UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

ESCUELA DE CIENCIAS DE LA TIERRA, ENERGIA Y AMBIENTE

TÍTULO: Sedimentological and paleoenvironmental study of the Peñas Coloradas Formation of the Chota basin, Ecuador

Trabajo de integración curricular presentado como requisito para la obtención

del título de Geóloga

Autor:

Fonseca Salguero Erika Aracely

Tutor:

PhD – Almeida Rafael

Co-tutor:

PhD – Merino Germán

Urcuquí, Junio del 2021

UNIVERSIDAD YACHAY TECH

Urcuquí, 1 de julio de 2021

SECRETARÍA GENERAL
(Vicerrectorado Académico/Cancillería)
ESCUELA DE CIENCIAS DE LA TIERRA, ENERGÍA Y AMBIENTE
CARRERA DE GEOLOGÍA
ACTA DE DEFENSA No. UITEY-GEO-2021-00006-AD

A los 1 días del mes de julio de 2021, a las 15:00 horas, de manera virtual mediante videoconferencia, y ante el Tribunal Calificador, integrado por los docentes:

Presidente Tribunal de Defensa	Dr. VAZQUEZ TASET, YANIEL MISAEL , Ph.D.
Miembro No Tutor	Dr. TORO ALAVA, JORGE EDUARDO , Ph.D.
Tutor	Dr. ALMEIDA GONZALEZ, RAFAEL VLADIMIR , Ph.D.

El(la) señor(ita) estudiante **FONSECA SALGUERO, ERIKA ARACELY**, con cédula de identidad No. **0503901142**, de la **ESCUELA DE CIENCIAS DE LA TIERRA, ENERGÍA Y AMBIENTE**, de la Carrera de **GEOLOGÍA**, aprobada por el Consejo de Educación Superior (CES), mediante Resolución **RPC-SE-10-No.031-2016**, realiza a través de videoconferencia, la sustentación de su trabajo de titulación denominado: **Sedimentological and paleoenvironmental study of the Peñas Coloradas Formation of the Chota basin, Ecuador**, previa a la obtención del título de **GEÓLOGO/A.**

El citado trabajo de titulación, fue debidamente aprobado por el(los) docente(s):

Tutor	Dr. ALMEIDA GONZALEZ, RAFAEL VLADIMIR , Ph.D.
Co - Tutor	Dr. MARTIN MERINO, GERMAN , Ph.D.

Y recibió las observaciones de los otros miembros del Tribunal Calificador, las mismas que han sido incorporadas por el(la) estudiante.

Previamente cumplidos los requisitos legales y reglamentarios, el trabajo de titulación fue sustentado por el(la) estudiante y examinado por los miembros del Tribunal Calificador. Escuchada la sustentación del trabajo de titulación a través de videoconferencia, que integró la exposición de el(la) estudiante sobre el contenido de la misma y las preguntas formuladas por los miembros del Tribunal, se califica la sustentación del trabajo de titulación con las siguientes calificaciones:

Tipo	Docente	Calificación
Miembro Tribunal De Defensa	Dr. TORO ALAVA, JORGE EDUARDO , Ph.D.	8,7
Tutor	Dr. ALMEIDA GONZALEZ, RAFAEL VLADIMIR , Ph.D.	9,1
Presidente Tribunal De Defensa	Dr. VAZQUEZ TASET, YANIEL MISAEL , Ph.D.	8,5

Lo que da un promedio de: **8.8 (Ocho punto Ocho)**, sobre 10 (diez), equivalente a: **APROBADO**

Para constancia de lo actuado, firman los miembros del Tribunal Calificador, el/la estudiante y el/la secretario ad-hoc.

FONSECA SALGUERO, ERIKA ARACELY
Estudiante

Dr. VAZQUEZ TASET, YANIEL MISAEL , Ph.D.
Presidente Tribunal de Defensa

Firmado electrónicamente por:
YANIEL MISAEL VAZQUEZ TASET

Dr. ALMEIDA GONZALEZ, RAFAEL VLADIMIR , Ph.D.
Tutor

RAFAEL VLADIMIR ALMEIDA GONZALEZ

Digitally signed by RAFAEL VLADIMIR ALMEIDA GONZALEZ
DN: cn=RAFAEL VLADIMIR ALMEIDA GONZALEZ, serialNumber=211020132449, ou=ENTIDAD DE CERTIFICACION DE INFORMACION, o=SECURITY DATA S.A. 2, c=EC
Date: 2021.07.01 21:56:21 -05'00'

Dr. TORO ALAVA, JORGE EDUARDO , Ph.D.
Miembro No Tutor

CERTIFICACIÓN ELECTRÓNICA
BANCO CENTRAL DEL ECUADOR
Firmado Digitalmente por: JORGE EDUARDO TORO ALAVA
Hora oficial Ecuador: 02/07/2021 10:57

TERÁN ROSALES, ANDREA YOLANDA
Secretario Ad-hoc

ANDREA YOLANDA TERAN ROSALES

Firmado digitalmente por ANDREA YOLANDA TERAN ROSALES
Fecha: 2021.07.01 17:30:49 -05'00'

AUTORÍA

Yo, **Erika Aracely Fonseca Salguero**, con cédula de identidad 0503901142, declaro que las ideas, juicios, valoraciones, interpretaciones, consultas bibliográficas, definiciones y conceptualizaciones expuestas en el presente trabajo; así cómo, los procedimientos y herramientas utilizadas en la investigación, son de absoluta responsabilidad de la autora del trabajo de integración curricular. Así mismo, me acojo a los reglamentos internos de la Universidad de Investigación de Tecnología Experimental Yachay.

Urcuquí, Julio del 2021.

Erika Aracely Fonseca Salguero

CI: 0503901142

AUTORIZACIÓN DE PUBLICACIÓN

Yo, **Erika Aracely Fonseca Salguero,** con cédula de identidad 0503901142, cedo a la Universidad de Investigación de Tecnología Experimental Yachay, los derechos de publicación de la presente obra, sin que deba haber un reconocimiento económico por este concepto. Declaro además que el texto del presente trabajo de titulación no podrá ser cedido a ninguna empresa editorial para su publicación u otros fines, sin contar previamente con la autorización escrita de la Universidad.

Asimismo, autorizo a la Universidad que realice la digitalización y publicación de este trabajo de integración curricular en el repositorio virtual, de conformidad a lo dispuesto en el Art. 144 de la Ley Orgánica de Educación Superior

Urcuquí, Julio del 2021.

Erika Aracely Fonseca Salguero

CI: 0503901142

DEDICATION

I want to dedicate this work to my mom Fanny Salguero and my dad Jaime Fonseca who always have been my support during all these years in goods and bad moments. Thanks for your confidence, dedication, and support in each one of my decisions. The dream of my parents since I was a child was to see their daughter with a profession. Now I can say I got it thanks to them, thank you for allowing me to dream.

Also, I want to dedicate this work to my dear aunt Laura Fonseca who died in 2019. She always was aware of my life since that I was a baby. Thank you for all your support and your optimism. I know that wherever you are, you are proud of me and overjoyed.

Erika Aracely Fonseca Salguero

ACKNOWLEDGMENTS

I want to express my gratitude to my advisor Rafael Almeida who give me his support, friendship, and guidance during this time. Thank you for your patient, tolerance, enthusiasm, and passion with this work. Thank you for share your knowledge and trust in me. I really appreciate that. Further, thank you for teaching me your sayings, “Nadie aprende en cabeza ajena” and “El que no chilla no mama” that is true, and I will always keep it in mind.

I also want to thank my co-advisor Germán Martín an extraordinary, cheerful, and patient person. Thank you for your motivation, knowledge, and guidance during this time.

Yachay Tech allowed me the opportunity to meet the best professors. I am very grateful to everyone for sharing their passion, knowledge, and experiences in geology. Thank you to Anna, Elissa, Celine, Yaniel, Alyssa, Edwin, Jorge T, Jorge G, Mateo, and Uwe.

On the other hand, I want to thank all my family for your support and confidence. In the same way, I would like to thanks my friends that become in my second family from the beginning to the end; Dianita Ch., Alejo, Katy, Dianita B., and Criss S.

Furthermore, thank my two best friends Karencita who has accompanied me throughout my career at all times. Thank you for your beautiful friendship, you are my sister, my confidant, and my colleague I love u!!, with you forever. Maria, who was my partner of field, my confidant, and my friend of laughter and crying during that time, thank you for everything.

Thanks to my geofamily, especially the third and fourth generation without them, going through the university would not have been fun. We have many anecdotes together thanks Anderson (Chavo-thank you for your friendship, enthusiasm, and humor), Harvisito, Danny, Bastian (Profits), Bryan (Chichi), Marito, Carlitos Lara, Andy, Jorgito, Luis (Luchito), Ari, Mariela, and Joshua. I hope to see you all shine, thanks a lot.

My eternal gratitude to each one of the people mentioned above, who converted Yachay Tech into one of the most wonderful experiences of my life.

Erika Aracely Fonseca Salguero

RESUMEN

Los Andes del Ecuador se dividen en dos cadenas montañosas orientadas norte-sur, la Cordillera Occidental (CO) al oeste y la Cordillera Real (CR) al este. Entre estos se encuentra la Depresión Interandina, un valle que se extiende con varias cuencas exhumadas de norte a sur como Chota, Guayllabamba, Latacunga-Ambato, Riobamba, Cuenca, Girón-Santa Isabel, Nabón, Loja, Vilcabamba y Zumba. Estas cuencas comprenden de depósitos de abanico aluvial, fluviátiles, lacustres y clastos volcánicos que conservan un registro de los escenarios sedimentológicos, estructurales y paleo ambientales del pasado. La cuenca del Chota es la cuenca inter-montana más septentrional de los Andes ecuatorianos. Este relleno de cuenca está definido por cuatro formaciones (Fm) estratigráficas: Chota, Santa Rosa, Peñas Coloradas y Carpuela. Este estudio llevó a cabo un análisis sedimentológico y paleo ambiental detallado de una parte de la Formación Chota y la Formación Peñas Coloradas (PCF). En nuestra área de estudio, Chota Fm tiene un espesor de ~ 48 m, y Peñas Coloradas Fm tiene ~ 413 m con un total de ~ 461 m de espesor. Realizamos una descripción detallada de registros sedimentarios a escala 1: 1000, recuento de clastos en conglomerados y un análisis XRD de arcilla. Estos métodos nos permitirán proponer depósitos ambientales, proveniencia y señales paleo climáticas que prevalecieron durante la deposición del PCF. Según el tipo de sedimentos, dividimos la Fm Peñas Coloradas en cuatro Miembros: Canales Colorados, Brillosas, Tabulares y Volcanicas. Estas están compuestas por una serie de intercalaciones de depósitos finos y gruesos que sugieren ambientes lacustres, abanicos aluviales, fluviales y de escombros. Además, el análisis de arcilla propone una transición en el paleo clima de húmedo a árido, y la procedencia sugiere áreas circundantes como la Formación Ambuquí, Los Volcánicos de Angochagua y los gneises de Sabanilla.

PALABRAS CLAVE: Peñas Coloradas; Formación; Miembros; sedimentología; ambientes; proveniencia.

ABSTRACT

The Andes of Ecuador is divided into two north-south sub-parallel chains, the Cordillera Occidental (CO) to the west and the Cordillera Real (CR) to the east. In between these is the Interandean Depression, a valley that spans of several exhumed basins from north to south such as the Chota, Guayllabamba, Latacunga-Ambato, Riobamba, Cuenca, Giron-Santa Isabel, Nabón, Loja, Vilcabamba and Zumba basins. They comprise alluvial fan, fluviatile, lacustrine, and volcanoclastic deposits that preserve a record of the past's sedimentological, structural settings, and paleoenvironment. The Chota Basin is the northernmost intermontane basin of the Ecuadorian Andes. This basin fill is defined by four stratigraphic formations: Chota, Santa Rosa, Peñas Coloradas, and Carpuela Formations (Fm). This study carried out a detailed sedimentological and paleoenvironmental study of a part of the Chota Formation and the Peñas Coloradas Formation (PCF). In our study area, Chota Fm has a thickness of ~48 m, and the Peñas Coloradas Fm is has a ~413 m with a total of ~ 461 m in thickness. We carry out a detailed description of sedimentary logs at a 1:1000 scale, clast count in conglomerates, and an XRD analysis of clay. These methods will allow us to propose environment deposits, source, and paleoclimatic signals that were prevalent during the deposition of the PCF. According to the type of sediments, we divided the Peñas Coloradas Fm into four Members: Canales Colorados, Brillosas, Tabulares, and Volcanicas Members (Mbr). They comprise a series of intercalation of fine and coarse deposits that suggest lacustrine, alluvial fans, fluvial, and debris flow environments. Furthermore, the clay analysis proposes a transition in the paleoclimate from humid to arid, and the provenance suggests to surrounding areas like Ambuquí Formation, Angochagua volcanic, and Sabanilla gneisses.

KEYWORDS: Peñas Coloradas; Formation; Members; sedimentology; environments; provenance.

TABLE OF CONTENTS

List of Figures

1. INTRODUCTION

The Andes mountain range is located along the western margin of South America, bordering the entire coastline of the Pacific Ocean. In Ecuador, the Andean chain has a length of ~600 km and a width of 150 -180 km (Coltorti & Ollier,2000). The Ecuadorian Andes is characterized by three important physiographic features; the Cordilleras (Western and Eastern/Real) and the Interandean Valley. Some of the events of the evolution of this orogen have been recorded by sedimentological and structural features preserved in intermontane basins within the Andes.

Sedimentary basins provide valuable details about the stratigraphic, structural and paleoclimatic processes (among others) in a determined zone and time. Therefore, deposited sediments preserve information for long geological periods that can help make a tectonic reconstruction of a determined area (Marocco et al., 1995; Einsele, 2000; Streit et al., 2017). The main driver of sedimentary deposition in a basin is the rate and magnitude of tectonic activity, sea level variations and climatic effects, which control the size, provenance, and transport of sediments as well as , weathering (physical, chemical, and biological processes), uplift and erosion, and creation of accommodation (McCann & Saintot, 2003). Therefore, intermontane basins can reveal the process of uplift and erosion through stratigraphic and paleoenvironmental records. This can be determined through a detailed study of change in the sedimentary provenance, variations in grain size, unconformities, and sedimentary structures (Streit et al., 2017).

Several continental, Inter-Andean basins were formed in Ecuador between 26 and 6 Ma related to the subduction of the Nazca plate beneath the South American plate (Barragán et al., 1996; Hungerbühler et al., 1995; Lavenú et al., 1995; Tibaldi & Ferrari, 1992). These are from North to South; the Chota, Guayllabamba, Latacunga-Ambato, Riobamba, Cuenca, Girón-Santa Isabel, Nabón, Loja, Vilcabamba and Zumba basins (Fig.1) (Marocco et al., 1995). The basin fills consist of continental sediments of reworked material derived from volcanoes and metamorphic rocks, deposited in alluvial fan, fluviatile, and lacustrine environments (Barragán et al., 1996; Hungerbühler et al., 1995; Marocco et al., 1995; Coltorti & Ollier,2000).

The Chota Basin is an intermontane basin located to the north of the Ecuadorian Andes in the Imbabura province. This basin conserves the best Neogene stratigraphic record in the northern sector of the country and is composed of fluvial, lacustrine and alluvial, as well as pyroclastic Pleistocene-Holocene deposits (Tibaldi & Ferrari, 1992). Several tectonic events have controlled the sediment fill and caused a cyclic evolution.

Though there are not many previous studies of the Chota basin, the ones that exist yield contradictory interpretations regarding the basin stratigraphy and structure. According to Barragán et al. (1996), the Chota basin is interpreted as an intermontane intra-arc basin, developed under two main stages, which controlled the sedimentary fill. The opening is characterized by a thinning and fining-upwards, result of a transtensional tectonic regime. The closure is characterized by a thickening and coarsening-upwards, a result of a compressive tectonic event. These events originated sub-basins defined by four formations: Chota Formation located in the central part, Santa Rosa Formation towards the western margin, and Peñas Coloradas Formation and Carpuela Formation developed towards the eastern of margin of the basin. According to Barragán et al. (1996) the sedimentary evolution of basin is defined by fluviatile and lacustrine deposits of the Chota Formation, followed by conglomeratic facies of prograding alluvial fans belonging to Santa Rosa, Peñas Coloradas and Carpuela Formations.

On the other hand, Winkler et al. (2005) define three formations geographically separated by a N-S lahar flow in the Cota basin. From base to top these are Peñas Coloradas, Chota, and Santa Rosa formations. The tectono sedimentary assemblage is interpreted within a full-ramp basin model in which reverse faults drive differential uplift of the basin-bordering cordilleras. The sedimentary sequence is defined as alluvial deposits in the Peñas Coloradas Formation, fluvial to lacustrine deposits in the Chota Formation, and fluvial to alluvial fan deposits in the Santa Rosa Formation.

One of the main issues with all of the previously mentioned studies is that they do not have detailed stratigraphic and sedimentological observations and analysis of the Peñas Coloradas Formation. This formation is formed by various sequences that have been interpreted as alluvial fan deposits, and is crucial to understand the basin evolution given its thickness and the various interpretations about its depositional position.

To address this gap in knowledge, in this study, we will carry out a detailed study of the sedimentology of the Peñas Coloradas Formation of the Chota basin, which is exposed in the eastern part of the basin (Fig. 1). To do this, we will create detailed sedimentary logs, measuring stratigraphic thickness, describing sedimentary structures, granulometry, and lithologies, as well as counting clasts in conglomerates for provenance analyses. Furthermore, we will carry out XRD analyses of clay to determine the pattern of clay types throughout the stratigraphic column. This will allow us to determine the source area of the deposit, and the conditions of transport and deposition (Reineck & Singh, 2012). Moreover, we will define the clay assemblages and infer paleoclimate conditions prevalent during the Peñas Coloradas Formation deposition.

Accordingly, all this will allow us to make a sedimentological and paleoenvironmental reconstruction of the Peñas Coloradas Formation, thus furthering our knowledge of the evolution of the Chota Basin.

Study Area

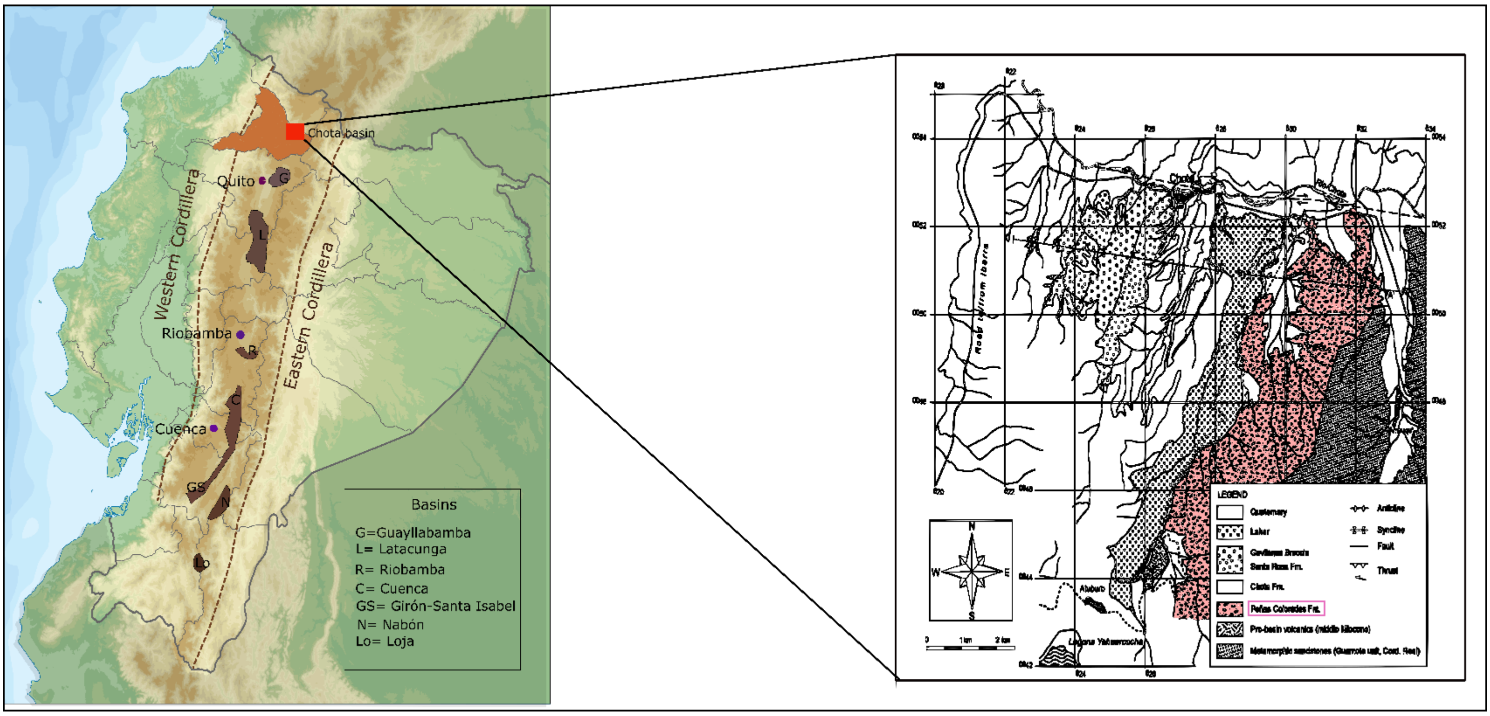


Figure 1. Map of the study area including from North to South the Chota, Guayllabamba, Latacunga, Riobamba, Cuenca – Girón - Santa Isabel, Nabón and Loja sedimentary basins. The red square shows the Chota basin located in the Imbabura province with a zoom-in of the study area the Peñas Coloradas Formation (pink color). The dash lines show the Cordilleras that bound the Interandean Zone. Maps modified from Marocco (1995) and Winkler et al. (2005).

2. GEOLOGICAL SETTING

The Andes of Ecuador are formed by the Western and Eastern Cordilleras and the Inter-Andean valley that separates them. These mountains form a continental volcanic arc due to the Nazca plate's subduction beneath the South American Plate with a mean rate of subduction of 58mm/yr. (Hungerbühler et al., 1995; Litherland & Aspden, 1992; Vallejo, 2007). This process triggered the uplift, volcanism, and deformation of these Cordilleras (Hungerbühler et al., 1995). Furthermore, it created a retro-arc thrust belt along the sub-Andean zone; thus, part of the Andean shortening has been accommodated by the Eastern Cordillera thrusting over the Amazonian craton (Litherland & Aspden, 1992). The Western Cordillera is composed of mafic, intermediate extrusive and intrusive rocks, and by deep-water, shallow marine and continental deposits of Late Cretaceous to Oligocene age (Toro Álava & Jaillard, 2005). The Eastern Cordillera is composed of metamorphic rocks and granitoids of Paleozoic and Mesozoic age (Vallejo, 2007; Vallejo et al., 2009). On the other hand, the Inter-Andean Valley (IAV) or graben is infilled by Pliocene and Quaternary volcano-sedimentary rocks (Hughes & Pilatasig, 2002), that could reach Oligocene and Miocene age (Villagómez, 2003). This topographic depression is bound by the Calacalí-Pallatanga-Palenque fault to the west and the Peltetec fault to the east (Aspden & Litherland, 1992).

2.1. WESTERN CORDILLERA

The Western Cordillera of Ecuador is a part of the Andean orogen and has an altitude between 1000 to 6300 meters above sea level (masl), characterized by the highest peak belonging to Chimborazo volcano (Vallejo, 2007). The major part of Western Cordillera is comprised of sub-greenschist facies, oceanic plateau basalts and ultramafic rocks of Early to Late Cretaceous age, Late Cretaceous to Paleocene and Eocene marine turbidites, an early Eocene basaltic to andesitic oceanic arc segment, shallow marine Eocene limestone, and an Eocene-Oligocene terrestrial sequence (Hughes & Pilatasig, 2002; Jaillard et al., 2006).

There are two oceanic terranes that accreted against the South American Plate margin, recognized in the Western Cordillera, the Pallatanga terrane to the east accreted during the Late Cretaceous and Macuchi terrane to the west accreted in the Eocene (Fig.2) (Toro Álava & Jaillard, 2005). The age of the accretions are 85-80 Ma and 40-35 Ma (Hughes & Pilatasig, 2002; Jaillard et al., 2006; Kerr et al., 2002; Toro Álava & Jaillard, 2005; Vallejo, 2007; Vallejo et al., 2009).

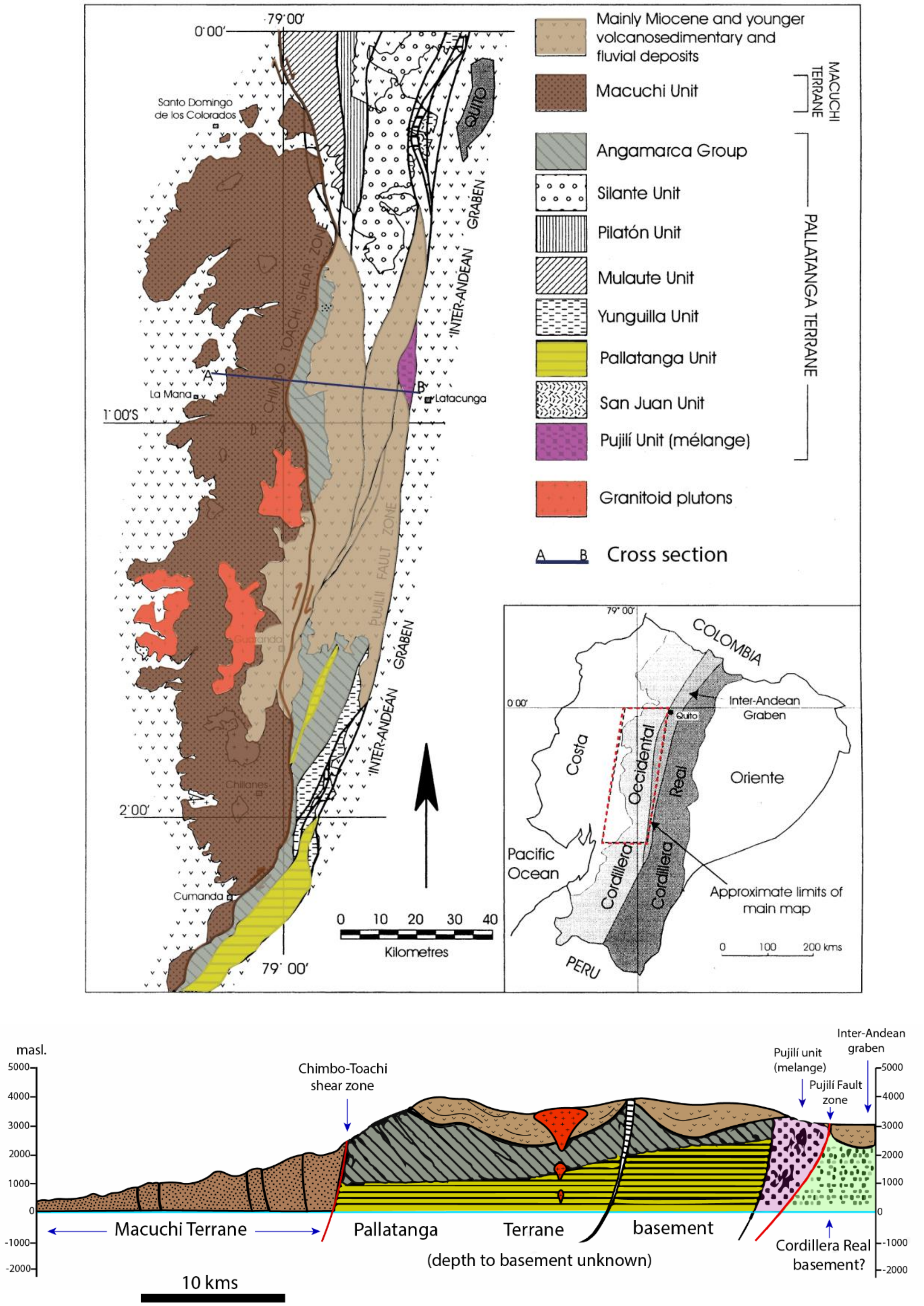


Figure 2. Schematic geological map and cross-section of main terranes of Western Cordillera (Pallatanga and Macuchi) and the Chimbo-Toachi shear zone. Modified image from Hughes & Pilatasig (2002).

PALLATANGA TERRANE

The Pallatanga terrane is exposed along the eastern border of the Western Cordillera, and it is limited to the east by the Pujilí fault zone and the west by the Chimbo-Toachi shear zone (Fig.2) (Hughes & Pilatasig, 2002; Kerr et al., 2002; Spikings et al., 2001; Vallejo, 2007; Vallejo et al., 2009). This block is exposed in various zones of the Sierra zone such as the Pallatanga valley, and along the Ibarra, Lita, Otavalo, Selva Alegre, Quito, Chiriboga, Calacalí, Pacto, Guaranda, and Riobamba roads (Vallejo, 2007).

The Pallatanga Terrane's origin is associated with a mantle plume because its composition is related to enriched mid-ocean ridge basalt (E-MORB) and oceanic plateau basalts that have the same composition as the Caribbean oceanic plateau (Kerr et al., 2002; Vallejo, 2007; Vallejo et al., 2009; Jaillard et al., 2009). Several recognized lithologies comprise Pallatanga terrane as basalts, microgabbros, peridotites, diabases, pillow lavas, dolerites, and hyaloclastites. According to Vallejo (2007), the age of crystallization of the mafic basement of the Pallatanga formation is 87.10±1.66 Ma.

