarado, A., Audin, L., Nocquet, J. M., Lagreulet, S., Segovia, M., Font, Y., Lamarque, G., Yepes, H., Mothes, P., Rolandone, F., Jarrín, P., & Quidelleur, X.	Active tectonics in Quito, Ecuador, assessed by geomorphological studies, GPS data, and crustal seismicity	Scientific Article	Tectonics
2015	Spikings, R., Cochrane, R., Villagomez, D., Van der Lelij, R., Vallejo, C., Winkler, W., & Beate, B.	The geological history of northwestern South America: from Pangaea to the early collision of the Caribbean Large Igneous Province (290–75 Ma)	Scientific Article	Geodynamic evolution of the Andes

2016	Vallejo, C., Soria, F., Tornos, F., Naranjo, G., Rosero, B., Salazar, F., & Cochrane, R.	Geology of El Domo deposit in central Ecuador: a VMS formed on top of an accreted margin	Scientific Article	Geology of Ecuador
2016	Alvarado, A., Audin, L., Nocquet, J. M., Jaillard, E., Mothes, P., Jarrín, P., Segovia, M., Rolandone, F., & Cisneros, D.	Partitioning of oblique convergence in the Northern Andes subduction zone: Migration history and the present-day boundary of the North Andean Sliver in Ecuador	Scientific Article	Geodynamic evolution of the Andes
2017	Cawood, P. A., & Pisarevsky, S. A.	Laurentia-Baltica-Amazonia relations during Rodinia assembly	Scientific Article	Geochemistry and tectonics
2017	Valarezo, M., Vallejo, C., Horton, B. K., Winkler, W., Spikings, R., Esteban, J., & Jackson, L. J.	Sedimentology and provenance analysis of the Alamor Lancones Basin, southern Ecuador: A late Cretaceous pre-accretionary forearc basin	Scientific Article	Geology of Ecuador
2019	Griffis, N. P., Montanez, I. P., Mundil, R., Richey, J., Isbell, J., Fedorchuk, N., Linol, B., Iannuzzi, R., Vesely, F., Mottin, T., da Rosa, E., Keller, B., & Yin, Q. Z.	Coupled stratigraphic and U-Pb zircon age constraints on the late Paleozoic icehouse-to-greenhouse turnover in south-central Gondwana	Scientific Article	Paleogeography and stratigraphy
2019	Jackson, L. J., Horton, B. K., & Vallejo, C.	Detrital zircon U-Pb geochronology of modern Andean rivers in Ecuador: Fingerprinting tectonic provinces and assessing downstream propagation of provenance signals	Scientific Article	Geochemistry and tectonics

2019	Vallejo, C., Spikings, R. A., Horton, B. K., Luzieux, L., Romero, C., Winkler, W., & Thomsen, T. B.	Late Cretaceous to Miocene stratigraphy and provenance of the coastal forearc and Western Cordillera of Ecuador: Evidence for accretion of a single oceanic plateau fragment	Scientific Article	Geology of Ecuador
2019	Sillitoe, R. H., & Perelló, J.	Porphyry copper systems: An introduction	Book	Geochemistry and tectonics
2020	Baize, S., Audin, L., Alvarado, A., Jomard, H., Bablon, M., Champenois, J., Espin, P., Samaniego, P., Quidelleur, X., & Le Pennec, J. L.	Active tectonics and earthquake geology along the Pallatanga fault, Central Andes of Ecuador	Scientific Article	Geochemistry and tectonics
2020	Vallejo, C. A., Almagor, S. M., Romero, C. A., Herrera, J. L. G., Escobar, V. M., Spikings, R. A., Winkler, W., & Vermeesch, P.	Sedimentology, provenance and radiometric dating of the Silante Formation: Implications for the Cenozoic evolution of the Western Andes of Ecuador	Scientific Article	Geology of Ecuador
2021	Vallejo, C., Romero, C., Horton, B. K., Spikings, R. A., Gaibor, J., Winkler, W., Esteban, J. J., Thomsen, T. B., & Mariño, E.	Jurassic to early Paleogene sedimentation in the Amazon region of Ecuador: Implications for the paleogeographic evolution of northwestern South America	Scientific Article	Geology of Ecuador

2021	Margirier, A., Strecker, M. R., Reiners, P. W., Thomson, S. N., Casado, I., George, S. W. M., & Alvarado, A.	Late Miocene exhumation of the western Cordillera, Ecuador, driven by increased coupling between the subducting Carnegie Ridge and the South American continent	Scientific Article	Geodynamic evolution of the Andes
2021	Berrezueta, E., López, K., González-Menéndez, L., Ordóñez-Casado, B., & Benítez, S.	Ophiolitic rocks and plagiorhyolites from SW Ecuador (Cerro San José): Petrology, geochemistry and tectonic setting	Scientific Article	Geology of Ecuador
2021	Villares, F., Garcia-Casco, A., Blanco-Quintero, I.F., Montes, C., Reyes, P.S., & Cardona, A.	The Peltetec ophioliticbelt (Ecuador): a window to the tectonic evolution of the Triassic margin of western Gondwana	Scientific Article	Geology of Ecuador
2022	Jaillard, E.	Late Cretaceous-Paleogene orogenic build-up of the Ecuadorian Andes: Review and discussion	Scientific Article	Geodynamic evolution of the Andes
2022	Jaillard, E.	Late Cretaceous-Paleogene orogenic build-up of the Ecuadorian Andes:Review and discussion	Scientific Article	
2023	Margirier, A., Strecker, M. R., Reiners, P. W., Thomson, S. N., Casado, I., George, S. W. M., & Alvarado, A.	Late Miocene exhumation of the western Cordillera, Ecuador, driven by increased coupling between the subducting Carnegie Ridge and the South American continent	Scientific Article	tectonics and oceanic plates

Table 1: Resources consulted as guidance for conducting this literature review

2.4. Analysis and synthesis

A critical reading of each source was carried out, extracting the relevant information and highlighting the most significant findings. The methodologies used in the studies were identified and relationships and connections between the different sources were established.

2.5 Writing the bibliographic review

A text was written that integrates the information collected from the different sources, following a logical and coherent structure. Adequate citations and bibliographic references were included to support the claims and provide credit to the original authors.

In summary, the methodology used in this literature review was based on an exhaustive search, careful selection, and critical analysis of relevant sources on the geology and tectonics of Ecuador. The chronological order of the sources allowed us to observe the evolution of knowledge in this field, and the final result is a coherent and updated synthesis of the available information.

CHAPTER 3: History Geology Evolution of Ecuador Region.

This paragraph summarizes the main geological eras in Ecuador's history, highlighting the key events and processes that shaped its geology.

3.1 Precambrian

Rodinia is known as Mesoproterozoic Supercontinent. It was formed around 1200-1000 Ma when different cratons were together due to plate convergence. (See Fig 02). The tectonic collision between Laurentia and Amazonia cratons produced two orogenic belts, Grenville and Susan (Cawood & Pisarevsky, 2017). At the current time, those cratons are along of America Continent. (Cordani et al., 2010).

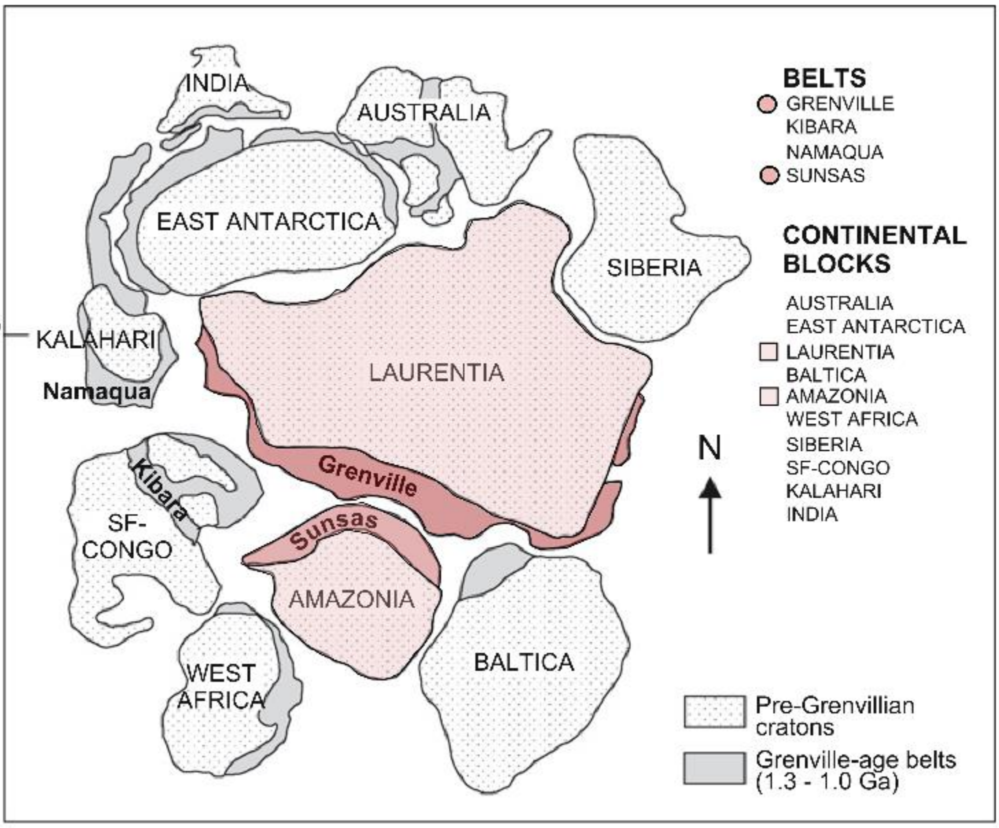

Fig 02. Reconstruction ancient Geology of Rodinia. (Note. Adapted From: Cordani et al., 2010)

The ancient metamorphic rocks around 1.2-1.3 Ga in the Colombian Andes resemble the Greenville belt in eastern Canada. Even Susan belt was located in eastern Bolivia and Southeast of Perú (Chew et al., 2011). Those orogeny extensions can be part of NE-SW of the geology of Ecuador due to similar tectonic evolution with their bordering countries.

3.2 Paleozoic

Ecuador's Paleozoic geology is marked by a complicated tectonic past that included numerous instances of subduction, collision, magmatism, metamorphism and sedimentation (Jackson et al., 2019). The Peltetec Complex (Villares et al., 2021) , which is depicted in violet in Fig 03 and comprises amphibolites, gneisses and schists from the Neoproterozoic to Cambrian periods, contains Ecuador's most ancient rocks. These rocks were penetrated by granitoids and covered by Paleozoic sedimentary and volcanic rocks from the Macuchi Group and Alao Formation. The Macuchi Group is primarily made up of quartzites, shales and limestones from the Ordovician to Devonian periods, while the Alao Formation contains volcaniclastic rocks, lavas and pyroclastics from the Carboniferous to Permian periods (Griffis et al., 2019).

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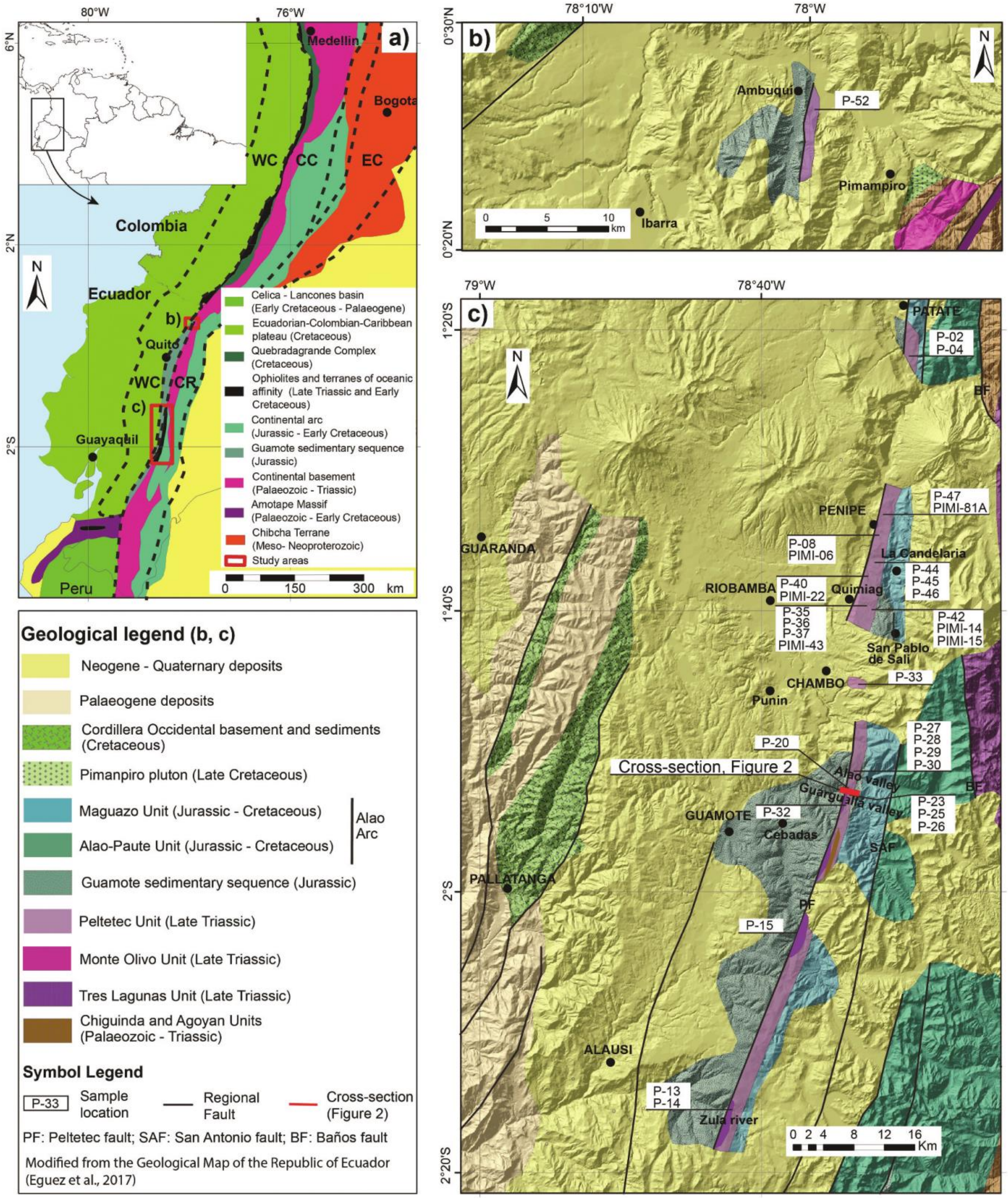

Fig 03. Illustrative outline of geological configurations in the Northern Andes and the positioning of the Pelpetec Unit. (Taken From :Villares et al., 2021)

The Paleozoic rocks of Ecuador record the evolution of a continental margin that was affected by the closure of the Rheic Ocean and the formation of Pangea (Jaillard et al., 2000). The Paleozoic rocks also preserve evidence of paleoclimatic changes, such as glacial deposits in the Carboniferous and Permian, and paleosols that indicate arid to semi-arid conditions in the late Paleozoic (Sheldon & Tabor, 2009). Glaciation deposits are the sediments left behind by glaciers that have retreated or melted. In the western Cordillera of Ecuador, glaciation deposits are found on some of the highest peaks, mostly of volcanic origin, with small ice caps and outlet glaciers (Hansen et al., 2003). These peaks include Cotacachi, Iliniza, Carihuairazo, and Chimborazo in the Cordillera Occidental, and Cayambe, Saraurcu, Antisana, Sincholagua, Cotopaxi, Quilindaña, Cerro Hermoso, Tungurahua, Altar, Cubillín, Sangay, Collay, and Cerro Ayapungo in the Cordillera Oriental (Hansen et al., 2003).

3.3 Mesozoic

A significant aspect of Ecuador's geological history during the Mesozoic era is the incorporation of the Amotape-Chaucha terrane, which underwent partial subduction beneath an existing continental arc system of the same period (Arculus et al., 1999). The Amotape-Chaucha terrane consists of Triassic mafic and granitoid rocks of the oro methamorphic complex. Also the component eclogite, blueschist and amphibolite of the Raspas metamorphic complex. These rocks were previously subducted but brought to the surface with tectonic activity (Aspden & Litherland, 1992). Another important aspect of the Mesozoic geology of Ecuador is the breakup of the supercontinent Gondwana, which is recorded by S-type granite plutons in the Triassic, followed by the intrusion of calc-alkaline batholiths in the Jurassic (Aspden & Litherland, 1992). These plutons and batholiths are related to subduction and magmatism along the western margin of South America (Chinner, 1997).

