UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

Escuela de Ciencias de la Tierra, Energía y Ambiente

TÍTULO: Stratigraphic and tectonic characterization of the Peñas Coloradas Formation, and its relation with the deposits of the Chota formation in the Chota Basin of northern Ecuador

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

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Urcuquí, agosto, 2021

Urcuquí, 16 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-2021-00009-AD

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DEDICATORIA

Dedico este trabajo a mis padres que me apoyaron incondicionalmente desde el principio de la aventura que representó Yachay y especialmente a mi hermano que estuvo ahí para escucharme y aconsejarme siempre.

AGRADECIMIENTOS

Quiero agradecer a todo el cuerpo docente de Yachay Tech, a los profesores de la escuela de geología y especialmente a mis tutores de este trabajo, Rafael Almeida y German Martín por su apoyo incondicional a lo largo de este trabajo, se convirtieron en una motivación para seguir y finalizar; nuestra inspiración y modelo a seguir. Gracias por que, durante los momentos de duda y desesperación, nos exigieron y ayudaron. Gracias infinitas a Yachay Tech, como institución y hogar. Este lugar cambio mis perspectivas de vida, cambio mi motivación y sueños. Y a la vez me dio algo que no sabía, mi carrera. La convivencia en el campus, las clases, las relaciones y los profesores que, a pesar de ser estrictos a veces, siempre fueron apasionados por la ciencia y el conocimiento, su pasión y devoción nos hicieron pensar en un futuro diferente para nuestro país.

Gracias infinitas a mis amigos Luis, Michael y Grace que, durante mis momentos más difíciles, nunca se negaron a una salida para caminar o tomar un café, escuchando quejarme o amar mi universidad, y que siempre creyeron en mí y en mi potencial. A mi familia B1-5 Genesis, Nadia, Vicky, Steven y Juan David, por las risas, conversaciones nocturnas, consejos, comidas, equipos deportivos y paseos. Gracias infinitas a mis colegas que se convirtieron en mi Geofamily: Jorge, Karen, Chavo, Luis, Bastian, Andy, Harvey, Mario, Joshua, Ari, que me acompañaron y fueron mis amigos para amanecernos tomando cerveza, haciendo deberes o estudiando. En especial a Erika y Javi, los mejores amigos que me dio la universidad y que han estado ahí para mis dramas, en las buenas y en las malas. A Steeven que quizás llego en la última etapa de este trabajo, pero siempre confió en que lo podía acabar, compartió mis noches de estrés y me soportó incluso en mis momentos más insoportables.

Finalmente, gracias a mis padres, que me apoyaron, aunque no les gustaba la idea de tenerme lejos, que me entendieron y siempre lo dieron todo por mí. Gracias a mi hermano, que siempre estuvo ahí para escucharme, ayudarme y aconsejarme. Siempre serás mi héroe y mi consejero favorito; gracias por ser más grande y amarme. Y mi mami Loli, por sentirse orgullosa siempre, por siempre estar y por sus infinitos mimos.

Resumen

La Cuenca del Chota se ubica en Ecuador, en la provincia de Imbabura; representa la cuenca más septentrional de la Depresión Interandina en Ecuador. Esta cuenca es una de las más relevantes para estudiar la evolución de la geología neógena en esta parte del país y data de aproximadamente 6 Ma. La importancia de este tipo de cuencas radica en que la estratigrafía y las estructuras que se exponen registran información sobre los procesos que crearon la Cordillera Occidental y la Cordillera Real que la rodean. El objetivo de este trabajo son los depósitos de brechas de la Formación Peñas Coloradas y su relación con la Formación Chota. Los depósitos de brechas de Peñas Coloradas Fm. están compuestos principalmente por conglomerados, areniscas y depósitos de brechas que no han sido descritos en detalle previamente. Los depósitos que subyacen a la Fm. Peñas Coloradas corresponden a la Fm. Chota, constituida por capas de areniscas inclinadas y volcadas, limolitas y lutitas que se deforman significativamente. Existen pocos estudios previos en esta cuenca, Tibaldi A. et al. (1992), Egüez, A. et al. (1994), Barragán et al. (1996) y Winkler et al. (2005), y las interpretaciones de diferentes aspectos de la cuenca son incongruentes entre ellos. Entre las principales diferencias está la edad de la cuenca, los procesos que conducen al origen de la cuenca, y la secuencia estratigráfica de la cuenca (la Fm Peñas Coloradas se ubica en la base o en el medio de la estratigrafía de la cuenca). Este estudio consiste en describir la estratigrafía y deformación de dos de las principales formaciones descritas previamente por Barragán et al. (1996) y Winkler et al. (2005): las Formaciones Chota y Peñas Coloradas; es necesario detallar la relación estratigráfica entre ellos. Para esto, realizamos observaciones estratigráficas y estructurales que nos permiten crear columnas estratigráficas locales, secciones transversales y hacer el análisis estructural, para comprender mejor la estratigrafía y las interpretaciones estructurales de los depósitos de estas unidades. Como resultado, creamos un mapa geológico del área de estudio, donde subdividimos la Fm. Peñas Coloradas en cuatro nuevos miembros: Canales Colorados Mbr, Brillosas Mbr, Tabulares Mbr y Volcanicas Mbr. Adicionalmente, el análisis de deformaciones y estratigrafía nos permite concluir que la Fm. Chota es más antigua que la Fm. Peñas Coloradas. Con base en las observaciones de campo, proponemos dos modelos para la evolución de la Cuenca del Chota durante el depósito de las formaciones estudiadas.

Palabras clave: Cuenca del Chota, Formación Peñas Coloradas, Formación Chota, estratigrafía, análisis estructural.

Abstract

The Chota Basin is located in Ecuador, in the province of Imbabura; it represents the northernmost basin of the Interandean Depression in Ecuador. This basin is one of the most relevant for studying the evolution of the Neogene geology in this part of the country and dates from approximately 6 Ma. The importance of this type of basin is that the stratigraphy and the structures that are exposed record a lot of information about the processes that created the Cordillera Occidental and the Cordillera Real that border it. The focus of this work is the breccia deposits of the Peñas Coloradas Formation and its relation with the Chota Fm. The Peñas Coloradas Fm breccia deposits are composed mainly of conglomerates, sandstone, and breccia deposits that have not been described in detail previously. The deposits that underlie the Peñas Coloradas Fm correspond to the Chota Formation, consisting of tilted and overturned sandstone layers, siltstone, and shales that are significantly deformed. There are few previous studies in this basin, Tibaldi A. et al. (1992), Egüez, A. et al. (1994), Barragán et al. (1996), and Winkler et al. (2005). Still, the interpretations of different aspects of the basin are incongruent between them. Among the main differences is the age of the basin, the processes that lead to the origin of the basin (i.e., inverted extensional basin vs. foreland setting), and the stratigraphic sequence of the basin (the Peñas Coloradas Fm is placed either at the base or the middle of the basin stratigraphy). This study consists of describing the stratigraphy and deformation of two of the principal formations described previously by Barragan et al. (1996) and Winkler et al. (2005): the Chota and the Peñas Coloradas Fms. It is necessary to detail the stratigraphic relation between them. We make stratigraphic and structural observations that allow us to create local stratigraphic columns, cross-sections, and do the structural analysis, to understand better the stratigraphy and structural interpretations of the deposits of these units. As a result, we create a geologic map of the study area, where subdivide the Peñas Coloradas Fm into four new members: Canales Colorados Mbr, Brillosas Mbr, Tabulares Mbr, and Volcanicas Mbr. Additionally, the deformation and stratigraphy analysis allow us to conclude that the Chota Fm is older than the Peñas Coloradas Fm. Based on the field observations, we propose two models for the evolution of the Chota Basin during the deposition of the studied formations.

Key words: Chota Basin, Peñas Coloradas Fm, Chota Fm, stratigraphy, structural analysis.

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INTRODUCTION

A sedimentary basin is a depression created by the dynamism of plate tectonics and sedimentary processes; this region is generally wide and accumulates within it, hundreds to thousands of meters of sediments, which can be preserved for long geological periods (Einsele, 2000). These depressions have variable shape and size, but generally are elongated with irregular boundaries and can be hundreds of km long and tens of km wide.

The classification of sedimentary basins is an issue addressed by different perspectives, so there are different classification systems according to the concepts of facies, depositional environments, characteristics of sediments that fill the basin, and even according to its geometry and occurrence. According to Einsele (2000), the regional deposition of sediments, non-deposition, or denudation of older rocks are controlled mainly by tectonic movements. Therefore, most attempts to classify sedimentary basins have been based on global and regional tectonic configurations. Einsele (2000) proposes a classification of sedimentary basins with seven categories. Those are continental or interior sag basins, continental or interior fracture basins, basins on passive continental margins, oceanic sag basins, basins related to subduction, basins related to collision, and strike-slip/wrench basins. The focus of this study is an intramontane continental basin, which is a special type of basin related to subduction/collision formed between mountain ranges and are limited in their borders by different kinds of structures such as faults and folds.

Intramontane basins are important because they register and record the stratigraphic and structural evidence of the processes that create the surrounding mountain range. According to Streit et al. (2017), intermontane basins can show us the evolution of elevation, denudation and environmental conditions of the mountain ranges that surround the basin. Catuneau (2000) explains that sedimentary basins are influenced by controlling factors that are autogenic and allogenic. The autogenic factors are those that are internally generated and influence the stratigraphy and architecture of the basin such as the mechanisms of storage (deposition) and release (erosion). On the other hand, the allogenic controls represent the external factors that are linked to the large-scale conditions of the basin, and the main ones are climate, tectonism and eustasy changes. Tectonic and eustatic variations are generally related to the control of the accommodation and geometry of the basin, while climate can modify the sediment supply by its direct influence on the weathering, erosion, sediment transport, and even on eustasy. The resultant stratigraphy is a consequence of the accommodation space and the sediment supply, and the basin generation forces that determine the geometry of the basin infill (Allen, 2013).

The geodynamic evolution of the Ecuadorian Andes is characterized by a series of events determined by the subduction of the Nazca Plate under the South American Plate, that has generated the formation of important features in Ecuador, such as the Cordillera Real and Cordillera Occidental mountain ranges, and the development of the Interandean Depression or Valley (Vallejo, 2009). The Interandean Valley is a structure that crosses Ecuador from north to south and, as its name implies, it is located between the Cordillera Occidental and the Cordillera Real. Ficcarelli (1992) explains that this depression has developed since the late Miocene, and was created by tectonic factors that triggered the opening of basins, orogenic uplift, and faults. Throughout this structure, several sedimentary basins were developed. The sedimentary infill preserves in these basins comprise alluvial fan deposits, volcanic deposits, and non-marine and marine sediments, generally limited by faults (Tamay et al. 2016). In general, the stratigraphic record of these sedimentary basins preserves important information about the formation and evolution of the Interandean Valley, as well as the Ecuadorian Andes.

The northernmost basin of the Interandean Valley in Ecuador is the Chota Basin, which constitutes an excellent example of the geodynamic evolution of the zone located between the Cordillera Occidental and Cordillera Real, in the Imbabura province near the town of Ambuqui at the north of Ecuador. This basin is one of the most relevant for the study of the evolution of the Neogene geology in the northern part of the country, because it dates from approximately 6 Ma (Barragán et al., 1996; Winkler et al., 2005) and preserves a geological record of the evolution of the surrounding mountains in its infill. There are few previous studies carried out in this basin, specifically those of Tibaldi A. et al. (1992), Egüez, A. et al. (1994), Barragán et al. (1996), and Winkler et al. (2005). Nevertheless, the interpretations of different aspects of the basin are incongruent between those studies.

The studies differ in several aspects, like stratigraphy for example. Barragán et al., (1996) indicate a stratigraphic sequence classified into four main units that are from base to top: Chota Fm, Santa Rosa Fm, Peñas Coloradas Fm, and Carpuela Fm. On the other hand, Winkler et al., (2005) propose a stratigraphic sequence composed of three formations, that are, from base to top: Peñas Coloradas Fm, Chota Fm, and Santa Rosa Fm. As we see, the stratigraphic sequence interpretations by Barragán et al., (1996) and Winkler et al., (2005) are totally different.

Another conceptual difference is related to the interpretation of the origin of the basin. Barragán et al., (1996) point out that the development of the basin formation occurs in two main stages, an opening and a closure; the first one is characterized by a transtensional tectonic regime and development of a subsiding depression, and the second stage is generated by the gradual change to compressive tectonic regime linked to reverse faults. On the other hand, Winkler et al., (2005) describe the origin of the basin as linked to the formation of the Interandean Valley and suggest that a compressive stress regime prevailed throughout the entire basin history.

Deciphering those differences can be a complicated process because it requires a study that covers the entire basin. Nevertheless, there are some procedures that can be carried out in order to help resolve the discrepancies in the time frame of this thesis. For this we focus on the Peñas Coloradas Fm, in the eastern side of the basin (Figure 1), where we will carry out fieldwork in an area of 16 km2.

The study consists of the description of the stratigraphy and deformation of two of the principal formations described previously by Barragan et al. (1996) and Winkler et al. (2005): the Chota and the Peñas Coloradas Fms. Due to the stratigraphic incongruences presented by the previous works, it is necessary to detail the stratigraphic relation between them. We will make stratigraphic and structural observations that will allow us to create local stratigraphic columns, cross-sections, and do structural analysis, to better understand the stratigraphy and structural interpretations of the deposits of these units. We expect that this will allow us to place new constraints on the evolution of the Chota basin, allowing us to recognize climatic, and tectonic changes that have influenced it during the formation and evolution.

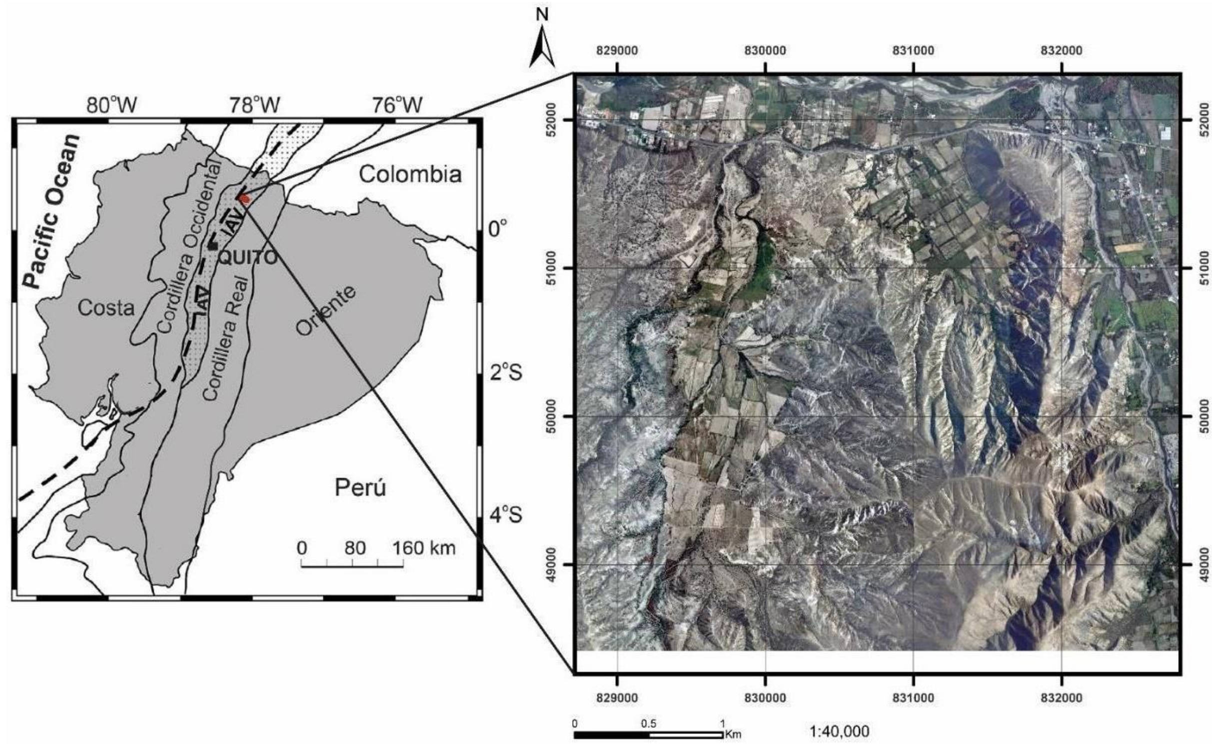


Figure 1. At the left, the map of Ecuador, taken from Tamay et al. (2016), marked with the principal features that surround the area of interest: the Interandean Valley (IAV), the Cordillera Real and Occidental, the dashed line is the Calacalí-Pallatanga fault. The red figure points out the area of study, which is also shown on the right. To the right, the figure shows orthophotos of the study area.

I. GEOLOGICAL FRAMEWORK

Continental Ecuador is divided into three geological provinces. The region of the west is known as the Coastal Region and it is a coastal plain with only a few low-lying mountains. It comprises a series of hydrocarbon-containing basins, such as the Manabí and El Progreso basins. Hughes (2002) states that they date from the Cretaceous until the Cenozoic. The rocks of an accreted oceanic crust terrane are locally exposed in the coastal ranges and underlie the entire region. To the east is located the Oriente Region which is represented by the Andean foothills and retro-foreland basin. The Oriente is a Mesozoic to Cenozoic hydrocarbon-rich sedimentary retro-foreland basin that includes a platform carbonate sequence superimposed on an older cratonic basement. And, there are granitoid batholith intrusions in the basement and in the cover sequences (Hughes, 2002). The center domain that separates the two previous regions, is the Andean Region known as the Sierra. The Ecuadorian Andes comprise two mountain ranges, the Cordillera Occidental and the Cordillera Real (Figure 3).

The Cordillera Real (Eastern Cordillera) (Figure 3) forms part of a metamorphic belt that runs from Colombia to the Peruvian border. It consists of Paleozoic to Mesozoic metamorphic rocks, intruded by granitoids and capped by Cenozoic to Quaternary volcanoes (Hughes, 2002). It is located to the east of the Interandean Depression and separated from it by the Peltetec fault, which is a continuation of Colombia's Romeral fault (Vallejo, 2009). This mountain range is divided into lithotectonic divisions separated by major faults. There are five lithotectonic divisions (from west to east): The Guamote, Alao, Loja, Salado, and Zamora divisions (Figure 2). Separating the lithological divisions are (from west to east): The Peltetec fault, Baños front, Llanganates fault, and the Cosanga Mendez fault (Aspden, 1992).

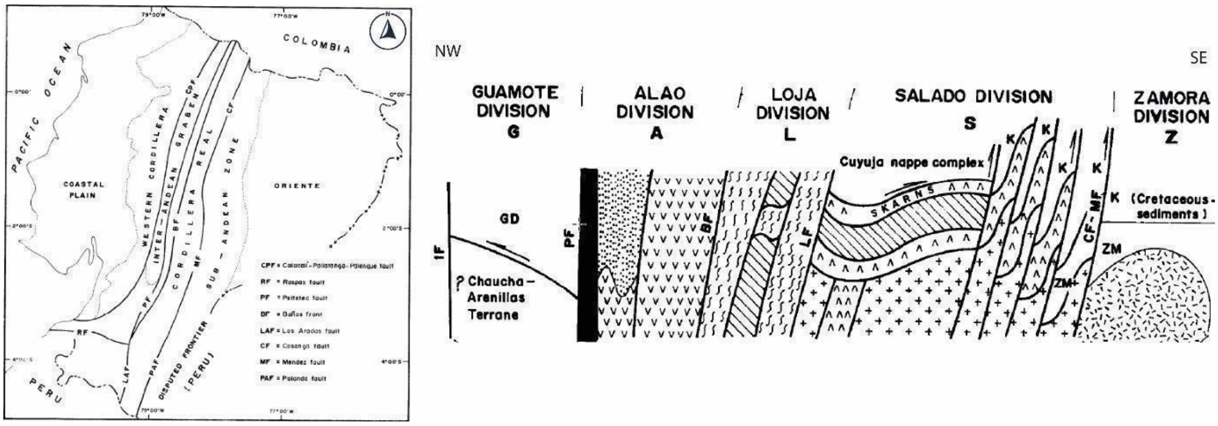


Figure 2. To the left, the map of Ecuador pointing out some structures that cross Ecuador. To the right, the Schematic section across the Cordillera Real, showing its principal divisions (Litherland & Aspden 1992.

The Cordillera Occidental (Western Cordillera) (Figure 3) was formed by the collision of an oceanic plateau with continental South America in the Late Cretaceous, where allochthonous terranes, including ophiolitic and oceanic crustal fragments were accreted (Hughes & Pilatasig, 2002, Vallejo, 2007; Vallejo et al., 2009, Vallejo et al., 2019). The Cordillera Occidental basement is formed by early to late Cretaceous oceanic plateau basalts and ultramafic rocks, overlain by late Cretaceous marine turbidites, an early Eocene basaltic to andesitic oceanic island arc series, a Paleocene to Eocene marine turbidite basin-fill sequence, and a late Eocene-Oligocene terrestrial sequence (Hughes, 2002). It is limited to the east by an approximate north-south trending ocean-continent suture zone reactivated with transcurrent fault displacement, called the Calalacli-Pujilí-Pallatanga fault (Egüez, 1986; Jaillard et al., 2004; Spikings et al., 2001; Vallejo, 2007; Vallejo et al., 2009). The Cordillera Occidental is subdivided into two different sequences with an assemblage of volcano-sedimentary tectonostratigraphic units (Jaillard et al., 2004; Toro & Jaillard, 2005). Fission-track and 40Ar/39Ar data show that the Cordillera Occidental records cooling at 85 to 60 Ma with a peak from 85 to 80 Ma (Spikings et al., 2005). Transcurrent faults structurally juxtapose successions of volcanic composition of different ages; it results in a complex assemblage tectonostratigraphic unit in the Cordillera Occidental (Vallejo, 2009).

The Western and Eastern cordilleras are separated by an axial depression called the Interandean Valley or Depression that hosts thick Pliocene-Pleistocene volcanic deposits (Vallejo et al., 2019). Lavenu (1995) defines the Interandean Depression as a compressional basin bounded by N-S trending reverse faults, which have been active since the Miocene. Located at its western flank is the Calacali-Pujili fault system exposed along the eastern edge of the Cordillera Occidental, whereas, the Peltetec fault bound it to the west; these faults represent crustal sutures (Vallejo, 2019).

The Interandean valley hosts a series of sedimentary basins filled by volcaniclastic and sedimentary deposits, which overlie either the cordilleras' basement rocks or a Miocene to Oligocene-aged volcanic succession, and has several volcanoes along its flanks (Fiorini, 2012).

Along the Interandean valley, the formation of the basins is due to a large-scale, late Miocene-Recent tectonic rearrangements in the Ecuadorian Andes (Winkler et al., 2005). The recognized basins from north to south, are: 1. Chota basin, 2. Quito-San Antonio-Guayllabamba basin, 3. Ambato-Latacunga basin, 4. Riobamba-Alausí basin, 5. Cuenca basin, 6. Nabón basin, 7. Vilcabamba basin, and 8. Zumba basin (Figure 3).