The Pallatanga terrane is divided into two main units: San Juan unit to the east and the Guaranda unit to the west (Toro Álava & Jaillard, 2005).

San Juan Unit is defined as the ultramafic root of the Pallatanga terrane and is the oldest sequence accreted around 85-80Ma (Toro Álava & Jaillard, 2005). This unit comprises serpentinized peridotites, fine-grained peridotites, dunites, olivine gabbros, fine to coarse amphibole gabbros, anorthosites, and dolerites (Vallejo et al., 2009). San Juan unit is limited to the east by the Yunguilla Fm, composed of Maastrichtian feldspathic greywackes, black cherts, and calciturbidites, and to the west with the Pallatanga Formation composed of amygdaloidal and pillowed basalts, hyaloclastites and massive dolerites (Kerr et al., 2002). It is exposed along the Saloya River, along the Quito-Chiriboga road, and San Juan and Totoras village in central Ecuador (Vallejo, 2007).

The Guaranda unit comprises transgressive limestones, deep marine shales, radiolarites, turbidites, and coarse-grained shallow marine sandstones or conglomerates. This unit's age is Late Maastrichtian between 68-65 Ma (Toro Álava & Jaillard, 2005). Two formations have been recognized to the west of the Guaranda unit; Apagua Fm is comprised by dark grey siltstones, mudstones, and medium-grained sandstones and is exposed along the Guaranda-Riobamba and la Mana-Latacunga road, and along the Rio Chimbo valley (Vallejo, 2007). The Rumi Cruz Fm is composed of continental and marine deposits like breccias, coarse-grained sandstones, red mudstones, shales, and fossil wood fragments; hence it suggests a fan delta environment and is exposed along Apagua- Angamarca road, to the south of Apagua village and the northwest of Quito (Toro Álava & Jaillard, 2005; Vallejo, 2007).

MACUCHI TERRANE

The Macuchi terrane is an island arc accreted to the South American margin in the Eocene (Fig.2) (Toro Álava & Jaillard, 2005). This terrane is composed of up 90% of volcano-sedimentary material, with a provenance that comes from oceanic island arc of basaltic to andesitic composition, product of submarine eruptions and deposition by gravity flow processes (Hughes & Pilatasig, 2002). Macuchi terrane is composed of volcanic sandstones, breccias with basaltic andesite fragments, tuffs, volcanic siltstones, cherts, pillow basalts, and andesitic intrusions (Hughes & Pilatasig, 2002; Kerr et al., 2002; Vallejo, 2007). The Macuchi unit is exposed along the western border of the Western Cordillera along the Aloag to Santo Domingo and Pilaló to La Maná roads, and the Rio Chimbo valley (Vallejo, 2007). This unit has economic importance because it includes at least two important sulfide mineral deposits like Macuchi and La Plata (Hughes & Pilatasig, 2002).

2.2. EASTERN CORDILLERA

The Eastern Cordillera or the Cordillera Real is a chain that forms part of the Northern Andes. This ridge extends to the North and is continuous with the Cordillera Central of Colombia, and the south is oblique with Eastern Cordillera of Perú. This Cordillera is formed by igneous and metamorphosed sedimentary rocks with ages from the Early Cretaceous to Paleozoic (Hughes & Pilatasig, 2002; Spikings et al., 2021; Spikings et al., 2001; Spikings & Crowhurst, 2004; Vallejo et al., 2009).

The uplift and exhumation of the Eastern Cordillera resulted from the Collision of the South American Plate against the Caribbean Plateau (Vallejo, 2007). The mountain chain's origin is dated of the Early Cretaceous, related to the Peltetec event where allochthonous terranes accreted against the Guyana shield. It is composed of metamorphic and granitic rocks (Pratt et al., 2005; Spikings et al., 2001; Spikings et al., 2000). The Peltetec fault bounds the Eastern Cordillera to the west, juxtaposing it to the N-S elongate inter-Andean depression. To the east, Cosanga-Palanda-Mendez faults place the Cordillera Real in contact with Cretaceous sedimentary rocks, a Jurassic plutonic regional belt (the Abitagua batholite) belt, and volcanic rocks (Aspden & Litherland, 1992; Spikings et al., 2001; Spikings & Crowhurst, 2004). Faults

(Peltetec, Baños Front, Llanganates, and Cosanga-Mendez faults) separate five lithotectonic divisions in the Eastern Cordillera. These divisions are Guamote (continental), Alao (island arc),

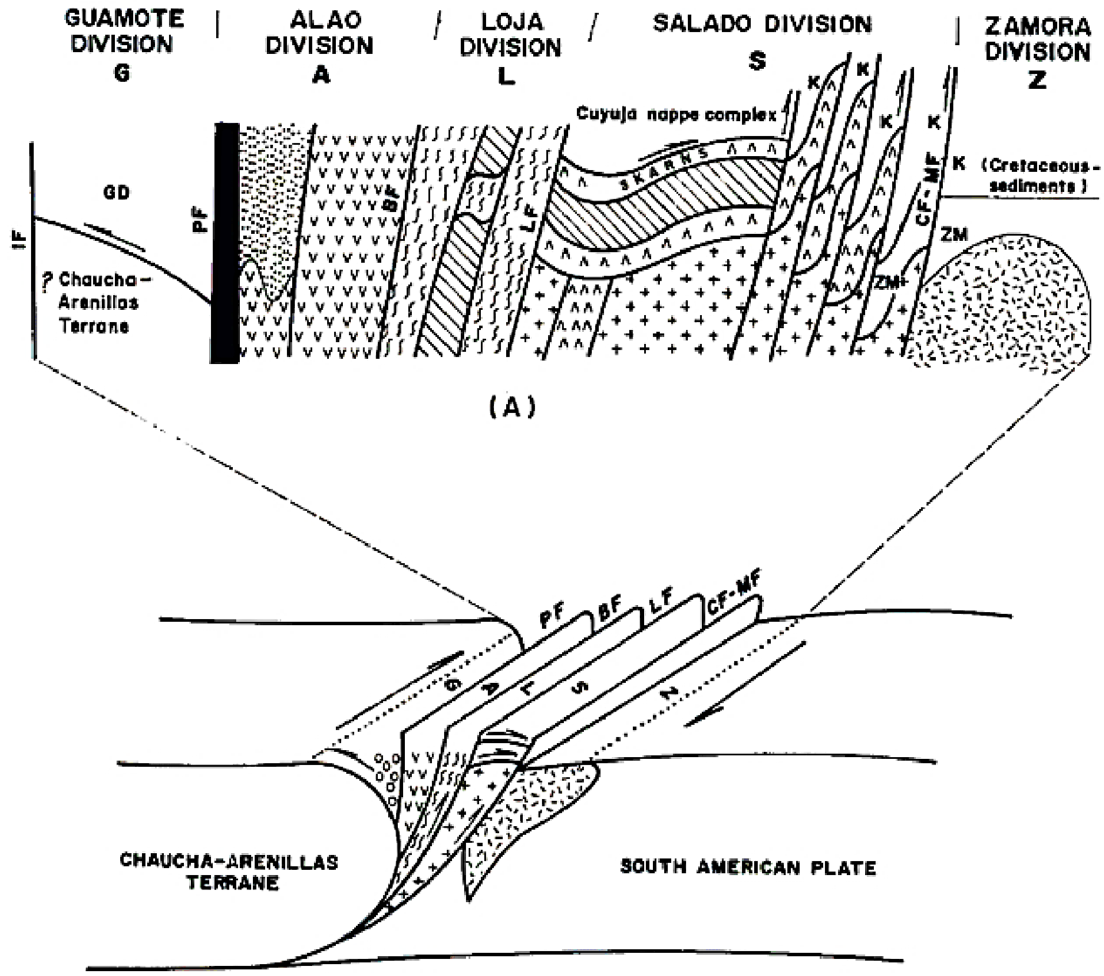


Figure 3. Schematic section across the Cordillera Real. I. Ingapirca fault; PF Peltetec fault; BF Baños front; Llanganates fault; CF-MF Cosanga-Mendez fault. Image taken from Aspden &Litherland (1992).

The Guamote division is located in the western part of Real Cordillera between Riobamba and Azogues. It is limited to the west by the Peltetec fault and the east is overlain unconformably by Yunguilla Formation. The Guamote division is composed of orthoquartzite, phyllites, and low-grade slates, sometimes present feldspathic minerals and blue quartz and interpreted to have formed in continental settings (Aspden & Litherland, 1992).

The Alao division is exposed along the western part of Cordillera in northern Ambato and Southern Cuenca and dated at 90 to 140 Ma. This division is limited by Baños front to the east and Peltetec fault to the west, and is composed of cherts, phyllites, basalts, dolerites, serpentinites, gabbros, and peridotite rocks. Alao is divided into two subdivisions Alao-Paute and Maguazo (Aspden & Litherland, 1992). Alao-Paute subdivision involves andesitic greenstones, greenschists, graphitic phyllites, quartz-silicate, meta-basaltic, meta-andesitic, marbles, and volcanic breccias (Aspden & Litherland, 1992; Pratt et al., 2005). The Maguazo subdivision is composed of turbidites, volcanic clastic, andesitic greenstones, carbonaceous slates, and cherts.

The Loja division is a sub horizontal belt that forms the Cordillera's middle tectonic level and is exposed along the Eastern Cordillera length between Cuenca and the Peruvian border. This division is limited by Baños front to the east and the Llanganates fault to the west. This division consists of metamorphosed, semi pelitic, and meta granitoid rocks (Aspden & Litherland, 1992). Loja has two subdivisions, Tres Lagunas and Sabanilla. Tres Lagunas subdivision contains foliated greenschist and quartzites rocks of medium to coarse-grained with minerals of alkali feldspar, garnet, cordierite, and pale blue quartz (Aspden et al., 1992; Aspden & Litherland, 1992). The Sabanilla subdivision contains foliated and migmatitic rocks of medium to high-grade like schists, gneisses, paragneisses, and amphibolites.

The Salado division is composed of andesitic and metasedimentary rocks and is divided into two deformed subdivisions, the plutonic Azafran and the volcano-sedimentary Upano (Aspden & Litherland, 1992; Pratt et al., 2005). The Azafran subdivision contains two main plutons, the Chingual and Sacha, with deformed rocks like granodiorites, orthogneisses, schists, tonalites, diorites, hornblendites, and gabbros. The Upano subdivision comprises deformed volcano-sedimentary rocks like metamorphosed andesites, stuff, greywackes, marbles, quartzites, and black phyllites, and metamorphic rocks such as greenschists and hornblende amphibolites.

The Zamora division is located to the east of the Cordillera and is a compound of two subdivisions, the Abitagua and Misahualli. Abitagua is formed by potassic Jurassic granites in the Eastern Cordillera and comprises three calc-alkaline batholiths, the Rosa Florida, Abitagua, and Zamora (Aspden & Litherland, 1992; Pratt et al., 2005). These batholiths are composed of silica lavas, pyroclastic, andesites, hornblende andesites, dacites rocks, and high-level subvolcanic intrusions. The Misahualli subdivision consists of continental volcanic sequence with subvolcanic and plutonic rocks (quartz syenite to quartz monzonite) associated to the Florida pluton (Aspden & Litherland, 1992; Pratt et al., 2005).

2.3. INTER-ANDEAN BASINS

The Inter Andean Valley (IAV) is a tectonic depression located between Western and Eastern Cordilleras and starts to form in the Late Miocene-Pliocene. The IAV is limited to the east by the

Pisayambo fault scarp and the west by La Victoria scarp. Furthermore, some volcanoes define the planar zone along the edges of the Interandean basin like active stratovolcanoes (Pichincha, Antisana, Cotopaxi, and Tungurahua) and old volcanoes (Iliniza, Sagoatoa, Igualata, Altar, and Chimborazo) (Lavenú et al., 1995). The inter-Andean Valley opening began during the Late Miocene at ~6-5Ma. It ended with a compressive inversion that started in the Middle Pleistocene (Hungerbühler et al., 1995). The aperture was mainly driven by major strike-slip movements along the Calacalí Pallatanga fault (Villagomez,2003).

Continental intramontane basins are common features along the South American Andes. According to Marocco et al. (1995) there are ten defined basins from North to south of Ecuador: Chota, Guayllabamba, Latacunga-Ambato, Riobamba, Cuenca, Giron-Santa Isabel, Nabón, Loja, Vilcabamba and Zumba basins (Fig.3). The Neogene continental basins are composed of reworked material, alluvial, lacustrine, volcanoclastic, and metamorphic basement rocks (Barragán et al., 1996; Hungerbühler et al., 1995; Marocco et al., 1995).

The northern Interandean Valley contains the Late Miocene to Pleistocene Chota, Guayllabamba, Latacunga-Ambato, and Alausi-Riobamba basins that are younger than the southern intermountain basins such as Cuenca, Giron-Santa Isabel, Nabón, Loja, Vilcabamba, and Zumba basins (Villagómez,2003).

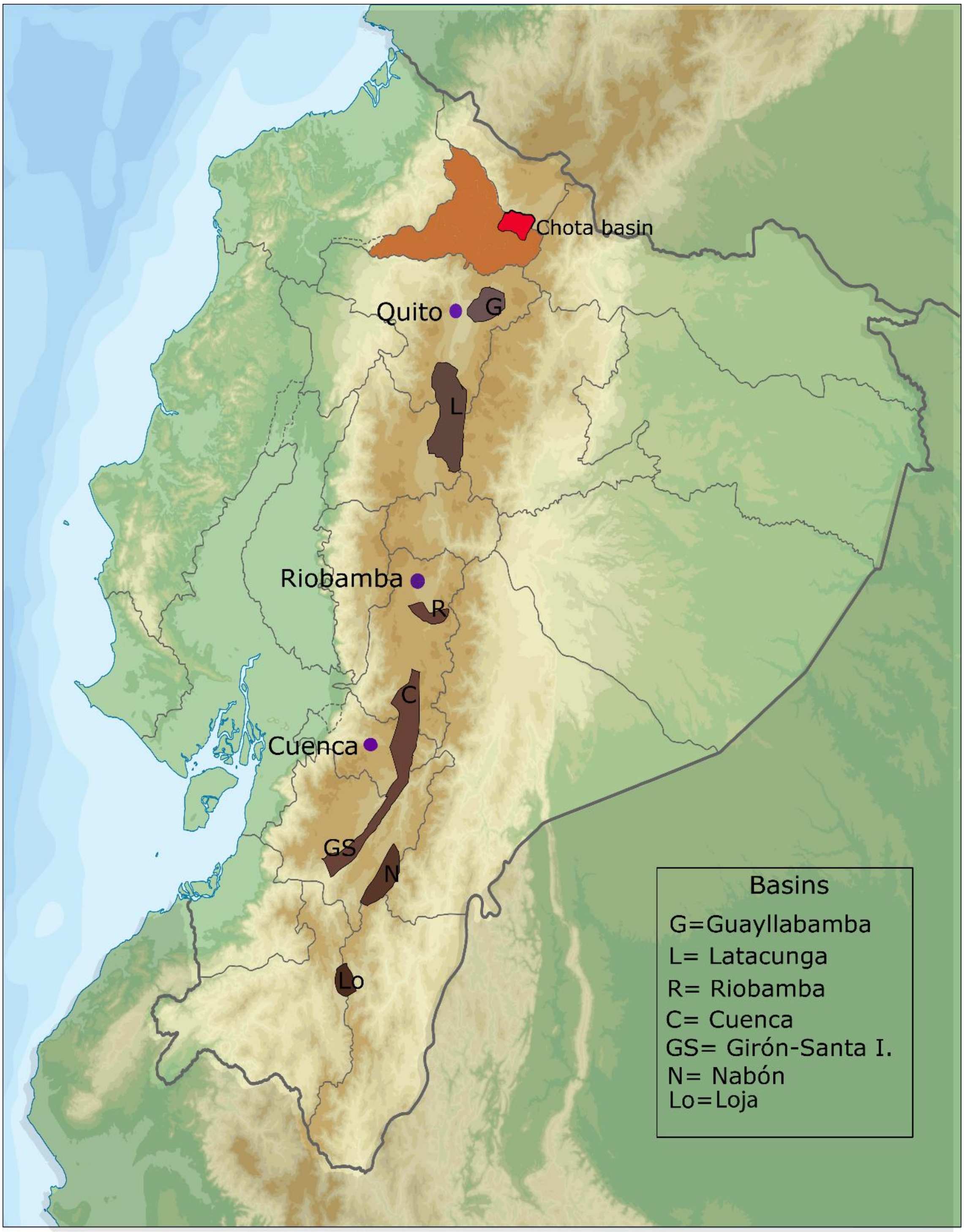


Figure 4. The Interandean basins of Ecuador from North to South: Chota, Guayllabamba, Latacunga, Riobamba, Cuenca, Giron-Santa Isabel, Nabón and Loja. The color in the map represents the variation of elevations. (Source: modified image of Marocco et al.,1995).

The Guayllabamba basin is located in the Central part of Ecuador in the Pichincha province. This basin comprises volcanic, fluvial, alluvial, lacustrine with interbedded volcanic, fluvial, deltaic, and turbiditic deposits (Villagómez, 2003).

The Latacunga-Ambato basin is limited to the east by the Pisayambo fault and the west by the La Victoria fault. It is composed of four different units with ~500m of the total thickness. The first unit comprises lahars, pyroclastic flows, andesite lavas, lacustrine and fluvial deposits. Unconsolidated fluviatile and lacustrine deposits form the second unit. Finally, the last units contain unconsolidated pyroclastic tuff. (Lavenú et al., 1995; Winkler et al., 2005).

The Riobamba basin is located to the south of Ecuador in the Chimborazo province. This basin has a total thickness of ~ 100 m and is filled with lahars, alluvial and fluvial conglomerates, and volcaniclastic rocks. Some coarse facies are deposited during synsedimentary deformation and a compressive tectonic regime (Lavenú et al., 1995; Winkler et al., 2005).

The Cuenca Basin is the largest Neogene intermontane basin in the southern part of the Ecuadorian Andes. The basin section has a thickness of ~4200 m, composed of lacustrine megaturbidites, fluvial and alluvial deposits. It has a coarsening-upward succession (Hungerbühler et al., 1995; Marocco et al., 1995).

The Giron-Santa Isabel sub-basins contain facies deposited at sea level, which drained into the larger Cuenca basin. This basin comprises an alluvial and fluvial fan, bedload river, and shallow marine deposits (Steinmann et al., 1999).

The Nabón basin is located 60 km to the south of Cuenca and is composed of Oligocene to Miocene volcanic series. It has a thickness of ~600m and consists of volcaniclastic breccias, sandstones, fluvial-lacustrine, ignimbrites, andesitic lava flows, and metamorphic rocks from Eastern Cordillera (Hungerbühler et al., 1995; Marocco et al., 1995).

Loja, Vilcabamba, and Zumba basins are located in the last southern part of Ecuador. These basins are composed of reworked material from volcanoes and adjacent metamorphic basement rocks (Hungerbühler et al., 1995) composing in conglomeratic proximal and distal alluvial fans (Toro Álava & Jaillard,2005).

Chota basin is located in the northernmost Ecuadorian Andes in the Imbabura Province, and it has the best stratigraphic record of the northern Inter Andean Valley (Fig.3) (Marocco et al., 1995; Tibaldi & Ferrari, 1992). There are previous studies that determine the tectonic evolution and stratigraphy of the Chota basin.

Tibaldi & Ferrari (1992) explain that the deformation of the northern sector of the Interandean valley that originated the morphology of the Chota basin suffered a phase of compressional deformation in the Pliocene epoch, causing cylindrical folds and reverse faults; and, after that, occurred an extensional stage in the Holocene developing pure and left-lateral normal faults. The oldest rock in this sector comprises lacustrine and volcano-sedimentary deposits (Pliocene andesite and Miocene continental deposits) belonging to the Chota group.

According to Egüez & Beate (1992), the basin presents a complex deformation, with synsedimentary folds and faults developed in the different phases of evolution of the basin. Three main faults controlled the development of the Chota basin, the Culebrón, Cariyacu, and the Ángel faults. This study defines four stratigraphic units from base to top. The Chota Formation has 380 m in thickness and comprises fluviatile and lacustrine deposits like shales, conglomeratic sand, and claystone. Santa Rosa Formation includes breccias and conglomerates with metamorphic and volcanic clasts and has 1000 m in thickness. Peñas Coloradas has 800 m in thickness and contains conglomeratic sandstones and a transition of shales to intercalation of conglomerates and sand. Finally, at the top, the Granalotal Formation is composed of fluvial-lacustrine deposits, and it has a thickness of 350m.

On other hand, Barragán et al. (1996) determined two stages of basin evolution, the opening, and closing. The basin opening is a consequence of a transtensional event that caused displacements along normal faults. These faults originated a depression that with time was filled with sediments. The Chota Formation is interpreted by Barragán et al. (1996) as a deposit formed in this stage and the change of fluvial to lacustrine environments was controlled by the velocity of tectonic subsidence. The closing of the basin is characterized by a compressive tectonic regime with NW-SE direction that caused dextral and inverse faults that led to the formation of marked reliefs on the western side of the basin that were recorded by the Santa Rosa Formation. Later a rotation of the main compressive stress vector occurred, shifting to a E-W direction that created dextral and inverse faults that developed reliefs to the eastern margin of the basin that resulted in the deposition of Peñas Coloradas y Carpuela Formations (Barragán et al., 1996). Therefore, Chota basin fill is defined by 4 Formations (Fm) from base to top; Chota Formation located in the central part, Santa Rosa Formation to the western margin, Peñas Coloradas and Carpuela Formations develop to the western margin of the basin. Chota Fm is interpreted like the older unit because it overlays the basement also it conformably and unconformably underlies the Santa Rosa and Peñas Coloradas Fm respectively. This unit is 500 m thick and is composed of fining-upwards alluvial sequences, volcanic-conglomerate clast, mudstones and clay intervals. Santa Rosa Fm to the west is overlying by the Chota Fm and the basement. It has a ~1000m in thickness and comprises metamorphic, volcanic, and sedimentary conglomerates as well fluviatile, clays, and silts deposits. The next Fm is Peñas

Coloradas which has a fault contact with the Ambuquí subdivision and an unconformable angular contact with the Chota Fm. This suggests that the Peñas Coloradas Fm former later than Santa Rosa Fm. Peñas Coloradas Fm has 600m of thickness and comprises alluvial fan deposits, sheet flow, debris flow, and coarse volcanic deposits. The last stratigraphic Formation is the youngest in the Chota basin is Carpuela Fm. This Formation has a fault contact with the metamorphic Pacheco subdivision (basement). Carpuela Fm has ~300m in thickness and is composed of coarse-grained conglomerates, as well as alluvial, metamorphic and volcanic deposits (Barragán et al., 1996).

Another study carried out by Winkler et al. (2005) proposes a ramp basin model to explain the development of the inter-Andean depression that generated different basins, including the Chota basin, which has suffered shortening with a compressive regime that originated reverse faults on both margins of the basin. During this process, three Formations were formed in the Chota basin with a total of approximately 1200–1400 m in thickness from base to top; Peñas Coloradas, Chota, and Santa Rosa Fm. In this study, Peñas Coloradas Fm is interpreted like the older unit due to a Zircon fission-track analysis obtaining an age of 5.4 ± 0.4 Ma. Chota Fm analysis range in age between 4.8 ± 0.4 and 2.9 ±1.5 Ma. Thus Winkler et al. (2005) suggest that the Peñas Coloradas Fm is older than Chota Fm. Peñas Coloradas Fm is comprises of alluvial fan, volcaniclastic breccias and metamorphic rocks. Chota Fm comprises volcanic, fluvial, and lacustrine deposits, and finally, The Santa Rosa Formation consists of fluvial to alluvial fan deposits.

3. METHODS

This work requires a sound basis of field data, aerial photogrammetry, field data processing, and XRD analysis lab work. The fieldwork (Fig. 4A) lasted two and half months and during this time 461 m of detailed sedimentary logs were recorded at a 1:1000 scale with descriptions such as bed thickness, grain size, clast composition (igneous, sedimentary or metamorphic rocks), sedimentary structures, matrix or clast support, tectonic structures, the roundness or angularity of clasts, color, contacts between beds, minerals, fossils, and another useful information. Additionally, the stratigraphic columns were digitized in a free software called Stratigraphic Data Analysis in R (SDAR) that allows to plot and analyze stratigraphic and sedimentological data taken in the field. SDAR is an analytical package in the R programming language that produces detailed stratigraphic columns. It can include multiple features, for instance, bed thickness, lithology, samples, sedimentary structures, colors, fossil content, bioturbation index, gamma-ray logs, etc. (Ortiz & Jaramillo,2020). The program outputs vectorized graphics that can be edited using the Adobe Illustrator software to insert any features not available in the program.

Another field data collected were clast counts, carried out in conglomeratic intervals throughout the Peñas Coloradas Fm. This process allows determining the composition and proportions of clasts within a bed. We used of "line method," which consists of counting individual particles along lines transverses (Fig. 4C). However, this technique creates differences in the statistics because we could find particles of different sizes (Howard,1993). We defined the particle size to count in a range of 5-11 cm and an area of 1 m^2 separate into parallel lines in 10 cm each one (Fig. 4D). We choose eleven locations to carry out the clast-count: five locations in the Canales Colorados Mbr, three in the Tabulares Mbr, and three in the Volcanicas Mbr. We did not carry out the clast count in the Brillosas Mbr, or the Chota Fm because they do not have conglomeratic intervals suitable for this. 1480 clasts were counted in total, and the categories used were lavas, pumices, and metamorphic rocks.

X-ray diffraction (XRD) analyses were carried out on eighteen clay samples. The clay samples were characterized in the laboratory of Chemical Science and Engineering at Yachay Tech University (Fig. 5A). Samples were dried in an oven (Fig. 5B) and then were crushed in an agate mortar to a fine powder (Fig. 5C). Subsequently, each sample was mounted in an aluminum sample holder with a multipurpose stage with 8-positions (Fig. 5D-E). The X-ray diffraction (XRD) analysis was carried out by a powder diffractometer, Mini-flex-600, from Rigaku, with a D/tex Ultra2 detector (Fig. 5F). The measurement conditions were 40 kV and 15 mA for the X-ray generator in a sealed tube with a CuKα1,2 radiation source. For collecting data, the selected angular region was 2θ = 5-100° with a step width of 0.02°. The data reduction (the smoothing, background and zero-point corrections, and peak search) of powders diffraction was carried out using the Qualx 2.8 program. The crystallography open data (COD) base was used as the powder diffraction database, and the search-match methodology was used to obtain the possible candidates' list as a constituent of the crystalline phases present. However, this method did not yield matching clay minerals, so the American Mineralogist Crystal Structure Database was used to determine the signal that corresponds to the main clay minerals, and these were manually searched for in each sample.

Orthomosaics were constructed with photogrammetry methods on images acquired with a DJI Inspire 2 drone equipped with a Zenmuse X4S camera belonging to the School of Earth Sciences, Energy and Environment at Yachay Tech University (Fig.4B). Guided flights were done using the Drone Harmony software and manually controlled flights were done with the DJIGo4 software. Panoramic, aerial, and frontal views of different outcrops were acquired. Finally, these images were processed into orthomosaics images with Pix4D Mapper software's with a 4cm/pixel final resolution. These orthomosaics provide a visual record of the geological features that were out of reach, or larger than outcrop scale.

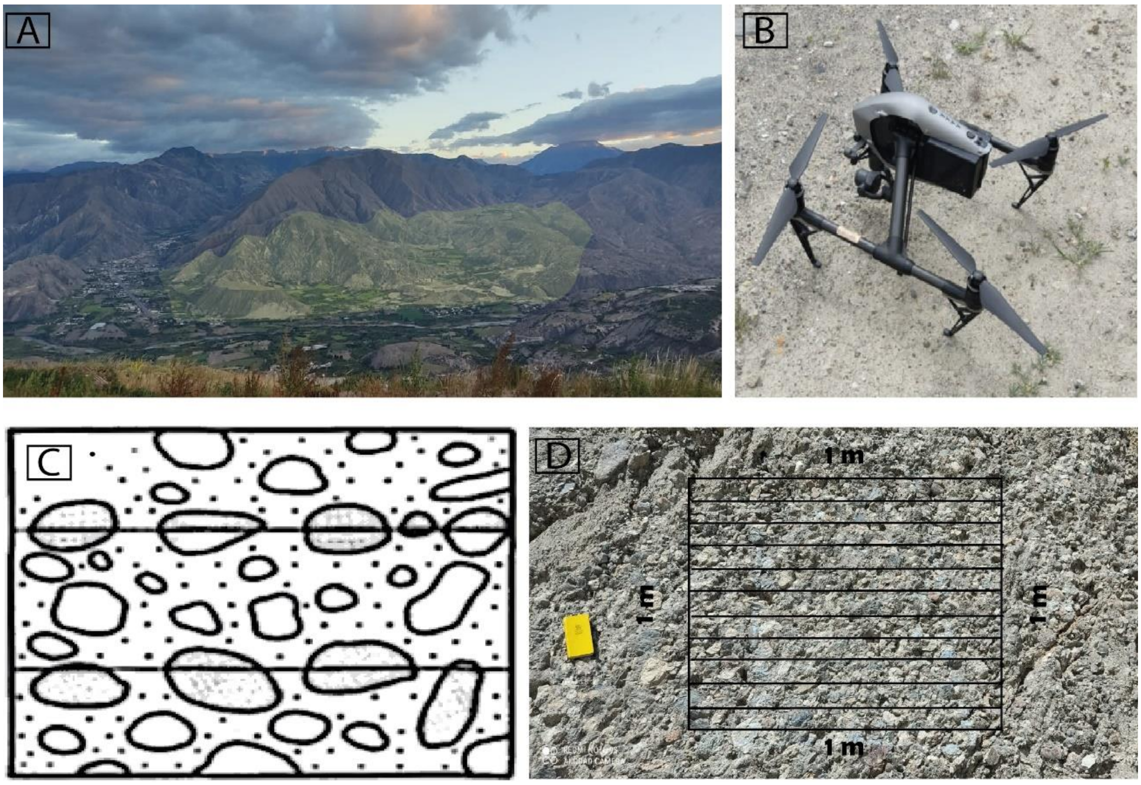


Figure 5. (A) fieldwork area, (B) DJI Inspire 2 drone equipped with a Zenmuse X4S camera, (C) line method, (D) Area of clast count (1x1 m2) divided into parallel horizontal lines of 10 cm of distance.