An additional characteristic observed in the Mesozoic geological landscape of Ecuador is the amalgamation of oceanic basalts that originated during the Jurassic and Cretaceous periods. These basalts, along with tuff, metasedimentary, and sedimentary rocks, comprise a belt of basalt and diabase stretching north to south within Ecuador (Aspden & Litherland, 1992). These rocks are part of a separate terrane that was added to the edge of the continent around 130 million years ago (Chinner, 1997) At the Mesozoic geology of Ecuador is the onset of Andean orogeny, which began in the Late Cretaceous and continued into the Cenozoic (Jaillard, 2022) . The Andean orogeny involved compression, uplift, deformation and volcanism along the western margin of South America, as a result of convergence between the Nazca and South American plates. The Andean orogeny created two main mountain ranges in Ecuador: the Western Cordillera WC and the Eastern Cordillera EC, separated by an inter-Andean depression ID. (Villamil & Pindell, 1998)

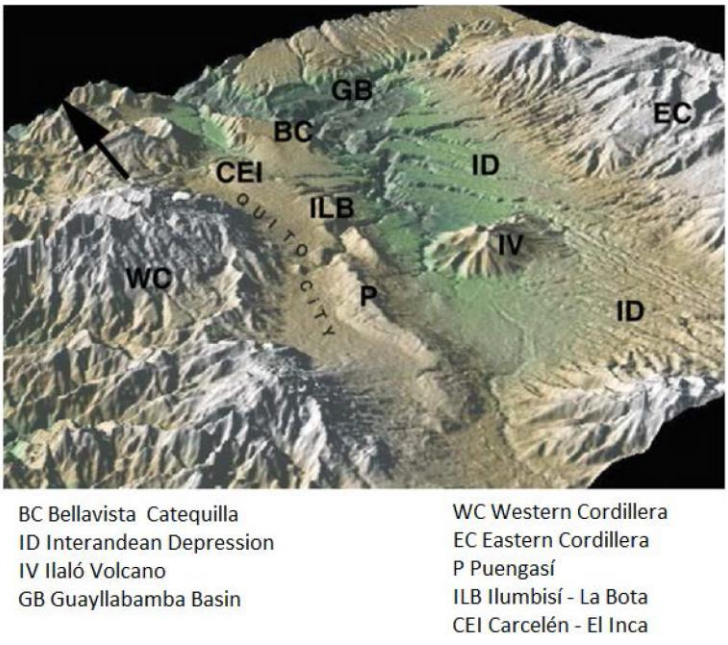

Fig 04. Three-dimensional view of Quito basin in the Interandean Depression. (Taken From: Alvarado et al., 2014)

3.4 Cenozoic.

During the Cenozoic era, the geology of Ecuador was significantly impacted by the accretion of oceanic terranes to the western edge of the continent. This formed a belt of basalt and diabase, along with tuff, metasedimentary and sedimentary rocks that extended north-south into Ecuador. This event took place around 130 million years ago in the early Cretaceous and was caused by the subduction of oceanic crust beneath the South American plate. Another major event was the intrusion of calc-alkaline batholiths in the Paleogene (66-23 million years ago), which are associated with porphyry copper and epithermal gold deposits (Aspden & Litherland, 1992)..

These batholiths are composed mainly of granodiorite and tonalite and are found in the Eastern Cordillera and Interandean Depression of Ecuador Fig 05 . They may have originated from an enriched mid-ocean ridge basalt (MORB) source and reflect the magmatic activity related to the process of the Nazca plate descending beneath the South American plate, known as subduction, is taking place (Chiaradia et al., 2004; Chiaradia, 2013). Another significant event was the intrusion of calc-alkaline batholiths in the Jurassic and Cretaceous, which are related to the subduction of oceanic crust and the formation of continental arcs (Romeuf et al., 1995). These batholiths are composed mainly of granodiorite, tonalite and quartz diorite and are exposed in the Western Cordillera and parts of the Eastern Cordillera. They are associated with porphyry copper deposits and epithermal gold deposits that formed in the Paleogene (Eocene to Miocene;) (Chiaradia, 2013).

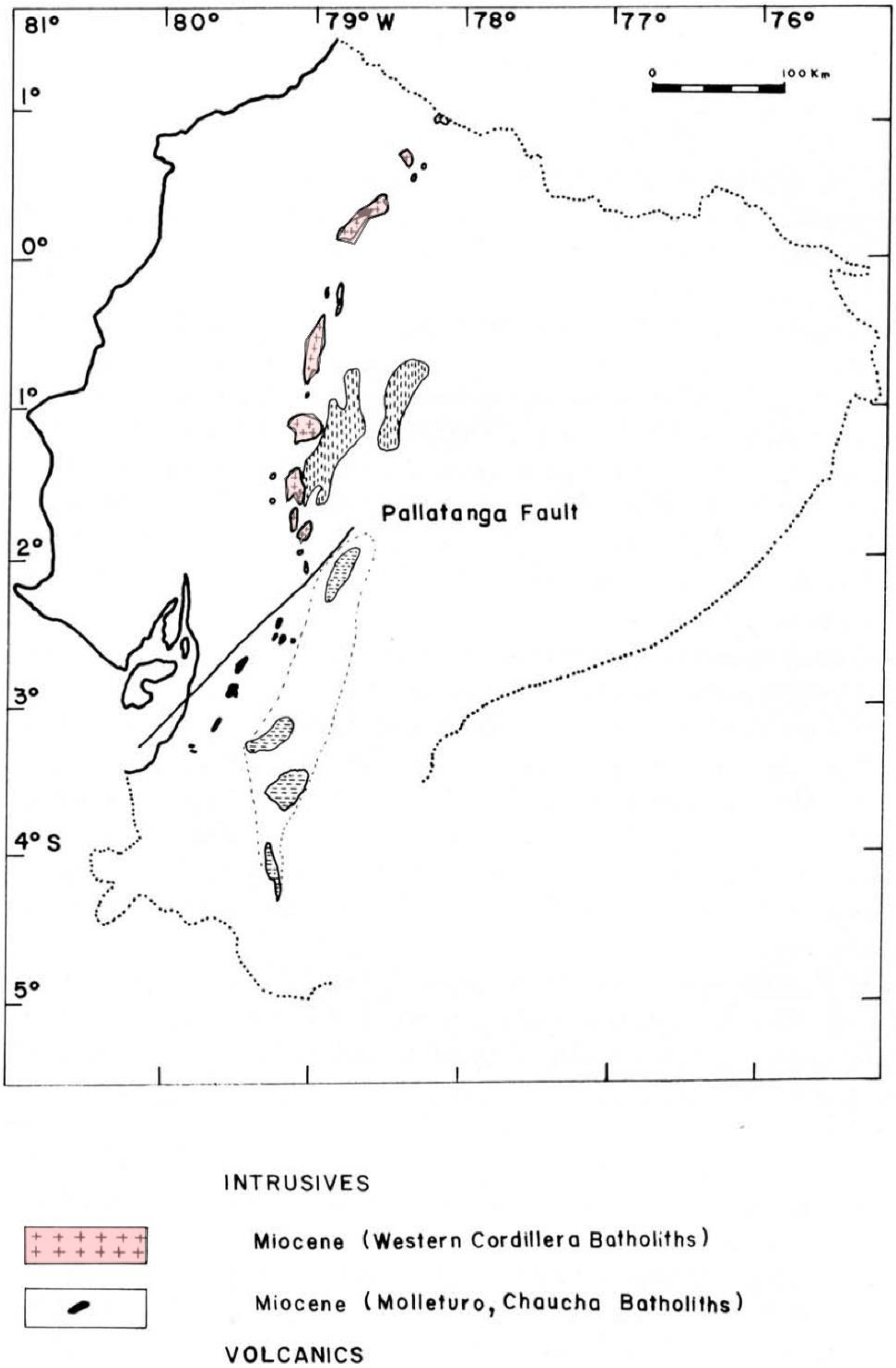

Fig 05. Distribution of Neogene Volcanic and Plutonic Rocks. (Taken From:Hall & Calle, 1982)

CHAPTER 4: Geological Framework of the Western Cordillera

4.1 Geologic Setting

Ecuador Region is part of a convergent active zone where the Nazca Plate is subducting below the South America Plate with a mean velocity of 58 mm per year and an angle between 25° to 35° concerning the spreading of Cocos-Nazca oceanic crust (Vallejo, 2007). Ecuadorian region it's divided into four areas from the East to the West.

The first is Oriente Basin; the sediments correspond to the Cretaceous to the present period, and the retro arc basin formation is due to the growth of the Andean Cordillera. The second is Eastern Cordillera, known as Real Cordillera, conformed by metamorphic rocks.

The third is Western Cordillera, conformed by magmatic rocks. Between both cordilleras, there is a separation known as Interandean Valley, which is composed of volcanic arc volcanic sediments, and finally, the Coastal Zone is formed by deposits from Paleogene to Neogene Sediments (Toro Álava & Jaillard, 2005)

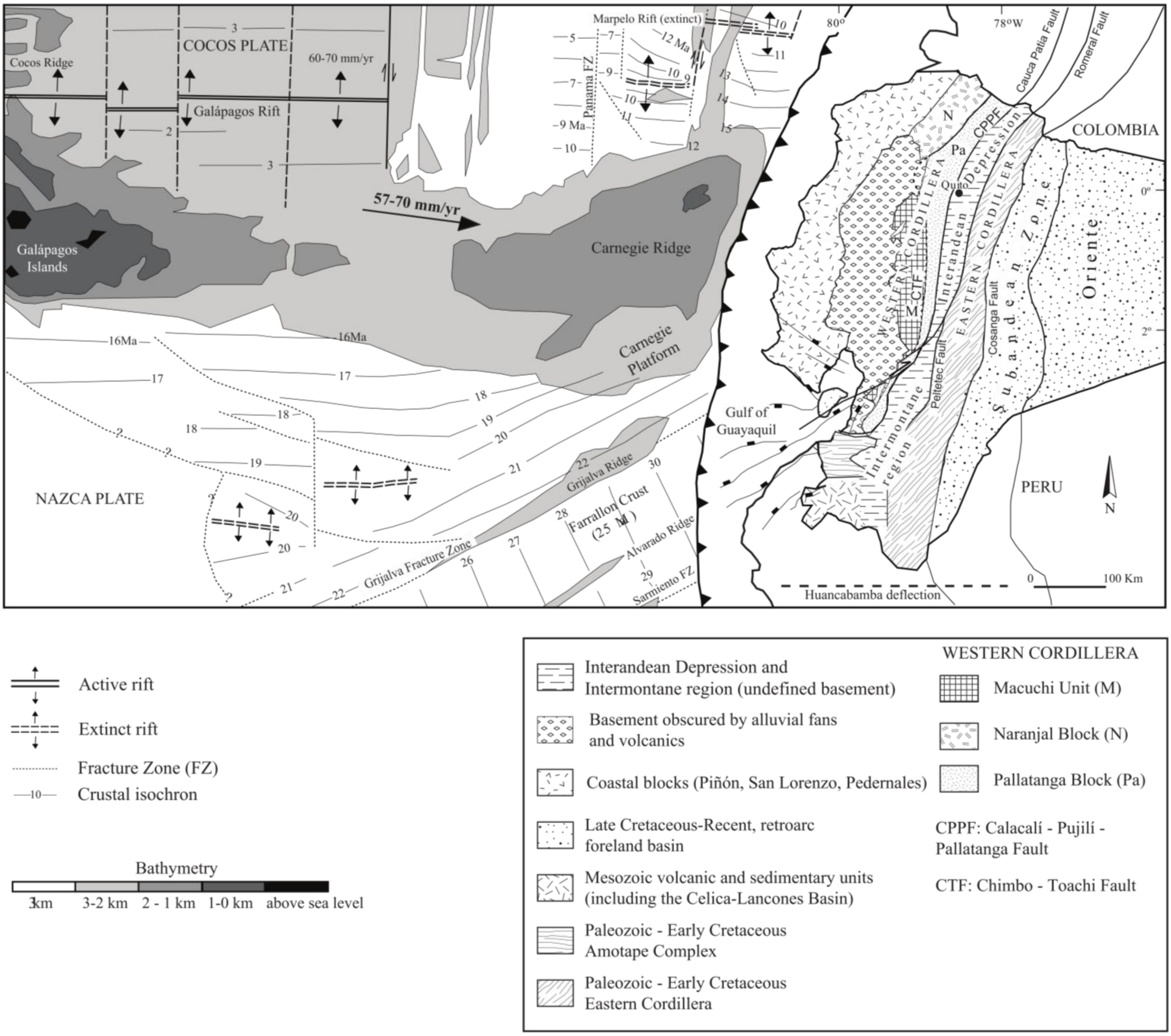

Fig 06. Geological setting of Ecuador, bathymetry, and magnetic anomalies of the Nazca Plate.

(Taken From: C.Vallejo, 2007)

4.2 Geology of Western Cordillera of Ecuador

The Western Cordillera has three main units that have been uplifted: the Macuchi Unit, the Naranjal Block, and the Pallatanga Block. Analysis of rare earth elements (REE) indicates that the Macuchi Unit is an oceanic island arc with rocks such as tholeiites and dacites (Roperch et al., 1987). Along the Western Cordillera's margin with the Toachi Fault are outcrops of massive andesitic lavas and pillow basalts similar to those found in southern Colombia. Additionally, sediments containing radiolarian fossils discovered in the Naranjal River have been dated to the Late Campanian (Kerr et al., 2002).

The principal characteristic of the Pallantanga unit is turbiditic deposits that correspond to Late Cretaceous-Paleocene. Also Pallatanga Unit is part of a fragment from oceanic Pleateu elevated through the Western Cordillera in the Late Cretaceous period (Toro Álava & Jaillard, 2005).

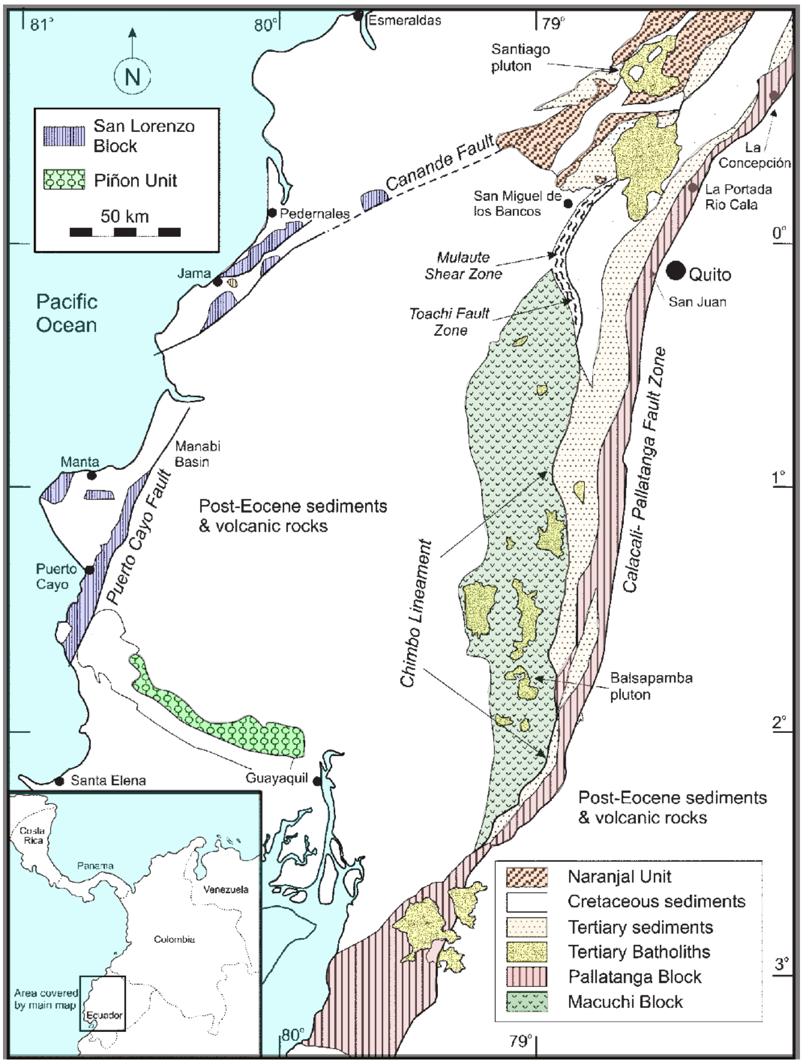

Fig 07. Geological sketch map of Ecuador, showing the main units. (Note. Adapted From: Kerr et al., 2002)

4.3 Principal Geologic Faults

4.3.1 CCPP (Chingual Cosanga Pallatanga Puna) fault

The Chingual-Cosanga-Pallatanga-Puna (CCPP) fault system is a major active tectonic feature in the Western Cordillera of Ecuador it belongs to a broad regional shear zone where right-lateral movement occurs, facilitating the displacement of the North Andean Sliver in relation to the South American continental plate (Baize et al., 2020). The CCPP fault system consists of several segments with different orientations and kinematics, such as the NE-SW Pallatanga strike-slip fault, the sub-meridian fault-related folds in the Inter-Andean valley, and the NE-SW Pisayambo fault in the Cordillera Real (Baize et al., 2020).