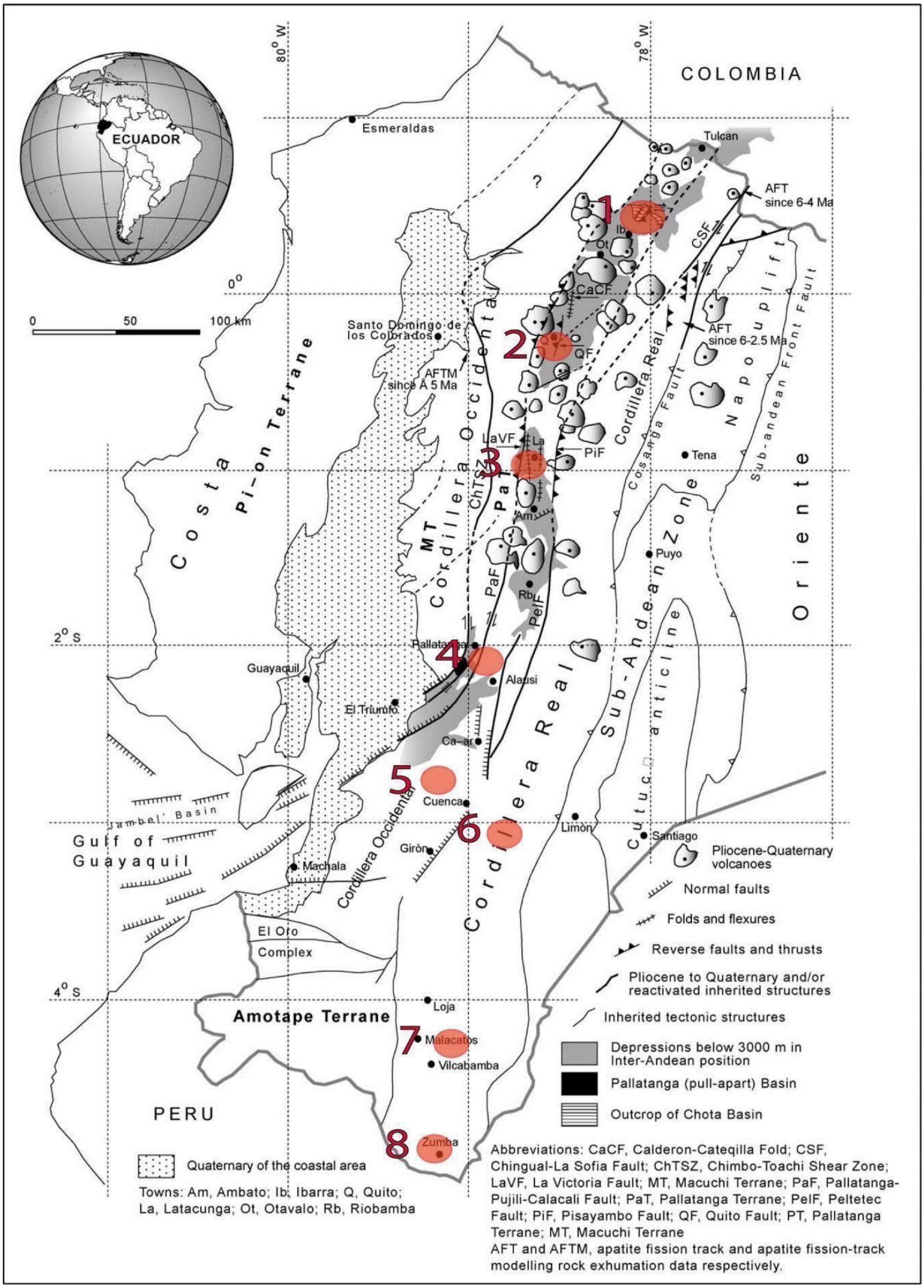


Figure 3. Map of the principal features and physiographic divisions of Ecuador, marked and numerated in red are the location of the Interandean basins: 1. Chota basin, 2. Quito-San Antonio-Guayllabamba basin, 3. Ambato-Latacunga basin, 4. Riobamba-Alausí basin, 5. Cuenca basin, 6. Nabón basin, 7. Vilcabamba basin, and 8. Zumba basin. Map taken from Winkler et al., (2005).

1.1. Previous works on the Chota Basin.

At the north of the Interandean Depression of Ecuador is located the Chota Basin. There are few previous works in the area that try to describe the age, origin, and stratigraphy of the basin. These works were carried out by Tibaldi et al. (1992), Egüez and Beate (1994), Barragán et al. (1996) and Winkler et al. (2005). There are several discrepancies between these works and various interpretations of different aspects of the basin.

Tibaldi et al. (1992), reconstruct the kinematic evolution of the Interandean Depression based on field data, which let them interpret it as a piggyback basin, that suffered two different regimes, semi continuous compression, followed by a transpressional to transtensional structural style. For the northern sector, they focus their study on the Chota basin. The authors divide the stratigraphy of the Chota basin into a younger section conformed by fluvial conglomerates and pyroclastic deposits of late Pleistocene-Holocene age and indicate that these deposits are affected by faults that mainly dip to the west. Whereas, the older section was known as the Chota group, composed of Pleistocene lacustrine and volcano-sedimentary deposits, Pliocene andesites and Miocene continental deposits.

Furthermore, Tibaldi et al. (1992) explain the deformation of the northern sector of the Interandean valley, based on the Chota basin's deformation, and describe three stages: 1. A compressional phase occurred in the Pliocene age, which produced cylindrical folds and low angle pure reverse faults. 2. During the Pleistocene, high angle strike-slip, pure reverse, and oblique faults are kinematically compatible with an N-S compression. 3. Finally, an extensional phase developed an N-S normal, and left-lateral normal faults occurred up to the Holocene.

Eguez & Beate (1992) focused on the description of mapping units, the stratigraphy, and structures of the Chota basin and proposed a new model for the geodynamic evolution of the basin. The Chota basin is limited to the east by the Cordillera Real, where it is possible to find metamorphic rocks. In Carpuela, green schists emerge that correspond to a tectonic scale of the Jurassic volcanic arc developed further east. To the west, it is limited by the reliefs of the hills and Salinas, and the Cordillera Occidental (Eguez & Beate, 1992). The sediments of the Chota basin and volcanic deposits cover the relationships between the metamorphic rocks of the Cordillera Real and the accreted oceanic terrains of the Cordillera Occidental.

The stratigraphic division that Euguez & Beate (1992) report is: first, the basement is composed primarily of metamorphic rocks, quartzites, and graphite schists highly deformed by at least two pre-Cenozoic phases. Overlying this is the Chota Fm, which lies unconformably below the Peñas Coloradas Fm in The Refugio sector (Figure 4). In Los Buitres hill, the Santa Rosa Fm is in progressive unconformity above the Chota Fm. The Chota Fm has a variable thickness and is composed of fluvial deposits consisting mainly of sandstone, shales, and siltstones. On top of it, the Santa Rosa Fm outcrops at the center of the basin. It is composed primarily of well-consolidated laharitic breccias and conglomerates. In the east of the basin, the Peñas Coloradas Fm is in contact with the metamorphic basement. It is composed primarily of sandstone sequences, red and grey metamorphic input conglomerates, shales and siltstones sequences, and finally, grey conglomerates and sandstones. The authors define a volcanic phase composed of dikes and sills that cut the sediments around the basin, recognized by its characteristic brownish and olive-green coloration. Additionally, the study describes young deposits covering the Chota basin, such as the Granalotal unit, Angochagua volcanic deposits, Huaguillaro-Chachimbiro deposits, Imbabura volcanic deposits, lahars, cangahua, and alluvial deposits (Figure 4).

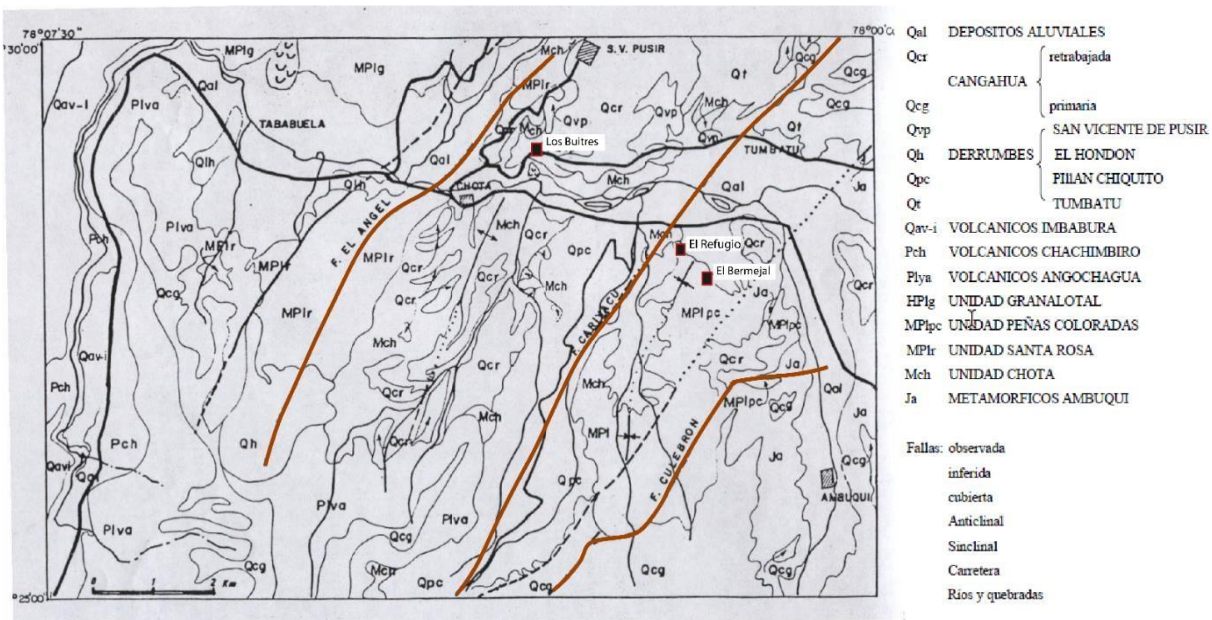


Figure 4. Geologic map presented by Euguez and Beate (1992), it shows the principal locations and the red lines point out the faults that limit the formations described in its work.

Meanwhile, for the tectonic description, Euguez & Beate (1992), report a complex deformation with folds and faults developed in different phases. For the Chota Fm they identify syn-sedimentary overturned folds, and explain that the unit is controlled by two faults: the Cariyacu fault and the El Angel fault. The Santa Rosa Fm is affected by El Angel fault that produces syn-sedimentary folds (Euguez & Beate, 1992). The Peñas Coloradas Fm forms an open syncline with the NNE-SSW direction axis, and with a progressive unconformity over the lahar deposits.

The authors divided the basin into three sub-basins, each one formed in different phases. The principal and central sub-basin is composed of the Chota Fm, and is the oldest one. Based on the accommodation required to deposit the observed lacustrine sediments of the Chota Fm, they propose an initial extensional phase. The western sub-basin was developed before the closure of the central sub-basin. The syn-sedimentary folding is an indicator of a compressive regime. The eastern sub-basin is filled with the Peñas Coloradas Fm. It developed concurrently with the last stage of the western sub-basin. This is a compressive phase controlled by the Culebron and El Angel faults (Figure 4), and according to Euguez & Beate (1992), it occurs in the early Pliocene.

Barragan et al. (1995) presents a detailed stratigraphic and tectonic analysis of the Chota basin, and defines four units accumulated in two mega sequences. The structural interpretation described two tectonic events, the first one produced the opening of the basin result of an extensional tectonic period, and the second one caused the closure of it, due to a regional N120°E compressive regime, which later rotated to an E-W compressive trend.

The four units proposed by Barragan et al. (1995) are from bottom to top: Chota Fm, Santa Rosa Fm, Peñas Coloradas Fm, Carpuela Fm (Figure 5A). The Chota Fm is exposed in the central part of the basin, overlying the metamorphic basement and underlying the Peñas Coloradas and Santa Rosa Formations. In this work, the Chota Fm is divided into two sequences, S1 and S2. The S1 sequence is defined by braided river deposits of volcanic, metamorphic and claystone composition. The S2 is composed of clay to muddy material intercalated with conglomerate and sandstone layers; furthermore, it presents fossil content, which indicates a lacustrine environment with sheetflood deposits.

Barragan et al. (1995) divided the Santa Rosa Fm, located in the western part of the basin, into six thick sequences. The sr1 is the first sequence, composed of fluvial deposits of alluvial fans of conglomerates, sandstone, clay and silt layers. The sr2 contains volcaniclastic material, combined with debris flow deposits, and andesitic lavas. The sr3, sr4 and sr5 correspond to sandstone to conglomerate sequences. The sr6 is a clayed and silty sequence combined with laminated sandstones and conglomerates. Unconformably overlying this unit, there are breccia deposits, that the authors name 'Gavilanes breccias'.

The third sequence is the Peñas Coloradas Fm, situated at the eastern part of the basin. This unit is in contact with the metamorphic basement and the Chota Fm. Barragan et al. (1995) divide this unit into six sequences, formed by alluvial fan deposits.

Finally, for the Carpuela Fm, the authors describe four thickening and coarsening sequences of conglomerates in a progradation of alluvial fans with a volcanic and metamorphic source. This unit is isolated from the others and is located in the easternmost part of the basin.

Another essential point developed by Barragan et al. (1992) was the structural analysis for each unit. The Chota basin is bounded by major faults that separate the sedimentary fill from the metamorphic rocks and influence the evolution of the basin. According to the tectonic analysis of this work, during the Neogene, three tectonic events occurred. The first one, an extensional event with the principal stress $\sigma 3$ oriented N130°E that produces a sinistral displacement along N60°E striking faults, normal synsedimentary faults-oriented N-S to N40°E, slickensides, and shearing features produced by faults and folds, affecting the Chota Fm. Then, a compressive event with $\sigma 1$ striking N120°E that affected the Chota and Santa Rosa Fm, contemporaneous with the deposition of the latter. This event developed the east-verging synsedimentary folds affecting the Santa Rosa Fm deposits and also of west-verging post sedimentary folds affecting the Chota Fm deposits. Finally, a compressive event with $\sigma 1$ oriented N90°E acting on all units and generating reverse displacements along the N-S to N40°E striking faults, and dextral displacements along the N60°E to N80°E striking faults. The open folds with N-S axis in the Peñas Coloradas and Carpuela Formations also form in this period.

Furthermore, the authors proposed a model for the geodynamic evolution of the Neogene Chota basin, which consists of two stages. The first one is the opening of the basin that occurred during the Miocene, as a consequence of extension and displacements along normal faults. It generates a depression with the contemporaneous formation of a braided river system flowing NE, represented by the deposits of the Chota Fm. Then, the lacustrine material with syn-depositional normal faults and slumps indicate the deepening of the basin related to an increased velocity of tectonic subsidence. The closure represents the second stage of the Chota basin evolution in which a change occurs in the source area and depositional environments. The Santa Rosa Fm recorded the gradual change towards a compressive regime with $\sigma 1$ oriented NW-SE. Then, the main compressive stress vector $\sigma 1$ rotates to a E-W direction, which resulted in the development of reliefs that outcrop the metamorphic basement as a pop-up structure and generate the deposition of Peñas Coloradas and Carpuela Formations.

Winkler et al. (2005) determined a chronostratigraphic framework for the Chota basin deposits combining apatite and zircon fission track data with the Cordillera Real and Cordillera Occidental evolutionary models as well as heavy minerals studies from the Chota basin. The results for the Peñas Coloradas formation give it an age of 5.4 Ma. (ZFT) cut by dykes of 3.7 Ma. (AFT). This specific result depicts that Peñas Coloradas is the same age or younger than the Chota Formation, previously dated at ~6.3 Ma (Barberi et al., 1988). For the Santa Rosa Formation, the ZFT result yielded an age between ~4.5 Ma and ~3.5 Ma. Based on this, they propose a different stratigraphic model which is from base to top: Peñas Coloradas Formation, Chota Formation, and Santa Rosa Formation, dating the Chota Formation at 4.8 Ma. Winkler et al, also presents a geological map of the zone (Figure 5B). The authors explained the deformation of the basin as a post depositional folding that affects the entire basin. They agree with the evolutionary model created by Barragan et al. (1996), but contrasting in some aspects; they suggest that the Chota Formation was deposited in an NW-SE extending regime followed by a WNW-ESE oriented compression regime. Finally, Winkler et al. (2005) conclude that the Interandean Depression was formed in a right lateral transpressive tectonic regime. The authors proposed a full-ramp basin model where reverse faults drive the uplift of the mountain ranges that border the Interandean Depression.

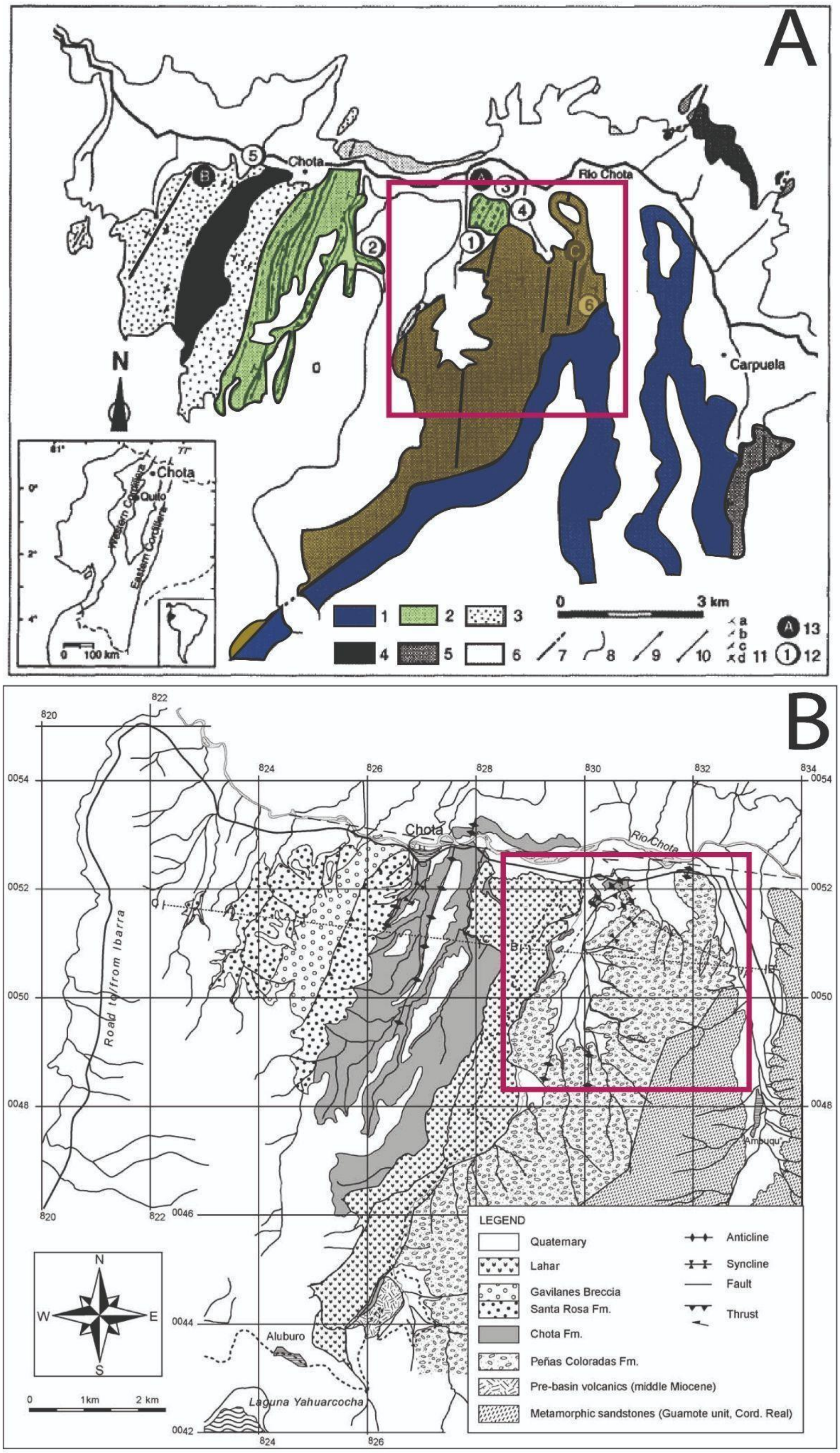


Figure 5. A) Geologic map from Barragan et al (1996). The numbers represent: 1. Metamorphic basement, 2. Chota Member, 3. Santa Rosa Member, 4. Gavilanes Breccias, 5. Peñas Coloradas and Carpuela Members. 6. Quaternary deposits. 7. Fault 8. Normal contact 9. Anticline axis 10. Syncline axis 11. Dipping 12. Location of studied folds 13. Location of studied microfractures sites. B) Geologic map from Winkler et al. (2005). The pinks squares represent the current study area.

II. METHODOLOGY

The methodology consists principally of fieldwork carried out in the eastern side of the Chota basin (Figure 1), focusing on the Peñas Coloradas and Chota Formations. The fieldwork duration was approximately two months. Using the data collected in the field, I constructed several local stratigraphic columns to determine stratigraphic relations, and bedding attitudes were measured to constrain the geologic structures in the region. A geological map and a cross-section of the area summarize the information collected and observed.

In order to characterize the Peñas Coloradas Fm, member-scale stratigraphic units were defined and described in detail, focusing on their sedimentary and tectonic features. The constructed stratigraphic columns considered the following parameters: layer thickness, color of the beds, contacts, tectonic structures, grain size, sedimentary structures, clast composition, roundness of clasts, sorting of clasts, and other notable information. The outcrops of the study area are well exposed, and therefore, the graphic logs were made in detail by hand. The Stratigraphic Data Analysis in R (SDAR) program was used to digitize these graphic logs, and the final edits were carried out in Adobe Illustrator.

Additionally, during fieldwork a geological map was created using a topographic base map with a scale of 1:40000 and contour line intervals every 50 m that we made in ArcMap using a 3 m resolution Digital Elevation Model (DEM). The first version of the geologic map was based on analyses of orthophotos and landscape features. This was improved with data collected in the field that consisted of measurements of faults, beds, joints, folds and their axial planes, lithologies and stratigraphic contacts. The structural data collected in the field was used to carry out a structural analysis of the field area. For this, lower-hemisphere, equal-area stereographic projections of attitude data were used. These, along with contours of the data, pole calculations and best fit girdle approximations, were done with the Stereonet 11 program. Furthermore, the collection of this data allows the creation of a structural cross-section where field data is projected into the sub-surface to estimate the basin geometry at depth.

III. DESCRIPTIONS AND RESULTS

This chapter contains a report of the field observations and results. Detailed cartography of the zone allowed the creation of a geological map (Figure 6) presented and described here. It shows the characteristic lithologies and units found, detailing the Peñas Coloradas Formation's stratigraphy. Additionally, this chapter covers the structural characteristics of the study area.