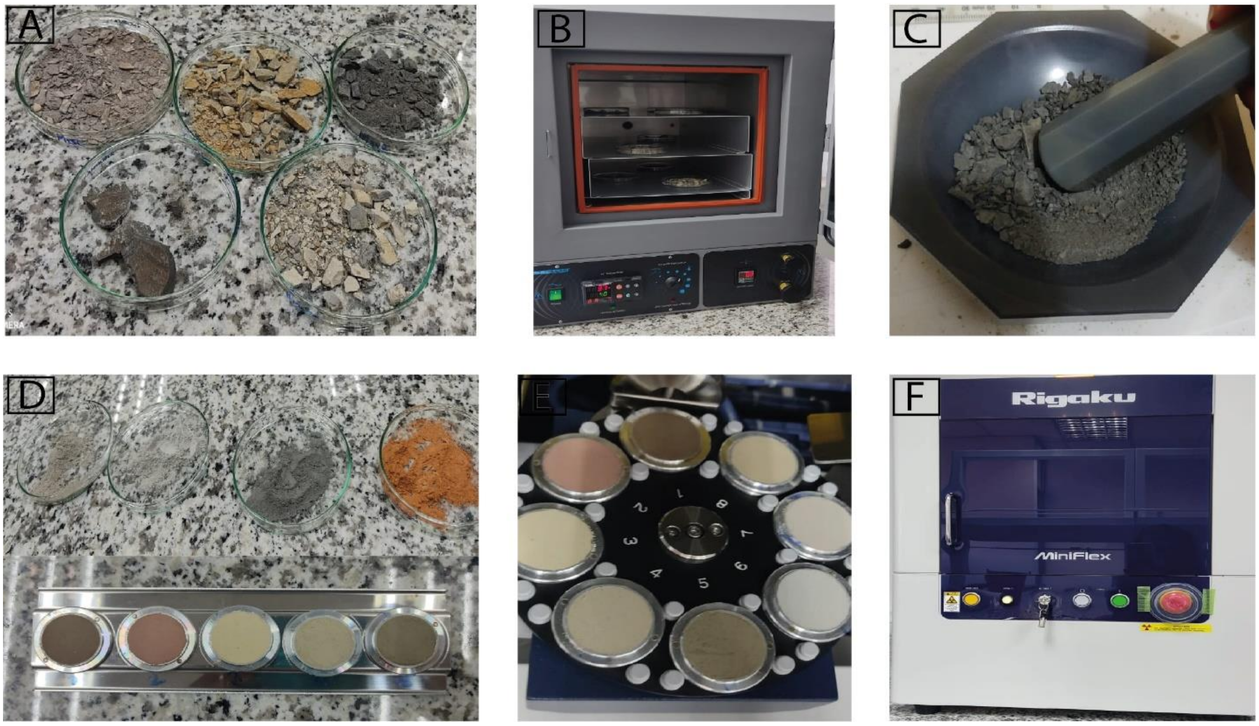


Figure 6. (A) clay samples, (B) oven extracting all moisture from samples, (C) Agata mortar for crushing samples, (D) powder and preparation of samples for the diffractometer, (E) aluminum sample holder with eight positions, (F) processing of samples inside of the powder diffractometer, Mini-flex-600.

4. RESULTS

We described the Chota Formation and the Peñas Coloradas Formation defining four members in the latter (Fig.6). The stratigraphy begins above the Ambuquí Formation, which is the local basement. The Ambuquí Formation consists of low to medium-grade metamorphosed rocks such as quartzites and phyllites with abundant mica and quartz. These rocks show evidence of brittle and ductile deformation (Fig.7F), with the presence of structures like folds, faults, and joints. Parts of the basement have a deep reddish color which we interpret as a laterized weathering surface formed on an exposed paleosurface.

The sedimentary section in our study area in the Chota basin is divided into two formations, the Chota Formation and the Peñas Coloradas Formation. The Chota Formation is composed of shales and sandstones with abundant sedimentary structures such as cross-stratification and lamination. Further, it contains much organic material and conserves fossils like bivalves, leaves, and roots. Its color varies from dark gray to yellowish (Fig.7E).

The Peñas Coloradas formation is composed by the Canales Colorados, Brillosas, Tabulares and Volcanicas members (Fig.6), which have concordant contacts between them.

The Canales Colorados Member has a thickness of ~128 m and has an underlying fault contact with the Chota unit and basal discordance with the basement. The predominant lithologies in this unit are conglomerates and breccias and it consists of intercalation of sandstones and conglomerates. The clast size varies from very coarse sand to boulders; the conglomerates are matrix supported, the clasts' shape is angular to subrounded, poorly to medium sorted. The Canales Colorados Member is characteristized by large channels with erosive bases. It has large cross-stratification structures and the colors differ between gray and red (Fig.7D).

The Brillosas Member has a thickness of approximately 146 m. It comprises very fine to medium coarse sand and some shale beds; the sands are well sorted with rounded clasts. This unit has a high content of micas giving it a shiny beige appearance. Brillosas contains cross-stratification and lamination structures. In the shale beds, there is organic matter conserved in fossils of bivalves and leaves (Fig.7C).

Tabulares member has ~67 m in thickness. It comprises intercalations of unconsolidated fine sand and consolidated medium to coarse sand, well sorted, and subangular shape. Furthermore, there are centimetric fine grained beds towards the base of the member. It contains fossils and cross-stratification (Fig.7B).

Finally, the Volcanicas member has a thickness of ~72 m. It comprises intercalations of dark gray volcanic, matrix supported breccia and light gray very coarse sandstone with cross-stratification. The predominant clasts in this unit are andesite, pumice, and gneiss lithics. The clast size is from pebbles to boulders (Fig.7A).

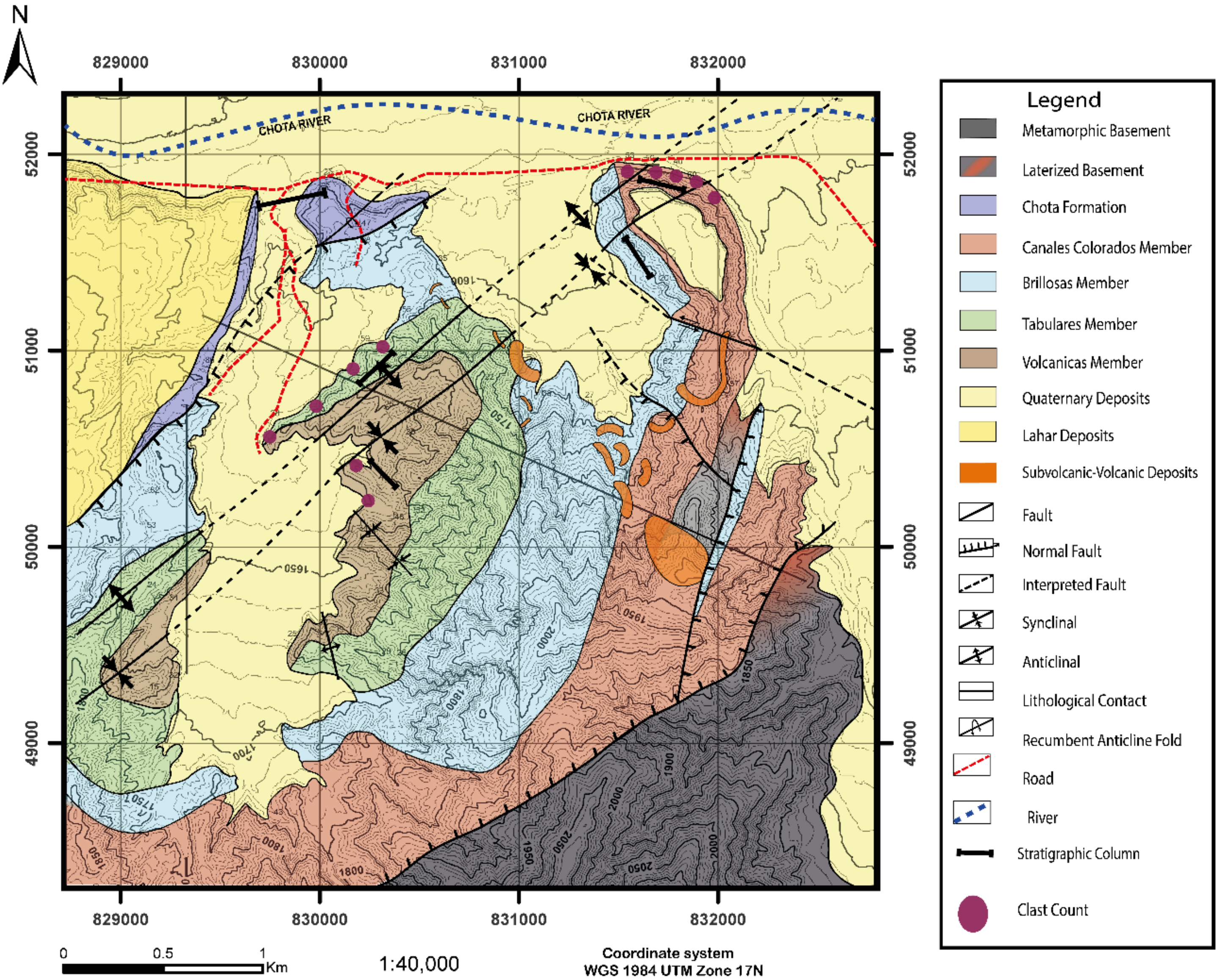


Figure 7. Geological Map showing the Chota Formation and Subdivisions of Peñas Coloradas Formation; Canales Colorados, Brillosas, Tabulares and Volcanicas Members. Locations of taken data of the Stratigraphic Columns and Clast Count.

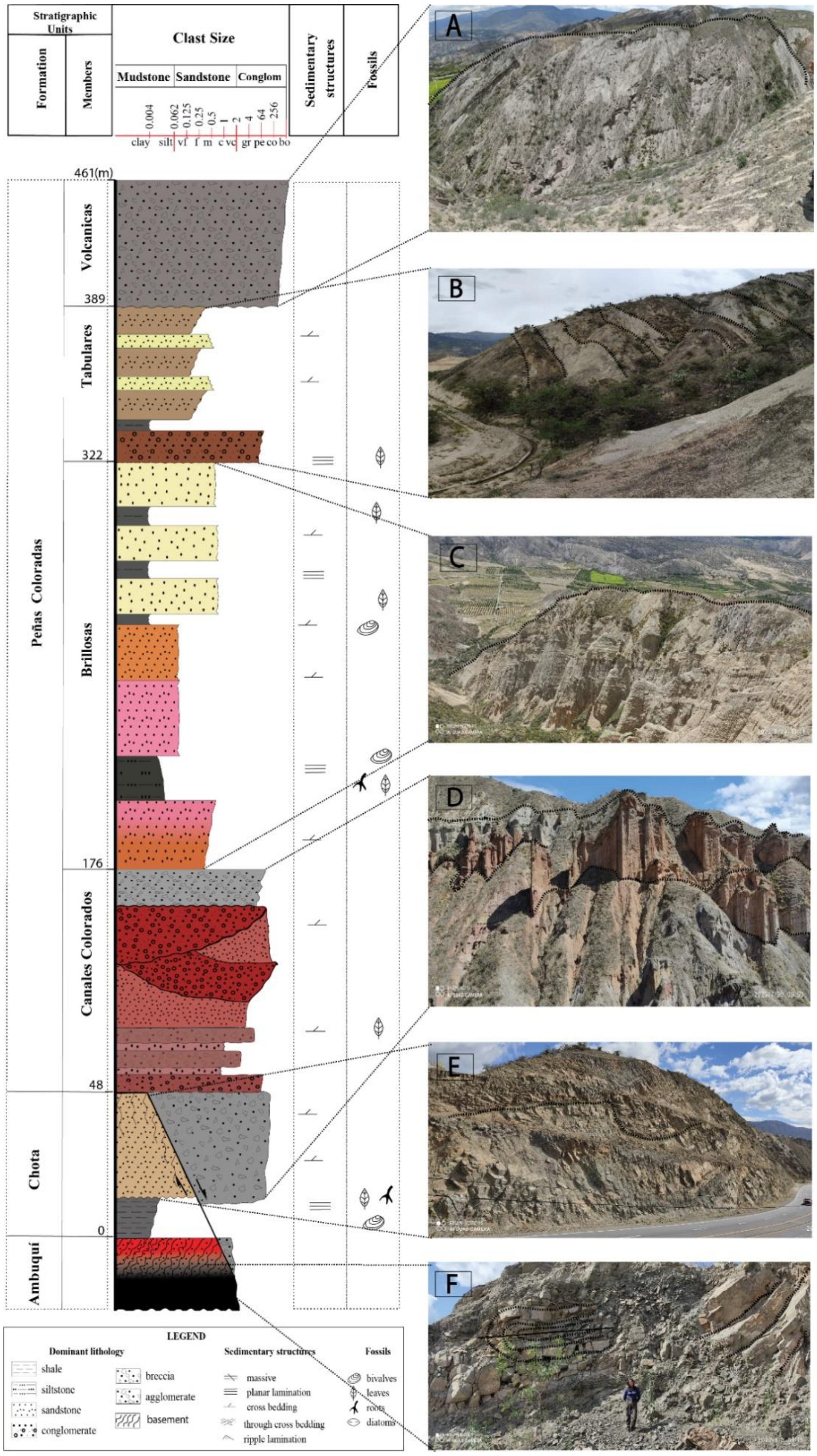


Figure 8. Schematic stratigraphic column with the composing units of the of Peñas Coloradas formation overlying the Chota Fm. and the Ambuquí Gp. (A) Volcanicas Member panoramic view, (B) Tabulares Member shows the intercalation of consolidated and unconsolidated sand, (C) Brillosas Member panoramic view, (D) Canales Colorados Member shows the large red channels, (E) deformed outcrop of Chota Formation and (F) the base of all sequence composed by deformed and folded metamorphic rocks.

4.1. CHOTA FORMATION

Description

The Chota Formation has a thickness of ~48 m in our study area. Figure 8 shows a synthetic stratigraphic log that summarizes observations from various outcrops. It comprises shale and sandstones. The base of the formation is not exposed, but the deepest part we can see begins with intercalations of claystone and fine to medium sandstone that transitions to medium to coarse sand in the upper part of the section. There is an upward coarsening trend overall, good sorting, subrounded clast shape, and dark gray to yellowish color. The common sedimentary structures are horizontal laminations, cross-stratification, flute casts, and load casts, which are also good stratigraphic polarity indicators. This formation contains much organic matter conserved in fossils of bivalves, roots, and leaves. The layers are deformed as a result of tectonic forces resulting in abundant folds in faults at the outcrop scale. The upper contact of the exposed Chota Formation is a fault that places it against the Brillosas Member of the Peñas Coloradas Formation.

4.1.1. Detailed stratigraphic column of the Chota Formation on the Panamericana roadcut.

Description

Here we present a stratigraphic column of a representative outcrop of the Chota Formation created at a 1:100 scale along a large roadcut of the Panamericana road that includes a quarry (Fig.6). The equivalent section in the synthetic column is marked in Fig. 8. The outcrop that belongs to this stratigraphic log is located next to the road (UTM 17N 830269E, 51728N, elev. = 1580 m). This section has a length of ~22 m, composed of intercalation of claystone and fine to medium sandstone beds. The basal part comprises intensely deformed clay beds (Fig. 9F) and sandstones rich in fossils like bivalves, leaves (Fig. 9E), and roots. This is followed by centimetric beds of very fine to fine sandstones with cross-bedding (Fig. 9D) good sorting, and sub rounded clasts with a few intercalated beds of mudstone with cross- stratification and parallel lamination structures and some fossils (Fig.9C). The layers are black, yellowish, and beige. Finally, in the upper part, the sequence comprises intercalation of sandstones and matrix supported conglomerates from coarse sand to gravel clast size, medium sorting, and subrounded to subangular clasts. There are also sedimentary structures such as cross-stratification (Fig. 9B) that are very marked due to the concentration of darker heavy minerals on some of the cross-beds, load casts, and flute casts (Fig. 9A) that are found on the base of the coarse sandstone layers.

The color of this part is dark gray and light gray and contains erosional and gradational contacts in the interbeds. The sandstones have abundant quartz, feldspar and micas, such as biotite, with some accessory minerals such as pyrolusite.

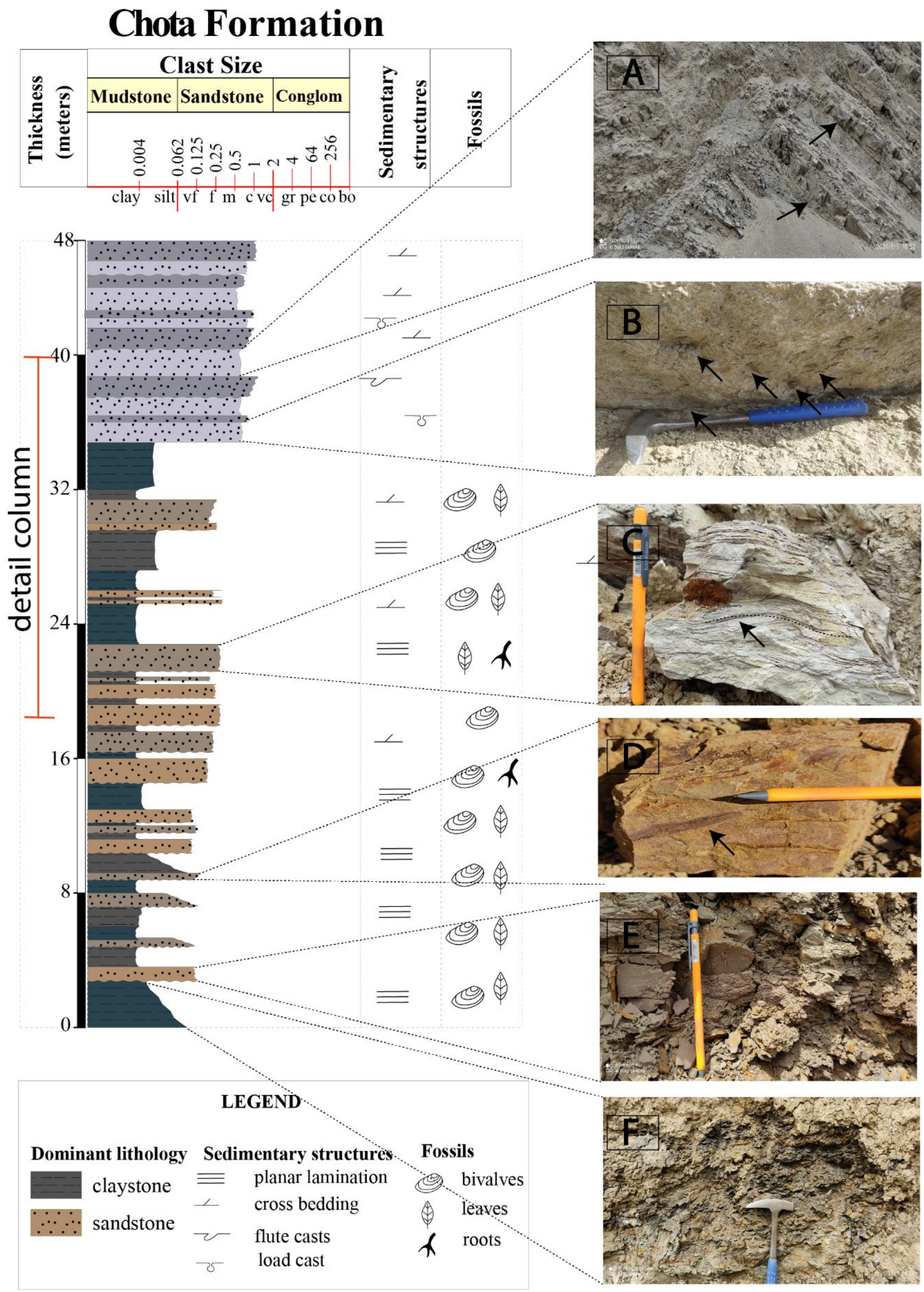


Figure 9. Simplified stratigraphic column of the Chota Formation resulted of observations from various outcrops. It shows the intercalation of clay and sand layers. (A) sand layers, (B) load cast under of sand bed (C) cross-stratification on medium sand (D) fossilized leaves (E) sandstone bed (F) claystone bed. Note (pencil measure sis 13.5 cm).

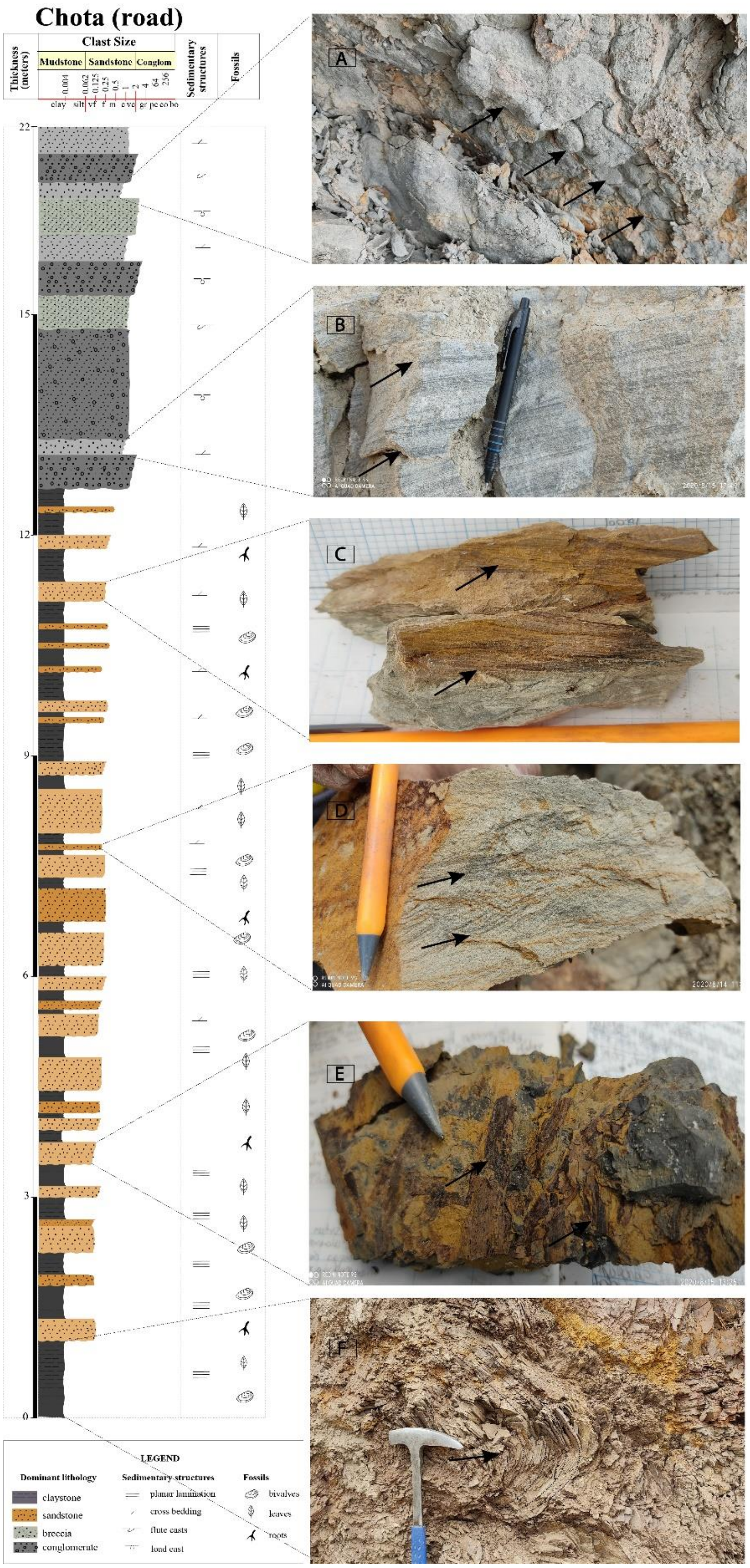


Figure 10. Detailed stratigraphic column of the top part of Chota Formation (Fig.8). The base of this stratigraphic log comprises of intercalation of very fine sand and clays and the top part by intercalation of medium to gravel sandstone. The pictures show (A) Flute casts, (B) cross-stratification marked due to heavy minerals, (C) fossilized leaves on sandstone, (D) cross-stratification on fine sandstone, (E) fossilized leaves on claystone, and (F) deformed clay layer. Location: UTM 17N 830269E, 51728N, elev. = 1580 m. Note (pencil measures is 13.5 cm).

4.2. CANALES COLORADOS MEMBER

Description

This member has ~128 m of thickness and is composed of different beds of breccias, conglomerates and sandstones. Figure 10 shows a synthetic stratigraphic log that summarizes observations from various outcrops. It is mostly composed of breccias and conglomerates. In the basal part, the succession overlies the metamorphic basement with a depositional contact and begins with a breccia of gray color, angular clast, massive, matrix supported, with clasts (some fractured in place) of metamorphic and volcanic rocks (pumice) and vein quartz (Fig. 10B). It has centimeter-thick quartz veins. The next bed is an intercalation of medium to very coarse sandstone of purple color. It's massive, poorly sorted, and contains a few metamorphic clasts, mica and quartz, and the contact between these layers is erosional. The next layer is a red conglomeratic bed matrix supported with few clastic dykes of very fine sandstones, massive, well sorted, subrounded clasts, with an erosional base. The following bed has fining upward grain size, with a basal part made of conglomerate with subrounded clast, good sorting, and matrix support, that grades into a massive, well sorted coarse sandstone. Above this there is a transitional contact into a poorly sorted, massive breccia with angular clasts that transitions into gradationally into tabular conglomerates comprised of normally graded pebbles, poorly sorted, subangular clasts and interbedded of medium to fine sand, with good sorting, and subrounded clasts with cross-stratification. Then, there is a green clay bed that separates the conglomeratic and breccia succession from the overlying the red channelized deposits. This bed comprises silt to clay clast size, and is well sorted with bioturbation, micas and pyrolusite minerals, and fossil roots and leaves.

The next part of the section is the thickest and is formed by red channelized deposits that give the member its name and are the characteristic feature of this unit with a thickness of ~70 m. It comprises intercalations of conglomeratic and sandstone beds. These intercalations are defined by erosional contacts (Fig.10A). The massive conglomeratic bed is composed of coarsening upward grain sizes, from pebbles to boulders, matrix supported, and subrounded clasts. On the other hand, the sandstone beds consist of fine to medium coarse grain size, well sorted, subrounded clasts with cross-stratification. Finally, the last bed of the succession comprises a gray breccia of pebble to cobble grain size, matrix supported, poorly sorted, massive, and very angular clasts shape.