The CCPP fault system has produced very large crustal earthquakes (M∼7.5) in historical times, such as in 1698, 1797, and 1949, causing severe damage to the environment and human settlements (Baize et al., 2020). The slip rates along the CCPP fault system vary from ∼2 to 6 mm/yr, depending on the location and geometry of the segments (Baize et al., 2020). The CCPP fault system is therefore a key element for understanding the active tectonics and seismic hazard in Ecuador.

4.3.2 Pallatanga Fault

The Pallatanga fault is a major active fault system in Ecuador that forms part of the Chingual Cosanga Pallatanga Puna Fault System (CCPPFS), a continental-scale shear zone characterized by right-lateral movement facilitates the displacement of the North Andean Sliver in relation to the South American continental Plate (Baize et al., 2020). The fault traverses the Western Cordillera, displaying a strike-slip orientation aligned in a northeast-southwest direction. It continues northward, reaching both the Inter-Andean valley and the Cordillera Real (Alvarado et al., 2016). The fault has been responsible for large crustal earthquakes (M∼7.5) during historical times, such as those in 1698, 1797, and 1949, causing severe damage to environmental and cultural features (Baize et al., 2020).

The fault also shows evidence of surface ruptures and morphological anomalies in Holocene deposits, indicating long-term seismic activity (Baize et al., 2020). Based on new geological data and digital elevation models, the slip rate of the Pallatanga fault has been estimated to range from ∼2 to 6 mm/yr for different segments of the fault zone (Baize et al., 2020). The study of the Pallatanga fault is important for understanding the active tectonics and earthquake geology of the Central Andes of Ecuador.

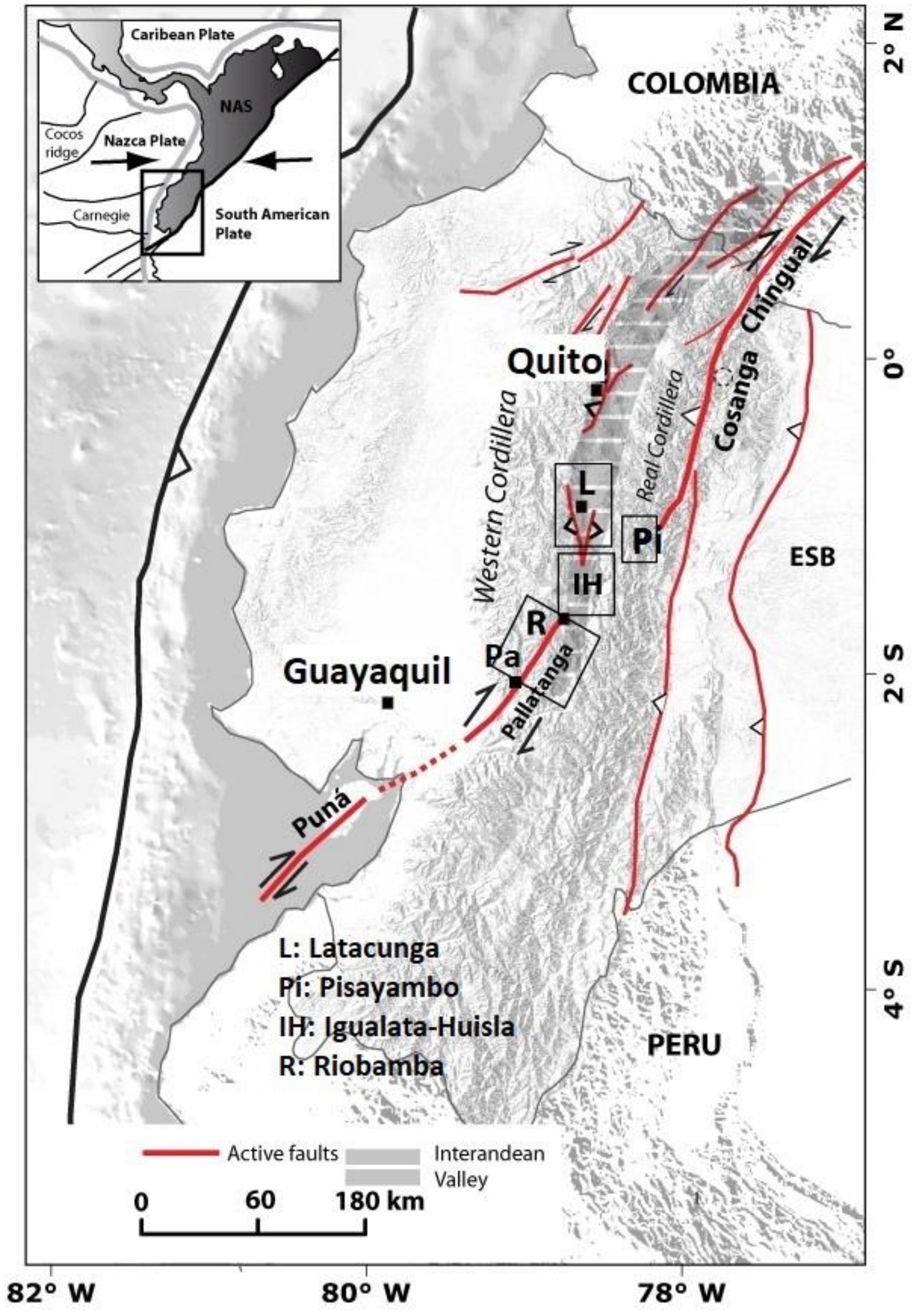

Fig 08. An overview of geodynamics emphasizing the crucial function of the CCPP (Chingual Cosanga Pallatanga Puna) fault zone in separating the South American Plate from the North Andean. (Taken From: Baize et al., 2020)

CHAPTER 5. Geological Evolution of the Western Cordillera: Previous and Current Theories

5.1 Previous Theories.

5.1.1 Proposal Theory by Lebras.

This theory suggested that the east-dipping subduction of oceanic crust of normal thickness produced the Macuchi Arc and Intraoceanic arc that formed on top of the Piñon Formation. According to these scientists, the Macuchi arc is Turonian-Santonian in age and was contemporary with the Celica arc in southern Ecuador and the Cayo Formation in the coastal region. (Lebras et al., 1987). This shows a proposed paleogeographic reconstruction of the Coastal, Western Cordillera, and Eastern Cordillera regions during the Late Cretaceous to Oligocene period.

The figure 09 illustrates how the Caribbean Plateau extruded in the Pacific region at nearly equatorial latitudes, and how it subducted westward below an island arc sequence that formed the Rio Cala Group, San Lorenzo arc and Cayo Formation. The figure also depicts how the Piñon and Pallatanga blocks, which are composed of oceanic plateau mafic rocks, were accreted to the South American continental margin at ~ 73 Ma, and how they received detrital input from continental basement rocks and volcanic arcs during Paleocene-Eocene sedimentation.

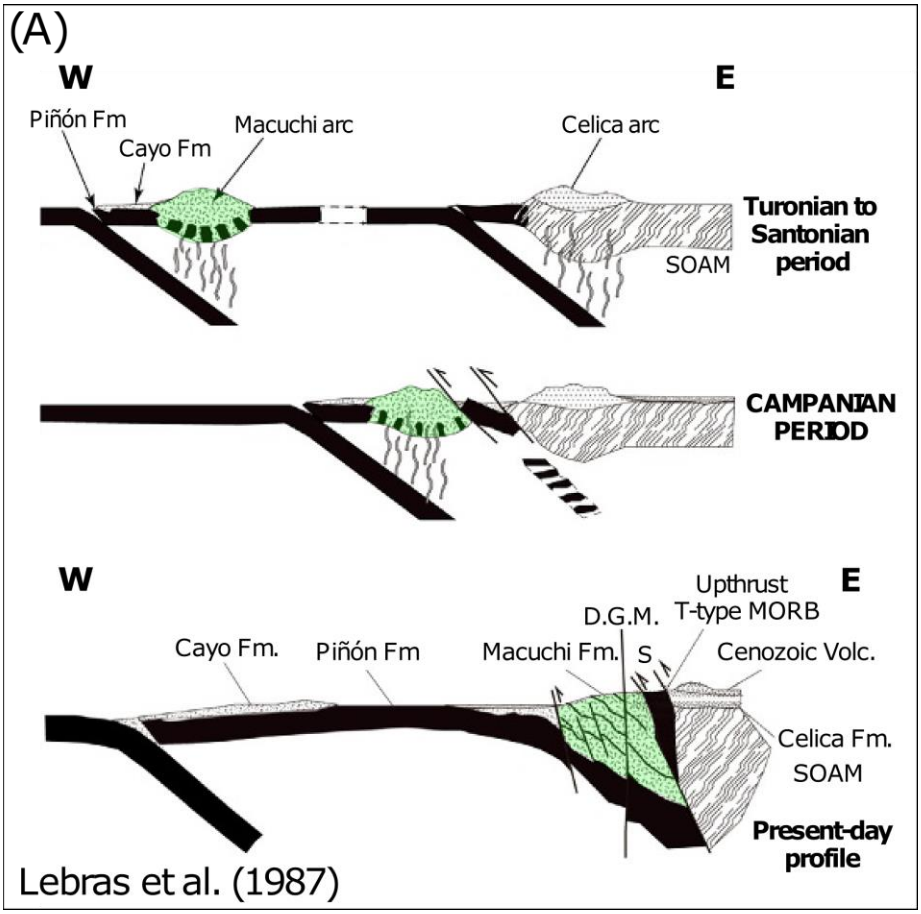

Fig.09. A Visual Guide to Proposed Plate-Tectonic Regimes through Schematic Cross-Sections. (Note. Adapted From: Lebras et al., 1987)

5.1.2 Proposal Theory by Van Thournout

The figure 10 shows a southwest-northeast movement of the Farallon Plate that produces two types of effects. In the northern part, local intraoceanic subduction with magmatic activity and possible back-arc spreading results in deposition of Lower Cretaceous to Paleocene volcanics and intrusives. In the southern part, subduction beneath an ensimatic island arc leads to deposition of tholeiitic to boninitic components of an ensimatic island arc during the Lower Cretaceous

According to (Van Thournout et al., 1992), the San Lorenzo arc and accompanying volcanic and sedimentary rocks of the Cayo Formation were created from the Early Cretaceous to Paleocene by the eastward subduction of oceanic crust beneath the Piñon Formation. The Macuchi submarine arc was created on top of accreted oceanic crust of the Piñon Formation during the middle to early Oligocene, following a westward shift in the subduction zone. At 70–50 Ma, this island arc was added to the margin, deforming the Yunguilla Formation's flyschoid continental-margin deposits. According to these authors, the Apagua unit corresponds to backarc basin deposits, while the West's San Mateo and Punta Blanca formations represent forearc deposits.

To determine that the Western Cordillera is made up of rocks from various oceanic tectonic settings, (Kerr et al., 2002) and (R. A. Hughes & Pilatasig, 2002) They had been analyzed geochemical data. These rocks include anomalously thick oceanic crust of oceanic plateau origin (Pallatanga and Piñon formations), island arc tholeiites (Naranjal and Macuchi units), and backarc basin basalts (La Portada Formation). These authors suggested that the Pallatanga block formed over a prolonged period in the Late Cretaceous. In contrast, the Late Cretaceous Naranjal and Eocene Macuchi island arcs may have formed during the Eocene along the Chimbo-Toachi and Mulaute faults, respectively, against the continental margin.

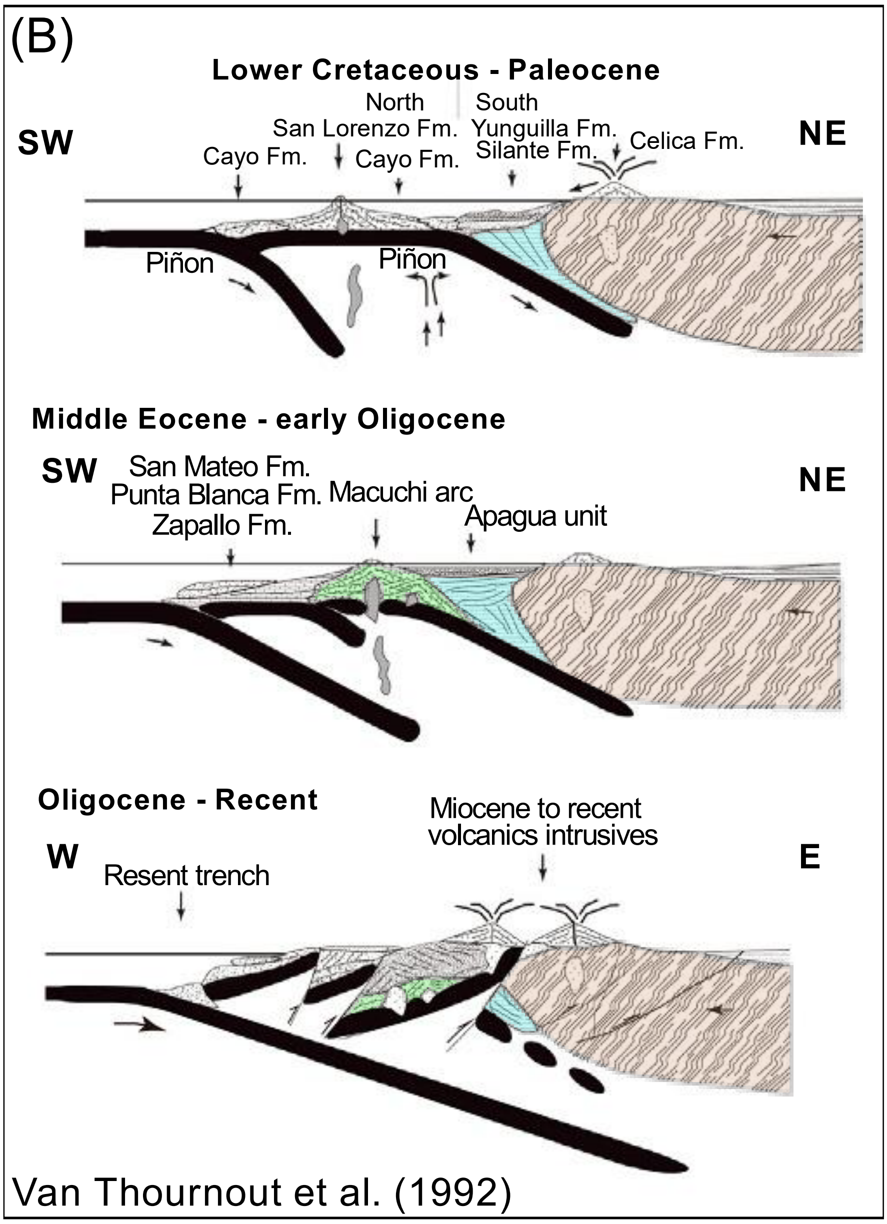

Fig 10. Van Thournout's Proposed Model for the Development of Ecuador's Western Cordillera and Coastal Region. (Note. Adapted From: Van Thournout et al., 1992)

5.1.3 Proposal Model by Kerr.

A series of schematic cross-sections over the Ecuadorian edge are shown in the figure 11 to demonstrate and explain the observed variance in the geology and timing of geological events along the length of the Cordillera Occidental. We suggest the following progression of events, beginning in the north.

(1) In Campanian period (83–74 Ma), the Pallatanga oceanic plateau collided with Ecuador's continental margin (Fig. 11a). The calc-alkaline lavas of the Rio Cala Arc, which erupted through the accreted Pallatanga plateau, were produced by a subduction zone that began near the plateau's trailing edge (Fig. 11b).