During the field mapping, seven different stratigraphic units were identified (Figure 6, Figure 7): the metamorphic basement, the Chota Fm, the Peñas Coloradas Fm divided into four units (Canales Colorados Member, Brillosas Member, Tabulares Member, Volcanicas Member), and the Quaternary deposits. In the following section we present the description of the stratigraphy and lithologies found in the study area.

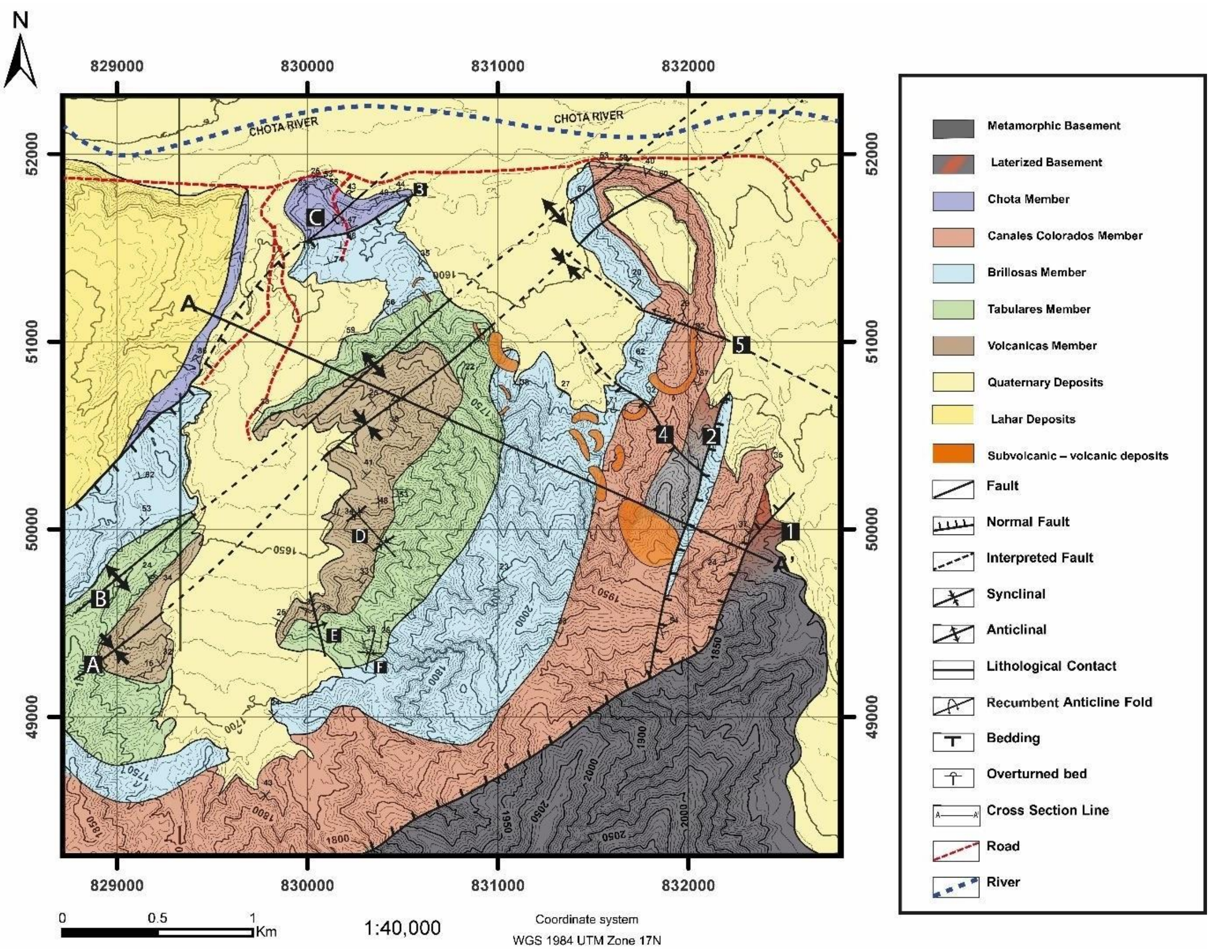


Figure 6. Geologic map of the study area, with the principal units and geological structures. The numbers are used to identify the main faults, and the letters represent the principal folds. The AA' line represents the cross-section line.

3.1. Stratigraphy of the Peñas Coloradas Fm. and Chota Fm.

During the field mapping, seven different stratigraphic units were identified (Figure 6, Figure 7): the metamorphic basement, the Chota Fm, the Peñas Coloradas Fm divided into four units (Canales Colorados Member, Brillosas Member, Tabulares Member, Volcanicas Member), and the Quaternary deposits. In the following section we present the description of the stratigraphy and lithologies found in the study area of 461 m of total vertical thickness.

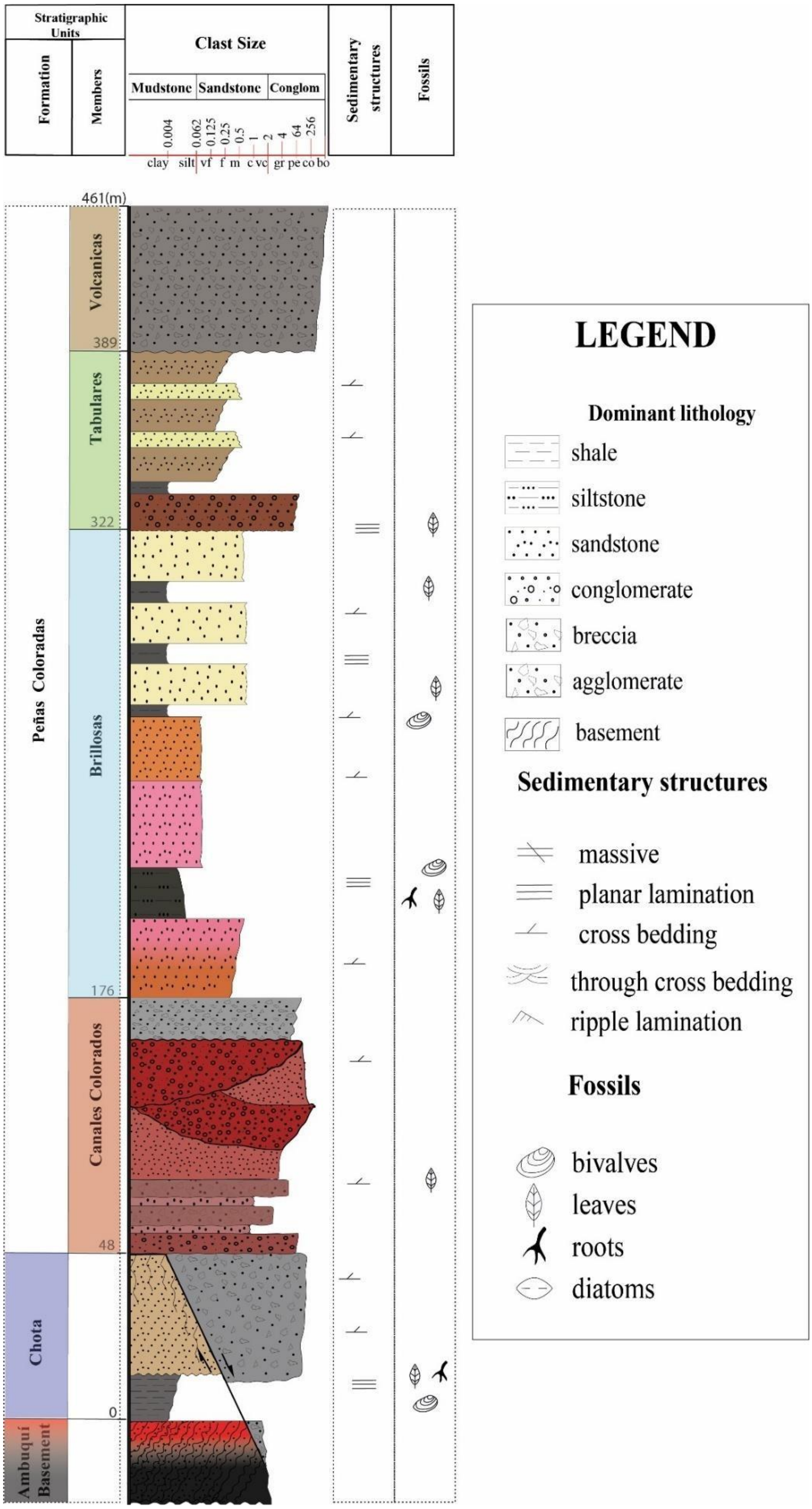


Figure 7. General stratigraphic column of the study area showing the Chota and Peñas Coloradas Fms. The colors to the left match with the colors of the formations in Figure 6.

4.1.1. Metamorphic basement.

The metamorphic unit corresponds to the Ambuqui Fm, and constitutes the basement of Chota basin in the studied area. It shows both depositional and fault contact with the Peñas Coloradas Fm, and it is possible to see it at the southeast of the study area (Figure 6). The basement rocks correspond to very deformed layers of grey quartzite, and graphitic schist (Figure 8A, B). It is highly fractured, folded and foliated (Figure 8A, B); additionally, it locally presents a chemical alteration, showing a red coloration due to laterization (Figure 8C).

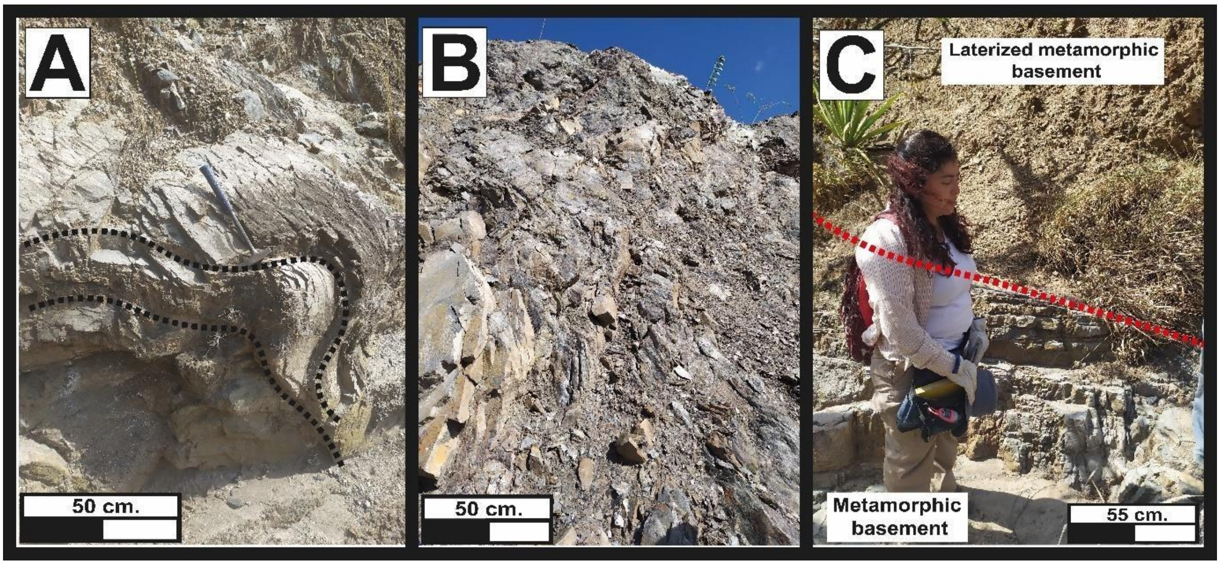


Figure 8. A) Folded foliations of the metamorphic basement. B) Quartzite rocks of the metamorphic basement. C) Metamorphic basement vs laterized metamorphic basement deposits.

4.1.2. Chota Formation.

The Chota Fm (Figure 9) is exposed in the central part of the Chota Basin. It outcrops at the northwest part of the study area (Figure 6). To the west of our study area, it is overlain by lahar deposits, and in the central northern part, it is in fault contact with the Peñas Coloradas Fm.

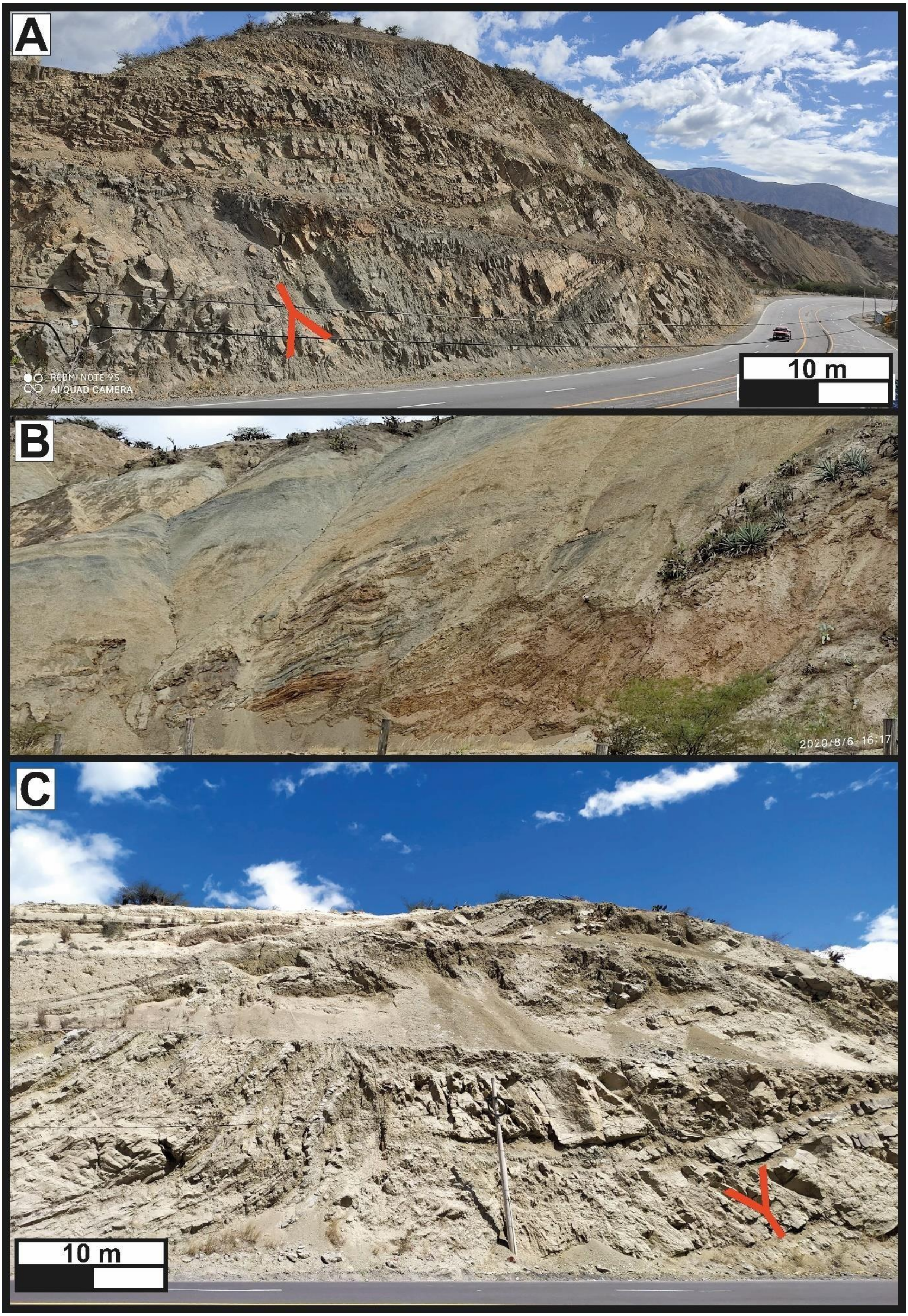


Figure 9. Chota Fm. A) Sandstone section of Chota Fm. upright sequences. B) Claystone and siltstone section of Chota Fm. Central deformed part of the recumbent fold, in this part are located the chevron

folds. C) Sandstone section of Chota Fm. overturned sequences. The polarity symbol indicates stratigraphic up. All the photographs have an E-W orientation.

This section comprises an intercalation of sandstone, mudstone, and shale layers, with a thickness of 48 m, that can be divided into two sequences. The first sequence is represented by the mudstone and shale layers (Figure 10A, D). The sediments of this sequence are bioturbated. It is possible to find fossils of plants like leaves and stems, and there are abundant animal fossils such as bivalves (Figure 10B). The sequence of shales is divided into an upper interval that is folded on a broad scale, and a lower section that is penetratively deformed by small folds controlled by local minor faults and buckling in the core of the larger anticline (Figure 10E). Both sections are separated by a fault. On the other hand, the second sequence is characterized by thick bioturbated and cross-laminated sandstone layers (Figure 10C). The lahar deposit that limits our study area is filling a paleo-valley, and in outcrops, the paleo-valley walls that were eroded into the Chota Fm rocks are still preserved (Figure 6).

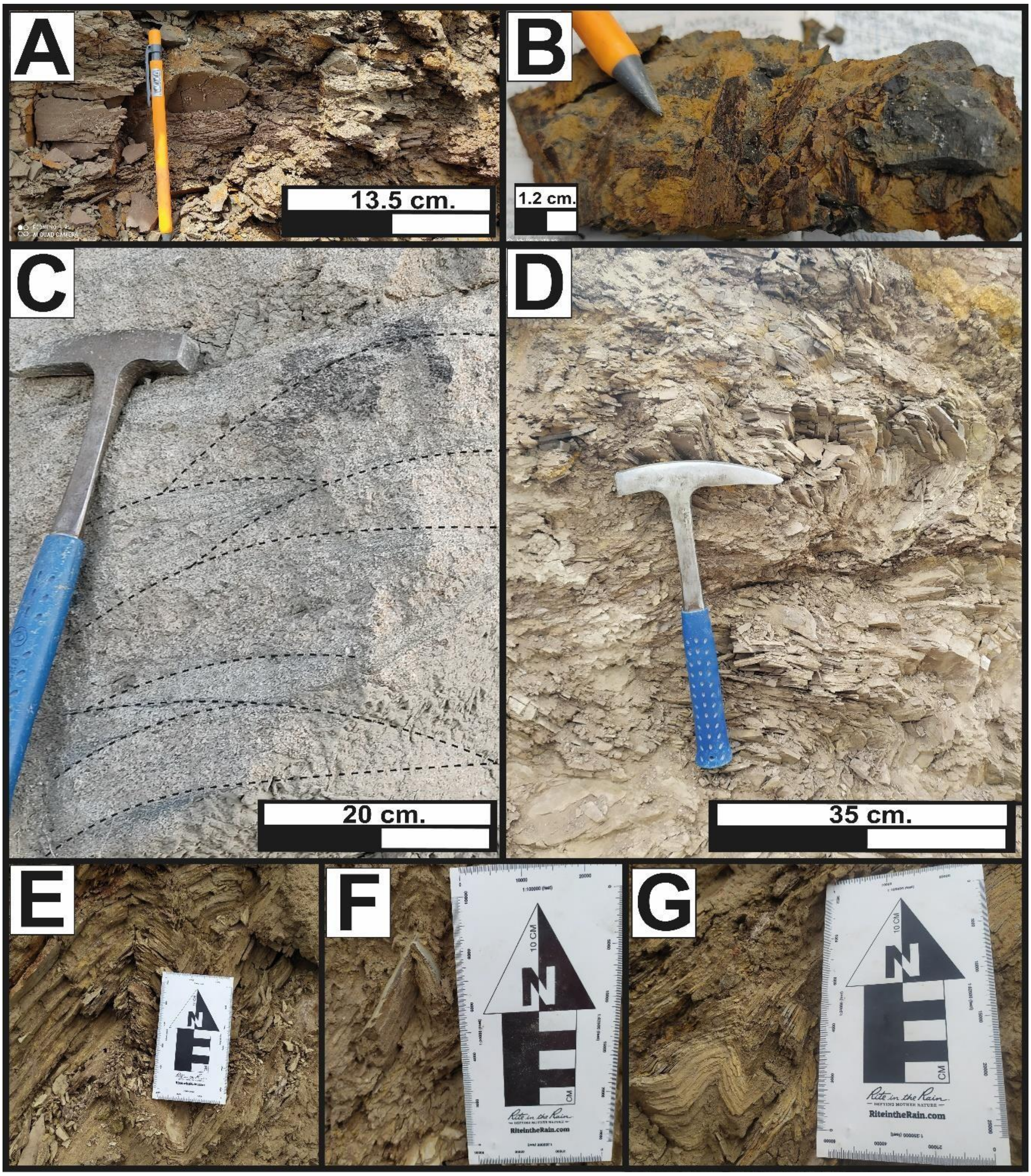


Figure 10. A) Shales of the Chota Fm. B) Bioturbation found in the shales of Chota Fm. C) Cross-laminated sandstone, overturned layer. D) Deformed shales in the Chota Fm. E, F, G) Chevron folds from the buckled shale section.

4.1.3. Peñas Coloradas Formation.

The Peñas Coloradas Fm., the main focus of this study, is located at the east of the Chota basin (Figure 6). This formation is found in fault contact with the Chota Fm at the northwestern - central part of the basin and with the metamorphic basement at its southern end. The formation is also in depositional contact with the basement in the southeastern part of the study area (Figure 6). We identified four new members within this unit: the Canales Colorados Member, Brillosas Member, Tabulares Member, and Volcanicas Member, with a total thickness of 413 m. (Figure 7).

4.1.3.1. Canales Colorados Member

The Canales Colorados Member is represented by an intercalation of conglomerates with sandstone and mudstone layers (Figure 11). The sequence begins at the basal unconformity with the metamorphic basement, with a layer of grey breccias composed primarily of metamorphic material. The clasts are angular, poorly sorted, and matrix-supported (Figure 12A). This stratum has a thickness of 20 m. Above this is an alternating package of cross-laminated sandstone layer and conglomerates or breccia deposits of reddish-brown color (Figure 12B). Next, the strata are composed of reddish deposits that alternate sandstone with conglomerate layers, in conformable contact with the previous layer. These deposits are tabular with lateral continuity and form an alternance of sandstone and conglomerate layers with metamorphic well-sorted, rounded clasts. It has a thickness of 15 m. The following layer consists of 6 m of a light green clay with metamorphic clasts (Figure 12C). Subsequently, and with erosive contact, there is a thick sequence of red channels that characterize the entire unit along the study area (Figure 12D). The channels are formed by conglomerates of rounded, metamorphic, poorly sorted clasts and have a thickness of 25 m. At the top of the unit, there is a layer of grey breccia deposits with angular metamorphic, poorly sorted clasts.

Figure 11. General view of a section of the Peñas Coloradas Fm., it is possible to identify the alternating sandstone with conglomerates, channelized deposits, and the grey breccia deposits.