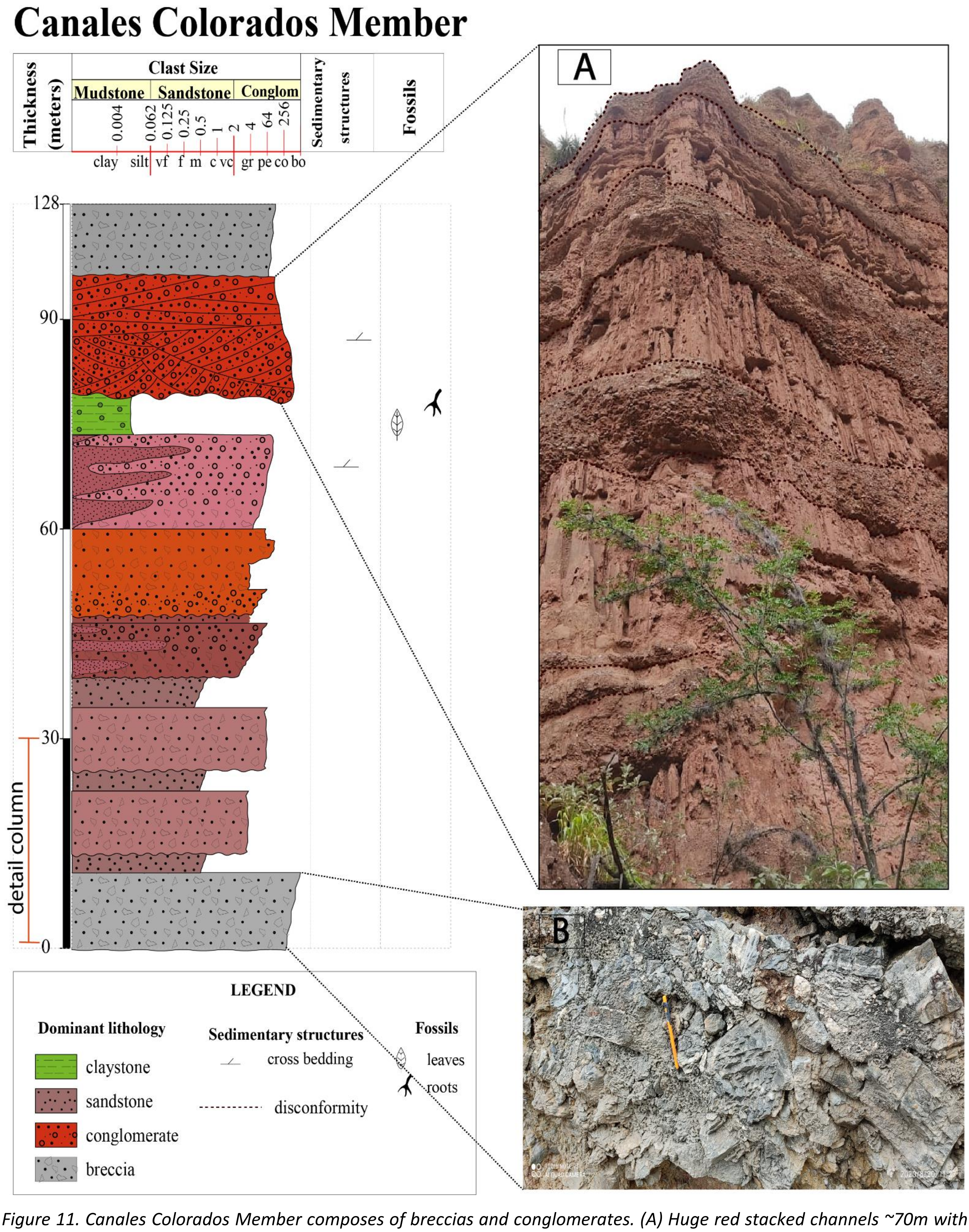


Figure 11. Canales Colorados Member composes of breccias and conglomerates. (A) Huge red stacked channels ~70m with intercalations of sandstones and conglomerates with erosion contacts interbedded. (B) Angular breccias comprised of quartzites Note (pencil measures is 13.5).

4.2.1. Detailed stratigraphic column of the Canales Colorados Member exposed on the Panamericana roadcut

Description

The stratigraphic column was measured on a section that forms an anticline located at a large roadcut along the Panamericana road (UTM 17N 831805E, 51896N elev. =1585 m) next to the Ambuqui road (Fig.6). This stratigraphic log comprises intercalations of conglomerates, sandstones, and breccias beds (Fig.11).

The base of the Canales Colorados is not exposed here. The measured section begins with an intercalation of dark and light gray matrix supported conglomerate and sandstone, , medium sorting, subrounded clast, cross-stratification, and fossilized leaves (Fig.11D), 6.8 cm maximum clast size, common minerals quartz, biotite, and feldspars. The clasts that compose this section are metamorphic (quartzites) and volcanic (pumice and some andesites). This is followed by coarse to very coarse red sandstone, with good sorting, subrounded clast, and cross-stratification structures (Fig.11E). The next part of succession comprises medium sand and breccias, matrix support, poorly sorted, angular clast. The size clast varies from gravel to pebble (Fig.11A) and it has cross-stratification structures (Fig.11B).

After this the section comprises angular breccias, poorly sorted, matrix support, 10.5 cm maximum clasts of metamorphic and volcanic rocks with cross-stratification (Fig. 11H-G). The top part of succession consists of conglomerates, subrounded, clast support, massive, medium sorting, pebble to cobble clast size (Fig. 11E), with, some beds of medium to coarse sandstones. Within these beds, there is a transitional change of sandstones to micro-conglomerates. They have good sorting, subrounded clast, cross-stratification sedimentary structure (Fig. 11F). There is erosion contact between conglomerates/breccias and sandstones.

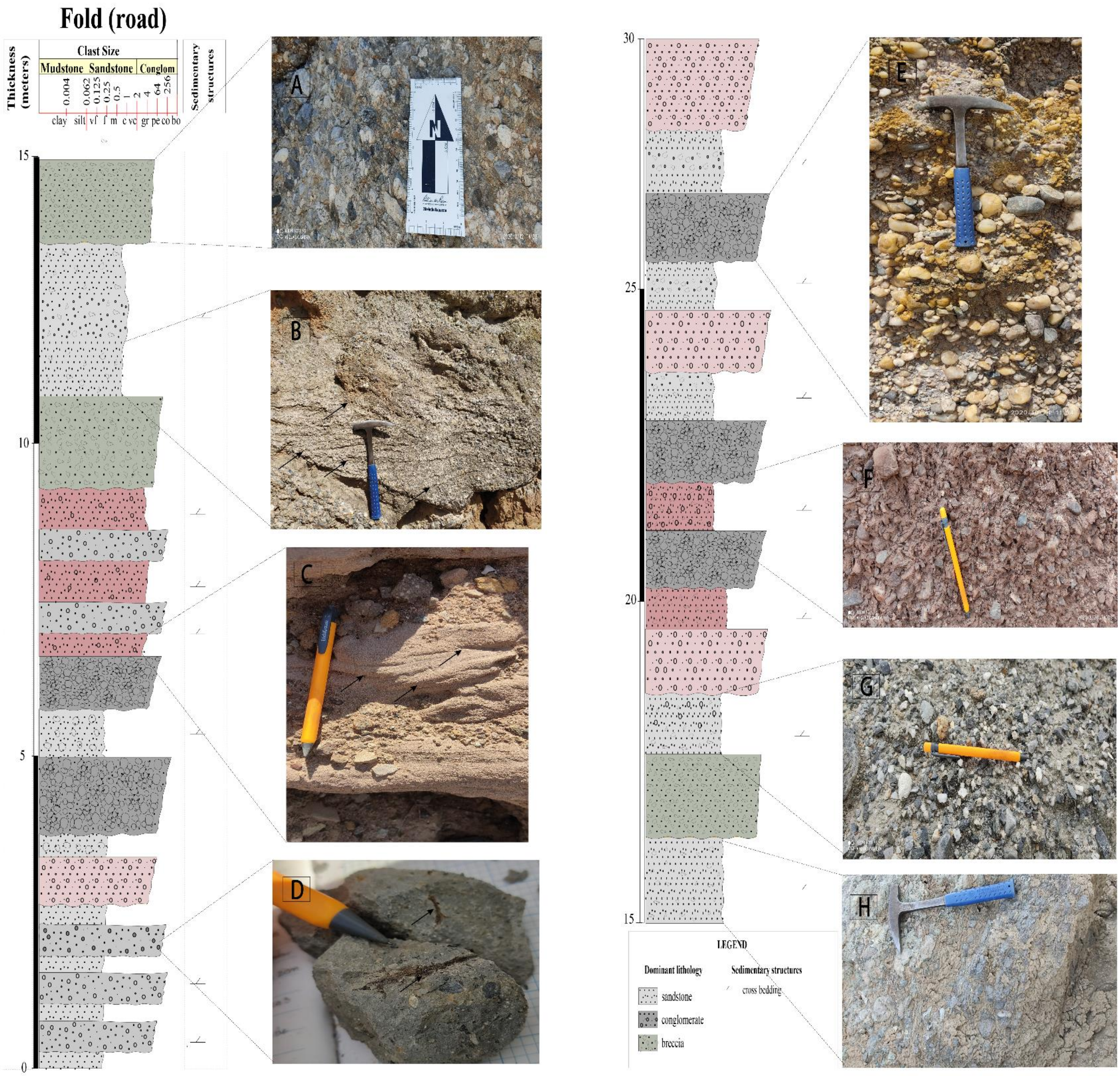


Figure 12. Detailed stratigraphic column of the base part of Canales Colorados Member (Fig.4). This stratigraphic log is composed of series of breccias, conglomerates, and sand. (A) breccia with volcanic and metamorphic clasts, (B) Cross stratification structure on a consolidated sandstone, (C) Cross stratification on fine red sandstone. (D) organic matter-leaves fossilized (E) subrounded conglomerate with clasts support (F) red microconglomerate (G) Gray breccia with angular clast and matrix support and (H) gray breccia, matrix support, subangular clast. Location: UTM 17N 831805E, 51896N elev. =1585 m. Note (pencil measures is 13.5).

4.3. BRILLOSAS MEMBER

Description

This member is the thickest of the Peñas Coloradas Formation, with ~146 m in thickness. Figure 12 shows a synthetic stratigraphic log that summarizes observations from various outcrops.

The defining characteristic of this unit is the high content of micas, that give it a shiny appearance, and the presence of abundant pumice.

This unit's base begins with very fine to fine ocher and pink sandstone, very well sorted, with rounded clast, and cross-stratification (Fig. 12E). Then there is a dark gray clay bed with fossils and parallel lamination (Fig. 12D). The next beds consist of very fine and fine pink and ocher unconsolidated sandstone. There are some interbeds of clays and fine sandstone that contain organic matter like leaves and parallel lamination structures (Fig. 12C)—followed yellowish fine sand layers, with pumice, good sorting, subrounded clasts, and cross-stratification structures (Fig. 12B). The last part of the section is defined by intercalations of fine to medium yellow sandstone and claystone with fossils of bivalves and leaves, and occasional layers of tuff (Fig. 12A).

4.3.1. Detailed stratigraphic column of the Brillosas Member taken along the base of the Meseta

Description

The stratigraphy log shows the top part of the Brillosas member taken along the secondary road that follows the base of the Meseta, (Fig. 12) located at UTM 17N 831723E, 51348N, elev. =1677 m (Fig. 6). This stratigraphic log comprises intercalations of fine sand and clay with fossils and cross-stratification.

The first part of the sequence is comprised of intercalations of dark gray clay and pink fine sand, well-sorted, with rounded clasts, abundant white micas (Fig. 13F), and fossil content as leaves and bivalves (Fig. 13E). Above this there is fine to medium yellowish, subrounded, medium sorted sandstones, and silt to clay material with parallel lamination, and fossilized leaves (Fig. 13D). There is another bed with medium sandstones with high content of pumice and quartz, subangular clast, and poorly sorted (Fig. 13C). In the last part of the sequence, there are claystone, and fine sandstones that are well rounded and sorted with fossils, parallel lamination and ripples (Fig. 13A-B). The common mineral in this section is white micas, quartz, and gypsum veins.

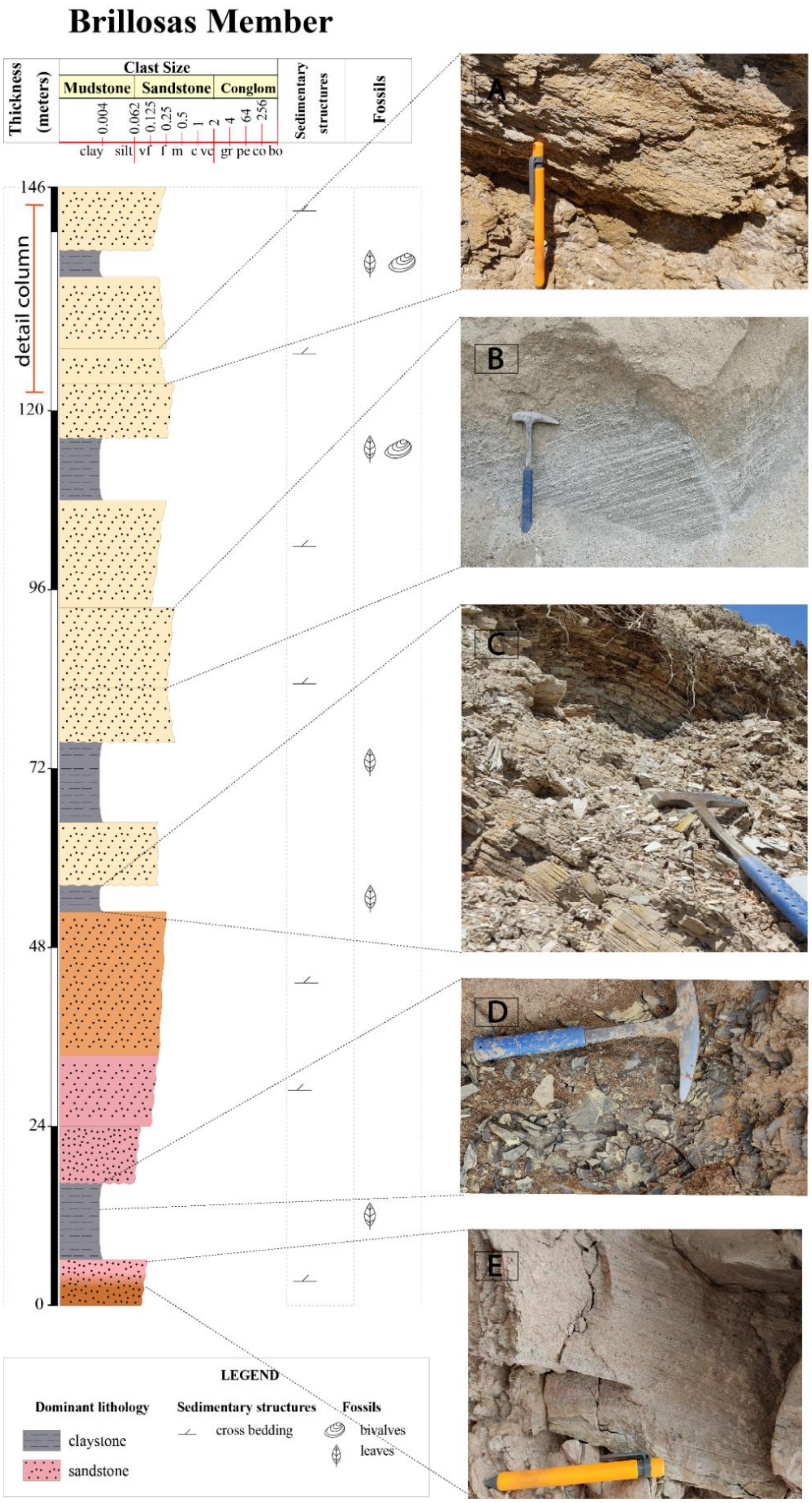


Figure 13. Graphic log of the Brillosas Member comprising a series of fine to very fine sand and some clay beds with cross-stratification, fossils, and high content of white micas and pumice. (A) sandstone comprises white micas and stratification, (B) micro interbed of pumice and sand. (C) centimetric beds of deformed clays, (D) Parallel lamination in claystone, and (E) cross-stratification on brownish fine sand. Note (pencil measures is 13.5).

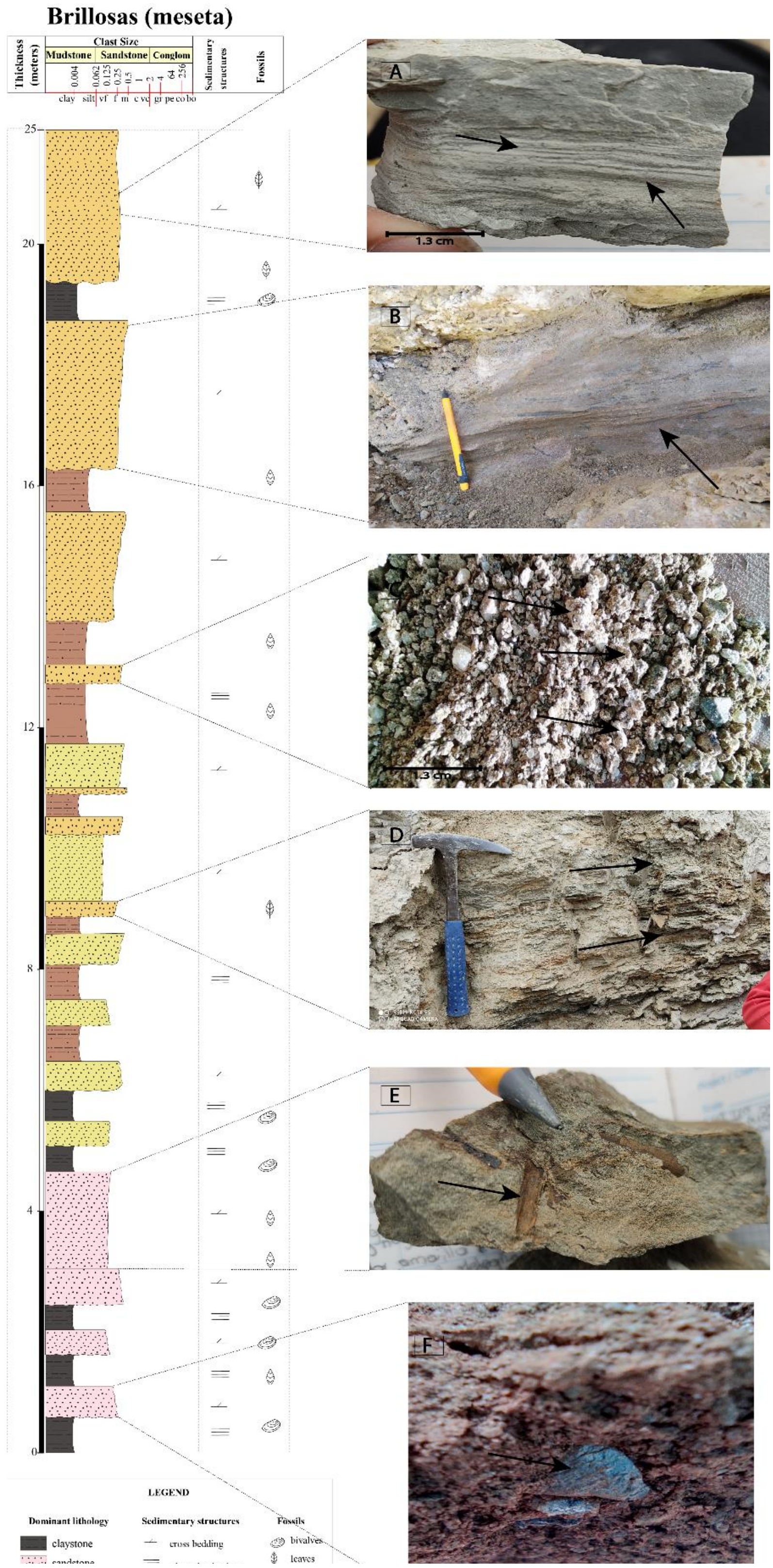


Figure 14. Detailed stratigraphic column of the top part of Brillosas Member (Fig.6). This stratigraphic log comprises intercalation of clay, silt, and very fine to fine sand with high content of white micas and fossils. (A) ripples on sandstone, (B) Cross stratification in unconsolidated fine sand, (C) pumices and quartz grains, (D) Parallel lamination in the clay layer, (E) fossilized leaves on sandstone, (F) white mica sheet. Location: at UTM 17N 831723E, 51348N, elev. =1677 m. Note (pencil measures is 13.5).

4.4. TABULARES MEMBER

Description

The Tabulares Member has a thickness of ~67 m. Figure 14 shows a synthetic stratigraphic log that summarizes observations from various outcrops.

The base of the member is defined by a conglomerate bed of pebble to cobble grain size, good sorting, and subrounded clast followed by intercalation of very fine sand with good sorting, subrounded clast with cross-stratification sand and clay, with lamination and fossilized leaves (Fig.14D). The middle of the sequence is very characteristic because it has tabular sandstone layers that are 2-3 m thick, very consolidated (Fig.14C), dark brown, with good sorting, subangular clasts, and cross-stratification, intercalated with very fine unconsolidated sand with good sorting, subrounded clast, and some cross-stratification (Fig. 14B). The common minerals in this section are quartz, feldspars and micas. The last part of the section comprises breccia with angular clast, poorly sorted, massive, and matrix support. Finally, the top of the member is defined by a massive, fine sandstone with medium sorting and subangular clasts (Fig. 14A).

4.4.1. Detailed stratigraphic column of the Tabulares Member along the secondary road in front of outcrops.

Description

The stratigraphic log shows the middle part of the Tabulares Member (Fig. 14) that was logged at the secondary road next to crops (Fig.6) (UTM 17N 830404E, 51182N, elev.=1623 m). This stratigraphic log has 20 m in thickness and comprises sand of different grain sizes. It begins with silty to very fine sand bed, good sorting, sub rounded clasts, with cross-stratification (Fig.15D). The middle part of the section comprises different beds of fine to medium sand, subrounded clasts, good sorting and some with cross stratification (Fig.15B-C). The common minerals present in this section are quartz, plagioclase, and white micas. In the upper part of the sequence comprises layers of coarse to medium sand, good sorting, subrounded clasts and cross-stratification (Fig.15A).

Tabulares Member

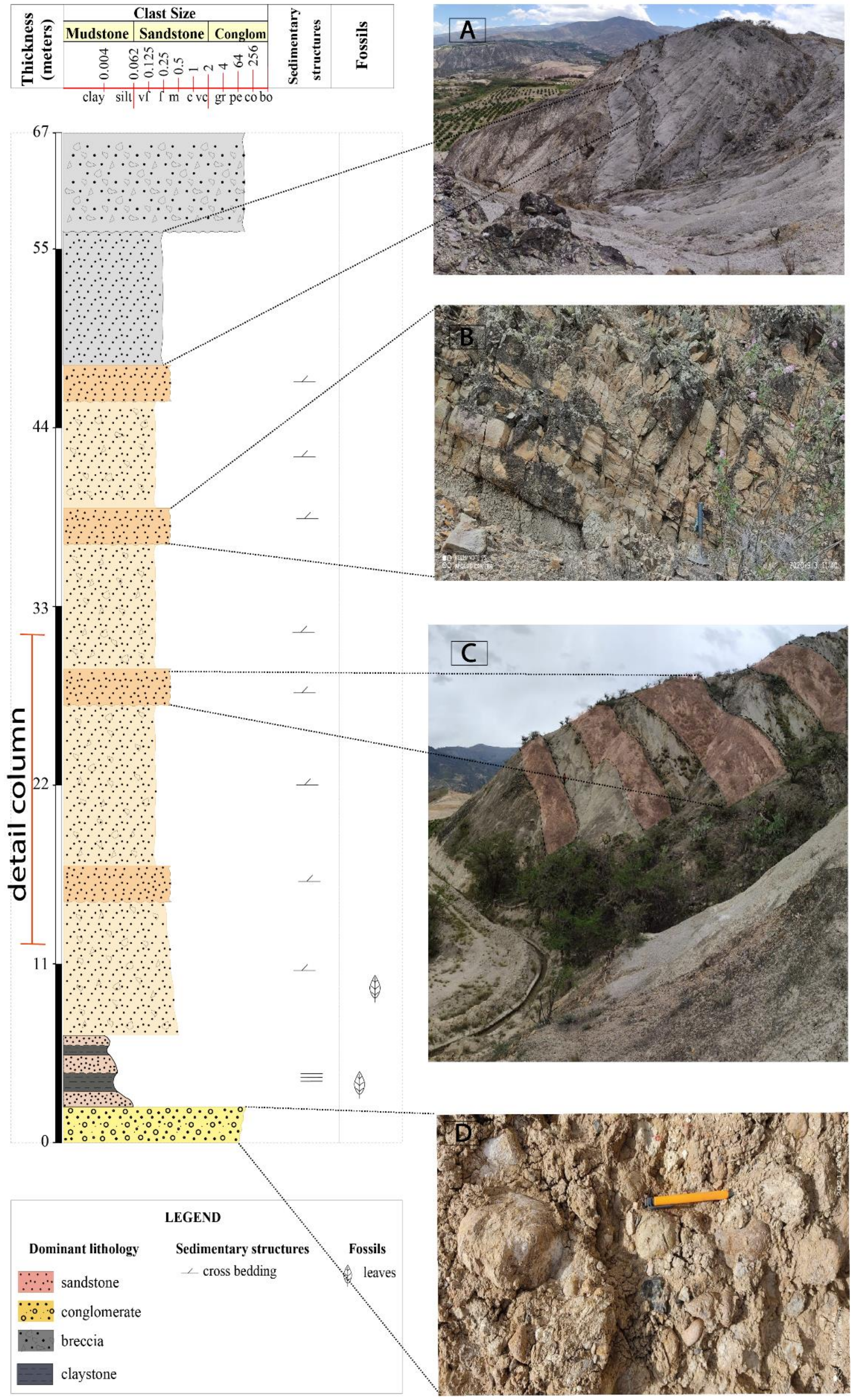


Figure 15. Tabulares Member, the base of sequence is defined by conglomerate and intercalation of very fine sand and clay beds. The middle part comprises very fine to fine sand, and the top has breccia and fine sand. (A) breccia with angular clast, (B) fine sand-tabular, (C) intercalation of tabular consolidated sandstone and unconsolidated sandstone, (D) conglomeratic bed with rounded clast. Note (pencil measures is 13.5).

Detailed graphic log of Tabulares Member

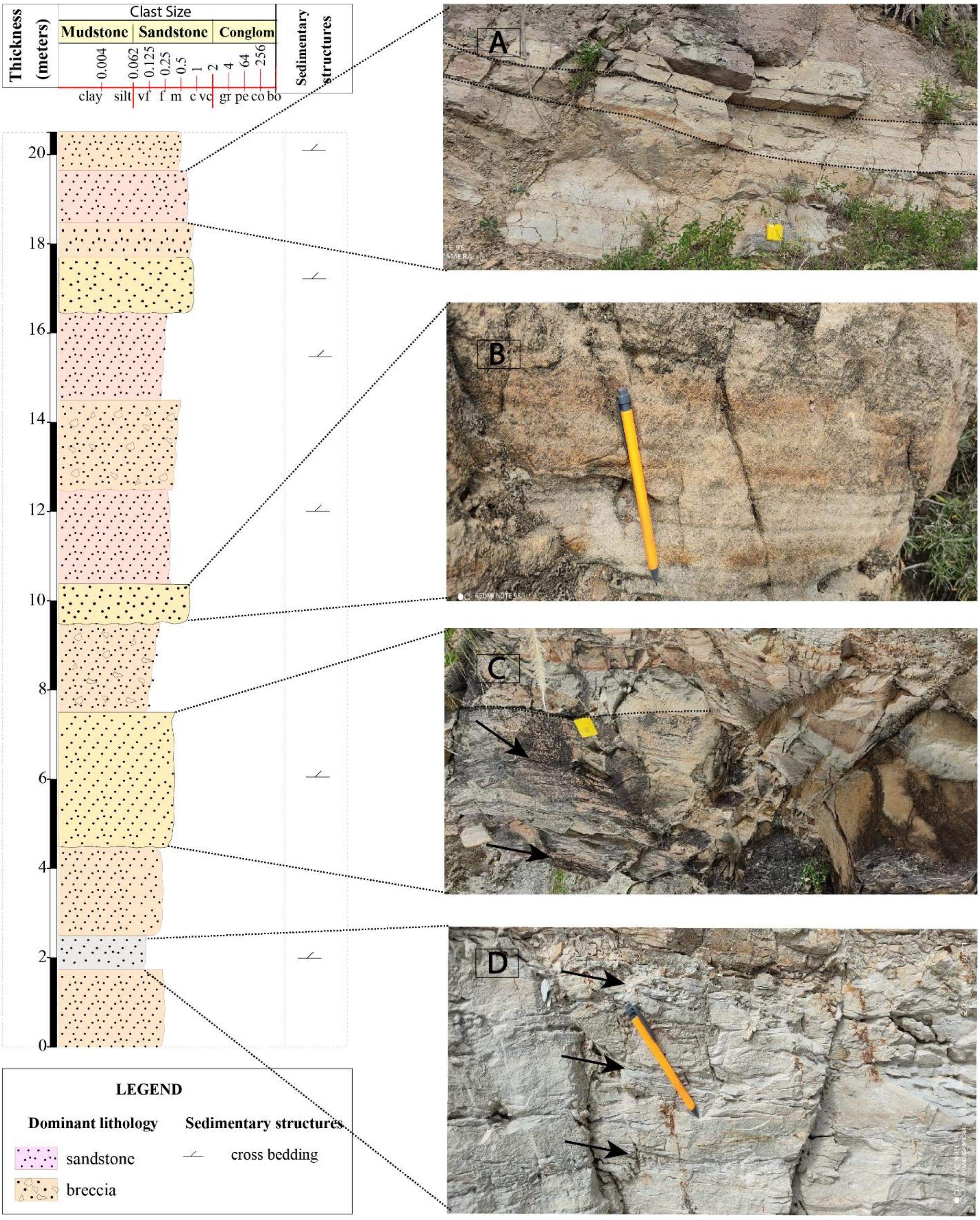


Figure 16. Detailed stratigraphic column of the middle part of Tabulares Member (Fig.14). (A) medium sand bed (B) medium to coarse sand (C) cross-stratification structures on fine sand (D) silty to very fine sand bed and cross-stratification. Location: UTM 17N 830404E, 51182N, elev. =1623 m. Note (pencil measures is 13.5).

4.5. VOLCANICAS MEMBER

Description

The Volcanicas Member has a thickness of ~72 m. Figure 16 shows a synthetic stratigraphic log that summarizes observations from various outcrops. The member's base is defined by a massive coarse sand, angular clasts, poorly sorted with high pumice content, (Fig. 16C). The next part comprises intercalation of medium to coarse sand, poorly sorted, very angular clast, massive and breccias of cobble to boulder grain size (Fig. 16B). The top part comprises coarse sand and breccia of granule clast size, angular clasts, poorly sorted, and massive (Fig. 16A).