(2) Activity in the Rio Cala Arc ended during the Late Campanian–Mid-Maastrichtian period (76–70 Ma), at the same time that the Naranjal Arc began to form and a back-arc basin (represented by the La Portada Unit) opened between it and the remaining portions of the Rio Cala Arc (Fig. 11c)

3) The Naranjal Arc's activity was transient and is assumed to have ended during the early Maastrichtian period with the approach and docking of an oceanic plateau. However, the La Portada back-arc basin did not completely shut until the early to early mid-Eocene, possibly because the impact occurred oblique to the continental edge (Fig. 11c).

(4) As a result of docking with the Naranjal plateau, the subduction zone moved backward to behind the Piñon plateau's trailing edge, causing calc-alkaline calc-alkaline lavas to erupt through the oceanic plateau and the San Lorenzo Arc to form (Fig. 11d).

5) Due to persistent compression (probably dextral) due to stress, the La Portada back-arc basin gradually closed over the Paleocene and early Eocene periods (Fig. 11e and f). The Mulaute Shear Zone, which symbolizes the closure, is located in northern Ecuador and was finished at the latest by early mid-Eocene epoch.

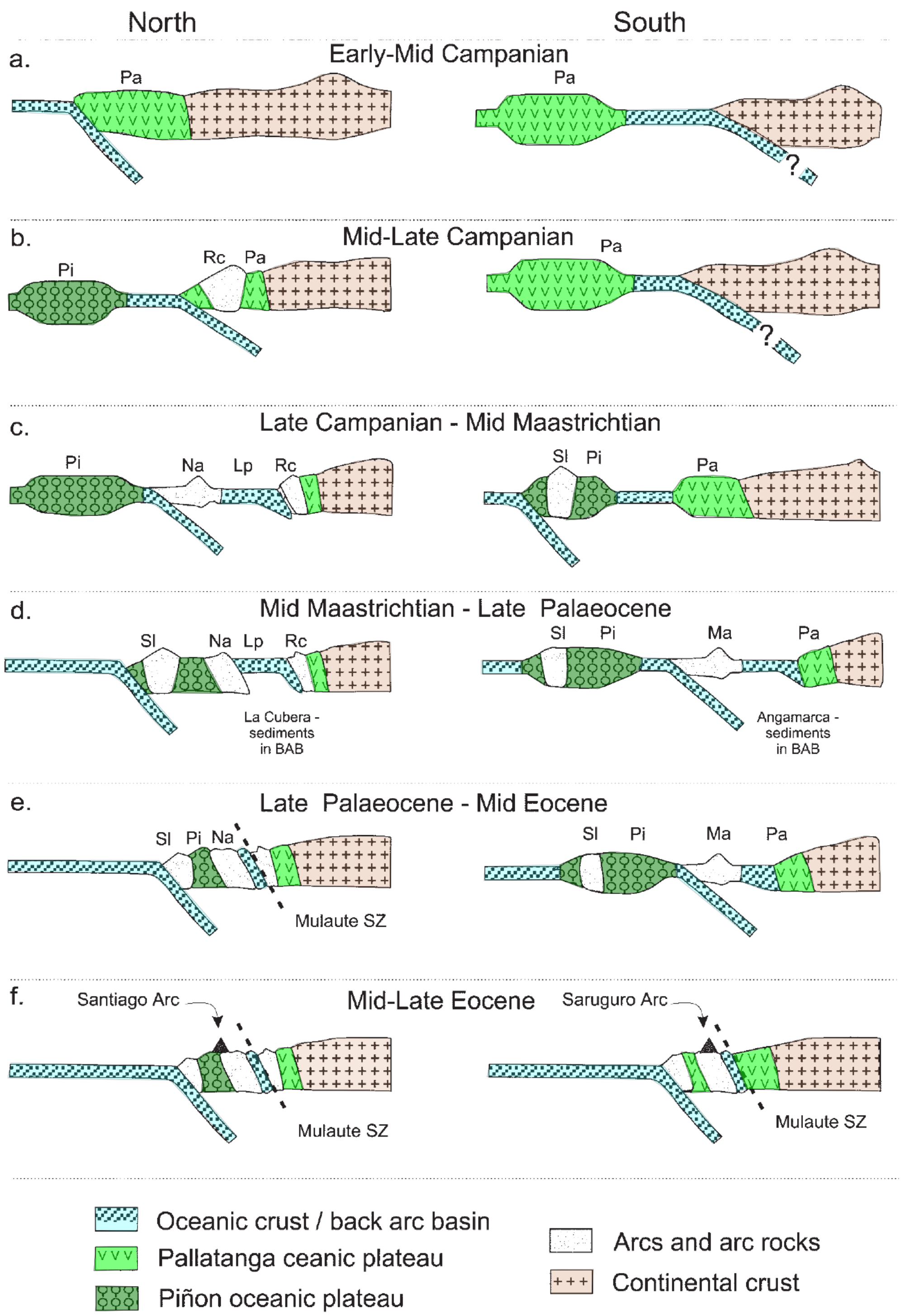

Fig 11. Diagrammatic Cross-Sections Illustrating the Tectonic Evolution of Ecuador's Northern and Southern Continental Margins. (Note. Adapted From: Kerr et al., 2002)

5.2 Current Theories

5.2.1 Insights into the Geologic Progression of the Western Cordillera from the Late Cretaceous to the Oligocene

The fig 12 is divided into several panels that represent different time periods and geological events. The leftmost panel shows the Late Cretaceous period, during which marine sedimentary rocks were deposited in a shallow sea. The middle panel shows the Paleocene to Early Eocene period, during which sedimentary rocks such as sandstone and shale were deposited in alluvial fans and braided rivers. The rightmost panel shows the Middle to Late Eocene period, during which volcanic activity decreased significantly in the Western Cordillera. Instead, sedimentary rocks such as sandstone and shale were deposited in a series of intermontane basins that formed as a result of tectonic activity. The top row of panels shows the Oligocene period, during which significant uplift and deformation occurred in the Western Cordillera due to continued tectonic activity Vallejo, 2007).

The leftmost panel shows that during this time period, surface uplift within the central Western Cordillera generated an emergent land mass, as documented by an angular unconformity between the Rumi Cruz formation and the overlying Miocene Zumbagua Formation. The middle panel shows that in the northern part of the Western Cordillera, the Oligocene San Juan de Lachas Formation is deposited unconformably on top of the Eocene Laurel Formation and Late Cretaceous Pilatón Formation Vallejo, 2007). These relationships presumably match with a major Oligocene event of the Western Cordillera. Finally, the rightmost panel shows that during this time period, volcanic activity resumed in the Western Cordillera with renewed vigor.

The Macuchi Arc was active during this time period, as shown by extrusive and intrusive igneous rocks in the Western Cordillera, which yield ages of ~35 Ma. Furthermore, volcanic material from this volcanic arc can be locally found in turbidites of the Apagua Formation. The volcanic detritus was regionally distributed, because Late Eocene sedimentary rocks of the coastal region (Punta Blanca, San Mateo and Zapallo formations) received large quantities of volcanic derived minerals Vallejo, 2007).

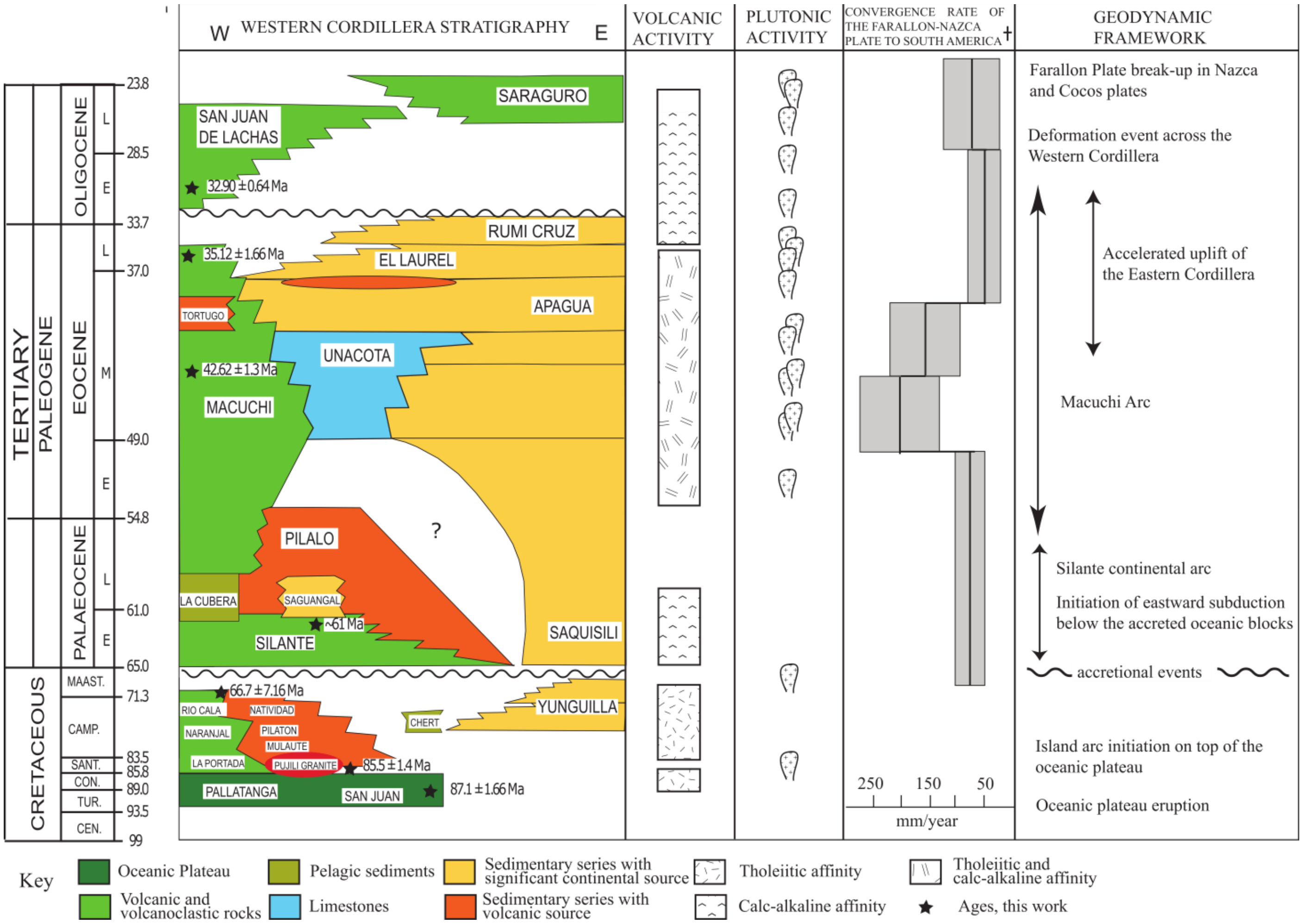

Fig 12. The Western Cordillera of Ecuador: A Study of its Geologic Evolution and Relationship with Stratigraphy, Igneous Activity and Geodynamics during the Late Cretaceous to Oligocene. (Note. Adapted From: Vallejo, 2007)

5.2.2 Insights into the Cenozoic Progression of Ecuador’s Western Cordiller

The highlighted text refers to Figure 13, which shows the Cenozoic evolution of the Western Cordillera of Ecuador. The figure has three sections (a), (b), and (c) which show the paleogeography of the region during the Paleocene and Eocene periods, respectively.

The initial uplift of the region started at the end of the Cretaceous period, which is around 66 million years ago. The Paleocene section (a) shows the Pilalo Formation, which is a submarine fan deposit that was formed during this time. The panel also shows the Tandapi arc, which was contemporaneous with the Pilalo Formation. The Tandapi arc is a volcanic arc that was active during the Paleocene period Vallejo et al., 2020.

The Eocene section (b) shows the Macuchi submarine arc, which was active during the Eocene period. The panel also shows sedimentation of the Silante Formation. The Silante Formation is a thick series of continental deposits that were deposited in an alluvial fan dominated by debris flow. The sediments found in the area originated from the erosion of a volcanic arc with a continental, calc-alkaline composition. This volcanic arc, known as the San Juan de Lachas volcanic arc, was active from the Oligocene to Miocene epochs Vallejo et al., 2020.

The section (c) of Figure 13 shows the tectonic evolution of the Western Cordillera of Ecuador during the Oligocene to Middle Miocene period (~25-16 Ma) This segment illustrates a swift elevation of both the Eastern and Western Cordilleras, accompanied by the accumulation of the Silante Formation within an intermountain basin environment. The term "intramontane basin setting" pertains to a basin situated between mountain ranges. The graphic also indicates the presence of the sea level (SL), signifying that the deposition of the Silante

Formation took place above sea level Vallejo et al., 2020.

These provides important information on the tectonic and sedimentary history of the Western Cordillera of Ecuador during the Oligocene to Middle Miocene period.

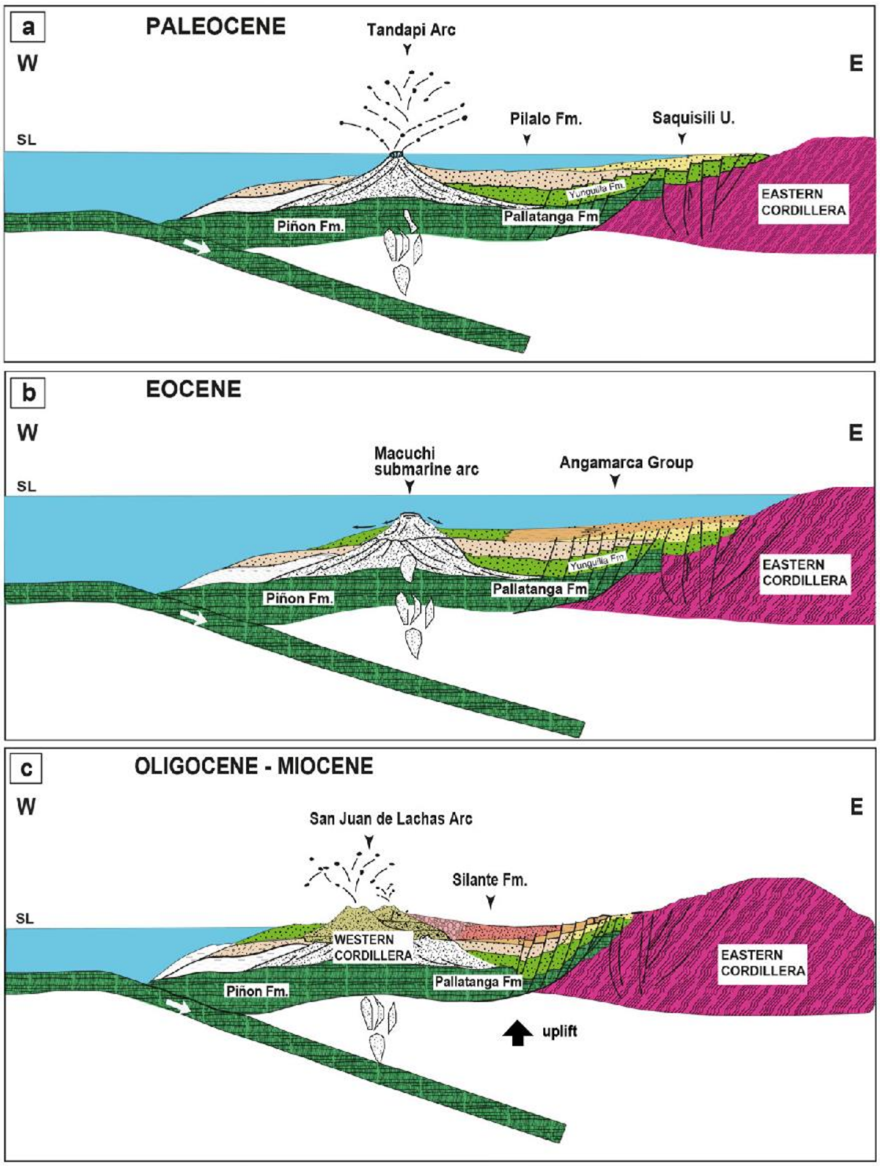

Figure 13. Tracing the Cenozoic Tectonic Development of Ecuador’s Western Cordillera. (Taken From: Vallejo et al., 2020)

5.2.3 The Western Cordillera: A Thermochronological Perspective on its Evolution

The Fig 14 shows a schematic cross-section of the Andean margin, which is a region of active tectonic activity that extends along the western coast of South America. The cross-section includes two main regions: the Western Cordillera and the Eastern Cordillera (Cordillera Real). The Western Cordillera is located closer to the Pacific Ocean and consists of volcanic and sedimentary rocks that were deposited during the Mesozoic and Cenozoic eras. The Eastern Cordillera is located further inland and consists of metamorphic rocks that were formed during earlier periods of mountain building. The thermal history envelopes shown in Fig 14 are based on thermochronological data, which provides information about how rocks have been heated or cooled over time. This data is obtained by analyzing isotopic ratios in minerals such as apatite and zircon, which are sensitive to temperature changes.