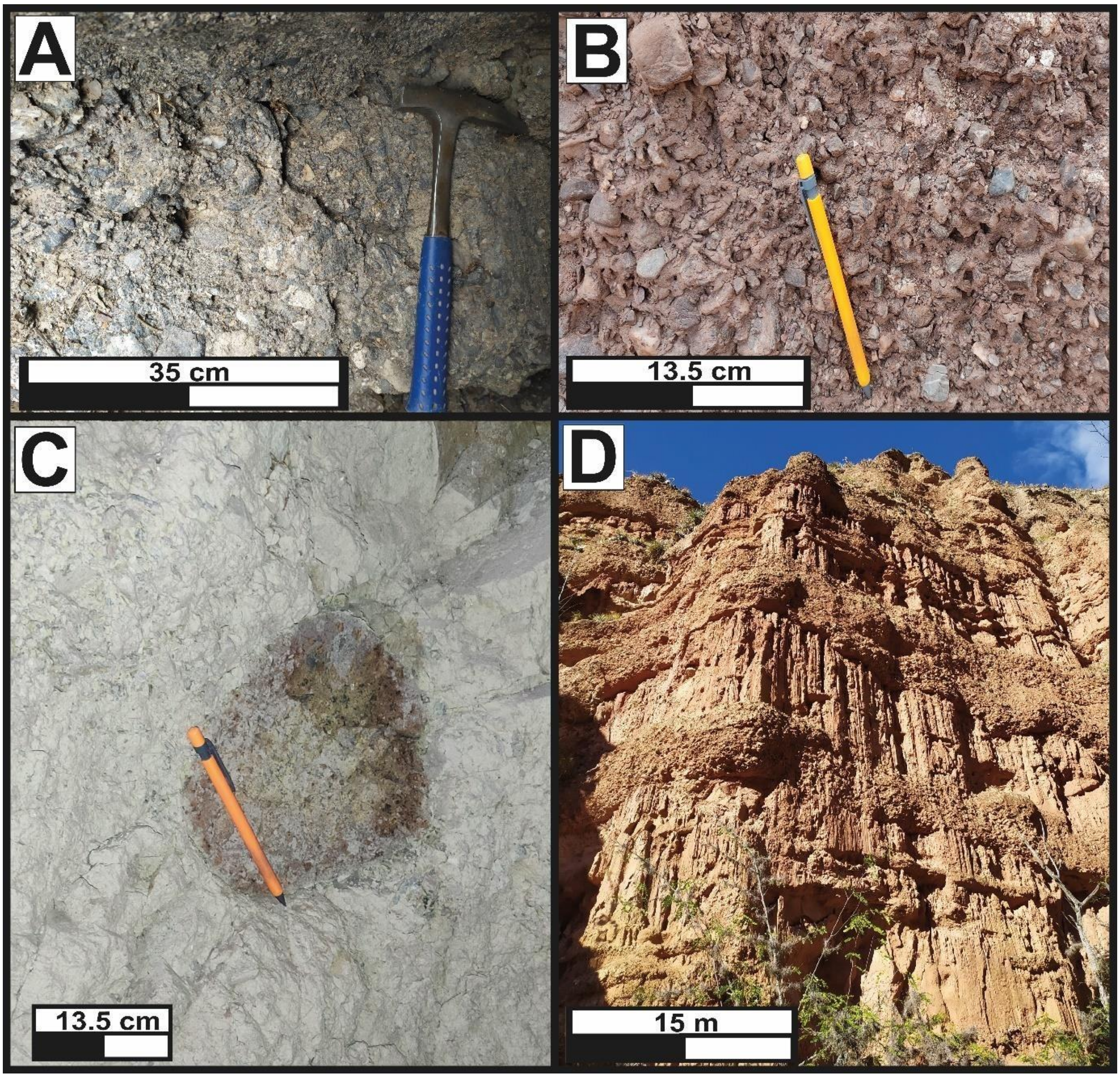
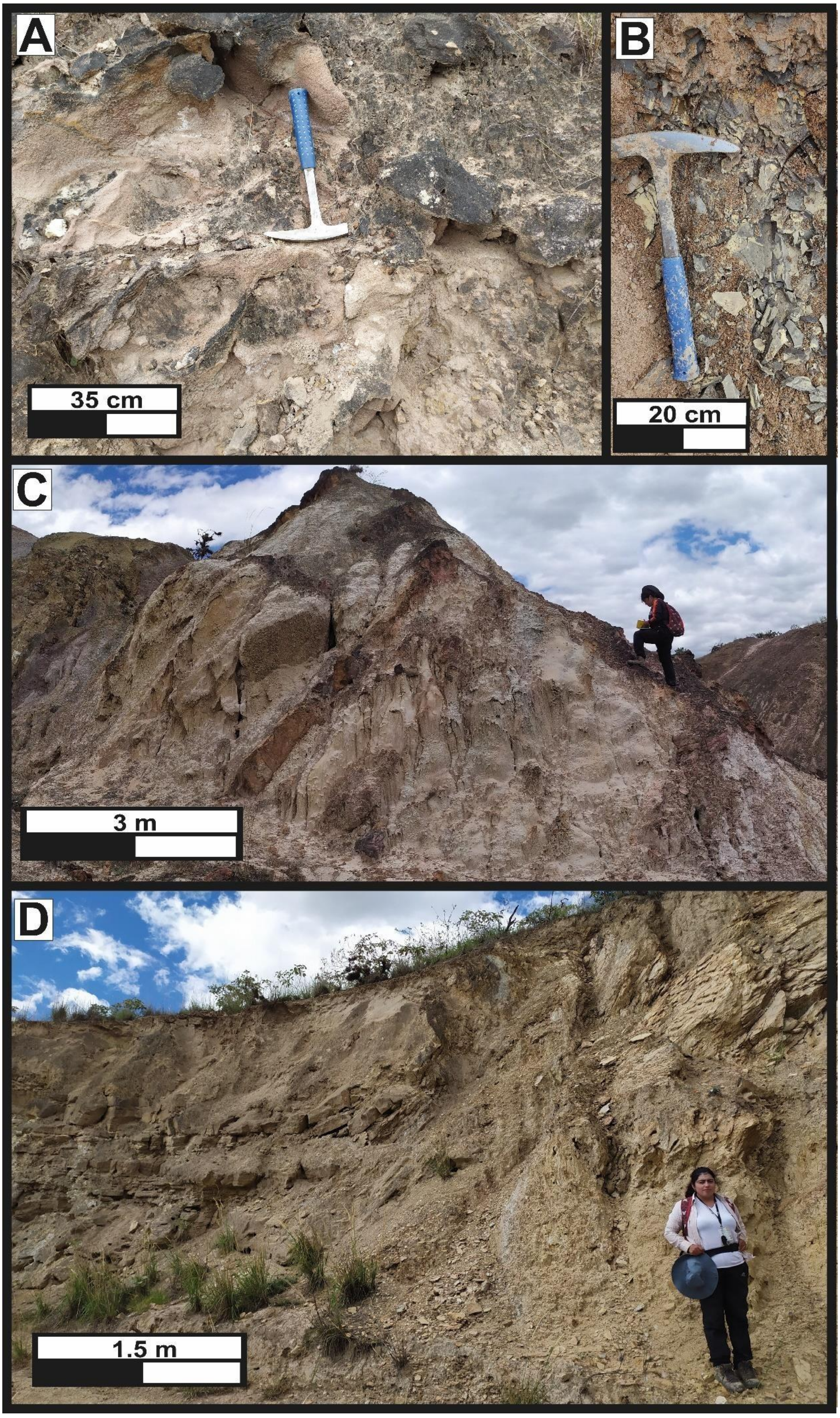


Figure 12. A) Basal grey conglomerates of the Canales Colorados Member. B) Reddish breccia deposits that overlie rocks of A). C) Green claystone layer that overlies rocks of B). D) Channelized layer of red conglomerates and sandstones that overlie C).

4.1.3.2. Brillsas Member.

This unit is conformed mainly by sandstones characterized by their high content of micas, which gives them a shiny appearance. It was found in depositional contact and overlying the Canales Colorados Member. The sequence has a total thickness of 146 m; it presents five packages of sandstone and claystone. The first one is composed of a very fine pink to ocher cross-laminated sandstone layer (Figure 13A). The next is formed by bioturbated claystone, with fossils of plants and deformed by faults and local folds (Figure 13B). The third one consists of a package of very fine pink to ocher cross-laminated sandstone layers (Figure 13C). Subsequently, there is an alternance of very fine to fine sandstone and packages of claystone with fossil content (~100 m of thickness) (Figure 13D, E, G). And finally, there is a sequence of very fine to fine sandstone.


A
35 cm
B
20 cm
C
3 m
D
1.5 m

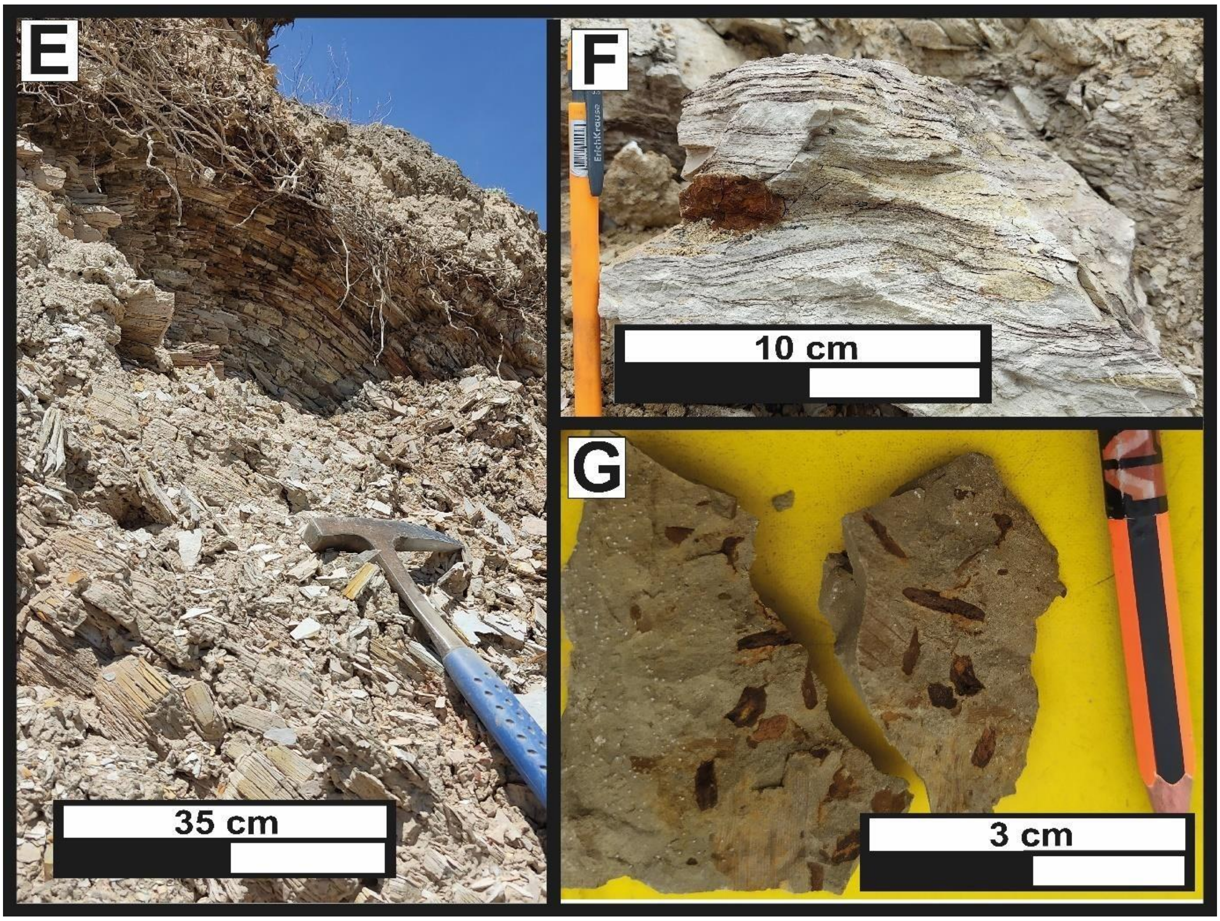


Figure 13. A) First sandstone layer of Brillosas Member. B) Second layer composed of claystone. C) Pink sandstone sequence. D. E) Sandstone and Claystone intercalation of layers. F) Sandstone layer with cross lamination. G) Bioturbated clay material.

4.1.3.3. Tabulares Member.

The Tabulares Member has a thickness of 67 m (Figure 14A). It consists of a sequence of 5 layers, mainly composed of tabular layers of sandstone. The first layer represents a poorly sorted, matrix-supported conglomerate with metamorphic and sedimentary clasts. The second one is alternating strata composed of clay to silt grain size material and very fine sand cross-laminated beds. The following one consists of an alternance of 8 layers between fine to medium sandstone; the medium-grained sandstone presents a reddish coloration and is more consolidated than the fine-grained sandstone, which is yellowish colored. Next, there is a layer of breccia deposits with metamorphic, sedimentary, and volcanic clasts. Those are poorly sorted, angular clasts, matrix-supported with erosive basal contact. The last stratum in the section consists of reddish-pink, very fine to fine-grained massive sandstone. Those layers show cross lamination, and erosive contacts between them (Figure 14B. C).

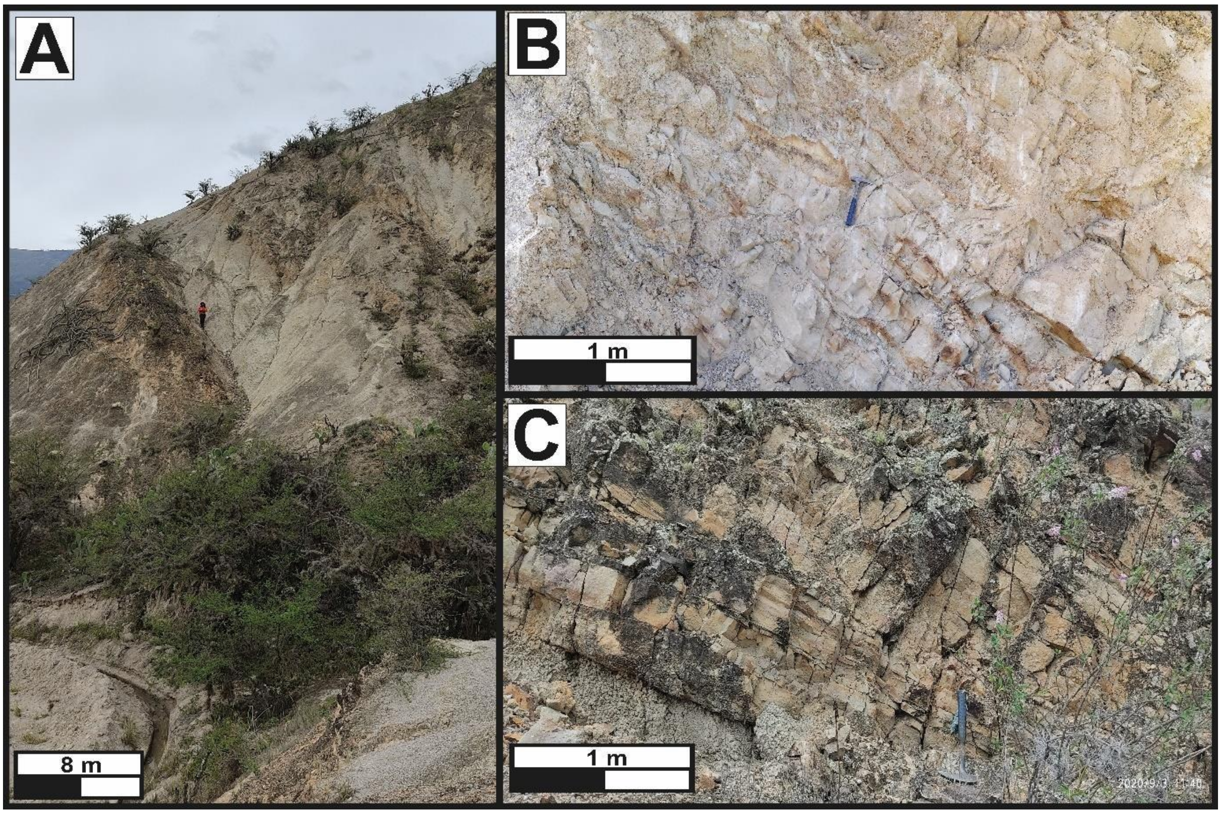


Figure 14. A) Tabulares Member, alternance of sandstone layers. B. C) Sandstone layers, with internal stratification and fractures.

4.1.3.4. Volcanicas Member.

The Volcanicas Member consists of alternating sandstone and breccia deposits with high volcanic clast content, and it has a total thickness of 72 m (Figure 15A, B). A group of breccias represent the beginning of the sequence with a poorly sorted, very angular mixture of volcanic and low input of metamorphic clasts (Figure 15C). The sandstone layers are coarse to very coarse grain size, alternating with the breccia deposits that progressively decrease their metamorphic clasts' content and increase volcanic ones (Figure 15D). The contacts between the layers are erosive.

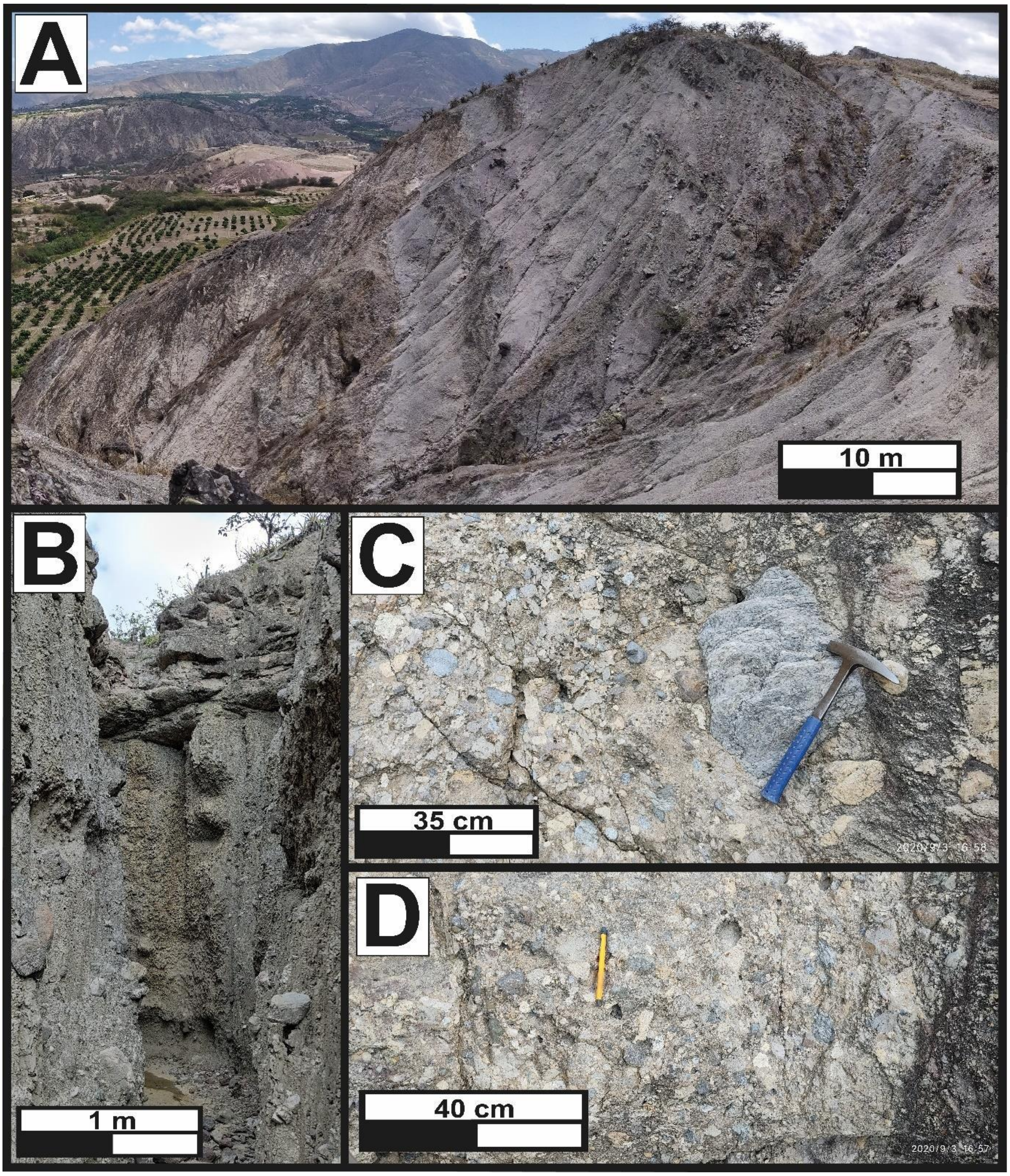


Figure 15. Panormaic view of the Volcanicas Member B) Sequence of breccia deposits of the Volcanicas Member. C) Breccia deposits with metamorphic and volcanic clasts. D) Breccia deposits with mainly volcanic composition

4.1.3.5. Subvolcanic–volcanic deposits.

Located in the Northeast sector of the study area), there are several volcanic intrusions (Figure 6,Figure 7,Figure 16). These intrusions are sills and dykes, located mainly in the Canales Colorados and Brillosas Members. Its most common color is yellow-orange; in general, those are very well consolidated, of varied thickness of metric order.

In the Canales Colorados member, they alter the material, giving a purple color to the surrounding rocks, while, in the Brillosas member, it is possible to find locally overturned beds near two large dykes caused by emplacement-generated stresses. Moreover, the bigger section of these deposits marked in the map, is composed of a pumice material, with metamorphic lithics sourced from nearby basement outcrops and large pieces of volcanic rock.