4.5.1. Detailed stratigraphic column of the Volcanicas Member along a secondary road to the southeast of the study area.

Description

Figure 17 shows the stratigraphic log shows the middle part of the Volcanicas Member exposed in the southeast part of the basin (UTM 17N 830180E, 50118N, elev.=1683 m). The section has a thickness of 20 m. The base of the sequence begins with a massive breccia of pebble clast size, matrix supported, poorly sorted, angular clast. In this bed there are metamorphic clasts embedded inside the volcanic matrix (Fig. 17E). the metamorphic clasts are gneisses with red garnets (Fig.17D), similar to the Sabanilla gneisses that outcrop near Pimampiro. The middle part comprises intercalation of massive coarse sand and breccias. The sandstones are composed of medium to coarse sand, massive, light gray color, medium sorted, and subangular clast shape (Fig.17B). The breccias are characterized by pebble to cobble clast, clast support, massive, poorly sorted, very angular clast, dark gray color, and consist of andesite rocks (Fig.17C). The upper section comprises breccias, matrix-supported, angular volcanic clasts with medium sorted, massive, pebble clast size and angular clasts (Fig. 17A).

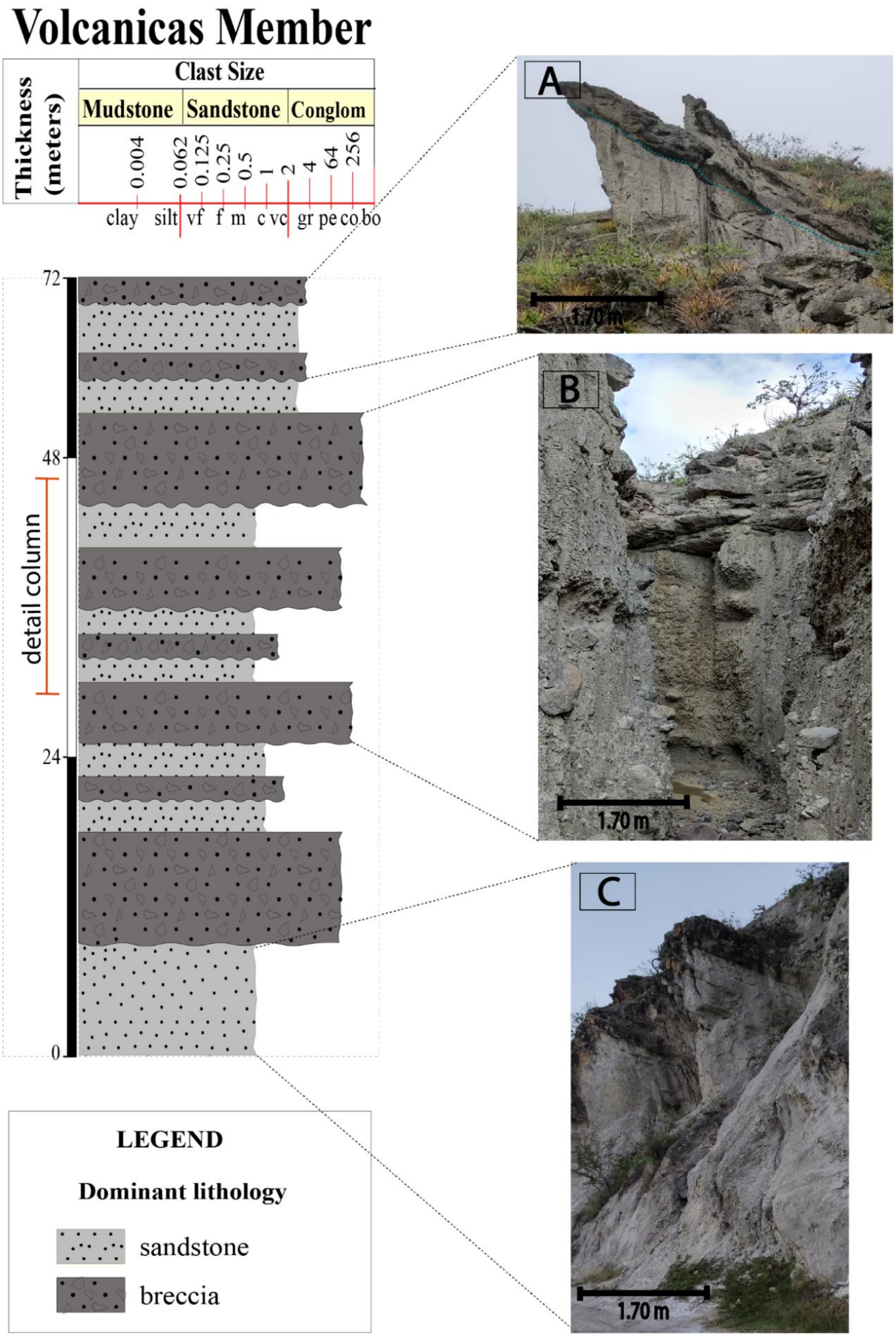


Figure 17. Stratigraphic column of Volcanicas Member, the sequence is defined by breccias and intercalation of very coarse sand and breccias of granule to pebble clast size. (A) top of the stratigraphic column showing the breccias and very coarse sand, (B) breccia, matrix support, very angular clast, cobbles to boulders clast size and matrix support, (C) base of the stratigraphic column comprises of pumices.

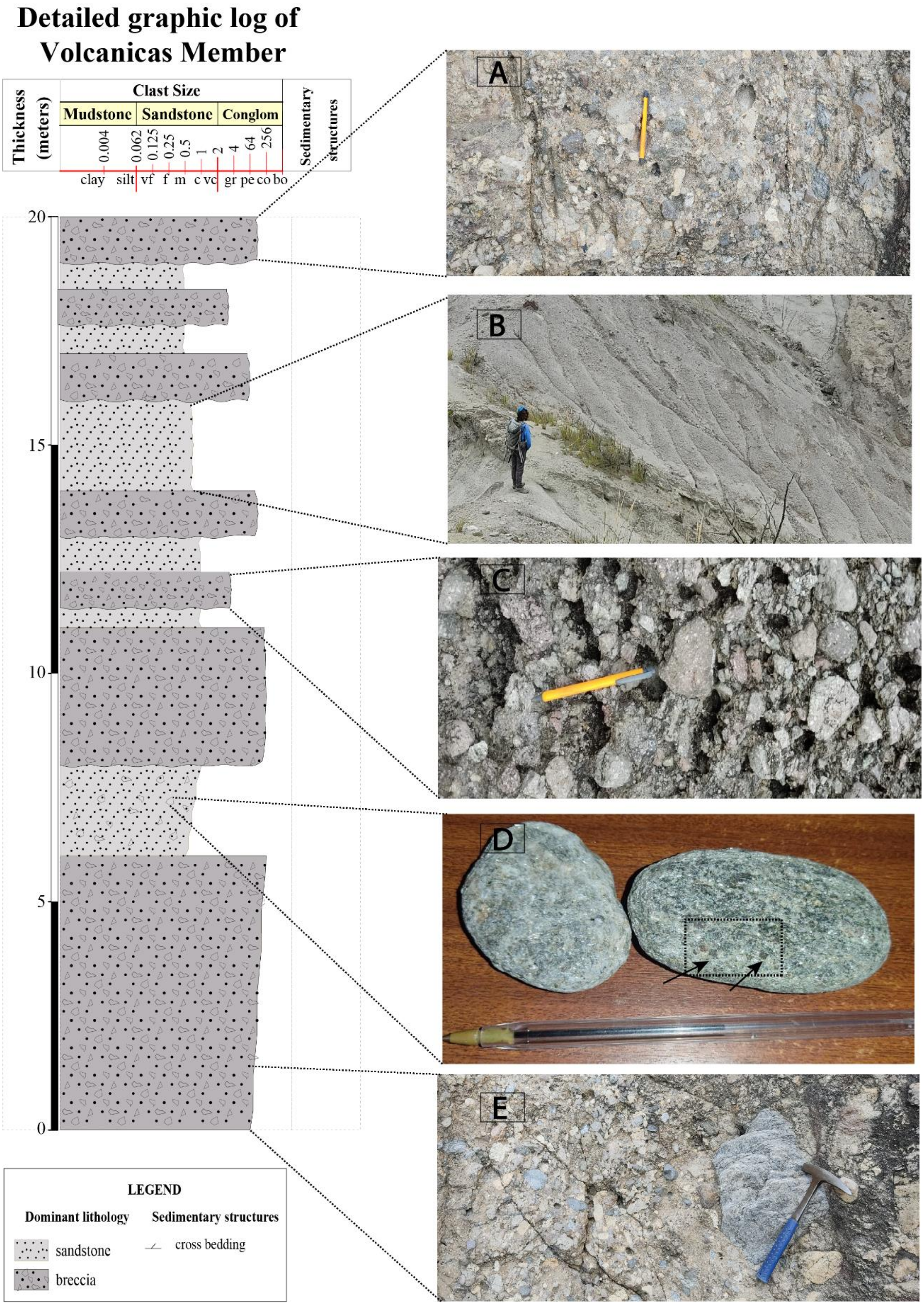


Figure 18. Detailed stratigraphic column of the middle part of Volcanicas Member (Fig.16). (A) volcanic breccia (B) massive coarse sand (C) andesites rocks (D) gneiss with garnet, (E) metamorphic rock embedded in a volcanic matrix. Location: UTM 17N 830180E, 50118N, elev.=1683 m. Note (pencil measures is 13.5).

4.6. XRD CLAY ANALYSIS

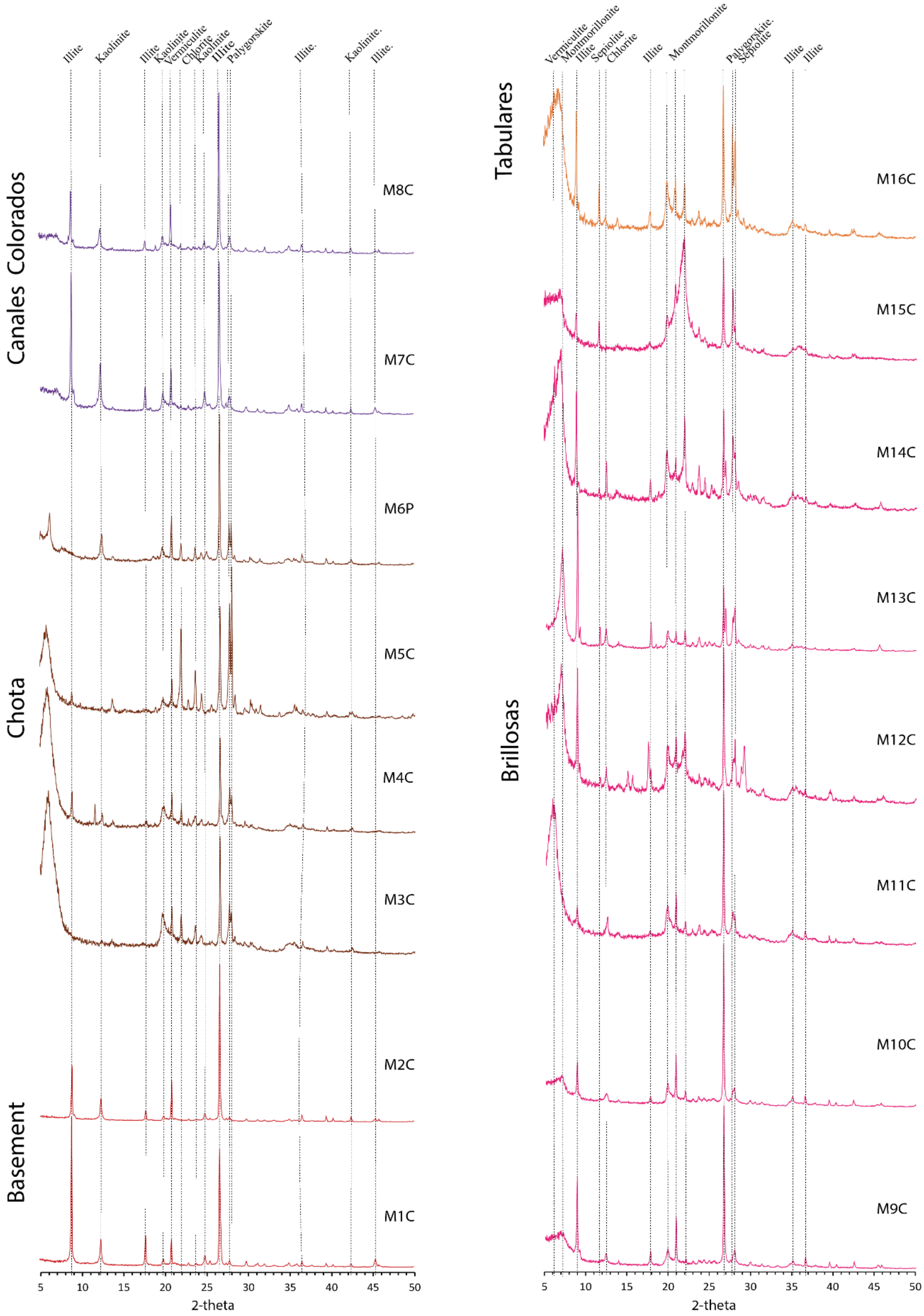


Figure 19. X-ray diffraction pattern of sixteen clay samples from base to top; Basement, Chota Formation, Canales Colorados Mb., Brillosas Mbr. and Tabulares Mbr.

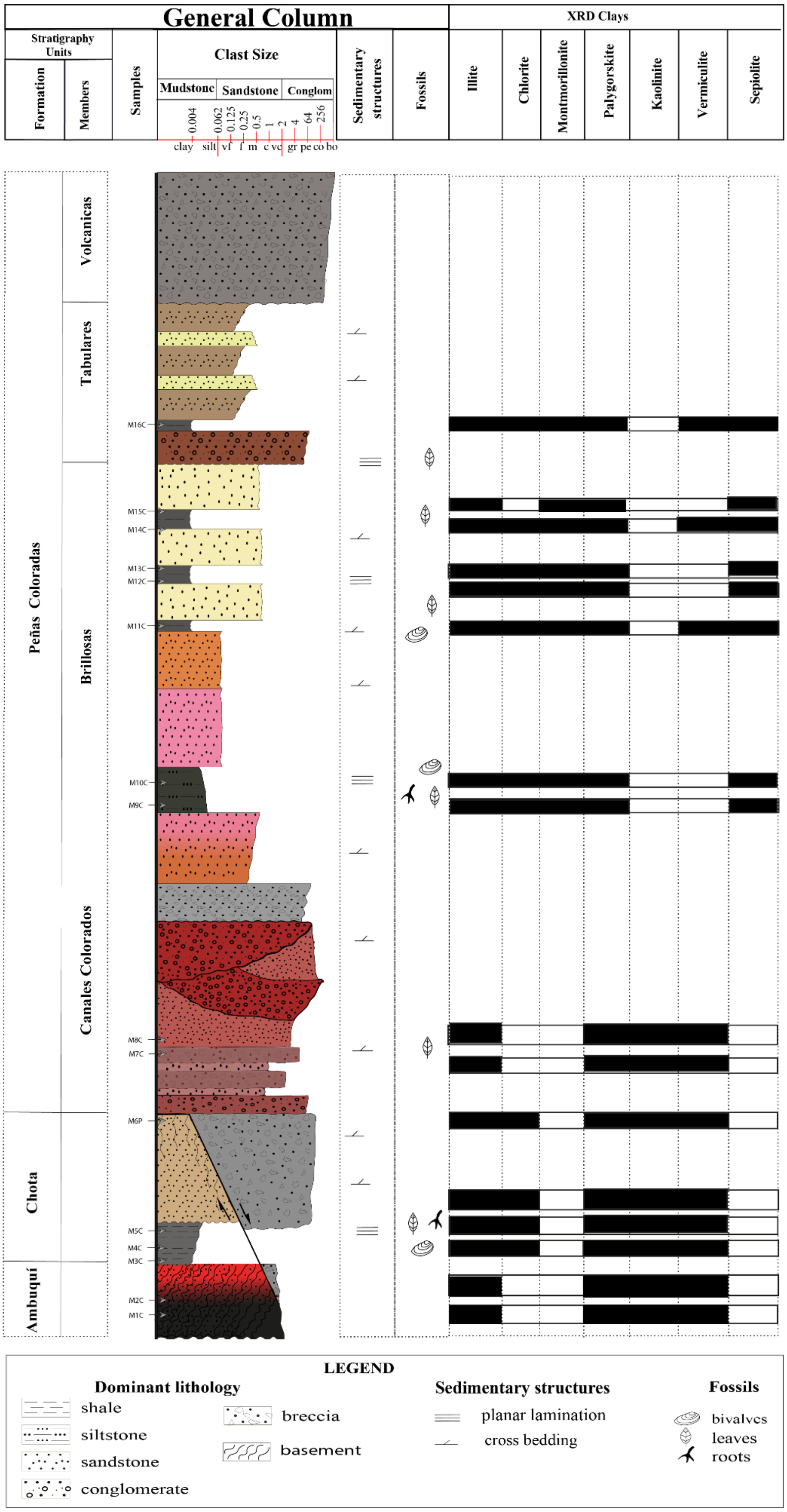


Figure 20. Schematic General Column with XRD comparison data; Illite, Chlorite, Montmorillonite, Palygorskite, Kaolinite, Vermiculite and Sepiolite clays.

XRD Analysis

Sixteen samples of clays were collected to run X-ray diffraction analysis (XRD), of which two belong to the laterized metamorphic basement (Bs), four to the Chota Formation (Ch), and ten to the Peñas Coloradas Formation (two to Canales Colorados Member (CC), seven to Brillosas Member (Br), and one to Tabulares Member (Ta) (Fig.19).

The XRD analyses show that the clay minerals mainly consist of illite, kaolinite, vermiculite, chlorite, palygorskite, montmorillonite (an expanding clay of the smectite group), and sepiolite. Furthermore, the data demonstrated that there is a variation in the proportions of clay assemblages, however, we did not carry out quantitative assessments of the clay composition in this work. In spite of this we are still able to determine the presence or not of a clay mineral in a sample.

All the samples had large diffractogram peaks showing palygorskite and illite. Chlorite and vermiculite showed medium peaks when present. Chlorite was present within the units Ch, Br and Ta, and vermiculite was present in Bs, Ch, and CC. Kaolinite, montmorillonite, and sepiolite were minor components, showing weak peaks, with kaolinite found in the lower three units (Bs, Ch and CC), and montmorillonite and sepiolite found in the upper two (Br and Ta) (Fig.18).

4.7. CLAST COUNT

We collected data from 11 locations belonging to three stratigraphic units: the Canales Colorados, Tabulares Mb., and Volcanicas Mb. of the Peñas Coloradas Formation. The conglomerate and breccia clasts are classified into metamorphics (schists and quartzites), lavas (andesites), and pumices (Table 1). The conglomerates of Canales Colorados members are dominated by beds of poorly sorted, matrix-to-clast supported conglomerates with subangular, pebble to cobble clast sizes. The five locations sampled from the Canales Colorados Member show similar compositions with average values of: metamorphic rocks 58%, pumices 35% and lavas 18% (Fig.20).

The Tabulares Member conglomerates are constituted by beds of poorly sorted, matrix support, subangular to surrounded. The stratigraphically lowest location shows a different pattern than the two stratigraphically higher sampling locations that are similar to each other. The location T1 represents a transition between the CC locations and T2-T3. The predominant clasts are the lavas with 64%, followed by pumices with 32%, and 4% metamorphic rocks (Fig.20). The final sampling site was the Volcanicas Member, composed of massive beds of angular breccias, matrix support, and poorly sorted. In this member, the majority is composed of lavas and pumices. The base of the member is formed by a 1.5 m bed that is 100% pumice, while samples V2 and V3 have similar compositions consisting of lavas with 61%, followed by pumices and metamorphic rocks in about equal proportions (Fig.20).

To summarize, the Canales Colorados Member is dominated by metamorphic clasts, and the Tabulares and Volcanicas members show similar clast compositions, dominated by volcanic rocks (lavas and pumices).

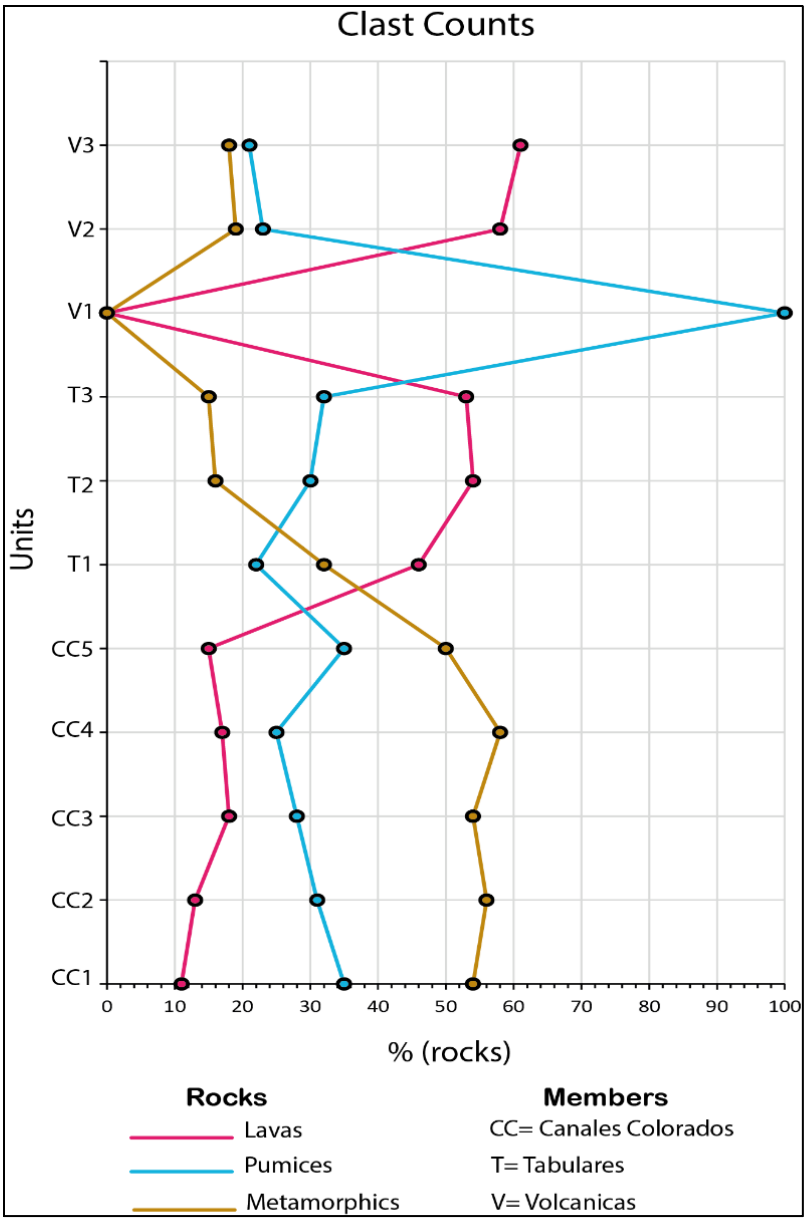


Figure 21. Relative abundance of clasts of Pumice, Metamorphic rocks and Lavas from the Peñas Coloradas Formation.

Members	% Rocks		
	Lavas	Pumices	Metamorphic
V3	61	21	18
V2	58	23	19
V1	0	100	0
T3	53	32	15
T2	54	30	16
T1	46	22	32
CC5	15	35	50
CC4	17	25	58
CC3	18	28	54
CC2	13	31	56
CC1	11	35	54

Table 1. Counting clast data. Three members Canales Colorados (CC), Tabulares (T) and Volcanicas (V). Eleven conglomerates count, five in CC Mbr, three in T Mbr and three in V Mbr.

5. DISCUSSION

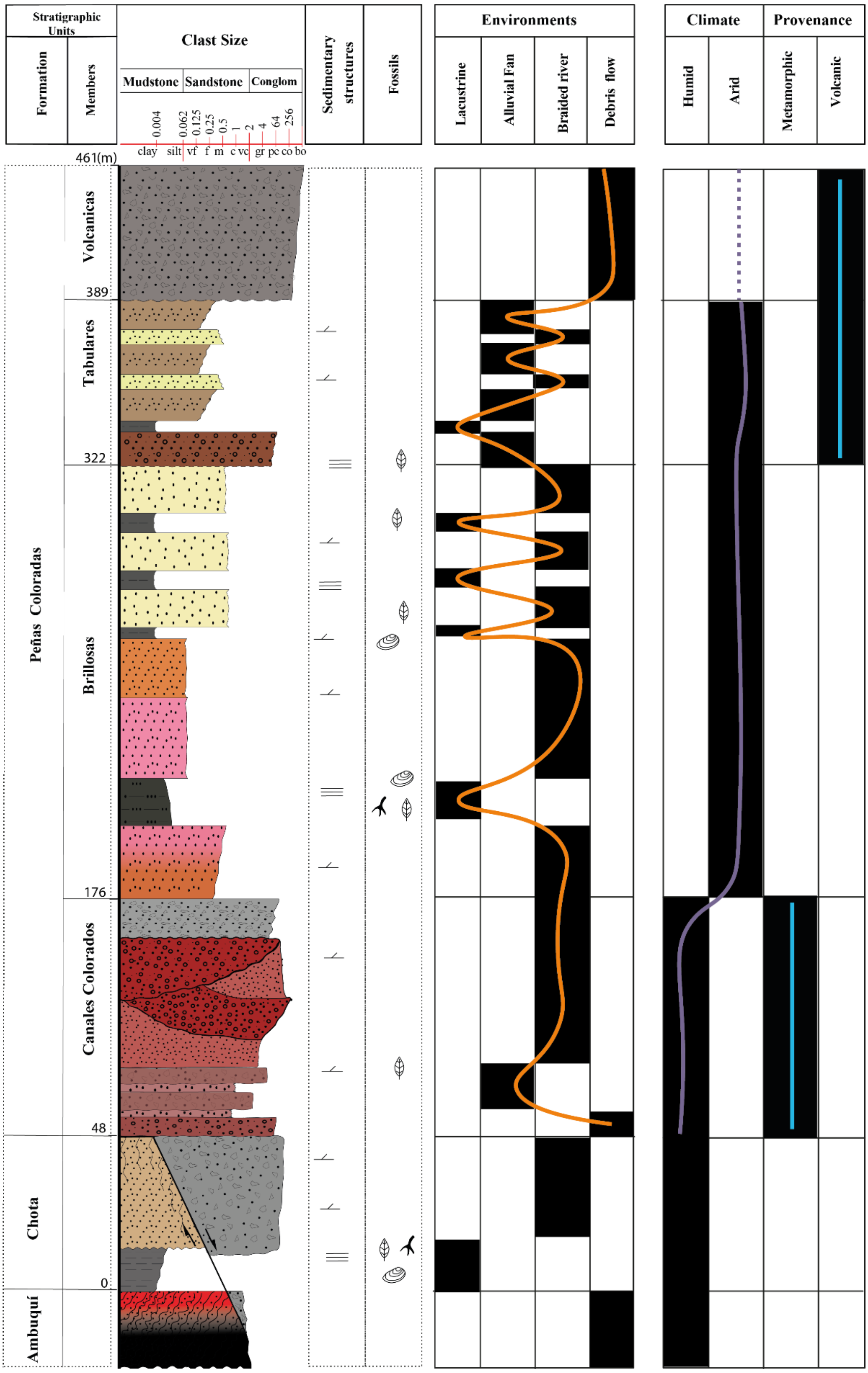


Figure 22. simplified results that relate sedimentary environments, climate and provenance.

We infer the depositional environments of the Chota and Peñas Coloradas Formations according to the descriptions and observations done in the field. In the case of the Chota Formation, the base is not exposed, however, the first beds we could see are shale with intercalation of very fine sand. The shale beds comprise high organic content preserved in fossils of bivalves and plant remains. According to Reineck and Singh (2012), bivalves live in shallow freshwater lakes, characterized by fine-grained deposits, low energy, oxygenated, and contain cross-lamination structures. Furthermore, bivalves need deposit-feeding with a high density of nutrients and algal that limit their survival and distribution (Vaughn & Hakenkamp,2001) therefore, we can suggest that the lowest exposed part of the Chota Fm belongs to a lacustrine environment (lakes) that preserved the fossil record. The very fine sand beds are massive and also contain fossils. These beds can be deposited as a result of a delta where the river channels reach the lakes. The delta can form suspended sediment plumes directed towards the central part of the lake (Reineck & Singh,2012). The next part of the sequence is the intercalation of medium sand and clay beds with cross-stratification and lamination. Reineck and Singh (2012) suggest sediments with these characteristics can form on the marginal part of an alluvial fan as a result of sub-channel flow (channels flowing under lacustrine environment). The last part of formation comprises amalgamated channels from medium to coarse sand with sedimentary structures like cross-bedding, flute cast, and load cast. The amalgamated channels are characterized by sand sediments in the upper parts of channel bars, while the floodplain sediment part is not preserved (Ramon & Cross, 1997). These features are common in Braided rivers that tend to be coarse-grained and contain abundant amalgamated channels, low sinuosity, steep slopes, abundant sediment supply, high and variable discharge (Miall,1977). Furthermore, we can find flute cast and load cast sedimentary structures formed where sandy and muddy laminae are differentially (Reineck & Singh,2012). These sands are composed of abundant content of feldspars (potassic and sodic), quartz, amphiboles, and a few micas. According to Lindsey (1999), the sedimentary rocks defined by this mineral composition are arkoses, which suggests that the sediments were not transported far from their source. Furthermore, this type of rocks is deposited by alluvial fans and braided to meandering streams and accumulate around basin margins. The source of these sediments is associated with granites by their mineral composition and results from ultra-rapid erosion on steep slopes in a humid tropical climate (Dapples, 1947). The Cordillera Real, located east of our study zone contains many igneous intrusions that could be the source of these sediments. Moreover, our clay analysis supports a humid climate by the presence of kaolinite, as does the presence of a deep laterization surface in the basement metamorphic rocks. Hence, we can infer that we had a humid environment that may have contributed to the weathering and erosion of the sediments deposited in the Chota Fm, as well as to the formation of the Chota lake.