By measuring these ratios, researchers can estimate how long ago rocks were at certain temperatures and how quickly they cooled or heated up. The thermal history envelopes in Figure 14 show how different regions in the Andean margin have experienced different temperature histories over time. For example, the Western Cordillera experienced a period of rapid cooling during the Late Cretaceous, followed by a period of slower cooling during the Paleogene. This suggests that this region was rapidly uplifted during the Late Cretaceous due to tectonic activity such as subduction or mountain building. In contrast, the Eastern Cordillera experienced a more gradual cooling history throughout the Cenozoic era. This suggests that this region was uplifted earlier than the Western Cordillera, possibly during an earlier period of mountain building.

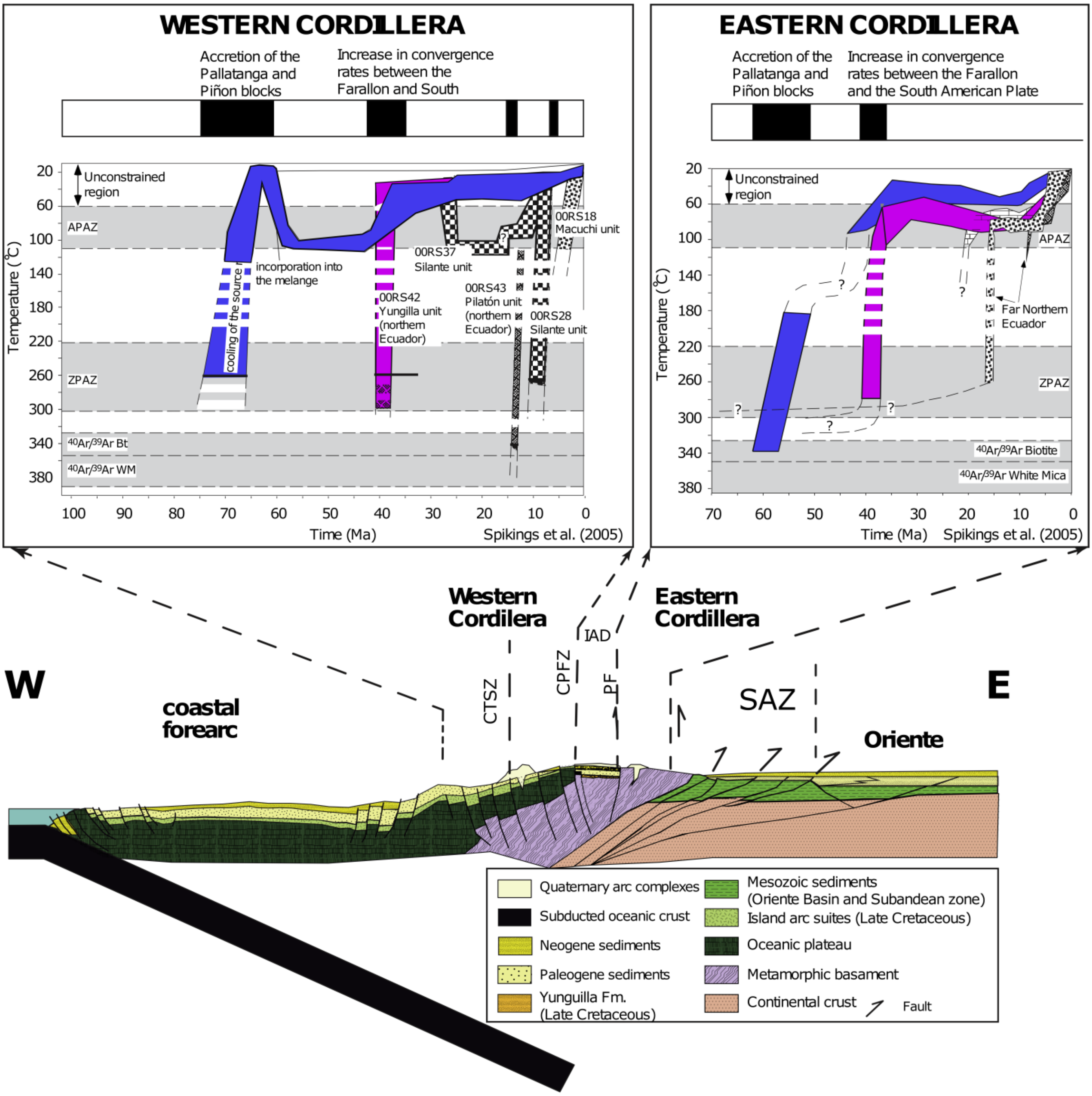

Fig 14. A cross-sectional representation of the Andean margin with thermal history envelopes for Western and Eastern Cordilleras (Cordillera Real) samples and their association with significant tectonic activity in Ecuador. (Taken From: Spikings et al., 2001)

CHAPTER 6. Geochronology of the Western Cordillera Units

6.1 Geology Description of Lithostratigraphic Units

The western Cordillera comprises several geological units that originated from the late Cretaceous to the Neogene. These units are represented in the Fig 15 proposal by (Vallejo et al., 2019) from latitude 1°00’N until 2°00’S. Although each of these units has different characteristics in terms of age and lithology, these formations are described in a stratigraphic sequence, the most ancient to recent building.

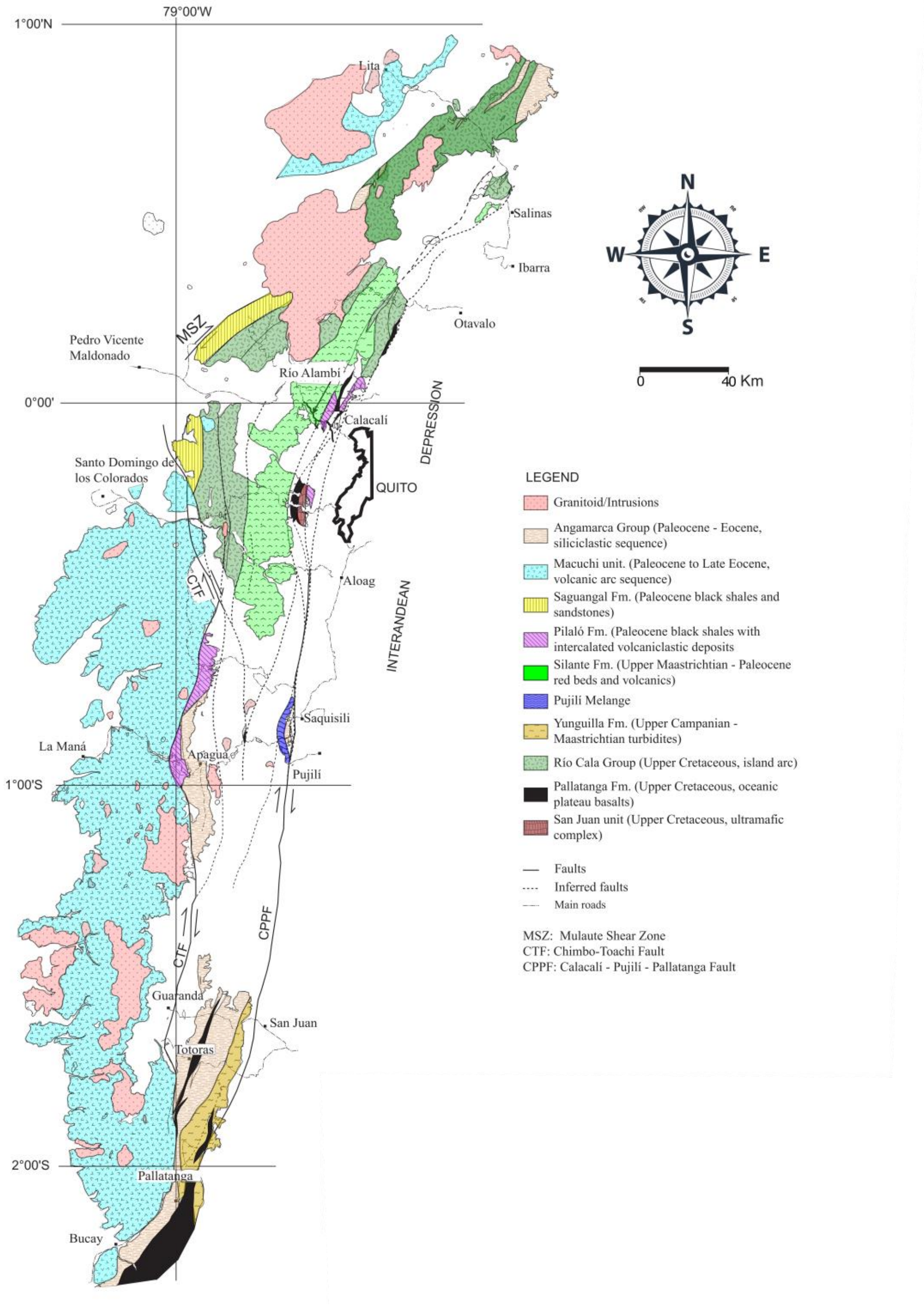

Fig 15. A simplified geological map of Ecuador's Western Cordillera was created using data from Hughes and Pilatasig (2002) and Vallejo (2007). (Note. Adapted From: Vallejo et al., 2009)

6.1.1 San Juan Unit.

The San Juan Unit is a geological formation in the Western Cordillera of Ecuador that consists of mafic and ultramafic rocks intruded by granitoids. It is interpreted as the intrusive component of an oceanic plateau that formed in the Early Cretaceous and was accreted to the South American margin in the Late Cretaceous (Mamberti et al., 2011; Vallejo et al., 2019). The San Juan Unit is exposed in several tectonic slices along the western flank of the Cordillera, where it is overlain by volcanic and sedimentary rocks of the Pallatanga Formation (Lapierre et al., 2000).

The San Juan unit comprises a sequence of cumulates ranging from dunite to gabbro, with minor pyroxenite and anorthosite, that show evidence of fractional crystallization and magma mixing processes (Mamberti et al., 2011; Lapierre et al., 2000). The cumulates are intruded by granitoids that have calc-alkaline to tholeiitic affinities and display isotopic signatures typical of oceanic plateaus (Mamberti et al., 2011). The granitoids have U-Pb zircon ages ranging from 123 ± 12 Ma to 87.10 ± 1.66 Ma, indicating a prolonged magmatic history of the San Juan Unit (Lapierre et al., 2000).

The San Juan Unit is considered as part of the Caribbean Plateau that formed in a mantle plume setting in the Pacific Ocean and collided with the South American margin during the Late Cretaceous (Vallejo et al., 2019). The accretion of the San Juan Unit resulted in deformation and metamorphism of the adjacent continental crust, as well as magmatism and mineralization along the continental margin (Vallejo et al., 2019). The San Juan Unit is therefore an important piece of evidence for understanding the tectonic evolution of the Western Cordillera and the interaction between oceanic and continental plates in Ecuador.

6.1.2 Pallatanga Formation

The Pallatanga block is composed of sedimentary and volcanic formations that can be divided into five categories: (1) basement rocks, which include basalts of the Pallatanga Formation and ultramafic rock of the San Juan complex; (3) Volcanoclastic rocks of Rio Cala Arc and submarine basaltic lavas from Late Cretaceous (Vallejo et al., 2019); (4) Submarine deposits of the Angamarca Group from Paleocene-Eocene (R. A. Hughes & Pilatasig, 2002); and (5) volcaniclastic rocks of calc-alkaline and subaerial volcanic from Oligocene-Miocene (Vallejo et al., 2019), and the south of Ecuador is located Saraguro Formation.

The Western Cordillera's basement, the Pallatanga Formation, contains dolerites and submarine basaltic lava. The basalts exhibit flat primitive mantle- and chondrite-normalized REE patterns and are thought to have developed in an interoceanic environment since they have a lot of chemical similarities with basalts from the Caribbean Plateau (Luzieux et al., 2006). Oceanic plateaus are often more than 10 km thick and occasionally approach 30 km (Sinton et al., 1998). What makes them challenging to subduct due to an excess of positive buoyancy. As a result, pieces of the oceanic plateau can be added to the continental margin.

Southwest of Quito, the San Juan ultramafic complex is exposed and contains stratified gabbros, dunites, and peridotites. According on REE geochemistry and isotopic evidence, the San Juan complex is thought to be the intrusive portion of an oceanic plateau. (Sinton et al., 1998).

6.1.3 Rio Cala Group

The Rio Cala Unit, as described by (Boland et al., 2000), has only been identified within the 0°-1°N region of the Western Cordillera. The most extensive exposures of this unit can be found in a fault block measuring approximately 2km by 12km, located a few kilometers east of La Portada. The Rio Cala Unit mainly consists of massive basaltic andesite to andesite lavas, along with volcaniclastic rocks that contain notable pyroxene phenocrysts.

Although the precise age of the Rio Cala Unit remains uncertain, it is thought to have originated prior to the Pallatanga Unit and may have formed at the same time as the Campanian-Maastrichtian volcaniclastic turbiditic sediments of the Natividad Unit, which can be seen to the immediate west (Boland et al., 2000)

The Rio Cala Group consists of volcanic and sedimentary layers that were formed in an intraoceanic island arc environment on top of the Pallatanga Formation. These stratigraphic layers, known as the La Portada, Mulaute, Pilatón, Natividad, and Rio Cala formations, were accumulated in the Late Cretaceous era (Vallejo, 2007).

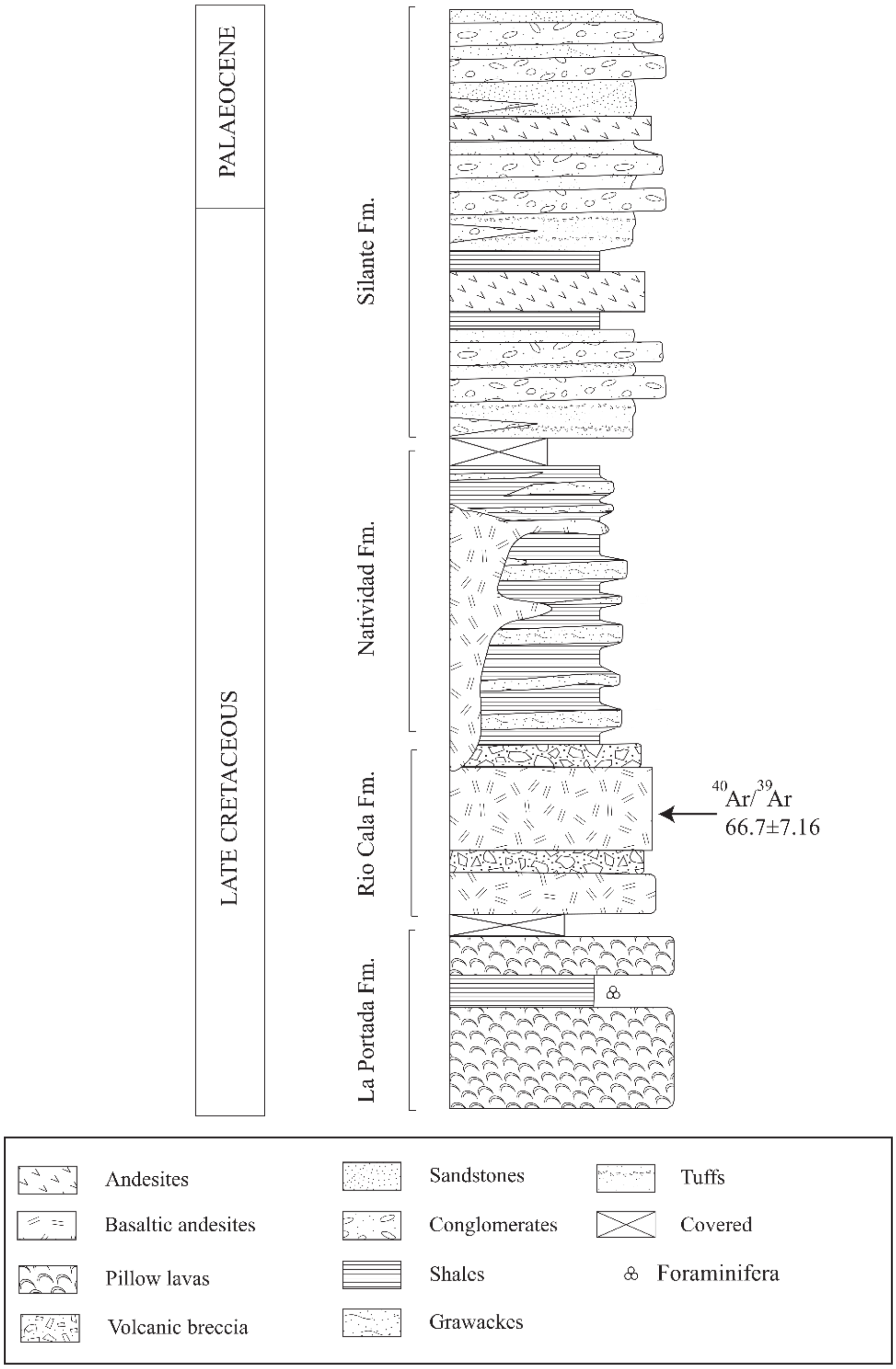

Fig 16. Idealized composite stratigraphic column of the Otavalo - Selva Alegre road section Age. (Taken From: C.Vallejo, 2007)

6.1.3.1 La Portada

Pillowed basalts and string lavas are found in the La Portada Formation along the Otavalo-Selva Alegre road stretch. Pumpellyite, chlorite, and epidote are partially recrystallized from the glassy matrix of the aphyric basalts. The volcanic rocks have undergone significant hydrothermal and oxidative alteration (Vallejo, 2007). Near the Silante Formation contact, calcite veining and zeolite filling vacuoles are frequently seen, and alteration intensifies. Although the lavas west of La Concepción hamlet are less oxidized and hydrothermal alteration is evidenced by numerous fissures filled with calcite, the lithologies in the exposures west of La Concepción are comparable to those in the Otavalo - Selva Alegre road. (Vallejo, 2007)

Along the road connecting Otavalo and Selva Alegre, pillow basalts from the La Portada Formation are exposed. To the East are turbidites from the Natividad Formation, and to the West are younger volcanoclastic rocks from the Silante Formation. Turbidites of the Natividad Formation and deformed volcanic rocks of the La Portada Formation are in tectonic contact close to La Concepción (Vallejo, 2007) .