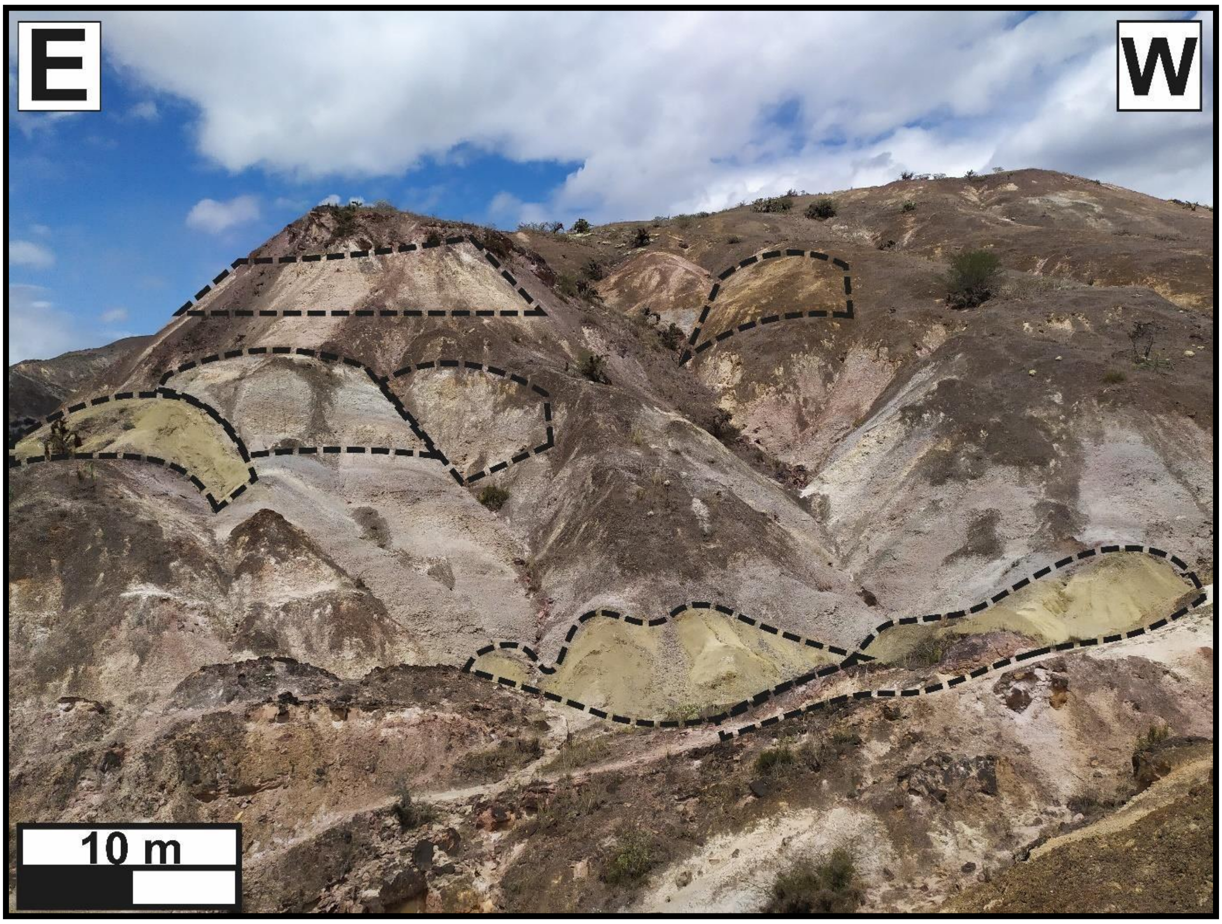


Figure 16. Photograph of the zone of the intrusions. The dotted lines represent the areas where the intrusions are located.

3.2. Structural Geology.

The study area is characterized by five principal faults, and many local minor faults scattered around the study area (Figure 6), many of which have slickensides. The folds are important structures that cut across the formations, there are six principal folds (Figure 6), drag and secondary folds. Additionally, there are joints throughout the entire study area. Below we show the results of our structural analysis.

4.2.1. Faults

The faults documented in the study area affect both basement and sedimentary infill. We only represent the principal faults (1, 2, 3, 4, 5 in Figure 6). The first fault (Fault 1, Figure 6) is a normal fault that puts in contact the Peñas Coloradas Fm with the metamorphic basement at the Southeast part of the study area (Figure 17). This fault uplifts the laterized metamorphic rocks to the surface, which we interpret as an ancient paleosurface that shows evidence of weathering that caused the alteration of the metamorphic section.

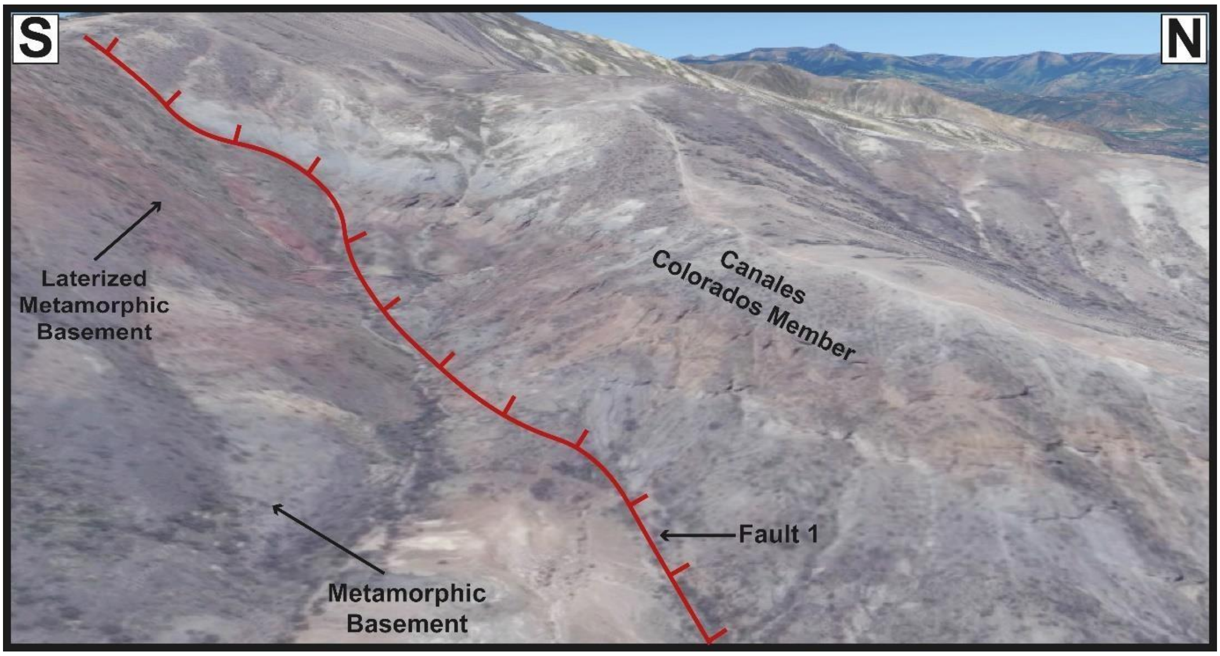


Figure 17. The line represents the Fault 1, contact between metamorphic basement and Canales Colorados Member. Picture taken from Google Earth.

The second fault is located at the east in the study area (Fault 2, Figure 6). This fault again uplifts the metamorphic basement, putting it in contact with the Brillosas Member. The kinematic of the fault is defined as normal, based on based on the evidence of the stratigraphy, where the Canales Colorados and Brillosas members are the hanging wall and the metamorphic basement represent the footwall, exposed by the fault. It dips to the east, forming an antithetic minor fault associated with the synthetic major Fault 1.

The third fault puts the Chota Fm in contact with the Peñas Coloradas Fm at the central northern part of the study area (Fault 3, Figure 6). There, the fault juxtaposes the Brillosas Member over the Chota Fm (Figure 18). The orientation of the fault and the slickensides indicates it has normal-oblique kinematics. The fault zone has a gouge layer of 20 cm in thickness, and the damage zone is extremely fractured, with small scale drag folds.

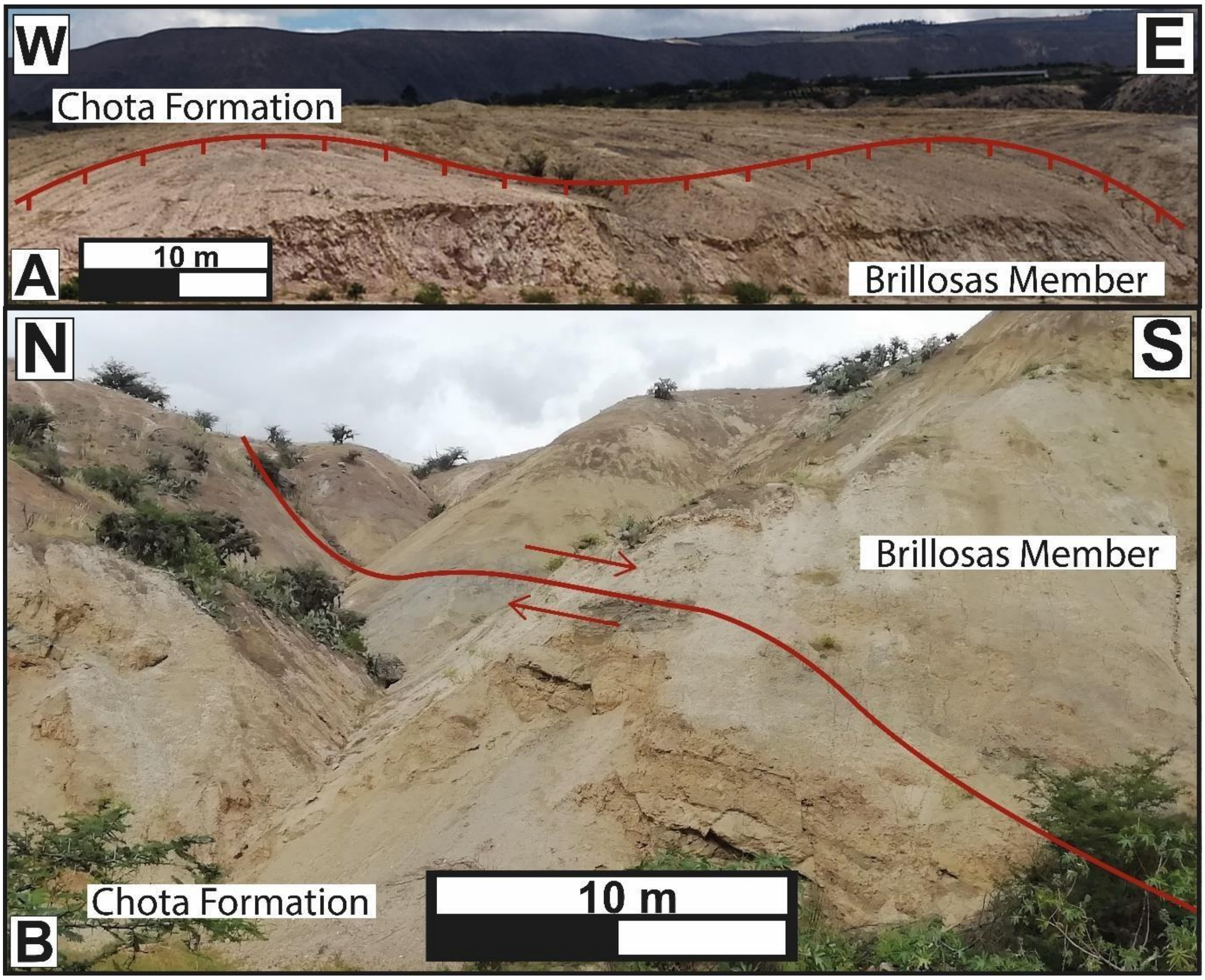


Figure 18. Normal fault that puts in contact the Chota Fm with Peñas Coloradas Fm. A) West-East direction view of the contact between the formations. B) North-South direction view of the contact between the formations.

In the NW part of the study area there is another main normal fault with a NW to SE direction (Fault 4, Figure 6). This fault offsets the contact between the Canales Colorados and Brillosas Members with a right-lateral separation (Figure 6).

Finally, there is a left-lateral strike slip fault (Fault 5, Figure 6) located at the end of the plateau, where the Canales Colorados Member is offset to the western part of the plateau.

In addition to these faults, throughout the basin, there are local minor faults that are not large enough to represent on the geologic map (Figure 19). These minor faults can be identified by gouge zones, folded and fractured material, and kinematic indicators. Various measurements of fault and slip (slickensides) orientations were taken when possible.

Figure 20 shows the faults measurements from both formations. The mean orientations of the faults were calculated using the Fisher mean vector of the fault poles. The mean pole orientation for all the faults is 185°/87°. The mean pole orientation of the Chota Fm faults is 294°/80° (Figure 20C). The mean pole orientation of the Peñas Coloradas Fm faults is 280°/81° (Figure 20D).

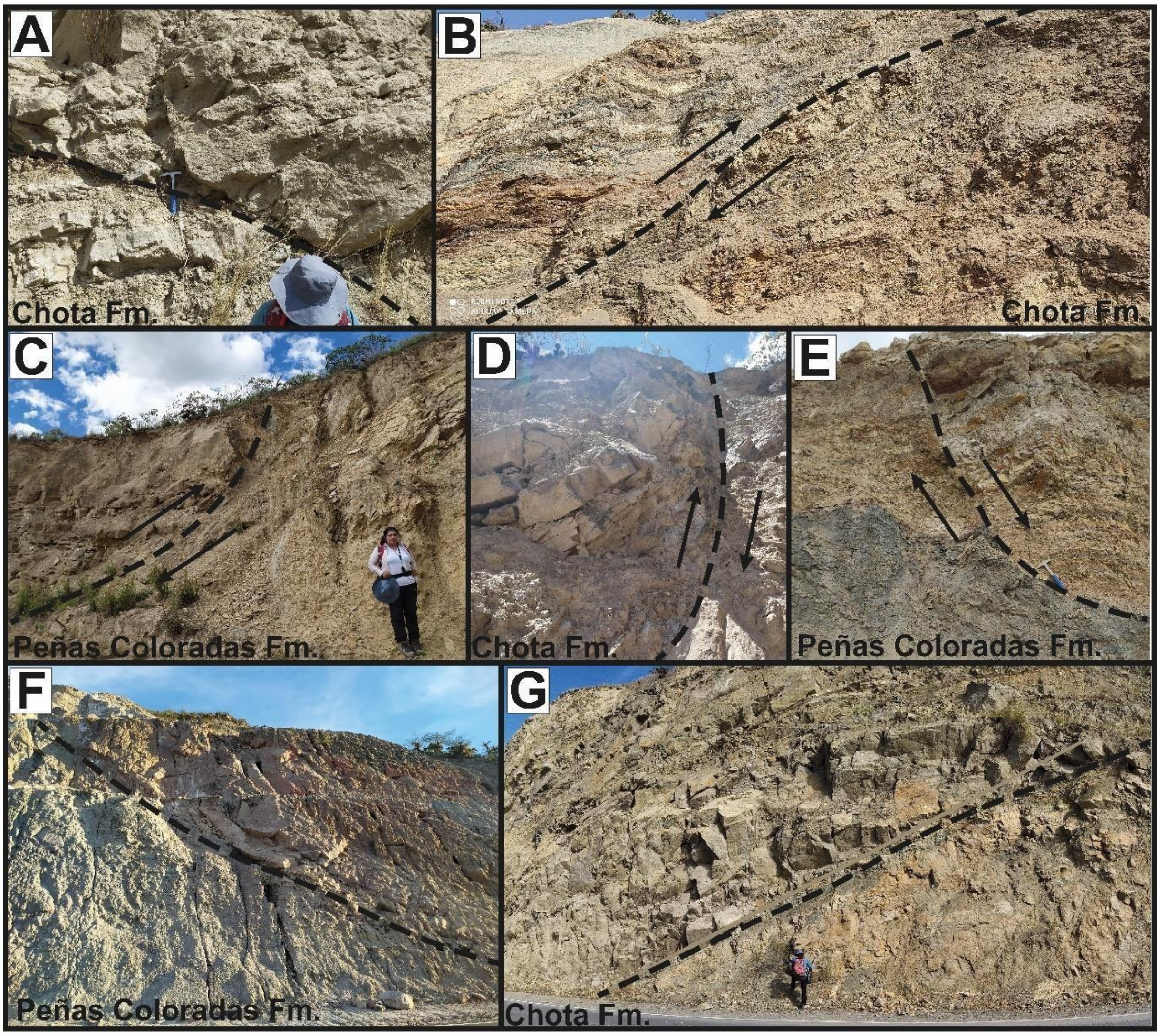


Figure 19. Photographs of the different local minor faults. A, B, D, G are faults in the Chota Fm. C, E, F are faults in the Peñas Coloradas Fm. in the Brillosas and Canales Colorados members.

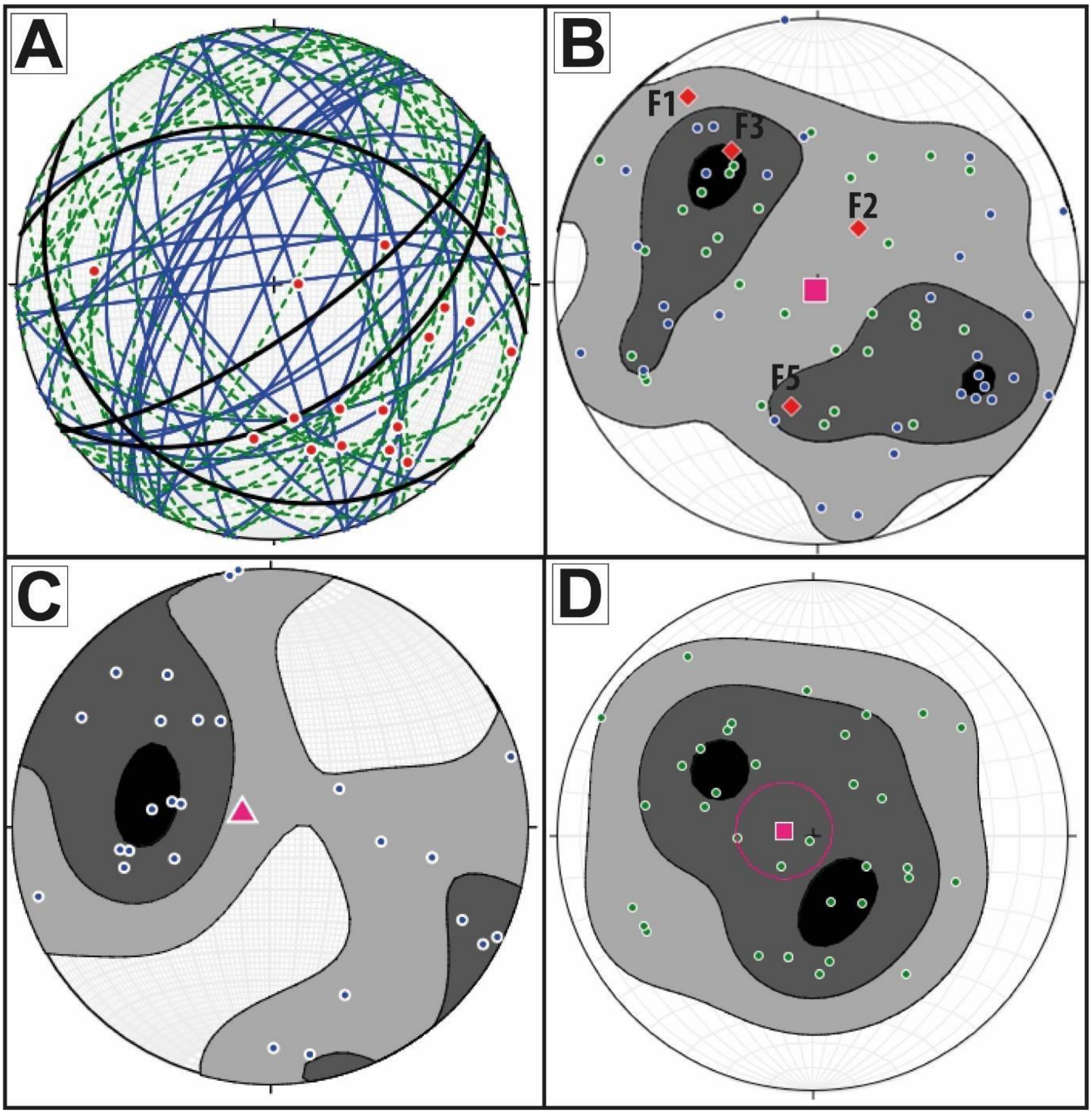


Figure 20. A) Stereonet projection of faults measured (n=68) with the slickensides measured (red points) (n=17); the green dashed lines represent the planes of the faults from Peñas Coloradas Fm.; the blue lines are the planes from the Chota Fm.; the black lines are the four principal faults of Figure 6 B) Poles of faults measured in the study area; diamond forms are the poles of the principal faults of Figure 6. The numbers correspond to the faults numbered in Figure 6. C) Stereonet of the poles to the fault measurements of the Chota Fm. D) Stereonet of the poles to the fault measurement in the Peñas Coloradas Fm. Blue points are the poles of the Chota faults. The green points are the poles of the Peñas Coloradas Fm faults. The pink squares and triangle represent the Fisher mean vector and the small circle is the 95% confidence interval. Contours obtained with the Kamb method (Kamb, 1959), with 2 sigma contour intervals. All stereonets are plotted on a lower hemisphere, equal-area stereonet projection.

Furthermore, we applied a fold test for the faults in order to observe if the dispersion of the data increased or decreased due to folding. To do this we rotate each fault so that the bedding of the location where it was measured returns to horizontal. Figure 21A indicates the fold test of the Chota Fm faults, where the new mean vector is

124°/63°, and Figure 21B indicates the fold test for the Peñas Coloradas Fm with a mean vector of 226°/57°. The fold test solution shows a more dispersed data after the unfolding, suggesting that the faults were formed after the folding process.

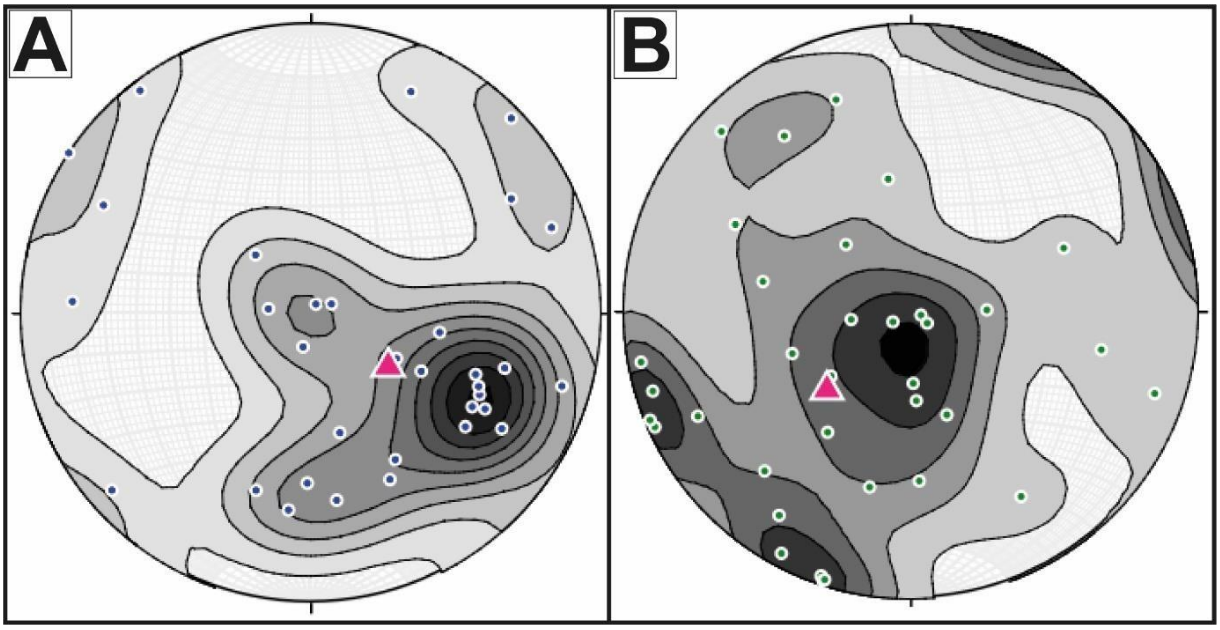


Figure 21. A) Stereonet of fold test of the faults of the Chota Fm B) Stereonet of fold test of the faults of the Peñas Coloradas Fm. Blue points are the poles of the Chota faults. The green points are the poles of the Peñas Coloradas Fm faults. The pink triangles represent the Fisher mean vector. Contours obtained with the Kamb method (Kamb, 1959), with 1 sigma contour intervals. All stereonets are plotted on a lower hemisphere, equal-area stereonet projection.