The base of the Peñas Coloradas Formation starts with the Canales Colorados Member. It comprises breccias of very angular clasts, pebble to cobble size, poorly sorted. This bed could result from rock avalanches in which masses of fragments move in a flow-like way due to precipitation, gravity, or landslides triggered by tectonic movements that eroded and mobilized rocks toward the base of the topography (Takahashi,1981). The next part of the sequence comprises intercalations of coarse-grained sand and breccias beds of different grain sizes. The sandstones have levees characteristics without sedimentary structures. With these features and observations, we can suggest that these deposits belong to an alluvial fan since, according to Reineck and Singh (2012), sediments of alluvial fans are laid down in beds parallel to the surface of the fan, and boulder and pebble beds alternate with sandy, silty, and muddy beds. Followed by a sequence of conglomerates and fine grains size, and sheet flow deposits. The sheet flows are turbulent flows with significantly more water and less mud than debris flows. Since the flows are turbulent, there is significant grain sorting and normally graded. Once a flow reaches the canyon's mouth, the flow spreads out, and the coarsest rocks are deposited first, and finer grains are deposited later. The deposition is very rapid, and the grading is commonly poor (Bull,1977). According to these characteristics and deposits, we can propose that these deposits are typical of alluvial fans.

In the upper part of the sequence, we have large red channels with intercalation of conglomerates and sands with eroded bases and cross-stratification followed by a gray breccia bed. These channels are characteristic of braided fluvial systems. Braided channels develop on steeper slopes causing larger sediment transport depending on flow stages, bank erosion, and discharge variability is huge. Braided rivers transport relatively coarse sediment as bedload and have unstable banks (Reineck & Singh, 2012). Furthermore, these rivers are characterized by wide channels and rapid and continuous shifting of the sediment. The channel bars are composed of coarser-grained deposits and fine-grained sediment on the top, which the flow could not carry (Reineck & Singh, 2012; Bridge & Lunt, 2009). On the other hand, the red color indicates deposition in an oxidizing environment of iron ($Fe3+$), suggesting humid tropical conditions (Reineck & Singh, 2012). According to our clast count along this sequence, we could determine that the main source of clasts was the surrounding metamorphic basement. Furthermore, we have conglomerates of boulders size that suggest that the source of the sediments was near, or that the river's energy in that time was high, possibly due to periods of precipitations that agree with our XRD analysis showing a humid climate.

The next member is Brillosas and is composed in the base by intercalating clays with organic matter (fossils) and fine sand with cross-stratification. In this case, we can suggest a fluvial-lacustrine environment because these depositional systems are extremely variable due to climate-controlled fluctuating water levels. Through factors such as the precipitation/evaporation ratio, this is a direct link between lake level and sediment supply (Scoot, Buatois, and Mangano,2012). On the other hand, the fine sand beds with sedimentary structures can suggest us a floodplain that essentially comprises of fine-grained sediment deposits or floodways that can sometimes be seasonal, meaning the channel is dry for part of the year (Reineck & Singh, 2012; Martinez., et al.,2008). Thus, we suggest a shallow lake controlled by climatic conditions intercalated with sediments of the flood plain of a fluvial system.

In the next part of the sequence, we find a change in the size grain with high pumice content and thin beds of clays. This injection of volcanic material could show us a period of volcanism provoking volcanic epiclastic deposits. Epiclastic deposits are reworked primary volcanic sediments include lahars and hyaloclastites. In continental settings, volcanic ash is carried into river systems and lakes by surface runoff, spread by the wind, and incorporated into soils. On the other hand, the diagenesis of volcaniclastic sediments can cause replace volcanic glass in clay minerals mainly into smectites, particularly montmorillonite and saponite (Tucker, 2001). Thus, in this sequence, we propose a period of rivers intercalated with ephemeral shallow lakes. According to our clay analysis, and based on the disappearance of kaolinite, we suggest a transition from a humid to arid climate that may have been stepwise causing the disappearance and reappearance of lacustrine deposits.

Tabulares Member starts with a conglomerate bed followed by thin layers of clay intercalated with the fine sand. The clay layers contain fossilized leaves and lamination, and the sands are massive. These layers could represent the last gasp of ephemeral lake formation, intercalated with fluvial systems that transition to alluvial fans. The middle part of Tabulares Mbr comprises intercalation of consolidated fine sand and unconsolidated fine sand. According to our clast count, the sequence contains igneous rocks like lavas and pumice. The pumices are found throughout the member in different grain sizes. The presence of porous pumices in some beds could be responsible for cementation and high compaction due to the diagenesis (Houseknecht,1987). This section has some beds with cross-stratification that suggest the variation of two environments, the alluvial fan and fluvial systems. In the upper part of the sequence, we have massive fine sand and breccias composed of volcanic clasts that show the transition to the Volcanicas Member possibly associated to debris flow. Since the entire sequence is composed of fine sediments, we can infer that there was either no discharge of large sediments during this period of deposition, or that we are in a more distal position of the source. Our XRD analysis shows a change of ephemeral lacustrine environment in the base. The rest suggests an arid climate because the Kaolinite disappears and appears in the Sepiolite and Montmorillonite clays.

The last Member of the Peñas Coloradas Formation is the Volcanicas Member. The base comprises of pyroclastic deposits and coarse sand followed by intercalation of breccias and medium to very coarse sand beds. All beds are massive, poorly sorted, and an angular grain shape. According to our clast count study, the major part comprises volcanic rocks and some metamorphic gneiss with garnet. These deposits have resulted from debris flow caused by erosion, gravity, or the landslide of surrounding areas. The volcanic rocks are andesites and pumices product of a surrounding volcanic system. According to Egüez & Beate (1992), the clast could come from the Angochangua volcanic that comprises andesitic lavas, tuffs, and volcano sediments. On the other hand, the gneisses could be the product of the erosion of the Sabanilla gneiss located in the Cordillera Real, near Pimampiro, ~16 km east of the outcrops.

To sum up, we have a series of intercalation of environments in Chota and Peñas Coloradas Formations that start with lacustrine environments that developed a thick succession of fine-grained sediments followed by an alluvial fan and fluvial system for Chota Formation and Canales Colorados Member. In this case, the fluvial system can be interpreted as a braided river that transported high sediments from very fine to boulders sediments. Besides, this shows us a period of high-water flow related to a humid climate.

Seasonal arid climates characterize the next part of the Peñas Coloradas Formation. The Brillosas and Tabulares Members show deposits of fine sand sediments with thin clay beds that we can interpret as ephemeral environments with low energy that consisted of lacustrine, alluvial and fluvial systems. This change in depositional environments is consistent with our clay analysis that shows the kaolinite disappears and appears of sepiolite and montmorillonite.

This climate transition from humid to arid climate could be the result of the uplifting of Cordillera Real. According to Spikings and Crowhursts (2004), their (U–Th)/He thermo- chronological study shows cooling and exhumation in the Cordillera Real during the Late Miocene to Pliocene corroborates the timing of the beginning of basins that reside in the Interandean from north to south. This information could suggest that the uplift of the Cordillera Real cutting off humid airflow from the Amazon causing increase aridity in our study area. On the other hand, we could relate this change with a global change during the Pliocene where the levels of temperature increased due to four possible drivers: palaeographic change, for instance, the altered of major mountain chains such as the western cordillera of North and South America; altered atmospheric trace gas concentrations and water vapor content; changes to ocean circulation and finally the feedbacks generated through altered land cover (including ice sheet extent), surface albedo, cloud cover and temperature (Haywood et al.,2009)

Finally, we could suggest that the provenance is the division into three different sources. First metamorphic rocks that belong to the surrounding Ambuquí Formation basement (Winkler et al.,2005; Barragan et al. 1996; Egüez & Beate,1992). The second provenance could come from volcanic pulses, possibly of Angochagua Volcanic source or another surrounding volcano active in that period (Egüez & Beate,1992). Finally, we suggest that the provenance of gneisses could be the Sabanilla gneisses located 15-20 km to the east of our study area in the Eastern Cordillera near Pimampiro.

6. CONCLUSION

The Chota basin is the most important Neogene intermontane basin of northern Ecuador. Our study focused on the eastern half of the basin. The stratigraphy of the basin can be divided into a metamorphic basement, overlain by the Chota Formation and then the Peñas Coloradas Formation. In this study, and for the first time, a division of the Peñas Coloradas Formation is proposed. Peñas Coloradas has a total thickness of 461 m divided into four members from base to top: Canales Colorados, Brillosas, Tabulares, and Volcanicas members.

The Chota formation has a thickness of ~48 m in our study area. It comprises interbedded clay and sandstones with parallel lamination and cross-bedding and much organic matter conserved in fossils like bivalves, leaves, and roots. The Canales Colorados Mbr has ~128 m of thickness and is composed of different beds of conglomerates, sandstone, and large red channels with intercalations of conglomerates and sandstone with erosional contacts and cross-bedding. The Brillosas Mbr is the thickest of the Peñas Coloradas Formation, with ~146 m in thickness. This Mbr comprises clay beds with intercalation of fine sand and medium sand beds with some fossils, parallel lamination, and cross-bedding. The Tabulares Member has a thickness of ~67m and comprises intercalations of very consolidated tabular sandstone with cross-bedding and unconsolidated sandstones. The last Mbr is Volcanicas and has a thickness of ~72 m. It is characterized by massive breccias with high content of volcanic lithics.

The depositional environments of Chota and Peñas Coloradas Formations vary from base to top as follows: the Chota Fm begins with a lacustrine, followed by the alluvial fan and fluvial environments. Canales Colorados Mbr starts with debris flow, followed by the alluvial fan and fluvial environments. Brillosas Mbr comprises fluvial-lacustrine environments in the base and fluvial intercalated with ephemeral lacustrine environments in the rest of the sequence. Tabulares Mbr comprises the last gasp of ephemeral lake environments intercalated with fluvial transitioned to alluvial fans environments and debris flow. Finally, for the Volcanicas Mbr, we suggest a debris flow product of the surrounding areas.

Analysis of clay analysis suggests a transition in the paleoclimate from humid to the arid climate. Our clay analysis in the Chota Formation and Canales Colorados Mbr propose a humid climate. The presence of kaolinite clay could relate to a high flow in the rivers since we find cobbles to boulders clasts and lacustrine deposits with high organic material. The next part of the Peñas Coloradas Formation comprised of Brillosas and Tabulares Mbrs shows an arid climate determined by montmorillonite and sepiolite clays possibly due to exhumation of Cordillera Real or a global climate change. Furthermore, we can associate this climate with fine sediment deposits resulted from the intercalation of ephemeral lakes with fluvial systems.

Provenance analysis from conglomerate clast counts suggests that the sources of the basin fill are surrounding or near the basin, such as the Ambuquí formation, Angochangua volcanic, or the Sabanilla gneisses. Finally, after this study, we suggest doing chronology work in this zone since the Pliocene´s paleoclimate is little known in tropical regions. Besides, this zone could be useful to determine in detail the paleoclimate and ages. Furthermore, those expected ages could relate to tectonic events or global climate changes.

7. REFERENCES

Allen, P., & Allen, J. (2005). *BASIN ANALYSIS Principles and Aplications* (p. 562). Blackwell Publishing.

Aspden, J. A., & Litherland, M. (1992). The geology and Mesozoic collisional history of the Cordillera Real, Ecuador. *Tectonophysics*, 205(1–3), 187–204. https://doi.org/10.1016/0040-1951(92)90426-7

Aspden, J. A., Harrison, S. H., & Rundle, C. C. (1992). New geochronological control for the tectono-magmatic evolution of the metamorphic basement, Cordillera Real and El Oro Province of Ecuador. *Journal of South American Earth Sciences*, 6(1–2), 77–96. https://doi.org/10.1016/0895-9811(92)90019-U

Barragán, R., Baudino, R., & Marocco, R. (1996). Geodynamic evolution of the Neogene intermontane Chota basin, Northern Andes of Ecuador. *Journal of South American Earth Sciences*, 9(5–6), 309–319. https://doi.org/10.1016/s0895-9811(96)00016-8.

Bridge, J. S., & Lunt, I. A. (2009). Depositional Models of Braided Rivers. *In Braided Rivers*. https://doi.org/10.1002/9781444304374.ch2

Bull, W. B. (1977). The alluvial-fan environment. *Progress in Physical geography*, 1(2), 222-270.

Coltorti, M., & Ollier, C. (2000). Geomorphic and tectonic evolution of the Ecuadorian Andes. *Geomorphology*, 32(1-2), 1-19.

Dapples, E. C. (1947). Sandstone types and their associated depositional environments. *Journal of Sedimentary Research*, 17(3), 91-100.

Egüez, A., & Beate, B. (1992). Estratigrafía y tectónica de la cuenca intramontañosa del Chota. II Jornadas en ciencias de la Tierra. *Resúmenes, EPN, Quito*, 131-144.

Einsele, G. (2000). *Sedimentary basins: evolution, facies, and sediment budget*. Springer Science & Business Media.

Guillier, B., Chatelain, J., Jaillard, E., Yepes, H., Poupinet, G., & Fels, F. (2010). Seismological evidence on the geometry of the orogenic system in central northrn Ecuador. *GEOPHYSICAL RESEARCH LETTERS*, 28(60), 3749–3752.

Haywood, A. M., Dowsett, H. J., Valdes, P. J., Lunt, D. J., Francis, J. E., & Sellwood, B. W. (2009). Introduction. Pliocene climate, processes and problems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 367(1886), 3-17.

Houseknecht, D. W. (1987). Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG bulletin*, 71(6), 633-642.

Howard, J. L. (1993). The statistics of counting clasts in rudites: a review, with examples from the upper Palaeogene of southern California, USA. *Sedimentology,* 40(2), 157–174. https://doi.org/10.1111/j.1365-3091.1993.tb01759.x

Hughes, R. A., & Pilatasig, L. F. (2002). Cretaceous and tertiary terrane accretion in the Cordillera Occidental of the Andes of Ecuador. *Tectonophysics,* 345(1–4), 29–48. https://doi.org/10.1016/S0040-1951(01)00205-0

Hungerbühler A., D., Steinmann, M., Winkler, W., & Seward, D. (1995). An integrated study of fill and deformation in the Andean intermontana basin of Nabón (Late Miocene), southern Ecuador. *SEDIMENTARY GEOLOGY*, 96, 257–279.

Jaillard, E., Lapierre, H., Ordónez, M., Toro, J., Amórtegui, A., & Vanmelle, J., (2009), Accreted oceanic terranes in Ecuador: southern edge of the Caribbean Plate?: *Geological Society Special Publication* 328: 469-485, London, doi:10.1144/SP328.19.

Jaillard, E., Ordóñez, M., Suárez, J., Toro Álava, J., Lugo, W., Jaillard, E., Ordonez, M., Suárez, J., Alava, J. T., & Iza, D. (2006). Stratigraphy of the Late Cretaceous-Paleogene deposits of the Western Cordillera Ecuador: Geodynamic implications. To cite this version: HAL Id : hal-00101729. *South,* 17, 49–58. https://hal.archives-ouvertes.fr/hal-00101729

Kerr, A. C., Aspden, J. A., Tarney, J., & Pilatasig, L. F. (2002). The nature and provenance of accreted oceanic terranes in western Ecuador: Geochemical and tectonic constraints. *Journal of the Geological Society*, 159(5), 577–594. https://doi.org/10.1144/0016-764901-151

Lavenú, A., Winter, T., & Dávila, F. (1995). A Pliocene–Quaternary compressional basin in the Interandean Depression, Central Ecuador. *Geophysical Journal International*, 121(1), 279–300. https://doi.org/10.1111/j.1365-246X.1995.tb03527.x

Lindsey, D. A. (1999). *An evaluation of alternative chemical classifications of sandstones* (No. 99-346). US Geological Survey.

Litherland, M., & Aspden, J. A. (1992). Terrane-boundary reactivation: A control on the evolution of the Northern Andes. *Journal of South American Earth Sciences*, 5(1), 71–76. https://doi.org/10.1016/0895-9811(92)90060-C

Marocco, R., Lavenu, A., & Baudino, R. (1995). Intermontane late Paleogene - Neogene basins of the Andes of Ecuador and Peru: sedimentologic and tectonic characteristics. *In: A.J. Tankard, R. Suárez-Soruco and H.J. Welsink (eds.), Petroleum Basins of South America,* AAPG Memoir 62, 597–614. http://search.datapages.com/data/specpubs/memoir62/31moracc/0597.htm

Martínez, M. A., Prámparo, M. B., Quattrocchio, M. E., & Zavala, C. A. (2008). Depositional environments and hydrocarbon potential of the Middle Jurassic Los Molles Formation, Neuquén Basin, Argentina: palynofacies and organic geochemical data. *Andean Geology*, 35(2), 279-305.

McCann, T., & Saintot, A. (2003). Tracing tectonic deformation using the sedimentary record: an overview. *Geological Society, London, Special Publications*, 208(1), 1-28.

Miall, A. D. (1977). A review of the braided-river depositional environment. *Earth-Science Reviews,* 13(1), 1-62.

Ortiz, J., & Jaramillo, C (2020). *Introduction to Stratigraphic Data Analysis (SDAR).* Retrieved from Stratigraphic Data Analysis: https://cran.r project.org/web/packages/SDAR/vignettes/introduction_to_SDAR.html#:~:text=SDAR%20is%20a%20fast%20and,to%20perform%20quantitative%20stratigraphic%20analyses.

Pratt, W. T., Duque, P., & Ponce, M. (2005). An autochthonous geological model for the eastern Andes of Ecuador. *Tectonophysics*, 399(1-4 SPEC. ISS.), 251–278. https://doi.org/10.1016/j.tecto.2004.12.025

Ramón, J. C., & Cross, T. (1997). Characterization and prediction of reservoir architecture and petrophysical properties in fluvial channel sandstones, middle Magdalena Basin, Colombia. *CT&F-Ciencia, Tecnología y Futuro*, 1(3), 19-46.

Reineck, H., & Singh, I. (2012). *Depositional sedimentary environments*: *with reference to terrigenous clastics.* Springer Science & Business Media.

Sajid, A., Stattegger, K., Liu, Z., Khelifi, N., & Kuhnt, W. (2019). Paleoclimatic and paleoenvironmental reconstruction at Tarfaya Atlantic coastal basin (Morocco) based on clay mineral records from Upper Cretaceous to Quaternary. *Arabian Journal of Geosciences*, 12(1). https://doi.org/10.1007/s12517-018-4156-4

Scott, J. J., Buatois, L. A., & Mangano, M. G. (2012). Lacustrine environments. In *Developments in sedimentology* (Vol. 64, pp. 379-417). Elsevier.

Spikings, R. A., & Crowhurst, P. V. (2004). (U-Th)/He thermochronometric constraints on the late Miocene-Pliocene tectonic development of the northern Cordillera Real and the Interandean Depression, Ecuador. *Journal of South American Earth Sciences,* 17(4), 239–251. https://doi.org/10.1016/j.jsames.2004.07.001

Spikings, R., Paul, A., Vallejo, C., & Reyes, P. (2021). Constraints on the ages of the crystalline basement and Palaeozoic cover exposed in the Cordillera real, Ecuador: 40Ar/39Ar analyses and detrital zircon U/Pb geochronology. *Gondwana Research*, 90, 77-101.

Spikings, R., Winkler, W., Seward, D., & Handler, R. (2001). Along-strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust. *Earth and Planetary Science Letters*, 186(1), 57–73. https://doi.org/10.1016/S0012-821X(01)00225-4

Steinmann, M., Hungerbuhler, D., Seward, D., & Winkler., (1999), Neogene tectonic evolution and exhumation of the southern Ecuadorian Andes: a combined stratigraphy and fission-track approach: *Tectonophysics,* 307 (255-276).

Streit, R. L., Burbank, D. W., Strecker, M. R., Alonso, R. N., Cottle, J. M., & Kylander-Clark, A. R. (2017). Controls on intermontane basin filling, isolation and incision on the margin of the Puna Plateau, NW Argentina (~ 23 S). *Basin Research*, 29, 131-155.

Takahashi, T. (1981). Debris flow. *Annual review of fluid mechanics*, 13(1), 57-77.

Tibaldi, A., & Ferrari, L., (1992), Latest Pleistocene-Holocene tectonics of the Ecuadorian Andes: *Tectonophysics, In: R.A. Oliver, N. Vatin-Perignon and G. Laubacher (Editors),* Andean Geodynamics, 205: 109-125.

Toro, J., & Jaillard, E. (2005). Provenance of the Upper Cretaceous to upper Eocene clastic sediments of the Western Cordillera of Ecuador: Geodynamic implications. *Tectonophysics,* 399(1-4 SPEC. ISS.), 279–292. https://doi.org/10.1016/j.tecto.2004.12.026

Tucker, M. E. (Ed.). (2001). *Sedimentary petrology: an introduction to the origin of sedimentary rocks*. John Wiley & Sons.

Vallejo, C. (2007). Evolution of the Western Cordillera in the Andes of Ecuador (Late Cretaceous-Paleogene). *ETH Zurich Research Collection*, 12–19. https://doi.org/10.3929/ethz-a-010025751

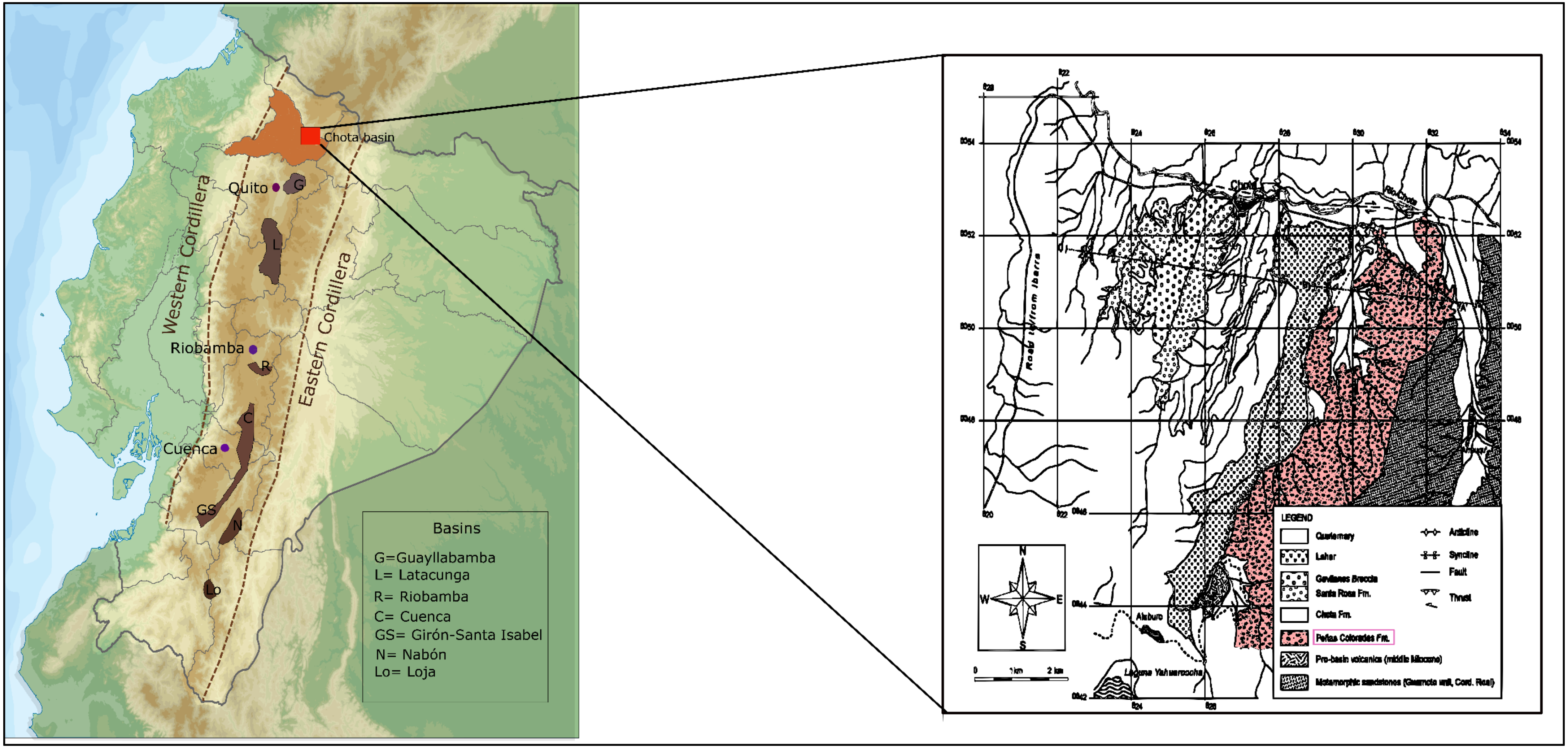
Vallejo, C., Winkler, W., Spikings, R. A., Luzieux, L., Heller, F., & Bussy, F. (2009). Mode and timing of terrane accretion in the forearc of the Andes in Ecuador. *Memoir of the Geological Society of America,* 204(09), 197–216. https://doi.org/10.1130/2009.1204(09)

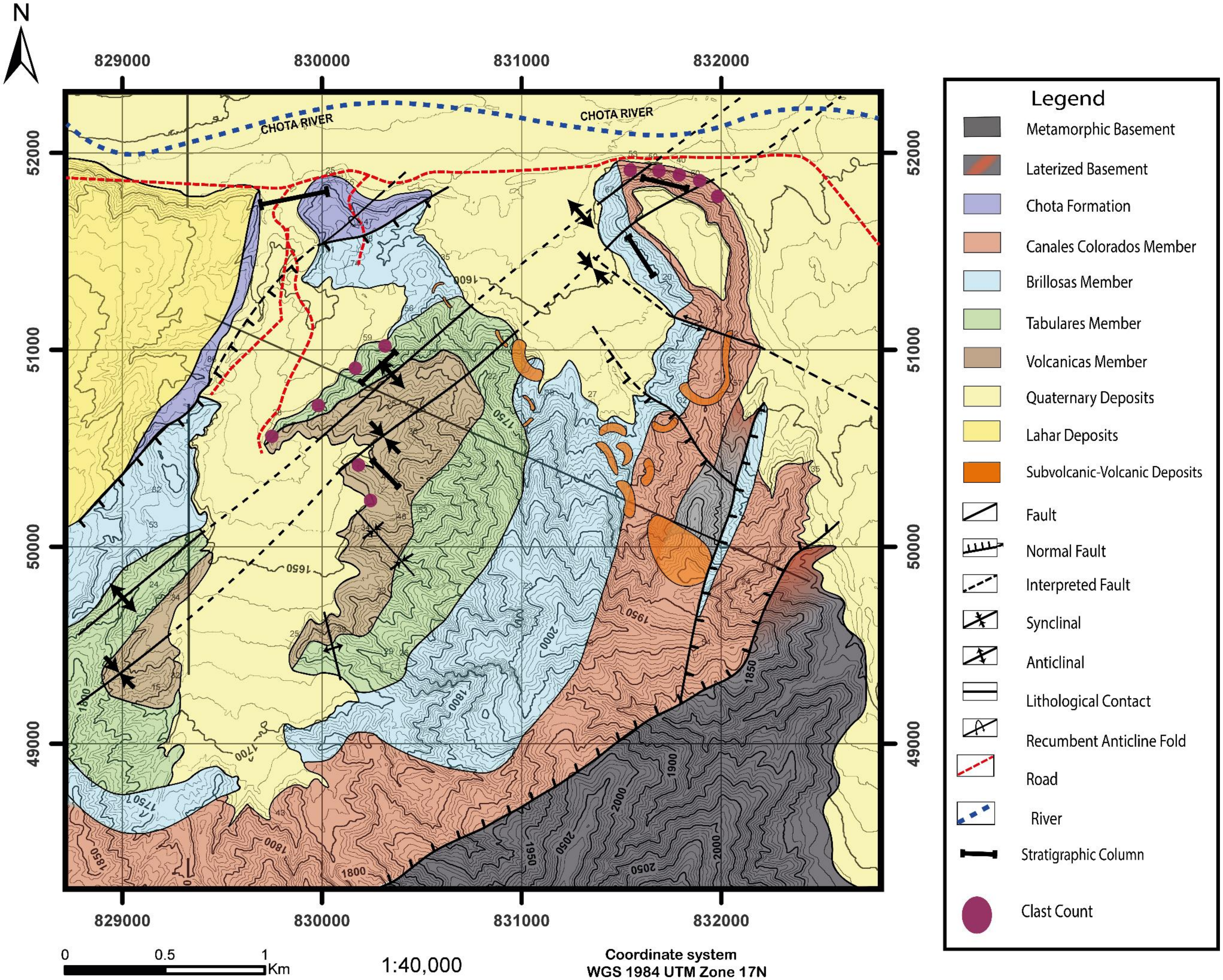
Vaughn, C. C., & Hakenkamp, C. C. (2001). The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology,* 46(11), 1431-1446.