6.1.3.2 Mulaute.

Along the Alóag-Santo Domingo road segment, the Mulaute formation has thick to medium-bedded turbidites , which are rich in plagioclase, pyroxene, and epidote. This facies, which is found west of the La Esperie Batholith, is lithologically related to the previously described Pilatón Formation of (Hughes & Bermudez, 1997). The sequence is dominated to the East by primary volcanic rocks, such as basaltic andesites, tuffs, and volcanic breccias. Epidote, pumpellyite, and chlorite are common in the volcanic rocks, which suggests a low-grade metamorphic overprint. This volcanic sequence, which produces island arc geochemical features, was formerly known as the Toachi Unit (Vallejo, 2007).

6.1.3.3 Natividad

The Natividad Formation, according to (Boland et al., 2000) is a sedimentary sequence made up of turbiditic sandstones, mudstones, cherts, intercalated lavas, and tuffs with a basaltic composition . The Otavalo - Selva Alegre route provides excellent access to lava flows and dykes that are part of the Natividad Formation. Basaltic andesites with millimeter to centimeter-sized clinopyroxene crystals make up the volcanic intercalations. Strongly silicified and tectonized, the sandstones are also rich in epidote, which is a byproduct of the low-grade metamorphism of mafic minerals.

In the Salinas - Lita road stretch , turbidites of the Natividad Formation can be seen in a coarsening-upward sequence. At this location, primary volcanic rocks with petrographic similarities to the Rio Cala Formation are intercalated with turbidites of the Natividad Formation. Due to their resemblance, (Boland et al., 2000) hypothesized that the Natividad Formation’s sediments originated from the Rio Cala basalts.

The Natividad Formation was identified as isolated exposures of marine sedimentary rocks with intercalated volcanic rocks along the eastern edge of the Western Cordillera, such as northeast of Nono town; The volcanic rocks’ lithologies and geochemistry, however, differ from those found in the type locality. Therefore, some of these exposures might not be associated with the Natividad Formation.(Vallejo, 2007)

6.1.3.4 Rio Cala

The Río Cala Formation is a geological unit that is part of the Río Cala Group, a set of volcanic and sedimentary rocks that were deposited in an intra-oceanic island arc during the Late Cretaceous in the Western Cordillera of the Ecuadorian Andes. The Río Cala Formation is mainly composed of andesitic and basaltic lavas with island arc geochemical affinities (Vallejo et al., 2006) . According to the radiometric ages obtained by the $^{40}Ar/^{39}Ar$ method on hornblende, the Río Cala Formation has a crystallization age that varies between ~85 and 72 Ma (Vallejo et al., 2006).

These ages coincide with the biostratigraphic ages in sediments of the Natividad Formation, indicating a Campanian-Maastrichtian age(Boland et al., 2000). The Río Cala Formation is related to the Great Cretaceous Caribbean Arc, which originated from westward subduction under the Caribbean-Colombian Oceanic Plateau (CCOP), a large oceanic igneous province of Late Cretaceous age that constitutes the basement of the Western Cordillera and the Coast of Ecuador (Vallejo et al., 2006).

6.1.4 Yunguilla Formation

The Yunguilla Formation is identified at Cordillera Occidental on the eastern flank (Thalmann et al., 1946). It is composed of relatively thin beds with a thickness of 10 to 20 cm, and it exhibits a rhythmic stratification pattern with fine-grained sandstones and massive siltstones alternating with mudstones. The sandstones are composed of quartz and exhibit turbidite subdivisions, which are thought to be the middle to outer portions of a submarine fan. Because of its poor mapping over the Western Cordillera, which is primarily based on lithological traits, the Yunguilla Formation can be mistaken for Paleocene and Eocene turbidites of the Angamarca Group.

Exiteloceras sp. and Phylloceras sp., two ammonites, indicate a Late Campanian to Early Maastrichtian age (Jaillard et al., 2004). The Yunguilla Formation exhibits a composition of heavy minerals such as zircon, tourmaline, rutile, garnet, and epidote. Minimal quantities of titanite, anatase, and brookite are present as trace elements. These observations suggest a notable contribution of detritus derived from granitic and metamorphic sources, originating from the reworking of older formations within the Eastern Cordillera (Vallejo et al., 2019). The Yunguilla Formation has a tectonic contact with the underlying Pallatanga Formation and was deposited in a forearc basin with a north-south orientation along the South American continental edge (Vallejo et al., 2019).

The Yunguilla Formation's lithologies vary greatly along the Western Cordillera's strike. Dark grey, huge siltstones, pelagic cherts, fine-grained, well-sorted sandstones, and calciturbidites are examples of typical lithologies. The sandstones are categorized as feldspathic litharenites and lithic arkoses and contain plagioclase, quartz, amphibole, and pyroxenes. Gradation and bedding cyclicity point to the deposition of the rocks by diluted turbidity currents. Strongly folded, fine-grained turbidites are found in a sequence in strata that are between 15 and 20 cm thick in the mapped Yunguilla Formation of the Alambi River. (Vallejo, 2007).

6.1.5 Silante Formation

The Silante Formation is a geological unit that represents the Cenozoic evolution of the Western Andes of Ecuador. It consists of continental deposits that were derived from the erosion of a volcanic arc and accumulated in an alluvial fan environment. The Silante

Formation unconformably overlies the Pilalo Formation, which is a Paleocene submarine fan with tholeiitic volcanism (Vallejo et al., 2020). The age of the Silante Formation is constrained by radiometric dating of detrital zircons, which yield a maximum depositional age of 18.5 ± 0.4 Ma (Vallejo et al., 2020). The deposition of the Silante Formation was coeval with regional uplift and exhumation of the Andean margin, as indicated by thermochronological data and regional correlations (Vallejo et al., 2020). The Silante Formation is exposed along a trench-parallel distance of about 300 km in the Western Cordillera of Ecuador, and has a thickness of up to 1500 m.

The lithofacies of the Silante Formation are dominated by conglomerates and sandstones, with minor siltstones and mudstones. The provenance analysis of the Silante Formation shows that it contains heavy minerals such as epidote, garnet, zircon, apatite, and tourmaline, which indicate a continental, calc-alkaline volcanic arc source (Vallejo et al., 2020). The detrital zircon U-Pb ages also support this interpretation, as they show a dominant peak at 23 Ma, which corresponds to the Oligocene to Miocene San Juan de Lachas volcanic arc (Vallejo et al., 2020). The Silante Formation is an important record of the tectonic and sedimentary history of the Western Andes of Ecuador, and provides insights into the interactions between subduction, volcanism, uplift, and erosion in this active margin.

6.1.6 Pilalo Unit

The Pilalo Formation is a sedimentary unit that crops out in the Western Cordillera of Ecuador. It consists of marine deposits of sandstone, siltstone, shale and limestone, with interbedded volcanic rocks. The age of the Pilalo Formation is controversial, but it has been assigned to the Late Cretaceous to Paleocene based on biostratigraphy and radiometric dating

(Vallejo et al., 2021). The Pilalo Formation records the sedimentary evolution of the Ecuadorian foreland basin during the initial stages of Andean orogenesis, as well as the influence of the Caribbean Plateau collision in the Late Cretaceous (Vallejo et al., 2020). The origin of the Pilalo Formation is mainly from a western volcanic arc, as indicated by the presence of volcaniclastic material, clinopyroxene grains and zircon U-Pb ages (Vallejo et al., 2021). The Pilalo Formation is covered by Eocene limestones belonging to the Unacota Formation, and this relationship is interpreted as a contact that maintains the same geological alignment (Vallejo et al., 2020).

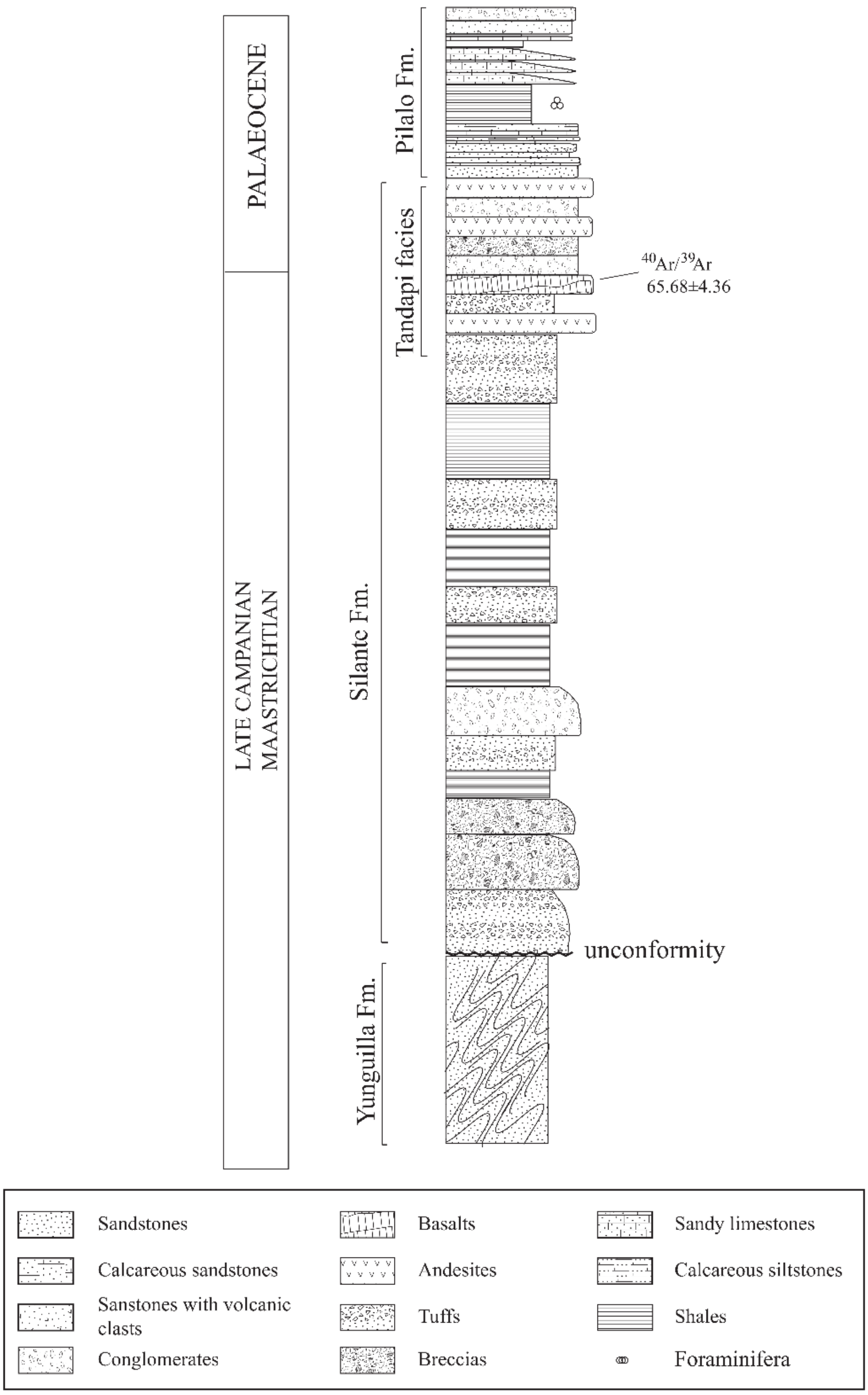

Fig 17. Stratigraphic column along the Nono - Tandayapa road section. (Taken From: C.Vallejo, 2007)

6.1.7 Saguangual Unit

The Saguangal Formation is a geological unit that outcrops in the Western Cordillera of Ecuador, south of Nobol (Guayas province). It consists of shallow-marine sedimentary rocks, mainly sandstones and shales, that overlie volcaniclastic rocks of the Rio Cala Formation. The age of the Saguangal Formation is uncertain, but it has been tentatively assigned to the Paleocene based on fossil evidence (Vallejo, 2007). The Saguangal Formation is interpreted as a forearc basin deposit that records the accretion of oceanic plateau rocks and island arc fragments to the continental margin during the Late Cretaceous to Paleogene (Vallejo et al., 2006). The origin of the Saguangal Formation is mainly from the Eastern Cordillera, where metamorphic and granitic rocks were uplifted and eroded during this tectonic event (R. Spikings et al., 2015).

The petrology and geochemistry of the Saguangal Formation have not been extensively studied, but some preliminary data are available from previous works. (Berrezueta et al., 2021) reported that the sandstones of the Saguangal Formation are mostly litharenites and feldspathic litharenites, with abundant metamorphic and magmatic rock fragments. They also observed that the shales have high contents of iron, titanium, chromium and nickel, suggesting a mafic-ultramafic source. These characteristics indicate that the Saguangal Formation was derived from a mixed source that included both continental crust and oceanic plateau rocks.(Berrezueta et al., 2021) also performed a detrital zircon U-Pb dating analysis on a sample of the Saguangal Formation, and obtained a maximum depositional age of 66.9 ± 1.2 Ma, which is consistent with a Paleocene age.

6.1.8 Macuchi Unit

The Macuchi Formation is a geological unit that crops out in the central-northern part of the Western Cordillera of Ecuador, hosting volcanogenic massive sulfide (VMS) deposits such as El Domo, La Plata and Macuchi. The formation consists of Cretaceous-Eocene basic to intermediate marine volcanic rocks, mainly tholeiitic basalts with some calc-alkaline affinities, that indicate an oceanic island arc setting (Aguirre & Atherton, 1987). The formation underwent low-grade metamorphism under greenschist facies conditions, resulting in the development of chlorite, epidote, albite and quartz assemblages (Aguirre & Atherton, 1987).

The VMS deposits are associated with submarine rhyodacite domes that intruded the Macuchi Formation and were overlain by mafic volcaniclastic rocks (Vallejo et al., 2016 , as cited in Sillitoe & Perelló, 2019). The mineralization includes massive and semi-massive sulfides composed of pyrite, sphalerite, chalcopyrite and minor galena, bornite, tennantite, stromeyerite and proustite (Vallejo et al., 2016 , as cited in Sillitoe & Perelló, 2019). The VMS formation is constrained by U/Pb zircon dating of the footwall rhyodacite at 42.13 ± 0.54 Ma and $^{40}Ar/^{39}Ar$ dating of the hanging wall volcaniclastic rocks at 41.49 ± 0.37 Ma (Vallejo et al., 2016 , as cited in Sillitoe & Perelló, 2019).