We calculated a paleo-stress inversion using the Faultkin program (Allmendinger, R. W., Cardozo, N., and Fisher, D.) using the fault and slickenside orientation data. The resulting fault plane solutions indicate the location of the extensional and compressional quadrants as well as of the pressure (P) and tension (T) axes. These axes are kinematic in nature, represent the principal axes of a fault, and provide the extension and compression direction (Begg and Gray, 2002). The tangent lineations are represented by the arrows plotted in the movement plane, showing the movement of the hanging wall block. (Twiss and Gefell, 1990; Twiss et al., 1991).

Even though there is uncertainty related to the exact location of the principal stresses within the compression and extension quadrants (McKenzie et al., 1969; Lisle et al.,1992), to facilitate the characterization of the stress field, here we will assume that the P axis corresponds to maximum principal stress ($\sigma 1$), and the T axis corresponds to the minimum principal stress ($\sigma 3$). Figure 22A shows the results from inverting the data from all the fault measurements in both formations where $\sigma 1$ = 042°/57°, $\sigma 2$ =

138/04 and σ3 =231°/32°. Figure 22B represents the inversion of the fault measurements only from the Peñas Coloradas Fm., where σ1 = 022°/51°, σ2 = 113°/01° and σ3 =203°/38°. Figure 22C represents the inversion of the fault measurements only from the Chota Fm., where σ1 = 039°/41°, σ2 = 301°/09° and σ3 =201°/46°. Finally, Figure 22D represent the inversion of the fault measurements only from that ones that was possible measure slickensides, where σ1 = 110°/42°, σ2 = 248°/39° and σ3 =358°/22°.

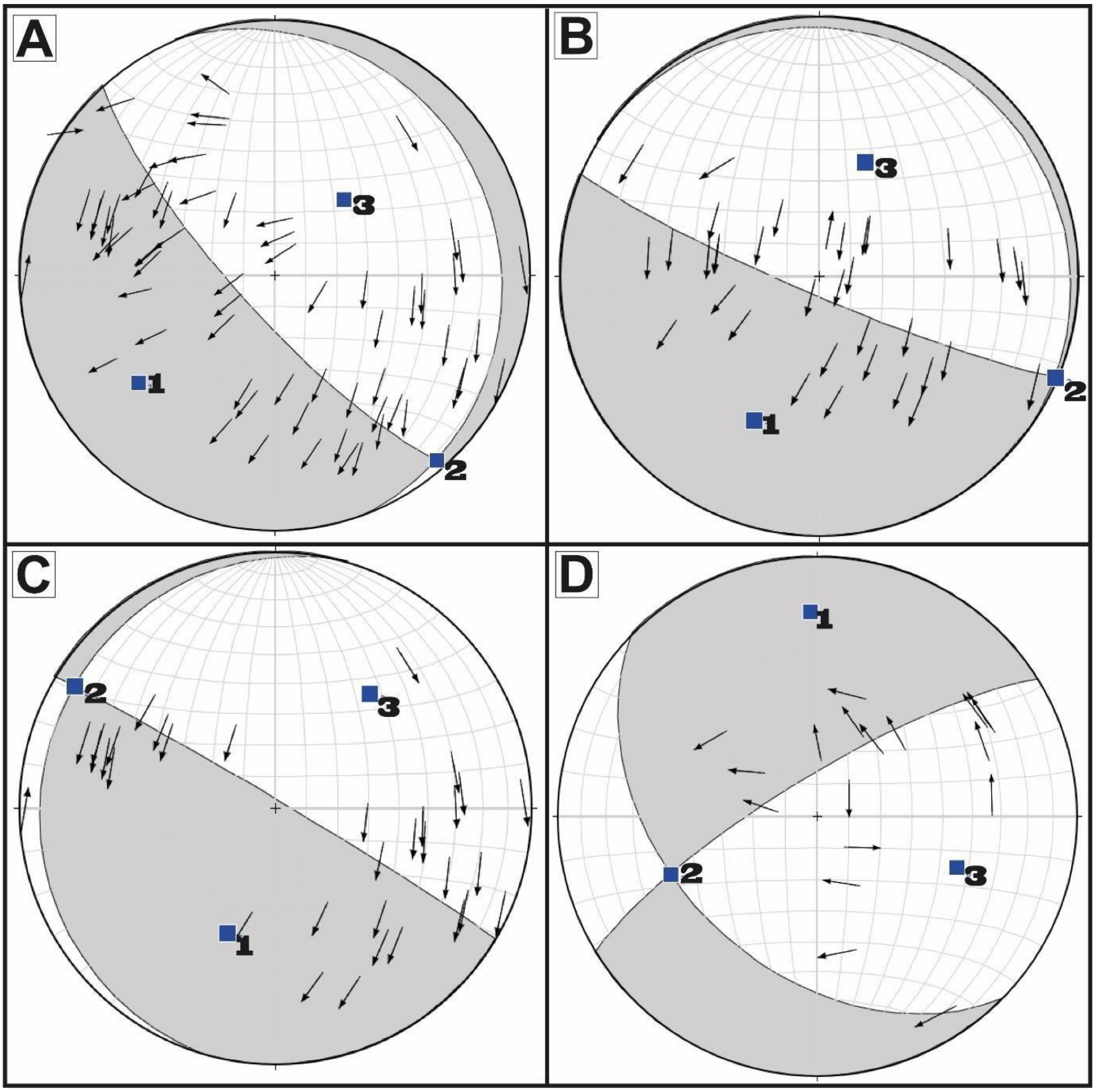


Figure 22. A) Stress inversion results obtained from 68 faults. B) Faultkin results obtained from the Peñas Coloradas Fm faults (n=35). C) Faultkin results obtained from the Chota Fm faults (n=33). These are Fault plane solutions, the blue squares and numbers represent the orientations of the principal stresses where P = 3, and T=1. The arrows show the tangent lineations of each measurement.

4.2.2. Folds

Folds are important structures in the Chota basin that are found throughout the study area and define the overall outcrop pattern. There are three large folds, two of them in the Peñas Coloradas Fm (Fold A and B, Figure 6), and the other one in the Chota Fm (Fold C, Figure 6) as well as some parasitic, minor folds.

The fold in the Chota Fm (Figure 23,Figure 24 A) is a west-verging recumbent anticline. The outer arc of the fold is defined by the thick sandstone beds of the upper Chota Fm section, while the core of the fold is formed by claystone and shale deposits that are extremely deformed, forming layers with chevron folds of approximately 15 cm of amplitude. The deformed fine-grained section is separated by a fault from an upper shale section that is folded on the same wavelength as the sandstones. The sandstone layers are very jointed with many small-scale faults, and occasionally have subsidiary folds characterized by the presence of polarity indicators that indicate overturned layers (Figure 10C).

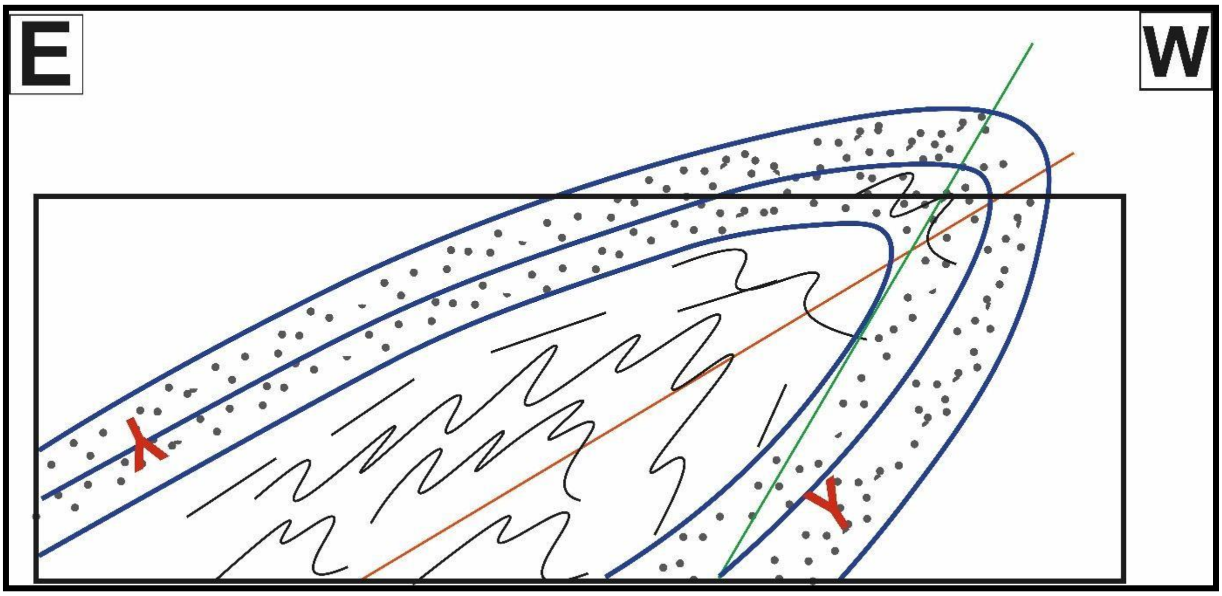


Figure 23. Schematic picture of the recumbent fold of the Chota Fm. The rectangle represents the outcrop seen in the field. The blue lines represent the sandstone sequences with its respective polarity symbol in red. The central part of the fold is completely deformed and with the presence of small-scale chevron folds. The red line indicates the axial plane. The green line represents a large-scale fault that cuts the outcrop.

The orientation of the recumbent anticline hingeline is 05°/161°, and of the axial plane is 030°/07°. The pole of the axial plane is 83°/300° (Figure 24B), the trend of which represents the direction of compression that formed the fold (if plain strain is assumed).

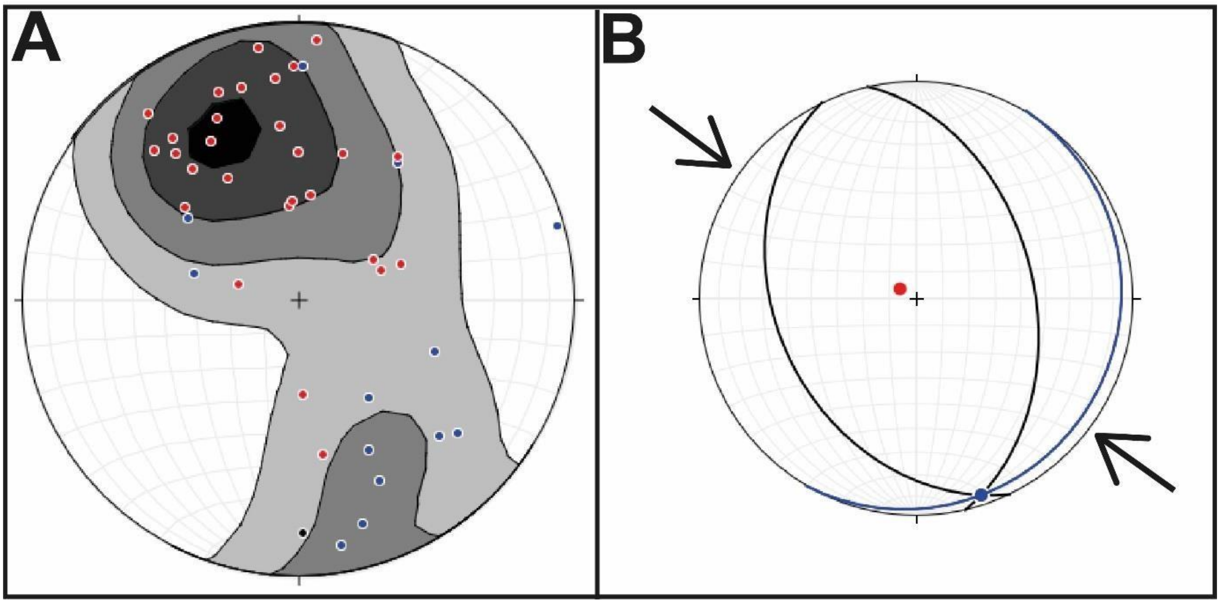


Figure 24. A) Stereonet of Fold C. of the Chota Fm (n=42), representation of the poles; the red points are the poles of the upright limbs of the fold; the blue points are the poles of the overturned limbs of the fold. Contours obtained with the Kamb method (Kamb, 1959), with 2 sigma contour intervals. B) Representation of the axial plane of the fold (blue line), and the pole of this axial plane (red point); the blue point is the hinge line of the fold. The arrows indicate the σ_{Hmax}.

We can also infer the direction of compression from the small-scale chevron folds in the core of the fold. Figure 25A represents the stereonet for the measurement of 30 pairs of limbs of these chevron folds. The mean vector for the poles of the W-dipping limbs is 121°/79°, and 316°/55° for the poles of the E-dipping limbs. We calculate the planes to these mean orientations to obtain the mean axial plane 227°/78° and hinge line 02°/223° of the folds. The pole of the axial plane has an orientation of 11°/132° representing the principal stress for these folds, which represents the direction of the principal compressive stress that formed the folds if plane strain is assumed (Figure 25B).

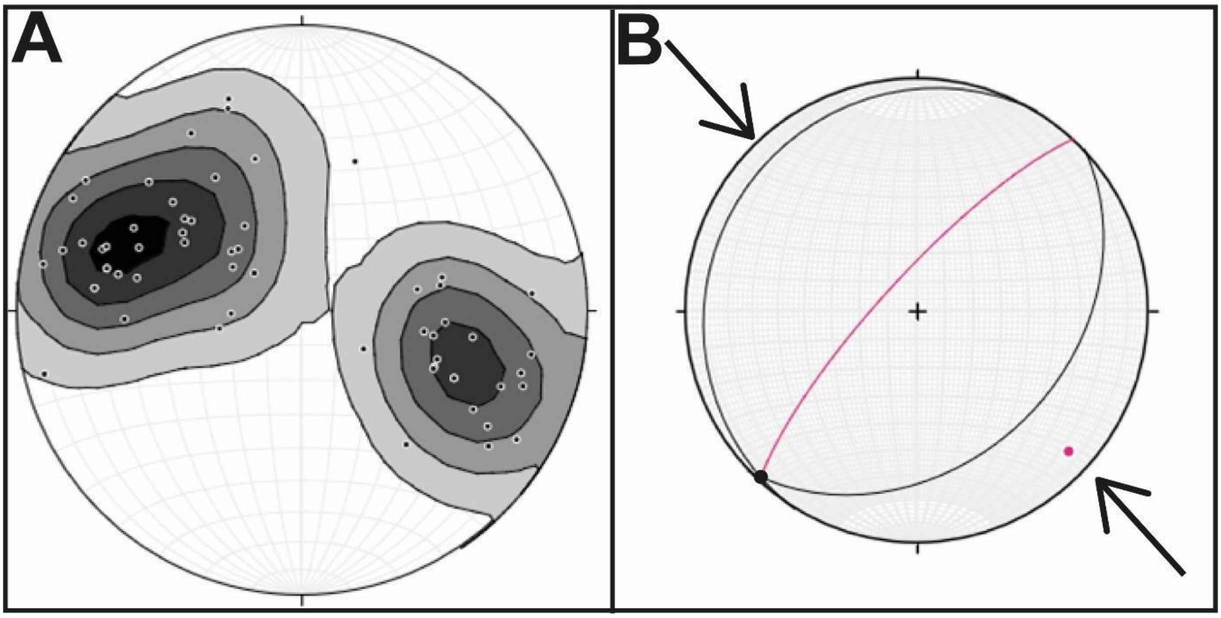


Figure 25. A) Stereonets of the chevron folds of the Chota Fm (n=30). Contours obtained with the Kamb method (Kamb, 1959), with 2 sigma contour intervals. C) Stereonet of the planes to the fold, the pink line is the axial plane of the folds, and the pink point is the pole to the axial plane, that represents the mean direction of the stress = 11°/132; the black point is the hinge line.

The style of folding in the Peñas Coloradas Fm is different, and it is affected by a syncline (Fold A, Figure 6) and anticline (Fold B, Figure 6) with a SW-NE fold axis direction. The folds are large structures (wavelength ~ 800 m) not visible at an outcrop scale, but dip measurements and panoramic views of the study area corroborate it. The two main folds are continuous and doubly-plunging, verging to the SE; the plunge of the hinge is visible, and forms the aspect of a bowl in the zone of the Volcanicas Member to the south of the study area. Additionally, there are some secondary folds that are well exposed in the Tabulares and Volcanicas Members, with a SE to NW direction (Folds D, E, F; Figure 6).

Figure 26A shows the bedding measurements of the principal folds (A & B) that yield an axial plane orientation of 232°/13°, which has a pole orientation of 77°/142°. This yields a compressive stress direction of 142°. Figure 26B indicates the measurements of bedding for the secondary folds that yields an axial plane orientation of 132°/12°, and principal stress directions of 77°/042°.

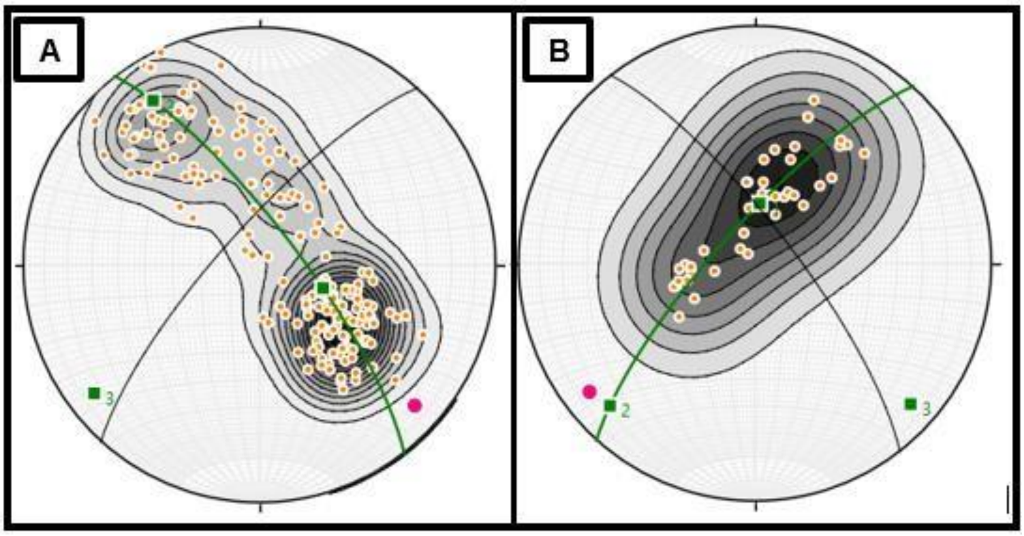


Figure 26. A) Stereonet of Fold 1 and fold 2 of the Peñas Coloradas Fm. Contours obtained with the Kamb method (Kamb, 1959), with 2 sigma contour intervals. B) Stereonet of secondary folds of Peñas Coloradas Fm. Contours obtained with the Kamb method (Kamb, 1959), with 2 sigma contour intervals. The black lines represent the axial planes of the folds. And the green lines represent the Best fit great circles. The pink dots are the poles to the axial planes, which represent the direction of the principal stresses of each fold.

4.2.3. Fractures

Another important and abundant structural feature are joints. These are widespread throughout the study area. The fractures are planar, and there are consistent truncations of one fracture direction against another with no shear between them. In the Peñas Coloradas Fm, they are commonly found in the more resistant lithologies such as the Tabulares Member sandstone beds (Figure 27). These joints have a preferred orientation of 77°/106° (Figure 28). Furthermore, in the Chota Fm, the joints are also found in the sandstone layers where they have a preferred orientation of 65°/100° (Figure 29A), additionally, we divide the data into two clusters where the data that dips to the west has a preferred orientation of 47°/066° (Figure 29B), and the data that dips to the south has a preferred orientation of 67°/157° (Figure 29C).

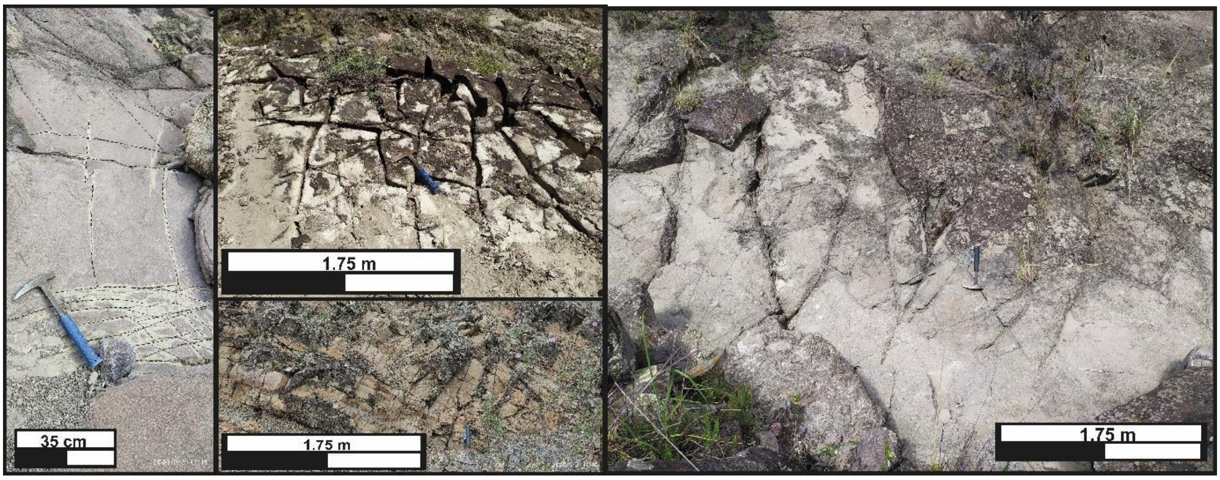


Figure 27. Photographs of joints in the field.

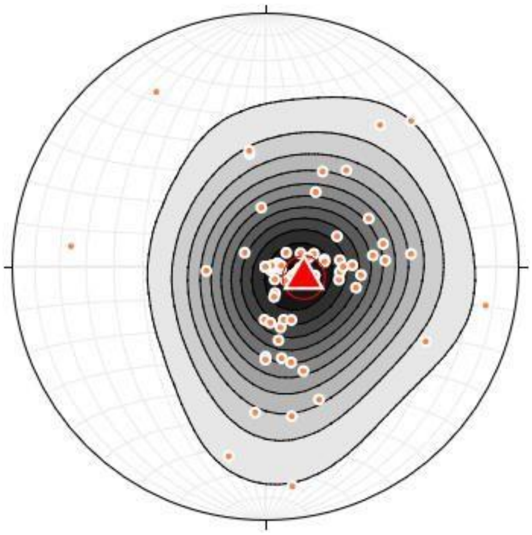


Figure 28. Stereonet representation of the joint's measurements in Peñas Coloradas Fm (n=68). The triangle represents the mean vector. Contours obtained with the Kamb method (Kamb, 1959), with 3 sigma contour intervals.