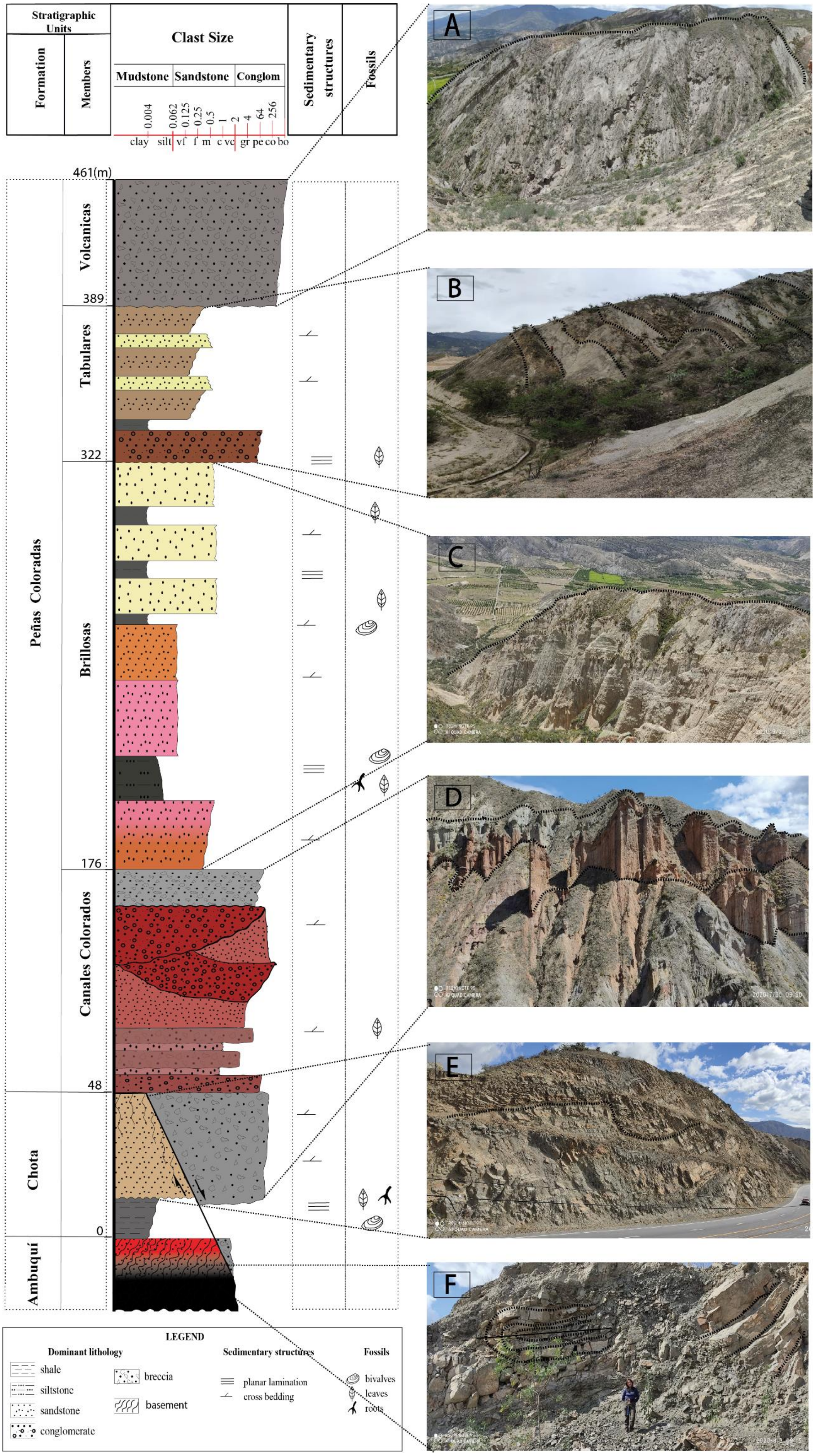
Villagómez D., (2003), Evolución geológica Plio-Cuaternaria del Valle Interandino central en Ecuador (zona de Quito-Guayllabamba-San Antonio): *Escuela Politécnica Nacional*, Tesis de grado previa la obtención del título de Ingeniero Geólogo, Facultad de Geología, Minas y Petróleos, pp. 133 + anexos, Quito

Winkler, W., Villagómez, D., Spikings, R., Abegglen, P., Tobler, S., & Egüez, A., (2005). The Chota basin and its significance for the inception and tectonic setting of the inter-Andean depression in Ecuador: Journal of South American Earth Sciences, 19: (1), 5-19.

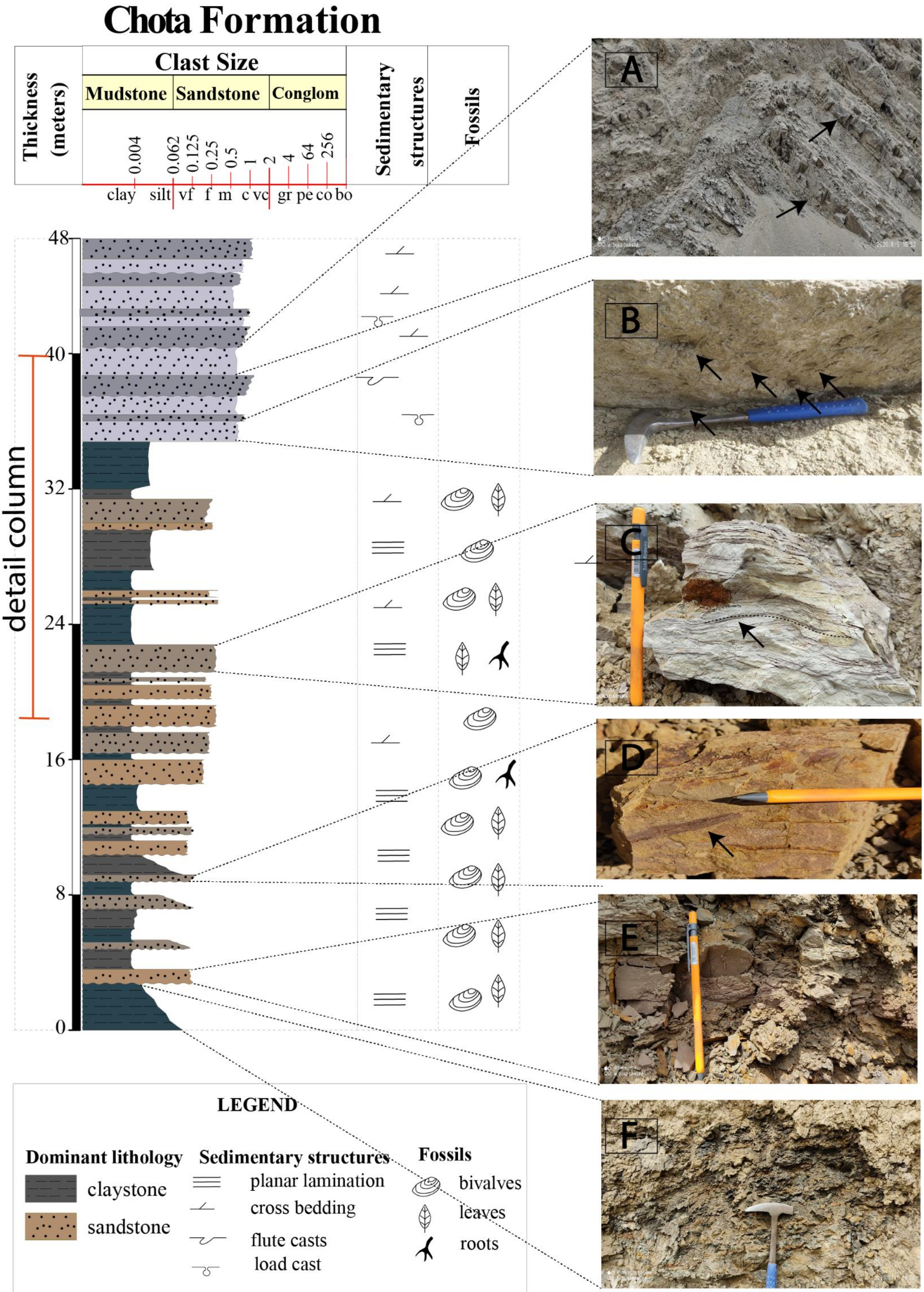
ANNEXES

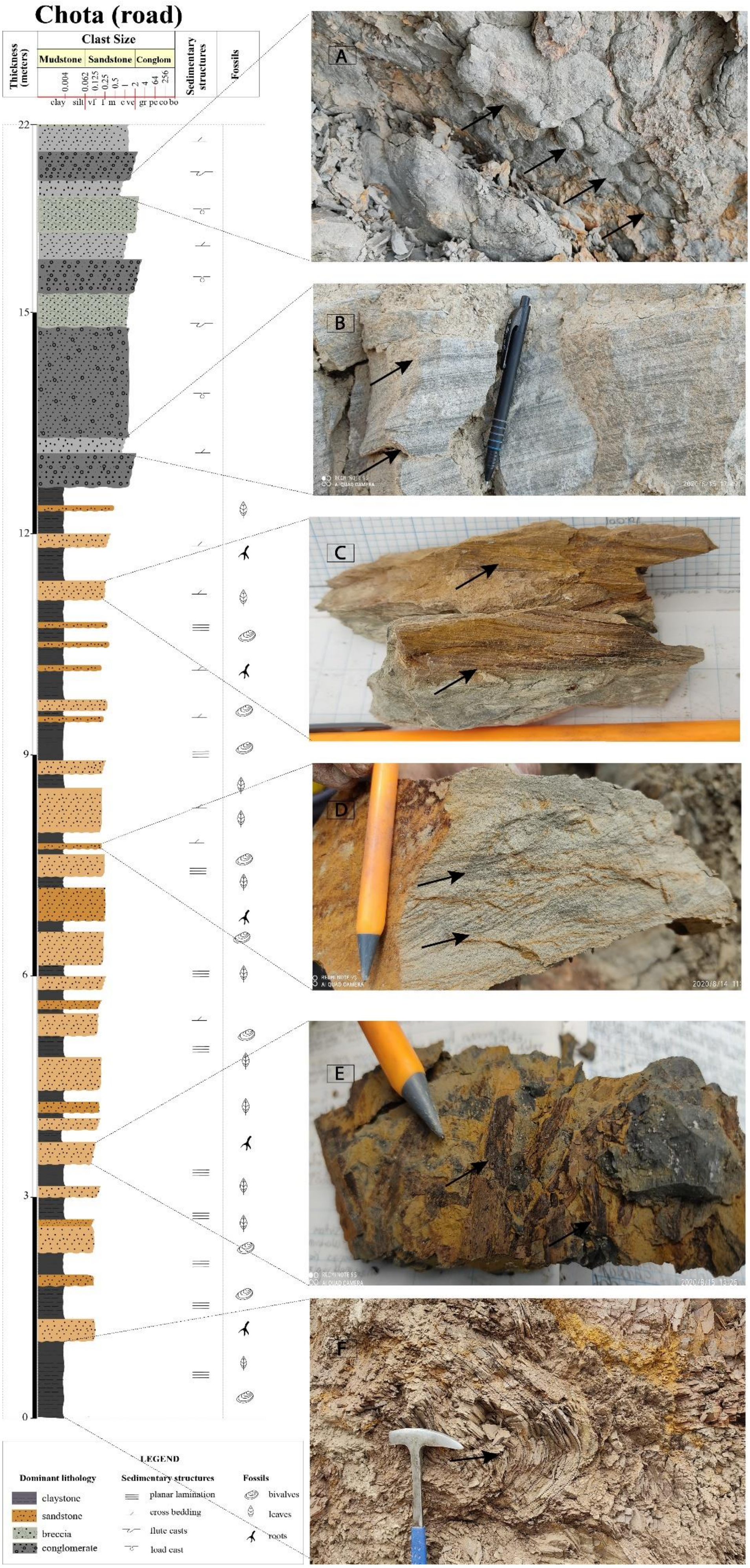

Chota basin
Quito
G
L
Western Cordillera
Eastern Cordillera
Riobamba
R
C
Cuenca
GS
N
Lo
Basins
G=Guayllabamba
L= Latacunga
R= Riobamba
C= Cuenca
GS= Girón-Santa Isabel
N= Nabón
Lo= Loja
Chota
Road to/from Ibarra
N
S
E
W
LEGEND
Anticline
Syncline
Fault
Thrust
Chota Fm.


N
829000
830000
831000
832000
52000
51000
50000
49000
CHOTA RIVER
CHOTA RIVER
Legend
Metamorphic Basement
Laterized Basement
Chota Formation
Canales Colorados Member
Brillosas Member
Tabulares Member
Volcanicas Member
Quaternary Deposits
Lahar Deposits
Subvolcanic-Volcanic Deposits
Fault
Normal Fault
Interpreted Fault
Synclinal
Anticlinal
Lithological Contact
Recumbent Anticline Fold
Road
River
Stratigraphic Column
Clast Count
0
0.5
1
Km
1:40,000
Coordinate system
WGS 1984 UTM Zone 17N

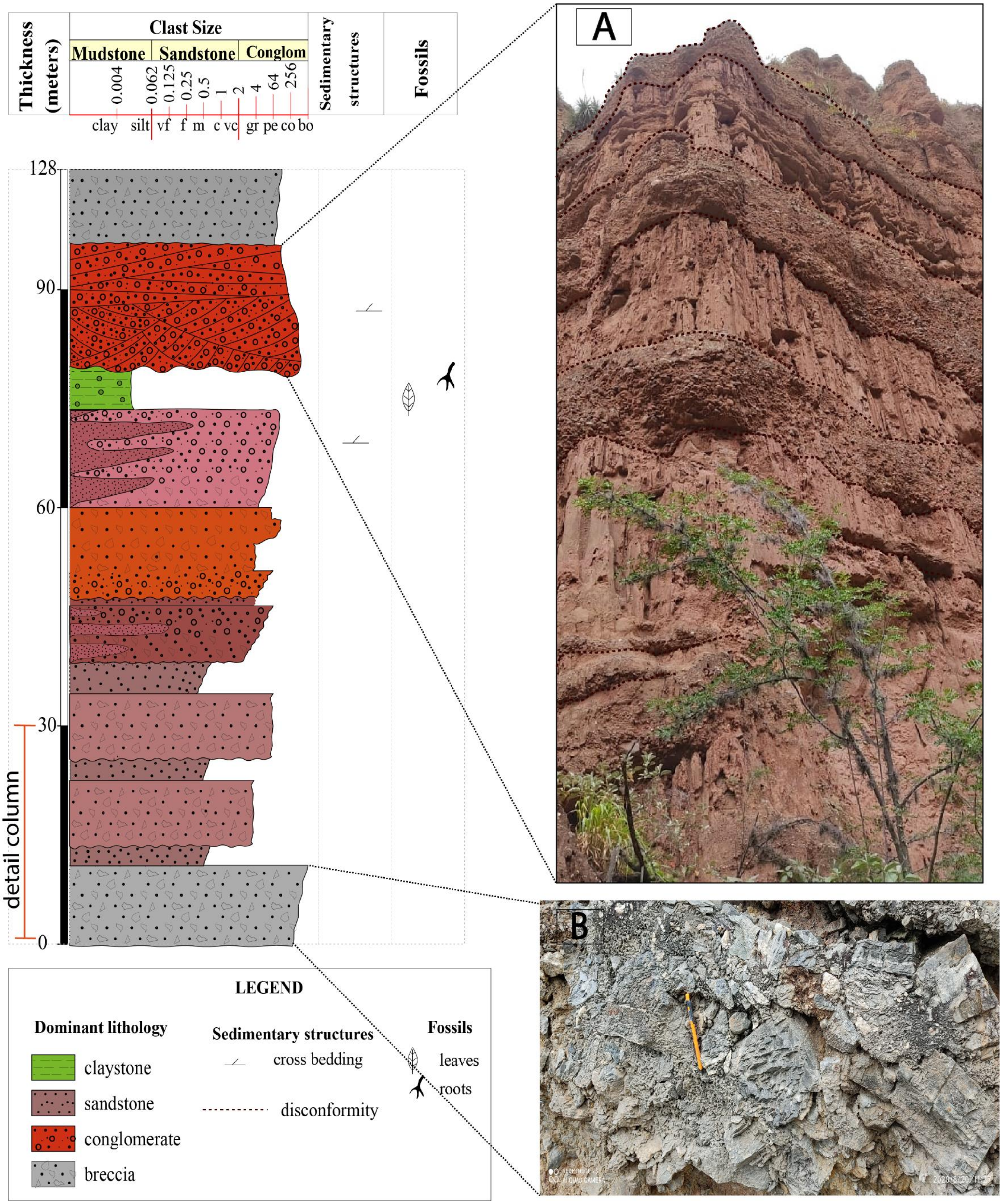


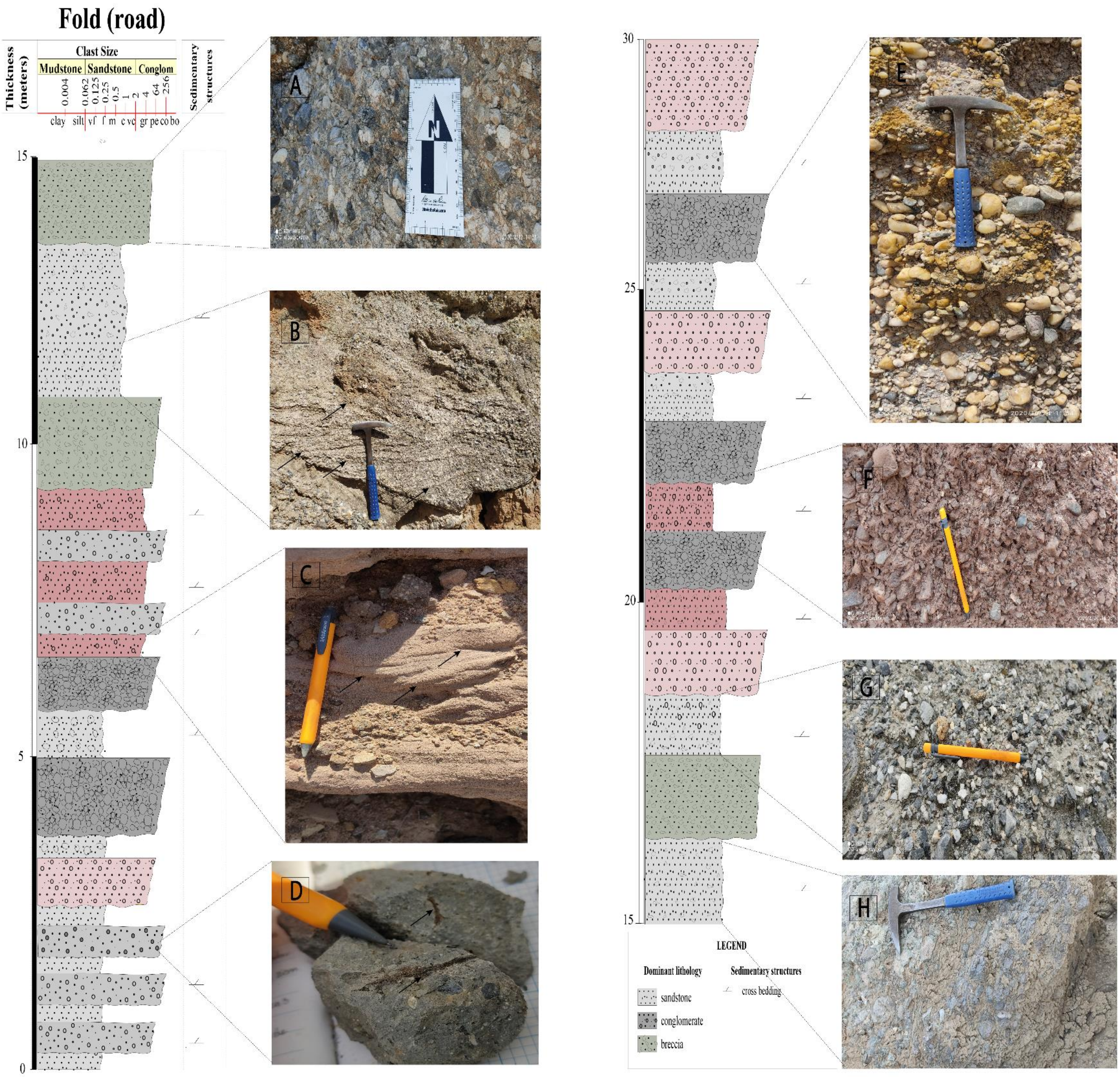
Stratigraphic Units
Formation
Members
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay
silt
vf
f
m
c
vc
gr
pe
co
bo
Sedimentary structures
Fossils
461(m)
389
322
176
48
0
Peñas Coloradas
Volcanicas
Tabulares
Brillosas
Canales Colorados
Chota
Ambuquí
A
B
C
D
E
F
LEGEND
Dominant lithology
shale
siltstone
sandstone
conglomerate
breccia
basement
Sedimentary structures
planar lamination
cross bedding
Fossils
bivalves
leaves
roots


Chota Formation
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay
silt
vf
f
m
c
vc
gr
pe
co
bo
Sedimentary structures
Fossils
48
40
32
24
16
8
0
detail column
A
B
C
D
E
F
LEGEND
Dominant lithology
claystone
sandstone
Sedimentary structures
planar lamination
cross bedding
flute casts
load cast
Fossils
bivalves
leaves
roots

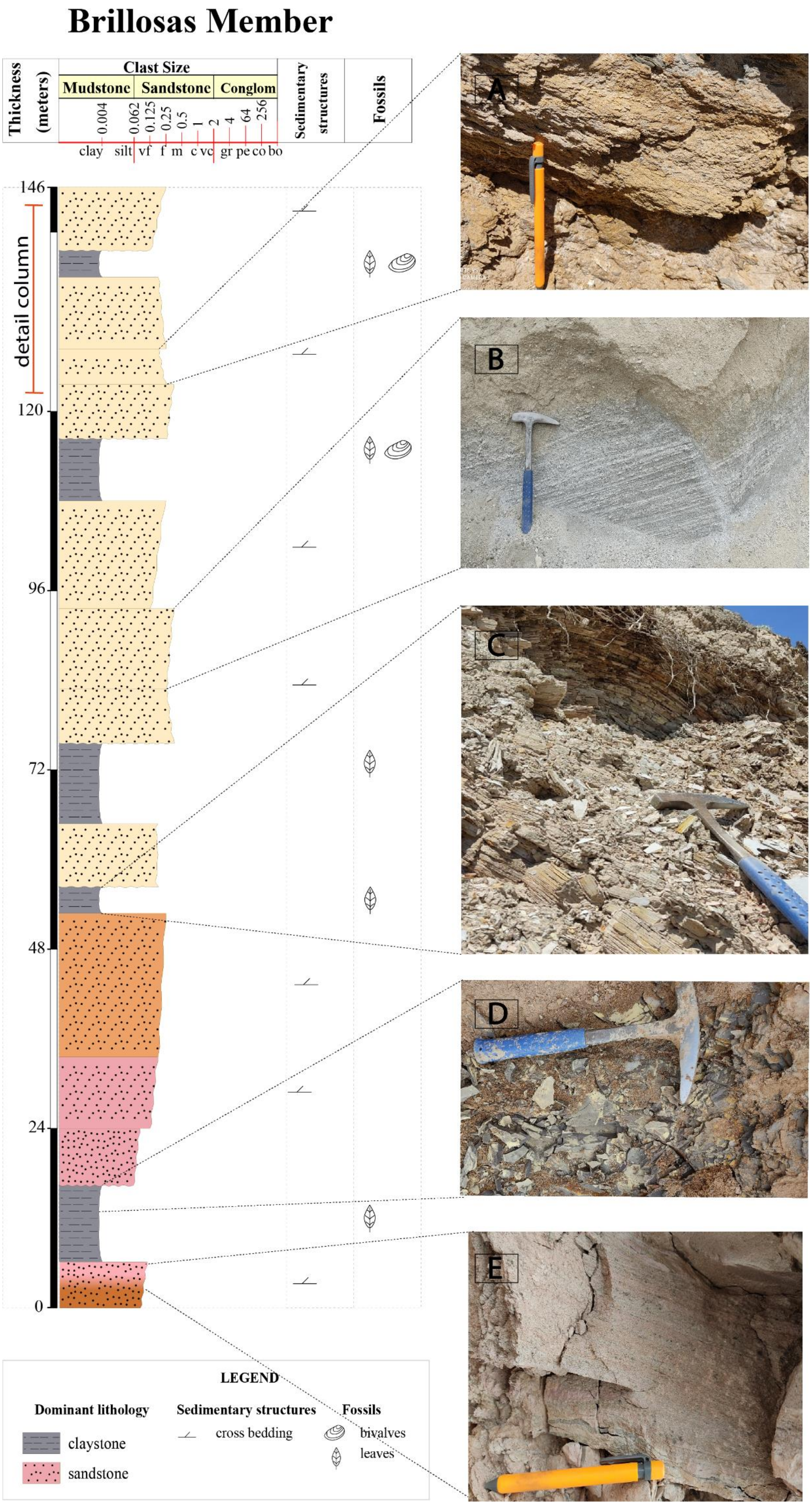

Chota (road)
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay
silt
vf
f
m
c
vc
gr
pe
co
bo
Sedimentary structures
Fossils
22
15
12
9
6
3
0
A
B
C
D
E
F
LEGEND
Dominant lithology
claystone
sandstone
breccia
conglomerate
Sedimentary structures
planar lamination
cross bedding
flute casts
load cast
Fossils
bivalves
leaves
roots

Canales Colorados Member

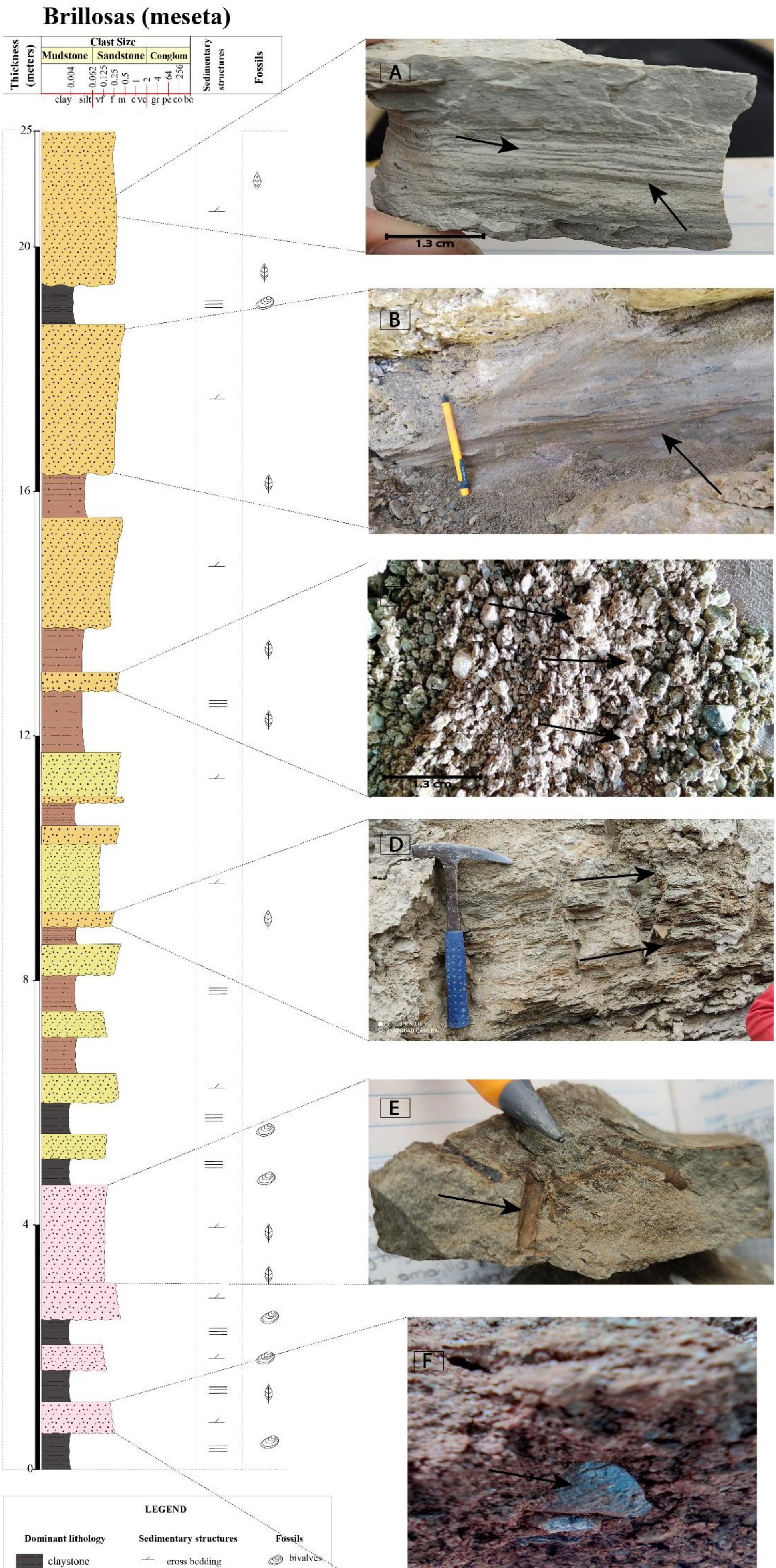


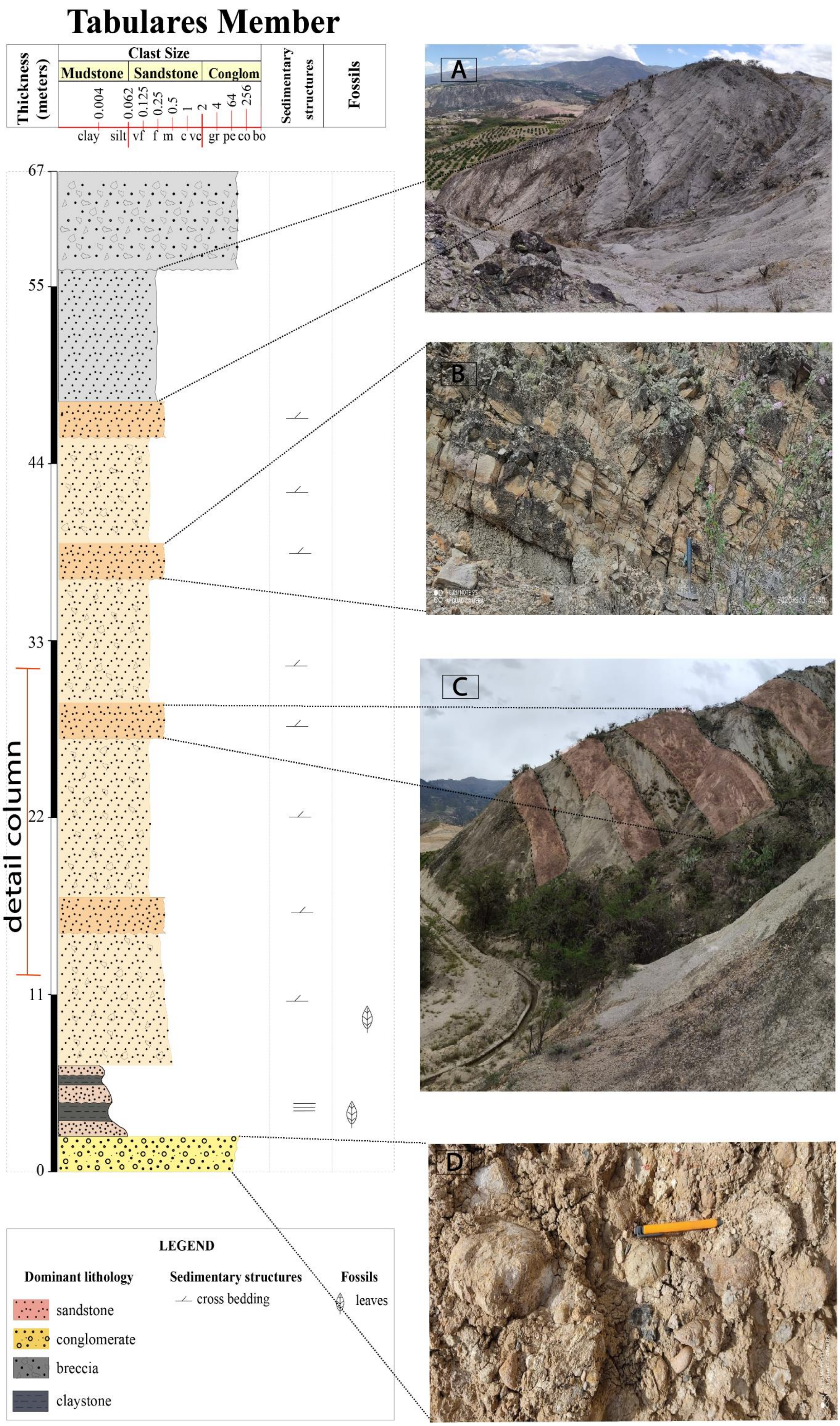


Fold (road)
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay
silt
vf
f
m
c
vc
gr
pe
co
bo
Sedimentary structures
0
5
10
15
20
25
30
A
B
C
D
E
F
G
H
LEGEND
Dominant lithology
sandstone
conglomerate
breccia
Sedimentary structures
cross bedding