6.1.9 Angamarca Group

The Angamarca Group is a sequence of siliciclastic rocks that includes sandstones and conglomerates deposited by turbidity currents, as well as a limestone layer. It was formed between the Paleocene and Oligocene epochs and is divided into four formations: Saquisilí, Apagua, Unacota, and Rumi Cruz. The El Laurel Formation is considered to be part of the Angamarca Group based on its lithology and origin. The Angamarca Group can be found east of the Macuchi Unit and was studied by (Hughes & Bermudez, 1997).

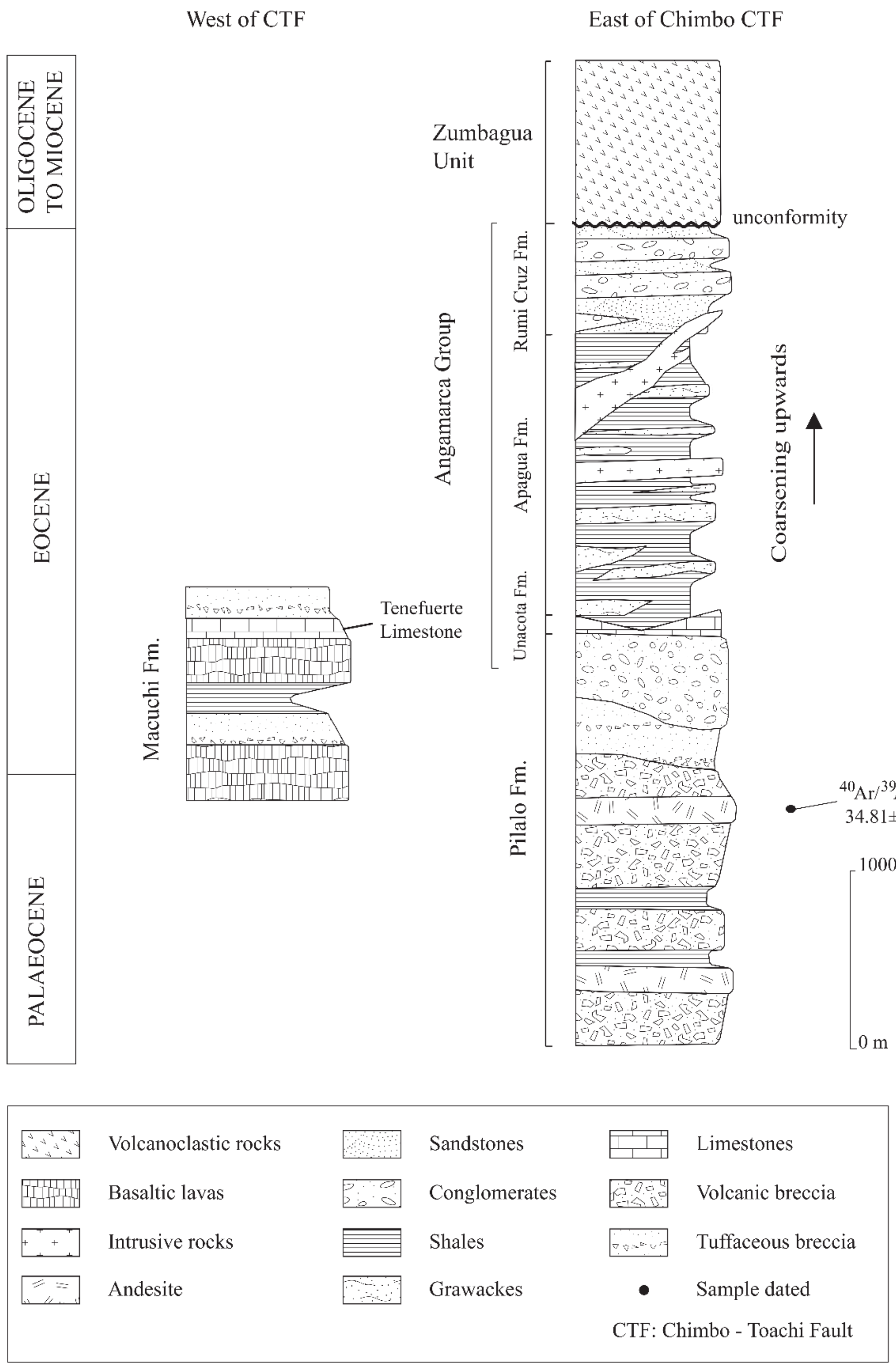

Fig 18. Stratigraphic column of the Latacunga - La Maná section. CTSZ = Chimbo Toachi Shear Zone. (Taken From: C.Vallejo, 2007).

6.1.9.1 Saquisilí Unit

The Saquisili Unit is a geological formation that consists of medium-to-fine-grained turbidite sandstones deposited in the early to middle Paleocene (Vallejo et al., 2019). It is located in the Western Cordillera of Ecuador, in the province of Cotopaxi, and is part of the Pallatanga block, an allochthonous terrane that was accreted to the South American continental margin at ~73 Ma (Vallejo et al., 2019). The Saquisili Unit corresponds to the farthest portion of a submarine fan system that received sedimentary contributions from the continental basement rocks of the Eastern Cordillera, as well as volcanic materials from the Tandapi and Macuchi volcanic arcs (Vallejo et al., 2019). The Saquisili Unit is intercalated with conglomerates (Gallo Rumi conglomerates) to the south, which indicate a more proximal depositional environment (Vallejo et al., 2019).

The Saquisilí Formation is a sedimentary unit of early to middle Paleocene age that unconformably overlies the Yunguilla Formation and black cherts in the Western Cordillera of Ecuador (Toro Álava & Jaillard, 2005). The Saquisilí Formation records the erosion of the continental margin after the accretion of oceanic terranes during the Late Cretaceous (Jaillard et al., 2008). The petrographic analysis of the sandstones reveals a mixed provenance from metamorphic, magmatic, and sedimentary rocks, with a dominant contribution from the Cordillera Real (Toro Álava & Jaillard, 2005). The Saquisilí Formation is interpreted as a forearc basin deposit that reflects the tectonic uplift and exhumation of the Andean margin during the Paleocene (Jaillard et al., 2008).

6.1.9.2 Apagua Formation

The Apagua Unit is a sedimentary formation that crops out in the Western Cordillera of Ecuador. It consists of turbiditic shales, siltstones, and medium-grained sandstones that were deposited in a backarc basin during the Paleocene to Eocene epochs(Egüez & Bourgois, 1986) .The sandstones are feldspathic and contain mafic minerals and lithic fragments, indicating a mixed provenance from continental and oceanic sources. The Apagua Unit overlies the Saquisili Unit, which is composed of basaltic lavas and breccias of oceanic plateau origin (Vallejo et al., 2019). The Apagua unit consists of turbiditic shales, siltstones, and medium-grained sandstones that contain feldspathic and mafic minerals and lithic fragments (Valarezo et al., 2017).

The Apagua Unit records the accretion of the Pallatanga Block, a fragment of the Caribbean Plateau that collided with the South American margin at ~73 Ma (Vallejo et al., 2019)(Vallejo et al., 2019) . The collision resulted in the uplift and erosion of the plateau rocks and the formation of a forearc basin to the west, where the Piñon Formation was deposited. The Piñon Formation is another fragment of the Caribbean Plateau that was accreted later, during the late Eocene(Vallejo et al., 2019). The Apagua Unit also received detrital input from the Tandapi volcanic arc and its submarine continuation, the Macuchi arc, which were active along the continental margin from the Late Cretaceous to the Eocene (Vallejo et al., 2019). The Macuchi arc is considered to be an in situ arc that developed on continental crust, rather than an allochthonous arc that was accreted as a separate terrane(Vallejo et al., 2019).

6.1.9.3 Unacota Unit

The Unacota Formation is a geological unit of late Cretaceous age that consists of bioclastic marine limestones within a sequence of siliciclastic turbiditic fans. It is located in the Cordillera Occidental of central Ecuador, where it is part of the accreted oceanic terrane known as the Pallatanga unit (Jaillard et al., 2004). The Unacota Formation is a Middle Eocene limestone unit that crops out in the Cordillera Occidental of central Ecuador. It is part of the Angamarca Group, which records the sedimentary evolution of the Ecuadorian foreland basin during the onset of Andean shortening (Vallejo et al., 2021). The Unacota Formation has been dated as Eocene based on biostratigraphic correlations with other units in the region (Jaillard et al., 1990). The Unacota Formation is overlain by coarse-grained conglomerates of the Rumi Cruz Formation, which mark a change in the sedimentary regime related to tectonic uplift and erosion (Jaillard et al., 1990).

The Unacota Formation represents a transgressive-regressive cycle that reflects the interaction between tectonic uplift, subsidence and sea-level changes in the Ecuadorian foreland basin. The transgressive phase is marked by the deposition of the Saquisilí Formation, which records the eastward migration of fluvial systems due to the flexural loading of the Andean thrust belt (Vallejo et al., 2021). The maximum flooding surface is represented by the Unacota Formation, which indicates a marine ingression that covered most of the basin. The regressive phase is marked by the deposition of the Apagua Formation, which records the progradation of turbidite fans from the Andes towards the basin center (Jaillard et al., 2004).

6.1.9.4 Rumi Cruz

The Rumi Cruz Formation is a clastic sedimentary unit that records a major change in the paleogeography of the Western Cordillera of Ecuador during the Late Eocene. It consists of coarse-grained sandstones and conglomerates that are partly subaerial and contain abundant clasts of black cherts (Toro Álava & Jaillard, 2005). The Rumi Cruz Formation overlies the mafic rocks of the Pallatanga Formation, which are interpreted as part of an oceanic plateau accreted to the South American margin at ~73 Ma (Vallejo et al., 2019).

The origin of the Rumi Cruz Formation indicates a mixed source area composed of oceanic plateau rocks, continental basement rocks of the Eastern Cordillera, and volcanic rocks of the Tandapi-Macuchi arc (Toro Álava & Jaillard, 2005). The deposition of the Rumi Cruz Formation was likely related to an upper Eocene accretion event that involved the collision of another oceanic terrane with the Western Cordillera (Alava & Jaillard, 2003). This event caused uplift and erosion of the previously accreted oceanic plateau and its associated volcanic arc, as well as deformation and exhumation of the Eastern Cordillera(Vallejo et al., 2019). The deposition of the Rumi Cruz Formation in the Western Cordillera of Ecuador during the upper Eocene period can be attributed to the response of clastic sediments to the process of accretion.

6.1.9.5 El Laurel Unit.

The Laurel Formation is a geological unit that crops out in the Western Cordillera of Ecuador, a mountain range that resulted from the accretion of an oceanic plateau and an intraoceanic volcanic arc to the South American continental margin during the Late Cretaceous (Vallejo et al., 2019). The Laurel Formation consists of submarine basaltic lavas and dolerites that have oceanic plateau geochemical affinities, indicating their origin from the Caribbean-

Colombian Oceanic Plateau (CCOP) that formed between 100 and 87 Ma (Reynaud et al., 1999).

The Laurel Formation is overlain by island arc sequences that formed by westward subduction beneath the CCOP, such as the Pujilí Granite, the Rio Cala Group and the Naranjal Unit, which have ages ranging from 85 to 72 Ma (Vallejo et al., 2019). The collision between the CCOP and the South American Plate occurred at around 73 Ma, as indicated by provenance analyses of Paleocene-Eocene sedimentary rocks that show detrital input from continental sources (Vallejo et al., 2019). The collision also caused accelerated uplift and exhumation of the Western Cordillera, as well as clockwise rotation of the coastal forearc region (Luzieux et al., 2006)

6.2 Setting Units with Geochronology Time

Starting from the bottom of the Fig. 19, we see that the first Unit is the Paleozoic basement, which is composed of metamorphic rocks such as gneiss and schist. This basement is overlain by a series of sedimentary rocks including sandstone, shale, and limestone that make up the Paleozoic to Mesozoic sequence. The next Unit is the Cretaceous to Oligocene sequence which includes several formations such as the Pallatanga Formation, Yunguilla Formation, Silante Formation, Pilaló Formation, and Saguangal Formation. The Pallatanga Formation consists of sandstone and shale with minor amounts of conglomerate and volcanic rocks. The Yunguilla Formation is composed of sandstone and shale with minor amounts of limestone.

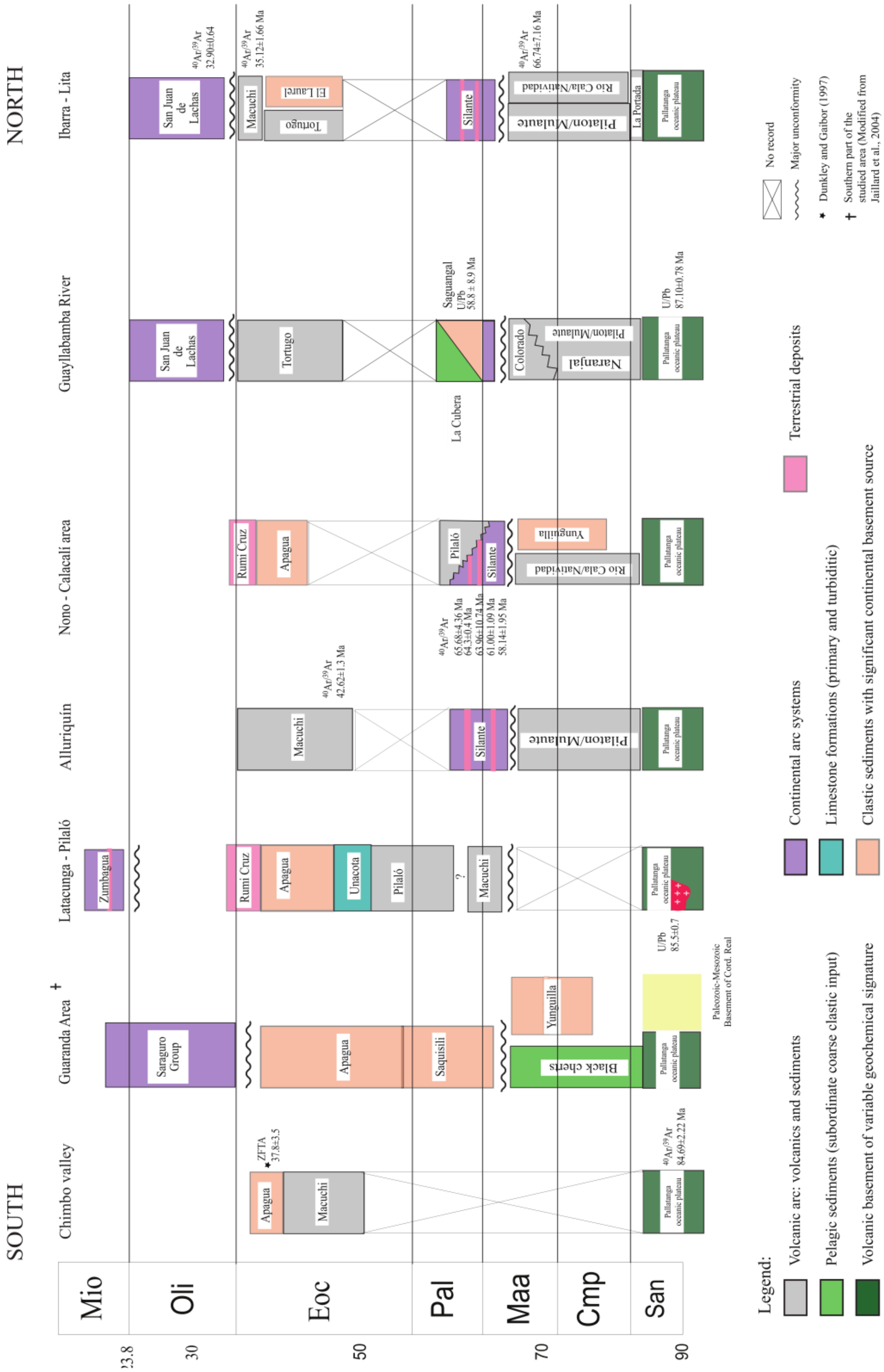

Fig 19. A Closer Look at Stratigraphic Columns from Principal Sections. (Taken From: Vallejo, 2007)

The Silante Formation consists mainly of volcanic rocks such as tuff and lava flows. The Pilaló Formation includes volcanic rocks such as andesite and rhyolite along with sedimentary rocks such as sandstone and conglomerate. Finally, the Saguangal Formation consists mainly of sandstone with minor amounts of shale. The topmost Unit shown in Fig 19 is the Neogene to Quaternary sequence which includes several formations such as the Pliocene-Pleistocene Chimborazo Volcanics, Late Pleistocene-Holocene Tungurahua Volcanics, Late Pleistocene-Holocene Cotopaxi Volcanics, Late Pleistocene-Holocene Cayambe Volcanics, Late Pleistocene-Holocene Chacana Volcanics, Late Pleistocene-Holocene Pululahua Volcanics among others. These formations are composed mainly of volcanic rocks such as andesite, basalt, and dacite. (Vallejo, 2007)

6.3 Relationship Between Units

- Pallatanga Block: This block is composed of various formations, including the Pallatanga Formation, San Juan Unit, Pujilí Melange and Granite, Totoras Amphibolite, and Rio Cala Group. It is an important part of the Western Cordillera's geology.