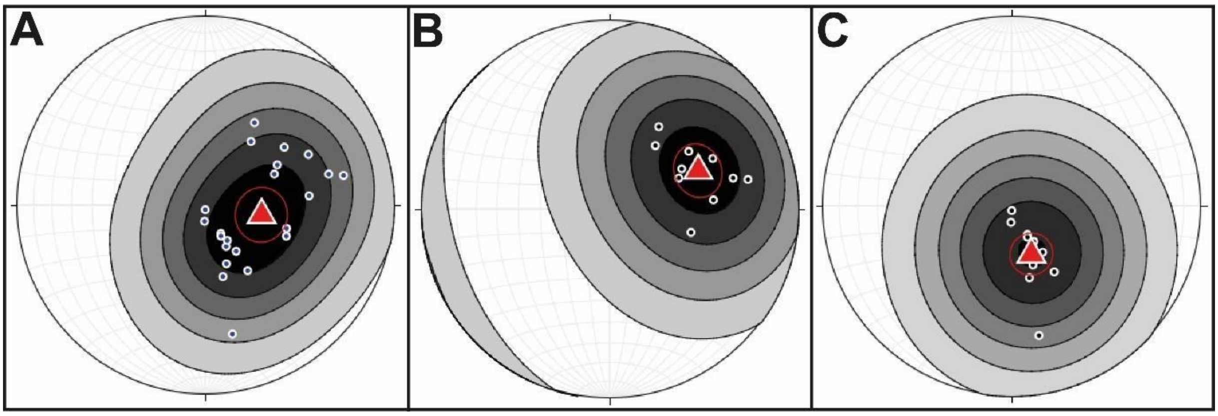


Figure 29. A) Stereonet representation of the joint's measurements in The Chota Fm (n=22). B) Stereonet representation of the joints that dip to the west in Chota Fm. C) Stereonet representation of

the joints that dip to the south in Chota Fm. The triangles represent the mean vectors. Contours obtained with the Kamb method (Kamb, 1959), with 3 sigma contour intervals.

4.2.4. Structural Cross Section

The field observations described above are summarized in the geological map (Figure 6) and the structural cross section (Figure 30) that shows the subsurface geology in the study area. The geological map shows the location of the section. Surface data was extrapolated to the subsurface using stratigraphic thickness and measured attitudes (Figure 30).

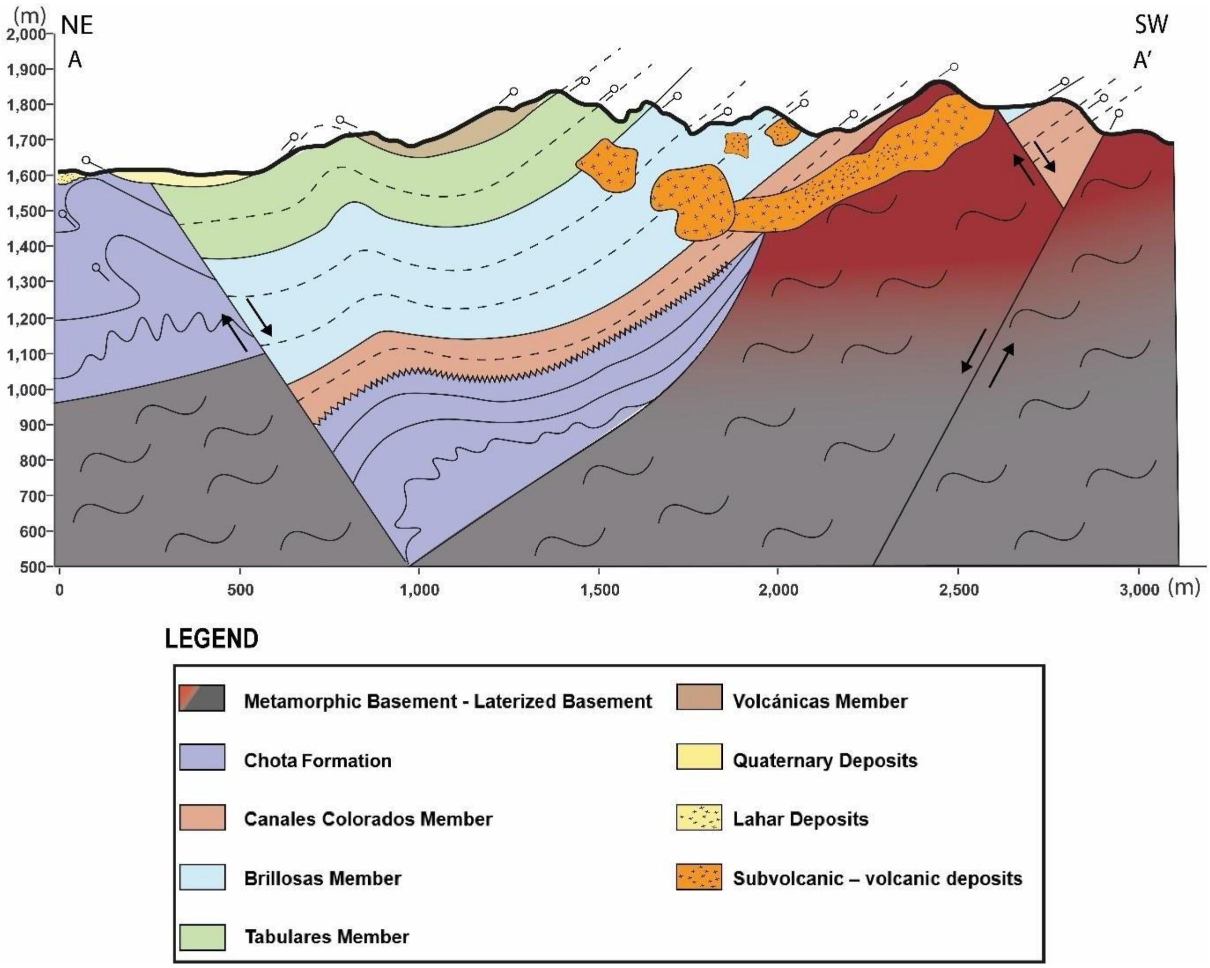


Figure 30. Structural Cross section of the study area. The location of the profile can be seen in Figure 6.

IV. DISCUSSION

4.1. Stratigraphy of the Peñas Coloradas Fm. and Chota Fm.

The lithologies found in the studied area are conformed primarily by the metamorphic basement and clastic lithologies from claystone and mudstone to sandstone and conglomerates. At the beginning of the work, we stated the differences between the stratigraphic model presented by Barragan et al. (1996) and Winkler et al. (2005). Barragán et al. (1996) indicate a stratigraphic sequence classified into four principal units that are from base to top: Chota Unit, Santa Rosa Unit, Peñas Coloradas Unit, and Carpuela Unit. On the other hand, Winkler et al. (2005) propose a stratigraphic sequence composed of three formations, that are, from base to top: Peñas Coloradas Fm, Chota Fm, and Santa Rosa Fm. Winkler et al. (2005) defined this sequence based on the Chota basin's chronostratigraphic framework. The predicament is if the Chota Fm predates or not the Peñas Coloradas Fm.

The fieldwork carried out allows the analysis of the rocks and structures of the study area, composed of the Chota and Peñas Coloradas formations. The studied sequences of the Chota Fm are not enough to subdivide it into new members, nevertheless, it is possible to identify two dominant lithologies, the sandstone and claystone layers; each developed in a specific and different environment.

In contrast, the Peñas Coloradas Fm is well exposed and the principal focus of study. We divide it into four new members from base to top: Canales Colorados, Brillosas, Tabulares, and Volcanicas Members. Different lithologies characterize each member. The Canales Colorados Mbr is composed of sequences of conglomerates and breccia deposits with high input of metamorphic clasts. The Brillosas Mbr represents a sequence of sandstones with high content of micas and alternating layers of claystone. The Tabulares Mbr consist of an alternance of different grain sizes and grade of consolidation of tabular sandstone layers. The Volcanicas Mbr are breccia deposits with high content of volcanic clasts. Finally, there are volcanic intrusions along the Canales Colorados and Brillosas Members, to the east of the study area, which is characterized by its high content of pumice (Figure 6). The previous studies presented geological maps showing the Peñas Coloradas Fm as a thick, single unit composed of conglomerates (Figure 5). However, we show that the Peñas Coloradas Fm stratigraphy is more complex and has varied lithologies.

Equally important is to define the stratigraphic relation of the deposits. We describe the following stratigraphic sequence (from base to top): metamorphic basement, Chota Fm, and Peñas Coloradas Fm. The Peñas Coloradas Fm is filling a paleo relief putting this formation in depositional contact with the metamorphic basement at the east, but also in fault contact with the same basement and the Chota Fm at the northwest part of the study area.

4.2. Structural geology of the study area.

The analysis of the faults measurements in the area shows that there is not a single preferred orientation of the faults. Figure 20 shows the stereonets results of the measurements of the faults of each unit. Figure 20C represents the measurements of the Chota Fm faults, and Figure 20D represents the measurement of the Peñas Coloradas Fm faults. Comparing these results, both datasets have 2 weak clusters of faults with SE and NW dips, but the Chota Fm has greater dispersion, and the clusters are more shallowly dipping. Additionally, the paleo-stress inversion gives us a clue of the stress state for a given fault populations. Figure 22A shows us the paleo-stress state of all the faults, Figure 22B for the faults from Peñas Coloradas Fm, Figure 22C for the faults of Chota Fm and Figure 22D for the faults with the slickensides measurements. This figure shows the most recent stress status, due to we assume based on the results of the fold test (Figure 21), that the faults were formed after the folding process. The different tension and pressure axes have similar orientations, and the tangent lineations also show similar patterns of movement, indicating a combination of strike-slip and normal motion.

The folds of the study area also show important results. We define a completely different style of folding from what Barragán et al. (1996) defined in his work in the studied area (Figure 5 vs Figure 6). A recumbent fold deforms the sediments of the Chota Fm (Figure 23, Figure 24). At the east of the Chota Fm outcrop, the sandstone layers have cross laminations, bioturbation, flute cast, groove cast, and erosive contacts, all of which are consistent with upright beds. The western part of the formation comprises the same sandstone layers, with the same internal structures that the ones at the eastern part, but the sedimentary structures clearly indicate that the layers are overturned in the forelimb of the large recumbent fold. The central part of the fold is highly deformed with faults and small-scale chevron folds (Figure 25).

On the other hand, sedimentary structures of the Peñas Coloradas Fm shows that the beds are upright. There are locally overturned beds in the Brillosas Mbr adjacent to large dikes, but we interpret this to be generated by the volcanic intrusion in the area. This shows that the intensity of folding of the Peñas Coloradas Fm is less than that of the Chota Fm.

In spite of the difference in folding style, the stresses that formed the folds in the Chota and Peñas Coloradas Fms have similar orientations (Figure 31).

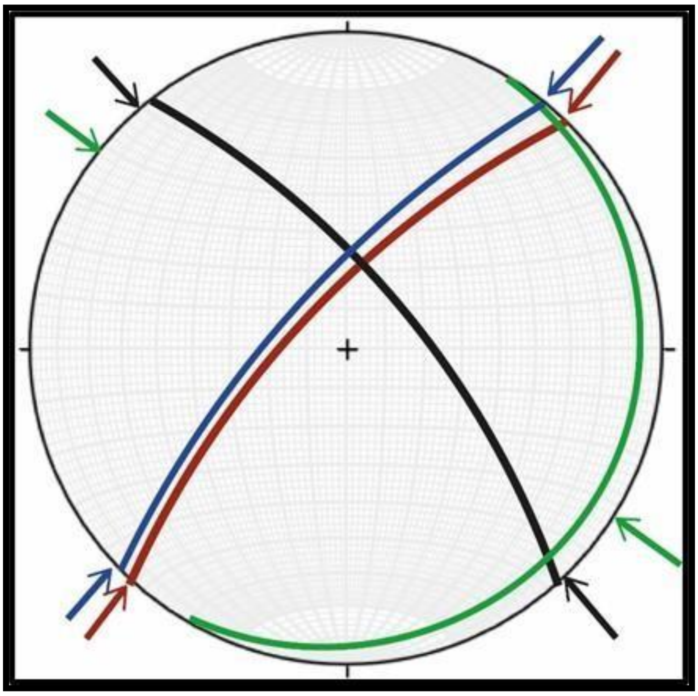


Figure 31. Black line and arrows represent the stress orientation of Fold A and B in Figure 6. Red line and arrows represent the stress orientation of the secondary folds of Peñas Coloradas (Folds D, E, F in Figure 6). Green line and arrows represent the stress orientation of Fold C in Figure 6, the recumbent fold of Chota Fm. Blue line and arrows represent the stress orientation of the small-scale chevron folds of the Chota Fm.

Figure 28 shows the stereonets of the fractures both in the Chota Fm and in Peñas Coloradas Fm. These figures show that the joints are sub-horizontal (especially in the Peñas Coloradas Fm), which indicates that σ3 is vertical, so the fractures likely represent unroofing joints. These joints form by decompression of the rocks due to tectonic uplift and removal of material from above the rock. The consistency in orientation (Figure 31 & Figure 32) leads us to assume that the joints have the same age, and were not tilted by subsequent deformation, suggesting that they are the youngest feature in the basin and probably related to the unroofing of the Chota basin.

4.3. Structural Cross Section

Figure 30 represents the structural cross-section of the study area. It presents the principal structures of the formations studied. The cross-section is divided into sections that show the main features.

Section 1 (S1): Laterized metamorphic basement deposits. These rocks underwent ductile deformation at greater depth that we interpret to have occurred before the formation of the Chota basin. The top 30-40 m of the metamorphic rocks form a lateritic paleosol indicating that the material was exhumed, forming a long-lived paleosurface that underwent weathering. Below it, the gray material represents the metamorphic basement. All is uplifted by fault 1. The weathered section suggests that the paleo-relief was low so the water could be retained and act as a weathering agent. Currently, the site has a high relief which is more conducive to mechanical erosion.

Fault 1 (Figure 6, Figure 32 F1): This fault is a normal fault responsible for uplifting the metamorphic basement, putting it in contact with the Peñas Coloradas Fm, specifically with the Canales Colorados Mbr. The hanging wall of the Fault 1 are the Canales Colorados and Brillosas Units outcrops.

Fault 2 (Figure 6, Figure 32 F2): We infer the presence of a minor antithetic normal fault due to the outcropping basement, which forms a slight ridge oblique to the prominent basement outcrop (which holds up the highest topography in the study area). This fault uplifts the metamorphic basement to the surface (Figure 6, Figure 30)

Section 2 (S2): Syncline and Anticline (Fold A, Figure 6; Figure 32). The cores of the main syncline and anticline are well expressed at landscape and mountain scale, and are evidence of the compressional regime that the whole basin suffered. In this zone we do not find the Chota Fm in contact with the Peñas Coloradas Fm, nevertheless, in the cross section we interpret it to be in unconformable contact with the Canales Colorados Member. The Chota Fm is interpreted as deposited in a half-graben, over the basement, that tapers to the east, and does not outcrop at the eastern side of our study area.

Fault 3 (Figure 6, Figure 32): Normal fault that puts the Chota Fm in contact with the Peñas Coloradas Fm. The fault is south-dipping and kinematic indicators show that it uplifts the Chota Fm and drops the Peñas Coloradas Fm. The kinematics of the fault are indicated by small scale drag folds observed in the fault zone. This is consistent with our interpretation of the Chota Fm underlying the Peñas Coloradas Fm.

Section 3 (Figure 32): The Chota Fm outcrops here in the footwall of Fault 3, which cuts the interpreted half-graben structure where the Chota Fm was deposited. The sandstones and shales of the Chota Fm that outcrop here are much more deformed than those of the Peñas Coloradas Fm, with penetrative crenulation in the shales at the core of the large recumbent fold and abundant small scale folding even in the thick-bedded sandstones (Figure 9). These rocks are also more lithified than the Peñas Coloradas Fm. We infer that these rocks underwent deeper burial and were later exhumed and juxtaposed against the Peñas Coloradas Fm by fault 3.

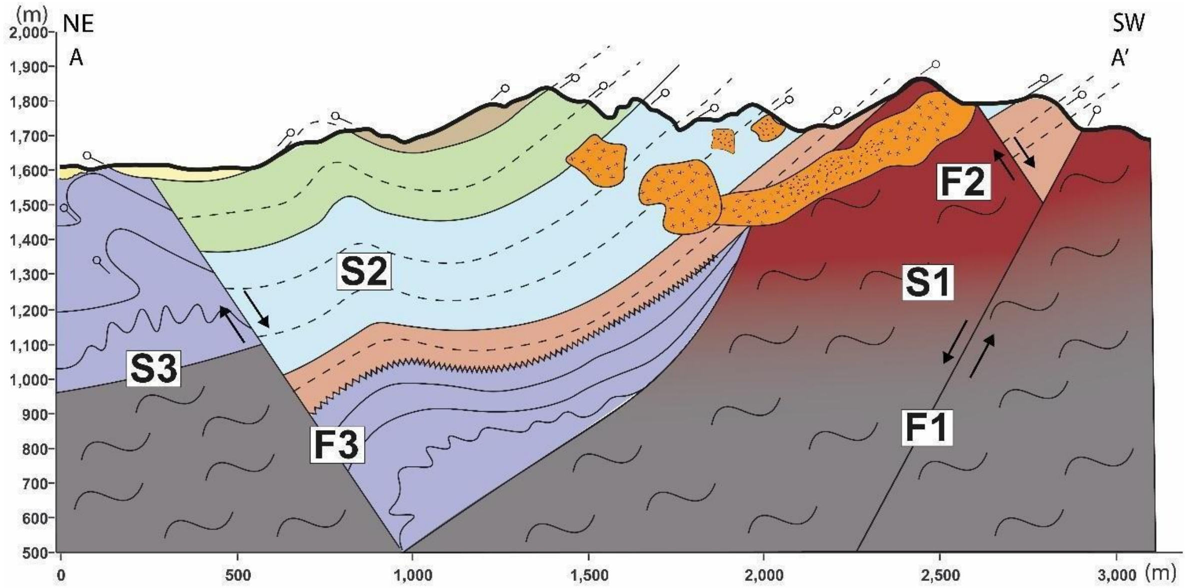


Figure 32. Structural Cross -Section divided into 3 principal sections and marked faults.

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4.4. Evolution of the Chota Basin during deposition of Chota and Peñas Coloradas Fms.

Based on the field observations, we propose two tentative models for the evolution of the study area. We don't have constraints of the age for each formation, but both models suggest that the Chota Fm. was deposited before the Peñas Coloradas Fm. The metamorphic basement was deformed by tectonic stresses long before the deposition of the Chota Basin sediments. Considering this, the first model consists of five principal stages:

First, the metamorphic basement formed a laterized paleorelief. The Chota Fm is deposited in an extensive tectonic regime in a half-graben structure created by a normal fault located east of the study area. Previous studies have suggested an age of 6 Ma for this phase (Barberi et al. 1988; Barragan et al. 1996).

Second, a compressive tectonic regime where the Chota Fm was intensely deformed by a period of compression that creates the NW-verging fold.

Third, a new extensive regime acted on the area, where faults cut and uplift the metamorphic basement, forming the second paleo-relief of the metamorphic basement. At the top of the mountains, the laterized material is completely eroded, and at the base, the material is conserved. This stage is continued by the deposition of the Peñas Coloradas Fm in the same extensive regime.

The fourth stage consists of a compression regime that deforms the Peñas Coloradas Fm and the Chota Fm. creating the folds and faults of each formation.

Finally, the fifth stage consists of another extensive regime that uplifts the Chota Fm to the surface, juxtaposing it to the Peñas Coloradas Fm, forming the last faults and joints.

The second model (Figure 33, Figure 34) is similar but considers the metamorphic basement as a rigid block that supports the deformation of the Chota and Peñas Coloradas formations. So, the first stage consists of an extensional tectonic regime under which the Chota Fm was deposited. The second stage (Figure 33A) consisted of the same extension regime, which exposed the metamorphic basement and led to the deposition of the Peñas Coloradas Fm above the Chota Fm. After this the third phase (Figure 33B) is a compressive period that folds both formations. Finally, there is a process of an extensional tectonic regime that uplifted the Chota Fm putting it in contact with the Peñas Coloradas Fm (Figure 33C&D).

The idea that supports model 1 is that the structural styles are different between each formation, and the folds have opposite vergence. However, model 2 considers that the structural styles are different, but the paleo-stresses of the folding are similar, which suggests that they were formed under the same regime. This model requires that the metamorphic basement acts as a buttress. Numerical models of compression adjacent to buttresses show that the layers that are truncated by the buttress can develop recumbent folding, while the layers above the buttress develop open folds (Vacas et al.,2004; Bastidas et al., 2014). The proposed phase of reactivation may have gently reactivated the pre-exiting normal faults, but there is no clear evidence of this, suggesting that the orientation of the faults was not favorable to be reactivated by this stress. Finally, there is a transition to an extensional regime where a normal fault uplifts the Chota Fm and juxtaposes it with the Peñas Coloradas Fm. This implies that the Chota Fm had deposits of Peñas Coloradas Fm above it, that have been eroded, and this also means that there are Chota Fm deposits under the Peñas Coloradas, which is consistent with Figure 30. The faults and joints show patterns that suggest that they were formed after the folding process in this final stage.

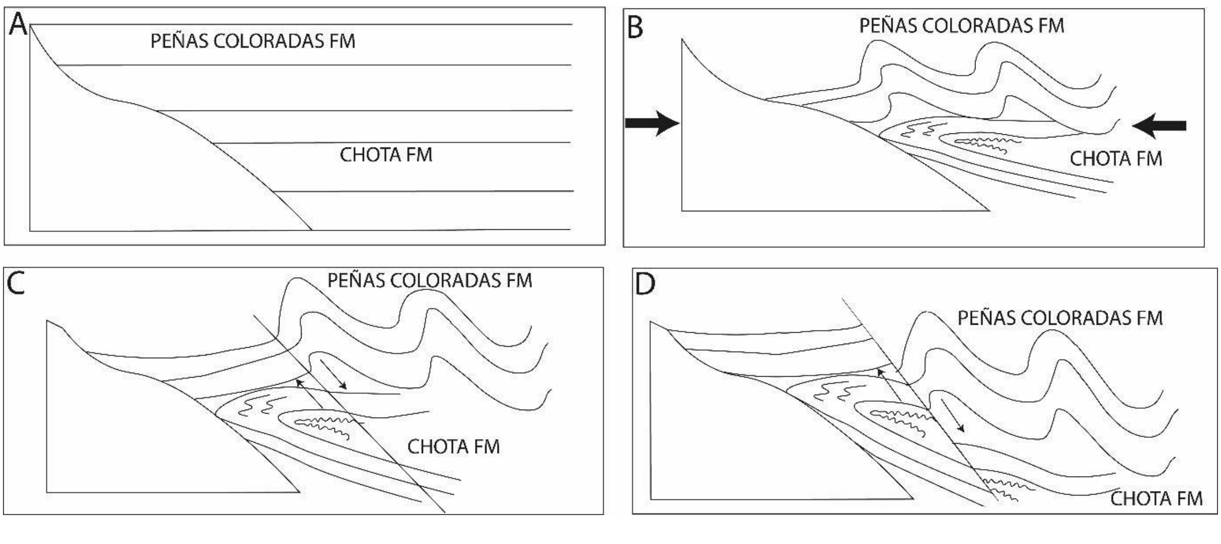

Figure 33. Schematic representation of the second evolution model of the study area. A) Stage 2. B) Stage 3, the arrows represent the compression that modelate the folds of the study area. C) Stage 4.