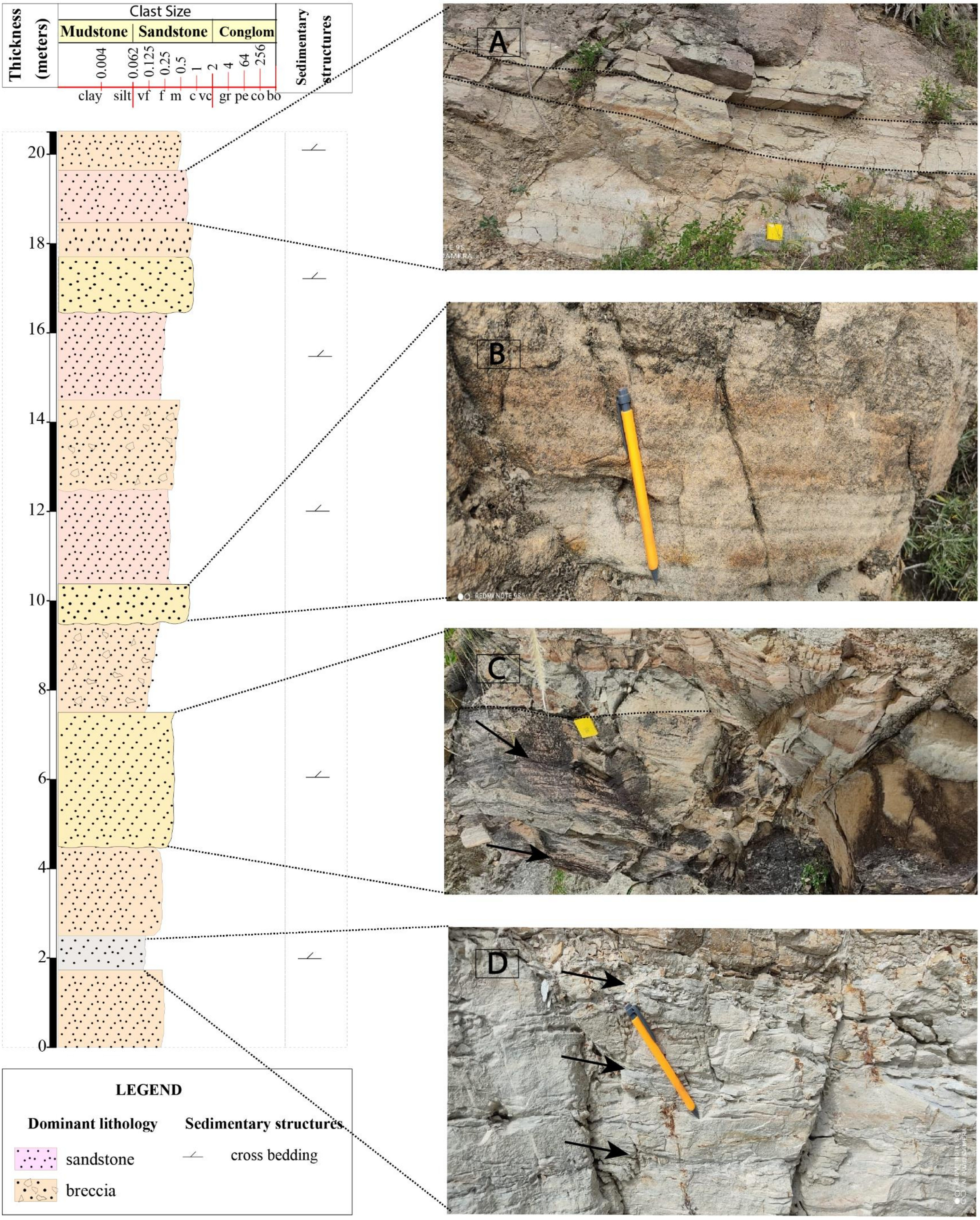


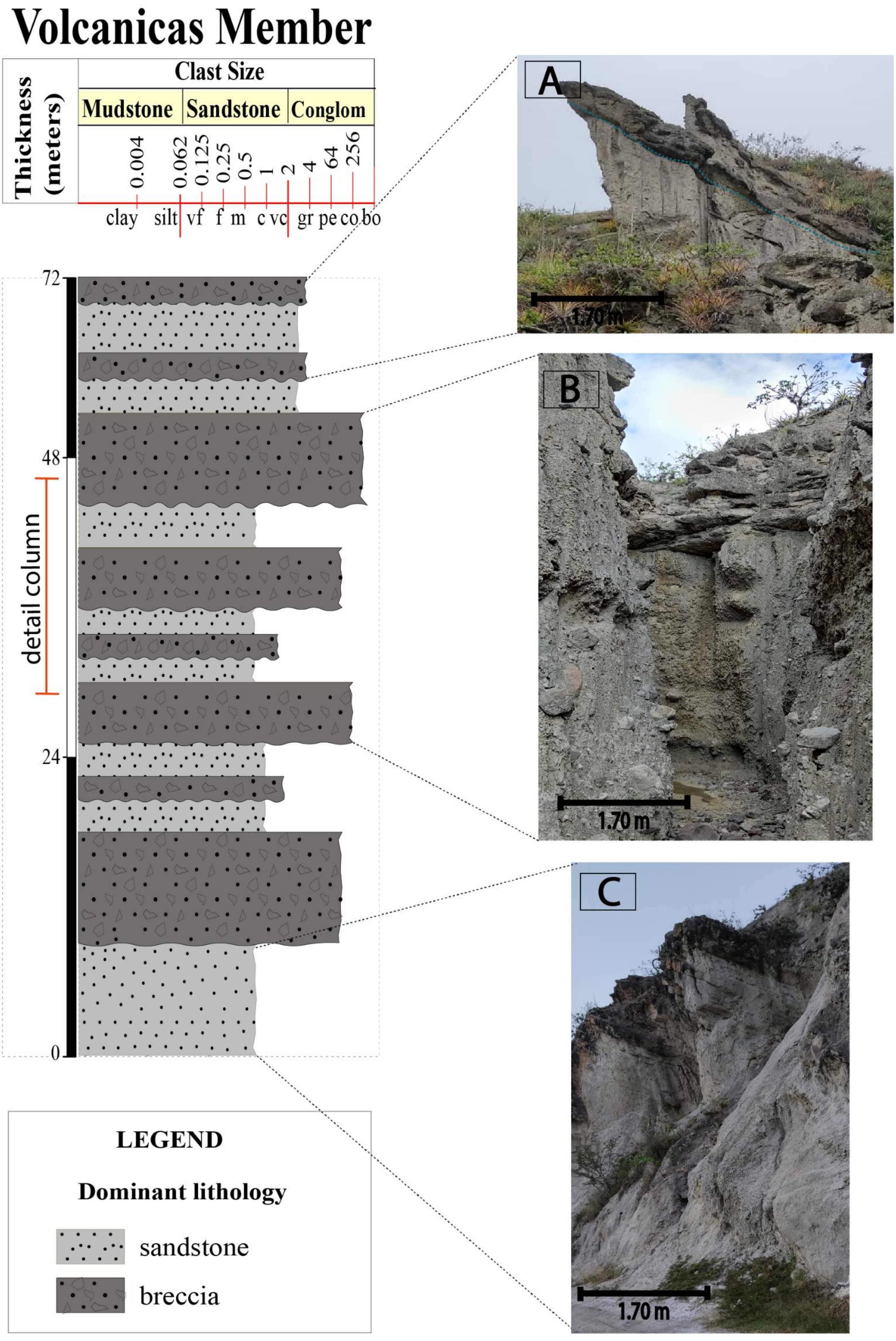
Brillosas Member
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
Fossils
146
120
96
72
48
24
0
detail column
A
B
C
D
E
LEGEND
Dominant lithology
claystone
sandstone
Sedimentary structures
cross bedding
Fossils
bivalves
leaves


Brillosas (meseta)
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
Fossils
25
20
16
12
8
4
0
A
1.3 cm
B
C
1.3 cm
D
E
F
1cm
LEGEND
Dominant lithology
claystone
sandstone
siltstone
Sedimentary structures
cross bedding
planar lamination
Fossils
bivalves
leaves

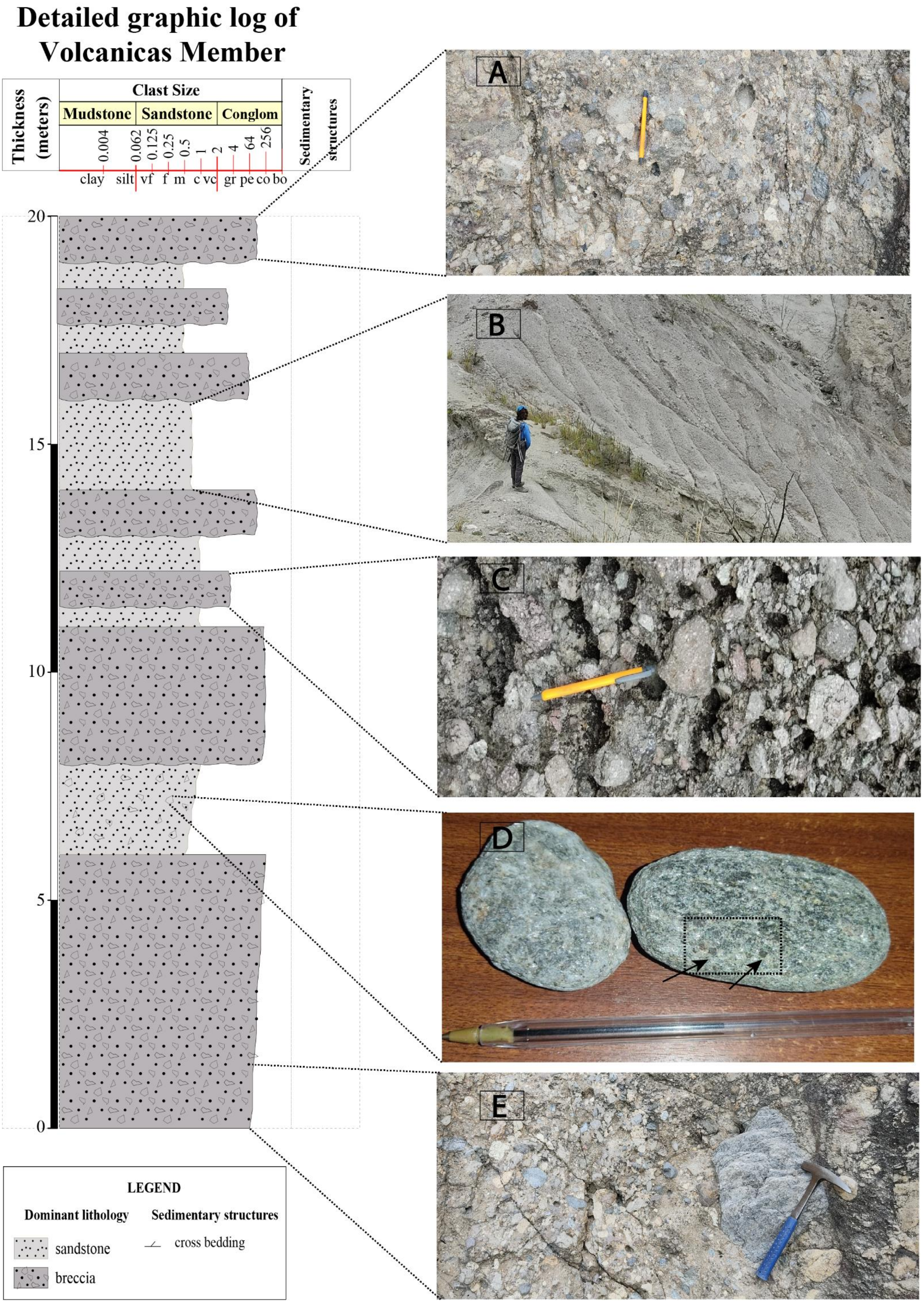

Tabulares Member
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
Fossils
67
55
44
33
22
11
0
detail column
A
B
C
D
LEGEND
Dominant lithology
sandstone
conglomerate
breccia
claystone
Sedimentary structures
cross bedding
Fossils
leaves

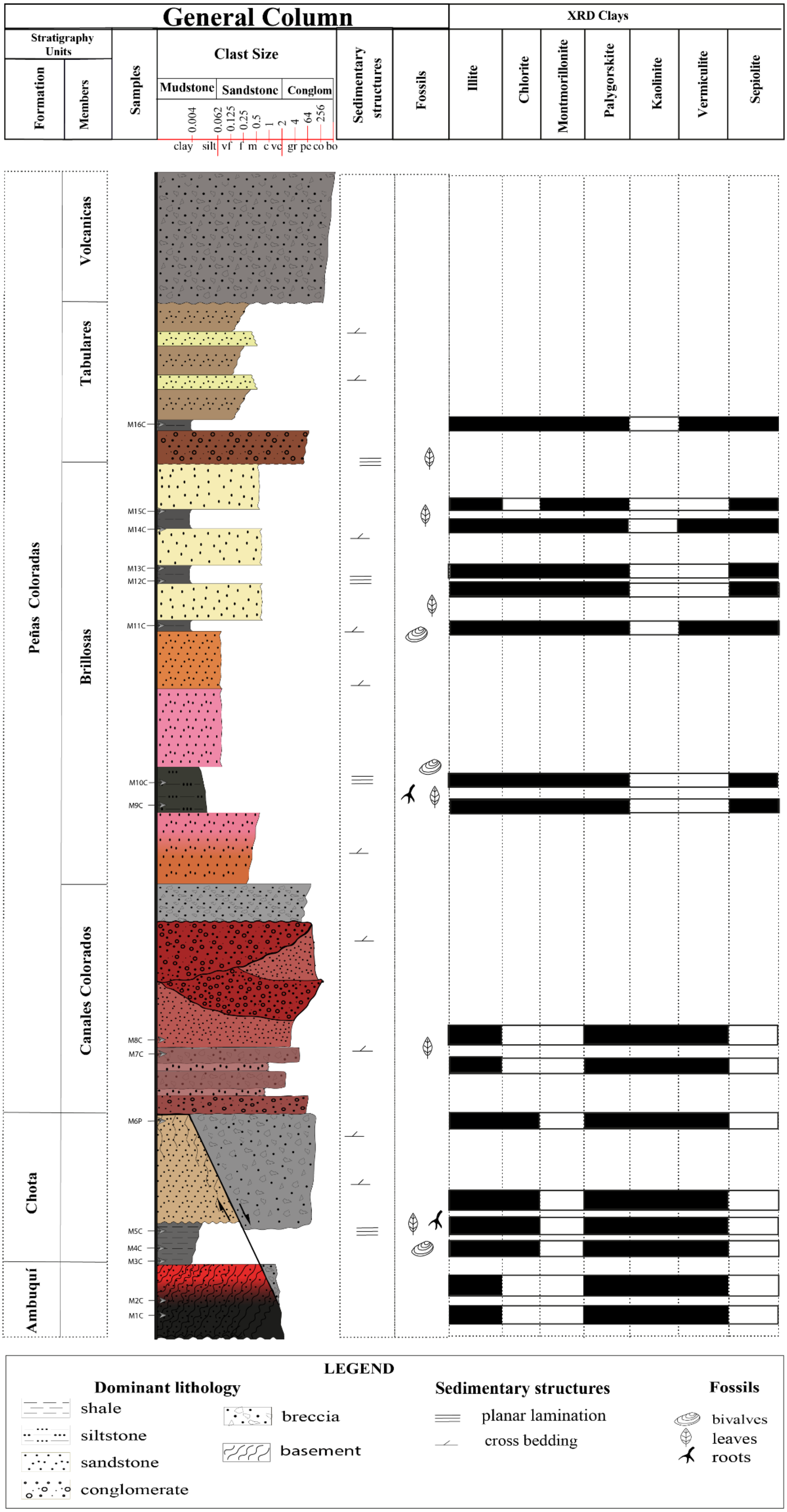
Detailed graphic log of Tabulares Member



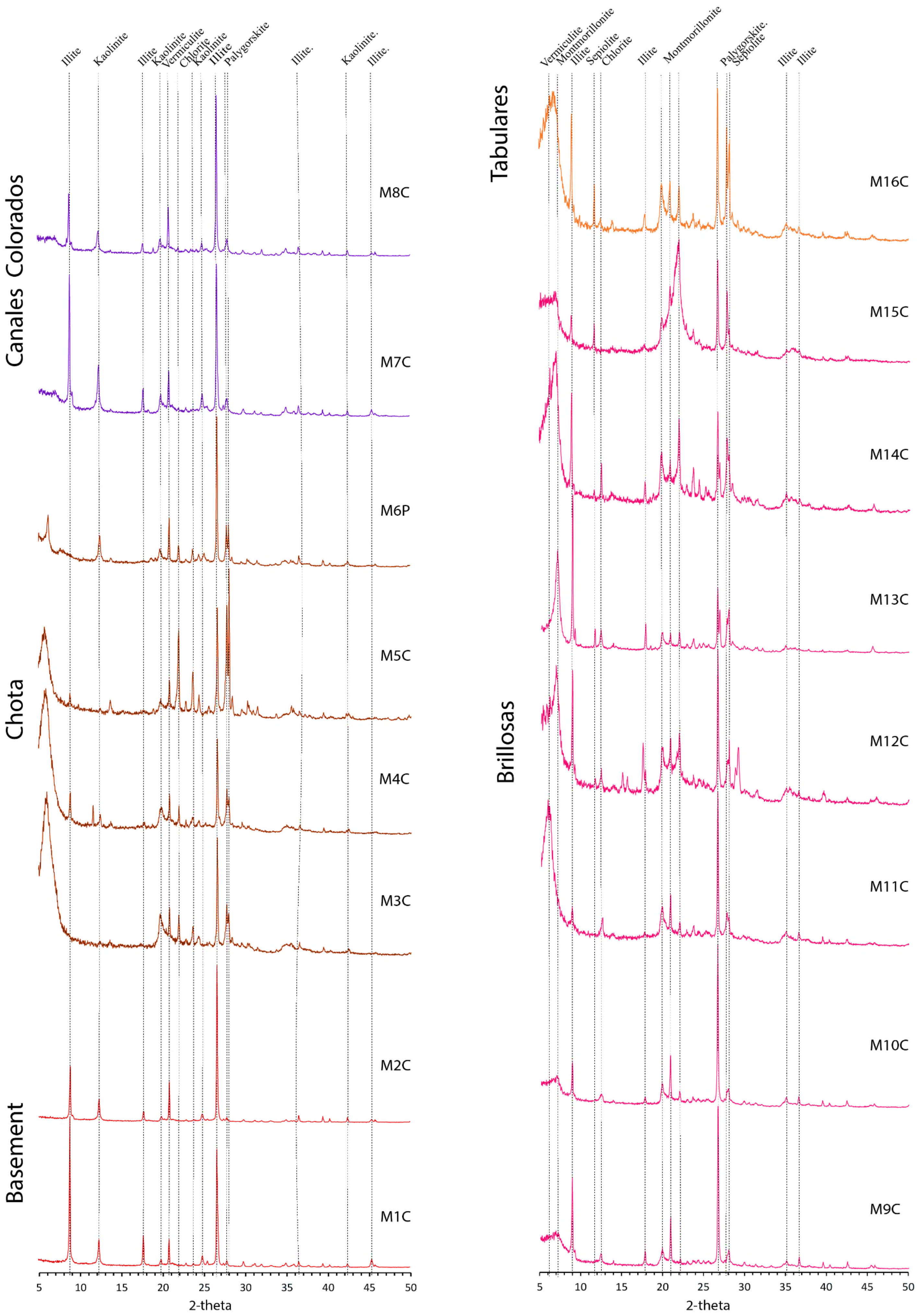


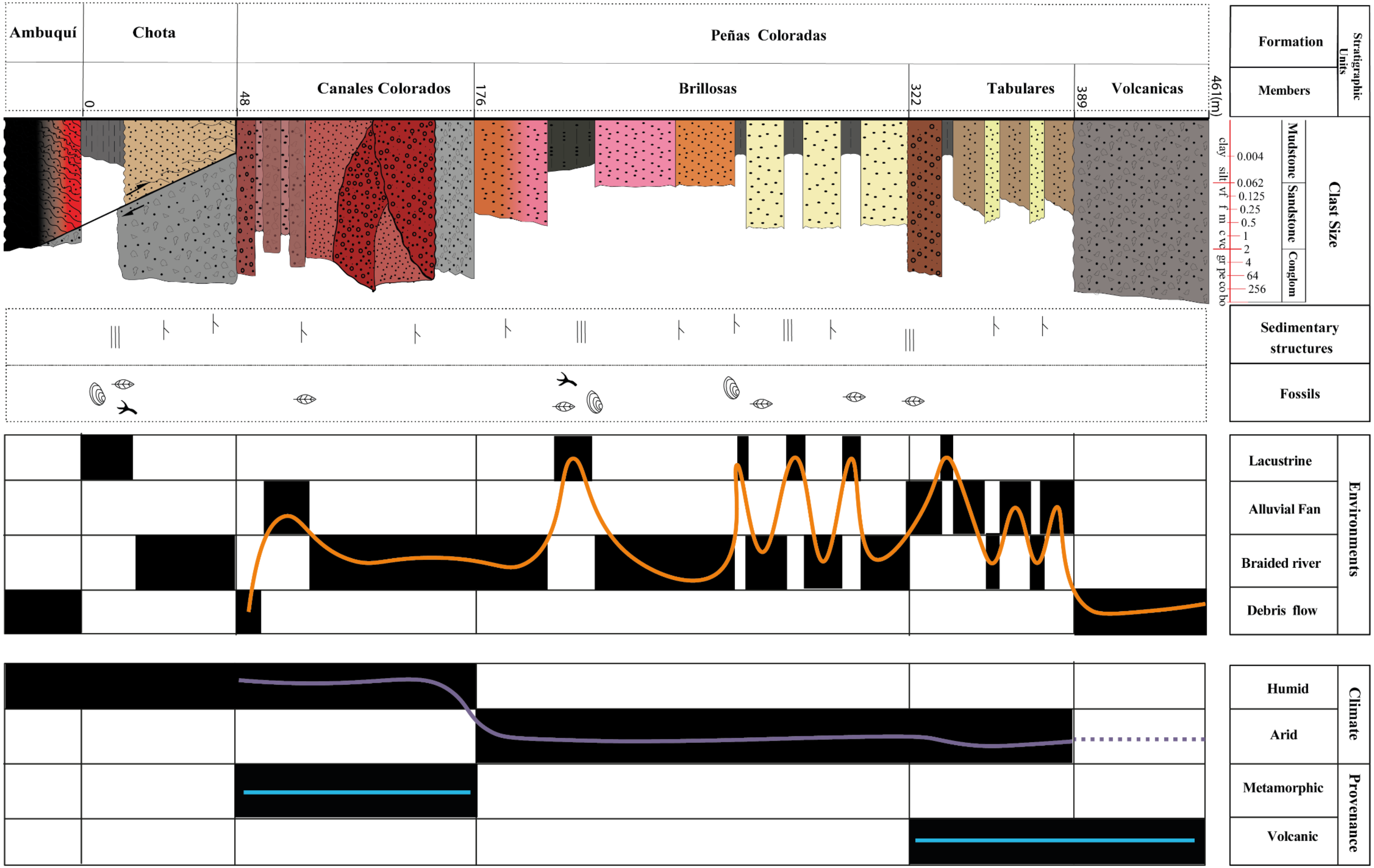
Volcanicas Member
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay
silt
vf
f
m
c
vc
gr
pe
co
bo
72
48
24
0
detail column
LEGEND
Dominant lithology
sandstone
breccia
A
1.70 m
B
1.70 m
C
1.70 m


Detailed graphic log of Volcanicas Member
Thickness (meters)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
20
15
10
5
0
A
B
C
D
E
LEGEND
Dominant lithology
Sedimentary structures
sandstone
breccia
cross bedding



General Column
XRD Clays
Stratigraphy Units
Formation
Members
Samples
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
Fossils
Illite
Chlorite
Montmorillonite
Palygorskite
Kaolinite
Vermiculite
Sepiolite
Peñas Coloradas
Volcanicas
Tabulares
Brillosas
Canales Colorados
Chota
Ambuquí
M16C
M15C
M14C
M13C
M12C
M11C
M10C
M9C
M8C
M7C
M6P
M5C
M4C
M3C
M2C
M1C
LEGEND
Dominant lithology
shale
siltstone
sandstone
conglomerate
breccia
basement
Sedimentary structures
planar lamination
cross bedding
Fossils
bivalves
leaves
roots


Illite
Kaolinite
Illite
Kaolinite
Vermiculite
Chlorite
Kaolinite
Illite
Palygorskite
Illite.
Kaolinite.
Illite.
Canales Colorados
Chota
Basement
M8C
M7C
M6P
M5C
M4C
M3C
M2C
M1C
5 10 15 20 25 30 35 40 45 50
2-theta
Vermiculite
Montmorillonite
Illite
Sepiolite
Chlorite
Illite
Montmorillonite
Palygorskite.
Sepiolite
Illite
Illite
Tabulares
Brillosas
M16C
M15C
M14C
M13C
M12C
M11C
M10C
M9C
5 10 15 20 25 30 35 40 45 50
2-theta



Stratigraphic Units
Formation
Members
Ambuquí
Chota
Peñas Coloradas
Canales Colorados
Brillosas
Tabulares
Volcanicas
0
48
176
322
389
461(m)
Clast Size
Mudstone
Sandstone
Conglom
0.004
0.062
0.125
0.25
0.5
1
2
4
64
256
clay silt vf f m c vc gr pe co bo
Sedimentary structures
Fossils
Environments
Lacustrine
Alluvial Fan
Braided river
Debris flow
Climate
Humid
Arid
Provenance
Metamorphic
Volcanic