- Yunguilla Formation: This formation is found in tectonic blocks juxtaposed against most other stratigraphic formations identified within the Western Cordillera. It is consistently associated with the Pallatanga Formation along the eastern border of the Cordillera. The Yunguilla Formation may be correlated with similar deposits in northern Peru.

- Silante Formation: This formation consists mainly of sandstones and shales with minor conglomerates. It is found in several areas throughout Ecuador and has been dated to be Late Cretaceous to Early Paleocene in age.

- Pilaló Formation: This formation consists mainly of volcanic rocks such as tuffs, breccias, and lavas. It is found in several areas throughout Ecuador and has been dated to be Late Cretaceous to Early Paleocene in age. - Saguangal Formation: This formation consists mainly of sandstones and shales with minor conglomerates. It is found in several areas throughout Ecuador and has been dated to be Late Cretaceous to Early Paleocene in age.

- Rio Cala Group: This group includes several formations such as La Portada Formation, Mulaute Formation, Pilatón Formation, Natividad For mation, and Rio Cala Formation. These formations are important because they provide insight into the geological history of Ecuador during the Late Cretaceous to Oligocene period. Overall, these units and formations are significant because they help us understand the geological history of Ecuador and provide insight into the tectonic processes that have shaped the country's landscape over millions of years.

Chapter 6.4. Stratigraphic Columns with Mineral Content.

6.4.1 The Geology and mineral content of the Yunguilla, Pilalo, and Silante Formations

The Pilalo and Silante formations show a clear difference in their composition, as they came from volcanic sources. On the other hand, the Yunguilla Formation's sediments from the Campanian–Maastrichtian period originated from granitic and metamorphic sources that were part of a continental plate. These sources now form the Eastern Cordillera.

Unit 1: Yunguilla Formation. The Yunguilla Formation, depicted as the earliest unit in Figure 20, primarily comprises sandstones with lesser proportions of siltstones and mudstones. These sedimentary rocks were laid down during the Campanian-Maastrichtian period and are believed to have originated from granitic and metamorphic sources within a continental plate setting. The sedimentary rocks in this Unit were shed from the Eastern Cordillera, which was uplifted during the Late Cretaceous to Paleocene period. (Vallejo et al., 2020)

Unit 2: Pilalo Formation The Pilalo Formation is the middle Unit in Figure 20 and consists mainly of sandstones, siltstones, and mudstones with minor amounts of conglomerates. These rocks were deposited during the Paleocene period and are interpreted to have been derived from a tholeiitic volcanic arc that formed on top of an oceanic plateau basement. The sedimentary rocks in this Unit were deposited by turbidity currents that flowed down submarine canyons into a deep marine basin (Vallejo et al., 2020).

Unit 3: Silante Formation The Silante Formation is the youngest Unit in Figure 20 and consists mainly of conglomerates with minor amounts of sandstones, siltstones, and mudstones. These rocks were deposited during the Miocene period and are interpreted to have been derived from volcanic sources. The sedimentary rocks in this Unit were deposited by alluvial fans that formed at the base of steep mountain fronts (Vallejo et al., 2020)

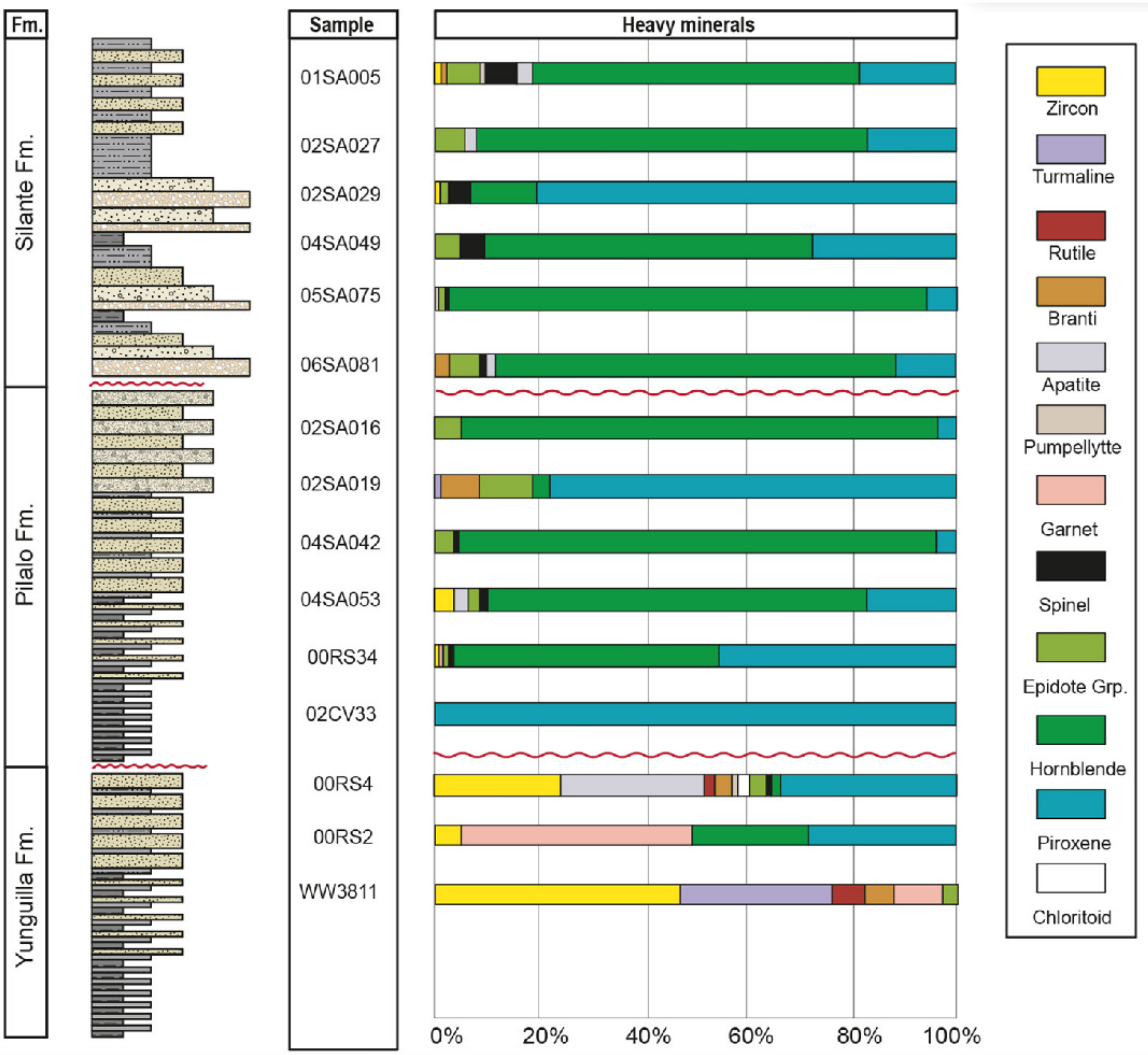

Fig 20. A composite column in a stratigraphic chart representing the Yunguilla, Pilalo and Silante formations, accompanied by heavy mineral frequency information on the right. (Taken From: Vallejo et al., 2020)

6.4.2 Mineral Assemblages in Upper Cretaceous to Neogene Stratigraphy

Mulaute, Pilaton, and Natividad formations: These formations belong to the Rio Cala Group and consist of sedimentary rocks from the Coniacian to Campanian periods. The heavy mineral assemblages in these rocks suggest that they were sourced from a volcanic arc and were deposited in an intraoceanic setting, far from continental influence.

Pilalo and Saguangual formations: These formations belong to the Pallatanga Group and are geochemically equivalent to the Piñon Formation. The heavy mineral assemblages in these rocks suggest that they were sourced from a volcanic arc and were deposited in an intraoceanic setting. Macuchi Formation: This formation consists of sedimentary rocks from the Eocene to Oligocene periods. The heavy mineral assemblages in these rocks suggest that they were sourced from a volcanic arc and were deposited in an intraoceanic setting. (Vallejo et al., 2019)

Apagua, Laurel, and Rumi Cruz units: These units belong to the Angamarca Group and consist of sedimentary rocks from the Oligocene to Miocene periods. The heavy mineral assemblages in these rocks suggest that they were sourced from metamorphic rocks, with some volcanic-derived minerals in the Apagua unit. Silante Formation: This formation consists of sedimentary rocks from the Miocene period. The heavy mineral assemblages in these rocks suggest that they were sourced from a volcanic arc and were deposited in an intraoceanic setting. (Vallejo et al., 2019)

In summary, the mineral content and geology relationship of the formations and units in the Western Cordillera of Ecuador suggest that they were sourced from a volcanic arc and were deposited in an intraoceanic setting, with some contributions from metamorphic rocks.

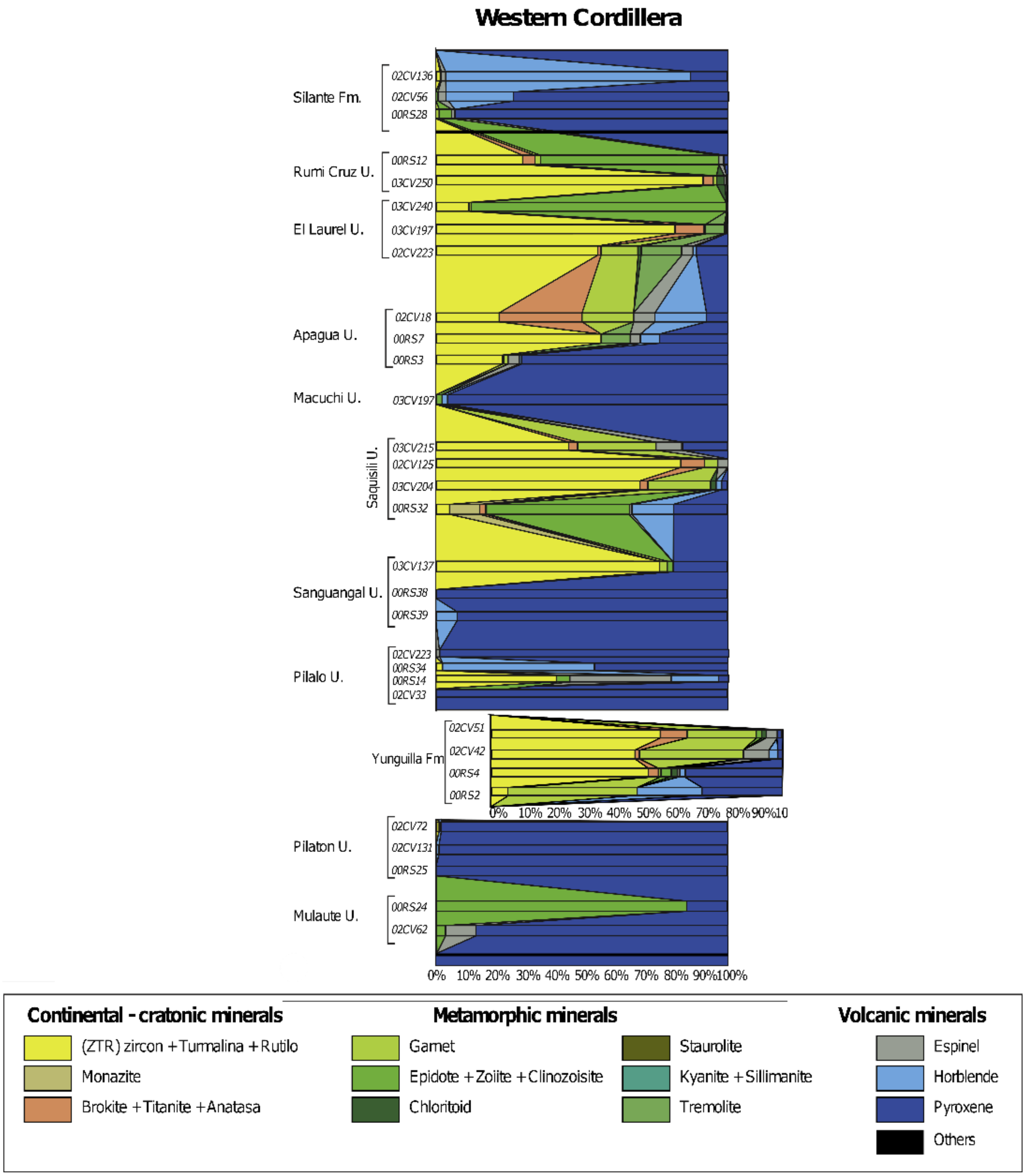

Fig 21. Graphs depicting the composition of heavy minerals in sedimentary rocks from the Upper Cretaceous to Neogene periods in the Western Cordillera. (Taken From: Vallejo et al., 2019)

CONCLUSIONS

- The Western Cordillera of Ecuador is a complex tectonic unit that resulted from the accretion of oceanic terranes and island arcs to the South American continental margin during the Mesozoic and Cenozoic.

- The Pallatanga Block in Ecuador is composed of several formations that provide insight into the tectonic processes that have shaped Ecuador's landscape over millions of years. These formations include the Pallatanga Formation, San Juan Unit, and Rio Cala Group. The Rio Cala Group itself includes several formations such as La Portada Formation, Mulaute Formation, Pilatón Formation, Natividad Formation, and Rio Cala Formation.

- A vast range of Late Cretaceous to Early Tertiary accreted oceanic igneous terranes, including island-arc sequences and their associated back-arc basins, oceanic plateau material, calc-alkaline arc rocks erupted through thickened oceanic plateau, and more, are preserved in Western Ecuador.

- Recent advances in techniques such as zircon dating, provenance analysis, isotopic dating, and apatite fission tracking have helped to better understand the nature, origin, and evolution of the different terranes in the Western Cordillera, as well as their geodynamic implications for the continental growth of Ecuador.

- Western Ecuador has undergone two distinct accretionary stages. The first stage was the accretion of the Pallatanga Unit, an oceanic plateau that occurred during the Late Cretaceous and lasted for around 10 to 20 million years. The second stage occurred during the early to late Eocene and was characterized by the accretion of the Piñon and

Pedernales-Esmeraldas oceanic plateau sequences as well as the Naranjal and Macuchi island arcs.

- The application of radiometric dating techniques has improved the precision and resolution of stratigraphic correlations in the Western Cordillera, and has helped to constrain the timing and duration of some rock units, and the use of these techniques has also allowed for the identification of different tectonic events that have affected the Western Cordillera, such as the accretion of oceanic terranes, the formation of magmatic arcs, and the development of extensional basins.

- Geochronological data from the Western Cordillera has revealed two main phases of cooling. The first phase is related to post-magmatic thermal relaxation after early and middle Miocene magmatism. The second phase is related to tectonically driven rock uplift and exhumation after 6 million years ago, coinciding with the onset of subduction of the Carnegie Ridge.

- The Western Cordillera of Ecuador is a unique and important geological region that deserves further attention and study to better understand its role in the tectonic evolution of the Andean margin and the growth of the South American continent.

RECOMMENDATIONS

- More radiometric dating is needed from various rock types, such as sedimentary and metamorphic rocks, and different regional locations better to understand Western Cordillera's thermal history and deformation patterns.

- More in-depth geochemical and isotopic studies are needed to understand better the origins and magmatic development of volcanic rocks from the oceanic plateau and island arc sequences.

- It is necessary to verify the rotational histories of the Western Cordillera, more paleomagnetic studies should be conducted on various rock units and structural domains within it

- To better understand the Western Cordillera's crustal structure and dynamics, geological data should be combined with geophysical data (such as seismic, gravity, and magnetic) and numerical models.

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