Normal fault. D) Representation of the fault movement that uplift the Chota Fm putting it in contact with the Peñas Coloradas Fm.

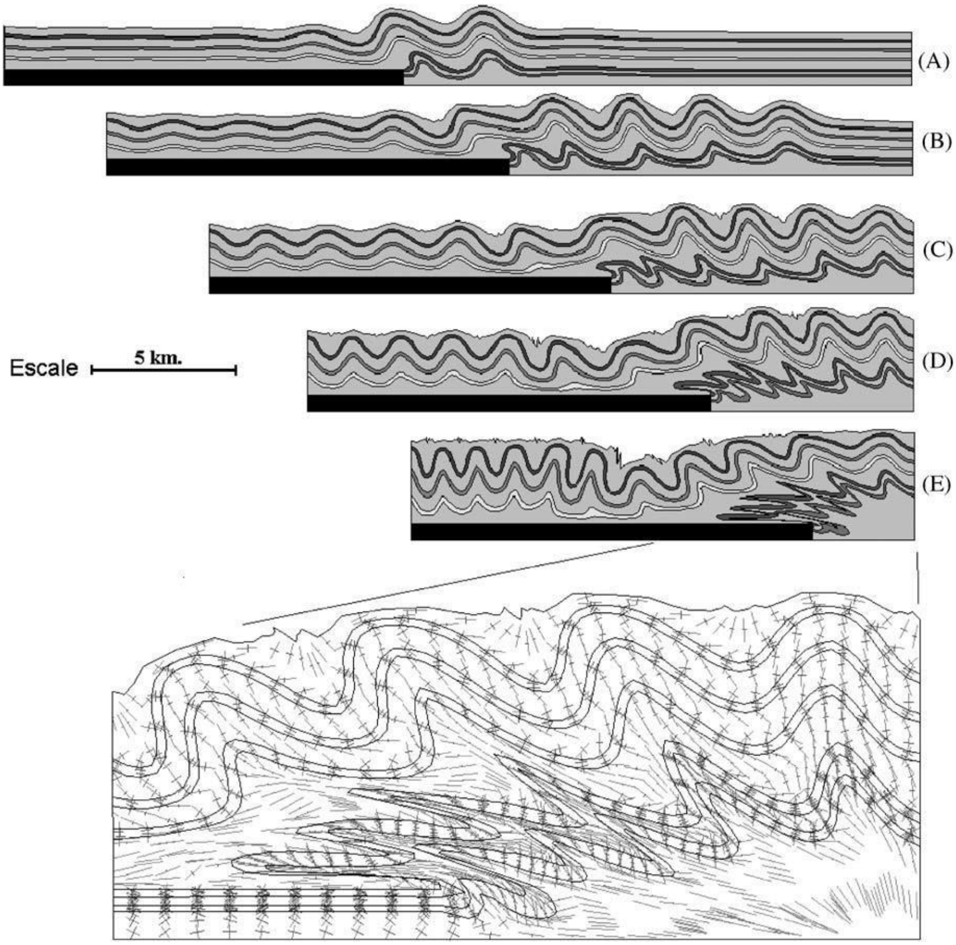

Figure 34. Schematic representation of the second evolution model of the study area. Taken from Vacas et al., 2004.

The more recent and last event that occurred in the study area was the emplacement of volcanic intrusions, that cut along the Peñas Coloradas Fm in the Canales Colorados and Brillosas Members.

V. CONCLUSIONS

During the thesis, I created a geological map of the Peñas Coloradas Fm and Chota Fm. Based on our field observations the Peñas Coloradas Fm was subdivided into 4 new members: Canales Colorados, Brillosas, Tabulares, and Volcanicas. The new subdivision of the Peñas Coloradas Fm also allows creating a more detailed stratigraphy of the zone, allowing us to understand the deformation better.

One of the present work objectives was to determine the stratigraphic sequence of the Chota basin. After determining the contacts of the formations, the structural structures, the sedimentary structures that are polarity indicators, and the deformation of each segment of interest, we conclude that the Peñas Coloradas Fm is stratigraphically above the Chota Fm.

The fault analysis showed different patterns between each formation. After performing the fold test for each group of faults, an increase in dispersion was observed, which led us to conclude that these faults were formed after folding, both for Chota Fm and Peñas Coloradas Fm. This means that the faults represent the most recent stress state, produced by the second extension period. Also, after calculating the paleo-stress state for the faults, we obtained a result that suggests a combination of strike-slip normal motion.

For Chota Fm, the main structure is a recumbent fold. Also, the central part of this fold is significantly deformed by the stress it suffered; there are small chevron folds in this part, which demonstrate the pervasive deformation that the Fm undergoes. In contrast, Peñas Coloradas Fm shows a style of large-scale open folds.

We propose two models to explain the observed structures but require more information to discriminate between them. In small-scale work, it is necessary to review the variation in thicknesses of the members to infer if the faults and folds influence the deposition. Furthermore, it is required a work that includes the stratigraphic relation of the other formations of the Chota basin to infer the complete evolution of the deposition in the entire basin. And even it is possible to relate the evolution of the basin with the whole Interandean Valley.

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ANNEXES.

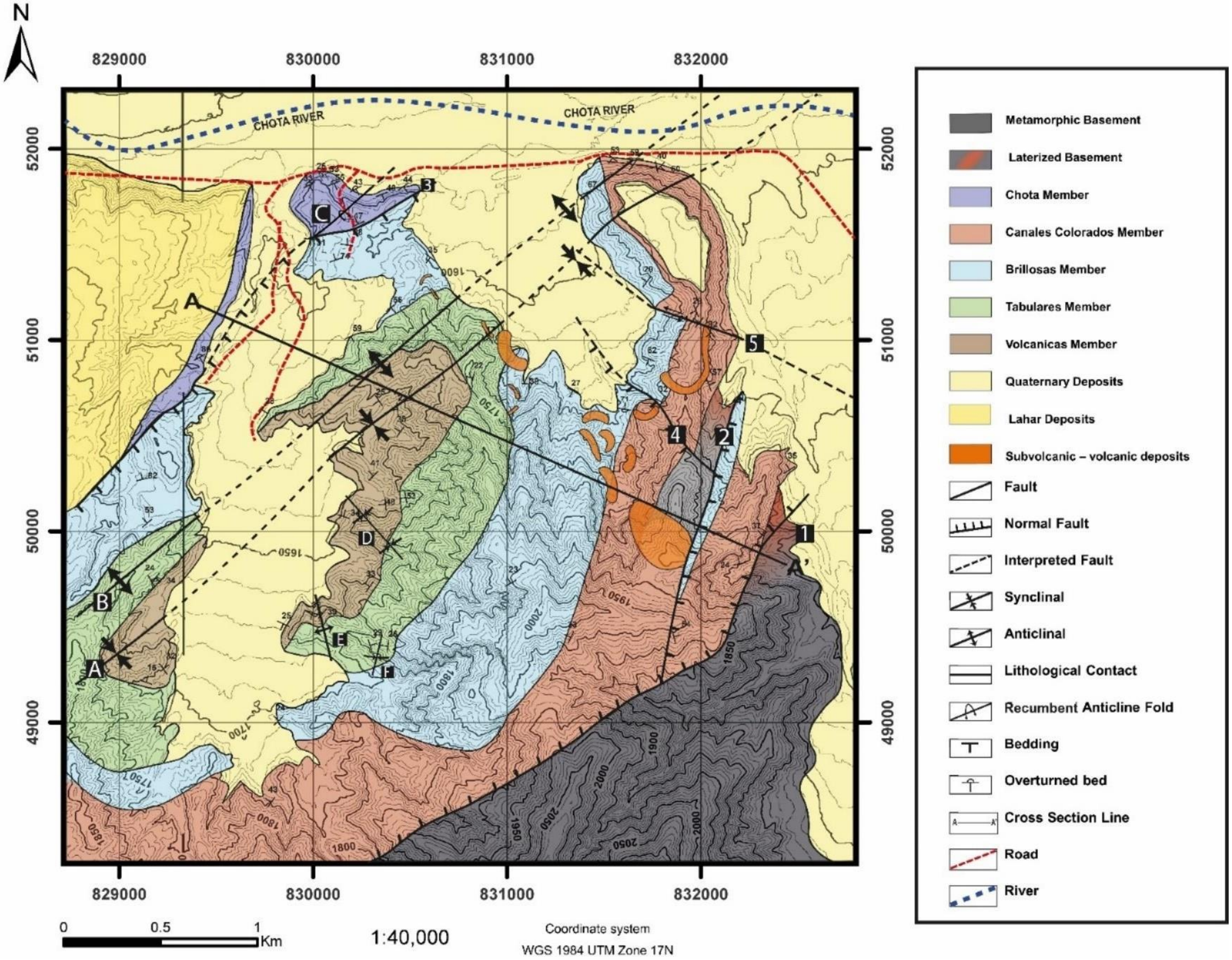

Figure 35. Amplied Geolgic map.

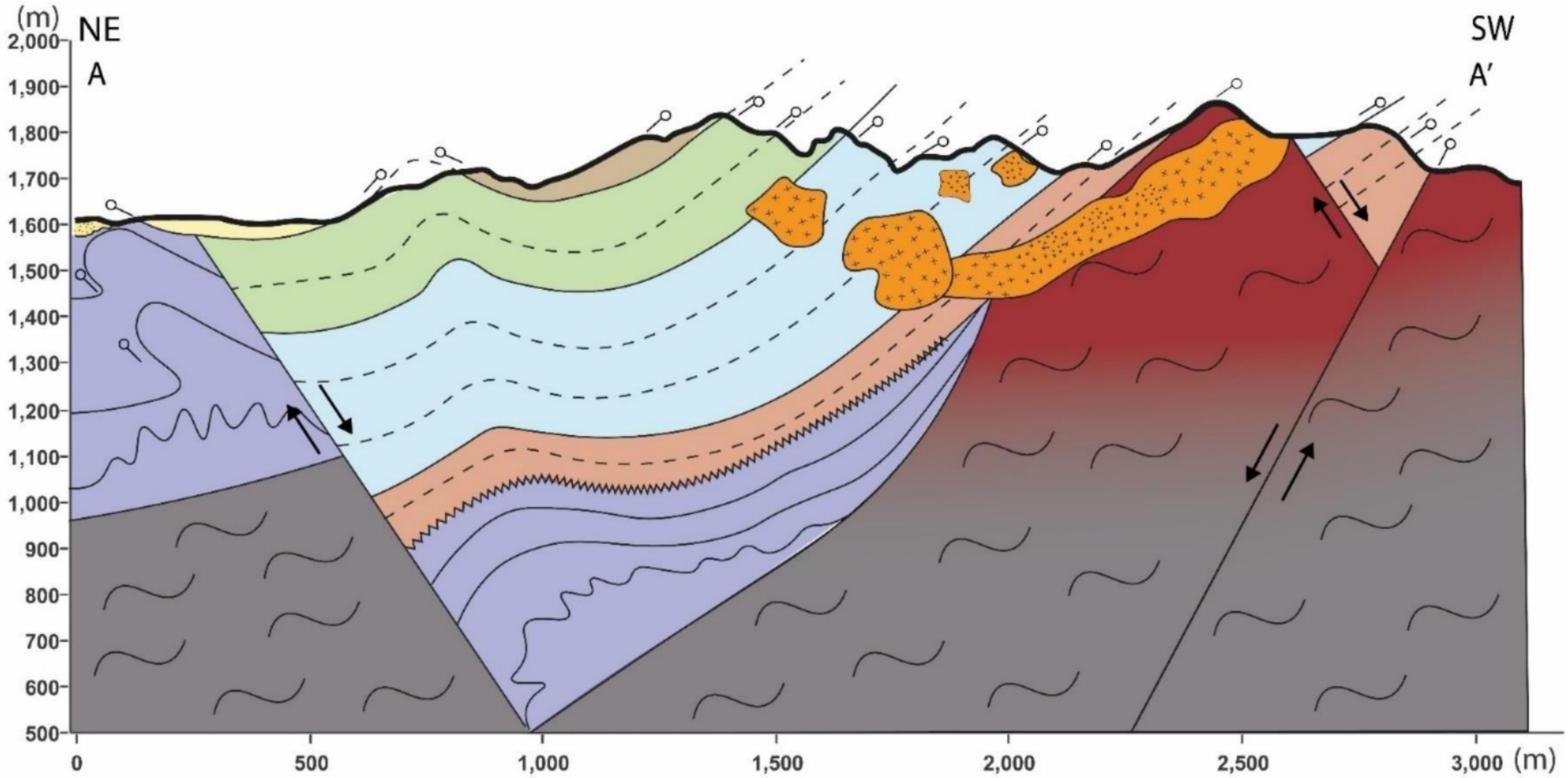

Figure 36g. Amplied geologic Cross section.

CHOTA FM FAULT MEASUREMENTS			PEÑAS COLORADAS FM FAULT MEASUREMENTS			FAULT MEASUREMENT			SLICKENSIDE MEASUREMENT	
25	57	NW	10	56	SE	85	46	SW	171	46
30	60	NW	15	36	SE	153	63	NE	139	27
32	64	NW	18	49	NW	159	60	SW	187	39
34	69	NW	24	34	SE	10	56	SE	71	52
36	64	NW	24	34	NW	15	36	SE	109	36
38	59	NW	51	44	SE	18	49	NW	98	33
57	49	S	54	27	NW	101	40	NE	106	4
66	61	NW	55	74	S	108	34	SE	145	22
81	88	E	82	41	NW	114	43	SW	157	32
83	90	E	101	40	NE	136	14	NW	167	34
161	32	NE	108	34	SE	144	61	SE	143	14
163	83	NE	114	43	NE	150	64	NE	139	35
164	87	SE	114	43	SW	158	65	NE	274	31
164	49	NW	121	2	E	199	32	NW	91	82
170	46	NE	129	21	SW	209	84	SW	101	23
171	49	NE	132	54	SW	231	29	SE	77	10
188	38	SE	136	14	NW	267	45	NW	152	44
188	36	NE	144	61	SE					
191	54	NE	150	64	NE					
191	54	NE	158	65	NE					
194	32	SE	199	32	NW					
194	29	SE	208	48	SE					
206	88	NE	209	84	SW					
206	72	NW	210	20	NW					
209	84	NW	218	46	SE					
210	73	SE	231	29	SE					
224	49	SE	234	45	SE					
225	73	SE	236	55	NW					
236	41	SE	255	22	NW					
236	60	SE	267	45	NW					
245	37	SE	268	47	S					
260	79	NW	281	40	N					
269	75	NW	332	25	SW					
332	25	SW	332	64	NE					
			358	24	E					

Tabla 1. Fault measurements.

BED PLANES CHEVRON FOLD						BED PLANES CHOTA RECUMBENT FOLD		
LIMB X			LIMB Y					
57	46	SW	211	77	SE	44	60	NW
40	59	SE	11	49	SW	40	64	NW
73	46	SE	6	62	SE	65	50	NW
19	71	NW	167	24	E	126	51	SW
238	62	SE	216	70	NW	164	87	SE
26	55	SE	23	42	NW	194	32	SE
17	69	SE	24	49	NW	201	44	NW
31	77	NW	18	61	SE	201	44	NW
33	41	SE	11	39	NW	216	41	SW
39	41	SE	21	64	NW	234	36	NW
26	78	SE	167	42	SW	254	73	NW
56	29	SE	177	52	NW	260	79	NW
218	17	SE	170	41	SW	271	73	SE
40	49	SE	9	51	NW	66	61	NW
73	46	SE	6	62	SE	50	58	SE
16	69	NW	177	20	E	60	42	SE
250	64	SE	210	59	NW	66	61	SE
21	51	SE	24	49	NW	69	69	SE
11	55	SE	20	42	NW	81	47	NE
32	66	NW	12	59	SE	90	44	S
30	39	SE	5	42	NW	125	53	SW
40	26	SE	11	71	NW	161	26	SE
14	75	SE	170	34	SW	161	32	SE
110	46	SW	10	81	SE	194	18	SE
32	23	SE	176	70	SW	219	44	SE
52	50	NW	12	59	SE	226	64	SE
251	67	SE	24	42	NW	231	75	SE
218	43	SE	212	21	NW	231	51	SE
17	62	SE	10	36	NW	232	63	SE
44	25	SE	166	82	NW	241	55	SE
						255	68	SE
						261	81	SE
						264	53	SE
						264	69	SW
						264	28	SE
						266	29	SE
						267	28	NE
						269	73	SE
						274	83	SE
						277	31	SW
						287	46	SW
						332	25	SW

Tabla 2. Measurements of bed planes used to create the stereonets of the chevron folds and the recumbent Chota fold.

Bed planes of Peñas Coloradas Fm.		
172	22	NE
255	82	NW
164	28	NE
166	24	NE
135	22	NE
50	53	NW
111	15	NE
150	24	NE
36	34	SE
145	32	NE
221	22	NW
210	35	NW
199	78	NW
223	83	NW
240	86	SE
215	28	SE
36	43	NW
46	24	NW
294	25	SW
294	25	SW
282	24	SW
287	24	SW
276	28	SW
280	40	SW
130	26	SW
95	36	SW
109	38	SW
157	44	SW
157	44	SW
142	36	SW
142	36	SW
110	55	SW
80	39	SE
90	40	SE
53	67	NW
40	39	NW
43	42	NW
36	80	NW
65	40	NW
48	42	NW
62	48	NW
55	50	NW
226	64	SE
55	42	NW
36	46	NW

48	51	NW
35	46	NW
54	49	NW
251	74	NW
25	43	NW
42	44	NW
45	34	NW
48	45	NW
48	45	NW
236	53	NW
253	63	NW
35	46	NW
50	40	NW
50	40	NW
32	30	NW
35	42	NW
135	4	SW
109	34	NE
29	43	NW
35	48	NW
56	39	NW
265	28	SE
69	42	SE
65	59	SE
263	47	SE
12	23	NW
109	43	SW
95	47	SW
110	55	SW
264	19	SE
20	49	NW
15	31	NW
85	39	NW
42	22	NW
35	25	NW
50	30	NW
22	29	NW
4	36	NW
8	40	NW
57	24	NW
66	33	NW
260	46	SE
56	44	NW
30	40	NW
26	40	NW
35	33	NW

45	34	NW
58	41	NW
56	44	NW
15	35	NW
45	41	NW
44	31	NW
63	16	NW
30	27	NW
18	33	NW
19	55	NW
73	49	SE
164	29	NE
34	28	NW
38	34	NW
54	34	NW
20	42	NW
145	25	SW
115	27	SW
70	11	SE
263	56	SE
276	24	SW
35	10	NW
25	24	NW
15	33	NW
19	36	NW
246	60	SE
250	69	SE
175	48	SW
197	26	NW
271	50	SE
231	56	SE
31	36	NW
61	48	NW
173	23	SW
31	38	NW
335	64	SE
40	38	NW
34	33	NW
170	53	SW
27	45	NW
45	46	NW
44	30	NW
231	54	SE
95	84	SW
130	35	SW
132	40	SW

15	22	NW
23	64	NW
145	17	SW
11	35	NW
24	29	NW
24	37	NW
175	40	SW
184	38	NW
184	38	NW
30	21	NW
208	28	NW
120	27	SW
53	33	NW
67	67	SE
155	31	SW
128	53	SW
222	54	NE
214	59	NW
41	34	NW
239	76	NE
193	44	SE
217	20	NW
205	72	SE
110	62	SW
193	77	SE
94	34	NE
168	40	SW
191	50	SE
199	41	SE
206	32	NW
234	35	NW
243	63	SE
243	63	SE
21	52	NW
79	74	SW
221	60	SE
158	29	SW
40	21	NW
322	82	SW
20	40	NW
340	57	NE
86	18	NW
74	36	NW
179	24	NE
110	44	NE
62	19	NW

261	20	NW
204	28	NW
238	35	NW
16	31	NW
40	64	NW
24	42	NW
23	64	NW
126	51	SW
198	51	SE
194	18	SE
264	28	SE
90	44	S
125	53	SW
177	22	NE
167	27	NE
176	26	NE
169	14	NE
177	41	NE
191	64	SE
236	41	SE
181	63	SE
184	47	SE
231	73	SE
129	27	NE
244	34	SE
252	53	SE
225	7	SE
234	4	SE
230	40	SE
263	51	SE
230	74	SE
220	61	SE
224	69	SE
215	69	SE
234	64	SE
226	70	SE
221	81	SE
234	66	SE
241	84	SE
245	88	SE
232	58	SE
242	62	SE
241	84	SE
225	64	SE
233	73	SE
215	56	SE

235	63	SE
224	50	SE
229	62	SE
214	46	SE
246	68	SE
236	61	SE
239	62	SE
238	53	SE
237	37	SE
231	48	SE
234	39	SE
270	81	NW
233	35	SE
219	51	SE
135	55	SW
259	82	NW
113	18	SW
150	22	SW

Table 3. Bed plane measurements in the Peñas Coloradas Fm.

JOINTS PEÑAS COLORADAS FM		JOINTS CHOTA FM	
304	82	78	26
352	53	66	57
352	52	61	54
356	71	76	33
181	73	106	53
87	51	153	70
79	51	178	88
84	55	85	44
69	78	36	56
89	62	182	83
124	88	160	63
124	82	166	58
144	85	151	76
266	71	153	75
31	54	64	39
98	85	111	52
100	74	168	31
114	89	31	48
108	81	54	47
103	60	146	66
101	80	147	56
170	66	148	72
175	72		

95	59
85	88
74	86
100	66
25	90
75	74
191	25
67	65
78	76
86	85
56	82
78	88
92	79
83	71
276	24
160	81
165	58
160	54
166	70
94	66
85	71
85	66
39	29
40	49
159	90
135	90
90	65
85	42
34	61
170	60
164	80
328	20
65	53
180	61
184	42
180	60
173	14
100	13
115	31
170	40
45	20
161	72
170	90
154	71
158	43

Table 4. Joints measurements in Chota Fm and Peñas Coloradas Fm